5

Reed Switches and Reed Relays

5.1 Who Invented a ''Reed Switch''?

Many engineers have come across original contact elements contained in a glass shell (Figure 5.1) However, not everyone knows that reed relays differ from ordinary ones not because of the germetic shell (sealed relays are not necessarily reed ones), but because of the fact that in a reed relay, a thin plate made of magnetic material functions as contacts, magnetic system, and springs at the same time. One end of this plate is fixed, while the other end is covered with some electroconductive material and can move freely under the effect of an external magnetic field. The free ends of these two plates, directed towards each other, are overlaped for from 0.2 to 2 mm and form a basis for a new type of a switching device — a ''germetic magnetically controlled contact'' (in Russian) or ''reed switch'' (in English). Such a contact is called a ''magnetically controlled contact'' because it closes under the influence of an external magnetic field, unlike contacts of ordinary relays which are switched with the help of mechanical force applied directly to them. The original idea of such a function mix, which was in fact the invention of the reed switch, was proposed in 1922 by a professor from Leningrad Electrotechnical University, V. Kovalenkov, who lectured on ''magnetic circuits'' from 1920 until 1930. Kovalenkov received a U.S.S.R. inventor's certificate registered under No. 466 (Figure 5.2).

In 1936, the American company ''Bell Telephone Laboratories'' launched research work on reed switches. Already in 1938 an experimental model of a reed switch was used to switch the central coaxial cable conductor in a high-frequency telecommunication system, and in 1940 the first production lot of these devices, called ''Reed Switches,'' was released (Figure 5.3). Reed switch relays (that is a reed switch supplied with a coil setting up a magnetic field — Figure 5.4a), compared with electromagnetic armature relays which are similar in size, have higher operation speeds and durability, a higher stability of transient resistance, and a higher capability to withstand impacts of destabilizing factors (mechanical, climatic, specific), in spite of their relatively low switching power.

At the end of the 1950s some western countries launched construction of quasi-electronic exchanges with a speech channel (which occupied over 50% of the entire equipment of an exchange) based on reed switches and control circuits on semiconductors. In 1963, the Bell Company created the first quasi-electronic exchange of ESS-1 type designed for an intercity exchange. In a speech channel of such an exchange more than 690,000 reed switches were used. In the ensuing years the Western Electric Company arranged a lot production of telephone exchanges based on reed switches with a capacity from 10 up to 65,000 numbers. By 1977, about 1,000 electronic exchanges of this type had been put into operation in the U.S.A.

FIGURE 5.1
Different types of modern sealed reed switches.

In, Japan the first exchange of ESS-type was put into service in 1971. By 1977, the number of such exchanges in Japan was estimated in hundreds. In 1956, the Hamlin Co. launched lot production of reed switches and soon became the major producer and provider of reed switches for many relay firms. Within a few years this company built plants producing reed switches and relays based on them in France, Hong Kong, Taiwan, and South Korea. Under its licensed plants in Great Britain and Germany, it also started to produce reed switches in those countries. By 1977, Hamlin produced about 25 million reed switches, which was more than a half of all its production in the U.S.A. Reed switches produced by this firm were widely used in space-qualified hardware, including man's first flight to the Moon (the Apollo program). The cost of each reed switch thoroughly selected and checked for this purpose reached $200 a piece.

In the former Soviet Union lot production of reed switches was launched in 1966 by the Ryazan Ceramic–Metal Plant (RCMP). Plants of the former Ministry of Telecommunication Industry (its 9th Central Directorate in particular) were also involved in production of weak-current relays based on reed switches. At the end of the 1980s there were 60 types of reed relays produced in the U.S.S.R. The total amount of such relays reached 60 to 70 million a year. Economic crises in Russia led to a steep decline in the production of both reed switches and reed relays. In 2001, plants producing relays (those which were still working in Russia) ordered only about 0.4 million reed switches for relay production.

Depending on the size of a reed switch, the working gap between contact-elements may vary between 0.05 and 0.8 mm (and more for high-voltage types) and the overlap of ends of contact-elements between 0.2 and 2 mm. Due to the small gaps between contacts and a

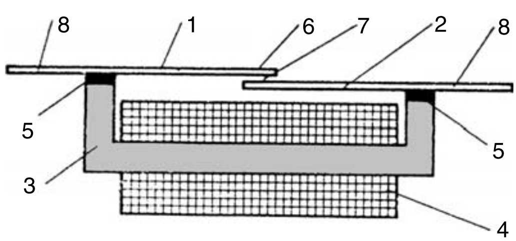


FIGURE 5.2
Kovalenkov's relay. 1 and 2 — contact-elements (springs) made of magnetic material; 3 — external magnetic core (the core of the relay); 4 — control winding (external magnetic filed source); 5 — dielectric spacers; 6 — ends of contact-elements; 7 — working gap in magnetic system and between contacts; 8 — contact outlets for connection of external circuit.

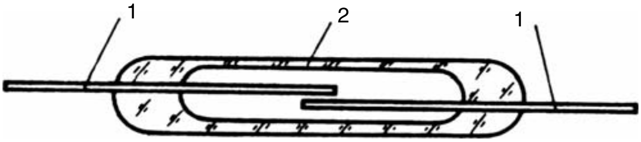


FIGURE 5.3
Construction of a modern reed switch. 1 — contact elements (springs) from permalloy; 2 — glass hermetic shell.

small total weight of movable parts, reed switches can be considered to be the most high speed type of electromagnetic switching equipment with a delay of 0.5 to 2 ms capable of switching electric circuits with frequencies of up to 200 Hz. The smallest in the world reed switches produce Hermetic Switch, Inc. (U.S.A.) (Figure 5.4b). The tiny oval shaped glass balloon of the HSR-0025 reed switch measures a mere 4.06 mm long, 1.22 mm wide, and 0.89 mm high. Maximum switching rating of HSR-0025: 30 V, 0.01 A, 0.25 W. Sensitivity ranges from 2 to 15 A-turns.

Bigger relays can switch higher switching current, as the contacting area of the contact-elements, their section, contact pressure, and thermal conductivity, increase. Most reed switches have round-shape shells (balloons), because they are cut from a tube (usually a glass one), the ends of which are sealed after installation of contact-points. Glass for tubes should be fusible with softening temperatures and coefficients of linear expansion similar to that of the material of contact-elements.

Contact-elements of reed switches are made of ferromagnetic materials with similar coefficients of linear expansion as for glass. Most often it is Permalloy, an iron–nickel alloy (usually 25% nickel in alloy). Sometimes Kovar, a more high-temperature alloy is used. It allows application of more refractory glass for tubes (560 to 600 °C) and as a result, more heat-resistant reed switches are obtained. To provide a better joint with the glass, contact-points are sometimes covered with materials providing better joints with glass than Permalloy. Sometimes contact-elements have more a complex cover consisting of sections with different properties. Contact-elements may also contain two parts, one of which joins well with the tube glass and has the required flexibility, and the other has the necessary magnetic properties. The contacting surfaces of contact-elements of average power reed switches are usually covered with rhodium or ruthenium; low-power reed switches designed for switching of dry circuits are covered with gold and high-power and high-

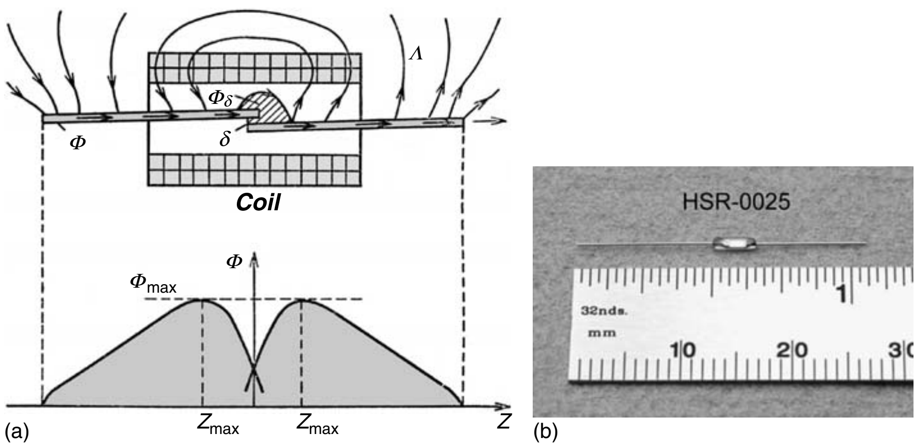


FIGURE 5.4
(a) Magnetic field in a sealed reed relay. δ — working (magnetic and contact) gap. (b) The smallest in the world reed switch, produced by Hermetic Switch, Inc.(U.S.)

voltage reed switches with tungsten or molybdenum. Covering is usually made by galvanization with further heat treatment to provide diffusion of atoms of a cover to the material. It can also be carried out by vacuum evaporation or other modern methods. Contact-elements of high-frequency reed switches are fully covered with copper or silver to avoid loss of or attenuation of high-frequency signals, and after that the contacting surfaces are also covered with gold.

The tube of a medium or low-power reed switch is usually filled with dry air or a mixture of 97% nitrogen and 3% hydrogen. A 50% helium–nitrogen mixture, carbonic acid, and other mixtures of carbon dioxide and carbonic acid can also be used. Carefully selected gas environments effectively protect contact-elements from oxidation and provide better quenching of spark as low powers are being switched. Reed switches designed for switching of voltages from 600 up to 1000 V have a higher gas pressure in the tube, which may reach several atmospheres. High-voltage reed switches (more than 1000 V) are usually vacuumized.

The fact that there are no rubbing elements, full protection of contact-elements from environmental impact, and the possibility to create a favorable environment in the contact area, provides switching and mechanical wear resistance of reed switches estimated in the millions and even billions. Reed switches which are in mass production and which are widely used in practice can be classified by the following characteristics:

1. Size
   - Normal or standard reed switches with a tube about 50 mm in length and about 5 mm in diameter
   - Subminiature reed switches with a tube 25 to 35 mm in length and about 4 mm in diameter
   - Miniature reed switches with a tube 13 to 20 mm in length and 2–3 mm in diameter
   - Micro-miniature reed switches with a tube 4 to 9 mm in length and 1.5–2 mm in diameter
2. Type of a magnetic system
   - Neutral
   - Polarized
3. Type of switching of electric circuit
   - Closing or normally open — A type
   - Opening or normally closed — B type
   - Changeover — C type
4. Switched voltage level
   - Low-voltage (up to 1000 V)
   - High-voltage (more than 1000 V)
5. Switched power
   - Low-power (up to 60 W)
   - Power (100 to 1000 W)
   - High-power (more than 1000 W)
6. Types of electric contacts
   - Dry (the tube is filed with dry air, gas mixture, or vacuumized)
   - Wetted (in the tube there is mercury wetting the surface of contact-elements)

7. Construction of contact-elements
   - Console type (symmetrical or asymmetrical) with equal hardness of the movable unit (Figure 5.3 — main type of reed switches)
   - With a stiff movable unit
   - Ball type
   - Powder type
   - Membrane type, etc.

5.2 Coruscation of Ideas and Constructions

The classification given above is relative and is true for classical constructions of reed switches produced on mass production lines. One should bear in mind, however, that there are so many patents for very original and sometimes even exotic constructions of reed switches that it is almost impossible to include them all in the given classification. Some reed switches are produced in limited numbers for specific purposes, others will always remain examples of engineers' inventiveness. However, even a brief description of their constructions can reveal major problems for designers on the one hand and on the other hand provide some solutions to these problems. For example, the most popular construction of a reed switch with console contact-elements with equal hardness along the length (Figure 5.3) turns out not to be so optimal, since it requires great efforts for curving of the contact-elements. The slightest deformation or inaccuracy of soldering in glass considerably reduces the contacting area and impairs its switching properties. Requirements for contact-elements are quite inconsistent; on the one hand, the bigger the section of the contact-elements, the better their magnetic conductivity and the greater the contact pressure that can be applied with specified magnetic flux of a control coil. On the other hand, the hardness also increases considerably and a greater mechanical effort is required to curve them to the closing point. Is it possible to increase magnetic conductivity of a reed switch without an increase of hardness of the contact-points?

Yes, it is! Moreover, there are several ways of doing it!

In fact, the tube of a reed switch must not necessarily be made of glass. It is true that glass provides a hermetic soldered joint with metal, but the whole tube must not necessarily be of glass. It can also be metallic with glass insulators, as in sealed relays in metal cases. Actually it is not even necessary to put insulators on both sides. One can connect electrically one of the contact-elements to a metal case, and one glass insulator will be enough. A more rational solution, though, would be perhaps to remove this contact-element and use a case instead. This idea was implemented by the inventor of the reed switch, as shown in Figure 5.5.

The use of a steel case instead of one of the contact-elements allows us to increase considerably the magnetic conductivity of the construction, and also contact pressure. Apart from other obvious advantages of replacement of glass with metal, one can also include greater strength of the reed switch, better heat abstraction from contacting area, etc.

The American inventor R. Alley chose another way (patent No. 2987593). He made contact-elements with unequal hardness along the length. A part with a small section resembling a flexible spring provided the required flexibility and stiffer parts with a greater section ending with massive contacts provided high magnetic conductivity (Figure 5.6). Another solution is to use three absolutely stiff ferromagnetic elements

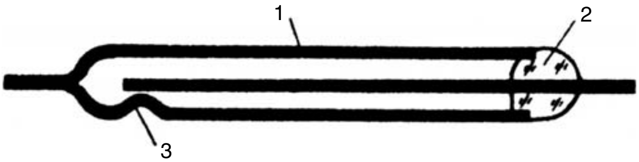


FIGURE 5.5
Reed switch with a tube made of ferromagnetic metal. 1 — tube; 2 — glass insulator; 3 — stationary contact.

with the central one swinging on hinges or moving linearly (Figure 5.7), linking the two other stiff stationary elements.

Some types of relays require reed switches with one-way outlets (Figure 5.8). In the place of the curve the movable contact-point of the closed reed switch has a smaller section, which also reduces its hardness.

In reed switches with reverse outlets there is an attracting force between differently magnetized contact-elements, while in reed switches with one-way outlets (Figure 5.8), there is a repulsive force between the equally magnetized parts of the contact-elements.

Both of these principles are used in changeover reed switches (Figure 5.9). When an external magnetic field affects such a reed switch, contact-elements 1 and 2 are magnetized differently creating an attracting force, and contact-elements 2 and 3 are magnetized equally, creating a repulsive force. As a result, the movable contact-point 2 curves switching the external circuit.

Another type of switched reed switch was invented by W. Eitel, an employee of the Penta Laboratories firm (U.S.A. patent No. 2360941, Figure 5.10). Reed switches produced by this firm are usually used for switching of high-frequency circuits when minimal capacity between contact-points is required. Such construction also has good magnetic and switching characteristics because the stationary contact-point is supplied with a ferromagnetic packing, which considerably increases permeance of the system and provides reliable contact pressure. A movable contact-point is constituent, as it contains a part of increased flexibility and a stiff part of quite a large section made of ferromagnetic material with a powerful contact at the end. Such a reed switch with a well vacuumized shell can withstand voltage between contacts of up to 20 kV and skip short current pulses with an amplitude of up to 100 A in the closed position.

The T-shape form of a reed switch with two symmetric magnetic cores (Figure 5.11), and two control windings on these cores, allows creation of a relay with a differential function, that is, a relay, the mode of which depends on a difference of currents in the control windings, on current direction in windings and different logical combinations.

In standard electromagnetic relays the magnetic circuit and the contact system are two independent systems connected to each other only by an insulated pusher, therefore only

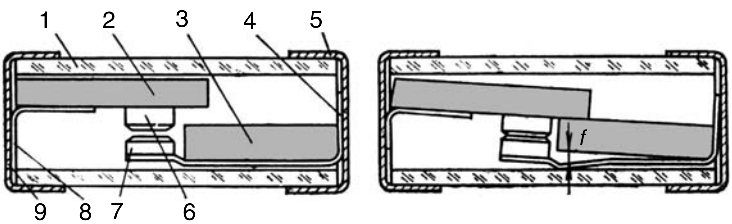


FIGURE 5.6
Power reed switch with contact-elements of unequal hardness. 1 — glass shell; 2, 3 — stiff parts of contact-elements; 4, 8 — flexible parts of contact-elements; 5, 9 — outlet contacts for external connection; 6, 7 — contact straps.

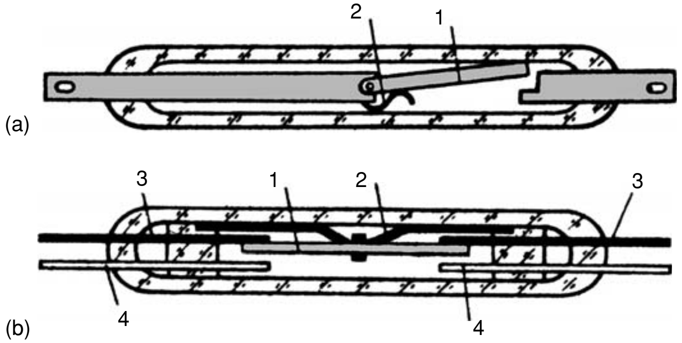


FIGURE 5.7
Reed switches with absolutely stiff contact-elements and an internal movable unit. 1 — movable unit; 2 — spring; 3 — passive (nonmagnetic) contact-points forming an opening contact; 4 — ferromagnetic contact-points forming a closing contact.

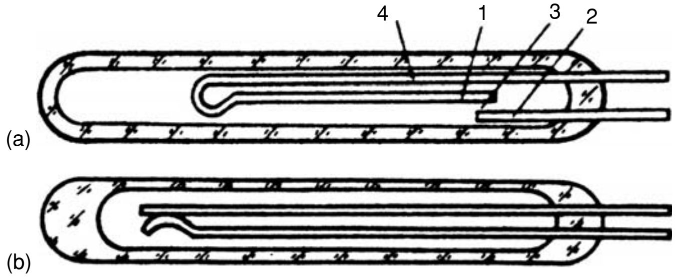


FIGURE 5.8
Closing (above) and opening reed switches with one-way outlets. 1 and 4 — forward and reverse parts of movable contact-elements; 2 — stationary contact-elements; 3 — gap between contacts.

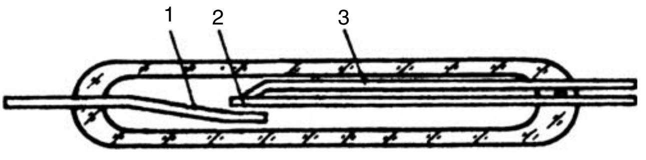


FIGURE 5.9
Changeover reed switch. 1 — stationary contact-element of the closed contact; 2 — flexible movable contact-element; 3 — stationary contact-element of the opening contact.

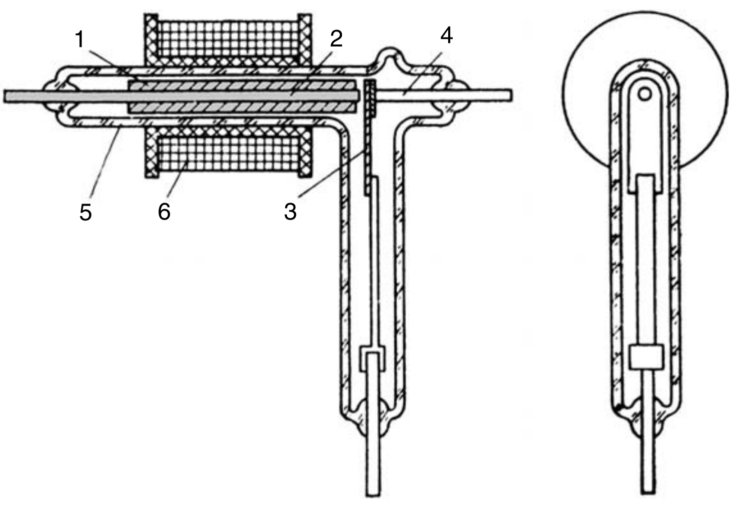


FIGURE 5.10
Switched T-shape vacuum reed switch. 1 — ferromagnetic packing for stationary contact-elements; 2 and 4 — stationary nonmagnetic contact-elements; 3 — stiff ferromagnetic part of the movable contact-point; 5 — glass tube; 6 — control coil.

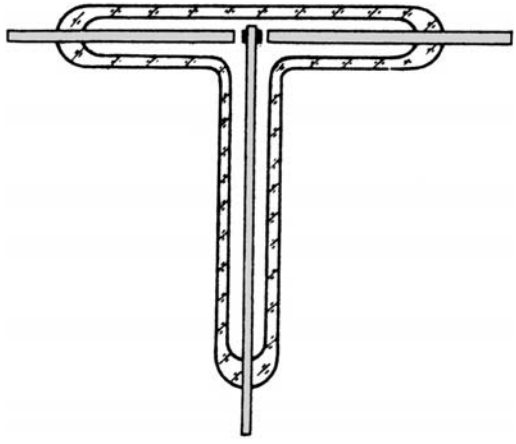


FIGURE 5.11
Symmetric T-shape reed switch.

the contact spring force determines contact pressure. In a reed relay, however, these systems are interrelated and the contact pressure directly depends on the magneto-motive force of control winding. As the reed switch becomes energized, the gap between the contacts is reduced, as well as the nonmagnetic gap in the magnetic circuit. This leads to an increase in electromagnetic tractive effort affecting the contact-elements and to higher moving speed of the contact-elements. As a result, the contact-points collide with more energy, rebound, collide again . . . causing the switching process of reed switches with dry contacts to be accompanied with considerable vibration of the colliding contact-elements (Figure 5.12). As can be seen from the oscillogram, the dynamic resistance of the reed switch varies from a minimal value tending to zero (this is the static transient resistance of closed contacts of a reed switch) up to infinity, that is up to a full break in the switched circuit.

Parameters of the transient switching process depend mostly on the size of the reed switch, the weight of the contact-elements, their elasticity, etc. It is obvious that vibration undermines wear resistance of contact-elements, which is why it is only natural that designers do their best to remove or at least to reduce vibration. In the German patent No. 1110308 a changeover reed switch with a split movable contact-elements 1 is described (Figure 5.13). Both parts of the split movable contact-point work as independent contact-points. Due to the difference in width their hardness is different and different tractive efforts are required to curve them. As a result, when a reed switch is energized these parts nonsimultaneously collide with the stationary contact-point and the oscillating process of

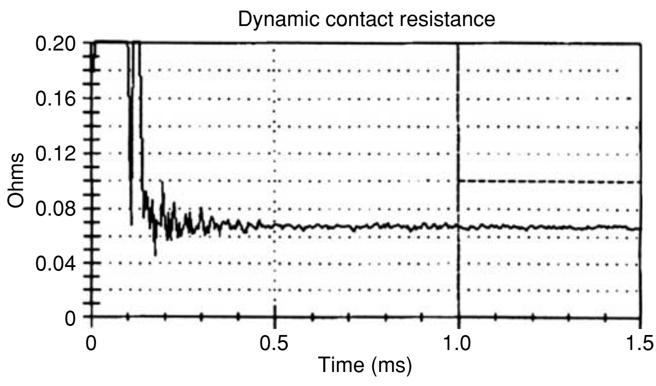


FIGURE 5.12
Oscillogram of the switching process of a closed miniature reed switch.

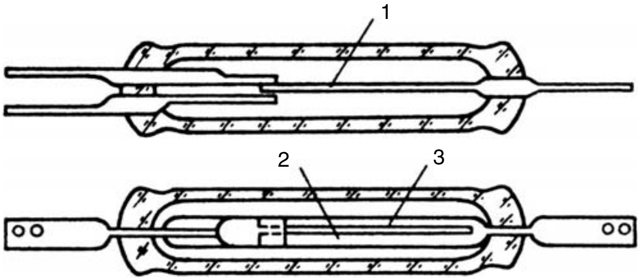


FIGURE 5.13
Bounce-free reed switch with split contact-elements. 1 — split movable contact-element; 2, 3 — parts of different width of the movable contact-element.

one of these parts is practically in antiphase with the other, which is why it is practically immediately dampened.

In another German patent (No. 1117761), there is a description of a reed switch with a movable contact-element supplied with a spring (2, Figure 5.14). As the contact-elements collide and start to vibrate, turns of the spring (2) move with regard to each other, with the considerable friction absorbing kinetic energy of the oscillating contact-elements.

The technical solutions described above were aimed at reduction of vibration, or at removal of the consequences of specific build-up of the magnetic field in a reed switch, while the solution suggested in the patent No. 1146738 registered in the former Soviet Union was aimed at removal of the original source of vibration, that is the increase in tractive effort affecting contact-elements when they are closing. In this construction there are special notches and lugs that fit each other without touching at the last stage of closing-in of contact-points. The configuration of the magnetic field in the gap between the contact-points leads to a weakening of tractive effort and the contact-points touch each other without any vibration (Figure 5.15).

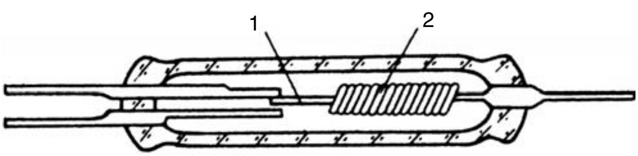


FIGURE 5.14
A bounce-free reed switch with a spring 2 on a movable contact-element 1.

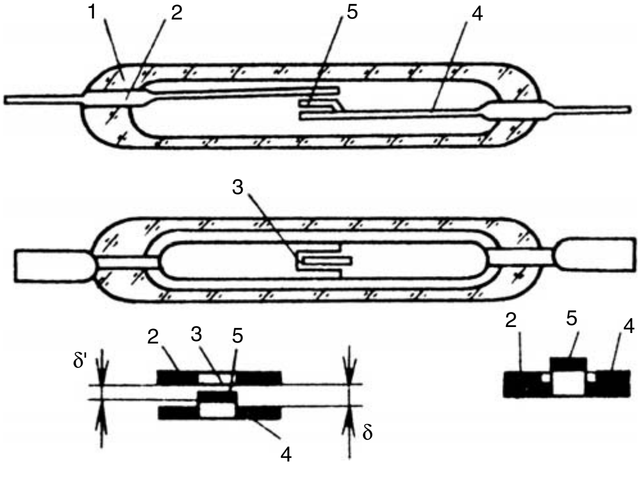


FIGURE 5.15
A bounce-free reed switch with special notches in contact-elements delaying the process of their closing in the last stage of the switching process. 1 — glass tube; 2 and 4 — contact elements; 3 — notch on the end of the contact-elements 2; 5 — deflected part on the end of the contact-elements 4.

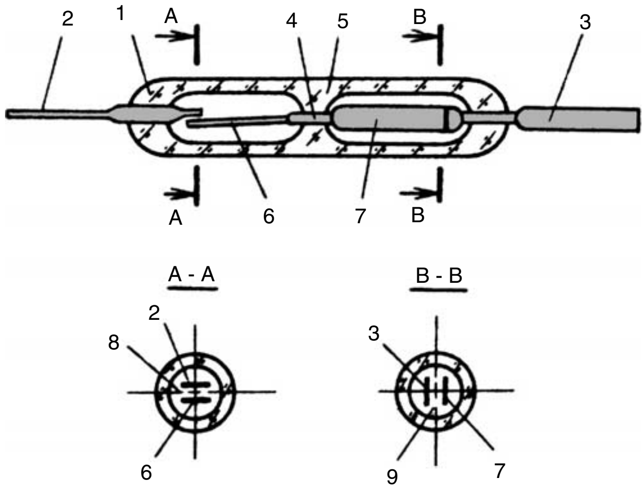


FIGURE 5.16
Vibration-resistant reed switch with three contact-points in mutually perpendicular planes. 1 — glass tube; 2 and 3 — stationary contact-points revolved through 90°; 4 — central (stationary) part of the movable contact-point; 5 — place of fixation of the movable contact in the tube; 6 and 7 — movable parts of the contact-point revolved through 90°; 8 and 9 — working gaps.

Apart from the problem of vibration of contact-elements in the process of operation (closing) of the reed switch, there is also a problem of resistance of the reed switch (and consequently reed relays) to external mechanical effects: vibration, accelerations, shocks. There are a number of technical solutions allowing an increase of resistance of the reed switch to spontaneous closing under mechanical impact.

In the construction described in the patent of the former Soviet Union No. 528624 (Figure 5.16), there are three contact-elements: two movable contact-elements (2 and 3) fused into the glass of the tube and revolved through 90°, and a stationary one fixed in the central part (4) of the tube and having the free ends (6 and 7) also revolve through 90°. The reed switch closes only when both ends (6 and 7) of the movable contact-elements simultaneously close, but since they can move only in perpendicular planes, their closing under external shocks or vibration is practically out of question.

Quite an original solution is described in the patent of the former Soviet Union No. 576618 (Figure 5.17). In this reed under no external magnetic field switch, the movable parts (4 and 5) of the central contact-elements are pressed to a flat stop (2). Under an external magnetic field of the coil both movable parts (4 and 5) are repelled and the stationary contact-elements (6 and 7) close. A flat stop disables simultaneous closing of the stationary part with parts 4 and 5, in case acceleration or shock occurs. It should be noted, however, that fast rotation of such a reed switch might cause separation of parts 4 and 5 under centrifugal force, leading to a closing of the stationary contact-points 6 and 7. For example, in airborne instruments and equipment of noncontrolled missiles, stabilization during the flight is carried out with the help of a special motor spinning the missile along its axis, and with stabilizers placed at certain angles to maintain the rotation of the missile during flight. For such cases, the author of this book has suggested (the patent of the former Soviet Union No. 1387069) filling the internal volume of a reed switch with

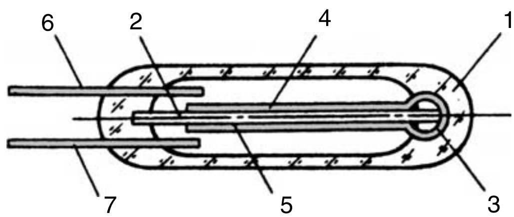


FIGURE 5.17
Vibration-proof reed switch with repelled contact-elements. 1 — glass tube; 2 — flat stop fixed on the butt-ends of the tube; 3 — place of fixation of a movable contact-elements in the glass of the tube; 4 and 5 — ends of the movable contact-elements; 6 and 7 — stationary contact-elements.

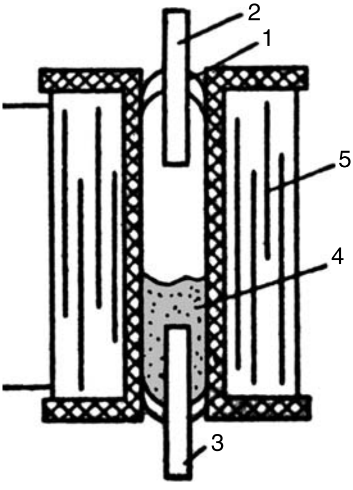


FIGURE 5.18
Reed switch with fusible movable contact-elements. Described in the patent of the former Soviet Union No. 1387069. 1 — glass tube; 2 and 3 — stationary contact-elements; 4 — fusible electro-conductive material with ferromagnetic filling; 5 — control coil.

some fusible material similar to paraffin which can be warmed by the current of the control winding and which melts before turning ON and OFF of the reed switch. When the material inside the tube becomes cool and hard, the reed switch is resistant to any type of external mechanical effects (Figure 5.18).

Moreover, it is possible even to reject the conventional construction of a movable contact-element by replacing it with electro-conductive material with ferromagnetic filling. In this case, two different coils or two different sources should be used to heat the material to form an electrode closing stationary contact-points 2 and 3.

In fact, there are a lot of different and exotic constructions with originally shaped movable contact-elements (Figure 5.19c, d):

- Contact-elements in the form of a ring fixed on one of stationary contacts shrinking under magnetic field of the coil, when it stretches, it closes the circuit between the stationary contact-elements (Figure 5.19a);
- Contact-elements in the form of a ball rolling back and forth under the magnetic field of the coil and closing the proper pair of stationary contact-elements (Figure 5.19b);
- Contact-elements in the form of ferromagnetic electro-conductive powder. Particles of such powder are aligned under the magnetic field of the coil and close stationary contact-elements (Figure 5.19c, d).

If we divide, in the last construction, the volume of the glass tube into several separate parts with the help of electro-conductive but nonmagnetic partitions (1a and 1b), we will have a multi-circuit reed switch capable of simultaneously switching several circuits.

Problems of construction of multi-circuit reed switches have puzzled and occupied designers for a long time. Over the years engineers and designers have found many original solutions. Take the construction shown on Figure 5.20, for example. In such a reed switch the movable contact (3) unwinds (untwists) under the influence of an external magnetic field, closing the stationary contact-elements 4 and 5.

In another construction of a multi-circuit reed switch (a patent of the former Soviet Union No. 595801) the movable contact-element has a more traditional form, while the stationary contacts are transversally located. To provide reliable contact of the movable

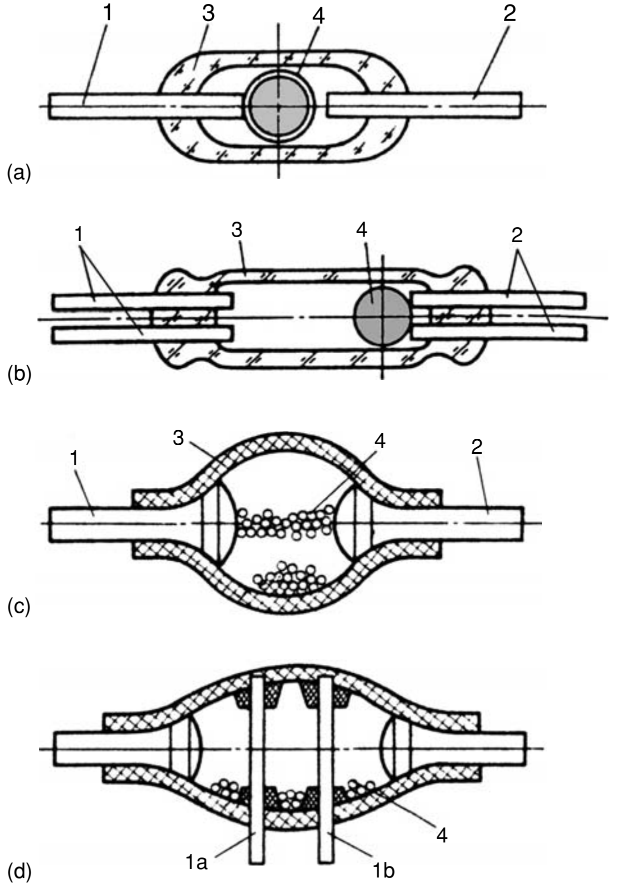


FIGURE 5.19
Reed switches with originally shaped movable contact-elements. 1 and 2 — stationary contact-elements; 3 — glass tube; 4 — movable contact-element.

contact-point with the transverse stationary ones, the latter must be sufficiently flexible (Figure 5.21).

More complex constructions of multi-circuit reed switches were proposed in Germany (Figure 5.22a), and in the U.S.A. (Figure 5.22b). Actually these are several pairs of contact-elements of the traditional form placed in the same glass tube, be it flat (Figure 5.22a) or round (Figure 5.22b). The author has no knowledge of whether such reed switches were actually produced, but a few scientific articles were published in the 1970s in Germany, which dealt with issues concerning the use of such four-polar reed switches in electronic exchanges.

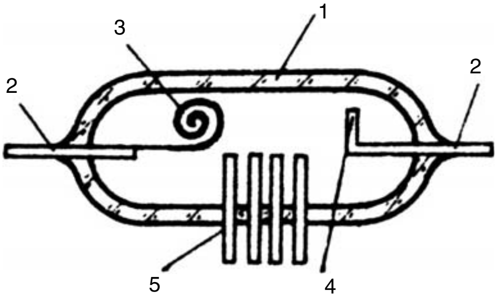


FIGURE 5.20
A reed switch with an unwinding (untwisting) movable contact-point.

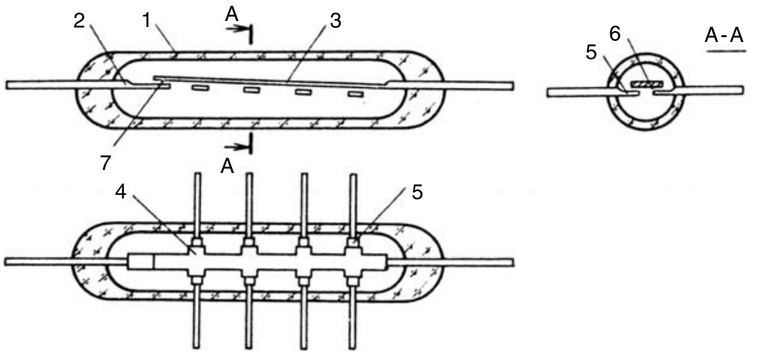


FIGURE 5.21
Multi-circuit reed switch with a movable contact-element of the traditional form. 1 — glass tube; 2 — main stationary contact-element; 3 — movable contact-element; 4 — lugs on the movable contact-element; 5 — additional pairs of stationary contact-elements soldered into glass across the longitudinal axis of the reed switch; 6 and 7 — working gaps between contacts.

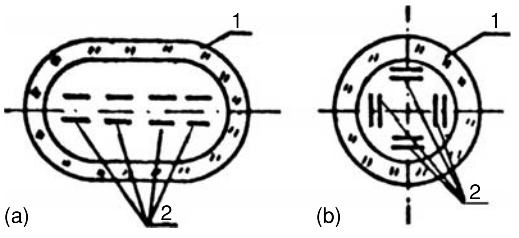


FIGURE 5.22
Four-polar reed switches for electronic exchanges suggested in Germany (a) and in the U.S.A. (b). 1 — flat or round glass tube; 2 — contact-elements of the traditional form.

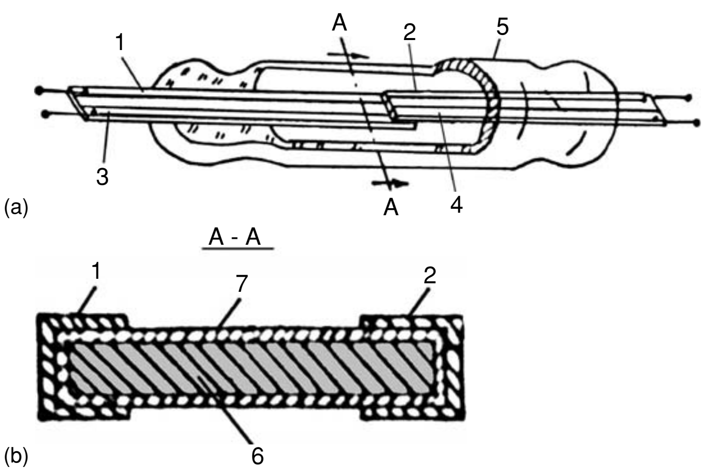


FIGURE 5.23
Double-circuit reed switched designed by the Bell Telephone Laboratories. 1 and 2 — the first pair of closing contacts; 3 and 4 — the second pair of contacts; 5 — glass tube; 6 — Remendur (semi-hard and very ductile magnetic alloy of 49% Co — 48% Fe — 3% V); 7 — glass.

Another complex construction of a multi-circuit, or double-circuit reed switch to be exact, was designed (also for the use in quasi-electronic exchanges) by the Bell Telephone Laboratories (Figure 5.23).

5.3 High-Power Reed Switches

The various constructions of reed switches described above were designed for switching of power up to 60 W, and all of them are considered ''low-power reed switches.'' Apparently, this usually does not have enough power for the reed switches used in industry relays, which is why it has been a long time since research work (and industrial production as well) has been carried out for high-power reed switches.

The English company Brookhirst Igranic Ltd is a pioneer in this field. At the end of 1960s it produced a reed switch 82400 H3100, which is more famous under the ''Powered'' brand name (Figure 5.24). In this construction, it implemented the already existing idea of division of functions of current switching and current carrying after switching, with the help of two pairs of contacts. One pair should be resistant to electric erosion, and the other pair should be able to conduct high current well in the closed (ON) position. In this reed switch the additional contacting pair (4, 5) from tungsten closes first and opens last. The main contacting pair (7, 8) shunts the additional contacting pair and unshunts it without arcing. The tube is filled with a nitrogen–helium–oxygen mixture. This reed switch was capable of switching ON up to 15 A and switching OFF up to 3 A at 125 V AC voltage, with an inductive load of power factor 0.35. Unfortunately, the complexity and high cost led to a halt of production of such reed switches already in the middle of the 1970s.

Using profound knowledge of physical processes proceeding on contacts when electric current is switched, American inventor J. Santi from the Briggs and Statton Co. patented in the 1970s a complex construction of a reed switch for DC switching (the most difficult mode for reed switches). In such a reed switch the contact having positive potential is made of molybdenum and the contact with negative potential of tungsten, a metal with a higher melting temperature (Figure 5.25).

At the initial stage of the opening process (at low voltages on contacts) molybdenum is transferred from the positive contact to the negative one. At the following stage, when voltage on the contacts increases, the direction of metal transfer changes to the opposite one and the molybdenum is transferred back to the positive contact. As the contact-elements close, under the external magnetic field of control coil, first the molybdenum, then component 2 closes with a part of tungsten strap (1′). Afterwards the tungsten strap (1) reaches the free part of the tungsten strap (1′). The opening process is carried out on the opposite order. Tests showed that this reed switch, supplied with a spark suppressing RC-circuit, can withstand 2×10^9 switches of DC at a voltage of 3000 V.

In 1977, the American A. Beavitt from the Square D Company patented a reed switch with an iron armature capable of switching power of more than 1 kW without spark

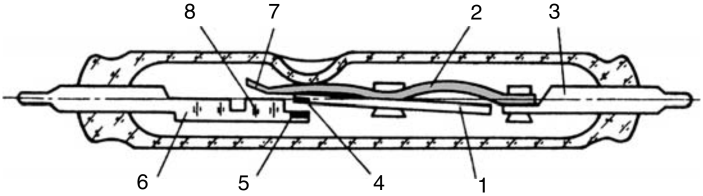


FIGURE 5.24
Powerful 82400 type reed switch (''Powered''). 1 — ferromagnetic armature; 2 — spring; 3 — outlet of the movable contact; 4 and 5 — additional contact pair from tungsten carbide; 6 — outlet of the stationary contact; 7 and 8 — main contacting pair from a silver alloy.

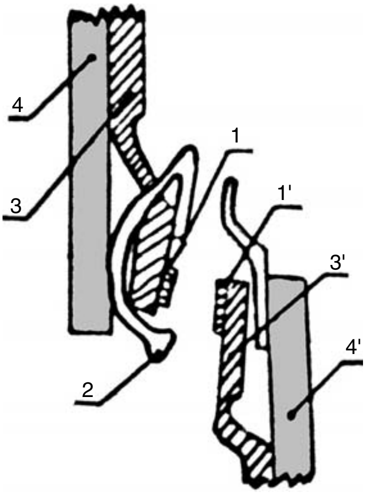


FIGURE 5.25
Power reed switch produced by Briggs and Statton Co. 1 and 1′ — tungsten contact straps; 2 — contact-element made of molybdenum; 3 and 3′ — ferromagnetic springs; 4 and 4′ — supports.

suppressing RC-circuits (Figure 5.26). Such a reed switch can switch currents up to 5 A at an AC voltage of 220 V.

In the Russian Scientific Research Institute of Relay Production a simplified (by elements, but not by the technical ideas implemented in it) construction of a power reed switch was designed on the basis of the ''Powered'' reed switch (Figure 5.27). Unlike the British reed switch, the Russian variant turned out to be quite easy to produce, which is why it continues to be produced by the Orel Electronic Instrument-Making Plant until now. In this reed switch, after closing of the tungsten contacts (1) the armature (2) continues moving, causing deflection of the spring (3) until it is connected to the stationary contact-element (4). The opening process has the opposite order. Part 5, with a smaller section (in later variants there is a special through hole at this place), is quickly saturated as the magnetic field of the control winding affects the reed switch. As a result, there are two poles under the lugs of the ferromagnetic armature to which it is attracted.

As it can be seen in this construction, which appears simple at first sight, not only technical ideas of the ''Powered'' reed switch, but also of the reed switch produced by Square D Company are applied (Figure 5.26). Currents switched by this reed switch vary within 0.001 to 5.0 A at DC voltages of 6 to 380 V, with power not more than 250 W. The maximum making and breaking current is 20 A (at voltage of 48 V) on AC and 4 A (at voltage of 24 V) on DC. The ON-time delay of such a reed switch is not more than 7 ms, and the release time is 5 ms. The tube of the reed switch is 7 mm in diameter and 52 mm in length, and its weight is 4 g.

When quite high currents (5 to 10 A) flow through closed contact-elements, those elements warm up considerably, sometimes even up to the Curie Point (magnetic transition temperature). At that point they are no longer held in the closed position by the

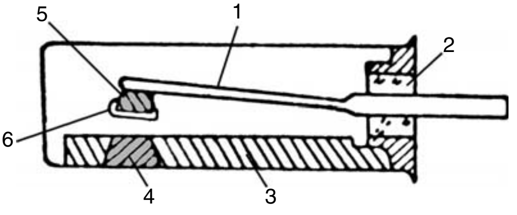


FIGURE 5.26
A powerful reed switch with an iron armature, patented by Square D Company. 1 — movable contact-element (a spring) from Permalloy; 2 — glass insulator; 3 — ferromagnetic stationary contact-element; 4 — copper insert as a contact strap; 5 — iron armature; 6 — tungsten cover.

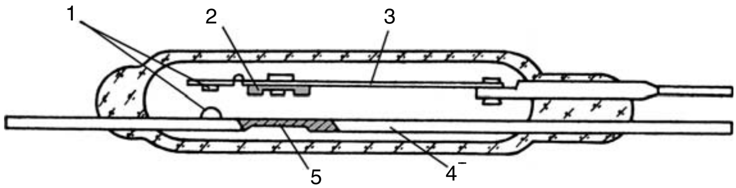


FIGURE 5.27
MKA-52202 type power reed switch (made in Russia). 1 — contact straps from tungsten; 2 — ferromagnetic armature covered with silver; 3 — flexible movable contact-element (a spring); 4 — hard stationary ferromagnetic contact-element covered with silver; 5 — part of the stationary contact-element with smaller section.

magnetic field of the control coil and separate, causing intensive arcing. If the contact-elements are not welded under the impact of arc, they close within a few seconds (after they cool and their magnetic properties are restored), and the process will start all over again. Obviously, after such spontaneous switching with intense arc, there is nothing left for the reed switch to do but to throw itself out.

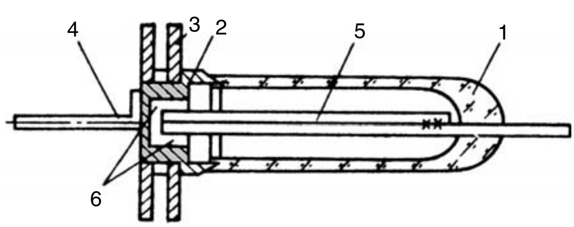
The solution to this problem is given in the patent of the former Soviet Union No. 440709, which describes a high-power reed switch supplied with a special heat sink on the stationary contact-element (Figure 5.28), providing intensive heat abstraction to the environment. In this construction, plates of the movable contact-element (5) affected by the external magnetic field, open like petals, closing with the stationary contact-element (2).

In one of the industry relays, the author came across an interesting construction of a high-power reed switch with a magnetic core plugged into the glass tube (Figure 5.29). The core of the external control coil (or a permanent control magnet) touches this magnetic core. This allows considerable reduction of the magnetic resistance of the system, and an increase of contact pressure. Such a reed switch has an important distinction from all the other constructions described above: its magnetic system is partially detached from the contact system.

This principle is also applied in some other constructions of reed switches, for example, in the construction shown in Figure 5.30. Such separation of the magnetic system from current-carrying components of a reed switch, even partial, allows avoidance of a negative peculiarity of reed switches: dependence of contact pressure (as well as drop-out values and reset ratio) on current flowing through the reed switch. Such dependence is obvious for reed switches of standard constructions: current carrying through contact-elements of the reed switch creates its own magnetic field, interacting with the magnetic field of the control coil. We have already described above the source of forces tending to open contacts in standard electromagnetic relays as very high currents (usually short-circuit currents) pass through them.

In reed switches this phenomenon is intensified because of a merging of the magnetic and contact systems. As a result, affected by even smaller currents than in a standard

FIGURE 5.28
Reed switch with a heat sink on the stationary contact-element. 1 — glass tube; 2 — stationary ferromagnetic contact-element in the form of cup; 3 — heat sink; 4 — outlet of the stationary contact-element; 5 — movable contact-element consisting of two plates welded at the point of the lead-in into glass; 6 — working gap between contacts.



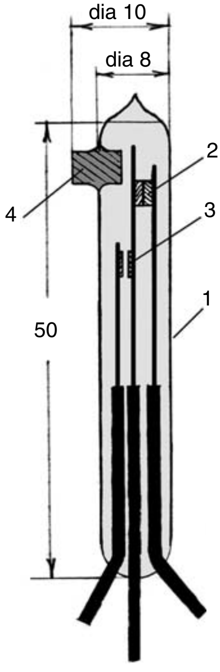


FIGURE 5.29
Power reed switch with a magnetic core plugged into the glass tube. 1 — glass tube; 2 — normally closed contact pair; 3 — normally open contact pair; 4 — magnetic core plugged into the glass tube.

electromagnetic relay, contact-elements may open. In constructions of reed switches shown in Figure 5.29 and Figure 5.30, such danger can be avoided.

The American branch office of the Yaskawa Company advertises its R14U and R15U type power reed switches, produced under the brand name ''Bestact'' (Figure 5.31), which belong to the same class of reed switches with partially detached magnetic and contact systems. This reed switch has current-carrying capacity up to 30 A. It can break similar current (as emergency one) 25 times in an AC circuit with a power factor of 0.7. Switched power in the AC circuit is 360 VA (inductive load), maximum switched current is 5 A, maximum switched voltage is 240 V. The electric strength of the gap between contacts is 800 V AC, mechanical life 100.000 operation for R15U and 50.000 for R14U. Operating and release time is 3 ms.

On the basis of such reed switches, the Yaskawa Company produces a great number of different types of switching devices: relays, starters, push-buttons, etc. The principle of separation of magnetic and contact systems, and inserting an additional magnetic core with a larger section inside the tube, was the basis of constructions of high-power reed switches designed by M. Koblenz in the All Union Scientific Research Institute of Electrical Apparatus (now a part of the Ukraine, Kharkov city). The external design of such

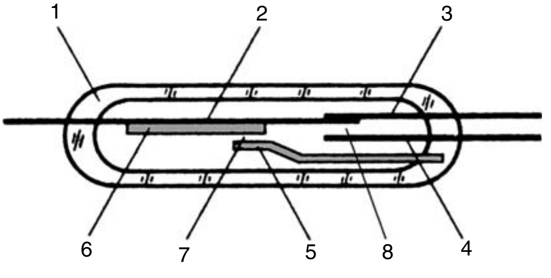


FIGURE 5.30
Reed switch with partially detached magnetic (elements 5 to 7) and contact (elements 2 to 4, 8) systems. 1 — glass tube; 2 — nonmagnetic movable contact-element; 3 and 4 — nonmagnetic stationary contact-element; 5 — stationary ferromagnetic component; 6 — movable ferromagnetic component fixed on the movable nonmagnetic contact-element 2; 7 — magnetic gap; 8 — gap between contacts.

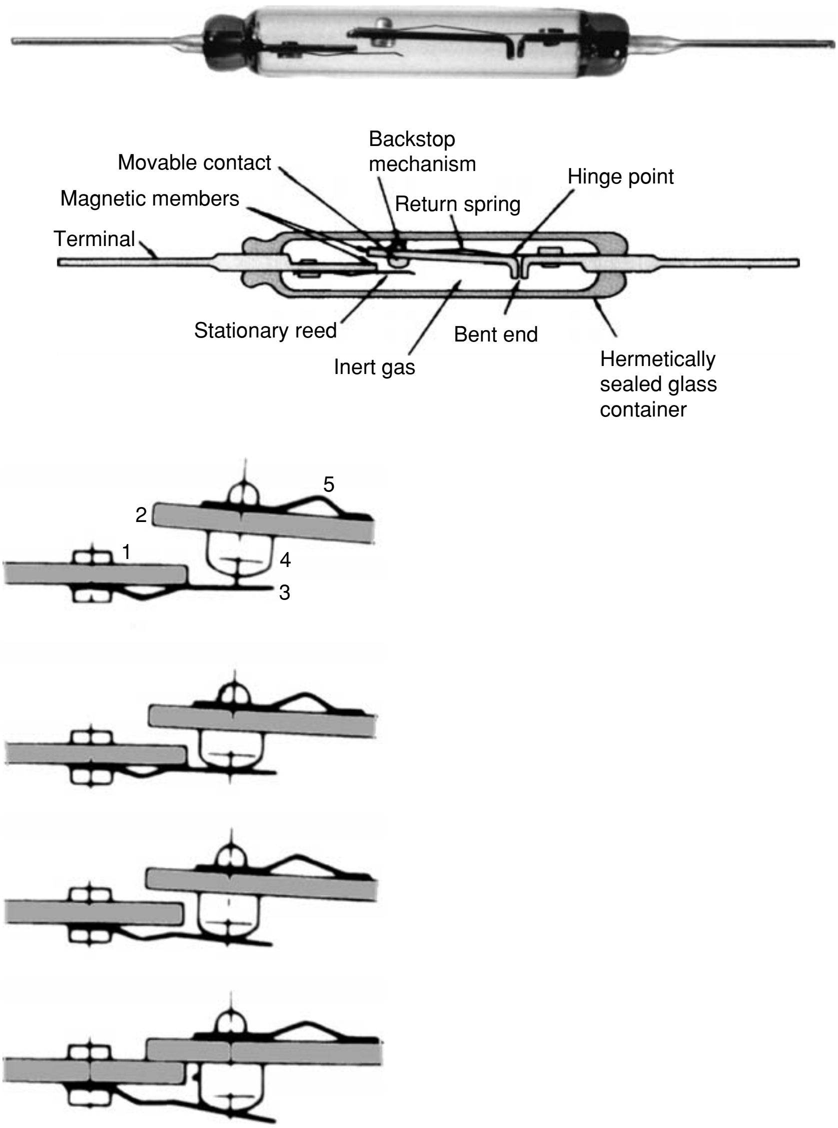


FIGURE 5.31
Power reed switch Bestact™ produced by Yaskawa Electric America and its closing/opening process. 1 and 2 — main silver coated contacts; 3 and 4 — auxiliary contacts from tungsten; 5 — spring. Dimensions of glass tube: diameter — 6 mm, length — 37 mm.

devices (called ''hersicon,'' from Russian words: ''Hermetical Power Contact'') differs greatly from that of traditional reed switches (Figure 5.32–Figure 5.34).

Through the hermetic shell of a high-power reed switch made of ceramics two ends (instead of as in the power reed switches described above), the massive magnetic core passes. This helps to reduce losses in magnetic circuit so that they do not exceed the losses in standard electromagnetic relays. The construction of the armature (6) allows us to combine to some extent some contradictory requirements for a movable armature (the term ''contact-elements'' is not appropriate for such a construction): the largest sectional area possible should be combined with the greatest flexibility possible. These

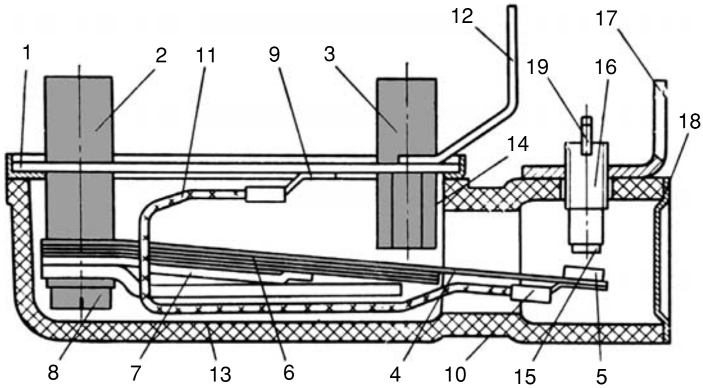


FIGURE 5.32
High-power reed switch (hersicon) of KMG12-19 type for 6.3 A nominal current and 440 V AC voltage (switching power up to 3 kW). 1 — board; 2 and 3 — poles of the magnetic system; 4 — spring-armature; 5 and 15 — contact straps; 6 — ferromagnetic element of the armature consisting of a package of thin flexible plates; 7 — limiter; 8 — screw; 9 and 19 — tips of flexible copper wire (11) used as a shunt; 12 and 17 — wireways; 13 — ceramic case; 14 — insulation layer unavailable to metallization; 16 — adjusting screw; 18 — cover; 19 — nipple.

requirements can be partially met by using a package of thin flexible ferromagnetic plates, the number of which is reduced as the moving end of the armature approaches. Of course, it should be noted that such a relatively successful solution only partially meets the requirements, because the section of the armature is not as big as it should be and its over-stiffness does not allow an increase in the gap between the contacts of more than 1.5 mm.

Flexible copper wire (shunting such a package of ferromagnetic plates with not very good electro-conductivity) provides almost a full separation of magnetic and electric circuits in the high-power reed switch. This is a key fact, because full separation of electric and magnetic circuits is typical for standard electromagnetic relays. Reed switches are distinguished from standard relays mostly by the fact that magnetic and electric circuits in them are combined in the same elements. Therefore a hersicon is just a hermetic contact node of the console type, with adjoining parts of the magnetic core sticking out of

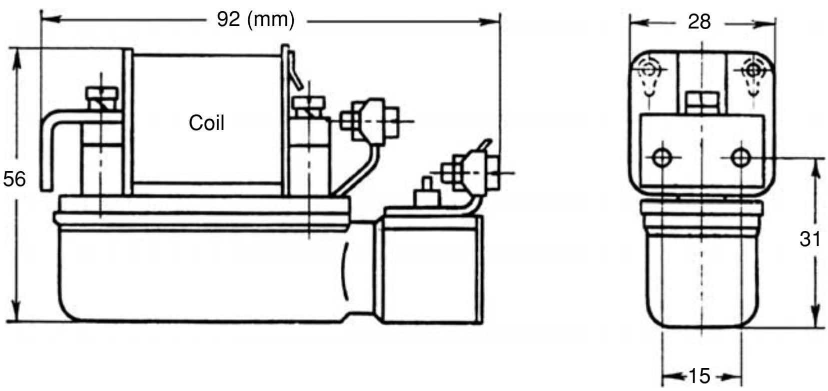


FIGURE 5.33
High-power reed switch (hersicon) of KMG12-19 type with a control coil fixed on poles of the magnetic system.

FIGURE 5.34
External view of single-pole hersicons for currents from 6.3 to 63 A produced by Electroceramics Plant (the Ukraine).

the hermetic shell, and with separate contact outlets. Being connected to the control coil such a contact node makes up a standard electromagnetic relay.

But if that is really so, the following questions arise: Why is it necessary to use an armature of a console construction as in standard reed switches, in such a relay, and then to do one's best to increase its flexibility and at the same time through a big section by introducing an additional wire shunt, further complicating the construction? Why not use a conventional turning stiff armature of the required section, supplied with a restorable spring with the required stiffness, as in a standard electromagnetic relay?

Such arguments brought the author of the book to the idea of a creation of a new type of switching device called REPROCON (RElay with PROtective CONtacts) (Figure 5.35). The description of such a device was published in 1994.

Having analyzed the history and tendencies of development of high-power reed switches, one may conclude that it is possible to enhance reed switches only up to certain limits of powers (up to 500 VA). An attempt to design much more powerful devices will lead to significant changes in the construction, so that the designed device can no longer be considered to belong to the category of ''reed switches.'' In such cases, the application of basic principles of construction of reed switches to such devices becomes unjustified.

5.4 Membrane Reed Switches

In membrane reed switches (including ''petal'' reed switches) the movable contact-element is made in the form of a membrane (petal) from ferromagnetic material supplied with slots (Figure 5.36). Under the effect of the magnetic field of the core (5), the leaf (4) sags and closes the circuit. There is, of course, no need to say that both the ferromagnetic core (5) and the leaf (4) must have a good electro-conductive cover.

Elements 1 to 5 are ferromagnetic with an electro-conductive cover. The cover (3) and the heelpiece (2) are welded along the contour, forming an internal hermetic volume of the reed switch filled with gas.

When the stationary contact-element (1) is magnetized, the central part of the membrane (8) sags, closing the circuit between the outlets joined to the heelpiece (2) and the stationary contact-element (1) (Figure 5.37).

Due to the complex configuration of notches, the central part of the membrane has several degrees of freedom and when moved fits cleanly with the butt-end of the stationary contact-element (1) even in the case of inaccurate assembly. This also reduces

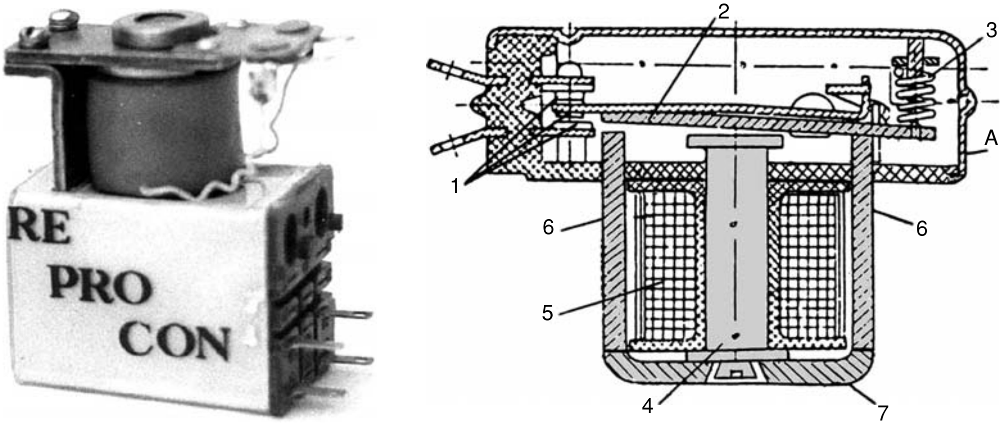


FIGURE 5.35
Reprocon designed by the author. 1 — contact straps; 2 — stiff ferromagnetic armature; 3 — restoring spring; 4 — core sticking out of the hermetic shell A; 5 — control coil; 6 — parts of the magnetic core sticking put of the hermetic shell A; 7 — removable part of the magnetic core.

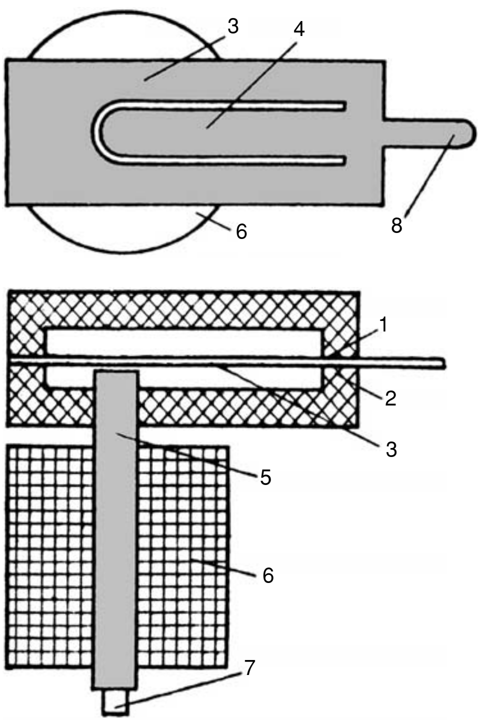


FIGURE 5.36
Principle of construction of a petal reed switch. 1 — cover; 2 — heelpiece; 3 — plate with a figured slop in the form of a peal; 4 — peal (membrane); 5 — ferromagnetic core; 6 — control coil; 7 and 8 — wireways.

bounce of the contact surfaces when they collide. It is much easier to choose the material for such a construction because the membrane is not welded to anything (while in standard reed switches the material of contact-element should be welded well into the glass, have a good adhesion to it and a coefficient of linear expansion similar to glass).

The patent of the former Soviet Union No. 750591 deals with a membrane reed switch with increased resistance to vibration, having two membranes instead of one, each

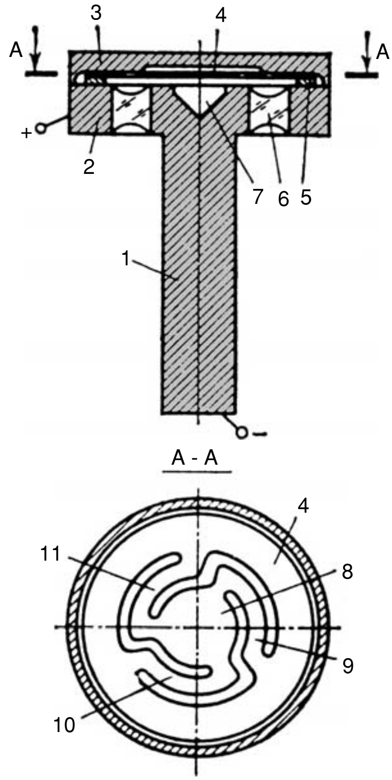


FIGURE 5.37
Membrane reed switch. 1 — stationary ferromagnetic contact-element; 2 — ring-shaped heelpiece; 3 — cover; 4 — membrane; 5 — gage block; 6 — glass seal; 7 — recess; 8 — central part of the membrane; 9 to 11 — membrane leaves.

moving towards the other when the device is energized (Figure 5.38). The cavities (4 and 5) are hermetically separated from each other and are filled with gasses of different pressures, to increase resistance of the membrane to vibration.

As is the case with standard reed switches, designers try to increase as much as possible the power switched by membrane reed switches by following the same way (Figure 5.39).

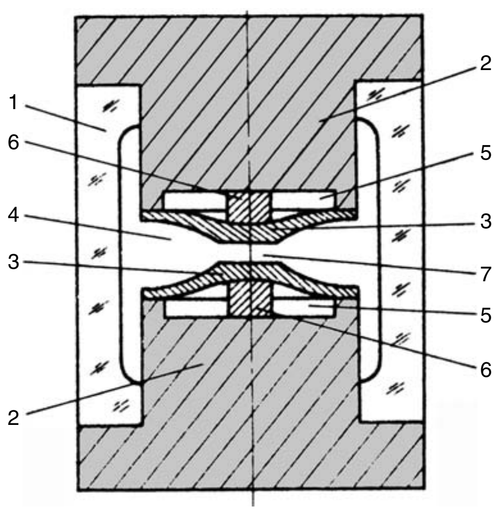


FIGURE 5.38
Vibration-resistant membrane reed switch with two membranes. 1 — glass tube; 2 — ferromagnetic cores; 3 — crimped membranes; 4 — main cavity filled with gas; 6 — nonmagnetic stops; 7 — working gap.

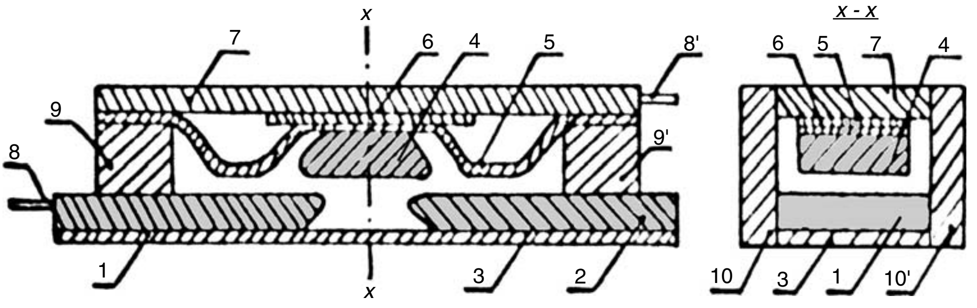


FIGURE 5.39
High-power membrane reed switch produced by Square D Company. 1 and 2 — stationary contact-elements; 3 — heelpiece; 4 — ferromagnetic armature (a movable contact-element); 5 — elastic diaphragm; 6 — damping plate; 7 — cover of the reed switch; 8 and 8′ — outlets of the reed switch; 9 and 9′ — end walls of the reed switch (plastic); 10 and 10′ — sidewalls (plastic).

In this construction the ends of the contact-elements (1 and 2) are splayed in the contacting area to reduce the stray flux. The contacting surfaces of the contact-elements are covered with tungsten.

Under the effect of the longitudinal magnetic field, the armature (4) is attracted to the stationary contacts (1 and 2), causing the membrane to sag. When the electric circuit between the outlets 8 and 8′ is closed, the electric load current flows through the armature and the membrane. Such a reed switch can switch currents up to 5 A with voltages up to 250 V AC. If the heelpiece (3) is made of dielectric material and the outlet (8′) is connected to the element (2) the switched load current will not pass through the thin membrane and it increases by several times.

5.5 Mercury Reed Switches

Mercury reed switches belong to the class of liquid–metal switching devices. These are devices in which current conducting elements are wetted with liquid metal fully or partially.

As mercury is the only pure metal capable of being in a liquid state at room temperature, when we say ''liquid–metal devices,'' we usually mean only mercury devices. The tube in such reed switches is filled with mercury of 0.1 to 0.15 volume (Figure 5.40), so that it does not overflow onto the contacts.

That is why most mercury reed switches can operate only in a vertical position (the maximum admissible deviation from the vertical is 30°). The mercury in such reed switches is necessary only for wetting of the contacting surfaces of the contact-elements. Wetting of contact-elements is carried out by pumping of the mercury from a reservoir, through capillaries or semicapillaries placed on the surface of the contact-elements.

The first constructions of mercury reed switches and relays already appeared in the latter half of the 1940s and by the 1960s they already looked liked modern ones. In earlier constructions the capillaries were made from two parallel pieces of wire while in modern ones they are made from several longitudinal cuts on the flat surface of the movable contact-elements. Surfaces that come into contact with the mercury are covered with a special amalgam providing for good wetting with mercury.

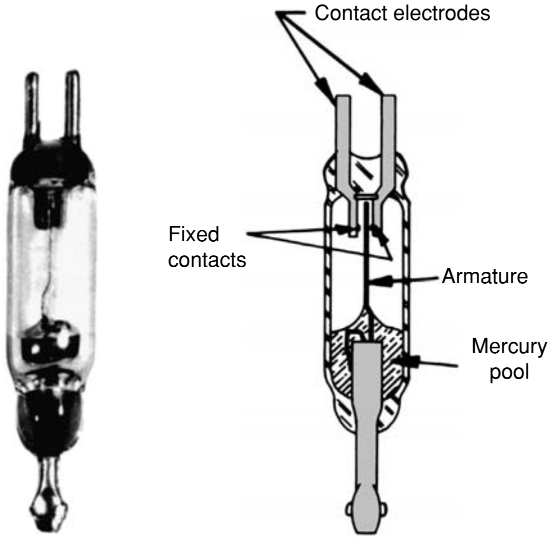


FIGURE 5.40
External view and construction of the most popular type of mercury reed switches.

When the contacts switching OFF, a mercury bridge is formed between them. As the contacts move apart, this bridge becomes thin and snaps (Figure 5.41).

Electric spark and even arc (in case it occurs) lead to vaporization of the mercury drop which then condenses on the sidewalls of the tube and flows down back to the reservoir. The surface of the contact-elements remains clean and undamaged. Apart from considerable multiplication of switching cycles, in mercury reed switches vibration of contact-elements during closing does not lead to a break of the bridge, which is why it does not affect the reed switch and external circuits as well. For safety purposes the tube in mercury reed switches is usually made of thicker glass than in dry reed switches and has quite a high strength. This allows the tube to be filled with hydrogen under pressure of up to 2000 kPa, which considerably increases switched current (up to 5 A), voltage (up to 600 to 800 V) and power (250 W) (Figure 5.42a).

In certain types of reed switches it is possible to considerably raise the switched voltage by increasing the gap between the contacts. For example, the Russian reed switch MKAP-58241 can switch voltage of up to 4500 V with insulation strength of up to 8000 V. However, enlargement of the gap between contacts in such a reed switch may lead to a prolongation of make delay, and a release time of up to 10 ms, increasing the magnetomotive force of operation up to 500 to 700 A, and reducing the switching frequency to 25 Hz. The tube of such a reed switch is 58 mm in length and 14.5 mm in diameter. Another interesting peculiarity of such a reed switch is a protective plastic shell

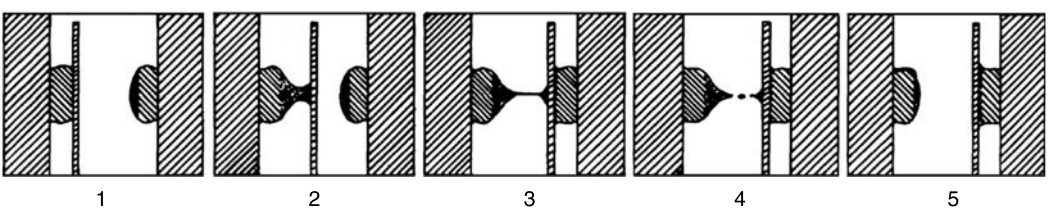


FIGURE 5.41
Stages of the process of switching of electric current by a switched contact wetted with mercury.

(a)

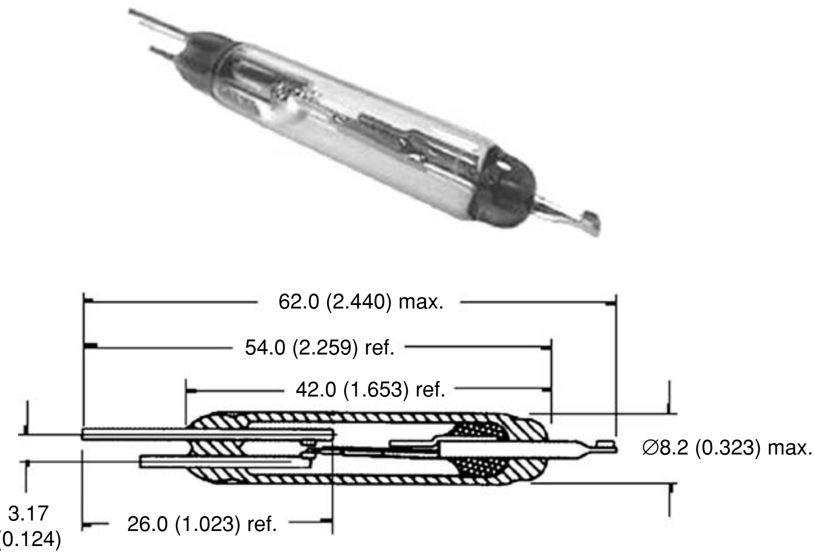


FIGURE 5.42
(a) Mercury wetted power reed switch HG 07 120 180 type, produced by Gunther Belgium. (Comus Group Companies) (Vertical mounted required)

preventing ingress of mercury in the ambient space in case of rapid depressurization of the glass tube.

The necessity of vertical installation of standard mercury reed switches with a mercury reservoir led to the invention of reservoir-free mercury reed switches in which the mercury is in the capillaries only. This allows us to exploit such reed switches in any position, but restricts switching capacity because of the small amount of mercury. For example, the Russian reservoir-free mercury reed switch MKAR-15102 has switched power up to 30 W, while practically the same mercury reed switch MKAR-15101 with a mercury reservoir up to 50 W.

The two shining parts of the tube, from the two sides of overlap of the contact-points, are made of a layer of amalgam covering the internal surface of the glass tube. To provide a reliable supply of mercury for contacting surfaces of contact-elements, most of the internal surface of the glass tube in such reed switches produced by CP Clare Corp. is covered with an amalgam based on nickel, thus two parts with a gap are formed in the overlap of contact-elements (Figure 5.42b). The mercury in this part is sufficient to provide a reliable contact.

One of disadvantages of mercury reed switches is their limited range of working temperatures: $-38 + 125°C$ when properties of mercury remain valid. Unfortunately, in the course of exploitation of a reed switch sometimes even within this interval of temperatures one can observe an increase in the tenacity and surface tension of the mercury. This may lead to maintenance of a contact bridge in the extreme position of separated contact-elements, that is to unopening of the reed switch. In addition, increased

(b)

FIGURE 5.42
(b) Mercury reed switch insensitive to the position in space. (Produced by CP Clare Corp.)

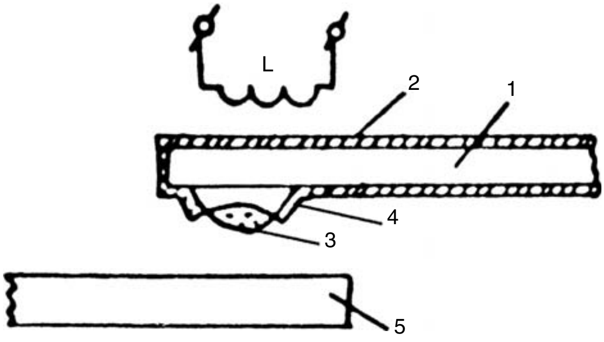


FIGURE 5.43
Original construction of contact-elements for a mercury reed switch. 1 and 5 — contact-elements; 2 — cover unwettable by mercury (tantalum, niobium); 3 — drop of mercury; 4 — cup-shaped element the internal surface of which is wettable by mercury.

temperature can sometimes cause inter-diffusion of metal of the contact-elements through a thin mercury film. To prevent this phenomenon S. Bitko (U.S.A. patent No. 3644603) suggested an original construction of the contact-elements (Figure 5.43). In this construction the surface tension makes a drop of mercury penetrate the cup-shaped element (4). Mercury leavings are absorbed into the internal cavity of this element from its surface, thus preventing unopening of the reed switch.

Deviation from use of traditional console construction in mercury reed switches allowed production of a miniature device with good switching properties (Figure 5.44). The stationary contact-elements (1 and 7) are welded into two separate glass tubes (2 and 6), which are linked by a metal bush (3), thus forming a common tube. The bush serves as a guide for the plunger (4) wetted by mercury. A disk outlet (5), together with outlets 1 and 7, are the stationary elements of the switching contact, which changes its positions as the plunger (4), moves under the effect of the external magnetic field.

The ''Logsell-1'' reed switch is very small in size: its tube is 7 mm in length and 1.2 mm in diameter, however, its switching characteristics are quite high for miniature reed switches: switching power is up to 15 W, current is up to 1 A and voltage up to 200 V. Minimum life is 5×10^7–10^9 switching cycles (depending on the parameters of the switched circuit). This reed switch will function in any position in space because there is no danger of overflowing of mercury in it. In addition, the Logsell-1 switch has quite a high console construction switching frequency, even for dry reed switches, of up to 200 Hz.

After removal of the external magnetic field the plunger in such a reed switch remains in one of its extreme positions by the forces of surface tension of the mercury film. Unfortunately, such a unique reed switch did not become a popular element due to its complexity and the high cost of its production.

Attempts to create new constructions of liquid–metal reed switches still continue. In patent descriptions it is possible to find a lot of original constructions, which have not succeeded in becoming commercial devices, like a hybrid of a ball and mercury reed switch for instance (Figure 5.45), which is controlled by a permanent magnet or a reed

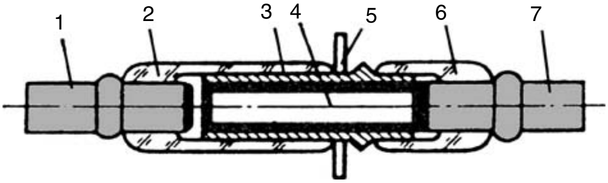


FIGURE 5.44
Mercury reed switch ''Logsell-1'' of the plunger type. 1 and 7 — stationary contact-elements with internal butt-ends wetted with mercury; 2 and 6 — separate parts of the glass tube; 3 — guide bush; 4 — ferromagnetic plunger wetted with mercury; 5 — disk outlet.

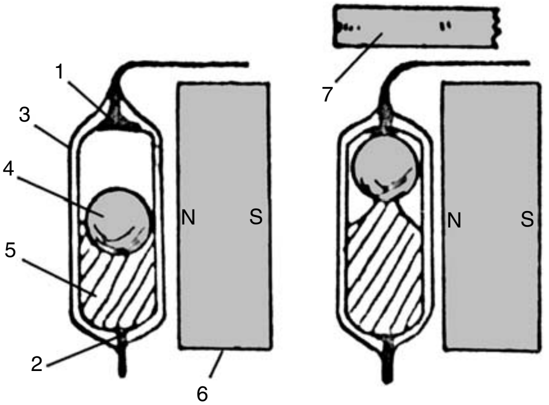


FIGURE 5.45
Ball mercury reed switch (Germany patent No. 1515775). 1 and 2 — contacts; 3 — glass tube; 4 — steel ball; 5 — mercury; 6 — permanent magnet; 7 — ferromagnetic control plate.

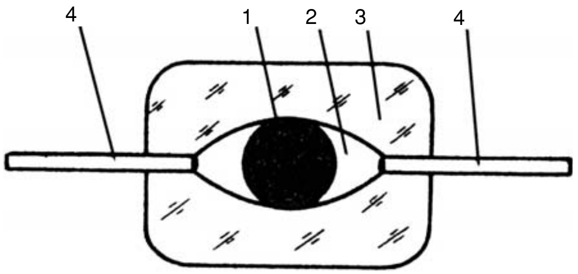


FIGURE 5.46
Reed switch with a movable contact-element in the form of a drop of electro-conductive ferromagnetic liquid (patent of the former Soviet Union No. 851522) 1 — a drop of electro-conductive ferromagnetic liquid; 2 — internal cavity of an original form; 3 — glass tube; 4 — ferromagnetic outlets.

switch with a drop of electro-conductive ferromagnetic liquid as a movable contact-element (Figure 5.46), etc.

In such a reed switch the movable contact-element is made in the form of a drop of a suspension of finely dispersed magnet-soft powder in an electro-conductive liquid. Its internal cavity (2) has such a form that under no external magnetic field will the drop conform to the shape of a ball. Only when the external longitudinal magnetic field affects it, will the ball-shaped drop stretch and close the outlets (4).

5.6 High-Voltage Reed Switches

In fact, classification of reed switches into low- and high-voltage ones is quite relative. In electrical engineering of strong currents devices designed for operation with voltages of more than 1000 V are considered to be high-voltage switches, while in electronic devices with voltages of more than a few hundred volts are also called high-voltage. According to such a division it appears that almost all gas-filled mercury reed switches are high-voltage ones. Unlike them, high voltages in dry reed switches are reached not through gas filling under high pressure but through deep vacuumization of the tube. There is practically no construction difference between reed switches for working voltages of up to 5–10 kV, and low-voltage reed switches, although the former ones have characteristic features — a remaining stem through which air is evacuated, and tungsten covering of the contact-elements.

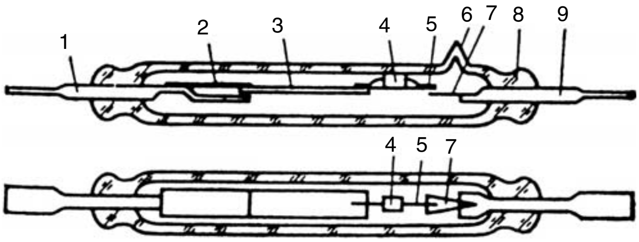


FIGURE 5.47
High-voltage vacuum reed switch for 20 kV DC. 1, 9 — outlets of contact-elements; 2 — restorable spring; 3 — ferromagnetic armature; 4 — ceramic stop; 5 and 7 — contact-elements; 6 — stem; 8 — tube.

Of course such reed switches have a bigger gap between contacts (and therefore increased magneto-motive operation force) and the proper size (as a rule, the tube is 50 to 55 mm in length and 5–6 mm in diameter). Reed switches for voltages of 15 to 20 kV have some additional constructive elements (Figure 5.47). The power of such reed switches with switched voltages of up to 1000 V does not usually exceed 50 W and with voltages of more than 1000 V up to 10–20 W. Switched current is only a fraction of a milliampere (current-carrying 3 A).

In the 1970s the main producers of high-voltage vacuum reed switches were the English firm FR Electronics and the American one Hamlin, Inc. In the period 1973–1974 the latter produced vacuum reed switches of the DRVT-30 type with switched voltage of up to 27.5 kV! The tube of such a reed switch was 58 mm in length and 7.4 mm in diameter, and was capable of switching currents up to 1 mA under working voltage. Operation time of such a reed switch was 20 ms and its magneto-motive operation force was 500 A.

In the former U.S.S.R. (Lvov firm ''Polyaron'') original vacuum reed switches of the BB-20 type for working voltages of up to 10 kV in the no-current switching mode and up to 5 kV in the current switching mode (up to 2 A) were produced at the end of the 1970s. It was possible to let current pass up to 20 A through the closed contacts. In the butt-ends of the tube there were deeply recessed pin-like outlets soldered into the tube. They were designed to be connected to the receptacle of the high-voltage sockets, which provided very high resistance of leakage along the surface and allowed insulation of the high-voltage outlets from the control coil. Ceramic bushes with sockets for standard banana-like connectors were used for experiments. These were quite large devices, with a tube 150 mm in length and 30 mm in diameter and with a movable contact-element of the plunger-type. The tube moved forward with typical noise from the end stationary part of one contact-element towards the stationary part of the second contact element, touching it with its butt-end. Operating time corresponded to the size of the construction and made up 15 ms. This was perhaps the biggest reed switch in the history.

In high-voltage reed switches, there is a problem alien to low-voltage constructions: electrostatic attractive force between the contact-elements. Such force is approximately proportional to squared voltage and the area of the overlap of contact-elements, and is in inverse proportion to the distance between them. With voltages of 15–20 kV the force may become so strong that under certain circumstances it can cause spontaneous closing-in of the contact-elements, to the distance that could allow a breakdown of the gap between contacts. On the other hand, those same forces prevent the contact-elements from opening after removal of the control magnetic field, which is why the area of the overlap of the contact-elements with such high voltages should be as small as possible, with switched current not exceeding a few milliamperes, anyway.

Because of the increased gap between the contacts the operating time of such reed switches is usually more than in low voltage reed switches, and is usually 3 to 5 ms, however, measurements carried out by the author show that the closing time of the external circuit with a voltage of 5 to 10 kV with the help of such a reed switch is considerably less than the closing time of a low-voltage circuit with the help of the same reed switch. This can be explained by the occurrence of high-voltage breakdown between the contact-elements as they close in, and holdover commensurable with small working currents, long before the contact-elements touch.

5.7 Reed Switches With Liquid Filling

In patent descriptions one can often come across a number of constructions of reed switches with a tube filled with chemically inert insulating liquids such as silicone oil, instead of gas (Japanese patent No. 4814590; U.S.A. patent No. 2547003; East Germany patent No. 53152; U.S.S.R. patent No. 477478; England patent No. 1520080; Germany patent No. 2512151, and many others).

Reed switches filled with such liquids have higher insulating characteristics and breaking-down voltages, and better dynamic and thermal properties. Trough-shaped contact-elements closing in such liquids do not rebound after closing because their movement is slowed down by the liquid. Such slowing down of movement does not change total operating time of a reed switch considerably, since due to high dielectric properties of dielectric liquids the gap between the contacts in such reed switches can be reduced to 0.025–0.07 mm. Moreover, there is even a saving of operating time with such reed switches.

The use of hollow movable contact-elements (in the form of a flat tube — Figure 5.48a), also allows it to obtain its ''neutral buoyancy'' and to increase its resistance to external mechanical shocks and vibrations. As it turns out, it is possible to fill not only dry reed switches with dielectric liquid, but also reservoir-free mercury ones (Figure 5.48b — England patent No. 1520080).

The appropriate selection of liquid and nonmagnetic material for contact-points wetted with mercury allows avoidance of vibration of the contact-points during closing and the so-called dynamic noise caused by magneto-strictive effects, after closing of standard reed switches. Moreover, it turns out that it is also possible to fill reed switches with dielectric liquid containing much mercury in the reservoir (Figure 5.49). In such a reed switch, under the effect of the magnetic field the ferromagnetic liquid (3) moves down, forcing

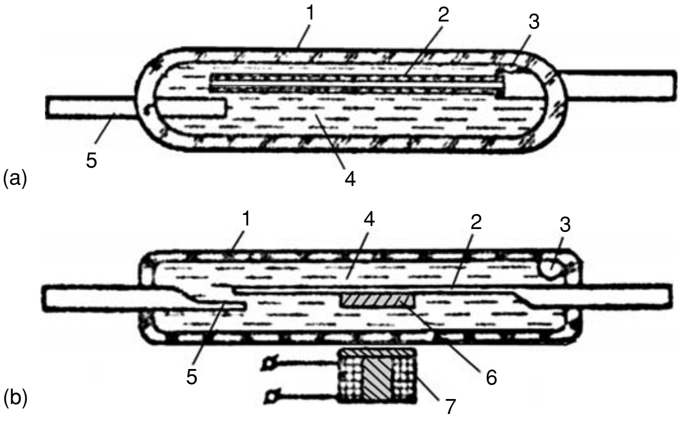


FIGURE 5.48
Reed switches with a liquid-filled tube. 1 — glass tube; 2 — movable contact-point; 3 — damping gas bubble; 4 — electro-insulating liquid; 5 — stationary contact-point; 6 — disk-shaped ferromagnetic armature fixed on the movable contact-point; 7 — control coil.

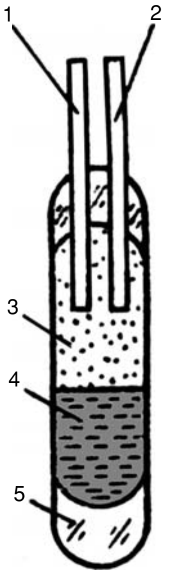


FIGURE 5.49
Mercury reed switch with ferromagnetic liquid. 1 and 2 — outlets of the reed switch; 3 — ferromagnetic insulating liquid; 4 — mercury; 5 — glass tube.

the mercury (4) upward, where it closes outlets 1 and 2. Ferromagnetic liquids are usually based on organic or inorganic (silicon, for instance) oils with finely dispersed ferromagnetic powder with a particle size of under 100 A (1 A $= 10^{-10}$ m).

Experiments carried out in the 1970s in the U.S.S.R which dealt with filling of tubes of standard dry reed switches with transformer oil showed electrical noise reduction by 5 to 6 times. Filling of the tubes with a more heavy substance caused reduction by more than 30 times. The American Magnavox Company used such reed switches in high-speed multi-way switches, carried out a number of successful experiments in this field in the 1960s.

Liquids filling the tube must retain their properties in the closed and small volume of the tube, without replacement during the entire service life of the reed switch. This is a difficult task because high-temperature electric spark and even the slightest arcing on opening contact-elements can cause destruction of most organic liquids, with a release of solid particles of carbon. There is a tendency to apply flurohydrocarbon liquids or Freon $C_3Cl_4F_4$, $C_5F_{10}HF$ $(C_3F_6O_2)O$; ether $(C_8F_{16}O)$; polyorganosiloxane liquids. The high costs of such liquids, and the considerable complexity of production of such reed switches, restrain their mass fabrication for the time being.

5.8 Polarized and Memory Reed Switches

Polarized reed switches are those reed switches that are sensitive to the polarity of the control signal applied to the control coil, in other words to the vector direction of the magnetic field *F* (Figure 5.50). Such sensitivity is caused by an additional static magnetic field produced by a permanent magnet placed nearby (or by an additional polarized winding, which is rarer). The external magnetic field of the control signal may have the same direction as the magnetic field of the permanent magnet. In this case as their fluxes are summed up, causing operation of the reed switch, the sensitivity of the reed switch to the control signal increases considerably.

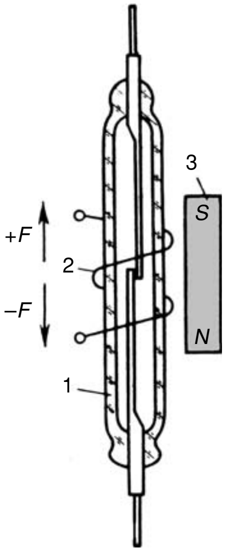


FIGURE 5.50
Polarized reed switch. 1 — neutral reed switch; 2 — control coil; 4 — polarized permanent magnet.

If vectors of the magnetic fluxes have opposite directions, the resultant magnetic flux is so small that the reed switch cannot be energized. One of the most important applications of such polarized reed switches is obtaining an opening (normally closed) contact out of a standard normally open one. In this case the magnet is selected in such a way that its magnetic field is enough to energize and hold a standard normally open reed switch in such a state. If the direction of the control magnetic field of the coil is opposite to the direction of the magnetic field of the permanent field, the total value of the magnetizing force affecting contact-elements will be less than their elastic force, and they will open, affected by these forces.

As far as construction is concerned a magnet can be placed not only along the tube or outside it, as it is shown in Figure 5.50. There are a number of different constructions with original combinations of control coils and permanent magnets, some of which are shown in Figure 5.51. With the help of permanent magnets it is possible to produce a three-position reed switch with a neutral mid-position, which would switch this way or that under effect of the magnetic field of the control coil of this or that polarity (Figure 5.52). Using several control coils placed in different parts of a reed switch, instead of one, it is possible to produce reed switches capable of carrying out standard logical operations AND, OR, NOT, EXCLUSION, NOR (OR-NOT), NAND (AND-NOT), XOR (EXCLUSIVE-OR), etc. (Figure 5.53). If such multi-wound reed switches are combined with permanent magnets (Figure 5.54), it is possible to obtain quite complex functional elements with adjustable operation thresholds, and remote switching of certain options. The number of such combinations is practically endless. This allows designers to implement almost fantastic projects.

Taking into account that the reset ratio of reed switches is less than 1 (that is, for operation a stronger magnetizing force is needed than for release) one may try to choose a magnet of such a strength which is sufficient for operation of a reed switch, and at the same time capable of holding closed the contact-elements which have already been closed by the control coil field. In this case the reed switch is switched ON by a short current pulse in the control coil and remains in this state even after the control impulse stops affecting it (that is, it ''memorizes'' its state). The reed switch can be switched OFF by applying a control pulse of the opposite polarity to the coil. Such a switching device, though in fact capable of operating, is not used in practice. There are several reasons for

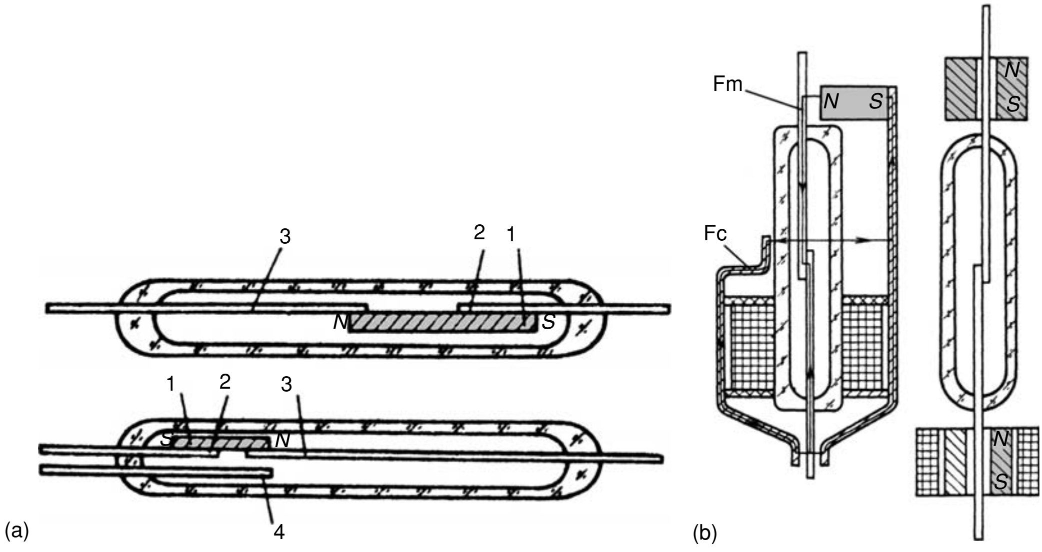


FIGURE 5.51
(a) Polarized reed switches with internal arrangement of magnets. 1 — permanent magnet with electroconductive covering; 2 — stationary contact-element to which a magnet is welded; 3 — movable contact-element; 4 — second stationary contact-element. (b) Polarized reed switches with external arrangement of magnets. Fm — magnetic flux of the permanent magnet; Fc — control magnetic flux.

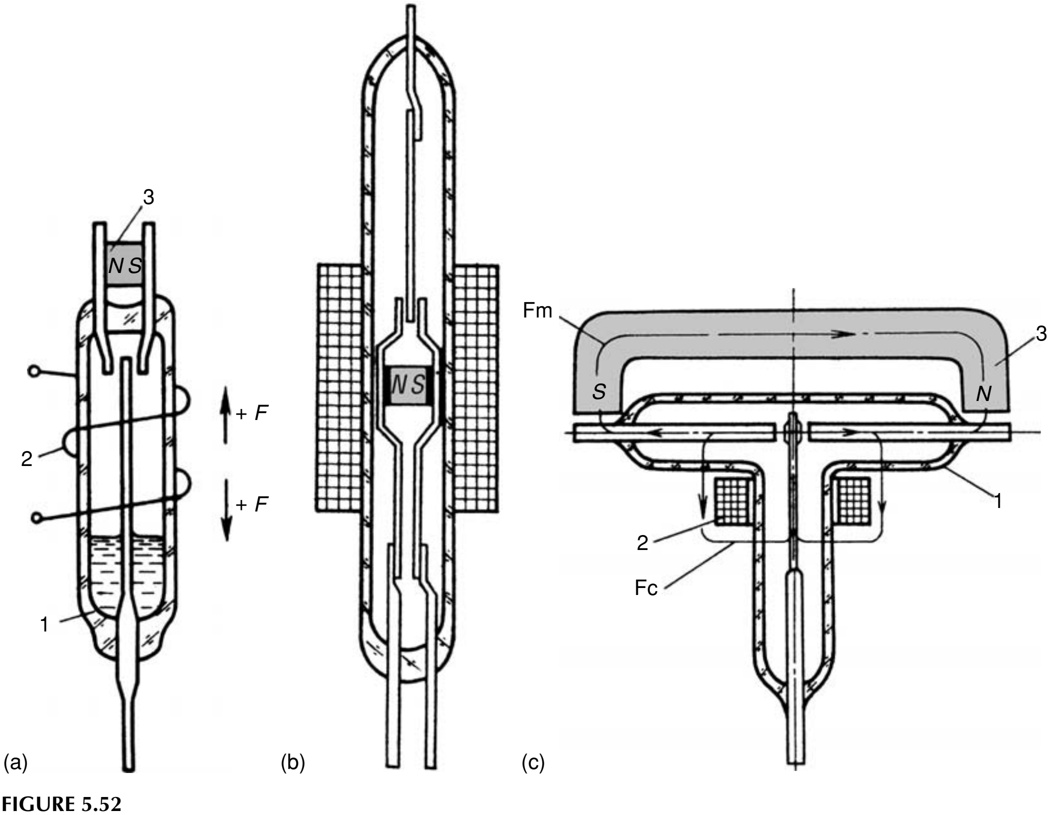


FIGURE 5.52
Three-position polarized reed switches: (a) mercury reed switch with an external magnet; (b) dry reed switch with an internal magnet; (c) high-frequency reed switch. 1 — glass tube; 2 — control coil; 3 — permanent magnet with external insulating covering which can also be made of ferrite.

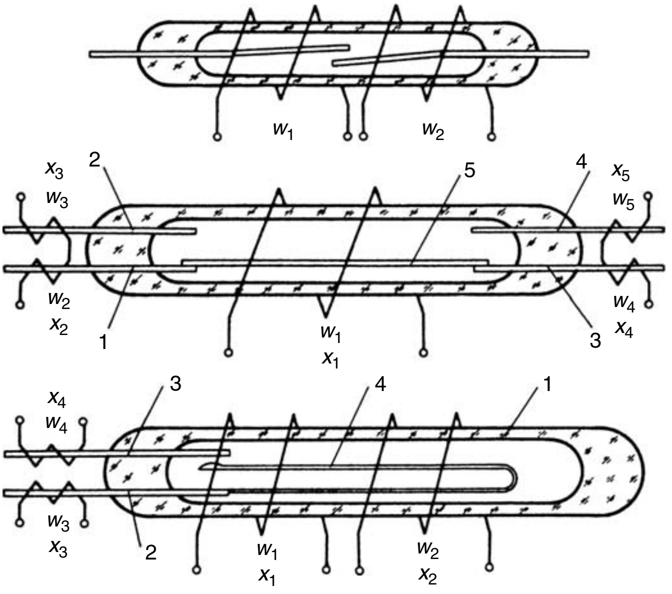


FIGURE 5.53
Multi-wound reed switches designed to carry out standard logical operations.

this. Firstly, such a device requires very accurate adjusting because the slightest excess of magnetizing force of the permanent magnet will cause spontaneous closing of a reed switch. If the magnetizing force is not strong enough, the reed switch will not remain closed after the control impulse stops affecting it. Taking into account great technologic differences between parameters of reed switches, magnets and control coils, each device will require individual adjusting, which is impossible for mass production. That is why even a device adjusted beforehand to a certain temperature may malfunction at other temperatures.

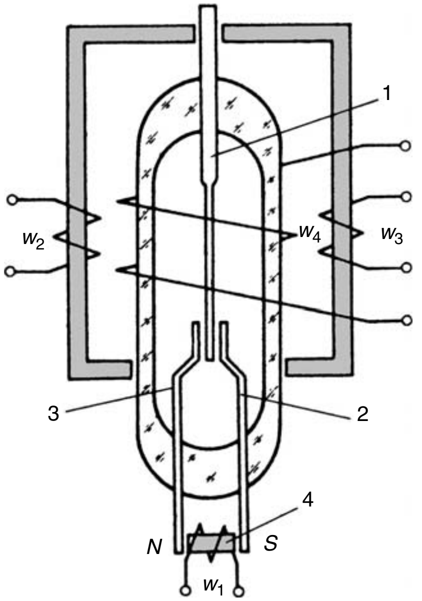


FIGURE 5.54
Combined switching logical device on a reed switch. 1 to 3 — contact-elements; 4 — permanent magnet.

In 1960 A. Feiner and his colleagues from Bell Laboratories published in the ''*Bell System Technical Journal*'' an article entitled ''Ferreed — A new switching device,'' in which they suggested that the way to overcome these difficulties was by creating memory reed switches. The idea was that the permanent magnet should become a magnet only when it and the reed switch are affected by the control pulse of the coil. Other details were technical. They chose magnetic material with a medium coercive force, which could be magnetized during the time of affecting of the control pulse, and remain magnetized for a long time, until the pulse of the magnetic field of the opposite polarity affects it (such material is called ''remanent''). This device, consisting of a reed switch and a ferrite element, was called ''ferreed'' (by the first letters of the words ''ferrite'' and ''reed switch''). Later, for advertising purposes, some firms began to name devices operating on the same principle in a different way: ''remreed,'' ''memoreed,'' etc.

It turns out that ferrite can be remagnetized for 10 to 50 μs while closing of contact-elements requires a time of 500 to 800 μs. This allows us to use very short pulses for ferreed control (in practice pulses with a reserve of up to 100 to 200 μs for closing are used). This means that contact-elements are not only held after closing of the magnetized ferrite, but also continue of closing process using the magnetic flux of the ferrite after the short control impulse stops affecting it.

It is obvious that ferreed with one control winding will be critical to the amplitude of the control pulse. When the amplitude of the switching current pulse (for switching OFF) is not high enough, the core in the control coil is not fully magnetized and the contacts will remain in a closed position. If the control signal is quite strong the core can be reversely remagnetized and obtain the opposite polarity. In that case the contact-elements will remain in a closed position also. To avoid this two control windings are applied (Figure 5.55).

The magneto-motive force of each winding is not enough to magnetize the core to the degree necessary for closing of the contact-elements. Only when switching-on current pulses of opposite polarity are applied to both windings is the total magnetizing force enough to magnetize the core, closing the contact-elements.

To open the contact-elements, switching-on current pulses of the same polarity are simultaneously applied to both windings. The polarity of magnetization of the halves of the ferrite core will be opposite, and both contact-elements are likely to be magnetized, therefore a repulsive force causing the contacts to open will arise between them. An additional shunt (4) made from soft magnetic material enhances configuration of the magnetic field in the overlap of the contact-points, and reliability of operation of the device.

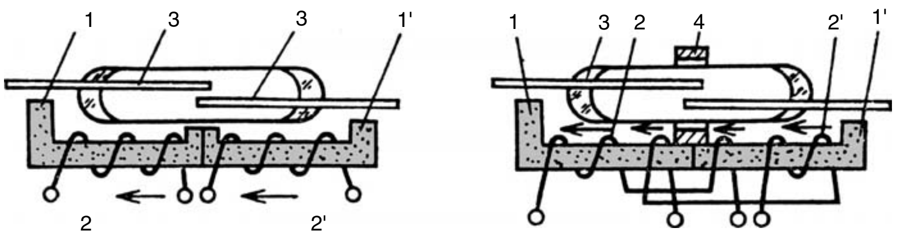


FIGURE 5.55
Ferreeds with two control windings. 1 — core from remanent material; 2 and 2′ — control windings; 3 — contact-elements; 4 — additional magnetic shunt.

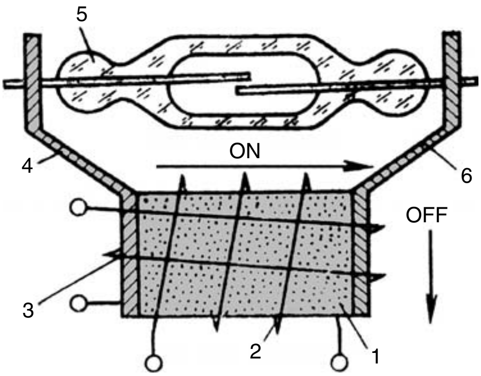


FIGURE 5.56
Ferreed with orthogonal control. 1 — core from remanent material; 2 — switching-on winding; 3 — switching-off winding; 5 — reed switch; 6 — magnetic core.

In a ferreed with a so-called orthogonal control (Figure 5.56), in order to change the state of the magnetization the vector turns by an angle of 90°, instead of 180° as in the previous case. The first such solution was patented by A. Feiner, from Bell Laboratories (U.S.A. patent No. 2992306). In his construction the magnetic flux of the winding (2) for switching ON passes through a magnetic gap between the contact-elements, and the magnetic flux of the winding (3) for switching OFF does not pass through the gap between the contact-elements, providing reliable switching OFF of the reed switch.

As in multi-wound reed switches, on ferreeds it is quite easy to implement single- or multi-circuit automation logic elements (Figure 5.57). For example, in multi-circuit relays with a cross-shaped core (Figure 5.57), there are 16 possible combinations of closed and opened reed switches, depending on what windings are switched ON.

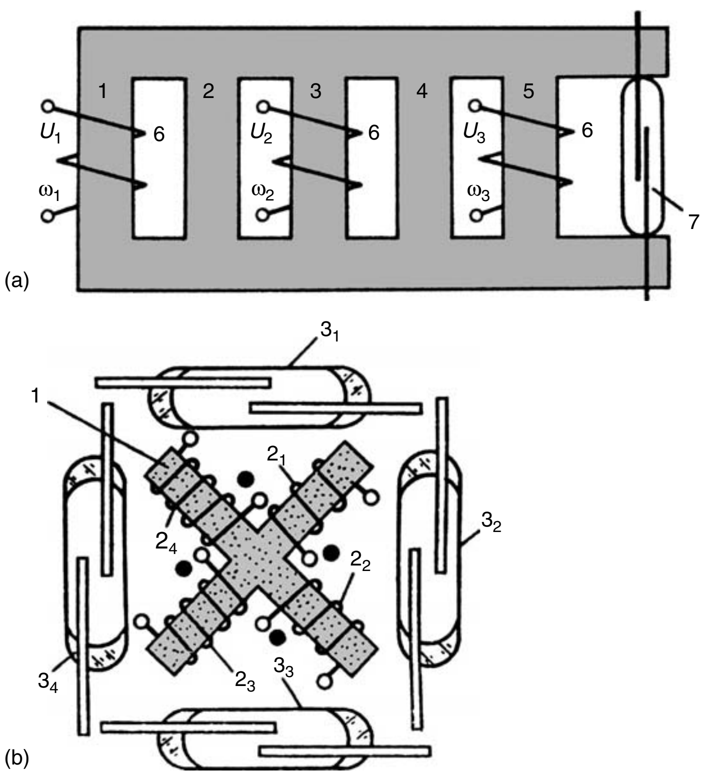


FIGURE 5.57
Automation logic elements on ferreeds.

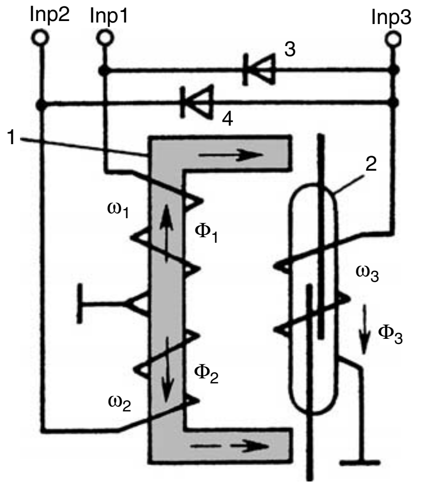


FIGURE 5.58
Device in which memorization option can be disabled.

In some constructions one can enable or disable memorization options with the help of additional control signals (Figure 5.58). In the construction described above a memory element of the external type is used. Since the 70s one can observe rapid development of ferreeds with internal memory, which were produced by Hamlin, FR Electronics, and Fujitsu. Their external design was practically identical to that of dry reed switches, but their contact-elements were made of special alloys, providing sealing of the reed switch after it was affected by the pulsed magnetic field. Thus no external elements are needed for such ferreeds. Originally, contact-elements of such ferreeds consisted of two parts: an elastic one and a hard magnetic one (from remanent material), but there were also excess joints with increased magnetic resistance. Later on, hard magnetic alloys were invented and used, so that the contact-elements could be made more flexible and elastic enough. Such an alloy consists of 49% cobalt, 3% vanadium, and 48% iron, or of 30% cobalt, 15% chromium, 0.03% carbon, and the rest iron. There are also bimetallic contact-elements (U.S.A. patent No. 3828828), the internal rod of which consists of an alloy of 81.7% iron, 14.5% nickel, 2.4% aluminum, 1% titanium, and 0.4% manganese, with the shell of the section made of an alloy containing 42% iron, 49% cobalt, and 9% vanadium.

5.9 Reed Switch Relays

Unlike electro-mechanic relays with many interacting elements, the simplest reed relay contains nothing but a reed switch and a winding (Figure 5.59).

In some cases the relay is supplied with a ferromagnetic shield protecting the reed switch from magnetic field impact, and that is it! The simplicity of construction and low

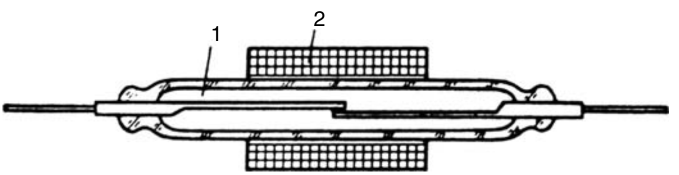


FIGURE 5.59
Simplest Reed Relay. 1 — reed switch; 2 — winding.

cost in mass production are the main advantages of reed relays, however, despite such simplicity there are several schemes for arranging magnetic circuits of reed relays by using additional ferromagnetic elements forming magnetic fields of the best configurations, and reducing flux leakage (Figure 5.60). There are also magnetic systems with internal (Figure 5.60a and b) and external (Figure 5.60c) reed switches. The choice of this or that variant is determined by many factors, including the size of the reed switch, the required sensitivity of the relay, size limitations, etc. In mass-produced relays all of the above variants are used.

In the 60s and 70s the most popular type in mass production was a relay with or without a ferromagnetic shield, in rectangular plastic cases covered with epoxide resin or silicon rubber (Figure 5.61). Later on, a ferromagnetic tube was used as a relay case. It allowed miniaturization and simplification of the construction. Typical examples of this are relays of the RES-55 and RES-64 type, which were produced in the U.S.S.R. in the 1970s (Figure 5.62). They were the smallest reed relays ever produced in the U.S.S.R. and belonged to the class of subminiature relays. The RES-55 type relay is based on a changeover reed switch (KEM-3), capable of switching voltages up to 127 V and currents up to 1 A (for voltage up to 36 V) with an active load and switched power of up to 30 W. The weight of such a relay is not more than 6 g. A RES-64 relay contains a normally open reed switch (KEM-2) switching under active load voltages of up to 130 V, currents up to 0.25 A (for voltage up to 30 V) with switched power of up to 9 W. The weight of this relay is also not more than 6 g.

Traditionally industrial automation relays, based on larger and more powerful reed switches, are considerably larger in size (Figure 5.63). In addition, relays designed for relay protection systems were produced in standard cases of electro-mechanic relays, whose volume exceeded that occupied by a reed relay (Figure 5.64). The main advantage of such a relay, compared with similar electro-mechanic ones, is its high speed of

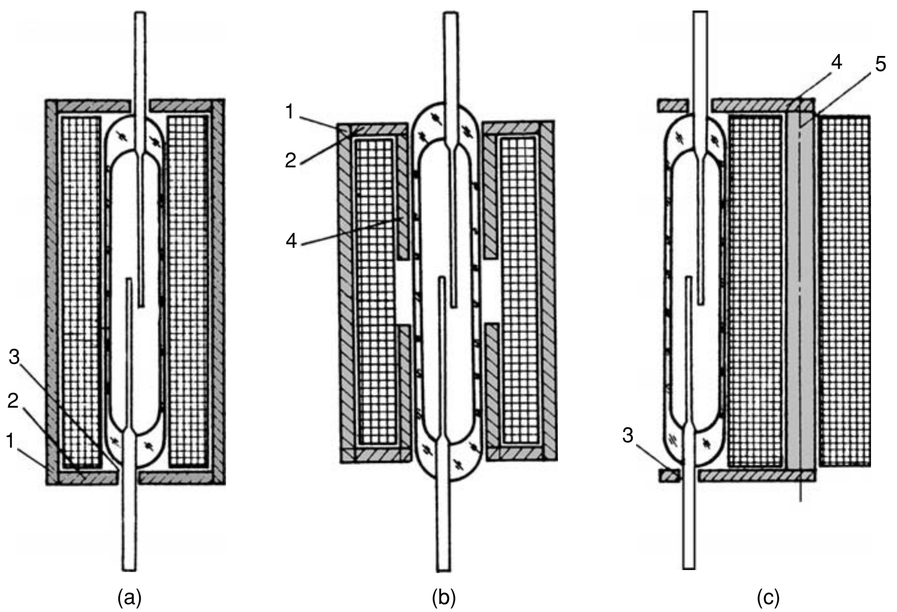
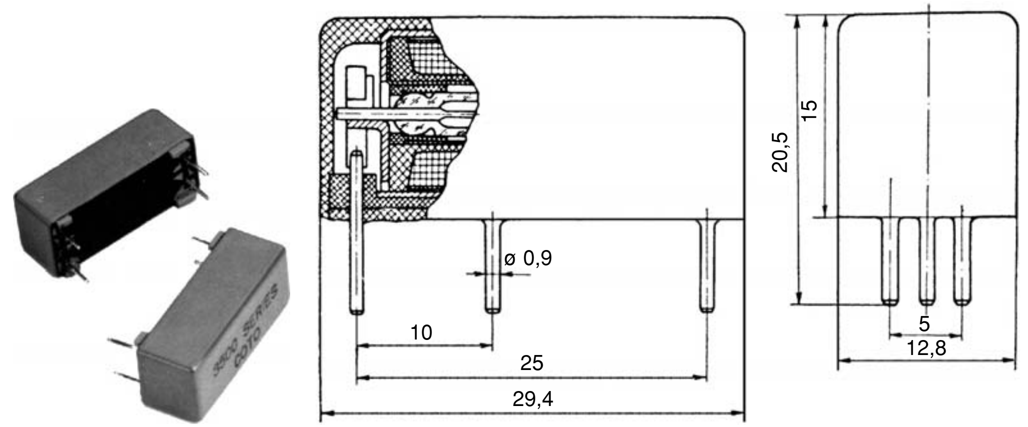
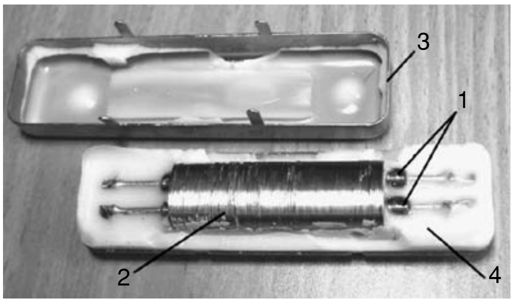


FIGURE 5.60
Construction schemes of magnetic circuits of reed relays. 1 — ferromagnetic shield (the same as part of a magnetic core); 2 — magnetic terminals; 3 — insulating gap; 4 — additional terminals; 5 — core.



(a)



(b)

FIGURE 5.61
(a) External design and construction of typical low-power reed relays in plastic cases produced by many companies in the 70s. (b) Reed relay of ARID-B-2A2 type with a ferromagnetic cover coated with soft silicon rubber (ERNI). 1 — reed switches; 2 — free-bobbin coil; 3 — ferromagnetic cover-shield; 4 — silicon rubber.

operation. In reference sources of the firm ASEA, this relay is specified as an especially high speed one.

As chips appeared and came into wide use in electronic devices and other electronic components installed on printed-circuit boards became smaller, the size of reed switches was no longer satisfactory for designers of electric equipment. In addition, enhancement of standard electro-mechanic relays led to considerable miniaturization of relays having the same switching capacities compared with reed switches (Figure 5.65).

Because of the necessity of miniaturizing electric devices, engineers started designing reed relays in so-called dial in-line package (DIP) and single in-line package (SIP) cases of a size similar to that of chips, and with distances between outlets similar to a standard grid with a pitch (1.0″ × 0.1″ or 1.0″ × 0.15″ — Figure 5.66). Enhancement of the construction of reed relays and reed switches allowed considerable reduction of their weight and size (Figure 5.67), and restored competitiveness compared with miniature electro-mechanic relays.

In practice, construction of multi-contact relays is similar to that of single-contact ones, the only difference being that instead of one reed switch, an unit of a few reed switches was inserted into the coil (which was, of course, large in size (Figure 5.68). Relays in such cases were produced in the U.S.S.R. in the 1960–70's. Their external design and size were very much like diode-transistor logic elements produced at that time from the series ''Logika-T'' (designed for construction of automation control systems and control

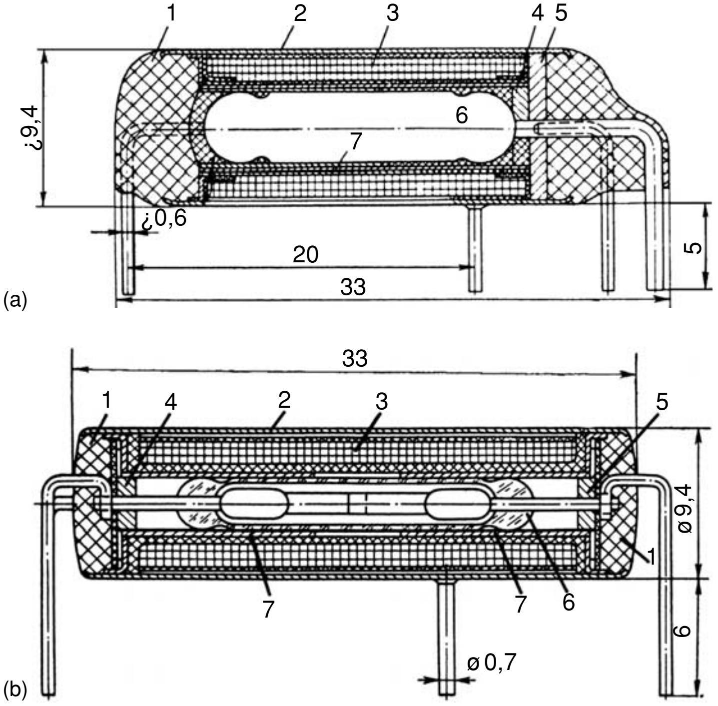


FIGURE 5.62
Reed Relays (RES-55 (a) and RES-64 (b)) with a ferromagnetic shield as a case, produced by plants of the former U.S.S.R. in the 70s. 1 — epoxide resin; 2 — case (a steel tube with a sidewall 0.2 mm thick); 3 — winding; 4 and 5 — ferroelastic disks; 6 — reed switch; 7 — electrostatic shield from brass 0.1 mm thick.

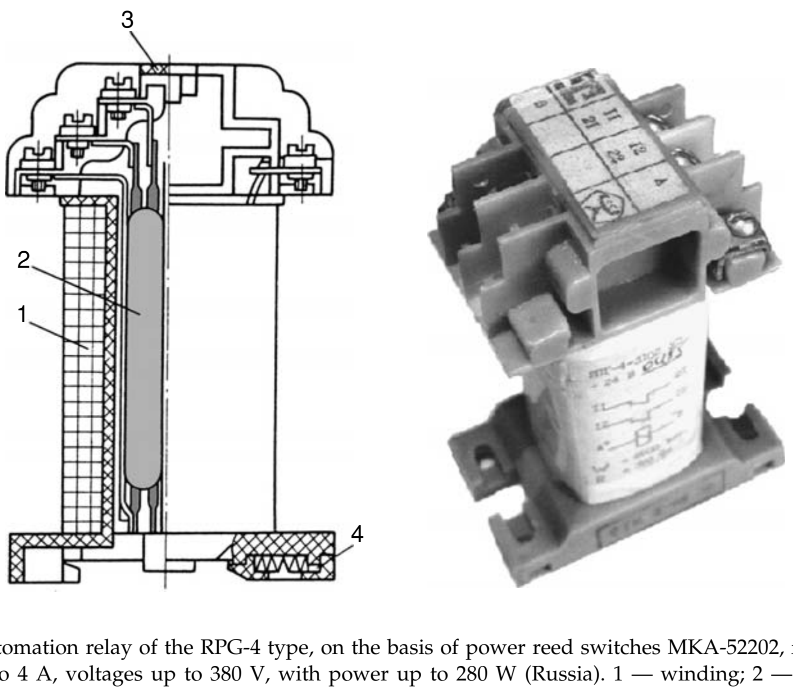


FIGURE 5.63
Industrial automation relay of the RPG-4 type, on the basis of power reed switches MKA-52202, for switching currents up to 4 A, voltages up to 380 V, with power up to 280 W (Russia). 1 — winding; 2 — reed switch; 3 — cover with a terminal socket; 4 — fixation elements of the relay on a standard DIN rail.

FIGURE 5.64
Reed relay of RXMT-1 type for devices of relay protection of power systems (produced by ASEA).

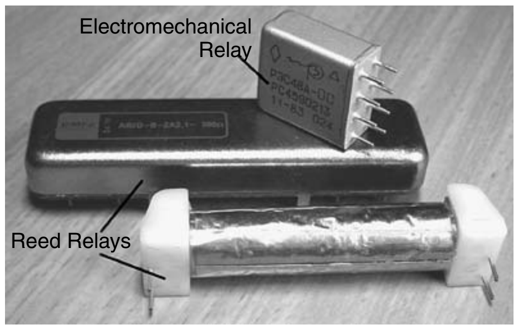


FIGURE 5.65
Multi-contact electro-mechanic relays with similar switching characteristics are smaller in size than reed ones.

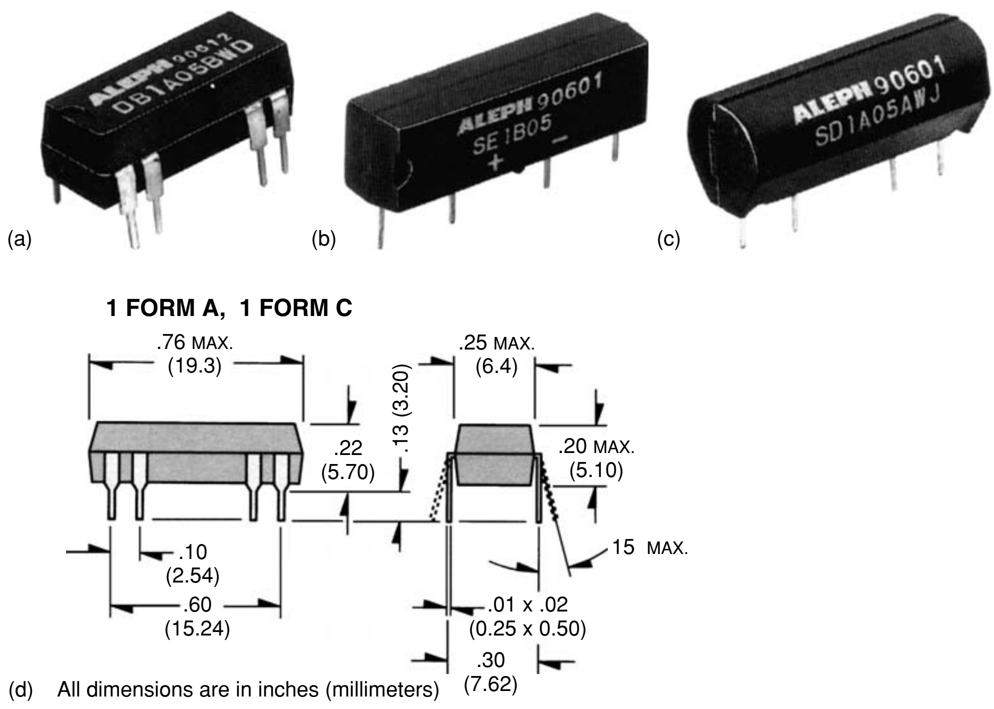


FIGURE 5.66
Modern miniature reed relays (produced by ALEPH) in (a) DIP and (b, c) SIP cases.

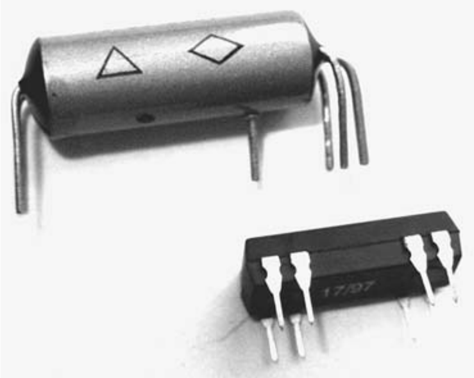
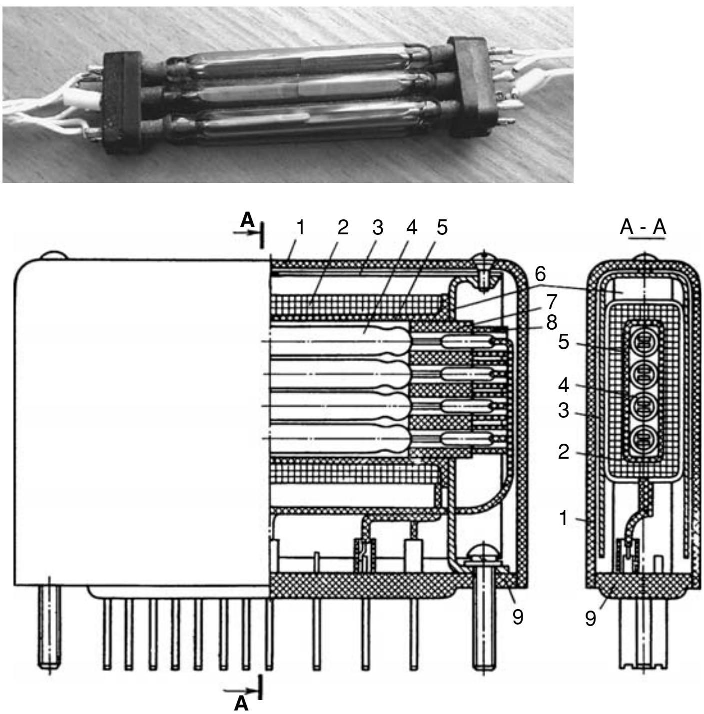


FIGURE 5.67
The smallest reed relays with a changeover reed switch produced in the 1970s — upper (In Russia it is still being produced) and modern ones in a DIP case — bottom.

of industrial processes), because they were used as outlet nodes of these logic elements. At that time such relays corresponded to the technical level. They switched currents up to 1 A and voltages up to 250 V with power of 50 W. When at the beginning of the 1980s production of logic elements of the ''Logika-I'' series started, based on antinoise integrated circuits, the external design of the industrial reed relays was also changed, causing them to very much resemble these logic elements (Figure 5.69), and a new type of installation — on standard DIN rail used in western countries — was applied.

(a)



(b)

FIGURE 5.68
(a) An unit of six reed switches of standard ''A'' form size (three reed switches in two lines) for installation in the internal cavity of a coil of a multi-contact relay. (b) Construction of multi-contact relay of RPG type based on reed switches of standard size for industrial automation systems. 1 — plastic case; 2 — winding; 3 — ferromagnetic shield; 4 — reed switches; 5 — coil bobbin; 6 — cramp; plastic sockets; 8 — rubber tubes; 9 — heelpiece.

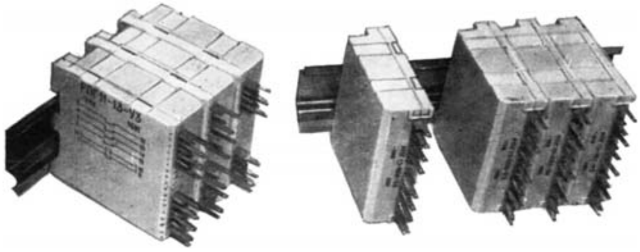


FIGURE 5.69
Reed relays RPG-11, RPG-13 for industrial automation systems in cases of logic elements of ''Logika-I'' (the U.S.S.R, Russia).

In the magnetic systems of multi-contact relays with external reed switches, the latter are placed outside the coil circle-wise (Figure 5.70). According to such construction schemes reed relays of the RPG-14 type, based on high power reed switches (4 A, 380 V, 250 W) were produced (Figure 5.71). Lately the production of low-power (50 W) and higher-power (up to 250 W) reed switches of normal size, and reed relays based on them (Figure 5.66–Figure 5.69) has been considerably reduced. This becomes clear when one compares multi-contact reed relays of these types with electro-mechanic relays with similar characteristics (Figure 5.72). In comparison, the reed relays were seen to be inferior, and it was obvious that large reed relays based on reed switches of normal size, designed for industrial automation systems, have no future (if we do not take into account some exceptional and unusual cases). At the same time miniature reed relays

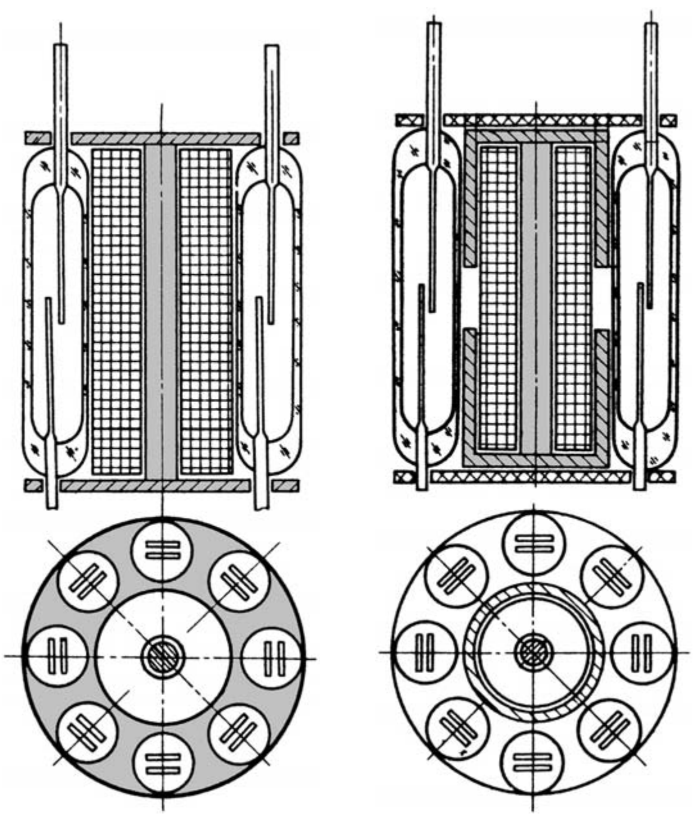


FIGURE 5.70
Magnetic systems of multi-contact relays with external reed switches.

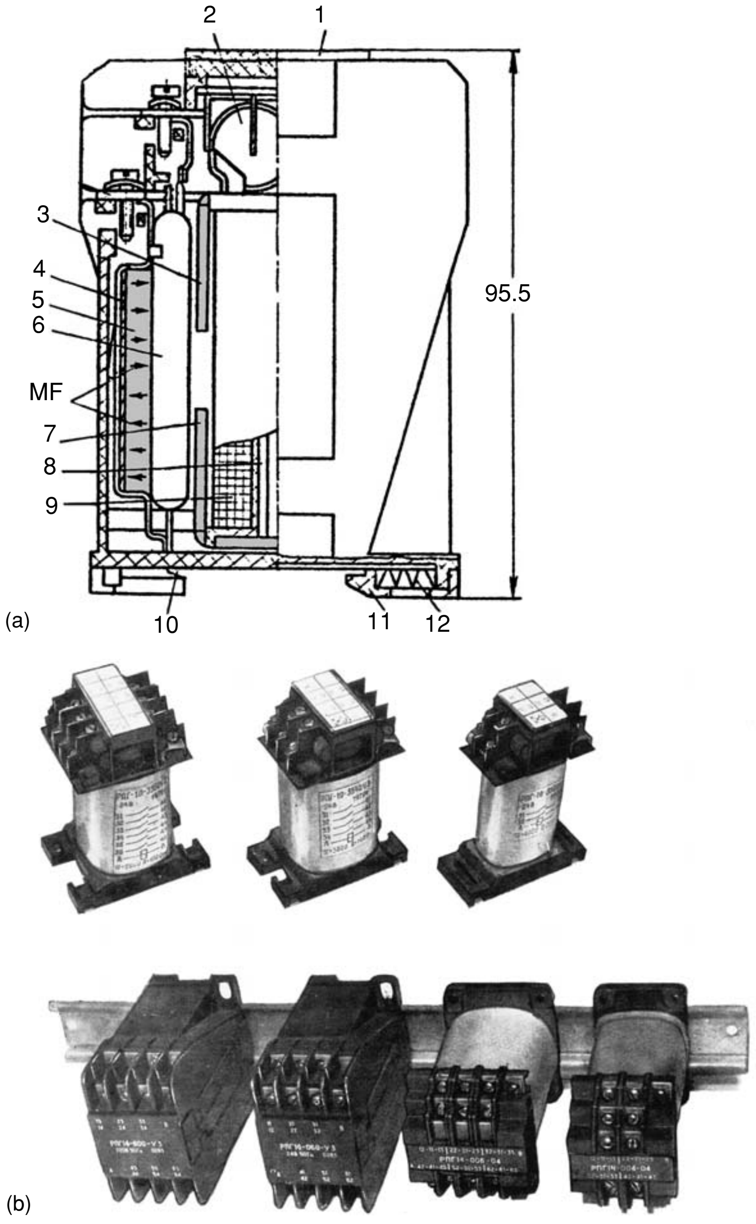


FIGURE 5.71
(a) Construction of a mass produced multi-contact relay RPG-14 based on power reed switches placed outside the coil. 1 — cover; 2 — varistor connected in parallel to the winding; 3 and 7 — magnetic cores; 4 — ferromagnetic plates; 5 — permanent magnet; 6 — reed switch; 8 — ferromagnetic core; 9 — winding; 10 to 12 — elements of relay fixation on a standard DIN rail. (b) Multi-contact power reed relays of the RPG-10 type (above) and RPG-14 (below), produced in the U.S.S.R. (Russia).

with switching reed switches in DIP and SIP cases continue to be in demand on the relay market, and their production has been scaled up.

It is not quite clear yet whether contactors based on high-power reed switches (hersicons) of the KMG type (see above), constructed in the former U.S.S.R. (Figure 5.73), will be used, as there is not yet enough international field experience. Apparently such

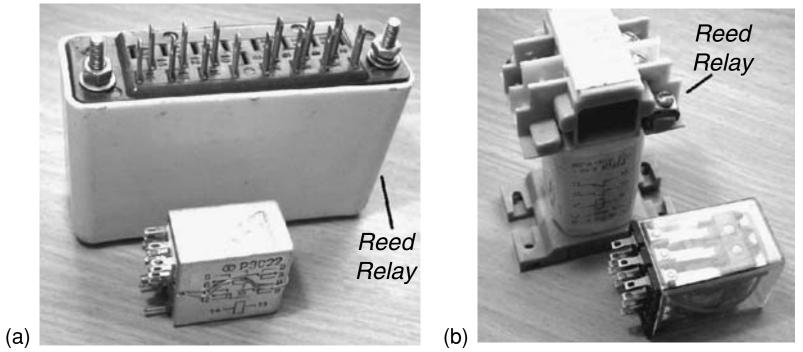


FIGURE 5.72
Comparison of sizes of relays based on (a) low-power and (b) higher-power reed switches of normal size with electro-mechanic relays with similar characteristics.

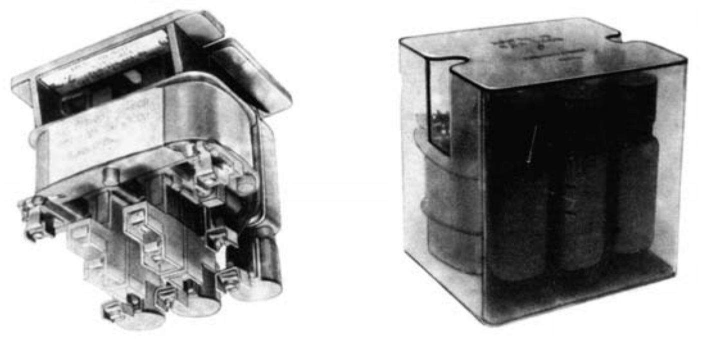


FIGURE 5.73
Three-phase contactors based on high-power reed switches.

constructions may be quite useful under special conditions, such as dust-laden and explosive atmospheres, intensive ammoniac vapors (in agriculture), salt spray atmosphere impact, etc.

5.10 Mercury Reed Relays

Relays based on mercury reed switches have been produced serially for a long time, perhaps since such reed switches were invented. The first constructions were produced in cases unusual for relays, similar to those for vacuum radio valves (Figure 5.74). Such cases provided good protection of a mercury reed switch from mechanical damages and had well-developed production techniques. When the air had been pumped out, the tube of the reed switch of this relay was filled with hydrogen under about 15 atm pressure, providing break-down voltage between contacts up to 8500 V, and preventing oxidation of the mercury. The relay was 28.1 mm in diameter and 81.2 mm in length. The weight was 113 g.

Because of mercury and high pressure, such relays are labeled with one or more of the following warnings (Figure 5.74b):

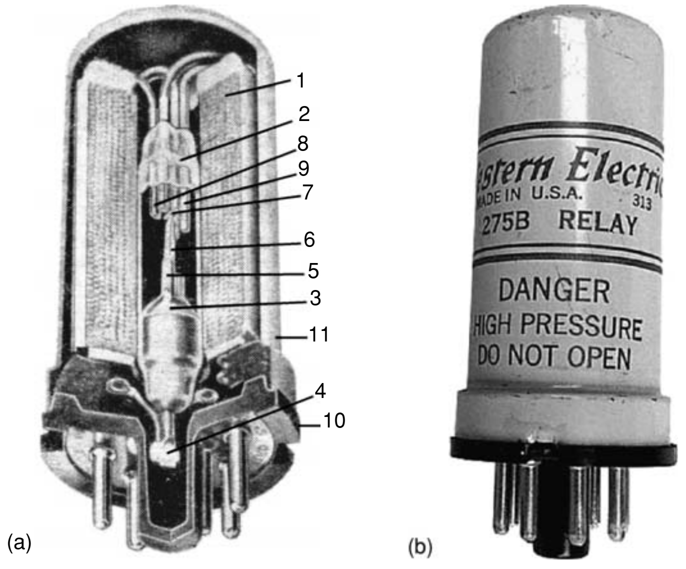


FIGURE 5.74
(a) Relays of HG type based on mercury reed switch in a case of a metallic radio tube (CP Clare Co., 1947). 1 — coil; 2 — glass tube of the reed switch; 3 — mercury; 4 — stem; 5 — lower pole terminal; 6 — armature; 7 — movable contact fixed on the armature; 8 — stationary contacts; 9 — terminals with stationary contacts; 10 — octal heelpiece; 11 — metallic case. (b) Mercury relay 275B type, produced by Western Electric Co. in the 1950–1960s years.

- ''UP''
- ''Danger''
- ''High Pressure, Do Not Open''

At present, a wide range of relays based on mass-produced mercury reed switches is manufactured. One can come across both relays in standard round cases, and in more common for relays rectangular (metal) cases (Figure 5.75). A typical feature of such relays is a large pointer on the relay case, which indicates its working position.

5.11 Winding-Free Relays

The winding in a reed relay is used to produce the magnetic field needed for reed switch operation, however, such a magnetic field can also be created by other sources, for instance by a permanent magnet or copper wire with a large current passing through it. In fact such sources of magnetic fields are widely used to control reed switches.

Different firms produce a great number of position pickups, liquid level detectors, pressure sensors, etc., based on reed switches controlled by moving permanent magnets. Such devices belong to detectors rather than to relays, and it is practically impossible to describe all of their peculiarities in the book. A reed switch placed at some distance from the conductor line, with currents of hundreds of amperes operating at a certain value of the current, is a current relay (Figure 5.76).

The operation threshold (pickup current) of such a relay (that is, its sensitivity) with invariable current value in the line, depends on the distance X between the line and the

FIGURE 5.75
Modern relays based on mercury reed switches produced by Midtex company.

reed switch, and the angle α between the longitudinal axis of the reed switch and the longitudinal axis of the line. Apparently, the maximum sensitivity of the device will be at minimum distance, and the angle $\alpha = 90^{\circ}$. One can adjust the pickup current of a relay by changing these parameters.

To obtain a nonlinear (sharper) change of the magnetic flux affecting a reed switch, a ferromagnetic shunt with a smaller section at the overlap of contact-elements is used, when current value in the line approximates the pickup current of the relay (Figure 5.77). At low values of current in the bus, far from the pickup current of the relay, the magnetic flux Φ in the upper part of the line closes through the shunt (3) and does not affect the reed switch. As current is increased to a certain value, the reduced part of the shunt is quickly saturated and the magnetic flux bulges saltatory at this part of the shunt. The reed switch is energized, affected by the magnetic flux.

Taking into account the sensitivity of real reed switches, and the necessity of holding the insulating distance X between the line and the reed switch, it is possible to provide a minimal pickup current starting from 50 to 100 A. In cases when that is not enough, an additional magnetic core concentrating the stray flux of the conductor line and directing it to the reed switch area is used (Figure 5.78). One can increase the sensitivity of a relay with an additional magnetic core by several times.

For current control in three-phase circuits, relays with three reed switches and a magnetic core of original construction are used (Figure 5.79). Principles of construction of winding-free reed relays described above can be applied to both DC and AC. In the latter case, relay ''operation'' means vibration of contact-points of the reed switch with doubled circuit frequency.

A vibrating reed switch can be included in the simplest electronic circuit, transforming a variable signal into a standard continuous one. Sometimes that is not very convenient, and sometimes it is just impossible, for instance, in case when a relay must be in the

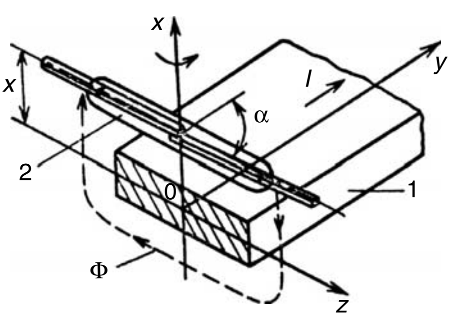


FIGURE 5.76
Winding-free current relay based on reed switches.
1 — conductor line; 2 — reed switch.

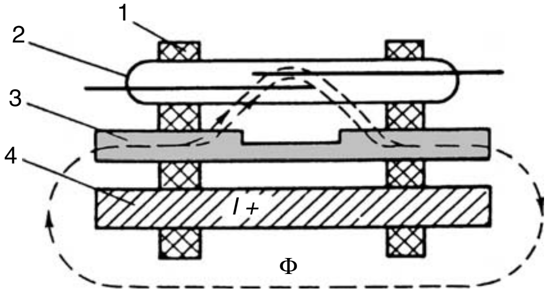


FIGURE 5.77
Winding-free reed current relays with a magnetic shunt. 1 — insulating fastening elements; 2 — reed switch; 3 — magnetic shunt; 4 — current-carrying bus.

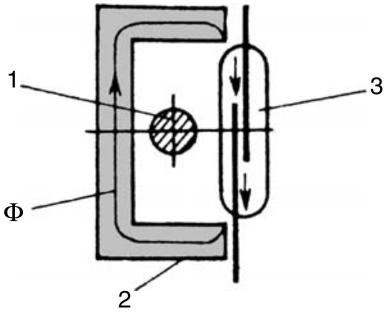


FIGURE 5.78
Winding-free reed relay with an additional magnetic core. 1 — current-carrying bus; 2 — external magnetic core; 3 — reed switch.

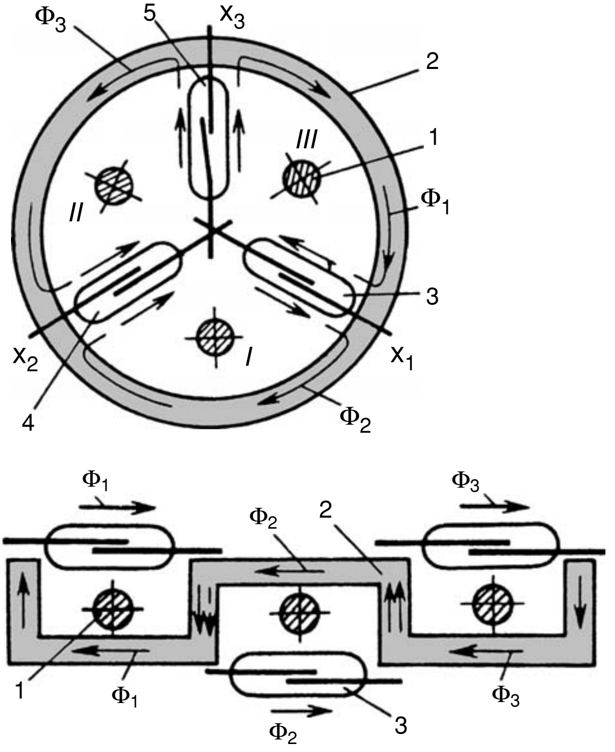


FIGURE 5.79
Winding-free reed relays for three-phase circuit. 1 — current-carrying bus; 2 — magnetic core; 3 to 5 — reed switches.

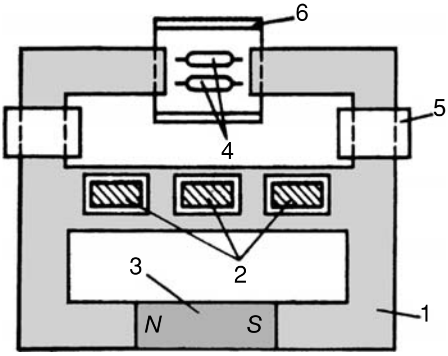


FIGURE 5.80
Three-phase winding-free reed AC relay, operating without vibration of the reed switch. 1 — magnetic core; 2 — current-carrying buses of the three-phase system; 3 — permanent magnet; 4 — reed switches; 5 — short-circuit windings; 6 — protective shield.

operated state for quite a long time. In these cases, certain trick techniques are used (Figure 5.80). In such a relay with no current (or of very small value) in buses (2) the ferromagnetic jumper strap is not saturated and the magnetic flux of the permanent magnet (3) is shunted by this strap, and does not affect the reed switches (4). As current in the lines increases, the strap becomes saturated. It stops shunting the magnetic flux of the permanent magnet (3) and the reed switches (4) are energized, under effect of the magnetic field of this permanent magnet. In the three-phase system of this relay, pulses of the resultant magnetic flux of the three phases affecting the reed switch are insignificant and, of course, do not cause any vibration of the reed switches.

The same solution can be applied in a single-phase relay. In order to smooth pulses of the magnetic flux one can use additional short-circuit windings (5). The patent No. 10003169 (U.S.S.R.) describes a single-phase winding-free reed AC relay where the alternating magnetic flux in the magnetic core, affecting the reed switch, seems to be ''rectified'' with the help of additional windings shunted by diodes (Figure 5.81).

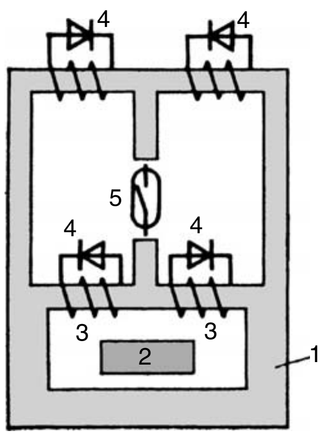


FIGURE 5.81
Winding-free reed relay with ''rectifying'' of the alternating magnetic flux. 1 — magnetic core; 2 — AC current-carrying bus; 3 — additional windings on the magnetic core; 4 — rectifier diodes; 5 — reed switch.

6

High-Voltage Relays

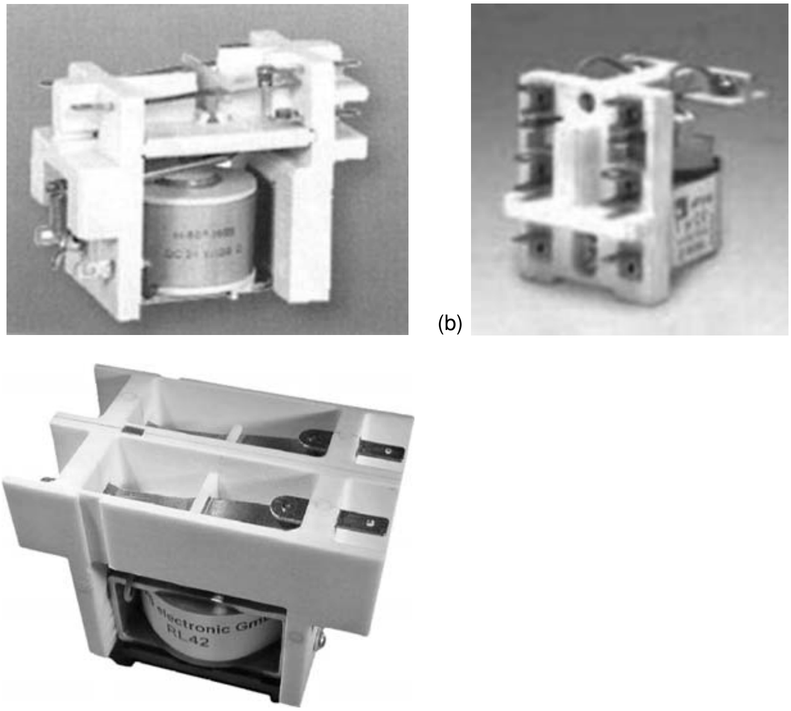
6.1 What is a ''High-Voltage Relay?''

Rapid development of electric technologies applying high voltages (power lasers, industrial accelerators, high-frequency metal and dielectric heating, etc.), use of powerful electronic equipment operating under high voltages (radar, TV, and radio transmitters) and also the need for systems for testing insulation of electrical devices of different voltage levels, were the causes that bought about the spread of high-voltage (HV) relays, operating under voltages from 5 to 300 kV and higher. Such relays can be divided into two groups: relays with HV insulation for all current-carrying elements switching high voltages, and relays with low-voltage (LV) contacts and high voltage insulation between the input elements (control coil) and the output ones (contacts). The second group marks a new direction in construction of relays, founded by the author in the 1970–80's. In fact, the founding of new directions in engineering is quite a rare phenomenon. Tens of patents and articles in technical–scientific journals published in the Ukraine and Russia and translated in the U.S.A. provide additional evidence of the author's precedence in founding this new direction in relay construction. His latest research in this field is published in his book, *Protection Devices and Systems for High-Voltage Applications* (Gurevich, V. 2003). The relays of the first group are applied in equipment similar to the relays described above (only under higher voltages), while relays of the second group have a more specific field of application: these are insulating interfaces designed for transmission of control instructions, alarm signaling and protection (over-current) of components of equipment operating under high potential differences.

Relays switching high voltages can be divided into contact, solid-state (semiconductor), and cathode-ray ones. Contact HV relays may be open or sealed (gas-filled or vacuum), and also reed ones.

6.2 Open Relays for High-Voltage Switching

Open HV relays for working voltages up to 5 kV alternating current (AC) and direct current (DC) are quite simple and cheap devices. The main differences between them and LV relays are an increased gap between contacts and some additional plastic components increasing electric strength between elements with opposite potentials (Figure 6.1). The increased gap between contacts in such relays requires greater armature travel and



(a) (b) (c)

FIGURE 6.1
HV relays (with maximum switched voltage 5 kV) of the open type produced by different firms: (a) Hengsler-Ka Co; (b) Italiana Rele; (c) SPS Electronic GmbH.

therefore a bigger initial gap in the magnetic circuit of the relay. This leads to a considerable increase of power consumed by the coil of the relay, and overheating.

In the W158HVX relay produced by the German company Magnecraft, this problem is solved by introduction of an additional corner toggle between the armature and the movable contact, at small travel of the armature (Figure 6.2). The power consumed by the coil of this relay is only 5 W. Further growth of working voltage necessitates a sharp increase in the relay size, and manufacture of contacts in the form of cylinders with hemispherical ends, and additional insulating rods linking the armature with the movable contact (Figure 6.3).

The Ross Engineering Company produces a great variety of such relays for voltages of 12 to 300 kV. It is necessary to take into account that Ross Engineering has specified in their catalogs that their relays withstand peak values of test voltages. Here is Ross Engineering's explanation for this:

> The peak test rating of high voltage relays should be 1.2 to 5 times the normal high voltage circuit operating voltage, depending upon the application. For lower power systems, where transients are unlikely or intermittent flashover is of no consequence, a safety factor of 1.2 to 1.5 may be suitable. For medium power systems, or where moderate transients are likely, a safety factor of 1.5 to 3 is desirable and 2 to 3 recommended. For higher power systems, or where transient over-voltages are expected, a safety factor of 2.5 to 5 should be considered and the factor should be

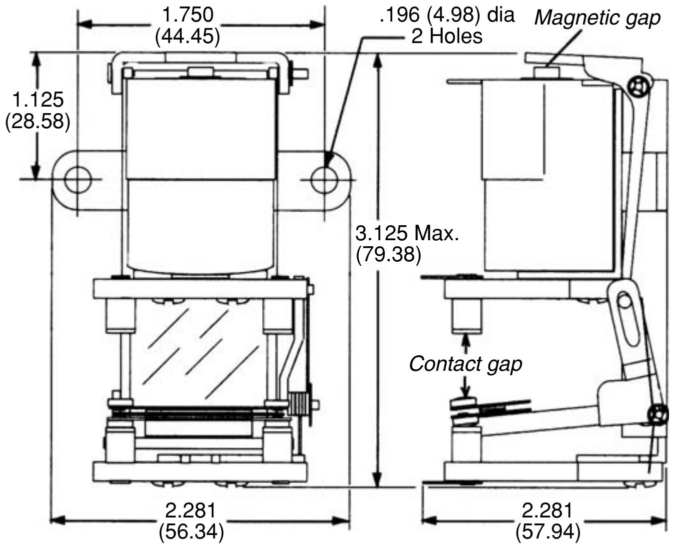


FIGURE 6.2
Open HV relay of W158HVX type with a large gap between contacts, and a small magnetic gap. Produced by Magnecraft.

based on the maximum probable transient. The peak test voltage to ground rating should be selected in the same way as is the contact to contact value.

From this explanation it becomes clear why it is impossible to specify the certain value of rated voltage that can be applied to all consumers. For one consumer the relay at 300 kV (catalog value) can be used in installations with a rated voltage of

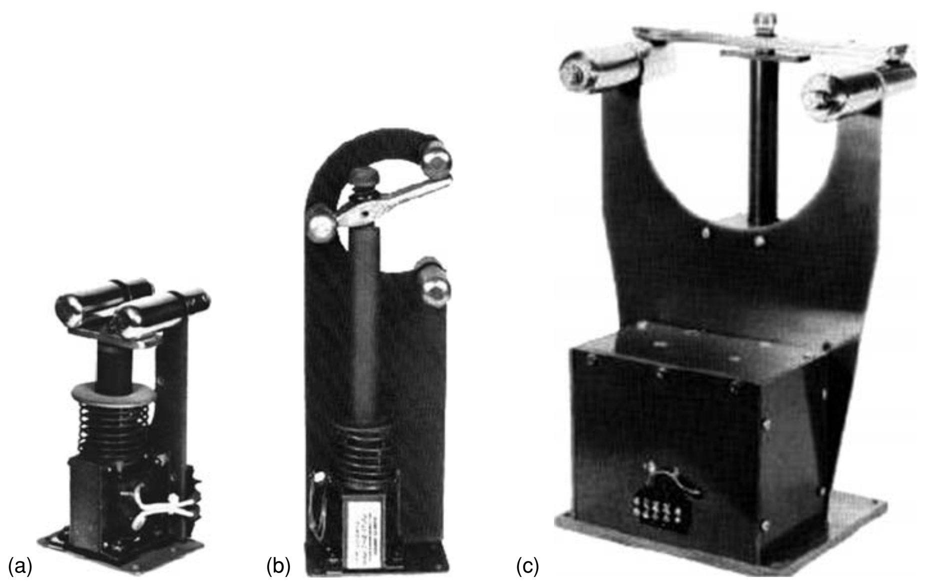


FIGURE 6.3
Open HV relays for voltages of 12, 60, and 300 kV (values indicated in the catalog) produced by Ross Engineering.

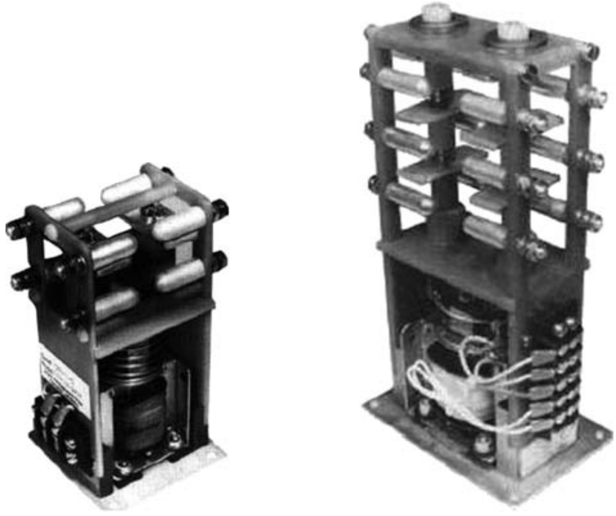


FIGURE 6.4
Multi-contact HV open relays produced by Ross Engineering.

200 kV, whereas for others, the same exact relay can be used only upto 50 kV. This is one of problems that we already noted above when discussing the level of isolation of the relays intended for use in LV electronic equipment and in powerful systems of industrial automatics. In our opinion, the Ross Engineering approach to this problem is fair and correct. It is also necessary to take into account that the value is given for relays in air, and if they are put into a tank with oil or into a hermetic reservoir filled with SF_6 gas under certain pressures, the working voltage can be increased twofold.

The size of a relay with 300 kV voltage indicated in the catalog is 650 × 914 × 1725 mm. The company also produces multi-contact relays operating according a similar principle (Figure 6.4). The Ross Engineering Company also produces HV relays with a pneumatic drive (Figure 6.5). Open relays produced by Ross Engineering are designed for shorting HV circuits for safety's sake, condenser discharge, etc., and are not designed for current breaks in the HV circuit. When charged, the HV capacitors are abridged, and the relay contacts are capable of withstanding closing pulse currents of up to tens of kilo-amperes (during the first 20 μs), and continuous currents in a closed position of up to 50–200 A.

FIGURE 6.5
HV open relay for voltages of 12 to 40 kV with a pneumatic drive, produced by Ross Engineering.

6.3 Vacuum and Gas-Filled High-Voltage Low Power Relays

Use of vacuum as a dielectric environment allows enhancement of the switching characteristics of a relay. Depending on the type of switching, low-power relays can be divided into two categories:

- Cold-switching of high voltages 12–70 kV
- Hot-switching with voltages up to 3–10 kV

There are two types of relays for hot-switching:

- Make-only relays, with pulse currents of up to a few kilo-amperes, with a duration of a fraction or a few milliseconds
- Power-switching relays, for currents of a few amperes

Industrial vacuum low-power relays (from the first category) were produced already in the 1950s by the General Electric Co. (Figure 6.6). Some of them had a small internal vacuum chamber with contacts and a flexible bellow (a crimped membrane providing moving of the movable contact by a certain value through a hermetic shell) and a winding placed outside the vacuum area (Figure 6.6a). Others had a bigger vacuum chamber containing all the elements of the relay including a winding (Figure 6.6b). Each of these constructions has advantages and disadvantages. The flexible bellow complicates a relay and makes it more expensive, and a coil placed in vacuum should have a ceramic bobbin

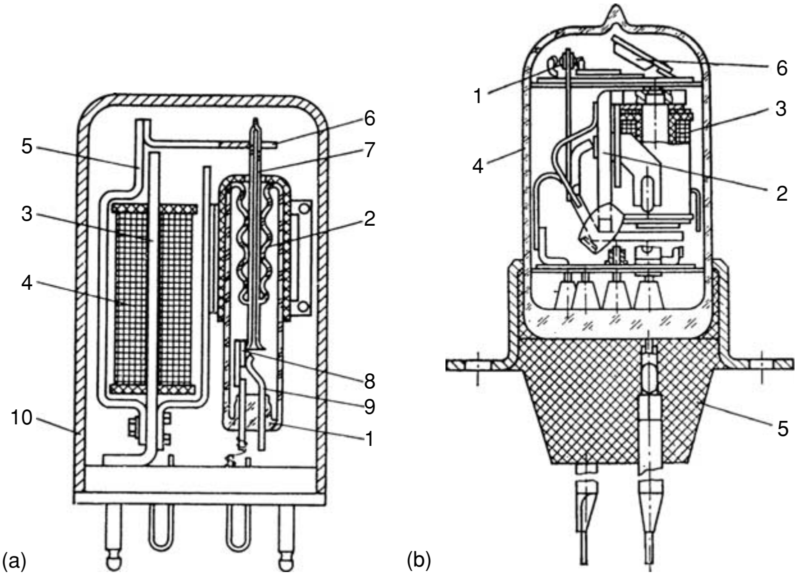


FIGURE 6.6
(a) HV vacuum relay with a flexible bellow and a coil placed outside the vacuum area. 1 — Glass shell of the vacuum chamber; 2 — flexible bellow (flexible membrane); 3 — core; 4 — winding; 5 — armature; 6 — pusher of the armature (steel); 7 — pusher of the contact system (glass); 8 and 9 — contacts; 10 — metal case. (b) HV vacuum relay with all elements placed in vacuum. 1 — Changeover contact; 2 — magnetic core with an attracted armature; 3 — coil; 4 — glass shell; 5 — heelpiece; 6 — baric getter.

and should be wound by a special wire in glass insulation, which does not evolve gas as it is being heated.

Vacuum is almost a perfect environment for relay contacts with very high dielectric strength (in relays vacuum with residual pressure of not more than 10^{-6} mm Hg is usually used. This provides a breaking-down voltage of up to 100 kV/mm), keeping the contacts absolutely clean, maintaining low resistance between the contacts, and also allowing use of magnetic systems with small armature travel and small weight, and therefore quick-operating.

The process of contact opening begins with a gradual reduction of contact pressure and an increase of resistance between the contacts, from a very small value up to infinity (when the contacts are opened). At this moment even at small currents the contacting points become intensely heated, up to melting temperature of metals, and a molten bridge appears on the separating contacts. As this bridge is broken, the arc begins to burn in the metal vapors of the contacts. On AC this arc goes out as soon as the current sinusoid passes through zero. There is no new arcing because the speed of restoration of electric strength in the vacuum is very high. The electric strength of the gap between the contacts is already restored entirely within 50 to 10 μs after current zero. A DC arc in vacuum does not decay of its own accord if the current value is enough for melting and evaporation of the contact material (for standard contact materials currents are a few amperes) and the source voltage is higher than arc-drop (about 20 V for tungsten contacts). It is interesting to note that even in very powerful vacuum contactors (which will be described below), switching OFF AC with amplitudes of tens of kilo-amperes are capable of switching OFF DC of only a few amperes. Here are specifications of the HB-204 vacuum contactor of Ross Engineering Corp., for example:

Voltage: 200 kV RMS (single phase operation)
Current: 50 to 1200 Amps continuous; 2,000 to 28,000 A AC, 1/2 cycle interrupt; 10 A DC interrupt; 5,000 to 80,000 A peak momentary.

That is why special schemes containing an LC oscillatory circuit forming a false zero current during switching are used to quench the arc.

Even microscopic doses of gases starting to evolve from metals and insulating materials at high vacuum are capable of impairing the dielectric properties of the vacuum, and can lead to malfunctioning of the relay. It is quite difficult to maintain a high vacuum during the service life in the complex construction consisting of tens of different elements with seals of glass and metal, which must remain absolutely hermetic for quite a long period of time and under considerable changes of temperature. In addition, any small-size construction containing two metallic electrodes in vacuum, between which a voltage of 10 to 20 kV is applied, can become a source of X-radiation, and HV vacuum relays are not an exception. As in a vacuum, the speed of restoring voltage on separating contacts is very high (10 to 20 kV/μs). Circumstances for arc decaying arise on AC of sinusoidal form before the current passes the zero value. A sharp break of current circuit occurs (so called ''current chopping'') if there is inductance in the load. Quite considerable spikes, capable of damaging the insulation of electric equipment, accompany such a sharp break of current.

Sulfur-hexafluoride (SF_6) or a mixture of it and helium filling the tube under pressure of few atmospheres, are another alternative to vacuum for use in HV relays. Such gas has an electric strength exceeding air strength by 2.5 times, and under increased pressure in a closed shell its insulating properties are almost similar to those of technical vacuum used in relays.

Compared with air sulfur-hexafluoride has a twofold energy-to-volume thermal capacity. That is why cooling capacity of this gas is noticeably higher than that of air, which is very important in small-size relays with heavily loaded current-carrying parts. Affected by high temperature of an arc, this gas decomposes and turns into a monatomic mixture of sulfur and fluorine. As soon as the arc decays, the mixture recombines, turning to the original gas again.

However, if there are admixtures of water and oxygen even in microscopic quantities, recombination is not full and properties of the switching device worsen sharply. In addition, remains of free sulfur in the closed shell have a negative impact on the contact surface as they form films that conduct current badly. As a result, transient contact resistance increases by a factor of 10^2. In real constructions of relays, it can reach 500 to 1500 mΩ, which restricts the wide use of sulfur-hexafluoride in relays. The peculiarity of this gas is that as the strength of the electric field between contacts of the relay increases (and this happens when the contacts approach each other during the process of closing), gas ionization occurs and becomes conductive, completing the circuit before the contacts of the relay close, and keeping the circuit closed as the contacts rebound when they collide. This prevents erosion of the contacts caused by vibration, especially when circuits with great pulse currents (caused by shorting of a charged HV capacitor) are switched. That is why in such cases it is almost always recommended to use a gas-filled relay; however, long ionization of this gas caused by the corona in nonhomogeneous electric fields, may lead to decomposition of the gas.

Decomposition products have strong toxic and corrosive properties, which is why relay construction must exclude the possibility of corona occurrence. International production of modern HV vacuum and gas-filled relays for switching voltages from 4 to 70 kV is almost entirely done by the American companies Kilovac, Jennings Technologies, and Gigavac, who produce relays with similar construction, similar external design, and similar characteristics (Figure 6.7).

The magnetic system of a HV relay in a glass case (Figure 6.7e), is a traditional one, with an attracted armature moving contacts with the help of an insulating rod. The upper end of the ferromagnetic core is hermetically embedded in a vacuum chamber with contacts. The rest of it is outside the vacuum chamber. A coil molded with plastic is installed onto this external part of the core. Such construction prevents contamination of the vacuum chamber by gases evolving from the materials of the coil, and in addition one can always replace the coil with another one, with the required characteristics.

In a relay of the diaphragm type (Figure 6.7g), the coil is inside the case and cannot be replaced, but it is also separated from the hermetic contact area with the help of a flexible diaphragm. The magnetic system is of the same type, with an attracted armature. Transmission of the effort on the movable contact, as in the previous case, is carried out with the help of an insulating rod.

In Russia, relays of P1D, V1V, V2V-1V, and other types, which are based on similar principles and have similar fields of application, have been constructed and produced by the Penza Scientific Research Institute of Electromechanical Devices for a long time already (Figure 6.8). It is worth mentioning that only a few types of HV vacuum relays produced by Jennings are designed for operation in hot switching modes. Such relays are capable of switching currents not exceeding 3 A, with voltage up to 2.5 kV. The firm Kilovac indicates in its catalog the possibility of using some of these types of relays, ''for power switching low current loads,'' without mentioning particular values of switched currents and voltages. Each specification of switching devices as a rule contains so called ''life curves,'' illustrating dependence of a number of operating cycles on switched power for several voltage levels. Such curves are never given for HV vacuum relays by firms producing them, which is also evident that the main purpose of such relays is not current switching.


0.24
(6.10)
Ø0.40
Ø(16.51)
0.31
(7.87)
R0.04 MAX
R(1.02)
1.66
(42.16)
1.03
(26.16)
Ø0.52
Ø(13.21)
0.17 (4.32)
0.40
(10.16)
R0.062 (1.575)
0.13 (3.30)
Ø0.062 (1.58)
2 PLC'S
Ø0.65 (16.51)
Coil terminals
2 PLC'S EQ. SP.
ON Ø0.32 (8.13) B.C.
(a)
(b)
GIGAVAC
(c)
Kilovac
K47A234
(d)

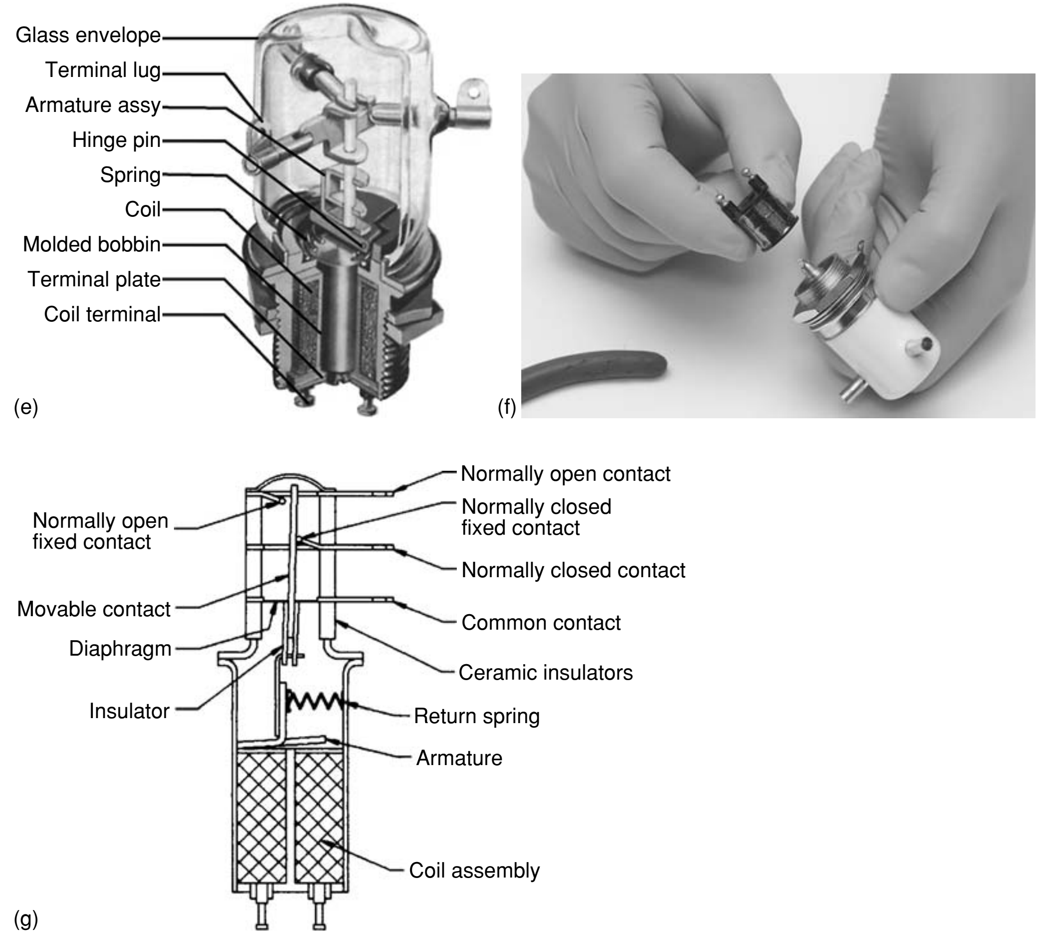


FIGURE 6.7 (*Continued*)
(a) Sizes of the HV vacuum relay of RF41–26S type (4 kV, 12 A) produced by Kilovac. (b) HV relay produced by Jennings (U.S.A.). (c) HV relay in metal–ceramic cases produced by GIGAVAC (Santa Barbara, CA). (d) HV relays in metal–ceramic cases produced by Kilovac (Santa Barbara, CA). (e) Construction of a HV relay in a glass case produced by Kilovac. (f) Process of assembly of the HV relay on the Gigavac company. The coil mounting in the relay after hermetic sealing and vacuuming of a shell with contacts. (g) Construction of a HV relay of the diaphragm type, in a metal–ceramic case.

The only difference in the construction of relays operating in hot switching modes is tungsten contacts, due to the fact that contact resistance of such relays is three times as much as that of relays with standard contacts. Arcing in the vacuum proceeds as long as the energy emerging on the contacts is enough to maintain the concentration of metal vapors and arcing. If tungsten, which does not vaporize intensely under the effects of electric arcing (the boiling-point is about 6000°C), is used, such relays can switch quite small direct currents (a few amperes) with voltages of only a few kilovolts. As vacuum is a very poor heat conductor, heat abstraction from contacts in vacuum relays is difficult, which is why in some types of small-size or miniature relays, as continuous currents of over 10 to 15 A pass through the contacts, radiators are applied to prevent overheating of such small-size relays.

FIGURE 6.8
Russian vacuum relay of V2V-1V type (15 A cold-switching, 4 kV).

6.4 High Power Vacuum Relays and Contactors

High power relays and contactors designed for switching currents of hundreds of amperes are also produced with vacuum insulation. According to data we have, the pioneer in this field was the firm ''Motor and Control Gear Division,'' which declared creation of the first high power vacuum contactor for voltage of 3.3 kV in 1965. Each contact in such devices was made as a separate item: the so-called vacuum interrupter (Figure 6.9). A solid case, from vacuum-tight ceramics and metal flanges, provides maintenance of pressure inside the chamber on the level of 10^{-5} Pa during the whole service life. In their initial state the contacts of the vacuum chamber, affected by the pressure difference inside and outside the chamber, are always closed. To open the contacts it is necessary to tug the external outlet of the current-carrying core 2. Freedom of movement of this core in the closed volume is provided by metal flexible membrane 5 (the so-called flexible bellow). The metal shield (3) protects the internal surface of the chamber from small parts of molten metal, from the electrodes of the chamber formed under arc effect when strong currents are switched off, and also equalizes the electric field strength in the contact area. Before a vacuum chamber is assembled, its elements are heated for a few hours at temperatures of over 400 °C, for degassing.

Contacts of the vacuum chamber are shaped in such a way that working current forms a magnetic field, forcing out the arc. A number of projects and patents are known on this subject. Contacts with spiral leaves are widely used (Figure 6.10). Contacts with spiral leaves have the form of disks, with peripheral parts cut by a spiral slot into sections which are joined in the central part. With strong current, when such contacts open under electrodynamic forces, the arc moves to the periphery of the disks in the direction of the bend of the spiral notches, and then starts to rotate on the surface of the electrodes. This prevents overheating and intensive melting of contacts in some places. As the contacts of the vacuum chamber (usually copper ones) are closed for a long period of time and are pressed to each other with a considerable effort, and also have clean unoxidized surfaces, they may be prone to the so-called *cold welding*, caused by inter-diffusion of atoms of the metal of the contacting surfaces. Welding of contacts can also be caused by spark breakdown when contacts approach each other while closing. Such problems are solved

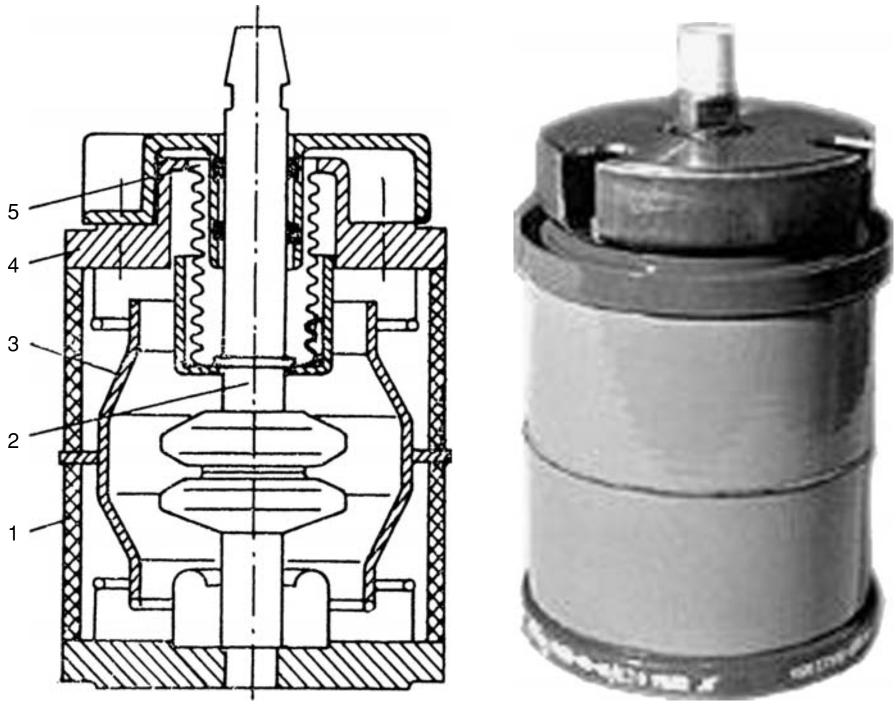


FIGURE 6.9
Construction and external design of vacuum interrupter. 1 — Ceramic chamber; 2 — current-carrying core with a movable contact at the end; 3 — metal shield; 4 — flange; 5 — metal bellows.

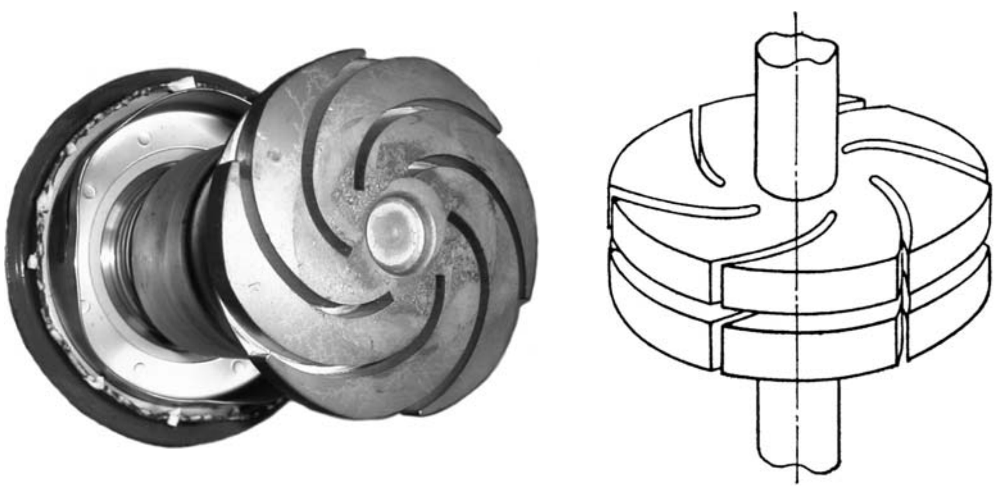


FIGURE 6.10
Contacts of a vacuum chamber with arc-suppressing leaves.

by using small amounts of bismuth, chrome, or beryllium. Such admixtures allow the relay to maintain arcing of alternating current in the vacuum almost until the sinusoids pass through the zero value, thus preventing current-chopping (that is arc extinction before crossing the zero value, caused by overheating).

In addition, the vacuum chamber contactor also contains a powerful electromagnet joined through a mechanical system, with part of the movable contact sticking out (Figure 6.11). Three-phase constructions contain three vacuum chambers installed on the same plate and equipped with three electromagnet coils, connected in parallel. HV contactors are equipped with insulating elements and current-carrying buses placed at certain distances. First constructions were quite big (Figure 6.12), but modern HV contactors are more compact (Figure 6.13). To increase switched voltage, the vacuum chambers are joined in series, and equipped with a common operating mechanism.

A typical example of such a construction is a HV single-pole contactor produced by Ross Engineering (Figure 6.14). It consists of four vacuum chambers connected in series. Toroidal shields are used for equalization of electric field strength in the construction, and for prevention from corona. Ross Engineering indicates a withstanding test voltage of AC (200 kV of peak) for this contactor. The consumer can choose maximum value of switched voltage on grounds of particular technical requirements and necessary voltage reserve.

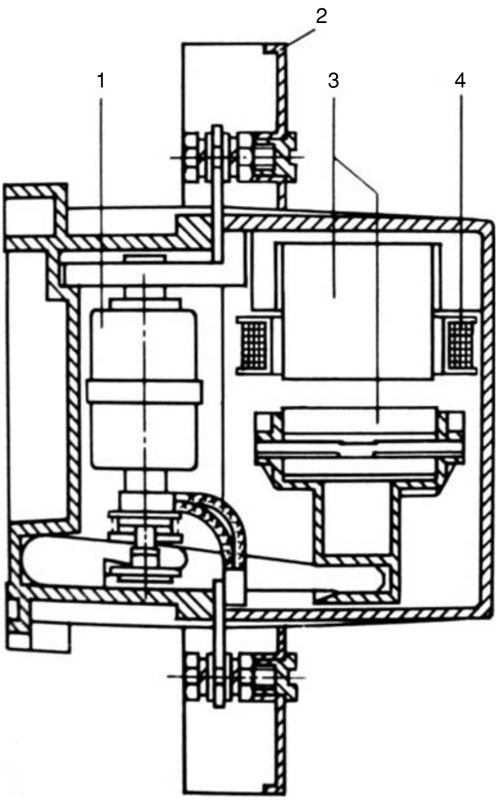


FIGURE 6.11
Construction of power single-pole vacuum contactor of 3TF68AC type for current of 630 A and voltage of 690 V, produced by Siemens. 1 — Vacuum chamber; 2 — terminal cover; 3 — ferro-magnetic core; 4 — coil.

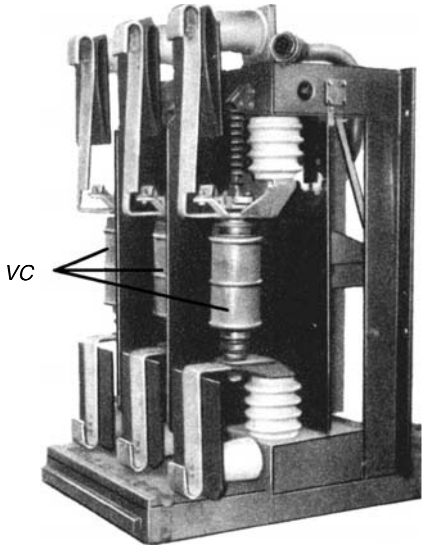


FIGURE 6.12
One of earlier constructions of HV vacuum contactors for 10 kV voltage. VC — vacuum chambers.

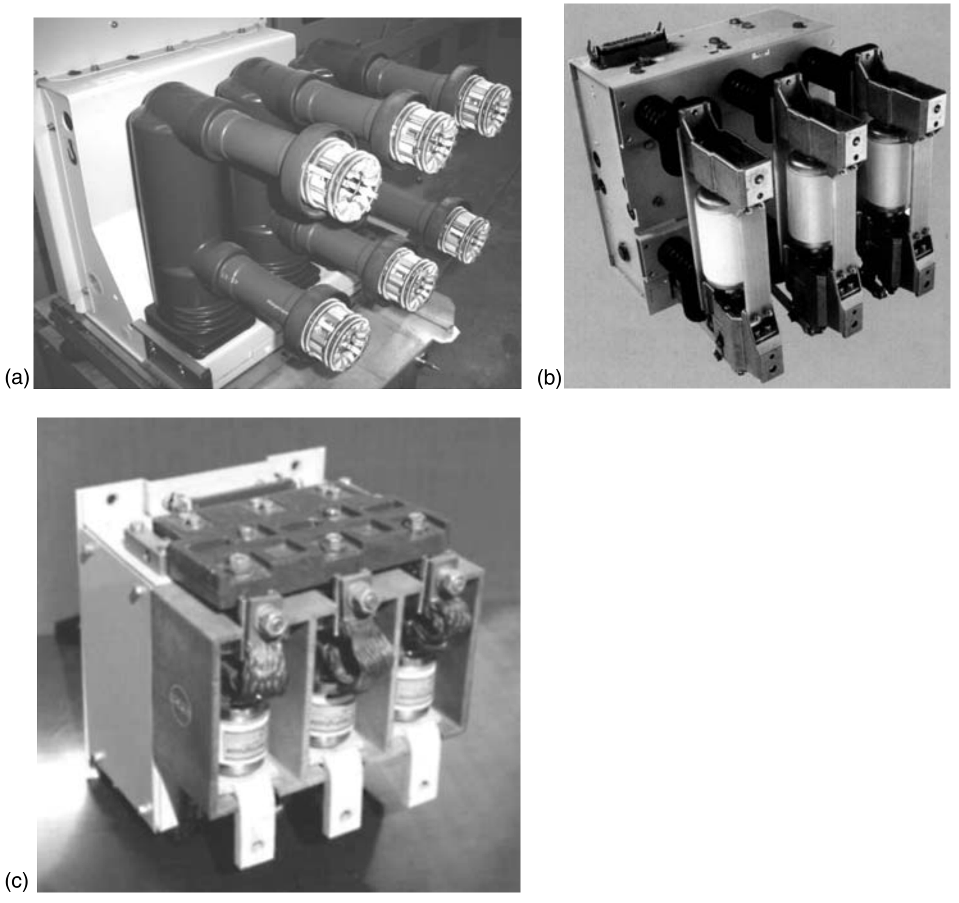


FIGURE 6.13
Modern HV three-phase vacuum contactors. (a) VD4 type, 12 kV, 1250 A (ABB); (b) CV-6 KA type, 7.2 kV, 720A (Toshiba); (c) CCV-JT type, 1.14 kV, 400 A (ICPE S.A., Romania).

FIGURE 6.14
HV single-pole contactor of HB-204 type (test voltage is 200 kV of peak), based on four vacuum chambers connected in series. Produced by Ross Engineering.

6.5 High-Voltage Reed Relays

HV reed relays differ from LV relays by the use of HV vacuum reed switches and increased insulation of the control coil from the reed switch. HV switched vacuum reeds (considered above) are standard items produced in mass lines by different firms, and are designed for switching of small currents with voltage of 5 to 10 kV DC (switched power is up to 50 W). Maximum switched current (with similar switched power, of course) can reach 3 A. The insulation of the coil from the reed switch is made for the same level of voltage as the insulation of the reed switch, which is for 5 to 10 kV of working voltage DC.

HV reed relays have some particular construction forms:

- *An insulated coil and an open reed switch* (a small coil entirely molded with plastic and placed in the central part of the reed switch; the HV outlets of the reed switch are open and distant from the coil; the reed switch can be easily put in and taken out of the coil — Figure 6.15).
- *An insulated reed switch and an open coil* (the open coil is wound on an insulating bobbin supplied with ''wings'' in the form of tubes, entirely covering the reed switch with its outlets — Figure 6.16);
- A reed switch with a coil entirely molded with plastic in the form of a solid construction (Figure 6.17).

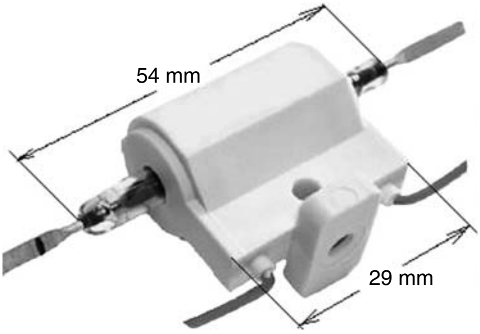


FIGURE 6.15
HV reed relay with an insulated coil and an open reed switch.

A switching device from the ''Goliath'' series, designed by the author in 1991 (Israeli Patent 130440), can also be referred to as a HV reed relay (Figure 6.18). Such a relay is constructed on the basis of one of the largest reed switches in the world, where transformer oil or sulfur-hexafluoride is used as a dielectric environment. A movable contact-element of this reed switch is made in the form of a turned T-shaped element, with a massive bridge contact and cylindrical ferromagnetic core fixed in the center of the bridge. This contact-element can freely move inside the dielectric shell within 60 mm distance on special guides along the standing axis of the device. Fixation of the movable contact-element in extreme positions is carried out with the help of permanent magnets (Figure 6.19).

''Goliath'' is a new type of high performance latching commutation device with the following unique characteristics: high voltage, low cost and relative small size. The ''Goliath'' design is based on reed switch technology and includes a minimal number of components with no need for vacuum technology, while assuring reliable operation at low cost. ''Goliath'' can be switched ON or OFF (fixed position) by control signals and consumes energy only during transition time. The actual position of the apparatus may be indicated by a light-emitting element (LED) on the operator's control console.

The ''Goliath'' consists of a dielectric body (1) formed with two isolated compartments: a large compartment for the contact system, a small compartment for magnetic systems and one more insulated open compartment which is concentric with the small compartment. In the large compartment are two fixed contacts, symmetrically positioned (2), a movable bridge-type contact (3), a fixed magnet (9) and a movable magnet (8), fixed in a housing that is connected to the central part of the bridge-type contact (3). This housing enters special guides (11) that limit the degree of freedom of the housing. From the other side of the central area of the bridge-type contact (3), a dielectric rod is attached (having a certain clearance) with a ferromagnetic core (6) fixed to its other end.

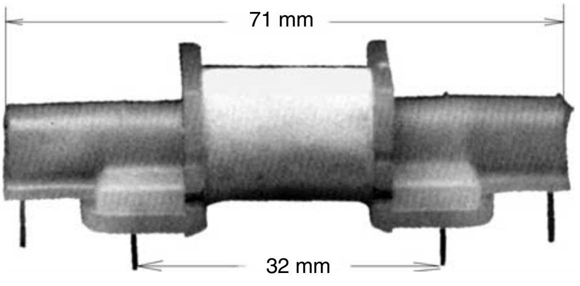
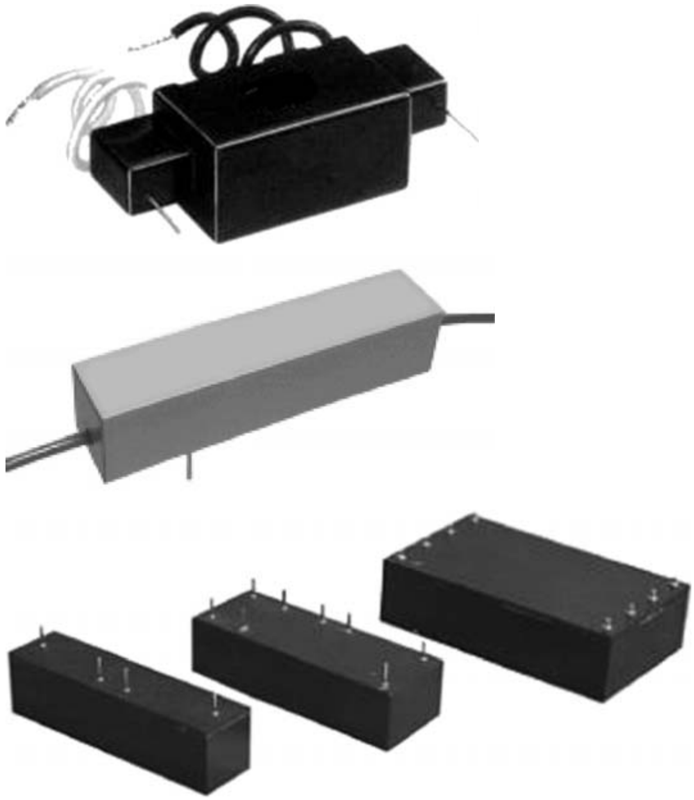


FIGURE 6.16
HV reed relay with an insulated reed switch and an open coil.



(a)

(b)

(c)

FIGURE 6.17
HV reed relays in the form of a solid construction, with a reed switch and a coil which are entirely molded with plastic. (a) — Relay with reed switch outlets for printed circuit and coil outlets — flexible wire; (b) relay with coil outlets for printed circuit and reed switch outlets from HV wire; (c) relay with reed switch and coil outlets for mounting on printed circuit board.

The permanent magnet (7) with steel bushings is located in the small compartment, and is free to move in the upper part of the compartment along its longitudinal axis by 1 to 1.5 cm. Two control coils (5 — the lower) and (4 — the upper), mounted in the small compartment and provided with magnetic circuits, are located in an open concentric cavity. After the control coils are mounted in the small compartment, it is filled with an

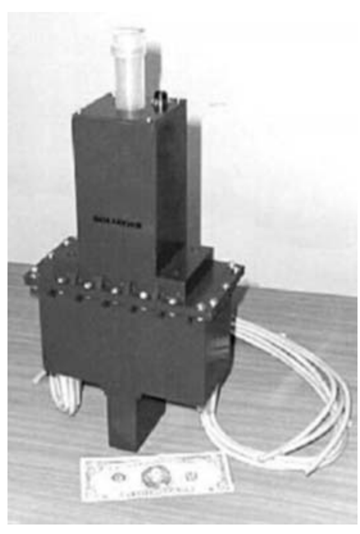


FIGURE 6.18
The biggest HV reed relay in the world, ''Goliath,'' designed by the author.

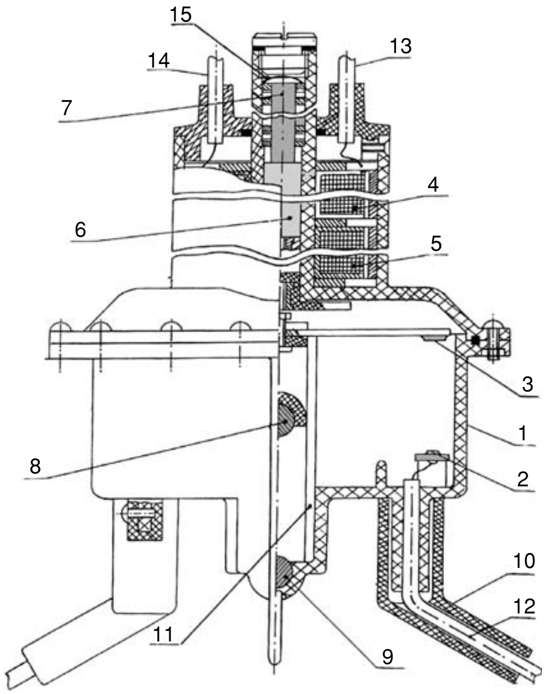


FIGURE 6.19
Construction of a HV reed relay of the ''Goliath'' type.

epoxy compound and covered with a cover having bushings with outputs (13, 14) formed as wires with HV insulation drawn through them. The ferromagnetic core (6) is 20 to 30% longer than the control coils. The outputs of the fixed contacts are formed as high voltage wires (12) drawn through the bushings (10).

With the external power supply cut OFF, the relay can be in one of its extreme positions: (a) either engaged, when core 6 with contacts 3 are in their lower position and magnet 8, being attracted to magnet 9, fixes this position and generates the required contact pressure, or (b) disengaged when core 6, with contacts 3 and magnet 8, are in their upper position, which is fixed owing to core 6 attraction to permanent magnet 7.

When lower coil 5 is connected to a DC power supply (rectifier), the magnetic field generated by this coil detaches core 6 from permanent magnet 7 and imparts a motion pulse to the core. As a result, the core quickly moves downward, carrying away contacts 3 and magnet 8 coupled with it. As the fixed contacts 2 are attained and the velocity is reduced by the elasticity of the spring located at the center of the bridge (that interconnects contacts 3, core 6, and all), the mobile elements connected to it are stopped in the lower position so that a few millimeters gap is left between magnets 8 and 9. Mutual attraction between magnets 8 and 9 prevents the springing back of contacts 3 from contacts 2 at their initial touch, providing the required contact pressure and fixation of the movable device elements in the lower position.

When upper coil 4 is connected to a DC power supply, the magnetic field generated in this coil acts on core 6 and imparts a motion pulse, as a result of which magnet 8 is detached from magnet 9 and, together with contacts 3, quickly moves upward until core 6 reaches the permanent magnet 7. Since the magnet is not fixed permanently and can move along its axis, inelastic impact of core 6 on magnet 7 is prevented, so that after they come into touch, their joint movement is preceded and damped by spring elasticity (15).

Here is ''Goliath'' main parameters:

Maximum switched voltage (kV) AC (rms)	60
Dielectric strength (kV) AC (rms), 1 min	120
Continuous current through closed contacts (A) (rms)	100
Current spike (for 20 ms duration) (A)	1500
Control voltage (V) DC	12, 24, 110
Control power (W)	5
Minimum control pulse width (duration) (ms)	300
Operating time (ms)	50
Temperature range (°C)	$-10 + 55$
Dimensions (mm)	$235 \times 95 \times 435$
Weight (kg)	5.2

6.6 High-Voltage Interface Relays

HV equipment (10 to 100 kV) has become very popular over the last few years. It is utilized in military and civil radar stations, powerful signal transmitters for communication, broadcasting and TV systems, technological lasers, X-ray devices, powerful electronic and ion devices, devices for inductive heating and melting of metals, technological electron accelerators for material irradiation, electro-physical and medical equipment, and industrial microwave ovens, among others.

Technical difficulties caused by the presence of functional components isolated from each other, not permitting direct connection owing to a high difference of potentials, are encountered when designing systems for control and protection against emergency conditions (over-current, sparks) in modern power HV equipment. To guarantee information and electrical compatibility, as well as to implement the required algorithms for interaction of functional components of equipment, special control instruments are required that have been called ''interface relays,'' or ''insulating interfaces'' (in technical literature).

Apart from problems connected with transmission of commands between parts with opposite potentials of HV equipment, there are also problems of current overload protection (level current trip) of such devices, caused by HV circuit insulation breakdowns or breakdowns in the high voltage devices. These problems still remain acute. The first is related to unfavorable conditions that cause moisture and dust to penetrate the equipment, and the second to unpredictable internal breakdowns in high voltage vacuum electronic elements (klystrons, tetrodes, etc.) or semiconductor elements (HV rectifier).

Current overload protection in such devices is usually resolved by inclusion of current sensors and electronic relays into the LV or grounded circuits. However, such protection is not necessarily efficient and in itself can cause many problems, which is why high-performance systems of protection of HV equipment from current overloading are based on interface relays.

The general principle of design of interface relays is the presence of a special galvanic decoupling unit between the receiving and final controlling systems of the relay. Interface relays with a working voltage of more than 10 kV have the greatest interest for these areas of engineering, to which the present study is devoted. In the design of devices classified as interface relays, some of the widely used physical principles may not be used in electrical relays of other types.

It is well known that any electromagnetic relay has a specific level of isolation of the output circuits from the input circuits, that is, it functions secondarily as an interface relay. However, in ordinary relays, this function is not decisive and is not at all considered in the existing system of classification. In the interface relay, the property of galvanic decoupling of the circuits has been repeatedly intensified, and the parameters of the galvanic decoupling unit are decisive from the standpoint of the function performed by this relay. On the other hand, the parameters associated with switching capacity are secondary and, significantly, there can be interface relays with the same level of galvanic decoupling. In this regard, an artificial assignment of interface relays to existing classes does not seem to be expedient. It seems more appropriate, rather, to classify them as a separate type of electrical equipment, having an intrinsic structure based mostly on a classification according to the characteristics of the galvanic decoupling unit. For example, according to the decoupling voltage level:

- Low level (to 10 kV)
- Medium level (10 to 100 kV)
- High level (above 100 kV)

According to principle of action:

- Opto-electronic
- Pneumatic
- Radio-frequency
- Electrohydraulic
- Transformer
- Ultrasonic
- Electromagnetic, and with mechanical transmission

According to speed:

- Super fast (up to 100 μs)
- Fast (100 μs to 2 ms)
- Inertial (above 2 ms)

Although such classifications may seem arbitrary, they fully reflect the most important properties of interface relays that have a decisive effect on the functions performed by them.

The simplest interface relays of the optoelectronic type typically consist of an LED built into the semiconductor structure (power SCR, triac) or LED and matching low power photothyristor or phototransistor in a switching mode, mounted close together and optically coupled within a light-excluding package having a galvanic decoupling voltage up to 4 kV.

Some companies (see above) produce high voltage reed relays for commutation voltage of up to 10 to 12 kV DC, and therefore have a galvanic decoupling voltage on the same level. All of these relays are intended for use only in DC circuits under normal climatic conditions and have no reserves for withstanding voltage required for high-power equipment.

In order to significantly increase the galvanic decoupling level of interface relays of the optoelectronic type, a fiber optic cable of appropriate length is installed between the LED and photo-receiving elements. These relays are also equipped with an electronic pulse shaper and an electronic amplifier. At a length of 5 to 20 mm of fiber optic channel connecting the transmitting and receiving units, the galvanic decoupling voltage ensured by the interface relay can reach 15 to 50 kV DC (for low power electronic equipment only!) (Figure 6.20a).

The input of the OPI1268 (Figure 6.20a) device consists of a high efficiency GaAlAs (Gallium Aluminum Arsenide) LED; a photodiode in the output integral circuitry (IC) detects incoming modulated light and converts it to a proportionate current. The current is then fed into a linear amplifier that is temperature, current, and voltage-compensated. The OPI125, OPI126, OPI127, and OPI128 (Figure 6.20b) each contain gallium arsenide infrared emitting diode coupled to a monolithic integrated circuit which incorporates a photodiode, an optic insulator, a linear amplifier, and a Schmitt trigger on a single silicon chip. The devices feature TTL compatible logic level output.

It is necessary to note, that it is as much as possible allowable levels of a voltage which should not be exceeded in any modes. In practice, certainly, working voltage should be chosen in 1.5 to 2 times less for the electronic equipment. For the industrial and power equipment this voltage should be even less. Additional essential reduction in a working voltage is required at work on an alternating current. In result, we shall have working voltage about 2.5 to 3.5 kV instead original 15 to 16 kV.

Interface relays of the optoelectronic type have also found application in electrical power configurations in which the transmitting and receiving units are connected by hollow porcelain insulators of fairly large dimensions, equipped with a built-in optical system. Such interfaces are used in 110 to 400 kV power networks to control the drives of HV circuit breakers as a device for protecting shunt capacitor batteries, etc. (Figure 6.20).

The developmental trends of interface relay technology suggest the use of optoelectronic systems as the prevailing design principle for galvanic decoupling units. It is agreed that the most important characteristic feature of optoelectronic systems is their noise immunity and insensitivity to electromagnetic fields; however, what is not considered here is that in addition to the fiber optic line itself and the output actuator, such a system includes a shaper of light pulses on the transmitting and electronic amplifier, with triggering units on the receiving end that are generally based on IC. It is precisely these elements, which have low activation levels, that are damaged by pulse noise on the side of high voltage power equipment (interferences, spikes, and high voltage discharges), which negates the main advantage of optoelectronic systems. Moreover, the optical fibers themselves are subject to a severe negative effect of ionizing radiation and external mechanical influence (very important for military applications). The arrangement of input and output circuits of such systems should be widely spaced (optical fiber length is 0.5 to 1 m for voltage 40 to 150 kV for power equipment), and it is this factor that determines the overall dimensions of the interface unit.

All of this indicates that the preferred use of an optoelectronic galvanic decoupling unit in interface relays is not always warranted, and it sometimes is merely the consequence of stereotypical thinking of developers, or a peculiar technical style. A new type of HV interface relays, based on the reed switch, were proposed by the author for the first time in 1977 (U.S.S.R. Patent 758462). Analysis of the characteristics of this type of reed switch-based HV interface relays (Relays of Gurevich — ''RG-relays'') developed by the author, as well as experience in creating and using them (see Gurevich V. *Protection Devices and Systems for HV Applications*. Marcel Dekker, New York, 2003) shows that they have a definite area of use within which they enjoy distinct advantages over other types of interface relays. These parameters include transmission of discrete control commands,

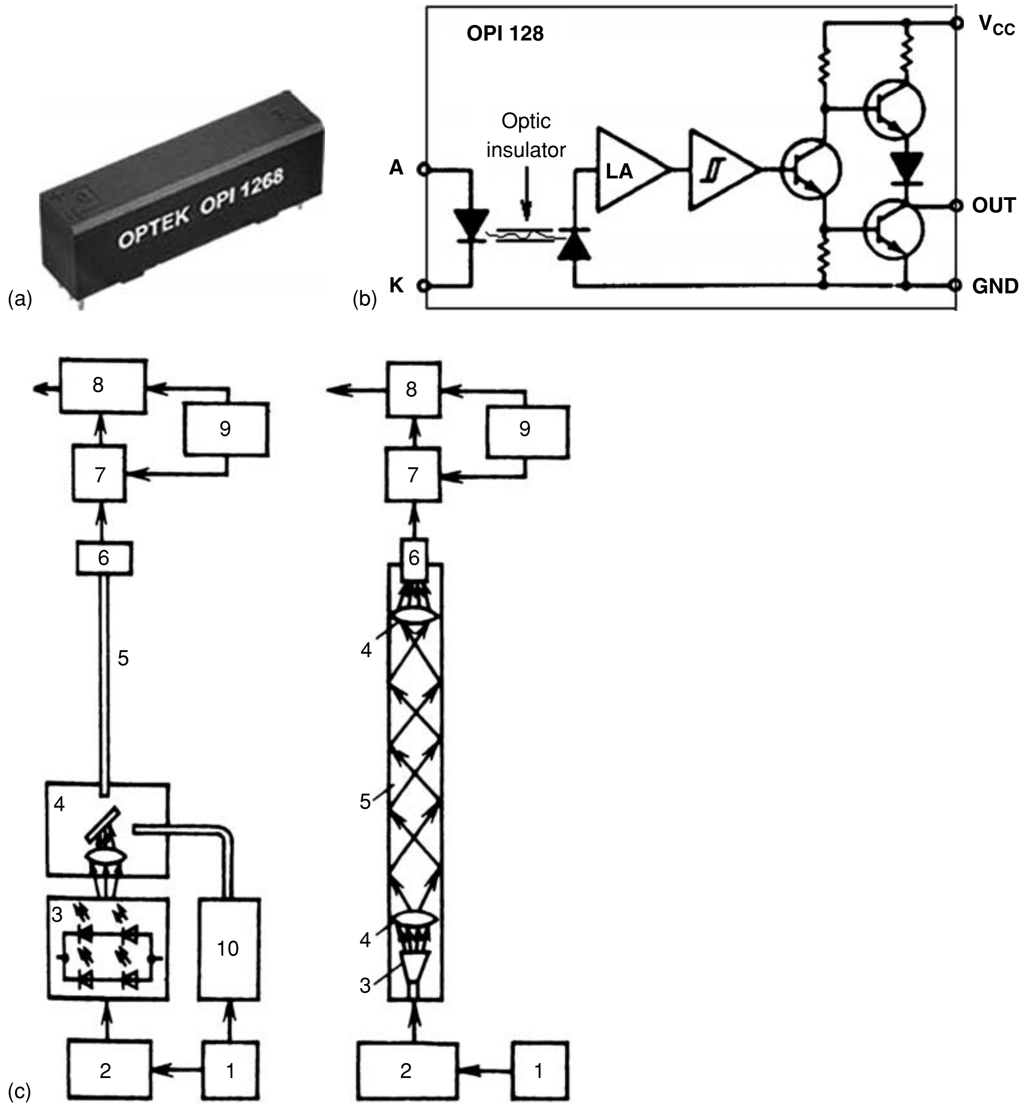


FIGURE 6.20
(a) Optical-insulating interface OPI 1268 type for maximum voltage input—output 16 kV DC. Dimensions: 9.0 × 6.5 × 28.0 mm (Optek Technology). (b) Function diagram of optical-isolated interface OPI 128 type (Optek Technology) for voltage level 15 kV DC (3750 V AC). (c) Interface relays of the optoelectronic type based on a fiber optic cable (on the left) and a hollow porcelain insulator (on the right). 1 — Power source on ground potential; 2 — electronic pulse shaper; 3 — optical emitter (transmitter); 4 — optical system; 5 — optical channel; 6 — phototransistor; 7 — electronic amplifier on the high potential; 8 — output final control element; 9 — power source on the HV potential; 10 — transmitter monitoring unit.

protection, and binary warning transferred by a frequency of up to 50 to 100 Hz, and an admissible speed of 0.8 to 1.5 ms, between parts of equipment under a potential difference of up to 100 kV. Within these parameter values, RG-relays are characterized by the highest degree of simplicity and reliability, and possess broad functional capabilities. Particularly attractive are such interface relay properties as a large overload capacity of the control circuit, a large power output circuit, insensibility to pulse noise, mechanical strength of

FIGURE 6.21
HV interface RG-series relays for industrial and military applications.

the design, and preservation of serviceability over a wide range of temperatures, pressure and humidity, suitable for military standard MIL-ST-202 requirements.

The relatively low cost of interface relays is also of no small importance in a number of cases. These properties of RG-relays are responsible for their widespread use for industrial and military applications in on-board, mobile and stationary powerful radio-electronic equipment, in relay protection and automation systems of electrical networks of the 6 to 24 kV, in electro-physical installation, in power converter technology, etc.

RG interface relays are a new type of HV device designed for automation systems for overload protection, fault indicating, interlocking of HV equipment, as well as for transfer of control signals from ground potential to HV potential (reverse connection). The series consists of the following devices: RG-15, RG-25, RG-50, RG-75, which are designed to operate under voltages of 15, 25, 50, and 75 kV DC, respectively (refer to Figure 6.21 and Table 6.1).

The operation of these devices is based on separation of the electric and magnetic electromagnetic field components. Each device is based on a magnetic field source (coil), connected to a high potential current circuit, a reed switch and a layer of high voltage insulation, transparent for the magnetic component of the field, and completely insulating the reed switch from the electric field component (Figure 6.22).

TABLE 6.1
Main Parameters of the RG Devices

RG-Relay Type	RG-15	RG-25	RG-50	RG-75
Nominal voltage (kV) DC	15	25	50	75
Test DC voltage 1 min (kV)	25	35	70	90
Control signal power (W)	0.2 . . . 0.4	0.2 . . . 0.5	0.5	0.9
Maximal switching voltage in the output circuit (V)				
DC	600			
AC	400			
Maximal switching output circuit current (A)	0.5			
Maximal response frequency (Hz)	100			
Maximal response time (ms)	0.5, . . . ,0.8			
Maximal dimensions (mm)	Ø26 × 47	56 × 27 × 70	Ø75 × 150	Ø75 × 190
Weight (g)	45	130	370	620

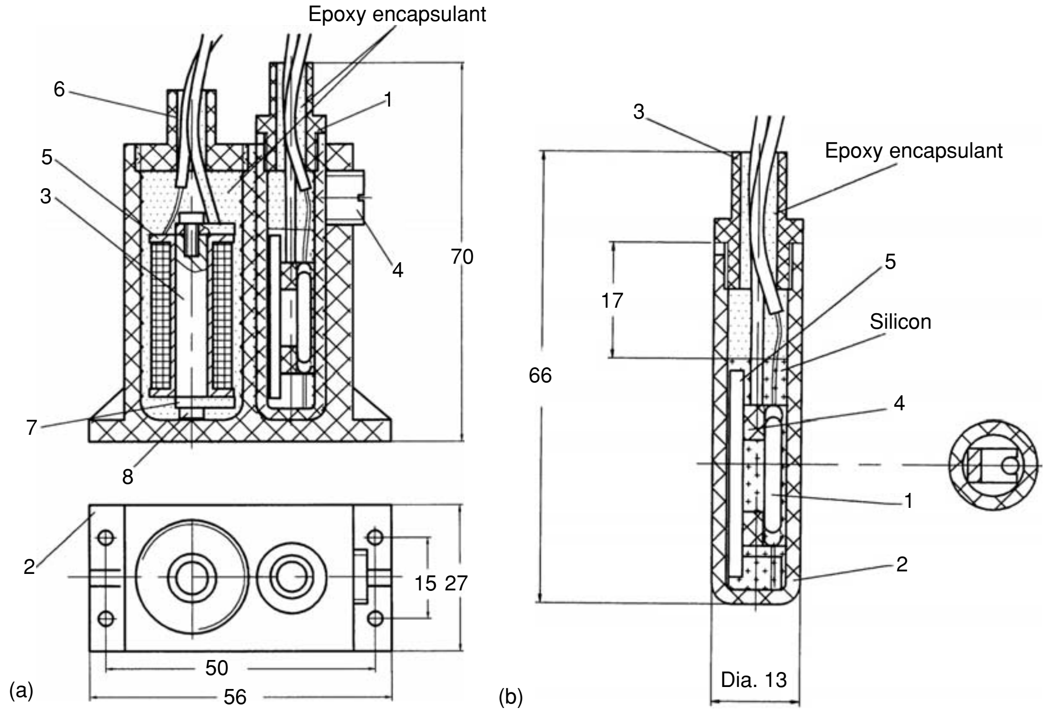


FIGURE 6.22
(a) Insulation interface RG-25 series intended for power lasers, industrial microwave ovens, medium power radar. 1, 6 — Bushings; 2 — main insulator; 3 — ferromagnetic core; 4 — plastic screw; 5 — coil, 7 — pole. (b) Revolving assembly part of RG-25. 1 — Reed switch; 2 — insulator; 3 — bushing; 4 — support; 5 — ferromagnetic plate.

The current pickup levels can be adjusted up to 50% (for each subtype). The option of operation threshold adjusting is an important peculiarity of interface relays when they are used as current relays in systems of protection from current overloading. Such adjusting is necessary to compensate parameter spread of the elements and accurate relay adjustment for any given operating current. Basically, there are a lot of ways of adjusting operation currents for reed relays. For HV interface relays only those methods are adequate which allow us to avoid, in the course of adjusting, parasitic air gaps in the HV construction, because in such a construction corona charge arises, which can destroy insulation. In an interface relay of the RG-25 type, when a movable insulator with a reed switch turns around its longitudinal axis the latter moves away from the terminals of the magnetic core, and a magnetic shunt takes its place (Figure 6.22b). Contacting surfaces of the movable insulator (with a reed switch) and the stationary insulator (with a winding) have conductive covering and are smeared with conductive grease, shunting entrapped air.

The RG-75 (and RG-50) relay (Figure 6.23) comprises the main insulator (1) formed as a dielectric glass, whose cylindrical part is extended beyond flange 2. The flat external surface of the bottom (3) of this glass smoothly mates with the extended cylindrical part (4), having threaded internal (5) and external (6) surfaces. The relay also includes control coil (7), with a Π-shaped ferromagnetic core (8) located inside the main insulator and a reed switch (9) located in an element for reed switch rotation through 90° (10). This element (10) is formed as an additional thin-walled dielectric glass with walls grading

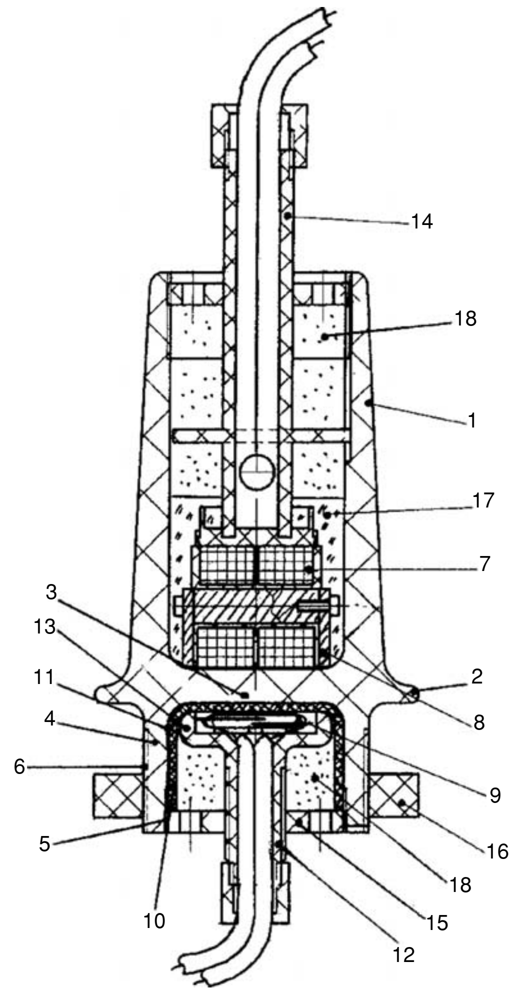


FIGURE 6.23
RG-75 and RG-50 series relay design.

into the bottom and mating with the inner surface of cylindrical part (4). These mated surfaces are coated with conductive material (11). Reed switch outputs (9) are conveyed through an additional insulator (12), formed as a tube extending beyond the reed rotation element body (10). The lower end of this tube is graded into oval plate (13), covering the reed formed with the conducting external coating. The control coil (7) outputs are also conveyed through the tube-shaped insulator (14), extending beyond the main insulator. The reed switch position fixation element is formed as disk (15) with a threaded side surface and a central hole, with insulator (12) conveyed through it. External attachment of the device is effected with dielectric nut (16). The lower layer of epoxy compound (17), filling the main insulator to the control winding, performs conduction by the addition of copper powder (60 to 70% of the volume). The rest of the filling compound (18) has been made dielectric. The element space (10) is filled with the same dielectric epoxy compound.

The shapes of the main insulator and the reed switch rotation element are chosen so that their mating surfaces, which contact with the conducting coating, do not form sharp edges emerging on the main insulator surface and at the same time provide for safe shunting of the air layer between them, removing the thin conducting sharp-edged layer from the design.

Significant reduction of the field intensity generated by the sharp outputs of the reed switch is achieved by adding one more tube-shaped insulator, extending beyond the main insulator used to convey the reed switch outputs, and causing the inner end of this tube to function as a plate with conducting coatings covering the reed switch. Applying the lower layer of epoxy compound, which fills the main insulator conducting space (holding the control coil with the ferromagnetic core), thus reduces the intensity of the field generated by the winding outlets and neutralizes the action of the air bubbles remaining between the coil windings.

Implementing the reed fixation element as a simple threaded disk, threaded into the respective part of the main insulator, forces the reed rotation element. Use is made of an additional dielectric nut threaded on the appropriate part of the main insulator as an element of the relay external attachment assembly, and the main insulator flange is used as a stop for this attachment assembly.

Device operation is based on the action of the magnetic field of the control coil (penetrating through bottom (3) of high voltage insulator (1) to reed switch (9).) When the reed switch threshold magnetic flux value is attained, it becomes engaged and appropriately switches the external circuits of the installation. The reed switch engagement threshold value is adjusted by changing its position relative to the magnetic field source. This change is effected by rotation of element (10) with reed switch (9) by an angle of 90° relative to the poles of Π-shaped ferromagnetic core (8). The position of element (10) with the reed is fixed by forcing element (10) as disk 15 is screwed in.

Each device from this series functions as four separate devices:

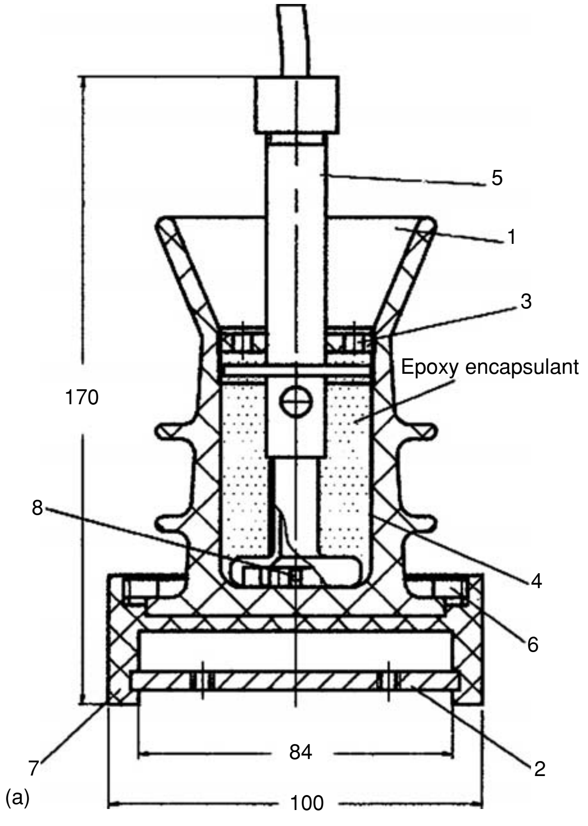
- Current level meter in an HV circuit
- Trip level adjustment unit
- Galvanic isolation assembly between the HV and LV circuits
- Fast response output relay in LV circuit

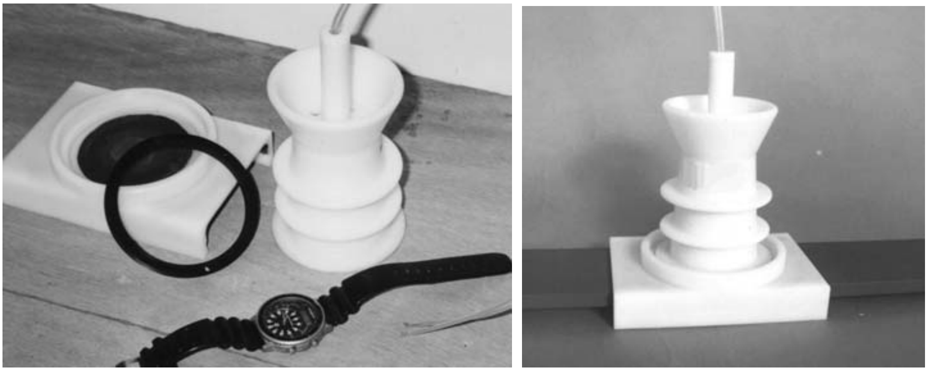
In current overload protection systems, the RG-Relays are usually connected to the open circuit of the HV power supply between the rectifier bridge and filter capacitor, when the acting current does not exceed 10 A (pulsating current amplitude up to 30 A), however, when the current is above 10 A, they are connected to the shunt. The RG-Relay is triggered when the current in the HV circuit exceeds the pickup level.

The RG-24-bus device (Figure 6.24), is designed to be used in overload protection units for 3 to 24 kV AC power networks, powerful electric motors, etc. The device output is a 100 Hz signal with 100 to 150 V DC or a standard ''ON–OFF'' type relay protection signal. The device design envisages its installation directly on a high voltage current-carrying bus or cable, as well as allowing for the possibility of wide range variations of the operation threshold (5 to 5000 A). Operating time is 1 ms.

The main advantage of these devices, as compared to those available on the market, is their possible direct installation on HV buses and output connection to LV automatic circuits. Medium voltage compact switchboard and switchgear cubicle systems (including SF_6 filled) can be significantly improved by using these devices. Built-in fault detectors and other automatic systems can now be produced as factory-standard equipment, and at affordable prices, and obtained without any alteration whatsoever of the HV equipment design.

The author designed a whole range of HV interface relays with specific properties for operation in strong magnetic fields, for instance (Figure 6.25). An interface relay with increased insulation level and effective protection from external magnetic fields was designed especially for use in electro-physical equipment (Figure 6.26).





(b)

FIGURE 6.24
(a) RG-24-bus device. 1 — Main insulator; 2 — fixative plate; 3 — inside nut; 4 — semiconductive cover; 5 — bushing; 6 — fixative nut; 7 — fastener; 8 — reed switch. (b) Installation of RG-24-bus device on a high voltage bus bar.

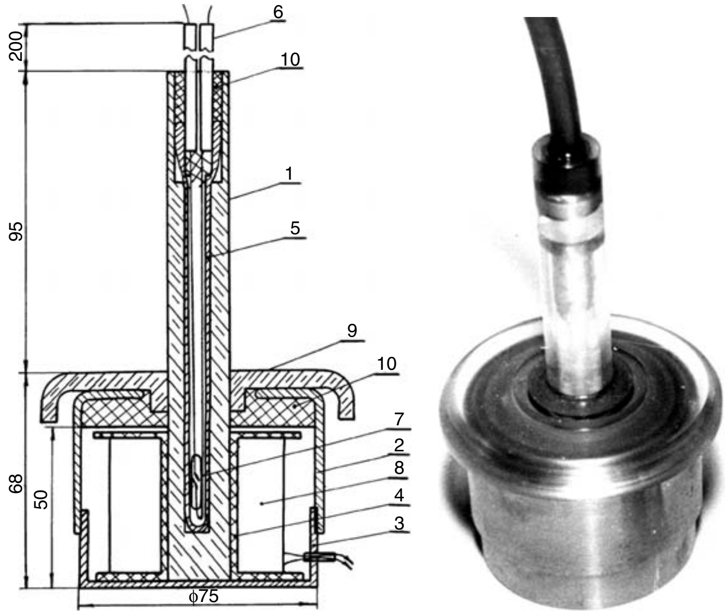


FIGURE 6.25
RG-relay with a high level protection from an external magnetic field. 1 — Main insulator (made as one unit with element 9); 2, 3 — thick wall ferromagnetic shield; 4 — bobbin; 5 — electrostatic shield; 6 — HV wires (reed switch's leads); 7 — reed switch; 8 — operate winding; 10 — epoxy encapsulant.

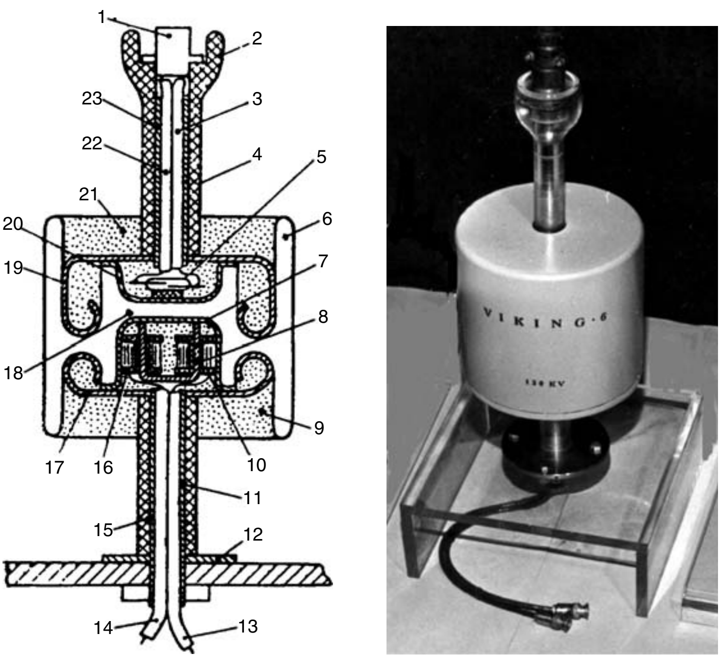


FIGURE 6.26
Ultra high voltage RG-relay. 1 — Connector; 2 — insulator for connector; 3, 22 — HV cables (reed switch leads); 4 — HV bushing; 5 — reed switch; 6 — main insulator; 7, 20 — aluminum shields; 8 — magnetic core; 9, 21 — epoxy encapsulant; 10, 16 — operating coils; 11, 15, 23 — lead shields; 12 — fastening element; 13, 14 — HV cables (operating coil leads); 17, 19 — ferromagnetic shields.

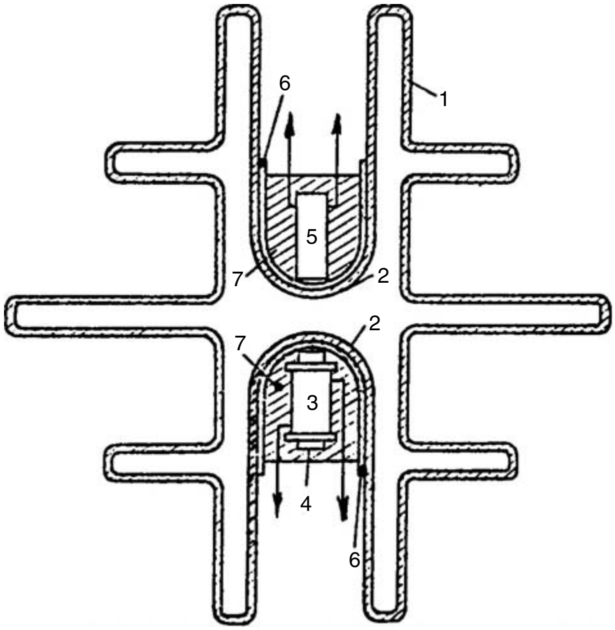


FIGURE 6.27
RG-relay with vacuum insulator. 1 — Main insulator (vacuum chamber); 3 — operate coil; 4 — ferromagnetic core; 5 — reed switch; 6 — electrostatic shield or conductive cover; 7 — epoxy encapsulant.

An original technical solution was found for HV interface relays with a vacuum chamber as a main insulator: to avoid the risk of vacuum failure caused by gases evolving from elements of the construction, they are all removed from the vacuum area and placed on the external surface of the vacuum chamber (the U.S.S.R. patent 836704, 1979 — Figure 6.27).

Over many years of work in this field, the author has designed many original constructions of HV interface relays. If you are interested in these constructions, you can find descriptions of them in the following books:

- Gurevich V., *High-Voltage Automatic Devices with Reed Switches*. Haifa, 2000, 367 p. (in Russian);
- Gurevich V., *Protection Devices and Systems for High-Voltage Applications*. Marcel Dekker, New York, 2003, 292 p.

7

Electronic Relays

7.1 Was It Thomas A. Edison who Invented a Vacuum Light Lamp?

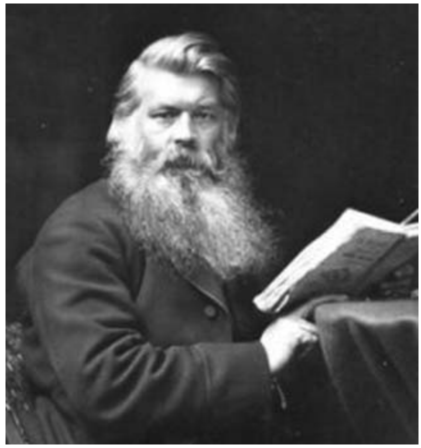
The history of electronic relays, like of all relays in general, begins with basic components from which relays are constructed. These were radio lamps (or ''electron tubes'' or ''vacuum tubes'') first, and then semiconductor devices.The basis for an amplifying radio lamp was a standard illuminating lamp. Thomas Alva Edison is usually considered to be the inventor of the vacuum light lamp. In fact he was not the first pioneer, but just developed an experimental illuminating vacuum lamp designed by the English physicist Joseph Wilson Swan (Figure 7.1a).

In 1860, Swan used carbonized paper as a filament in his lamp; however, low vacuum level and source power prevented Swan from success. It was only 15 years later that Swan resumed his experiments and then, due to the use of better vacuum and carbonized thread, he managed to demonstrate an operating incandescent lamp (Figure 7.1b). Moreover, in 1880 Swan arranged a first international trade fair of electric lamps in Newcastle, England, but still the lamp invented by Swan was imperfect; he lost interest in his invention soon afterwards and devoted himself to other problems.

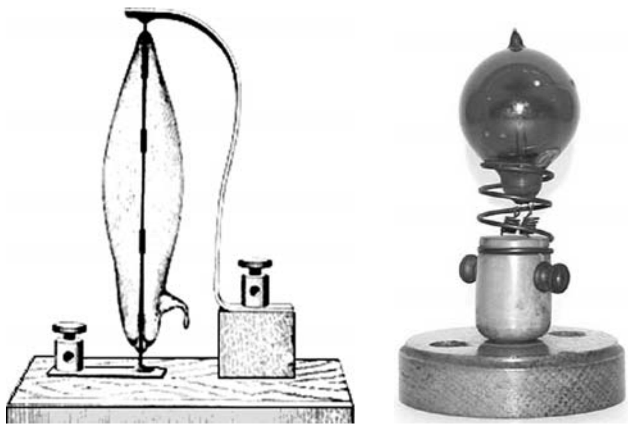
Edison performed thousands of experiments, selecting appropriate materials for filaments and developing the lamp's construction. Unlike Swan, he was more purposeful and persistent in the achievement of his goal, and sought to turn a commercial profit from the implementation of his lamps. The first lamps coming into the market were rightfully called ''Edison–Swan Lamps'' (sometimes simply: ''EdiSwan'' — Figure 7.2). Later, for different reasons, the name Swan was gradually forgotten and now Edison is ''known'' to be the inventor of the electric light lamp. During his numerous experiments in 1883, Edison came across an unknown (at that time) effect which was later called ''Edison's effect'' and it became the basis of the whole of modern radio engineering.

Edison discovered that if a metal plate is placed near the filament and is connected to the positive battery terminal (Figure 7.3), electric current will pass between the filament and the plate. At that time the reason was inexplicable, as there was no electric current conductor. The fact that electric current stops when battery polarity is changed remained even more unclear. Despite his instinct for profit and his intuition, Edison failed to apply the effect invented by him. It was only implemented in engineering after more than 20 years.

In 1904, on the basis of this effect, the English physicist John Ambrose Fleming designed and patented the first radio lamp in the world, called a ''radio valve'' or ''thermionic diode,'' designed for the conversion of alternating current to direct current and for radio signal detection (Figure 7.4). Many inventors tried to design a more perfect Fleming diode for higher-quality detection of radio signals and wireless telegraphy, and



(a)



(b)

FIGURE 7.1
(a) Joseph Wilson Swan; (b) Swan's first lamps.

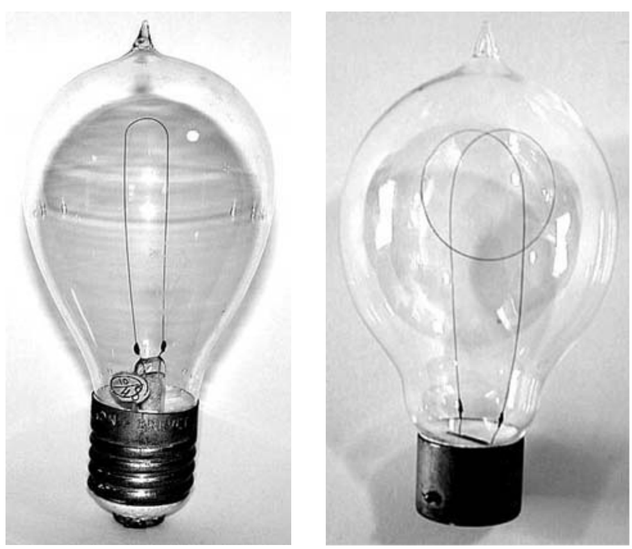


FIGURE 7.2
First commercial light lamps bearing the name of Edison and Swan (''EdiSwan Lamps'').

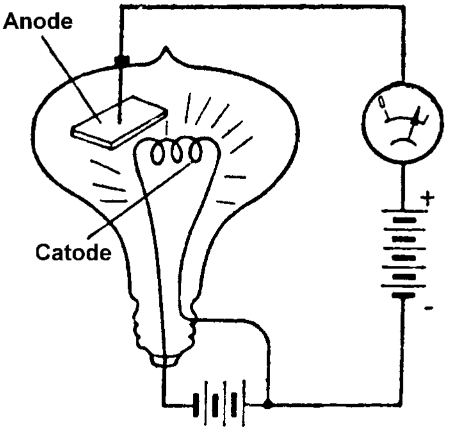


FIGURE 7.3
Edison's effect.

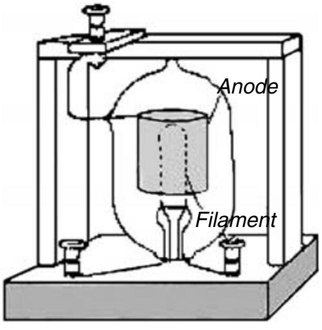


FIGURE 7.4
Fleming's vacuum diode with an additional electrode ''anode'' in the form of a cylinder encircling the filament.

FIGURE 7.5
One of the first constructions of vacuum diodes of increased power (for current up to 6 A) based on the incandescent lamp.

later sought to apply it to rectification of alternating current of increased power (Figure 7.5). It can be well seen in Figure 7.5 that this diode differs from an incandescent lamp with a spiral filament (a later construction of an incandescent lamp) by an additional plate only (an ''anode'').

7.2 Lee De Forest Radio Valve: From its First Appearance Until Today

The American engineer Lee De Forest achieved more success in this field when he placed an additional curved electrode between the cathode and anode (Figure 7.6).

In 1907, Lee De Forest patented a new construction of its vacuum tube, naming it ''Audion'' (now such type of vacuum tubes with three-electrodes called ''triodes'') (Figure 7.7) . The anode of this device was constructed in the form of a split cylinder, with the first electrode placed between the filament (the spiral), and the external anode made in the form of a large spiral with a large lead covering the internal spiral (Figure 7.8).

Later De Forest founded a company, ''De Forest Wireless Telegraph Co'' (according to other sources it was called ''DeForest Radio Telephone & Telegraph Company''), where he launched production of vacuum tubes and radio receivers (Figure 7.9).

De Forest created the ''Audion Piano,'' the first vacuum tube instrument in 1915. The Audion Piano was a simple keyboard instrument but was the first to use a beat-frequency (heterodyning) oscillator system and body capacitance to control pitch and timbre. The heterodyning effect was later exploited by the Leon Termen (Russian radio-engineer Lev

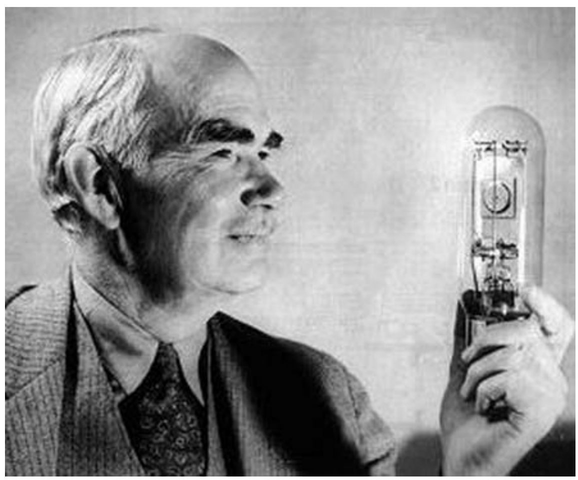


FIGURE 7.6
Lee De Forest.

FIGURE 7.7
The first three-electrode vacuum tube constructed by Lee De Forest.

FIGURE 7.8
One of Lee De Forest's constructions of "Audion."

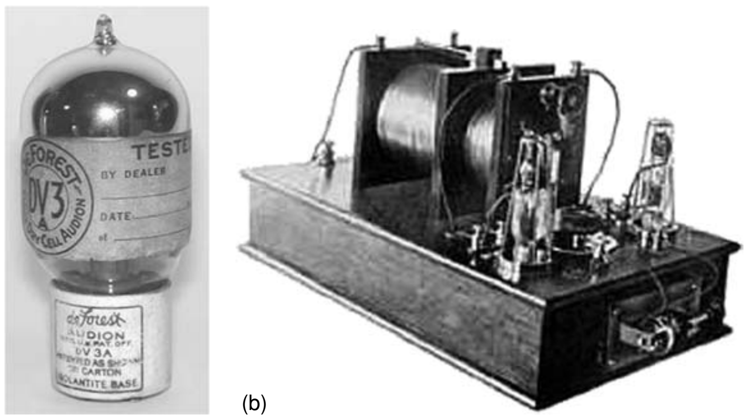


FIGURE 7.9
(a) Vacuum tube produced by "De Forest Company," and (b) the first radio set constructed by Lee De Forest in 1907.

Sergeivitch Termin) with his "Theremin" (also "Termenvox," "Aetherophone") — series of unique electronic musical instruments. The Audio Piano used a single triode per octave, which was controlled by a set of keys allowing one note to be played per octave. The output of the instrument was sent to a set of speakers that could be placed around a room, giving the sound, a dimensional effect.

De Forest later planned a version of the instrument that would have separate triode per key allowing full polyphony. It is not known if this instrument was ever constructed. De Forest described the Audio Piano as capable of producing: "Sounds resembling a violin, Cello, Woodwind, muted brass, and other sounds resembling nothing ever heard from an orchestra or by the human ear up to that time — of the sort now often heard in nerve racking maniacal cacophonies of a lunatic swing band. Such tones led me to dub my new instrument the "Squawk-a-phone." (Lee de Forest Autobiography, "The Father of Radio," 1915, pp. 331–332.)

During the 1930s de Forest developed Audion-diathermy machines for medical applications and, during World War II, conducted military research for Bell Telephone Laboratories. Although bitter over the financial exploitation of his inventions by others, he was widely honored as the "father of radio" and the "grandfather of television." He was supported strongly but unsuccessfully for the Nobel Prize for Physics.

The first commercial vacuum tubes produced in different countries had quite different external designs, but construction was practically similar to De Forest's Audion (Figure 7.10).

In Russia first vacuum tubes were named ''cathode relay'' and ''pustotnoye relay'' (''pustota'' is vacuum in Russian).'' The first serial vacuum tubes produced in Russia was constructed in the Nizhni Novgorod Radio Laboratory under the supervision of M. Bonch-Bruevich and was called PR-1 (Pustotnoye Relay, model No. 1). The name of a receiving vacuum tube of the R-5 type produced in 1922 by Petrograd Electrovacuum Plant stands for ''Relay, Development No. 5.'' A new tube produced in 1923 with a thoriated-tungsten cathode, consuming ten times less filament current than an R-5 relay, was called ''Micro'' valve.

A space-charge tetrode with a ''cathode grid,'' which was also quite economical by incandescence, was called MDS standing for ''micro-two-grid.'' By 1920–30's, vacuum tubes had similar external designs to the modern ones now (Figure 7.11). Despite

FIGURE 7.10
One of the first commercial three-electrode vacuum tubes (triodes) replicating the internal construction of ''Audion'' of De Forest, produced by different firms.

FIGURE 7.11
''Radiotrones'' produced by the American firm RCA in 1930: 6A7, 75, 80, 6D6.

amazing progress in semiconductor technology, vacuum tubes are still produced and used in high-end audio equipment of different types and specific electronics. A vacuum tube, operating in the mode of generation of a powerful ultra-high-frequency signal, with voltages on the electrodes of up 30–45 kV, is indispensable in powerful broadcasting transmitters and in radar. One can come across very powerful vacuum tube of this type (Figure 7.12). Modern vacuum tubes (Figure 7.13) are products of high-tech industry and cost a lot.

FIGURE 7.12
High-power triode.

FIGURE 7.13
Modern vacuum radio valves in glass and metallic tubes, produced up to now in many countries.

7.3 How a Vacuum Tube Works

When a tube cathode is incandesced, it seems to be surrounded by a cloud of electrons flying out from it. Affected by the electric field of the positive anode, electrons start to move towards the anode, creating anode current of the tube. The higher the voltage on the anode, that is the stronger its electric current, the more the current will be. If a metal grid is placed between the cathode and the anode and is not under voltage, the situation will not change.

Electrons will freely pass through the grid and will rush to the anode, because the holes of the smallest grid are enormous in comparison with the size of the electrons, but as soon as an electric charge is applied to the grid, an electric field occurs around it and the grid starts to influence the process of passing of electrons towards the anode.

If the grid is positively charged with respect to the cathode, it will help the anode attract electrons, thus increasing the anode current. If it is negatively charged, it will repel electrons, preventing them from passing through the grid and thus reducing the anode current (Figure 7.14). Thus, the grid controls the anode current of the vacuum tube and it is worth mentioning that the slightest changes of voltage on it will considerably change the anode current. Such property allows a vacuum tube to amplify electric oscillation.

Thus, alternating voltage applied to the controlling grid of a vacuum tube is transmitted to the anode circuit with amplification, but there is capacitive coupling between the anode and the control grid. Due to such coupling voltage changes are transmitted back to the circuit of the control grid and two variants are then possible; first of all, feedback voltage may increase the total voltage on the control grid, if positive and negative half-cycles of the feedback voltage and the voltage applied to the control grid concur. An increase of voltage amplitude on the control grid will cause an increase of voltage amplitude on the anode, and this in its turn will lead to higher feedback voltage and therefore to an increase of voltage on the control grid, etc. Such feedback is called ''positive.'' If it is strong enough, progressive increase of voltage amplitude on the control grid and on the anode of the valve will lead to spurious oscillation of the amplifier circuit, but the feedback voltage may also bring about a decrease in total voltage on the control grid. Such feedback is called ''negative'' because it causes a decrease of amplification of the vacuum tube, which is why feedback — especially considerable feedback — through the capacity ''anode-grid'' is undesirable. Of course feedback in electric circuits arises not only due to capacity between the anode and the grid. Capacities between circuits of the electrodes, between components and wire, etc., also can play an important part in feedback occurrence; however, well-thought-out arrangements of the components and wire, and accurate assembling will make such capacities negligible. It may seem that it is possible to decrease capacity between the control grid and the anode by just miniaturizing

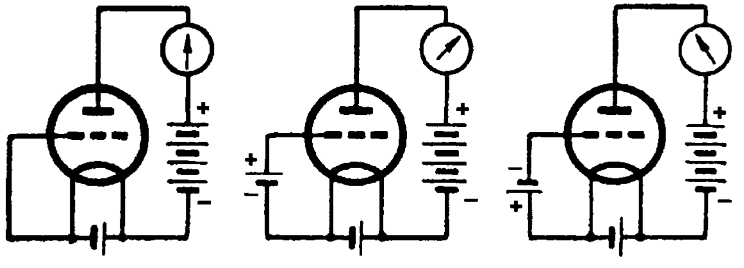


FIGURE 7.14
Principle of functioning of a three-electrode vacuum tube–triode.

the anode and the grid, and by moving them away from each other, but this leads to a sharp deterioration of the amplifier properties of the valve, lowering its power and capacity to operate under very high frequencies.

That is why some other methods of reduction of capacity between the anode and the control grid of the valve were needed. It turned out that it was possible to considerably reduce such capacity by introducing a shield in the form of an additional grid between the electrodes. Positive voltage could be applied to it, but lower in value than the anode one. Such a new grid did not prevent electrons moving to the anode, because of its positive potential. On the contrary, it even helps to ''attract'' electrons. It is called a ''screening grid,'' and a vacuum tube with two grids is called a ''tetrode'' (the total number of electrodes is four).

The third grid, which in a vacuum tube is called a ''pentode,'' can also protect the valve from the so-called ''dynatron effect,'' when electrons hitting the anode at a high speed knock out secondary electrons, which when rebounding from the anode are attracted by the positive shield grid, thus causing reverse electric flux deteriorating the valve operation. To remove such a negative phenomenon, another additional grid had to be placed between the anode and the positive shield grid, but it should be negatively charged with respect to the anode. Such a grid repels electrons flying out from the anode back to the anode and is called ''protective.''

In most cases automation devices, radio sets, and other electronic devices are fed from standard AC network (through a rectifier, of course). Incandescence of the filament is fed with similar AC supply voltage, which is lowered up to several volts with the help of a transformer, but as the current is alternating, the temperature of the incandescent filament changes in accordance with its changes. If the filament serves as a cathode (as is shown on the simplified scheme, Figure 7.15), number of electrons flying out will change simultaneously with the filament temperature, which is why the anode current of the vacuum tube will also vary together with the AC frequency. To avoid this, the filament should be insulated from the cathode. The filament only heats up the massive cathode, and due to its considerable thermal inertia, the variation of filament temperature does not affect the number of electrons flying out. This is a so-called ''cathode with indirect heating.'' Sometimes the number code of the tube indicates the heater voltage: for example, 12BY7A is a tube that has a heater operated at 12.6 V (not 12 V), and 7 means 6.3 V.

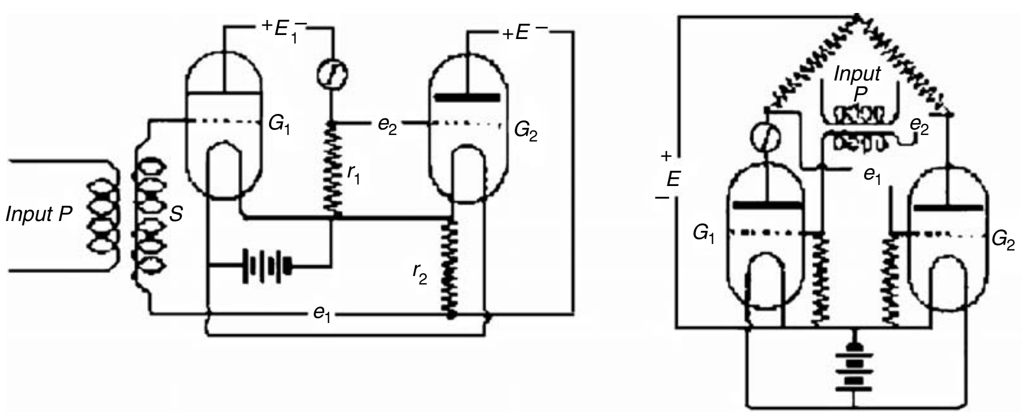


FIGURE 7.15
Circuit diagram of the first electronic relay described by W.H. Eccles and F.W. Jordan in 1919. (From W. Eccles and F. Jordan, A Trigger Relay Utilizing Three-Electrode Thermionic Vaccuum Tubes, Vol. 1, No. 3, 1919. With permission)

These voltages originally came from the days of using lead acid batteries as a power source, since many people did not have any other source of electricity. The voltage of a fully charged ''6 V'' lead acid battery (2.1 V per cell) is 6.3 V and the voltage for a six cell battery such as those used now in all cars (three cell batteries were used until the late 1950s in the U.S.) is 12.6 V. This is the reason why we have seen power transformers in the old days with 6.3 V on the secondary windings as a supply of heater voltage.

7.4 Relays with Vacuum Tubes

Very often devices consisting of a sensor of some physical quantity (pressure, temperature, light, etc.), an electronic amplifier and an electric relay at the output, are called electric relays. Such devices are really energized at a certain threshold value of the input quantity (pickup) and operate like any other relay, however that fact can be explained only by an electromagnetic relay at the output in such a device. In fact, we have in this case an electromagnetic relay with a preamplifier of the input signal. This is another modification of a relay that will be considered below. In this section we are considering only electronic devices with relay characteristics.

The first electronic device based on vacuum tubes with relay properties (Figure 7.15), was described in an article by W.H. Eccles and F.W. Jordan, ''A trigger relay utilising three-electrode thermionic vacuum tubes.'' *Radio Review*, Vol. 1, No. 3 (December 1919): pp 143–146.

In order to understand how an electronic relay operates, it is necessary to consider a schematic of the simplest two-stage resistance-coupled amplifier on triodes (Figure 7.16 and Figure 7.17 — filaments are not usually shown on such schemes).

When negative voltage u_{in} (section AB) on Figure 7.17 is high, the triode VT1 is blocked and its voltage on the anode equals the voltage of the power source U_a. Voltage on the grid of the triode VT2 exceeds the negative offset voltage applied from the source of the offset, and the triode becomes unblocked, that is maximum anode current i_{a2} passes through it. Voltage on its anode is on the contrary minimal, and is determined by the difference between the power source voltage and the voltage drop on the anode resistor R_{a2}, that is U_a — $i_{a2}R_{a2}$. When the growing voltage u_{in} reaches pickup potential of the triode VT1

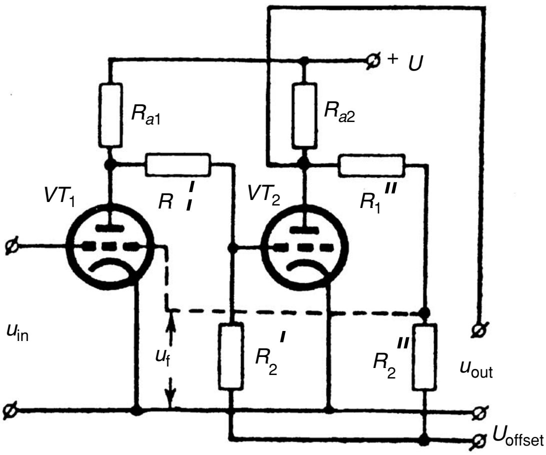


FIGURE 7.16
Two-stage electronic amplifier on triodes. Dependence of output voltage u_{out} on input voltage u_{in} of an amplifier is shown in Figure 7.17.

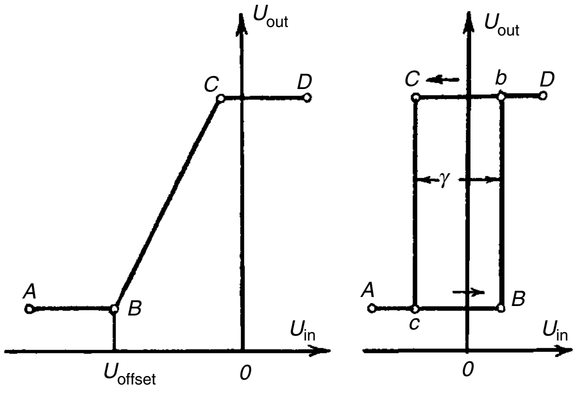


FIGURE 7.17
Transient characteristics (dependence of an output signal on an input one) of the electronic amplifier: on the left — without feedback; on the right — with positive feedback.

(point *B*), the triode is opened. Voltage on its anode will decrease (i.e., it is in the similar mode as triode VT2 has been before). This will lead to a decrease in the positive voltage on the grid of the triode VT2 and therefore an increase of voltage on its anode. Output voltage u_{out} will also increase (section *BC*). Finally, voltage on the anode of the triode VT1, and therefore on the grid of the triode VT2, will decrease to such an extent that the triode VT2 will be blocked (*C* is the blocking point of the triode VT2). Then an increase of the input voltage u_{in} on the grid of the triode VT1 will not affect the voltage of the anode of the triode VT2, and therefore will not affect the output voltage u_{out} (section *CD*).

If positive feedback is introduced into this scheme (as shown in the pointed line in Figure 7.16), the process of opening of the triode VT1 and closing of the triode VT2 at increased input voltage, will be very short. Indeed, increase of input voltage (after the point *B* of the characteristic) will lead to a decrease of voltage on the anode of the triode VT1 and therefore to an increase of voltage on the anode of the triode VT2, that is to additional decrease of negative voltage on the grid of the triode VT1 (because of the feedback). In its turn, this will cause further voltage decrease on the anode of the triode VT1 and a voltage increase on the anode of the triode VT2, etc. A chain reaction seems to arise and as a result the circuit is rapidly, turned to a new state when the triode VT1 is opened and the triode VT2 is closed.

Thus the amplifier with positive feedback can function on three states. The first one implies that the triode VT1 is blocked and the triode VT2 is enabled. In this state, the device is in the initial position selected by us. It will be stable because without input voltage the device can function in such a state as long as possible. In order to switch the device to another stable state, one should apply to the grid of the triode VT1 a positive firing pulse of such a value that the voltage on the triode grid becomes lower than the blocking potential. When it reaches such a position (point *B* in the right part of Figure 7.17) the device will be turned to another stable state (point *b*), characterized by the upper branch of the *CD* characteristic. The device may operate in the stable state when the triode VT1 is enabled and the valve VT2 is disabled, as long as possible.

In order to turn the device back to the initial stable state characterized by the branch AB, theoretically it is necessary to apply a negative blocking pulse on the grid of the triode VT1, and after that the device will be turned stepwise to point *c* of the characteristic, however in practice, the negative blocking pulse may not necessarily have the amplitude equal to the potential of triode blocking, because even the slightest voltage reduction on the grid of this triode (similar to a voltage decrease on the coil of an electromagnetic relay) will lead to a considerable voltage increase on its anode, and therefore to a voltage increase on the grid of the triode VT2. As a result, the triode will be enabled, a chain reaction will arise and the device will be ''overturned'' to the initial stable state.

Finally, a third state is possible when the device is at the moment of switching from one state to another one. In such a state both triodes are enabled and the state is unstable. The circuit turns saltatory from this position to one of the stable ones. In the right part (Figure 7.17), it can be seen that at continuous input voltage change, output voltage is extremely volatile (the same as the state of an electromagnetic relay). Upsurges occur when input voltage passes threshold values determined by the extreme points B and C of characteristic. The distance between these points is marked by γ and is called hysteresis voltage, as it is in electromagnetic relays. Hysteresis voltage depends on the circuit amplification factor, and the more it is, the more the amplification factor.

7.5 Gas-Tubes with Relay Characteristics

A triode gains a completely new quality when it is filled with some rare gas. In a gas-filled appliance, electrons that have flown out from the heated cathode are accelerated by the positive field of the anode. They collide with gas atoms and ionize them, and as a result the number of electrical current carriers in the tube goes up sharply.

Charged particles with both signs, which are in great concentration between the cathode and the anode, form electronic-ionic plasma. The process of current, passing through the gas interval followed by a formation of plasma, is called an electric discharge. In gas-filled triodes, the effect from the grid differs from that in vacuum triodes. In vacuum triodes considered above, the grid allows fluent changes of the value of the electric flux passing through it, while in gas-filled triodes the grid just controls the moment of occurrence of an electric discharge between the cathode and the anode, and is unable to quench the discharge after it has been initiated.

Fixation of the moment of discharge initiation is carried out by applying a considerable negative potential with respect to the cathode, to the grid, and by replacing it with a more negative (or even a positive) one when it is initiated (Figure 7.18). While the negative field predominates in the area between the grid and the cathode and also in the grid holes, electrons going out from the cathode are slowed down by the field, which is why the number of electrons reaching the area between the grid and the anode is very small.

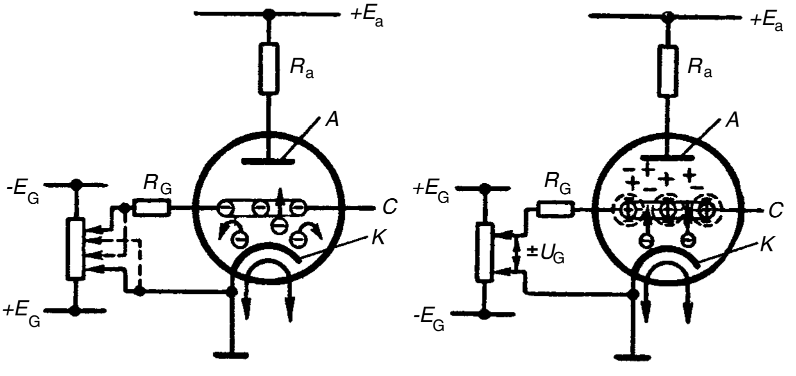


FIGURE 7.18
Scheme of the grid functioning in a gas-filled triode: on the left — before the discharge is initiated; on the right — after its development.

When a considerable negative potential on the grid is replaced with a less negative (or more positive) grid potential, the slowing down effect of the grid is considerably weakened. That is why a great number of electrons reach the area between the grid and the cathode. In that area electrons are accelerated by the positive field of the anode and receive enough energy for ionization of gas atoms. This is the starting point for discharge development. Further stages of development are concerned with avalanche-like multiplication of carriers, which leads to occurrence of arc discharge within a short period of time.

Such a gas-filled triode changing its state spasmodically (that is having a relay characteristic) is called a thyratron. A thyratron is in fact a real electronic relay. The discharge in the thyratron belongs to the nonindependent type, because primary agents (electrons) providing the ground for the discharge, are emitted by an incandescent cathode to which power is applied from the outside. Like vacuum tetrodes and pentodes, gas-discharge thyratrones can be with one or two additional grids. Thyratrones with an arc discharge can be both low power (Figure 7.19), and power capable of working under high voltages (tens of kilovolts) and strong currents (tens and hundreds of amperes in the continuous mode, and tens of thousands of amperes in the mode of short pulses switching — Figure 7.20).

FIGURE 7.19
Low-power thyratrones with an incandescent cathode, produced in Russia.

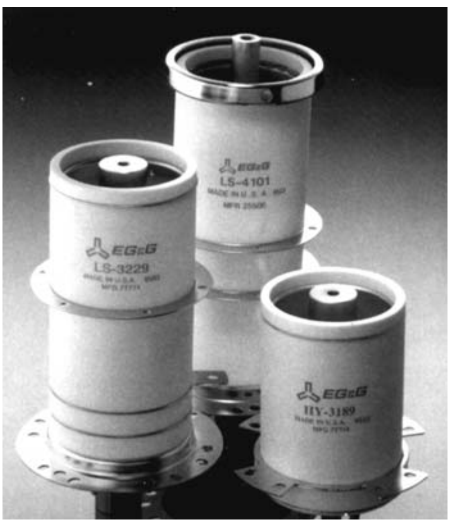


FIGURE 7.20
Modern high-voltage power pulse thyratrons in metal cases (produced by EG & G).

There are thyratrones not only with an incandescent cathode, but also with a cold one (Figure 7.21). The cathode of such a thyratron is made in the form of a metal cylinder activated by cesium. The anode is a molybdenum core placed in the glass tube with a free end sticking out of the glass. The starting electrode (a grid) has the form of a disk with a central hole and is placed between the anode and the cathode. The glass tube where the electrodes are placed is filled with neon with a small admixture of argon under a total pressure of 20 to 30 mmHg. The distance between the electrodes and the gas pressure is chosen in such a way that a discharge between the controlling electrode and the cathode occurs under lower voltage than a discharge between the anode and the cathode.

Along with single-grid thyratrones (triodes), double-grid thyratrones (gas-filled tetrodes) are widely used. When a voltage pulse of positive polarity is applied to the circuit of the control grid (control electrode) the potential of the grid increases and the field strength in the area between the control grid and the cathode is enough for gas ionization. An additional discharge occurs between the control grid and the cathode. Then it moves to the anode, and the thyratron is started.

After the thyratron is started, the grid loses its controlling properties. It is impossible to change the value of the anode current or to extinguish the thyratron by changing the potential of the grid of a started thyratron. In order to extinguish the thyratron, it is necessary to switch OFF the anode supply, or to decrease the anode voltage to a value that is lower than the voltage of combustion. A scheme providing a cut-off of the thyratron is shown in Figure 7.22. The capacitor in this scheme is charged through the open thyratron, which is open at that moment, and is discharged the next moment when the second thyratron is enabled. Thus, if the thyratron T_1 is enabled, the capacitor C is charged through this thyratron and the resistor R_{a2}, with the polarity indicated on top of the capacitor. When the positive pulse enables the thyratron T_2, the capacitor C is discharged through both thyratrones, creating direct current in thyratron T_2 and back current in the thyratron T_1. After thyratron T_1 closing, capacitor is charged through the resistor R_{a1} and then the open thyratron T_2. In such schemes load (resistors R_{a1}, R_{a2}) is switched ON and OFF just as in electromechanical relay. The value of the

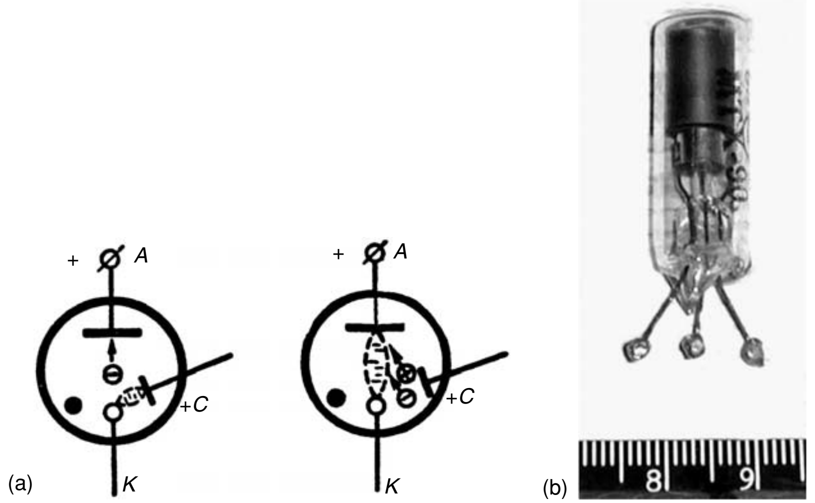


FIGURE 7.21
(a) Principle of functioning and (b) external design of the thyratron with a cold cathode.

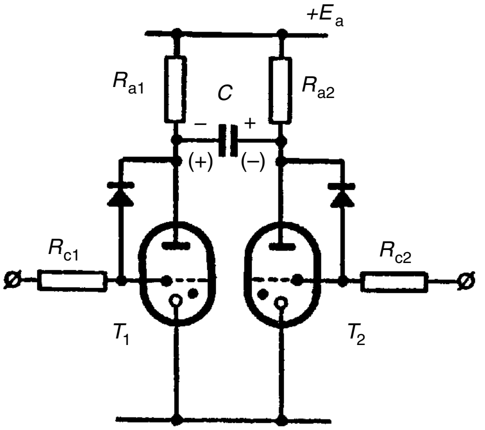


FIGURE 7.22
Scheme of the so called ''forced commutation'' of thyratrons.

capacitor *C* must be enough so that after switching the current from one thyratron to the other, the former has negative voltage for some time in order to restore its blocking properties.

7.6 Power Mercury Valves

Power mercury valves in which a liquid mercury cathode and graphite anodes are used should be considered separately. Such devices were widely used in industry in 1940–60's. According to the construction, they were split into glass and metal tubes, single-anode and multi-anode (2-, 3-, 6-, 12- and 24-anode) ones, with natural air or forced-water cooling.

The simplest glass mercury valve (Figure 7.23), consists of a vacuum glass tube (1) with two anode sleeves containing graphite anodes 2 and 3. The tube which is relatively big in size is used for better cooling of the device and creates better conditions for condensation

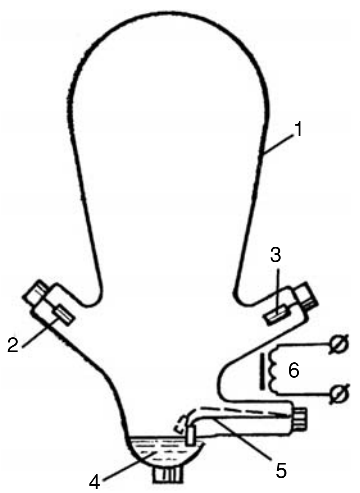


FIGURE 7.23
Power double-anode mercury valve.

of mercury vapors. In the lower part of the tube, there is a mercury cathode (4) and a movable igniting anode (5) moved by the electro-magnet. Alternating voltages in anti-phase are applied to the anodes 2 and 3 from the secondary winding of the transformer. To initiate the valve, a short-term control signal is applied to the electromagnet (6), which sinks the igniting anode (5) into the mercury and closes the circuit of the igniting anode. When the igniting anode is lifted, the mercury ''bridge'' between the cathode and the igniting anode breaks and at the break point an electric arc occurs. The arc occurrence is accompanied by a liberation of free electrons.

Affected by the electric field of anodes, free electrons move to one of the anodes, which has the positive potential with respect to the cathode at that moment, and ionizes mercury vapors in the area between the cathode and the anode. Electric ion plasma, through which load current passes, is formed between the cathode and the anode. The discharge is maintained by electrons coming from the so called ''cathode spot'' formed on the surface of the cathode. To maintain such a cathode spot and to provide the needed number of electrons, current not less than 3 to 5 A is required.

Unlike in the mercury valves considered above, in which igniting anodes are used for maintenance of arcing, in devices called ignitrons arc initiation occurs during each positive half-period of anode voltage, with the help of an additional electrode called igniter. An ignitron is a glass or metal vacuumized tube (Figure 7.24 and Figure 7.25), containing mercury cathode, anode, and igniter.

An igniter is the most important element of the ignitron. It has the form of a conic rod made of a mercury-unwettable semiconducting material as carborundum, or boron

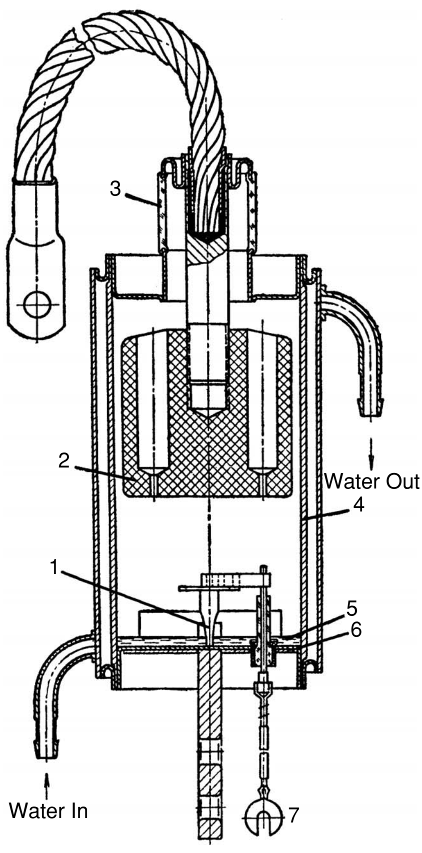


FIGURE 7.24
Construction of an ignitron with water cooling in metallic case. 1 — igniter; 2 — graphite anode; 3 — insulator from quartz glass; 4 — metal case with double-layer walls; 5 — mercury (cathode); 6 — metal bowl for mercury; 7 — ignitor's outlet

FIGURE 7.25
External design of an ignitron of the GL-5550-1 type, without additional cooling, in a metal case (General Electric Co.).

carbide for instance, submerged 3 to 5 mm into the mercury cathode. An insulation microfilm is formed between the igniter and the cathode. Voltage pulses of up to 170–200 V with a current upto 30 A are applied to the igniter.

If an igniting pulse is applied with positive voltage on the anode, arcing arises and plasma occurs. A cathode spot emerges on the surface of the mercury, that surface being the source of electrons maintaining the discharge. If the voltage half-period is negative, there will be deionization of the mercury vapors, and arc decaying, which is why during each positive half-period of the anode voltage, it is necessary to apply an igniting pulse on the igniter. Apparently, igniting pulses must be applied synchronously with the anode voltage. The function of an igniter in an ignitron is similar to that of a control grid in a thyratron.

A glass ignitron of the I-100/1000 type (Figure 7.26), designed for a rectified current of 100 A, with permissible reverse voltage of 1000 V, is made in a welded construction containing a copper cylinder (4) cooled by water which is the outlet of the cathode, and a glass cylinder (molybdenum glass) (2) — an anode tube. The graphite anode (3) has the

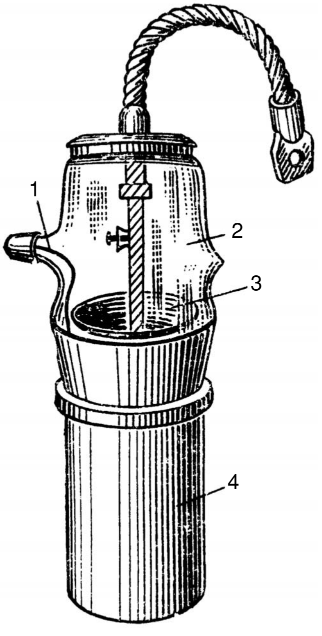


FIGURE 7.26
External design of a glass ignitron of the I-100/1000 type (U.S.S.R.).

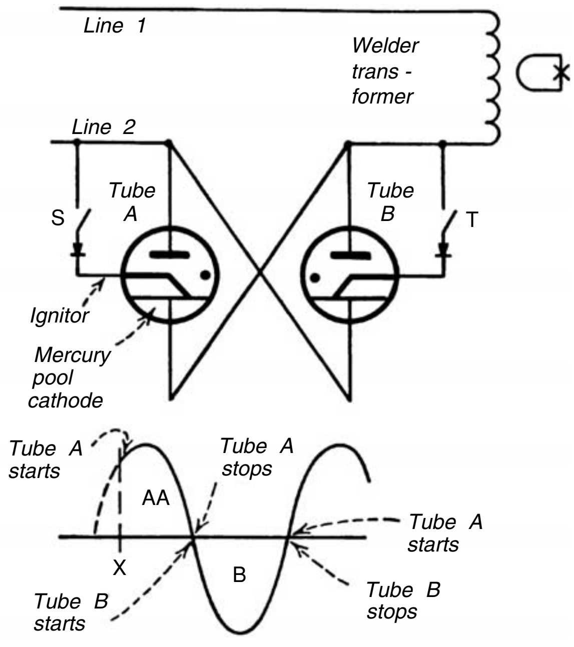


FIGURE 7.27
AC contactor on ignitrons for control of a power welding transformer (1940s—1950s).

form of a cylinder or a hemisphere. The outlet of the igniter (1) is made in the sidewall of the glass cylinder.

As a separate ignitron can conduct electric current only within a half-period of AC voltage, two parallel-opposition connected devices are used for switching both of the half-waves (Figure 7.27).

7.7 Electron-Beam Switching Tubes

An electron-beam switching tube can be considered a hybrid of a multi-anode valve and an electron-beam tube (that is, a television tube used in TV sets and computers). It is a device in which quick switching of circuits is carried out by moving an electron beam, by an electric field, created by deflected electrodes. The difference between an electron-beam switching tube and a standard television tube is that instead of a luminophore it contains a system of electrodes shorted by an electron beam (Figure 7.28). Modern electron-

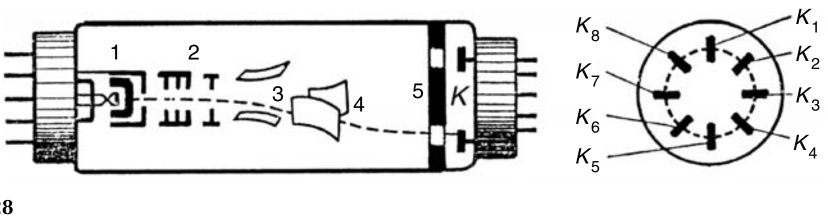


FIGURE 7.28
Principle of functioning of electron-beam switching tubes. 1 and 2 (cathode and anode) — the so called ''electron gun'' or ''electron injector,'' creating an electron beam; 3 and 4 — vertically and horizontally deflecting electrodes; 5 — protective disk with holes (''mask''), K — contact electrodes.

FIGURE 7.29
Power high-voltage electron-beam switching tubes, produced in Russia.

beam switching tubes are capable of switching circuits with currents of tens and hundreds of amperes, and with voltages of hundreds of thousands of volts (Figure 7.29).

7.8 Semiconductor Relays

7.8.1 First Experiments and First Semiconductor Devices

The history of semiconductor relays starts with the history of the application of the first crystals for radio-signal detection. As far as I know, the earliest paper on asymmetrical conduction was written by Karl Ferdinand Braun in 1874: ''Ueber die Stromleitung durch Schwefelmetalle'' (''On current flow through metallic sulfides''), Poggendorf's Annalen. He discovered that galena (lead sulfide) and copper pyrites, among others, could rectify. Of course, these experiments predated radio, so application of Braun's discoveries to wireless communication took a couple more decades. Perhaps the first to apply semiconductor diodes to the radio art was the remarkable Jagadis Chandra Bose, who applied for a patent on a galena detector in 1901 (it was finally awarded in 1904). This was used in his research work in the area of millimeter-wave RF!

The Peroxide of Lead detector devised by S.G. Brown of England is illustrated in Figure 7.30. This detector has proven quite successful and is used with a pair of sensitive telephone receivers and a critically adjusted battery current. The instrument comprises a

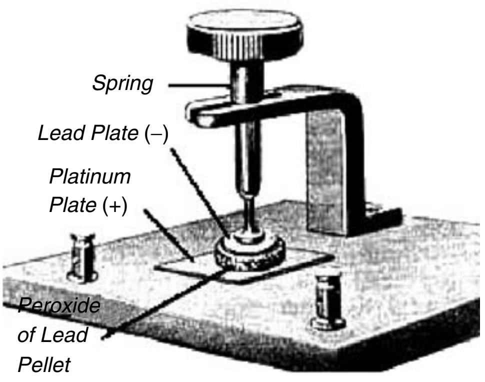


FIGURE 7.30
The peroxide of lead detector.

peroxide of a lead pellet, mounted between an upper lead disk and a lower platinum one; the pressure on the peroxide of the lead pellet being adjustable by means of a thumb screw and spring in the usual fashion. This detector has been termed, more or less correctly, the dry electrolytic detector and its action is supposed to depend upon the fact that an incoming oscillation intensifies the counter-electromotive force set up by the cell (an electro-chemical reaction due to the lead peroxide–lead platinum couple) and which is opposite to the applied battery current (about 1.5 V), thus causing the detector to increase its effective resistance. This results in a drop of current in the phone circuit; as soon as the oscillation ceases the phone current increases.

Henry Harrison Chase Dunwoody (a Brigadier-General of U.S. Army and later a vice-president of ''DeForest Company'') patented a silicon carbide (carborundum) detector (U.S. Patent 837616) in 1906 and that device also worked quite well, although a bias was essential for proper operation. In all of these point contact structures, the ohmic contact was made either by immersing the crystal specimen in a low melting-point alloy (Wood's Metal), or simply with a clamp of some sort (Figure 7.31). The carborundum detector in its usual form comprises two rather stiff springs, adjustable as to pressure, between which the carborundum (carbide of silicon) crystal (preferably an extremely jagged, greenish specimen) is placed. A pair of high resistance telephones are shunted across the detector and the incoming Hertzian wave oscillations, representing the points and dashes of the telegraphic code, are manifested as short and long signals in the phones, owing to the fact that the carborundum crystal will pass currents several hundred times better in one direction than it will in the reverse direction.

This action is enhanced by mounting the crystal in a cup or clamp of a large section, and making the second electrode of very small contact area. A steel needle has been used effectually as the small electrode and in one commercial instrument an even smaller electrode has been made. Greenleaf Whittier Pickard worked harder than anyone else to develop point-contact detectors. He tested over 31,000 combinations of minerals and wires in a search for the ''best'' detector. He patented a silicon-based point-contact detector in early 1907, and it worked exceedingly well.

The silicon detector (Figure 7.32) employs a piece of the mineral silicon embedded firmly in a brass cap. A solder or low heat alloy such as Hugonium metal is best used in mounting such minerals, so as not to injure their radio detecting properties or sensitivity. The Silicon detector is generally used without any battery and acts as a rectifier, similar to the carborundum detector. A pair of 2000 Ω phones or higher resistance ones are usually shunted across the detector, and owing to the rectifying action already described, the incoming Hertzian wave currents are manifested as short and long sounds in the phones. As it turned out, the quality of signal detection and sensitivity of the detectors depended much on he properties of the joint point of the metal needle and the crystal.

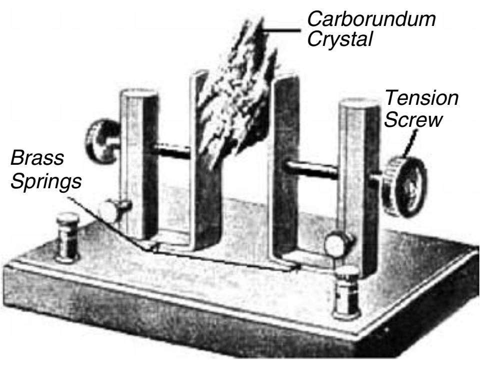


FIGURE 7.31
The carborundum detector, discovered by H.H.C. Dunwoody.

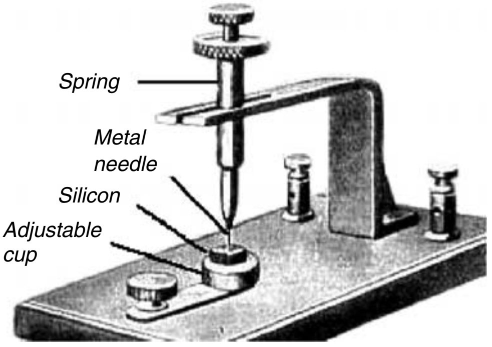
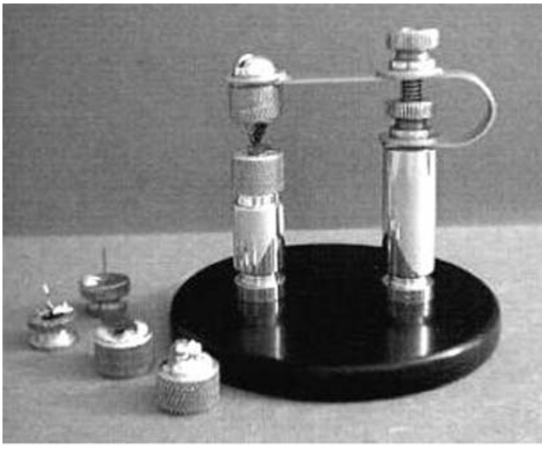


FIGURE 7.32
Silicon detector.

Such properties were very unstable, which is why in the course of work one had to search for an optimal contact point. That's why all earlier constructions of detectors were equipped with simple mechanisms for moving, changing pressure degree and fixation of the working point, and also for replacement of crystals (Figure 7.33). Due to the rapid development of industrial electronics and automation, in the middle of the 20th century demand for relatively powerful (for currents of a few and even tens of amperes) and cheap rectifier diodes arose. Detector diodes used in radio engineering were not quite adequate for these purposes. In 1940–50's copper-oxide diodes were very popular (Figure 7.34). The n-type electroconductivity area is formed inside the copper-oxide area with oxygen deficiency. The p-type area (with oxygen excess) is formed on the surface of the layer. Very thin soft leaden disks are used as packing, providing good electric contact of current conducting lamellas with a valve unit (the disks — 3). One of



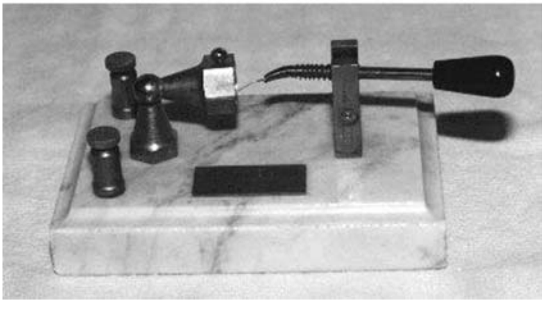


FIGURE 7.33
Crystal radio detectors, with replaceable ''cups'' so you can change to different minerals and wires.

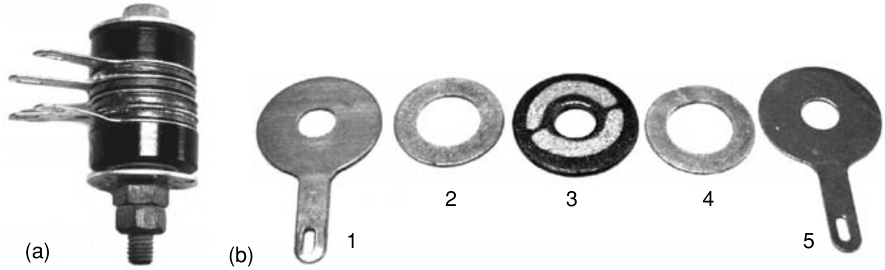


FIGURE 7.34
External design (a) of the column of four copper-oxide diodes and elements (b) of its construction (produced by Westinghouse). 1 and 5 — current conducting lamellas; 2 and 4 — lead disks; 3 — copper disk with copper oxide (Cu_2O) layer applied to one of its sidewalls and silver plates in the form of semirings.

such elements rectifies alternating current with voltage of not more than 8 to 10 V. Permissible current density is 40 to 60 mA/s m^2.

To increase working voltage, such elements are connected in series. Copper-oxide valves had not very high, but stable characteristics and that's why they were used even in electrical measurement equipment. These were such simple and reliable elements that they had been applied in engineering for quite a long period of time. It is worth mentioning that cheap copper-oxide diodes for low voltages were produced until the 1970s, along with more complex and at the same time more expensive silicon diodes.

Selenium diodes can be referred to as a whole epoch (Figure 7.35). All electrical engineers who started to work in the 1950–60's remember well such ribbed small and large (with the ribs of up to 15 cm) devices. There still exist electric installations with selenium rectifiers. The author happened to come across large selenium valves in powerful battery charger produced in the 1960s, which were still functioning in 2003! Selenium rectifiers, like copper-oxide ones, consist of separate valve units in the form of round or square disks beaded on an insulated stud. A selenium valve unit consists of an

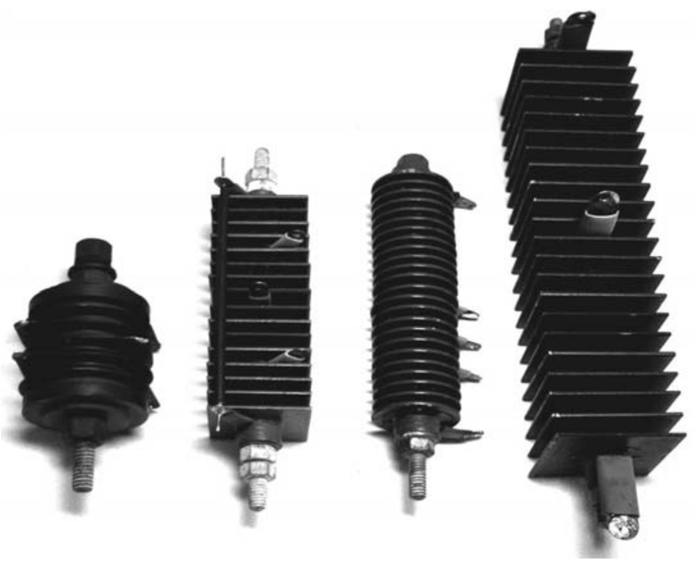


FIGURE 7.35
Showing how average power rectifiers for currents of a few amperes, assembled from selenium valves, look.

aluminum disk with a polished area in the center, with a layer of crystalline selenium obtained from the amorphous state with the help of thermal treatment.

For better contact of selenium and aluminum, a thin bismuth layer is sometimes sprayed between them. Such crystalline selenium has conductivity of the p-type (see below). On the surface of selenium, a tin–cadmium alloy in the molten state is applied. The selenium layer with a cadmium admixture forms an n-type layer (see below). Permissible current density for such valves was 0.8 to 1.0 A/s m^2. Big aluminum disks were used as heat sinks cooling the valve unit and were always a component of power and high-power diodes. Low current high-voltage selenium diodes were made in the form of a dielectric tube 6 to 8 mm in diameter and 10 to 16 cm in length. Tens of thin selenium disks, pressed by electrodes twisted in from the ends, were attached to it.

The rectifying unit consisted of tens of separate disks (diodes) connected in series (it should be noted that modern silicon diodes do not allow such connection in series without additional elements equalizing voltage distribution on the diodes that are connected in series). Selenium diodes also had another interesting property not common in modern diodes: localization of the breakdown spot in the crystal and removal of the damaged area from work, that is restoration of the working capacity after partial crystal disruption. Modern crystal diodes are elements designed for detection of radio signals and rectification of alternating current in power electronics and automation. They resemble the first detectors a lot: a similar crystal; similar metal needle (Figure 7.36). Of

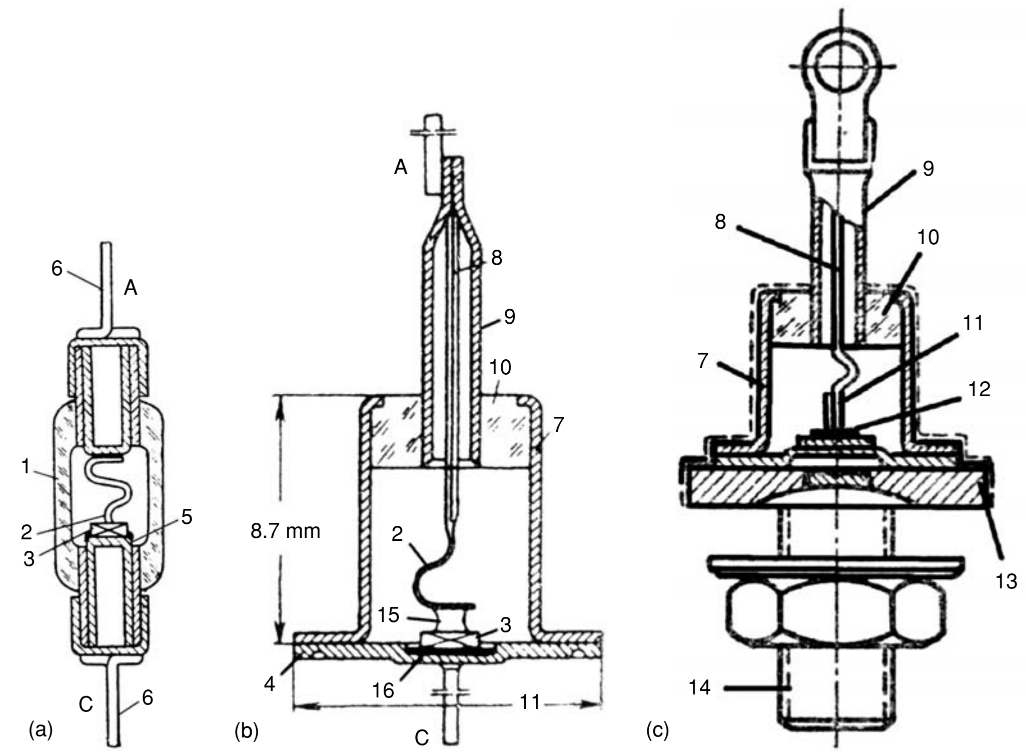


FIGURE 7.36
Construction of modern diodes: a, b — germanium low power and power diodes; c — silicon high-power diode. 1 — ceramic or glass case; 2 — upper tungsten electrode; 3 — crystal; 4 — metal flanges; 5 — crystal enclosure; 6 — wire terminals; 7 — metal case; 8 — flexible anode outlet (copper multiple stranded conductor); 9 — steal tube; 10 — glass insulator; 11 — contact outlet from the p-layer crystal; 12 — silicon crystal with a p—n barrier; 13 — copper heel piece; 14 — cathode outlet in the form of a screw-bolt; 15 — indium; 16 — outlet from the n-layer.

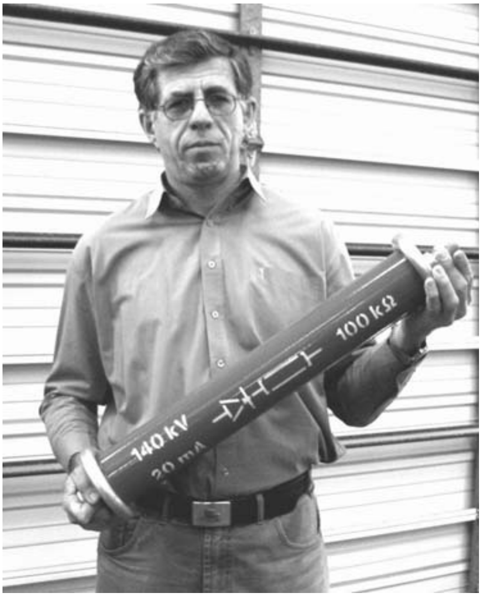


FIGURE 7.37
Semiconductor diode for voltage of 140.000 V in a joint case with a resistor for 100 kΩ, connected in series.

course now applied materials are modern and technologies of mass production are different, and the needle is not simply pressed to the crystal but fused into it, thus avoiding instability of contact properties. Modern technologies allow production of semiconductor diodes for such voltages that were unimaginable for designers of the first diodes (Figure 7.37).

Design and application of the first detectors (rectifiers) did not require an understanding of physics of the processes taking place in them. Until the 1940s they were based only on numerous experiments with different materials. Later, it turned out that the physics of these processes is very complex and that their full understanding is possible only on the basis of knowledge of modern physical theories of substance structure. This book is not aimed at considering fundamental theories of solid-state physics, which is why we will give only a simplified explanation of the processes taking place, in those elements which concern us.

7.8.2 Semiconducting Materials and P-N-Junction

As is known, all substances depending on their electro-conductivity are divided into three groups: conductors (usually metals) with a resistance of 10^{-6}–10^{-3} $\Omega\cdot$cm, dielectrics with a resistance of 10^{9}–10^{20} $\Omega\cdot$cm, and semiconductors (many native-grown and artificial crystals) covering an enormous intermediate range of values of specific electrical resistance.

The main peculiarity of crystal substances is typical, well-ordered atomic packing into peculiar blocks — crystals. Each crystal has several flat symmetric surfaces and its internal structure is determined by the regular positional relationship of its atoms, which is called the lattice. Both in appearance and in structure, any crystal is like any other crystal of the same given substance. Crystals of various substances are different. For example, a crystal of table salt has the form of a cube. A single crystal may be quite large or so small that it can only be seen with the help of a microscope. Substances having no crystal structure are called amorphous. For example, glass is amorphous, in contrast to quartz which has a crystal structure.

Among the semiconductors which are now used in electronics, one should point out germanium, silicon, selenium, copper-oxide, copper sulfide, cadmium sulfide, gallium arsenide, and carborundum. To produce semiconductors two elements are mostly used: germanium and silicon.

In order to understand the processes taking place in semiconductors, it is necessary to consider phenomena in the crystal structure of semiconductor materials which occur when their atoms are held in a strictly determined relative position to each other due to weakly bound electrons on their external shells. Such electrons, together with electrons of neighboring atoms, form valence bonds between the atoms. Electrons taking part in such bonds are called valence electrons. In absolutely pure germanium or silicon at very low temperatures, there are no free electrons capable of creating electric current, because under such circumstances all four valence electrons of the external shells of each atom that can take part in the process of charge transfer, are too strongly held by the valence bounds. That is why that substance is an insulator (dielectric) in the full sense of the word — it does not let electric current pass at all.

When the temperature is increased, due to the thermal motion some valence electrons detach from their bonds and can move along the crystal lattice. Such electrons are called free electrons. The valence bond from which the electron is detached is called a hole. It possesses properties of a positive electric charge, in contrast to the electron, which has a negative electric charge. The more the temperature is, the more the number of free electrons capable of moving along the lattice, and the higher the conductivity of the substance is. Moving along the crystal lattice, free electrons may run across holes — valence bonds missing some electrons — and fill up these bonds. Such a phenomenon is called recombination. At normal temperatures in the semiconductor material, free electrons occur constantly, and recombination of electrons and holes takes place.

If a piece of semiconductor material is put into an electric field by applying a positive or negative terminal to its ends, for instance, electrons will move through the lattice towards the positive electrode and holes — to the negative one. The conductivity of a semiconductor can be enhanced considerably by putting specially selected admixtures to it — metal or nonmetal ones. In the lattice the atoms of these admixtures will replace some of the atoms of the semiconductors. Let us remind ourselves that external shells of atoms of germanium and silicon contain four valence electrons, and that electrons can only be taken from the external shell of the atom. In their turn, the electrons can be added only to the external shell, and the maximum number of electrons on the external shell is eight.

When an atom of the admixture that has more valence electrons than required for valence, bonds with neighboring atoms of the semiconductor, additional free electrons capable of moving along the lattice occur on it. As a result, the electro-conductivity of the semiconductor increases. As germanium and silicon belong to the fourth group of the periodic table of chemical elements, donors for them may be elements of the fifth group, which have five electrons on the external shell of atoms. Phosphorus, arsenic, and stibium belong to such donors (donor admixture).

If admixture atoms have fewer electrons than needed for valence bonds with surrounding semiconductor atoms, some of these bonds turn out to be vacant and holes will occur in them. Admixtures of such a kind are called p-type ones because they absorb (accept) free electrons. For germanium and silicon, p-type admixtures are elements from the third group of the periodic table of chemical elements, external shells of atoms of which contain three valence electrons. Boron, aluminum, gallium, and indium can be considered p-type admixtures (accepter admixture).

In the crystal structure of a pure semiconductor, all valence bonds of neighboring atoms turn out to be fully filled, and occurrence of free electrons and holes can be caused only by deformation of lattice, arising from thermal or other radiation. Because of this, conductivity of a pure semiconductor is quite low under normal conditions. If some donor admixture is injected, the four electrons of the admixture, together with the same number in the filled valence, bond with the latter. The fifth electron of each admixture atom appears to be ''excessive'' or ''redundant,'' and therefore can freely move along the lattice.

When an accepter admixture is injected, only three filled valence bonds are formed between each atom of the admixture and neighboring atoms of the semiconductor. To fill up the fourth, one electron is lacking. This valence bond appears to be vacant. As a result, a hole occurs. Holes can move along the lattice like positive charges, but instead of an admixture atom, which has a fixed and permanent position in the crystal structure, the vacant valence bond moves. It goes like this. An electron is known to be an elementary carrier of an electric charge. Affected by different causes, the electron can escape from the filled valence bond, having left a hole which is a vacant valence bond and which behaves like a positive charge equaling numerically the negative charge of the electron. Affected by the attracting force of its positive charge, the electron of another atom near the hole may ''jump'' into the hole. At that point recombination of the hole and the electron occurs, their charges are mutually neutralized and the valence bond is filled. The hole in this place of the lattice of the semiconductor disappears. In its turn a new hole, which has arisen in the valence bond from which the electron has escaped, may be filled with some other electron which has left a hole. Thus, moving of electrons in the lattice of the semiconductor with a p-type admixture and recombination of them with holes can be regarded as moving of holes. For better understanding one may imagine a concert hall in which for some reason some seats in the first row turn out to be vacant. As spectators from the second row move to the vacant seats in the first row, their seats are taken by spectators of the third row, and so on. One can say that in some sense vacant seats ''move'' to the last rows of the concert halls, although in fact all the stalls remain screwed to the floor. ''Moving'' of holes in the crystal is very much like ''moving'' of such vacant seats.

Semiconductors with electro-conductivity enhanced due to an excess of free electrons caused by admixture injection, are called semiconductors with electron-conductivity or in short, n-type semiconductors. Semiconductors with electro-conductivity influenced mostly by moving of holes are called semiconductors with p-type conductivity or just p-type semiconductors.

There are practically no semiconductors with only electronic or only p-type conductivity. In a semiconductor of n-type, electric current is partially caused by moving of holes arising in its lattice because of an escaping of electrons from some valence bonds, and in semiconductors of p-type current is partially created by the moving of electrons. Because of this, it is better to define semiconductors of the n-type as semiconductors in which the main current carriers are electrons and semiconductors of the p-type as semiconductors in which holes are the main current carriers. Thus, a semiconductor belongs to this or that type depending on what type of current carrier predominates in it. According to this, the other opposite charge carrier for any semiconductor of a given type is a minor carrier.

One should take into account that any semiconductor can be made a semiconductor of n- or p-type by putting certain admixtures into it. In order to obtain the required conductivity, it is enough to put in a very small amount of the admixture, about one atom of the admixture for 10 millions of atoms of the semiconductor. All of this imposes special requirements for the purification of the original semiconductor material, and accuracy in dosage of admixture injection. One should also take into consideration that the speed of current carriers in a semiconductor is lower than in a metal conductor or in a vacuum. Moving of electrons is slowed down by obstacles on their way in the form of inhomogeneities in the crystal. Moving of holes is half as slow because they move due to jumping of electrons to vacant valence bounds. Mobility of electrons and holes in a semiconductor is increased when the temperature goes up. This leads to an increase of conductivity of the semiconductor.

The functioning of most semiconductors is based on the processes taking place in an intermediate layer formed in the semiconductor, at the boundary of the two zones with the conductivities of the two different types: ''p'' and ''n''. The boundary is usually called the p–n junction or the electron–hole junction, in accordance with the main characteristics of the type of main charge carriers in the two adjoining zones of the semiconductor.

There are two types of p–n junctions: planar and point junctions, which are illustrated schematically in Figure 7.38. A planar junction is formed by moving a piece of the admixture — for instance indium, to the surface of the germanium — of n-type, and further heating until the admixture is melted. When a certain temperature is maintained for a certain period of time, there is diffusion of some admixture atoms to the plate of the semiconductor, to a small depth, and a zone with conductivity opposite to that of the original semiconductor is formed. In the above case, it is p-type, for n-germanium.

Point junction results from tight electric contact of the thin metal conductor (wire), which is known to have electric conductivity, with the surface of the p-type semiconductor. This was the basic principle on which the first crystal detectors operated. To decrease dependence of diode properties on the position of the pointed end of the wire on the surface of the semiconductor, and the clearance of its momentary surface point, junctions are formed by fusing the end of the thin metal wire to the surface of a semiconductor of the n-type. Fusion is carried the moment a short-term powerful pulse of electric current is applied. Affected by the heat formed for this short period of time, some electrons escape from atoms of the semiconductor, which are near the contact point, and leave holes. As a result of this some small part of the n-type semiconductor in the immediate vicinity of the contact turns into a semiconductor of the p-type (area 3 on Figure 7.38a).

Each part of semiconductor material, taken separately (that is before contacting), was neutral, since there was a balance of free and bound charges (Figure 7.39a). In the n-type area, concentration of free electrons is quite high and that of holes quite low. In the p-type area on the contrary, concentration of holes is high, and that of electrons low. Joining of semiconductors with different concentrations of main current carriers, causes diffusion of these carriers through the junction layer of these materials: the main carriers of the p-type semiconductor — holes — diffuse to the n-type area because the concentration of holes in it is very low. And vice versa, electrons from the n-type semiconductor,

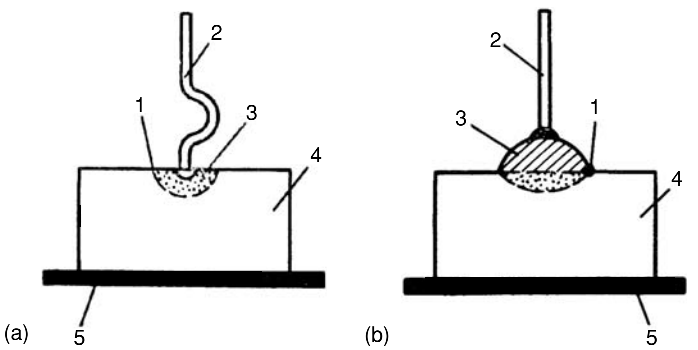


FIGURE 7.38
Construction of point (a) and planar (b) p—n junctions of the diode. 1 — p—n junction; 2 — wire terminal; 3 — p-area; 4 — crystal of n-type; 5 — metal heel piece.

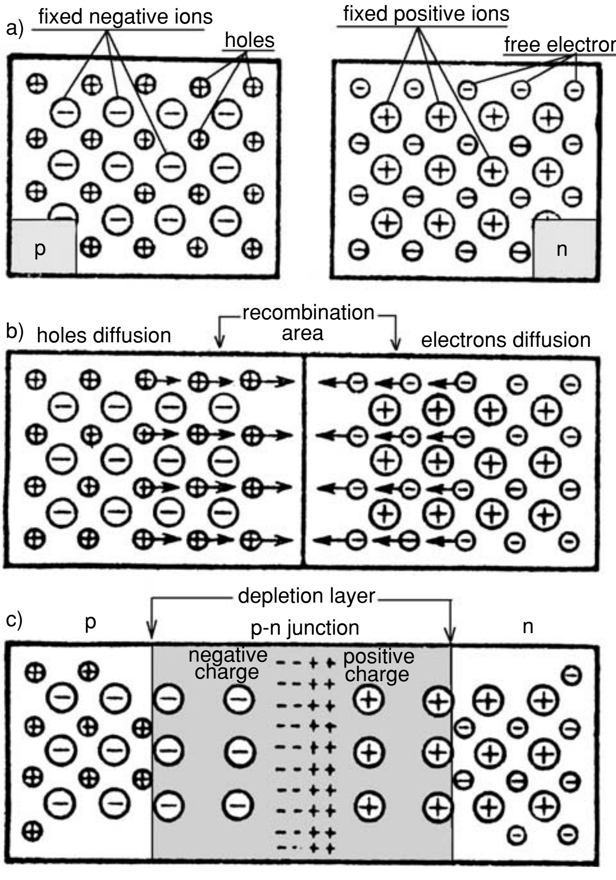


FIGURE 7.39
Formation of a blocking layer when semiconductors of different conductivity are connected.

with a high concentration of them, diffuse to the n-type area, where there are few of them (Figure 7.39b).

On the boundary of the division of the two semiconductors, from each side a thin zone with conductivity opposite to that of the original semiconductor is formed. As a result, on the boundary (which is called a p-n junction) a space charge arises (the so-called potential barrier), which creates a diffusive electric field and prevents the main current carriers from flowing after balance has been achieved (Figure 7.39c).

Strongly pronounced dependence of electric conductivity of a p–n junction from polarity of external voltage applied to it, is typical of the p–n junction. This can never be noticed in a semiconductor with the same conductivity. If voltage applied from the outside creates an electric field coinciding with a diffusive electric field, the junction will be blocked and current will not pass through it (Figure 7.40). Moreover, moving of minor carriers becomes more intense, which causes enlargement of the blocking layer and lifting of the barrier for main carriers. In this case it is usually said that the junction is reversely biased. Moving of minor carriers causes a small current to pass through the blocked junction. This is the so-called reverse current of the diode, or leakage current. The smaller it is, the better the diode is.

When the polarity of the voltage applied to the junction is changed, the number of main charge carriers in the junction zone increases. They neutralize the space charge of the blocking layer by reducing its width and lowering the potential barrier that

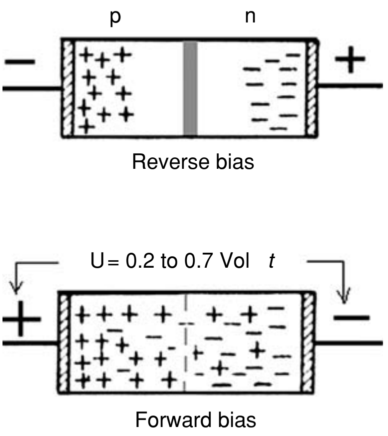


FIGURE 7.40
p—n-junction with reverse and forward bias.

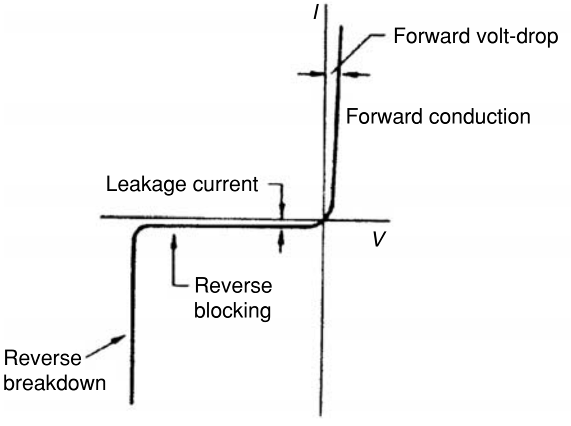


FIGURE 7.41
Volt–ampere characteristic of a single p–n junction (diode).

prevented the main carriers from mobbing through the junction. It is usually said that the junction is forward biased. The voltage required for overcoming of the potential barrier in the forward direction is about 0.2 V for germanium diodes, and 0.6 to 0.7 V for silicon ones.

To overcome the potential barrier in the reverse direction, tens and sometimes even thousands of volts are required. If the barrier is overpassed, irreversible destruction of the junction and its breakdown takes place, which is why threshold values of reverse voltage and forward current are indicated for junctions of different appliances. Figure 7.41 illustrates an approximate volt–ampere characteristic of a single junction, which is dependence of current passing through it on the polarity and external voltage applied to the junction. Currents of forward and reverse directions (up to the breakdown area) may differ by tens and hundreds of times. As a rule, planar junctions withstand higher voltages and currents than point ones but not work properly with high frequency currents.

7.8.3 Diode Switch of Electric Circuits

A diode can be used for switching of electric signals (Figure 7.42), like relays. But in this device control voltage u_{contr} must be higher than the voltage of the power source (and of course higher than the working voltage of the load). Depending on the polarity of the control voltage, the working point of the diode may be biased to the direct and reverse branch of the volt–ampere characteristic.

The diode operates either in the mode of conductivity — the switch is closed (point *A* in Figure 7.42) or in the cut-off mode — the switch is open (point *B*). To make a long story short, if the polarity of the control voltage coincides with the polarity of the power source (E), the diode is open and current flows to the load from the power source. If it does not, the diode is closed and the load is without current (it is implied that the voltage of the control signal is high by the absolute value than the voltage of the power source). If changes in the value control voltage of the blocking polarity are applied to the diode, the diode will be automatically enabled and let current flow to the load, the moment the control voltage is lower than the voltage of the power source.

There are also types of diodes with characteristics specially selected for operation in the switch mode. For example, ''tunnel diodes'' (Figure 7.43). The tunnel diode was invented by Leo Izaki in 1958. It was named ''tunnel'' after the effect on the basis of which it operates. This is a very complex physical effect, which can be described in simple terms as original behavior of electrons which cannot pass through the potential barrier of the blocking layer in the usual way, and therefore pass under the barrier, as if through a ''tunnel.'' Such a tunnel is formed when there is a high concentration of admixtures (semiconductor degenerates to ''semimetal'') and junction depletion region so narrow

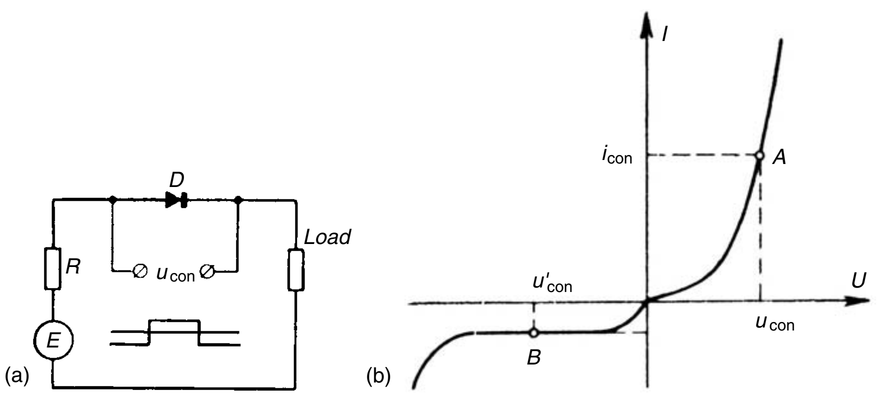


FIGURE 7.42
Diode signal switch and changes of the working point of the diode on the static volt–ampere characteristic during work.

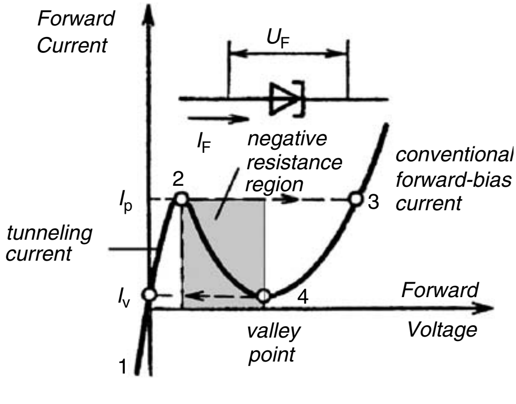


FIGURE 7.43
Notation and volt–ampere characteristic of a tunnel diode.

that both holes and electrons can transfer across the p–n junction by a quantum mechanical action called ''tunneling.'' The conductivity of such material becomes close to the conductivity of the metal when forward or reverse voltage is increased (the ''tunnel effect''). However, further increase of forward voltage causes weakening of the effect and the behavior of the diode becomes regular, which is why after a certain sharp curve (the area with negative resistance (NR) where the positive voltage increment corresponds to the negative current increment) the volt–ampere characteristic of the tunnel diode becomes regular. In other words, the resistance to current flow through the tunnel diode increases as the applied voltage increases over a portion of its region of operation. Outside the NR region, the tunnel diode functions essentially the same as a normal diode.

The three most important aspects of the characteristic curve are (1) the forward current increase to a peak (I_p) with a small applied forward bias, (2) the decreasing forward current with an increasing forward bias to a minimum valley current (I_v), and (3) the normal increasing forward current with further increases in the bias voltage. The portion of the characteristic curve between I_p and I_v is the region of NR.

Tunneling causes the NR action and is so fast that no transit-time effects occur even at microwave frequencies. The lack of a transit-time effect permits the use of tunnel diodes as super high frequency switch in a wide variety of microwave applications. Unfortunately, the tunnel diode is difficult to use in power applications due to low working voltages and strong temperature dependence.

7.8.4 The Transistor: A Piece of Silicon with Three Wires that Has Changed the World

Despite the wide use of semiconductor diodes, vacuum tubes have continued to be used for amplification, generation of signals, and high-speed switching of electric current for a long period of time. Over the decades, vacuum tubes were improved and used in more and more complicated circuitry. At the 1939 World Fair, for example, vacuum tubes were showcased in fully electronic television, and by 1945 the high-speed computer ENIAC was built, containing more than 17,000 tubes. Although successful, ENIAC and its offspring showed the real limitations of vacuum tubes: to make more powerful computers more tubes were needed, but at some point available space and energy prevented further growth. Vacuum tubes were bulky, used a lot of energy, were somewhat fragile and easily overheated. Engineers knew that they needed to find something better. The telephone companies had problems with vacuum tubes, too, and hoped to find something better for switching telephone calls. The idea of somehow using semiconductors (solid materials such as silicon that conduct electricity, but not as well as a conductor such as copper) had been tossed about before World War II, but the knowledge about how they worked was scant, and manufacturing semiconductors was difficult.

In 1945, however, the vice president for research at Bell Laboratories established a research group to look into the problem. The group was led by William Shockley and included Walter Brattain, John Bardeen, and others, physicists who had worked with quantum theory, especially in solids. The team was talented and worked well together. In 1947, John Bardeen and Walter Brattain, with colleagues, created the first successful amplifying semiconductor device (Figure 7.44). They called it as a transistor (from ''transfer'' and ''resistor''). In 1950, Shockley made improvements to it that made it easier to manufacture. His original idea eventually led to the development of the silicon chip. Shockley, Bardeen, and Brattain won the 1956 Nobel Prize for the development of the transistor. It allowed electronic devices to be built smaller, lighter, and even cheaper.

Bell Laboratories began to license the use of transistors (for a royalty) and offered courses on transistor technology, helping spread the word throughout the industry.

FIGURE 7.44
(a) Inventors of the transistor, the Nobel Prize laureates: William Bradford Shockley, John Bardeen, and Walter Houser Brattain. (b) This is how the first laboratory sample of a transistor looked.

W. Shockley left Bell Laboratories in 1955 and served as visiting professor and consultant at various universities and corporations. Bardeen and Brattain continued in research (Bardeen later won another Nobel prize).

W. Shockley started his own semiconductor company in Palo Alto to develop transistors and other devices. The business changed hands a few times and finally folded up in 1968, but its staff went on to invent the integrated circuit (the ''chip'') and to found the Intel Corporation. In 1963, Shockley was appointed professor of engineering at Stanford University, where he taught until 1975.

It can be seen in Figure 7.45 that a transistor contains two semiconductor diodes connected together, and has a common area. Two utmost layers of the semiconductor (one of them is called an ''emitter'' and the other a ''collector'') have p-type conductivity with a high concentration of holes, and the intermediate layer (called a ''base'') has n-type

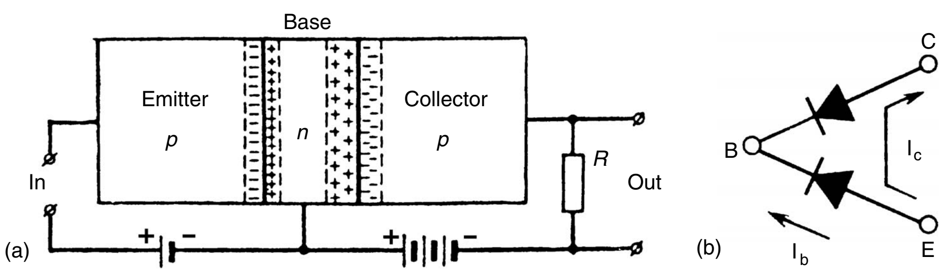


FIGURE 7.45
Circuit (a) and the principle(b) of operation of a transistor.

conductivity with a low concentration of electrons. In electric circuits, low voltage is applied to the first (the emitter) p–n junction because the junction is connected in the forward (carrying) direction, and much higher voltage is applied to the second (the collector) junction, in the reverse (cut-off) direction. In other words, emitter junction is a forward biased and collector junction is a reverse biased. The collector junction remains blocked until there is no current in the emitter-base circuit. The resistance of the whole crystal (from the emitter to the collector) is very high. As soon as the input circuit (Figure 7.45) is closed, holes from the emitter seem to be injected (emitted) to the base and quickly saturate it (including the area adjacent to the collector). As the concentration of holes in the emitter is much higher than the concentration of electrons in the base, after recombination there are still many vacant holes in the base area, which is affected by the high voltage (a few or tens of volts) applied between the base and the collector, easily overpassing the barrier layer between the base and the collector.

Increased concentration of holes in the cutoff collector junction causes the resistance of this junction to fall rapidly, and it begins to conduct current in the reverse direction. The high strength of the electric field in the ''base-collector'' junction results in a very high sensitivity of the resistance of this junction in the reverse (cutoff) state to a concentration of the holes in it. That is why, even a small number of holes injected from the emitter under the effect of weak input current can lead to sharp changes of conductivity of the whole structure, and considerable current in the collector circuit.

The ratio of collector current to base current is called the ''current amplification factor.'' In low-power transistors, this amplification factor has values of tens and hundreds, and in power transistors — tens. The transistor, named M1752 (Figure 7.46a) uses a very small

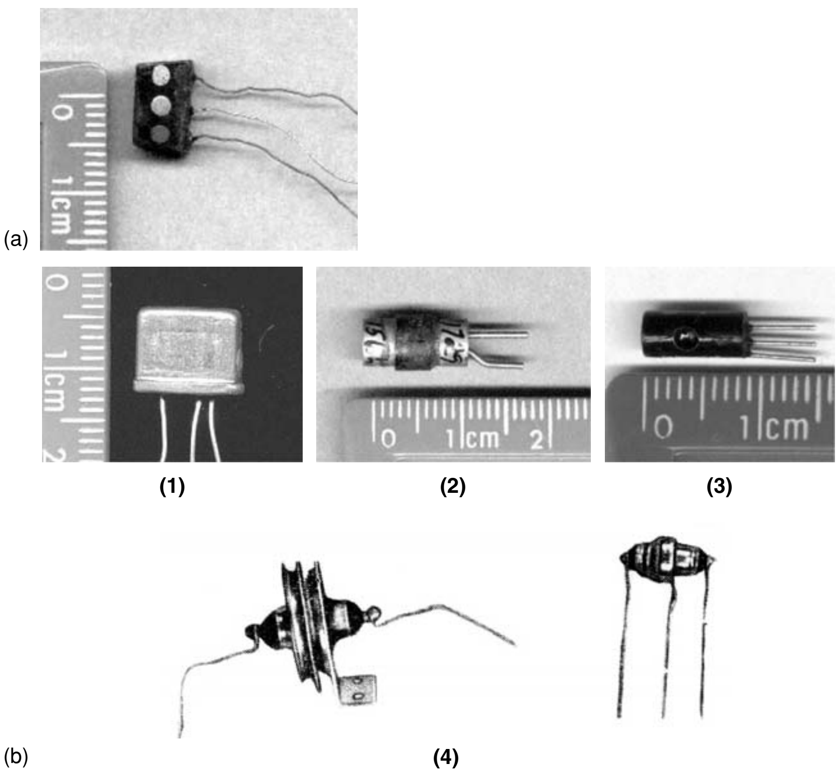


FIGURE 7.46
(a) First industrial sample of a transistor produced by Bell in 1951. (b) First industrial transistors produced by Motorola (1), Western Electric (2), General Electric (3), and by the former U.S.S.R. (4) in the 1950s.

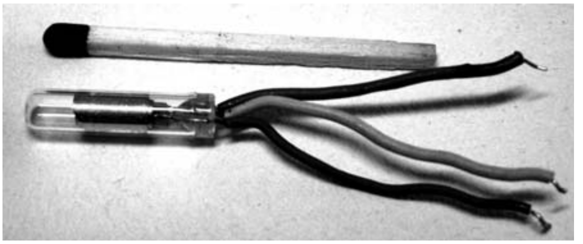


FIGURE 7.47
A transistor in a glass case, found by the author in an old electric device produced by AEG in 1961.

plastic package. It is identified, like most early Bell types, by a four-digit number, coded in colored paint dots on the package. The colors are purple–green–red, namely 7–5–2, to which 1000 must be added. The lead wires are made of steel, not copper, because the thermal expansion coefficient of steel matches that of glass and a small glass block was used to anchor the wires.

Some companies began to produce transistors using their electro-vacuum technology for the production of vacuum tubes (Figure 7.47).

7.8.5 Bipolar ... Unijunction ... Field ...

In the 1970s transistor engineering developed very rapidly. Hundreds of types of transistors and new variants of them appeared (Figure 7.48). Among them appeared transistors with reverse conductivity or n–p–n transistors, and also unijunction transistors (as it contains only one junction such a transistor is sometimes called a two-base diode) (Figure 7.49). This transistor contains one junction formed by welding a core made from p-material to a single-crystal wafer made from n-type material (silicon). The two outlets, serving as bases, are attached to the wafer. The core, placed asymmetrically with regard to the base, is called an emitter. Resistance between the bases is about a few thousand ohms. Usually the base B_2 is biased in a positive direction from the base B_1. Application of positive voltage to the emitter causes strong current of the emitter (with insignificant voltage drop between the emitter E and the base B_1). One can observe the area of NR (see Figure 7.49) on the emitter characteristic of the transistor where the transistor is very rapidly enabled, operating like a relay.

In fact, modern transistors (Figure 7.50), are characterized by such a diversity of types that it is simply impossible to describe all of them in this book devoted to relays, therefore only a brief description of the most popular types of modern semiconductor devices, and the relays based on them, are presented here.

Besides the transistors described above, which are called bipolar junction transistors or just ''bipolar transistors'' (Figure 7.51), the so-called field effect transistors (FET — Figure 7.52) have become very popular recently. The first person to attempt to construct a field effect transistor in 1948 was again William Shockley. But it took many years of additional experiments to create a working FET with a control p–n junction called a ''unitron'' (unipolar transistor), in 1952. Such a transistor was a semiconductor three-electrode device, in which control of the current caused by the ordered motion of charge carriers of the same sign between two electrodes, was carried out with a help of an electric field (that is why it is called ''field'') applied to the ford electrode.

Electrodes between which working currents pass are called source and drain electrodes. The source electrode is the one through which carriers flow into the device. The third electrode is called a ''gate''. Change of value of the working current in a unipolar transistor is carried out by changing the effective resistance of the current conducting area, the semiconductor material between the source and the drain called the ''channel''.

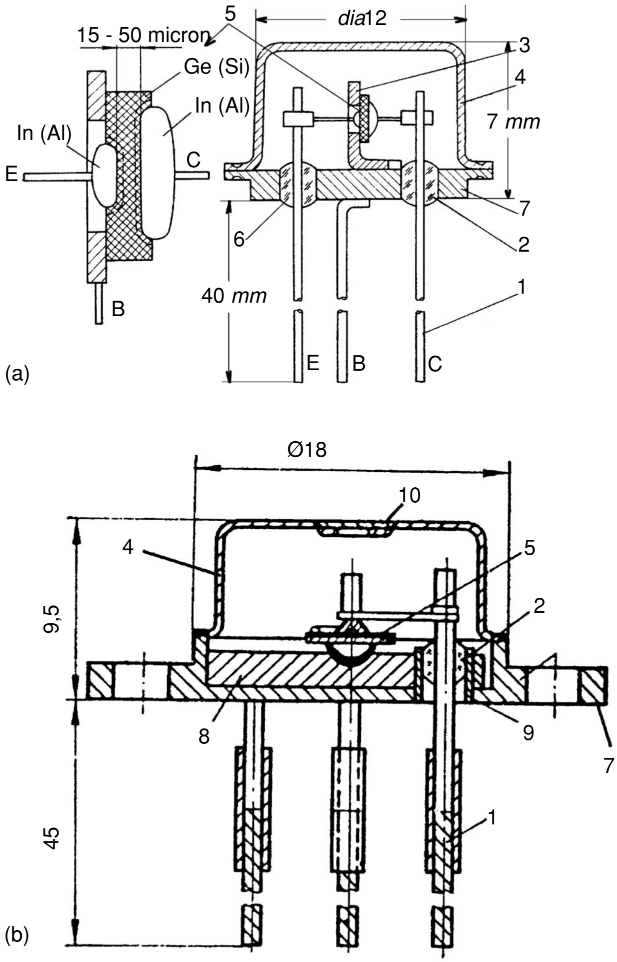


FIGURE 7.48
Transistors produced in the 1970s: (a) low-power transistor; (b) power transistor. 1 — outlets; 2 and 6 — glass insulators; 3 — crystal holder; 4 — protection cover; 5 — silicon (germanium) crystal; 7 — flange; 8 — copper heat sink; 9 — Kovar bushing; 10 — hole for gas removal after case welding and disk for sealing-in.

That change is made by increasing or decreasing area 5 (Figure 7.52). Increase of voltage of the initial junction bias leads to expansion of the depletion layer. As a result, the rest area of the section of the conductive channel in the silicon decreases and the transistor is blocked, and vice versa, when the value of the blocking voltage on the gate decreases, the area (5) depleted by current carriers contracts and turns into a pointed wedge. At the same time, the section of the conductive channel increases and the transistor is enabled.

Depending on the type of the conductivity of semiconductor material of the channels, there are unipolar transistors with p and n channels. Because of the fact that control of the working current of unipolar transistors is carried out with the help of a channel, they are also called ''channel transistors''. The third name of the same semiconductor device — a ''field transistor'' or FET (field effect transistor) points out that working current control is carried out by an electric field (voltage) instead of electric current as in a bipolar transistor. The latter peculiarity of unipolar transistors, which allows them to obtain very

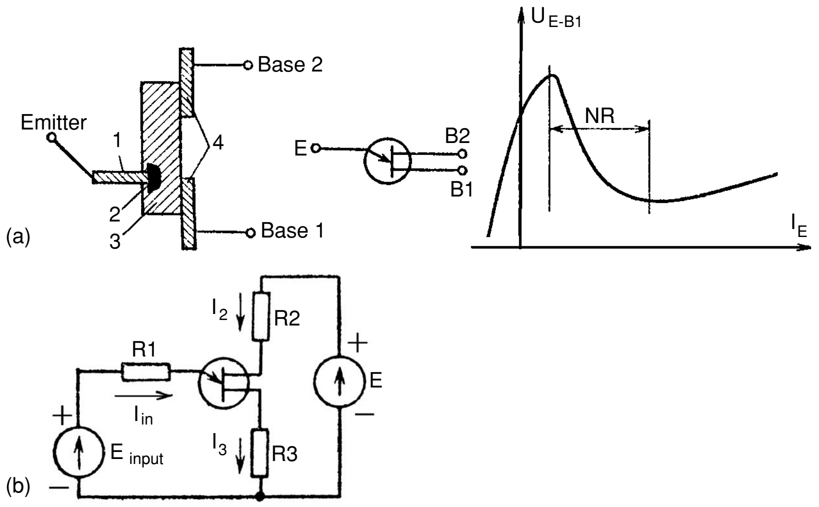


FIGURE 7.49
(a) A unijunction transistor (or two-base diode) and (b) its circuit. 1 — p-type core; 2 — p—n-junction; 3 — n-type plate; 4 — ohmic contacts; (c) NR — negative resistance area.

high input resistances, estimated in tens and hundreds of meg-ohms, determined their most popular name: field transistors (Figure 7.53).

It should be noted that apart from field transistors with p–n junctions between the gate and the channel (FET), there are also field transistors with an insulated gate: metal-oxide-semiconductor FET (MOSFET) (Figure 7.54). The latter were suggested by S. Hofstein and F. Heiman in 1963. Field transistors with an insulated gate appeared as a result of searching for methods to further increase input resistance and frequency range extensions of field transistors with p–n junctions. The distinguishing feature of such field transistors is that the junction biased in a reverse direction is replaced with a control structure ''metal-oxide-semiconductor,'' or a MOSFET-structure in abbreviated form. As shown in Figure 7.52 this device is based on a silicon mono crystal, in this case of p-type. The source and drain areas have conductivity opposite to the rest of the crystal, that is of the n-type.

The distance between the source and the drain is very small, usually about 1 μm. The semiconductor area between the source and the drain, which is capable of conducting current under certain conditions, is called a channel, as in the previous case. In fact the channel is an n-type area formed by diffusion of a small amount of the donor admixture to the crystal with p-type conductivity. The gate is a metal plate covering source and drain zones. It is isolated from the mono crystal by a dielectric layer only 0.1 μm thick. The film of silicon dioxide formed at this high temperature is used as a dielectric. Such film allows us to adjust the concentration of the main carriers in the channel area by changing both value and polarity of the gate voltage. This is the major difference of MOSFET, as opposed to field ones with p–n junctions, which can only operate well with blocking voltage of the gate. The change of polarity of the bias voltage leads to junction unblocking and to a sharp reduction of the input resistance of the transistor.

The basic advantages of MOSFET are as follows: first there is an insulated gate allowing an increase in input resistance by at least 1000 times in comparison with the input resistance of a field transistor with a p–n junction. In fact it can reach a billion megohms. Second, gate and drain capacities become considerably lower and usually do not exceed

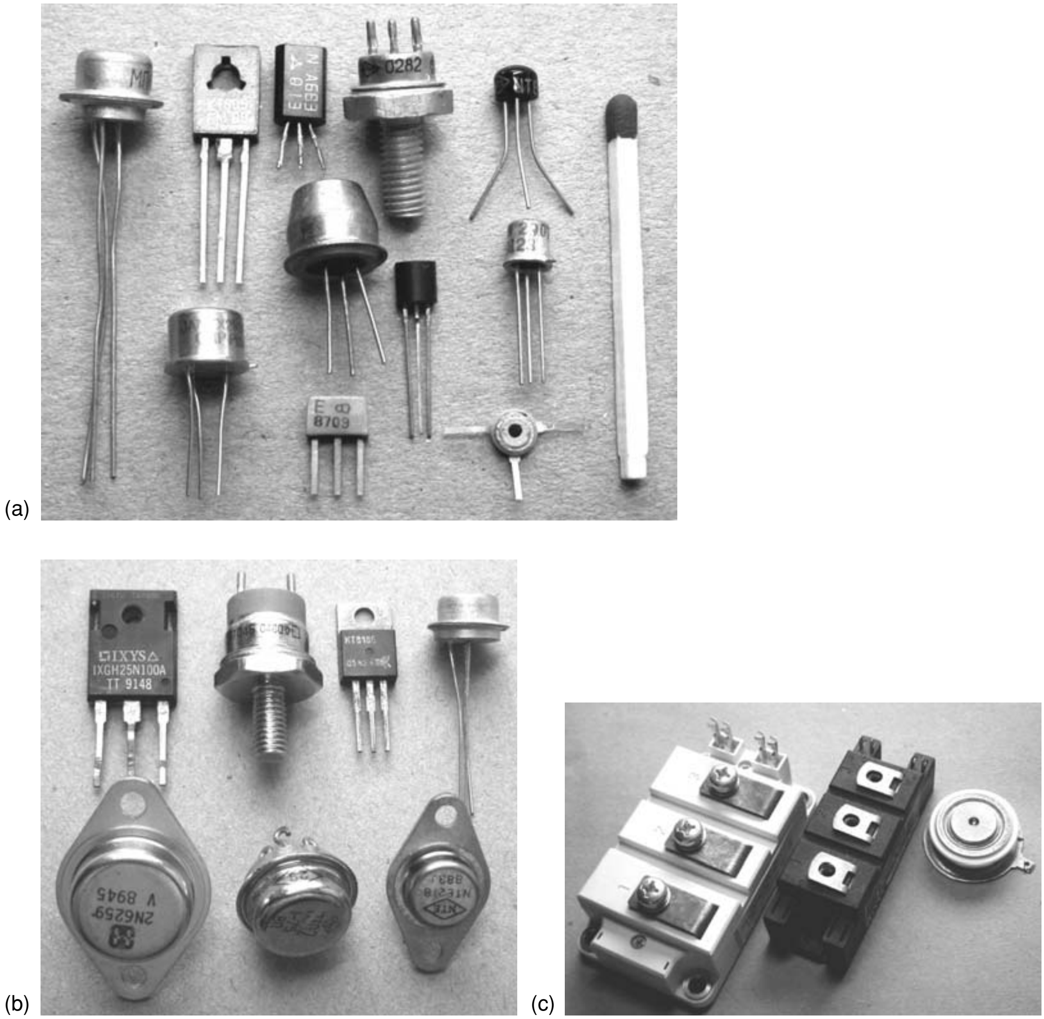


FIGURE 7.50
This is how modern (a) low-power transistors, (b) power transistors and (c) high power transistors look.

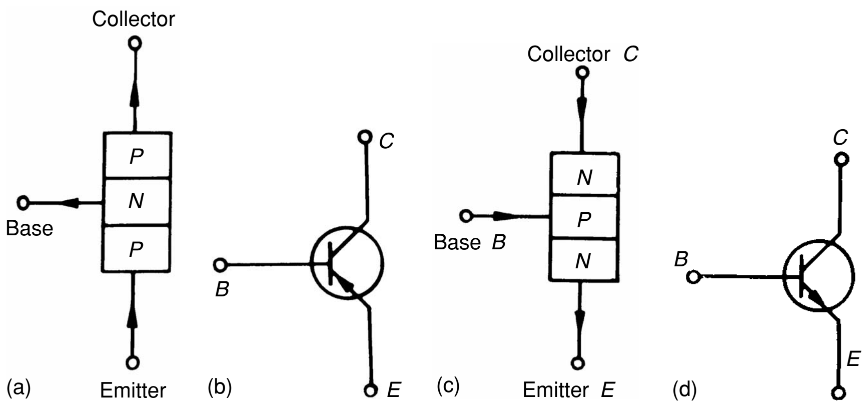


FIGURE 7.51
Structure and symbolic notation on the schemes of bipolar transistors of (a, b) p—n—p and (c, d) n—p—n types.

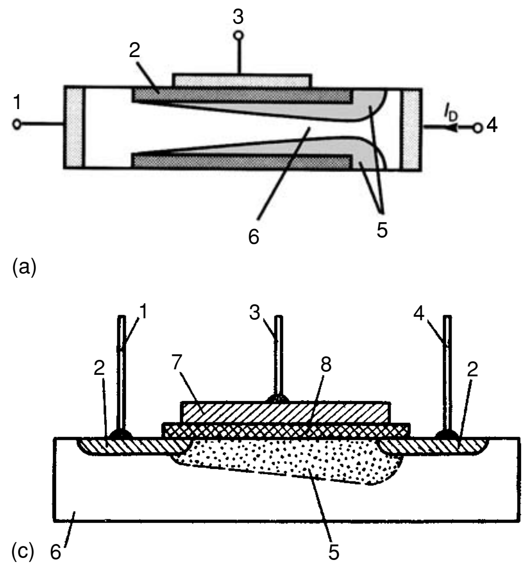


FIGURE 7.52
(a, b) Simplified structure of FET and (c) MOSFET. 1 — source; 2 — n-type admixture; 3 — gate; 4 — drain; 5 — area consolidated by current carriers (depletion layer); 6 — conductive channel in silicon of p-type; 7 — metal; 8 — silicon dioxide.

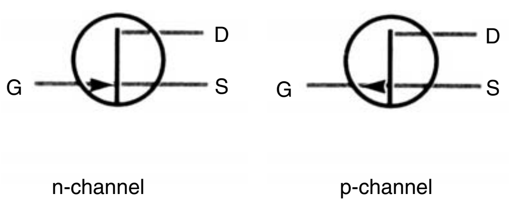


FIGURE 7.53
Symbolic notation of FET with n- and p-channels. G — gate; S — source; D — drain.

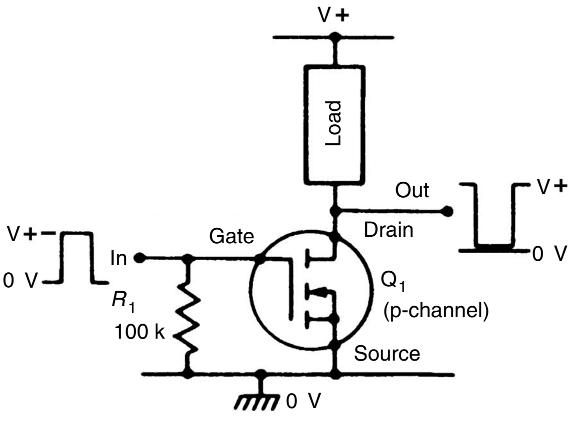


FIGURE 7.54
Symbolic notation and the circuit of a MOSFET.

1 to 2 pF. Third, the limiting frequency of MOSFET can reach 700 to 1000 MHz, which is at least ten times higher than that of standard field transistors.

Attempts to combine in one switching device the advantages of bipolar and field transistors led to the invention of a compound structure in 1978, which was called a "pobistor" (Figure 7.55). The idea of a modular junction of crystals of bipolar and field transistors in the same case was employed by "Mitsubishi Electric" to create a powerful switching semiconductor module (Figure 7.56).

Further development of production technology of semiconductor devices allowed development of a single-crystal device with a complex structure with properties of a "pobistor": an insulated gate bipolar transistor (IGBT) transistor. The IGBT is a device which combines the fast-acting features and high power capabilities of the bipolar transistor with the voltage control features of the MOSFET gate. In simple terms, the collector–emitter characteristics are similar to those of the bipolar transistor, but the control features are those of the MOSFET. The equivalent circuit and the circuit symbol are illustrated in Figure 7.57.

Such a transistor (Figure 7.58) has a higher switching power than FET and bipolar transistors and its operation speed is between that of FET and bipolar transistors. Unlike bipolar transistors, the IGBT does not operate well in the amplification mode and is designed for use in the switching (relay) mode as a powerful high-speed switch.

The IGBT is enabled by a signal of positive (with regard to the emitter) polarity, with voltage not more than 20 V. It can be blocked with zero potential on the gate, however, with some types of loads a signal of negative polarity on the gate may be required for reliable blocking (Figure 7.59). Many companies produce special devices for IGBT control. They are made as separate integrated circuits or ready-to-use printed circuit cards, so-called drivers (Figure 7.60). Such drivers are universal as a rule and can be

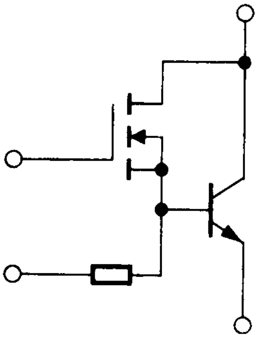


FIGURE 7.55
Compound structure — "Pobistor."

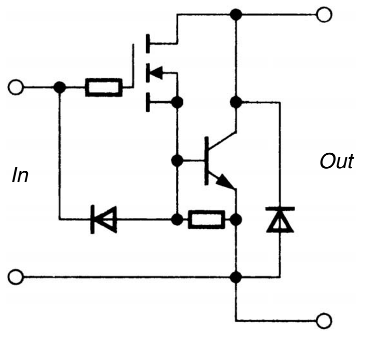


FIGURE 7.56
Scheme of a power switching module CASCADE-CD, with a working voltage of 1000 V and currents more than 100 A ("Mitsubishi Electric").

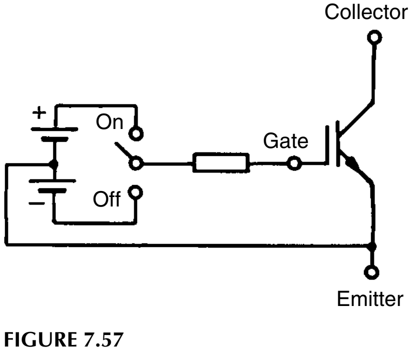


FIGURE 7.57
Insulated gate bipolar transistor (IGBT).

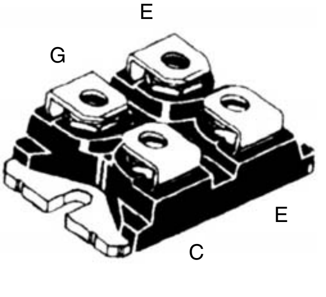


FIGURE 7.58
An IGBT IXDN75N120A produced by IXYS with a switched current up to 120 A, and maximum voltage of up to 1200 V (dissipated power is 630W). With such high parameters the device is quite small in size: 38 × 25 × 12 mm.

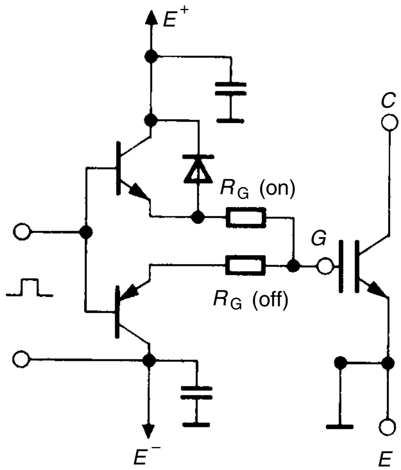


FIGURE 7.59
Model scheme of the IGBT control, providing pulses of opposite polarity on the gate required for reliable blocking and unblocking of the transistor.

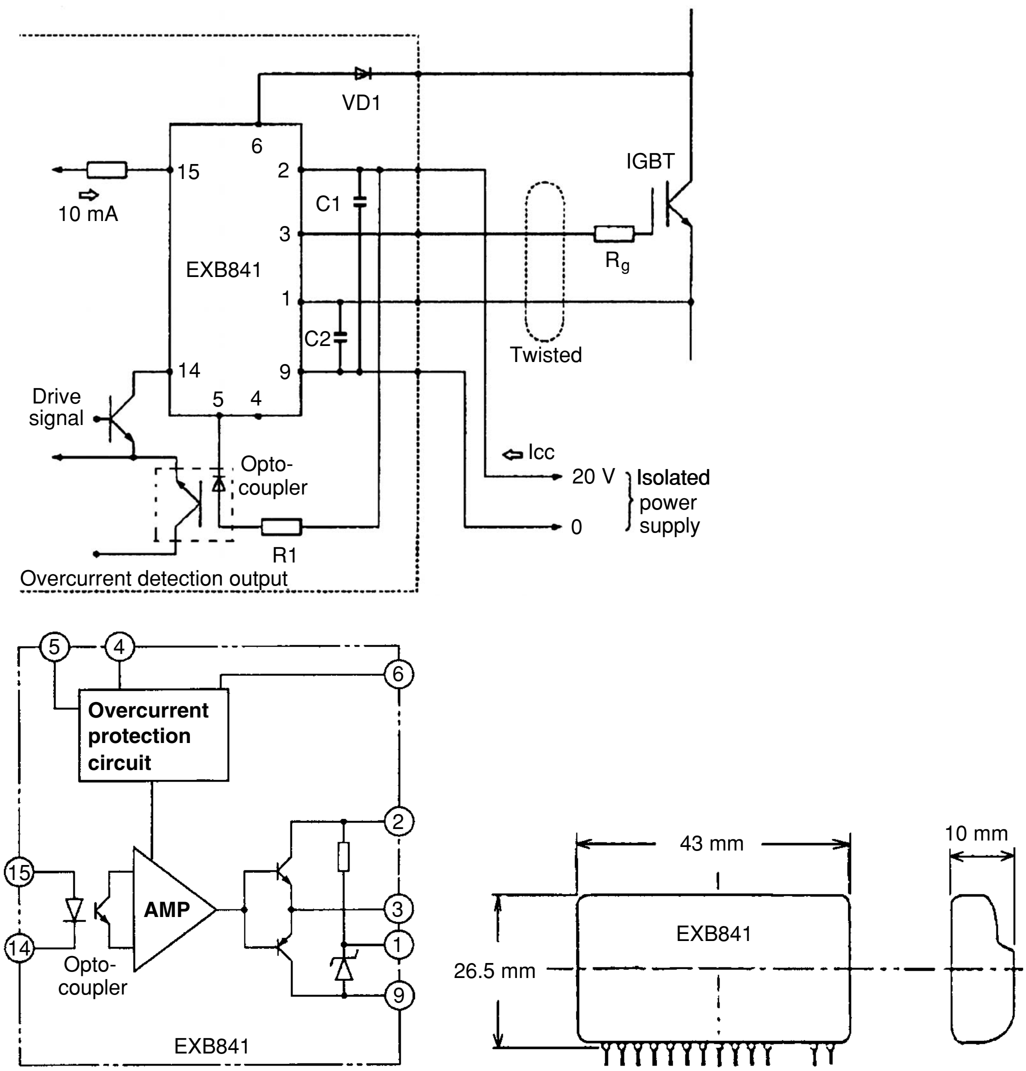


FIGURE 7.60
IGBT-driving hybrid integral circuit EXB841 type (Fuji Electric).

applied to any type of power IGBT. Apart from forming control signals of the required level and form, such devices often protect the IGBT from short circuits.

In spite of progress in IGBT development, different firms continue producing standard high-power bipolar transistors in capsule packages (Figure 7.50c). In power devices such transistors, equipped with big aluminum heat sinks and fans, are united to power blocks (Figure 7.61), which can weigh tens of kilograms. Heat sinks for such transistors are made in the form of two separate halves pulled together with special screw-bolts, with insulation covering between them, inside of which there is a transistor.

To provide a good thermal contact between the transistor and the heat sink the hold-down pressure must be strong enough, but must not exceed the threshold value of the transistor. Special torque spanners or spring disks with a scale are used (Figure 7.62). To increase switched current transistors are connected in parallel (Figure 7.63). Current grading through appliances connected in parallel is carried out with the help of low-value resistors cut in to a circuit of emitters of the transistors. When there is a great number of parallel connected transistors (Figure 7.63b), the total current of all base electrodes (control current) becomes commensurable with the working (collector) current, which is why in this case an additional transistor is used on the input side (Figure 7.63b).

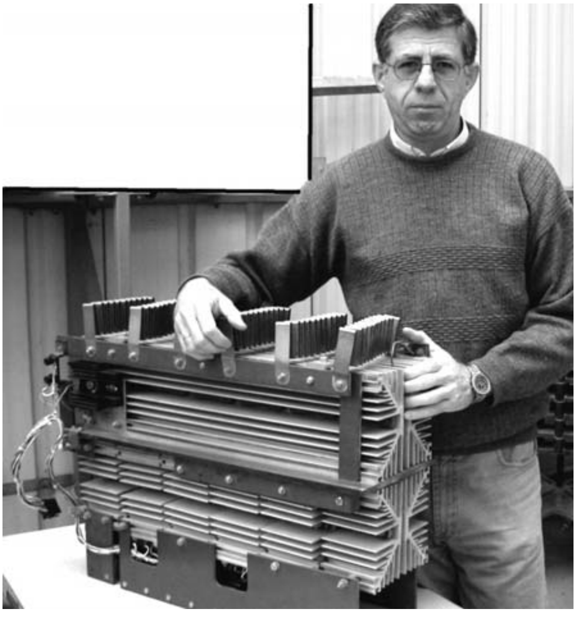


FIGURE 7.61
Unit of bipolar transistors in a capsule package equipped with aluminum heat sink.

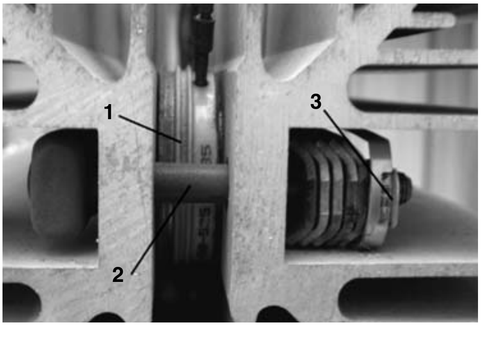


FIGURE 7.62
Attachment point of power wafer transistor in a heat sink. 1 — transistor; 2 — insulated screw bolt; 3 — torque measuring disk with a scale.

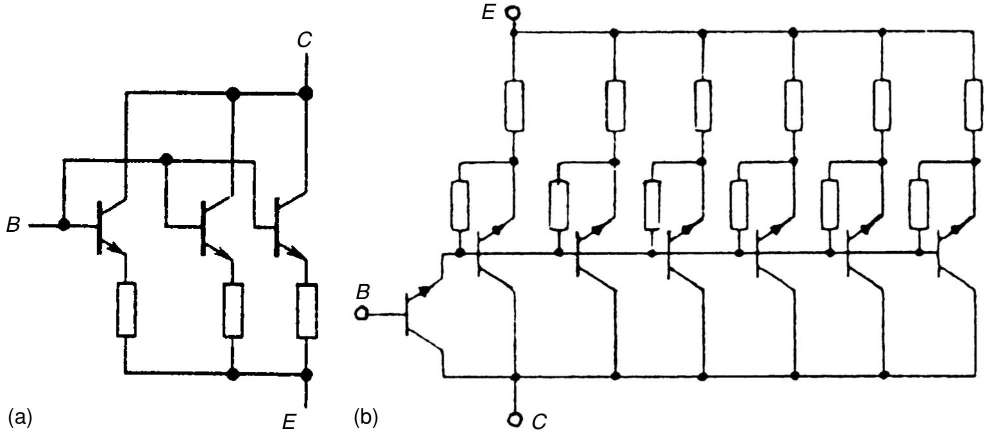


FIGURE 7.63
Parallel connection of bipolar transistors.

7.8.6 From Micromodules to Microchips

As engineering tends to develop in different, often opposite directions, micro-modular electronics, along with power transistor modules, also began to develop in the 1950–60's (Figure 7.64a). The first compact modules were produced from standard elements placed on printed circuit cards, assembled to a solid pack or a stack, and then from special elements including case-free transistors in the form of a ball 1 to 1.5 mm in diameter, with very thin outlets from golden wire.

Such micro-modules (so-called ''multi-chip circuit'') were mounted on small ceramic plates, with high packaging density (up to 30 elements per 1 s m^3) (Figure 7.64b). Some plates were linked with the help of welding or soldering. The ready micro-module was covered with epoxy resin. The use of this new (for that time) technology allowed miniaturization of feeble current equipment by almost 20 times.

In those days, electrical engineers were aware of the potential of digital electronics, however, they faced a big limitation known as the ''Tyranny of Numbers.'' This was the metaphor that described the exponentially increasing number of components required to design improved circuits, against the physical limitations derived from the number of components that could be assembled together. Both Jack St Clair Kilby (born in 1923) at Texas Instruments, and Robert Norton Noyce (1927–1990) at Fairchild Semiconductor were working independently on a solution to this problem during 1958 and 1959 (Figure 7.64c). The solution was found in the monolithic (meaning formed from a single crystal) integrated circuit (Figure 7.64d). Instead of designing smaller components, they found the way to fabricate entire networks of discrete components in a single sequence by laying them into a single crystal (chip) of semiconductor material. Kilby used germanium and Noyce used silicon.

Kilby wrote in a 1976 article titled ''Invention of the IC,''

> Further thought led me to the conclusion that semiconductors were all that were really required — that resistors and capacitors (passive devices), in particular, could be made from the same material as the active devices (transistors). I also realized that, since all of the components could be made of a single material, they could also be made *in situ* interconnected to form a complete circuit.

Two electrical engineers, working separately, each filed for patents for an invention. Texas Instruments filed for a patent in February 1959. Fairchild Semiconductor did the

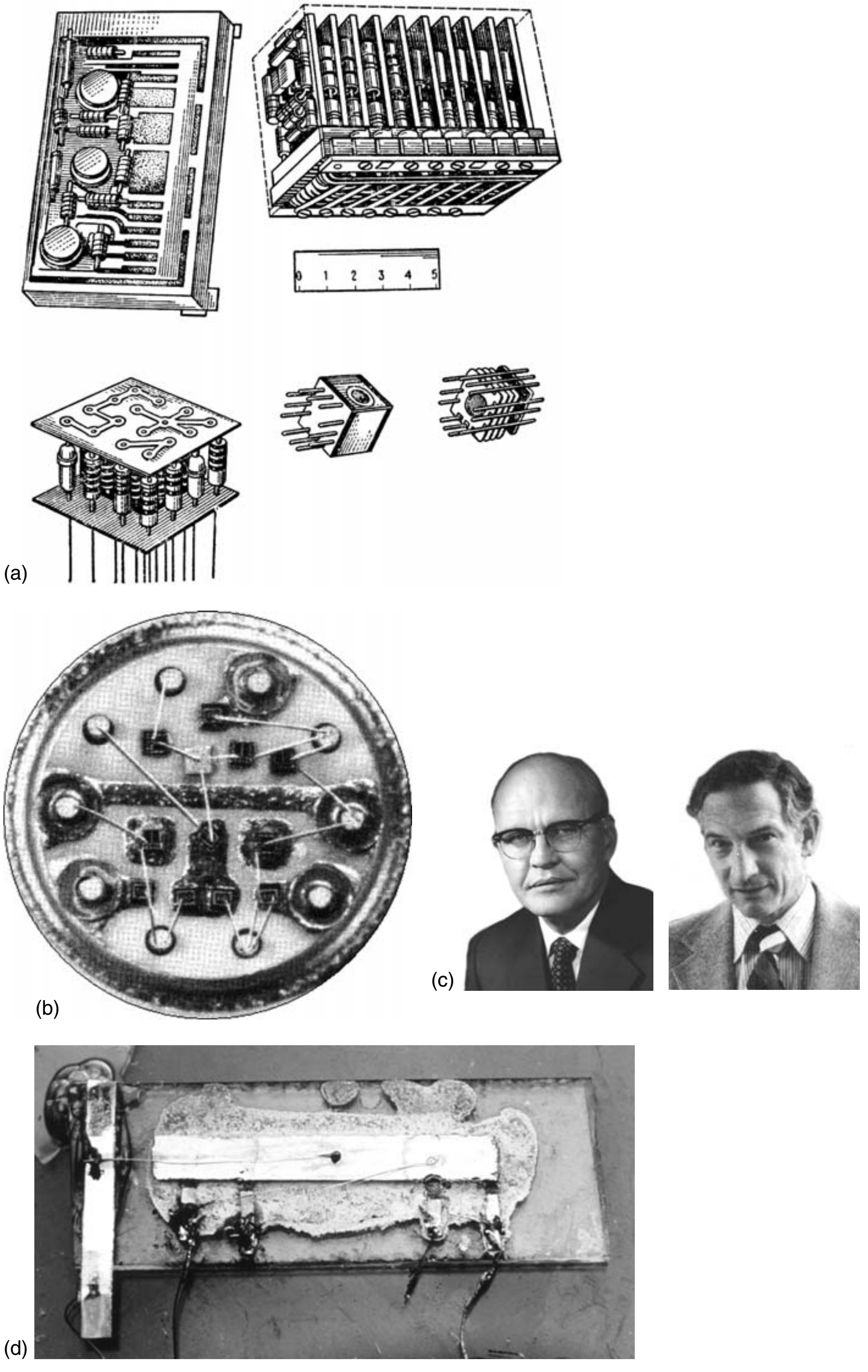


FIGURE 7.64
(a) Electronic micro-modules on discrete elements in the 1950–60's; (b) Multi-chip circuit placed on a standard transistor metal case. (c) Jack Kilby (left) and Robert Noyce (right) in 1958, the year they invented the world's first integral circuit IC. (d) The first Jack Kilby's 7/16 × 1/16-in. IC comprised of only a transistor, three resistors, and a capacitor on a slice of germanium. (From the Texas Instruments Website: www.ti.com)

same in July 1959. Naturally, both firms engaged in a legal battle that lasted through the decade of the 60s until they decided to cross-license their technologies. In the end, the patent No. 3,138,743 (''Miniaturized Electronic Circuits'') was issued to Jack S. Kilby and Texas Instruments in 1964, and the patent No. 2,981,877 (''Planar Integrated Circuit'') was granted to Robert Noyce.

Jack Kilby was named, along with three Russian scientists, as winners of the 2000 Nobel Prize in physics for their work in laying the foundations of information technology. Zhores Alferov and Herbert Kroemer of Russia, with Kilby from the U.S. share one half of the $1 million prize for work on developing semiconductors. Kilby, of Texas Instruments won the award for his part in the invention of the integrated circuit and as a co-inventor of the pocket calculator. The JK flip-flop (one of variants of bistable SR-multivibrator) is named after him, as is the The Kilby Center, TI's research center for

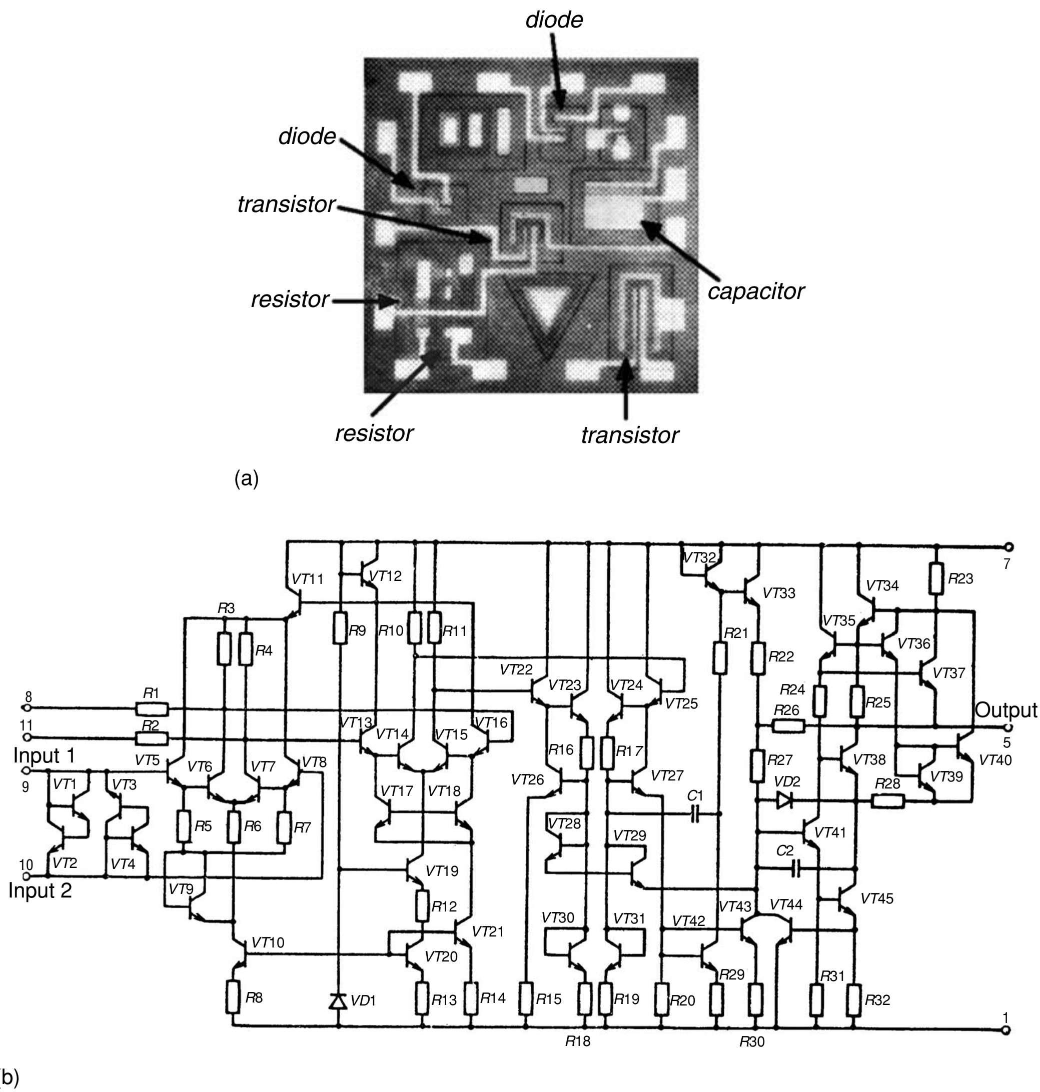
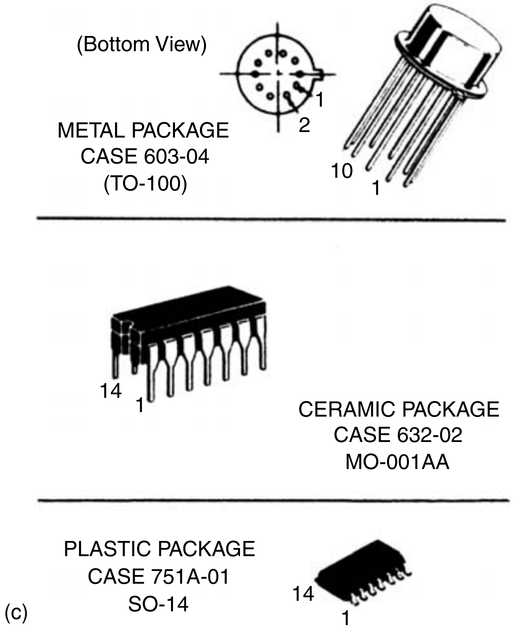


FIGURE 7.65
Electronic amplifier produced by integrated technology (45 transistors, 32 resistors, 2 capacitors, and a diode) and placed in the small case: structure fragment (a) and circuit diagram (b).

silicon manufacturing. Kilby officially retired from TI in the 1980s, but he has maintained a significant involvement with the company that continues to this day. In addition, he still consults, travels, and serves as a director on a few boards.

Kilby's and Noyce's inventions changed the world. They virtually created the modern computer industry — the basis of our future. During the 1970s the modern technology of integrated circuit production was developed. Packaging density was brought up to 2000 elements per 1 s m^3. Such devices (Figure 7.65) are made on the basis of an artificial crystal with the p–n junctions of transistors and diodes inside. Capacitors and resistors also form electron-hole junctions biased in a nonconducting direction.



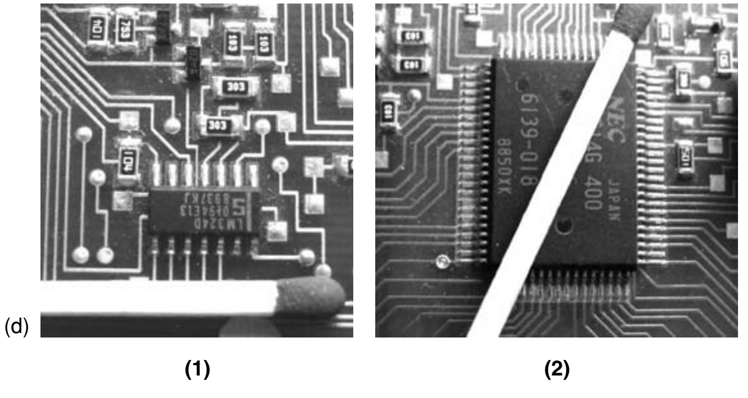


FIGURE 7.65 (*Continued*)
External design (c) of modern integrated circuits with 10 and 14 outlets for surface mounting on the printed circuit board and for ordinary montage. Fragments of the printed circuit (d) board with surface mounting, compared with a match of the standard size. (1) an integrated circuit LM3240; (2) an integrated circuit produced by NEC.

With the help of the same technology numerous variants of triggers (even several items in a case), logical elements, and other circuits with relay characteristics, are made. When a very weak signal is applied to the base of the transistor, a small current I_b begins to flow through the base circuit and is enabled, letting strong current I_c pass through the load. In this case it carries out another relay function — signal amplification.

7.8.7 Transistor Devices with Relay Characteristics

One of the often-used operation modes of a transistor is the switching (that is relay) mode; even a single transistor can work as a high-speed switch (Figure 7.66). For switching current from one circuit to another one, a two-transistor circuit (Figure 7.67) is used. In this circuit stable offset voltage is applied to the base of the transistor (T_2) and control voltage to base T_1.

When $u_{inp} = u_{offset}$, the currents and voltages in the arms of the circuit are the same. If the input voltage (u_{inp}) exceeds the offset voltage (u_{offset}), transistor T_2 is gradually blocked and the whole current flows only through transistor T_1 and load resistor R_{C1}, and vice versa. When input voltage decreases below the level of the offset voltage ($u_{inp} < u_{offset}$), transistor T_1 is blocked and T_2 is unblocked, switching the sole current to the circuit of the resistor $R_{C2.}$

As is known, contacts of several electromagnetic relays, connected with each other in a certain way, are widely used in automation systems for carrying out the simplest logical operations with electric signals (Figure 7.68). For example, the logical operation AND is implemented with the help of several contacts connected in series, switched to the load circuit (Figure 7.68a). The signal y will be the output of this circuit (that is the bulb will be alight) only if signals on the first input x_1 and on the second input x_2, operate simultaneously (that is when both contacts are closed). Another simple logical operation OR (Figure 7.68b), is implemented with the help of several contacts connected in parallel. In this circuit in order to obtain the signal y on output (that is for switching-on of the bulb), input of signal or on the first input (x_1), or on the second input (x_2), or on both of the inputs simultaneously, is required. Implementation of logical operations with electric circuits is one of the most important functions of relays. Transistor circuits successfully carry out this task. For example, the function NOT can be implemented on any type of single transistor (Figure 7.69).

In the circuit in Figure 7.69, when an input signal is missing, the transistor is blocked, that is the whole voltage of the power source E is applied between the emitter and the

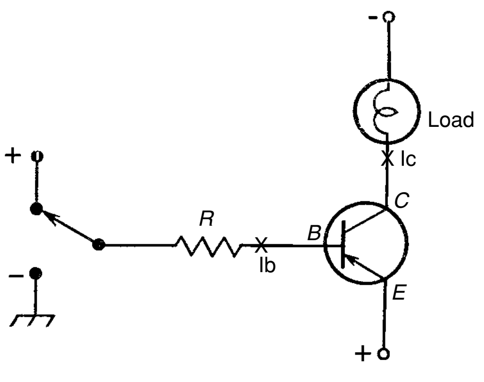


FIGURE 7.66
Electronic switch on a single transistor.

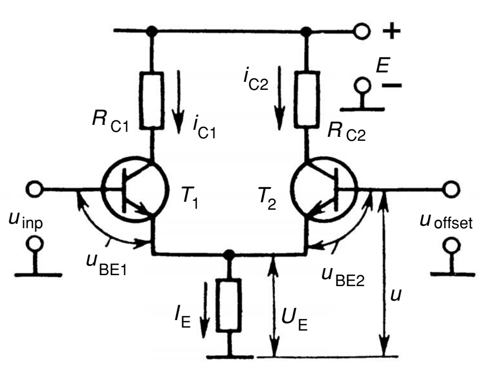


FIGURE 7.67
Transistor switch for two circuits.

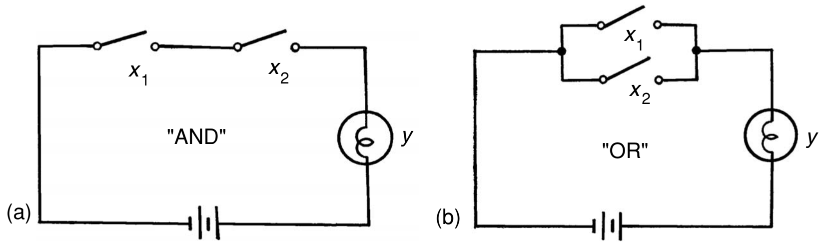


FIGURE 7.68
(a) and (b) Implementation of the simplest logical operations, with the help of electromagnetic relay contacts.

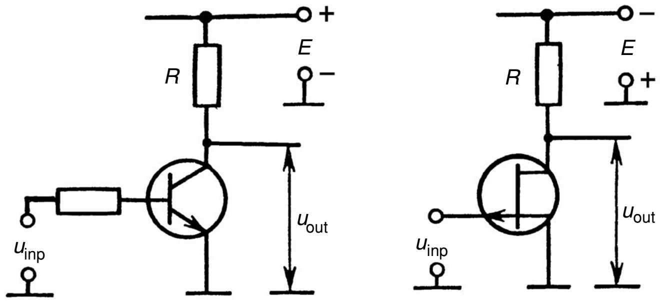


FIGURE 7.69
Logical element NOT implemented on a bipolar and field transistors.

collector (the drain and the source) of the transistor, and since the output signal is voltage on the collector (the source) of the transistor, that means that if there is no signal at the input, there will be a signal at the output of this circuit. And vice versa, when the signal is applied at the input, the transistor is unblocked and voltage drops to a very small value (fractions of a volt) and therefore the signal disappears at the output.

The logical element AND-NOT can be implemented by different circuit methods. In the simplest case, this is a circuit from transistors connected in series (Figure 7.70a). When control signals are applied to both inputs x_1 and x_2 simultaneously, both transistors will be enabled and the voltage drop in the circuit with two transistors connected in series will decrease to a very small value. This means no output signal Y. In the second circuit diagram (Figure 7.70b) even one signal on any input (x_1 or x_2) is enough for the voltage on output Y to disappear.

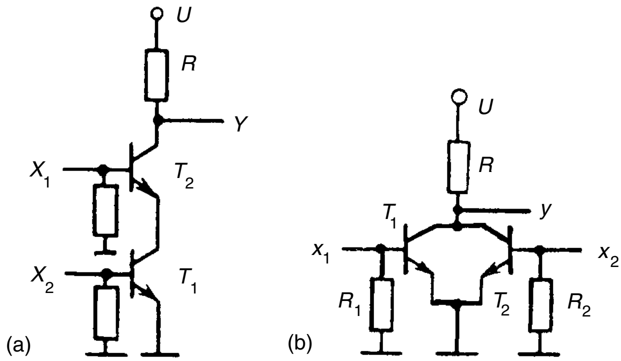


FIGURE 7.70
Transistor logical elements AND-NOT (a) and OR-NOT (b).

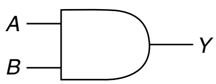
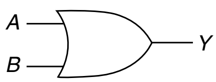
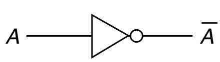
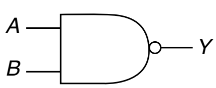
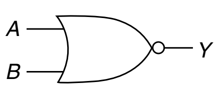
Self-contained logical elements are indicated on circuit diagrams as a special signs, Table 7.1. A signal strong enough for transition of a logical element from one state to another is usually marked as ''1.'' No signal (or a very weak signal incapable of affecting the system state) is usually marked as ''0.'' The same signs are used for indication of the state of the circuit elements: ''1'' — switched-on; ''0'' — switched-off. Such bi-stable (that is having two stable states) devices are called triggers.

When supply voltage is applied to such a device (Figure 7.71) one of the transistors will be immediately enabled and the other one will remain in a blocked state. The process is avalanche-like and is called regenerative. It is impossible to predict which transistor will be enabled because the circuit is absolutely symmetrical and the likelihood of unblocking of both transistors is the same.

This state of the device remains stable just the same. Repeated switching ON and OFF of voltage will cause the circuit to pass into this or that stable state. The essential disadvantage of such a trigger is no control circuit, which would enable us to control its

TABLE 7.1

Basic logical elements (according to certain standards logical elements are also indicated as rectangles)

Logical Function	Conventional Symbols	Boolean Identities	Truth Table: Inputs B	Inputs A	Output Y
AND		$A \bullet B = Y$	0	0	0
			0	1	0
			1	0	0
			1	1	1
OR		$A + B = Y$	0	0	0
			0	1	1
			1	0	1
			1	1	1
NOT		$A = \overline{A}$		0	1
				1	0
AND-NOT (NAND)		$\overline{A \bullet B} = Y$	0	0	1
			0	1	1
			1	0	1
			1	1	0
OR-NOT (NOR)		$\overline{A + B} = Y$	0	0	1
			0	1	0
			1	0	0
			1	1	0

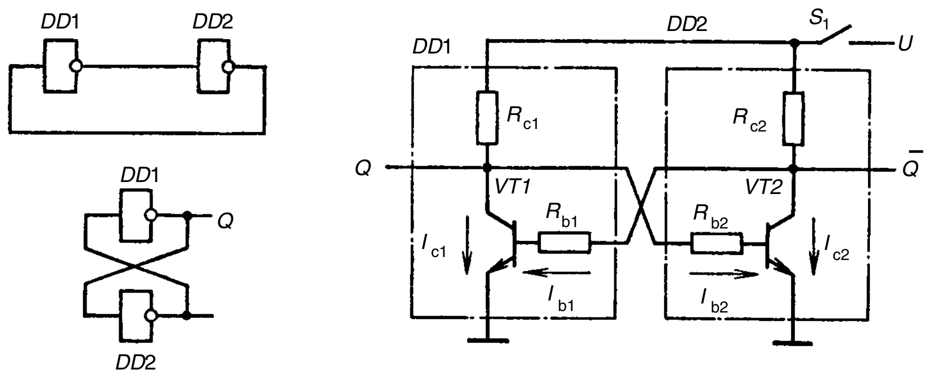


FIGURE 7.71
Bistable relay circuit with two logical elements NOT.

state at permanent supply voltage. In practice, the so-called Schmitt-Trigger are often used as electronic circuits with relay characteristics. There are a lot of variants of such triggers, possessing special qualities. In the simplest variant, such a trigger is a symmetrical structure formed by two logical elements connected in a cycle of the type AND-NOT or OR-NOT, (Figure 7.72); it is called an asynchronous RS-trigger.

One of the trigger outlets is named direct (any outlet can be named so as the circuit is symmetrical) and is marked by the letter *Q*, and the other one is called inverse and is marked by the letter $\bar{Q}$ (''Q'' under the dash), to signify that in logical sense, the signal at this output is opposite to the signal at the direct output. The trigger state is usually identified with the state of the direct output, that is to say that the trigger is in the single (that is switched-on) state when $Q = 1$, $\bar{Q} = 0$, and visa versa.

Trigger state transition has a lot of synonyms: ''switching,'' ''change-over,'' ''overthrow,'' ''recording,'' and is carried out with the help of control signals applied at the inputs *R* and *S*. The input by which the trigger is set up in the single state is called the *S* input (from ''set'') and the output by which the trigger turns back to the zero position — the *R* input (from ''reset''). Four combinations of signals are possible at the inputs, each of them corresponding to a certain trigger position (Table 7.2).

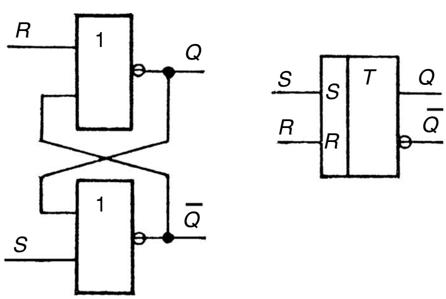


FIGURE 7.72
Asynchronous RS-trigger formed by two logical elements NOR.

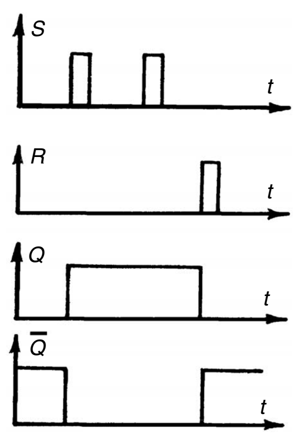


FIGURE 7.73
Time diagram of an asynchronous RS-trigger.

TABLE 7.2

Combinations of Signals at the Inputs and the RS-Trigger Position

Input			**Output for Logical Element Type**			
			AND-NOT		**OR-NOT**	
***S* (Set)**	***R* (Reset)**	**Notes**	***Q***	***Q***	***Q***	***Q***
0	0	Forbidden mode for *AND-NOT*	Uncertainty		Without changes	
1	**0**		**1**	**0**	**1**	**0**
0	**1**		**0**	**1**	**0**	**1**
1	1	Forbidden mode for *NOR*	Without changes		Uncertainty	

As can be seen from the table, when there are no signals on both of the trigger inputs on the elements AND-NOT, or when there are signals on both of the trigger inputs the elements OR-NOT (NOR), the trigger state will be indefinite which is why such combinations of signals are prohibited for RS-triggers.

From the time diagram of the asynchronous RS-trigger (Figure 7.73), it can be seen that after transfer of the trigger to the single state no repeated signals on the triggering input *S* are capable of changing its state. The return of the trigger to the initial position is possible only after a signal is applied to its ''erasing'' *R* input. The disadvantage of the asynchronous trigger is its incapacity to distinguish the useful signal of starting from noise occurring in the starting input by chance. Therefore, in practice so-called synchronous or D-triggers, distinguished by an additional so-called synchronizing input, are frequently used.

Switching of the synchronous trigger to the single state (ON) is carried only with a both signals: starting signal at the *S* input and also with a simultaneous signal on the synchronizing input. Synchronizing (timing) signals can be applied to the trigger (C input, Figure 7.74) with certain frequencies from an external generator.

Apart from increase of resistance to noises, synchronization provides time registration of signals and unites the operation of many units of the equipment. Different types of triggers are produced by many forms; in standard cases in the form of integrated circuits (Figure 7.75).

Simple relay devices are constructed also on the basis of so-called operational amplifiers (OA). OA are complex many-stage transistor circuits (see Figure 7.65b, for example) with a very high coefficient of amplification made by the integrated technology in

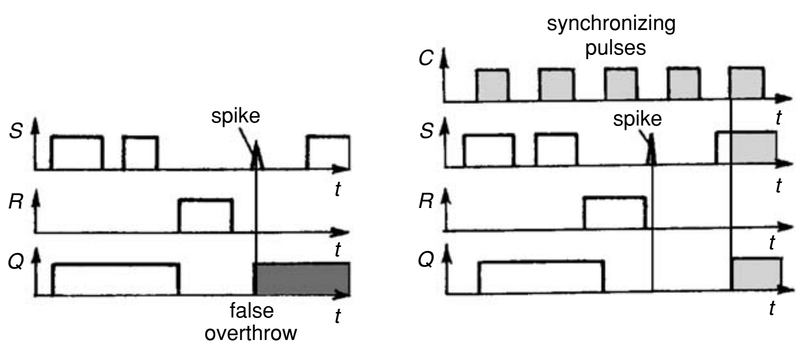


FIGURE 7.74

Time diagrams of operation of an asynchronous trigger (left) and synchronous trigger (right) when there is noise.

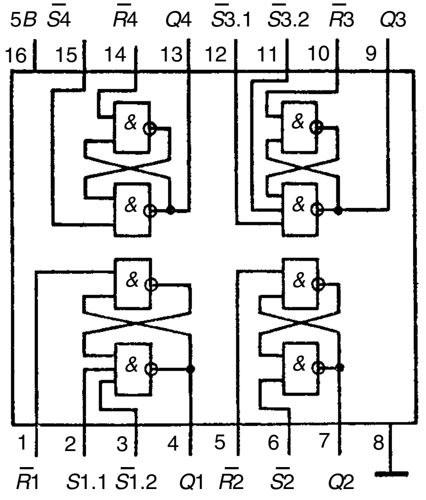


FIGURE 7.75
Structure of an integrated circuit of the 74LS279 type, containing four RS-triggers on logical elements AND-NOT.

standard cases of chips. When they are used directly for that purpose (as amplifier), that is for signal amplification, such OA are supplied, as a rule, with negative feedback (a signal from the output of the amplifier is applied to the input but with the opposite polarity), which slightly reduces amplification but increases operational stability and the quality of amplification considerably (Figure 7.76).

It should be noted that "+" and "−" on the scheme indicate the direct and inverse inputs of the amplifier, and not the polarity of the supply (supply circuits of OA are usually not indicated in order not to complicate the scheme). If an OA is supplied with positive feedback instead of negative (Figure 7.77), such an amplifier will start to work as a trigger (or a relay), being energized when input voltage exceeds a certain level, and turning to the initial position when the level of the input signal decreases.

It is very convenient to use a miniature OA as electronic relay, but not obligatory. A simple amplifier with two transistors, with positive feedback, also has similar properties (Figure 7.78). In initial position, when there is no voltage (or when voltage is very low) at the input of the circuit, transistor VT1 is closed (locked up). There is voltage on VT1 collector, which opening transistor VT2. The emitter current of transistor VT2 causes a voltage drop on the resistor R3, which blocks transistor VT1 and holds it in closed position. If input voltage exceeds the voltage in the emitter on VT1 transistor, it will be opened and will become saturated with very small collector–emitter junction resistance. As a result, the

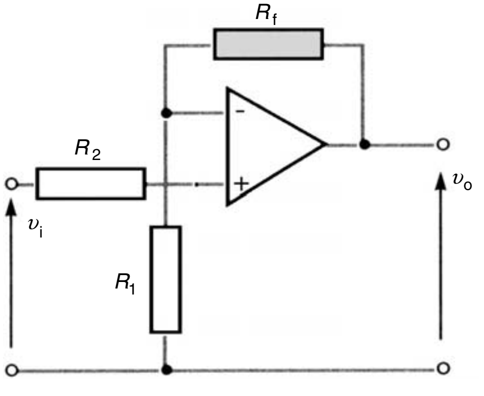


FIGURE 7.76
Operational amplifier with negative feedback carried out through a resistor R_f. v_i — input signal; v_o — output signal.

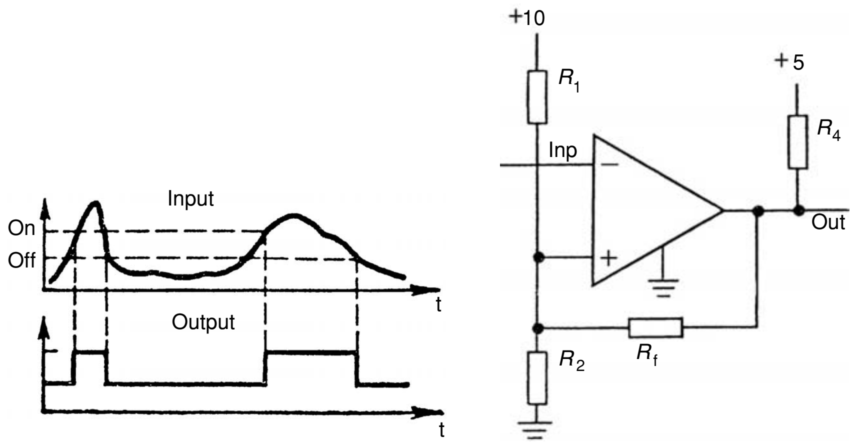


FIGURE 7.77
Operation amplifier with positive feedback working as a trigger.

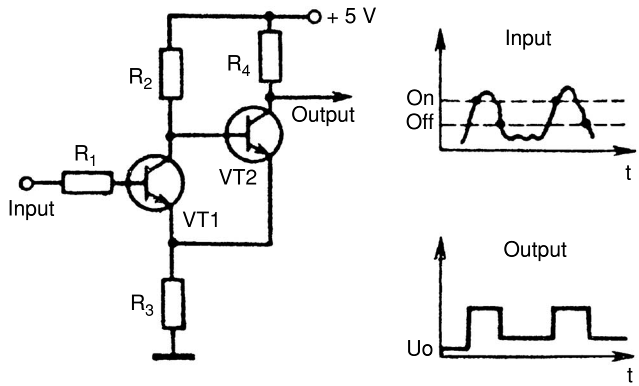


FIGURE 7.78
A simple two-transistor trigger.

potentials of the base and the emitter of transistor VT2 will be equal. Transistor VT2 will be blocked. At the output there will be voltage equal to the supply voltage. When input voltage decreases, transistor VT1 leaves the saturation mode, and an avalanche-like process occurs. Emitter current of transistor VT2, causing blocking voltage on resistor R_3, accelerates closing of the transistor VT1. As a result, the trigger returns to its initial position.

7.8.8 Thyristors

The history of development of another remarkable semiconductor device with relay characteristics begins with the conception of a ''collector with a trap,'' formulated at the beginning of 1950s by William Shockley, familiar to us from his research on p–n junctions. Following Shockley, J. Ebers invented the two-transistor analogy (inter-bounded n–p–n and p–n–p transistors) of a p–n–p–n switch, which became the model of such a device (Figure 7.79).

In 1954–1955 John Moll estimated the performance capabilities of a p–n–p–n switch and a group of scientists from ''Bell Telephone Laboratories'' under his direction constructed the first working silicon p–n–p–n devices. The work of this group and the principles of operation of such devices were described in 1956 by Moll, Tanenbaum, Goldey and

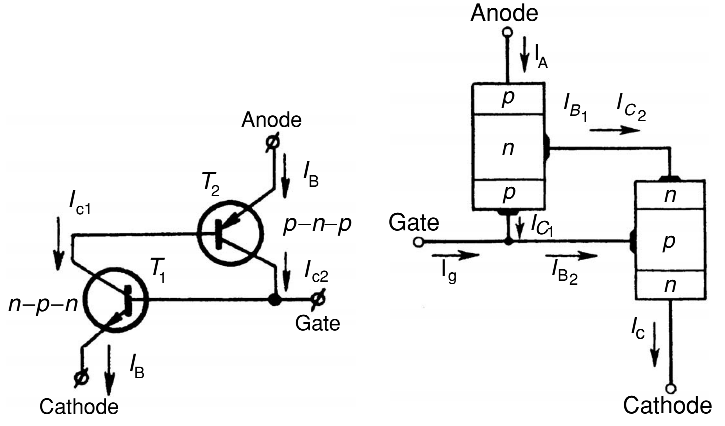


FIGURE 7.79
Two-transistor model of a thyristor.

Holonyak, in a scientific article which became the basis for further research carried out in this field.

The p–n–p–n switch had a destiny similar to some other devices in 1956–1957: not many people understood the principles of its operation and in practice it was not used very much, but R.A. Iork (from the General Electric Co.) realized the importance of the researched carried out in Bell Laboratories, became interested in the semiconducting "thyratron," and initiated a successful project of production of a silicon switch for strong currents (Figure 7.80).

The working element of this new semiconductor device with relay characteristics was a four-layer silicon crystal with alternating p- and n-layers (Figure 7.80). Such a structure is made by diffusion into the original monocrystal of n_1-silicon (which is a disk 20 to 45 mm in diameter and 0.4 to 0.8 mm thick, or more for high-voltage devices) admixture atoms of

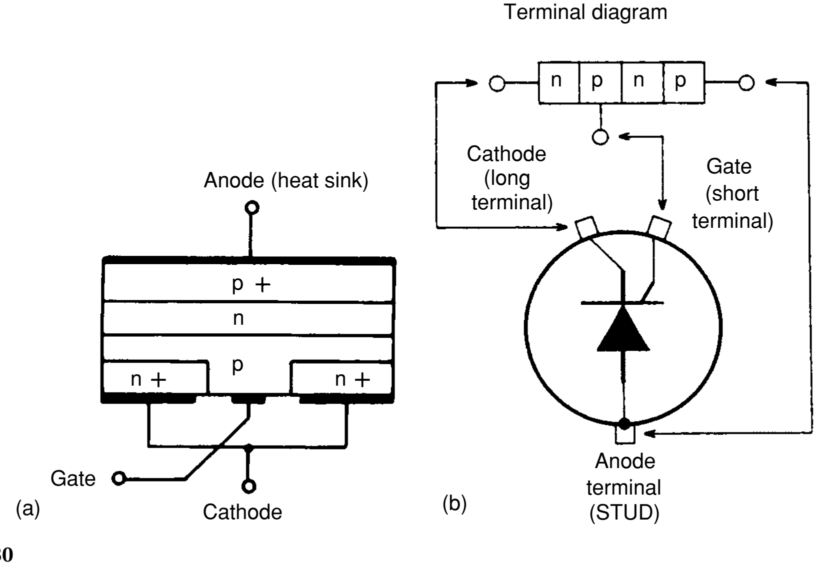


FIGURE 7.80
(a) and (b) Structure and symbolic notation of a semiconducting thyratron — "thyristor."

aluminum and boron from the direction of its two bases to a depth of about 50 to 80 μm. Injected admixtures form p_1 and p_2 layers in the structure.

The fourth (thinner) layer n_2 (its thickness is about 10 to 15 μm) is formed by further diffusion of atoms of phosphorus to the layer p_2. The upper layer p_1 is used as an anode in the thyristor, and the lower layer p_2 — as a cathode. The power circuit is connected to the main electrodes of the thyristor: the anode and the cathode. The positive terminal of the control circuit is connected through the external electrode to layer p_2, and the negative one — to the cathode terminal.

The volt–ampere characteristic (VAC) of a device with such a structure (Figure 7.81), much resembles the VAC of a diode by form. As in a diode, the VAC of a thyristor has forward and reverse areas. Like a diode, the thyristor is blocked when reverse voltage is applied to it (minus on the anode, plus on the cathode) and when the maximum permissible level of voltage ($U_{R\max}$) is exceeded there is a breakdown, causing strong current and irreversible destruction of the structure of the device.

The forward area of the VAC of the thyristor does not remain permanent, as does that of a diode, and can change, being affected by current of the control electrode, called the "Gate." When there is no current in the circuit of this electrode, the thyristor remains blocked not only in reverse but also in the forward direction, that is, it does not conduct current at all (except small leakage current, of course). When the voltage applied in the forward direction between the anode and the cathode is increased to a certain value, the thyristor is quickly (stepwise) enabled and only a small voltage drop (fractions of a volt) caused by irregularity of the crystal structure remains on it.

If low current is applied to the circuit of the gate, the thyristor will be switched ON to much lower voltage between the anode and the cathode. The more such current, the lower the voltage that is required for unblocking of the thyristor. At a certain current value (from a few milli-amperes for low-power thyristors up to hundreds of milli-amperes for power ones) the forward branch of the VAC is almost fully rectified and becomes similar

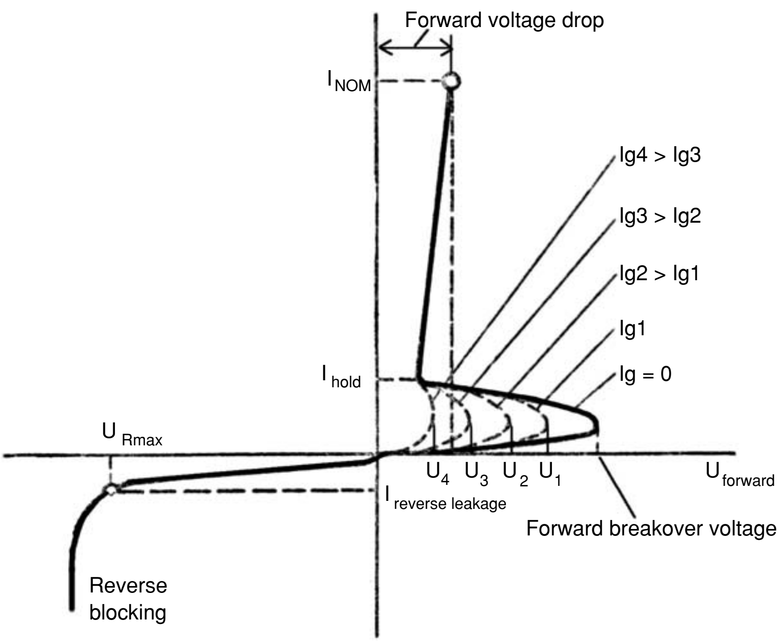


FIGURE 7.81
Volt–ampere characteristic (VAC) of a thyristor.

to the VAC of a diode. In this mode (that is, when control current constantly flows in the gate circuit) the behavior of the thyristor is similar to that of a diode that is fully enabled in the forward direction and fully blocked in the reverse direction. However, it is senseless to use thyristors in this mode: there are simpler and cheaper diodes for this purpose.

In fact, thyristors are used in mode when working voltage applied between the anode and the cathode does not exceed 50 to 70% of the voltage, causing spontaneous switching ON of the thyristor (when there is no control signal, the thyristor always remains blocked) and control current is applied to the gate circuit only when the thyristor should be unblocked and of such a value that would enable reliable unblocking. In this mode, the thyristor functions as a very high-speed relay (unblocking time is a few or tens of microseconds).

Perhaps many have heard that thyristors are used as basic elements for smooth current and voltage adjusting, but if a thyristor is only an electric relay having two stable states like any other relay: a switched ON state and a switched OFF one, how can a thyristor smoothly adjust voltage? The point is that if nonconstant alternating sinusoidal voltage is applied, it is possible to adjust unblocking moment of the thyristor by changing the moment of applying a pulse of control current on the gate with regard to the phase of the applied forward sinusoidal voltage. That is, it is as though a part of the sinusoidal current flowing to the load were cut off (Figure 7.82). The moment of applying a pulse of unblocking control current (such pulses are also called ''igniting'' by analogy with the control pulses of the thyratron) is usually characterized by the angle α.

Taking into account that average current value in the load is defined as an integral (that is the area of the rest part of the sinusoid) the principle of operation of a thyristor regulator becomes clear. After unblocking, the thyristor remains in the opened state, even after completion of the control current pulse. It can be switched OFF only by reducing forward current in the anode–cathode circuit to the value less than hold current value. In AC circuits the condition for thyristor blocking is created automatically when the sinusoid crosses the zero value. To unblock the thyristor in the second half-wave of the voltage it is necessary to apply a short control pulse through the gate of the thyristor. To control both half-waves of alternating current two thyristors connected antiparallel are used. Then one of them works on the positive half-wave and the other one — on the negative one.

At present such devices are produced for currents of a few milli-amperes to a few thousands amperes, and for blocking voltages up to a few thousands volts. The first industrial examples of power and high-power thyristors produced in different countries had the so-called ''pin-like'' (stud and flat base types) construction (Figure 7.83). As it can

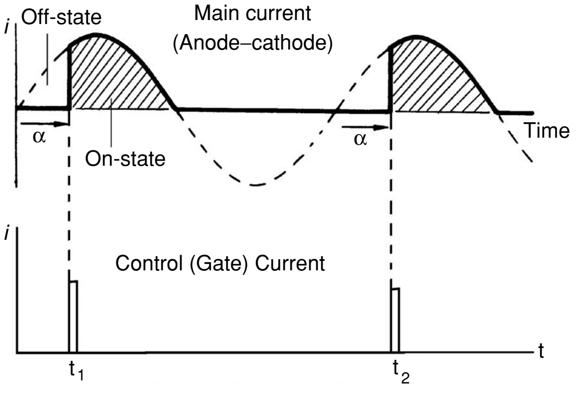


FIGURE 7.82
Principle of operation of a thyristor regulator.

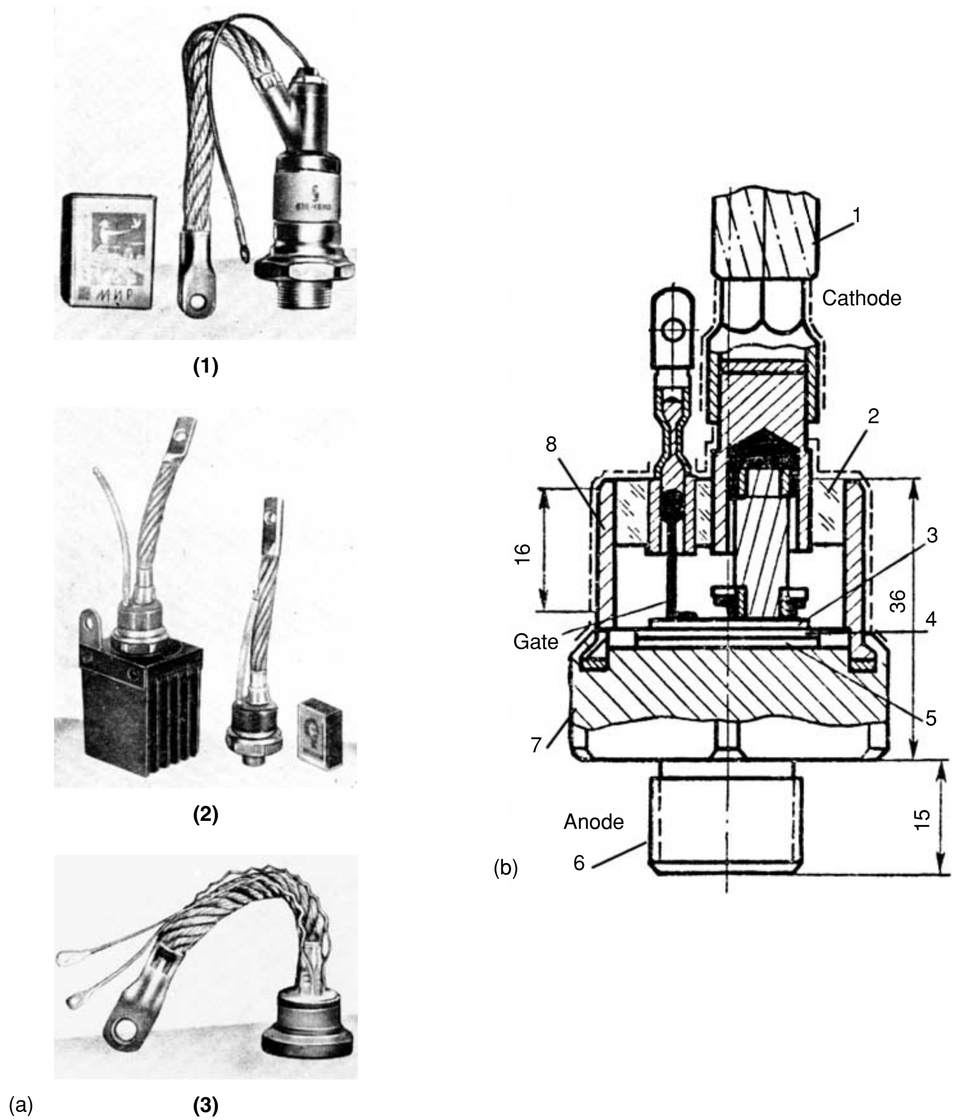


FIGURE 7.83
(a) Industrial samples of the first pin-like (1, 2 — stud; 3 — flat base) thyristors for currents up to 100–150 A, produced in 1960s. 1 — Bst L02 (Siemens); 2 — BTY-16 (AEG); 3 — BKY-100 (Russia). (b) Construction of power stud type thyristor. 1 — multiple-strand flexible copper braid with a point at the end; 2 — glass or ceramic insulator; 3 — layer n_2 of the semiconductor structure; 4 — silicon monocrystal (layer n_2); 5 — layer p_1 of the semiconductor structure; 6 — anode outlet made in the form of a screw-bolt; 7 — copper heel piece; 8 — steel cylindrical case.

be seen from the VAC, a certain voltage drop takes place even on a fully open thyristor because of imperfections in its crystal structure. This voltage is very small in comparison with working voltage. It totals only fractions of a volt; however, when strong working currents pass through the thyristor, such a voltage drop may lead to considerable power dissipation of the thyristor. For example, with voltage on an open thyristor of 1.5 V and current of 200 A, thermal power equal to 300 W is constantly being released. This is very high power and if certain measures for cooling the thyristor are not taken, its temperature will quickly exceed 150 to 160 °C and voltage will cause a breakdown of the crystal structure.

That is why all high power thyristors are always equipped with heat sinks. These are big ribbed constructions from aluminum alloy for air cooling or more compact for water cooling (Figure 7.84). Another problem with heating of thyristors was destruction of the joint points of the silicon crystal with a copper heelpiece and a cathode outlet, which were made with the help of standard tin solder. In the first power thyristors, already after several tens of thousands of switched OFF and ON cycles (when the thyristor was heated up to 100 to 120 °C and then to be cooled up to 20 to 30 °C) there was cracking of solder caused by the difference of linear expansion coefficients of the various materials.

Later on, they managed to cope with this disadvantage by introducing special temperature compensators and using pressure contacts instead of soldered ones (Figure 7.85).

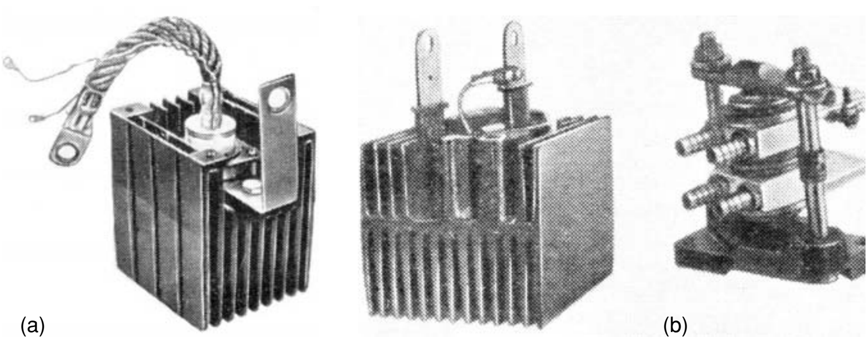


FIGURE 7.84
Air (a) and water (b) heat sinks for thyristors.

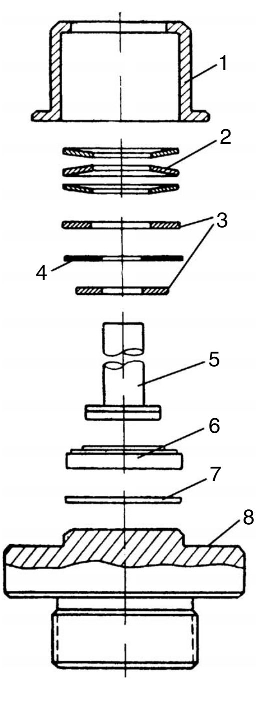


FIGURE 7.85
Construction of a stud-like thyristor with pressure contacts and a temperature compensator. 1 — pressure cup; 2 — disk spring; 3 — metal disk; 4 — mica disk; 5 — contact stamp with a temperature compensating plate; 6 — semiconductor crystal structure on a temperature compensating plate; 7 — silver contact spacer; 8 — copper piece heel of the case.

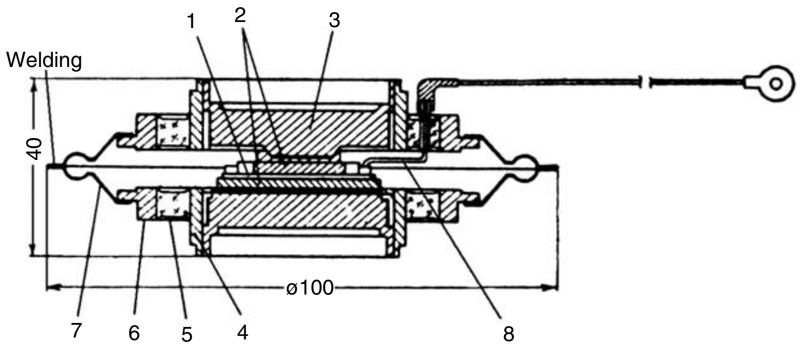


FIGURE 7.86
Earlier construction of a capsule type thyristor with pressure contacts. 1 — semiconductor crystal structure; 2 — pressure tungsten disks; 3 — copper contact elements (anode and cathode); 4 and 6 — metal rings; 5 — glass insulator; 7 — spring goffered disk; 8 — gate.

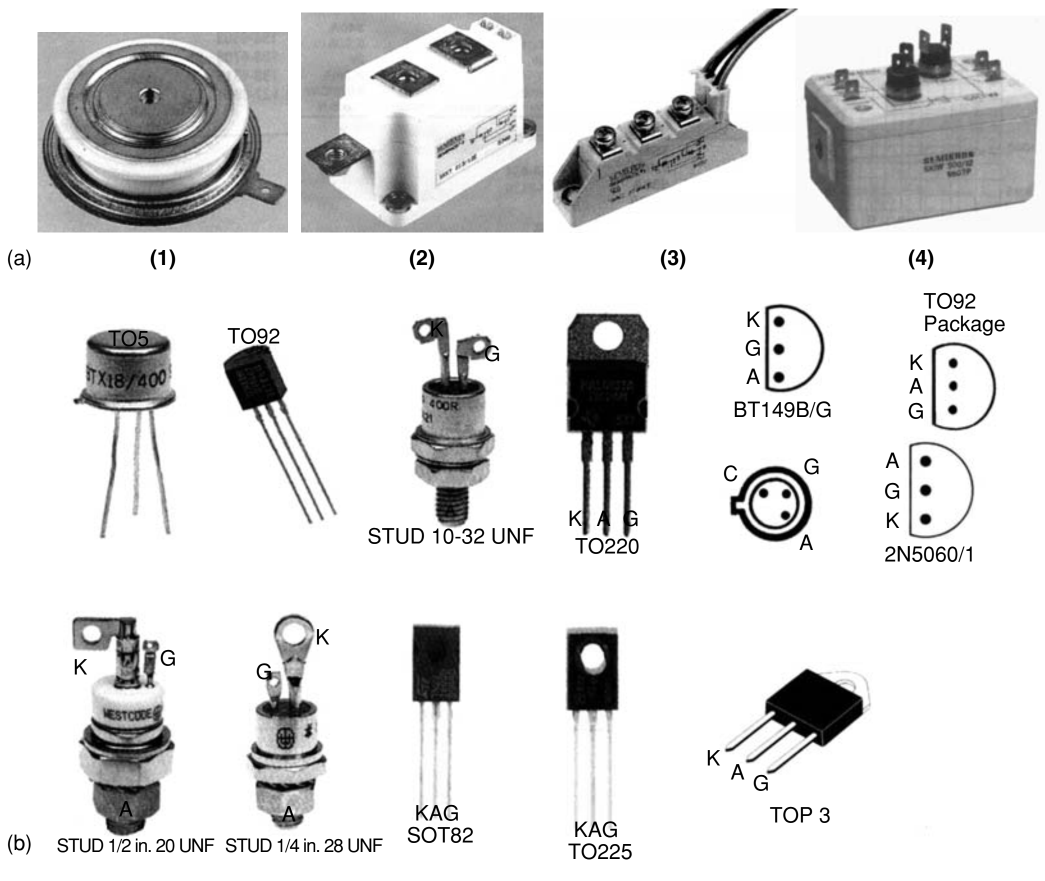


FIGURE 7.87
(a) Modern high-power thyristors. 1 — single thyristor; 2 and 3 — dual thyristor module with common anode or common cathode; 4 — high current (900 A) antiparallel thyristors with isolated (via aluminum oxide — AlO_2) water flow. (b) Modern low power and power thyristors.

Later, it turned out that it is more convenient to produce and exploit tablet construction (called capsule types) in the form of a disk, as in the construction of pressure contacts (Figure 7.86). When such constructions began to be produced, high-power pin-like thyristors were almost entirely forced out of production. The stud-like construction remained only for low power and power thyristors (for currents up to a few tens of amperes).

Modern thyristors have a distinguishing diversity of forms and sizes (Figure 7.87). Current progress in solid-state physics and new technological advances in semiconductor production have allowed development of mass production of thyristors with characteristics that the inventors of thyristors could not even imagine (Figure 7.88 and Figure 7.89).

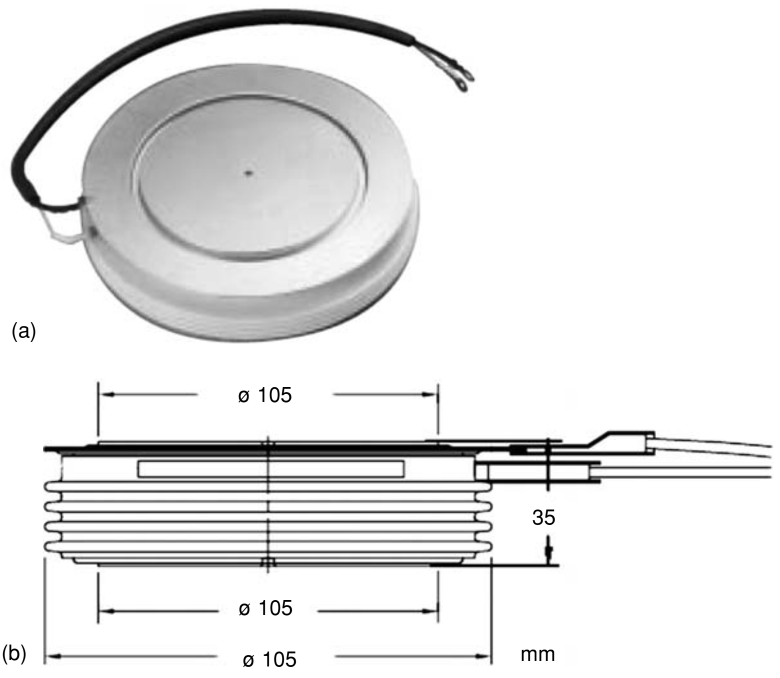


FIGURE 7.88
Ultra high-voltage thyristor FT1500AU-240 type (12 kv; 1500 A) produced by Powerex and Mitsubishi Electric.

FIGURE 7.89
Commercial thyristor of the SF3000GX21 type (Toshiba) with switched current up to 3000 A (surge current is 60.000 A) and switched voltage up to 4000 V. (From Toshiba Commercial Thyrstor online catalog 2004.)