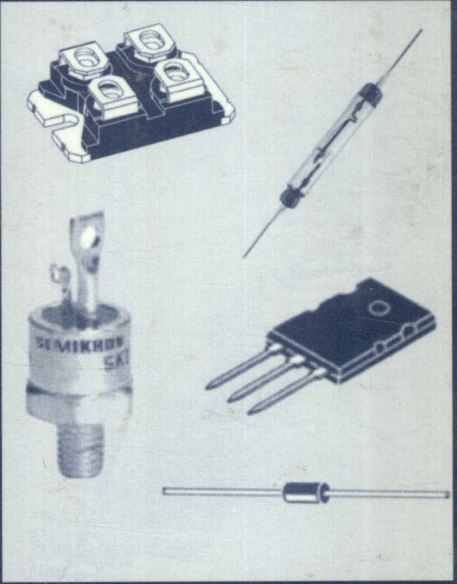
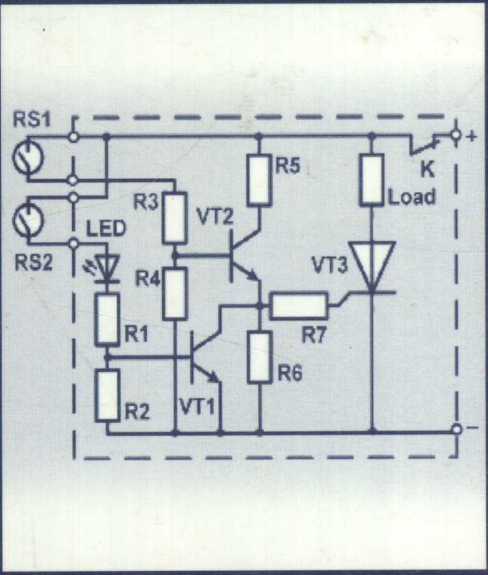
Electronic Devices on Discrete Components





for Industrial and Power Engineering

Vladimir Gurevich

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Preface

Integral microchips and microprocessors have come into our lives so swiftly and completely that sometimes it seems that modern equipment simply cannot exist without them, which is true. However, dependence of modern equipment on microelectronics and microprocessors does not mean that there are no problems in this area. The integrity of many functions distributed earlier among separate devices of a complex system in a single microprocessor leads to the reduction of system reliability because damage to the microprocessor or to any number of peripheral elements serving the microprocessor leads to failure of the whole system but not of its separate functions as it was in pre-microprocessor time. Added to this is the extra sensitivity of microelectronic and microprocessor-based equipment to electromagnetic interferences (EMI) and the possibility of intentional remote actions breaking the normal operation of the microprocessor-based devices (electromagnetic weapons, electromagnetic terrorism). Intensive investigations into the electromagnetic weapons field are being carried out in Russia, the U.S., England, Germany, China, and India. Many world-leading companies work intensively in this sphere creating new devices of these weapon systems functioning at a distance of several dozens of meters to several kilometers, which while specialized in their use are still available to everybody (as they are freely sold on the market).

The need for specialized power supplies of microprocessors, different types of memory, special input and output circuits, special software – in short, all of the above-mentioned – has led to the situation where documentation and manufacturing of automation devices has become available only to serious companies having all the necessary resources for this. Development tendencies of this area of technique make it more and more unavailable to individual engineers and technicians wishing to apply their knowledge and ingenuity to improve production or technological processes to their companies. At the same time, lately in the market a number of new types of small-size, discrete electronic components with previously inaccessible parameters appeared. They are miniature transistors meant for currents of dozens of amperes and voltages of 1200 – 1600 V; miniature vacuum reed switches with operational speeds of milliseconds capable of sustaining voltages of 1,000 – 2,000 V; and other no less interesting elements. These new discrete components serve as the basis for creating industrial automation and control devices that are fed directly from networks of 220 – 250 V and work directly with input and output signals of the same voltage level. Hybrid devices combining advantages of semiconductor (transistors, thyristors) and electromechanical (reed switches) elements are of particular interest.

This book is concerned with the description of different functional units and automation devices for industry and electric power engineering implemented by modern discrete electronic elements without using microelectronics and microprocessor-based technologies. The devices described in this book turn out to be much simpler and cheaper; they may be produced not only by large companies, but even by independent amateurs. This book presents for the readers' judgment dozens of unusual but very simple realizable devices, which may be easily created by any engineer or technician wishing to improve automation systems. Some of the technical decisions presented by the author may serve as the basis for the creation of new types of devices of relay protection and automation free from disadvantages of complex microelectronic systems.

The book consists of seven chapters and appendices containing reference data. The first three chapters are devoted to the theory and operating principles of modern discrete components designed for automation devices: transistors, thyristors, dinistors, reed switches, and high-voltage reed switch relays. The fourth chapter describes dozens of different functional modules of automation systems incorporating discrete elements with direct supply from 220 – 250 V networks: switching devices, generators and multivibrators, timers, logic elements, elements sensitive to overcurrents and overvoltages, voltage regulators and stabilizers, pulse expanders, etc. The fifth, sixth, and seventh chapters are devoted to the description of concrete examples of automation devices for industry and electric power engineering based on discrete electronic components and also hybrid ones: semiconductors and reed switches.

The book makes a smooth transition from theory and the properties of modern electronic elements by means of examination of operating principles and examples of realization of separate functional units of automation devices to the description of concrete examples of those that are finished and ready for use. The author thinks that this approach to the material will make it possible for the readers not only to repeat the constructions that are described, but to understand and master the general principles of automation devices on discrete elements and to apply them in the future for creation of new necessary constructions. As an aid to complete understanding, voluminous reference material has been included containing information about the most modern components specially selected by the author and classified in the appendices.

Author

Vladimir Gurevich was born in Kharkov, Ukraine, in 1956. He received an M.S.E.E. degree (1978) at the Kharkov Technical University, named after P. Vasilenko, and a Ph.D. degree (1986) at Kharkov National Polytechnic University. His employment experience includes: teacher, assistant professor and associate professor at Kharkov Technical University, and chief engineer and director of Inventor, Ltd. In 1994, he arrived in Israel and works today at Israel Electric Corp. as a specialist of the Central Electric Laboratory. He is the author of more than 140 professional papers and 4 books and holder of nearly 120 patents in the field of electrical engineering and power electronics. In 2006 he was Honorable Professor with the Kharkov Technical University, and since 2007 he has served as an expert with the TC-94 Committee of International Electrotechnical Commission.

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Solid-State Electronic Elements

1.1 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} Ohm·cm, dielectrics with a resistance of 10^{9}-10^{20} Ohm·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 in size 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 that 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's 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 non-metal 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 this 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" to 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, etc. 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.

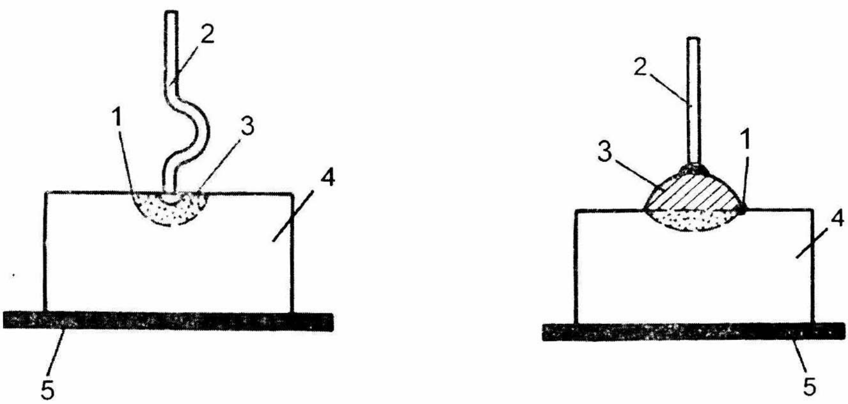
Semiconductors with electro-conductivity enhanced, due to an excess of free electrons caused by admixture injection, are called semiconductors with *electron-conductivity* or in short, *n-type semiconductors.* Semiconductors with electro-conductivity influenced mostly by moving of holes are called *semiconductors 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 Fig. 1.1. 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.



a) b)

FIGURE 1.1 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.

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 Fig.1.1a).

Each part of semiconductor material, taken separately (that is before contacting), was neutral, since there was a balance of free and bound charges (Fig. 1.2a). 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, with a high concentration of them, diffuse to the n-type area, where there are few of them (Fig. 1.2b).

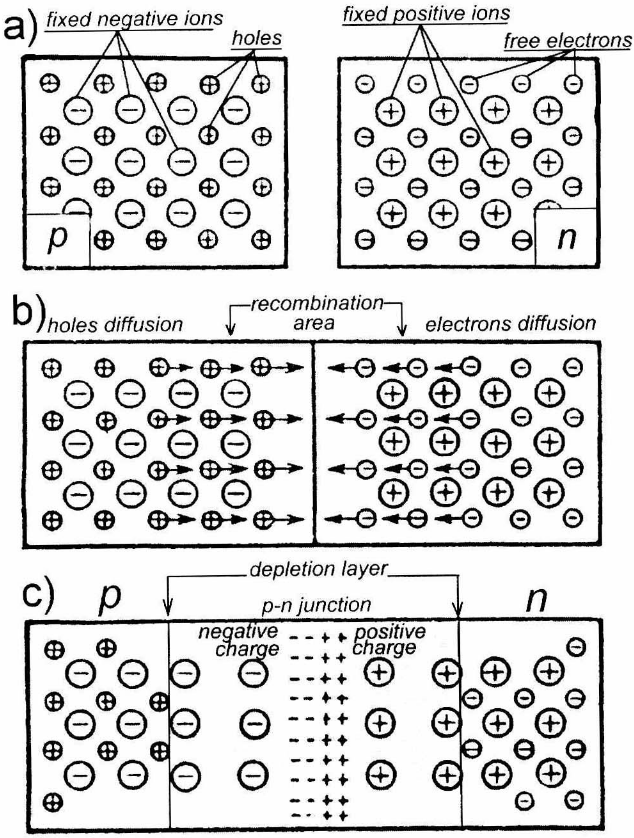


FIGURE 1.2 Formation of a blocking layer when semiconductors of different conductivity are connected.

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 (Fig. 1.2c).

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 (Fig. 1.3).

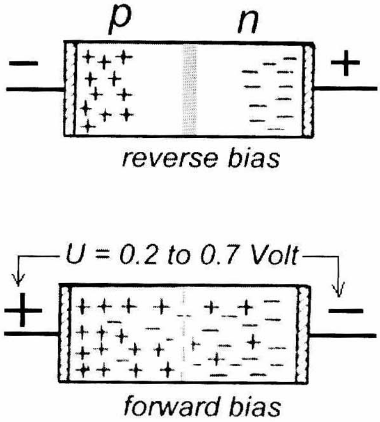


FIGURE 1.3 *p-n-* junction with reverse and forward bias.

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 bias.* 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 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 0.2V for germanium diodes, and 0.6-0.7V 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.

Fig. 1.4 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 direction (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 do not work properly with high frequency currents.

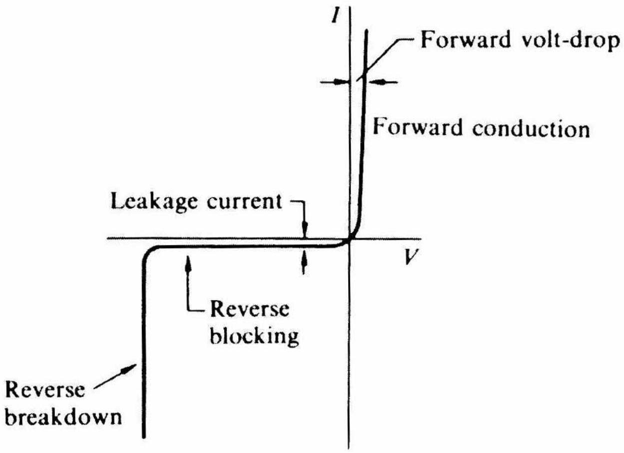


FIGURE 1.4 Volt-ampere characteristic of a single p-n junction (diode).

1.2 THE TRANSISTOR'S PRINCIPLE

The idea of somehow using semiconductors had been tossed about before World War II, but 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. They called it 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.

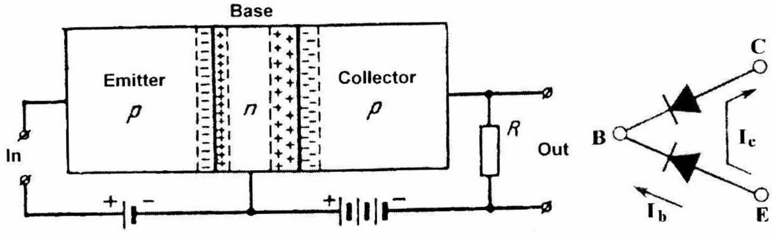
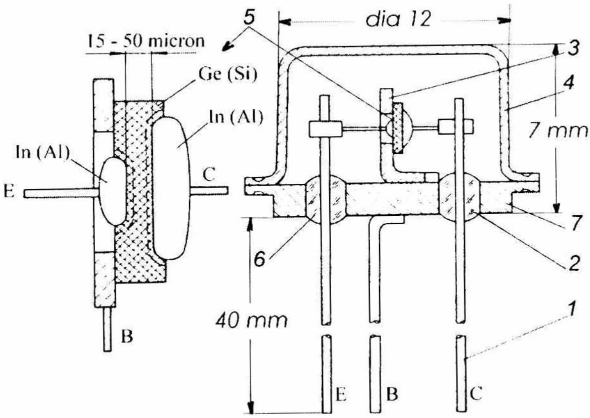


FIGURE 1.5 Circuit and the principle of operation of a transistor.

It can be seen in Fig. 1.5 that a transistor contains two semiconductor diodes, connected together, and having 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 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 (Fig. 1.5) 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.



a)

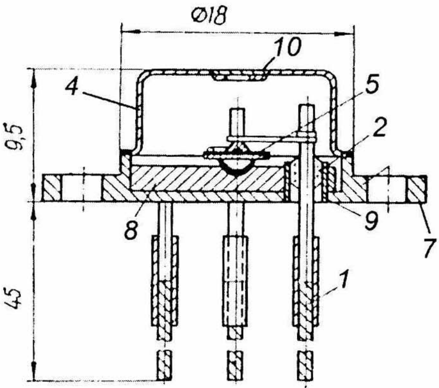


FIGURE 1.6 Transistors produced in the '70's: a) low power transistor; b) power transistor.

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.

b)