

Amorphous Semiconductors In Micro And Nanoelectronics

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Abstract: *The differences between the physics of disordered semiconductors and the physics of single crystals, the issues of controlling the properties of non-crystalline semiconductors and their applications are considered.*

Keywords – non-crystalline semiconductors, chemical and structural modification, application.

1. Introduction. Considering the history of solid-state electronics, it is easy to see that the main path of development (from a material science point of view) was to improve the atomic order in semiconductor materials. The first semiconductor devices (rectifiers) were created on the basis of polycrystalline copper oxide and selenium. Then came the era of single crystals. Since that time, the main goal of semiconductor materials science has been to produce single crystals of large sizes with fewer defects. In contrast, over the past 30 to 40 years, serious attention has been paid to the antipode of single crystals – disordered semiconductors. Unlike "generally accepted" crystalline semiconductors, the latter do not have a long-range order in the arrangement of atoms and translational symmetry.

The term non-ordered refers to semiconductor materials in which there are significant violations of the long-range order in the arrangement of atoms. These materials include:

- non-crystalline solid (amorphous) materials;
- nano and microcrystalline materials;
- chemically disordered alloys;
- organic materials;
- melts and liquids.

All these materials, along with significant violations of translational symmetry, are more or less characterized by a hopping mechanism of electrical conductivity and a reduced sensitivity of the properties to alloying impurities.

In this article, we will mainly focus on non-crystalline (amorphous) materials. The term "non-crystalline semiconductors" came into use after the discovery of chalcogenide glassy semiconductors by B. T. Kolomiys and N. A. Goryunova in 1954.

2. Definitions of non-crystalline solids. It is advisable to start any task with the definition of the subject of study. However, in the case of non-crystalline materials, even at this stage, serious difficulties arise, which consist in the fact that the general principle of determination – from general to particular in this case, is necessarily violated.

Chronologically, the first of the non-crystalline solids was defined by the concept of glass. The USSR standard of 1939 gives the following definition: "Glass is called all amorphous bodies obtained by supercooling the melt ... and having, as a result of an increase in viscosity, the mechanical properties of solids...". It is easy to see that this definition is not an object, but only the method of its manufacture, its prehistory. This is unfortunate not only because it contradicts the general principle of determination (from general to particular), but also because the quenching of the melt is not the only method of obtaining a substance in a glassy state.

However, glass is only a special case of non-crystalline bodies. Let's look at how this class of materials is defined in general. We can say that this definition is already given in the name of the materials. Indeed, from the point of view of the relative arrangement of atoms, all materials can be divided into two groups:

- **crystals** in which the atoms are arranged in a periodic crystal lattice. In other words, there is translational symmetry or long-range order in the arrangement of atoms in crystals. In diffraction patterns, the crystals give sharp reflexes;

- **non-crystalline bodies.** These include all systems that do not have a long-range order in the arrangement of atoms. The loss of the long-range order leads to the disappearance of sharp reflexes characteristic of crystals in the diffraction patterns and the appearance of diffuse halos.

Thus, we can define non-crystalline materials as materials in which there is no long-range order in the arrangement of atoms. However, the negative nature of the definition is fraught with a number of complications. It is not even a matter of contradicting the general principle of definitions, but of practically more important things. For example, in the answer to the question: is a particular sample a crystal or a non-crystalline material.

Indeed, only an ideal single crystal of infinite size has an ideal long-range order in the arrangement of atoms. On the other hand, the absence of long-range order in non-crystalline bodies does not necessarily lead to complete disorder in the arrangement of atoms. In the vast majority of amorphous bodies, there is a so-called near order in the arrangement of atoms, due to their chemical nature. Moreover, it was found that in non-crystalline materials, there is also a middle order. Consequently, the order in the arrangement of atoms in non-crystalline materials extends over distances significantly greater than the distances between the nearest neighbors. It follows that the answer to the question whether a particular sample is crystalline or not depends on the extent to which the extended order in the arrangement of the atoms is assumed to correspond to the crystal, that is, on a subjective assessment.

It would seem that to answer this question, we can use the results of a diffraction experiment, which gives clear reflections on the diffractograms of crystals and diffuse halos in the case of non-crystalline materials. However, this approach is hardly justified, since different equipment has different accuracy, sensitivity, etc. In addition, samples consisting of ultrafine crystals give a diffraction pattern in the form of diffuse halos, exactly the same as non-crystalline materials.

3. The place of the physics of disordered systems in solid state physics. The problem of disordered semiconductors belongs to one of the most interesting and least studied areas of condensed matter physics. Indeed, the gap between the possibilities of condensed matter theory and the real world that surrounds us is quite obvious. The theory of condensed matter has achieved the greatest success in its application to an extremely idealized object – the monocrystalline state of matter. On the other hand, it is obvious that single crystals are much rarer than disordered systems-micro and nanocrystals, disordered alloys, amorphous and glassy materials. In many cases, the basic principles of the physics of single crystals are not applicable to the listed materials, since the latter are based on the existence of a periodic crystal lattice (translational symmetry). As a result, we are faced with a paradoxical situation when, based on the "classical" theory cannot explain the simplest and most obvious properties of non-crystalline materials.

Summing up, we can say that in the academic plan for the future there is a problem of creating a theory of a wide class of condensed matter, which, as a special case, would include the existing theory of single crystals.

4. Control of the properties of non-crystalline semiconductors. It is known that the electrical conductivity of crystalline semiconductors is highly sensitive to the presence of impurities. The introduction of impurities in the amount of thousandths or hundredths of a percent changes the absolute values of electrical conductivity by orders of magnitude, changes the type of conductivity of the semiconductor. It is the possibility of fairly simple control of the properties of crystalline semiconductors by doping that has allowed the creation of various semiconductor devices and ensured the development of modern solid-state electronics and microelectronics.

However, when impurity atoms are introduced into a non-crystalline semiconductor, the electrical properties of the latter, as a rule, practically do not change. Consider the causes of this phenomenon. The first of them, characteristic of chalcogenide glassy semiconductors (CSPs), is that due to the lack of long-range order and the soft structural grid of glass, impurity atoms can saturate all their valence electrons. As a result, the impurity atoms become electrically inactive. But even if a sufficient number of electrically active impurity atoms were formed during the doping of the CSP melt, the rearrangement of the material structure leads to a change in the ratio between positively and negatively charged intrinsic defects (C_3^+ vs C_1^+). As a result, the position of the Fermi level does not change, and therefore, the electrophysical properties of the material do not change.

The second reason, characteristic of amorphous silicon, is the high density of localized states due to intrinsic defects in the band gap of the semiconductor due to the loss of long-range order in the conditions of a rigid four-coordinated structural grid. Under these conditions, even with the formation of active donor or acceptor levels, their concentration is significantly less than the concentration of intrinsic defects and, therefore, does not affect the position of the Fermi level and the properties of the material.

The complexity of property management is a serious obstacle in the application of non-crystalline semiconductors. Therefore, in recent decades, methods for controlling the properties of non-crystalline semiconductors have been intensively developed and are being developed.

5. Doping of hydrogenated amorphous silicon. The most important feature of hydrogenated amorphous silicon, which has predetermined its wide application in various devices and devices, is the possibility of purposefully changing the properties of the material by doping. This was first demonstrated by V. Speer in 1976 on $a-Si:H$ films obtained by the decomposition of silane gas (SiH_4) in a glow discharge plasma. The presence of hydrogen in $a-Si:H$ passivates the broken bonds of silicon atoms and significantly reduces the density of localized states in the band gap of the semiconductor. As a result, the concentration of donor (or acceptor) levels exceeds the concentration of the levels of intrinsic defects, which leads to a shift in the Fermi level when impurities are introduced.

Since $a-Si:H$ films are produced from a gaseous material, the most common method for doping $a-Si:H$ is to introduce phosphine (PH_3) or diborane (B_2H_6) additives into the gas medium in a controlled manner during the film production process. The dependence of the conductivity at room temperature on the degree of doping of $a-Si:H$ obtained by the decomposition of silane in a glow discharge plasma is shown in Figure 1 [1]. As can be seen from the figure, a change in the concentration of the dopant leads to a change in the absolute values of electrical conductivity by 7 to 10 orders of magnitude.

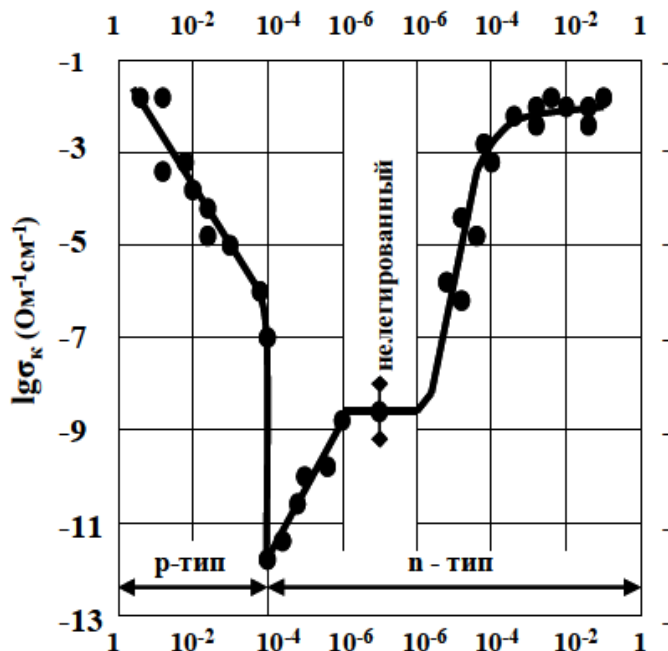


Figure 1-Dependence of the $a-Si:H$ conductivity at room temperature on the doping level

6. Chemical modification of CSP films. As noted above, chalcogenide glassy semiconductors are insensitive to doping in the usual sense of the word due to the relaxation of the glass structure around the impurity atoms. Thus, in order to preserve the electrical activity of the impurity atoms, it is necessary to avoid relaxation of the glass structure. To do this, it is necessary to introduce impurity atoms under such conditions that any rearrangement of the material structure is difficult. In other words, it is necessary to introduce the impurity atoms into the solid. In this case, the mobility of the main atoms will be small and there will be no relaxation of the structure. The implementation of this is possible by the method of co-spraying of CSP and impurity on a cold substrate. Based on these principles, in 1977, S. Ovshinsky developed a method for chemical modification of CSP films [2].

Modified films are prepared by high-frequency ion-plasma sputtering of CSP and modifying metal on a cold substrate. The metal in the form of disks with a diameter of several millimeters is placed on the surface of the target made of CSP. The metal concentration in the film is determined by the ratio of the surface areas of the CSP and the metal on the target and the sputtering coefficients of these materials. Figure 2 shows the temperature dependences of the conductivity of $Ge_{32}Te_{32}Se_{32}As_4$ CSP films modified with nickel.

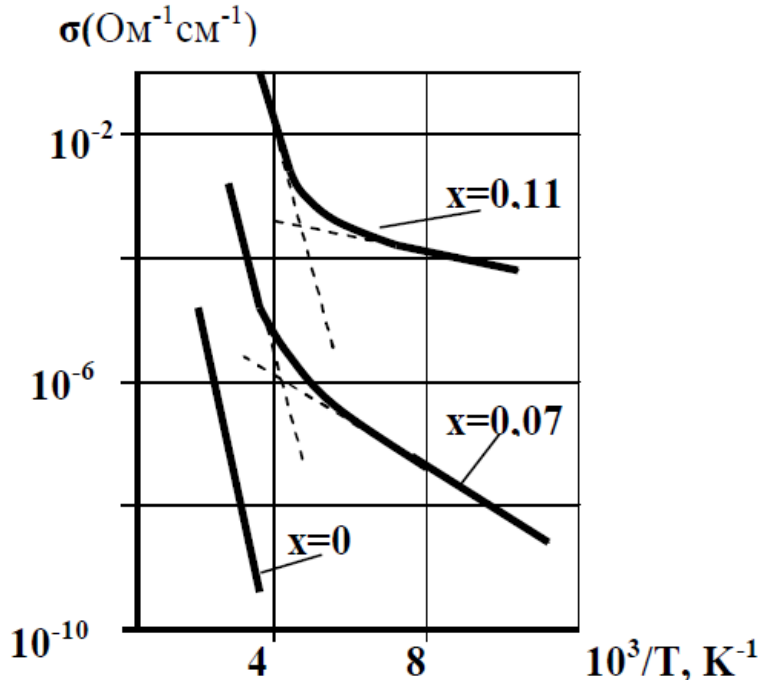


Figure 2-Temperature dependences of the conductivity of films $(Ge_{32}Te_{32}Se_{32}As_4)_1 - xNi_x$

As can be seen from the figure, in unmodified samples, the activation energy of the conductivity is constant over the entire temperature range of measurements and is approximately half the width of the band gap. Modification of XSP films with nickel leads to an increase in the absolute values of the conductivity to eight orders of magnitude and to the appearance of an impurity conductivity region at the dependences $\sigma(1/T)$. The activation energy in the impurity conduction region decreases from 0,74 to 0,18 eV with increasing nickel concentration. In this case, the optical band gap varies slightly. This indicates that the changes in the activation energy of the conductivity are due to a shift in the Fermi level. In addition, measurements of the thermal EMF showed that with an increase in the nickel concentration, its absolute values decrease, and then the thermal EMF changes sign, that is, there is a transition from the hole to the electronic type of conductivity. Thus, the chemical modification of CSP films leads to effects similar to the doping of crystalline semiconductors and $a - Si : H$.

7. Structural modification of the properties of non-crystalline semiconductors. One of the most significant features of non-crystalline semiconductors is their weak sensitivity to impurities. Although the exceptions to this rule described above have been found, the methods for controlling the properties of these materials remain very limited. On the other hand, due to the lack of long-range order, the structure of non-crystalline semiconductors can change when the conditions and modes of material manufacturing change. For a long time, the influence of manufacturing conditions on the structure and properties of non-crystalline solids was regarded as a lack of these materials, leading to poor reproducibility of the properties of the resulting samples. However, knowledge of the causes and patterns of this influence can not only provide highly reproducible results, but also provide a new method for managing properties.

As an alternative to the method of controlling the properties of semiconductors by doping them, a method of structural modification of the properties of non-crystalline materials was proposed, which consists in controlling the properties by changing the structure with the same chemical composition of the material. The physical basis of the method is the presence of several minima in non-crystalline materials on the dependence of the potential energy on the generalized coordinate, corresponding to various metastable states of the system [3].

There are four levels of structural modification, characterized by different changes in the structure of the material: at the level of the near order in the arrangement of atoms, at the level of the middle order in the arrangement of atoms, at the level of morphology and at the level of the defect subsystem.

Effects on the structure **at the near-order level in the arrangement of atoms lead to significant changes** in all the fundamental properties of the material. Thus, polymorphic crystalline modifications of carbon (diamond, graphite, carbene) have diametrically opposite physicochemical properties due to different hybridization of electronic orbitals. This leads to a different

atomic structure at the near-order level. Amorphous carbon films contain structural units of various allotropic modifications. Their ratio in a particular sample is determined by the modes of manufacture and can vary widely even within the framework of a single manufacturing method. Accordingly, the coordination of the atoms (from 2 to 4) and other parameters of the first coordination sphere change. Therefore, in amorphous carbon films, drastic changes in the properties of the material are possible when the production modes change. Thus, in films obtained by ion-plasma sputtering, the resistivity varied by more than 10 orders of magnitude (from $5 \cdot 10^9$ ohmcm for films with a diamond-like structure to 0.1 ohmcm for films with a graphite-like structure), and the band gap varied from 1.85 to 0.02 eV depending on the manufacturing modes (substrate temperature and discharge power) [3].

Changes in the structure **at the level of the average order** are changes in the distributions of values and signs of dihedral angles, the degree of polymerization of molecules, the degree of chemical ordering of alloys, etc. These changes in the constant near-order lead mainly to changes in the macro-properties of the material: viscosity, microhardness, Young's modulus, film photosorption, etc. The efficiency of controlling the properties of a non-crystalline semiconductor by modifying its structure at the level of the middle order is determined by the mobility of its structural grid.

Structural modification **at the morphological level**. A necessary condition for obtaining any non-crystalline solid is a thermodynamically nonequilibrium process of its synthesis. In accordance with the principles of synergetics, non-equilibrium conditions of material production lead to the formation of inhomogeneities in it due to self-organization processes. The presence of macro-inhomogeneities (columns, globules, cones, etc.) with sizes of tens of nanometers or more in films of non-crystalline materials is considered as the presence of morphology. A certain morphology is present in the films of many non-crystalline semiconductors. Morphology control is possible by changing the sample production modes. Changes at the morphological level affect properties that are sensitive to macro-odnonosty (optical properties, electrical conductivity at alternating current, and others).

Structural modification **at the level of the defect subsystem**. As you know, defects create levels of localized states in the forbidden zone. Therefore, changes in the defect subsystem lead to a modification of the spectrum of localized states, and consequently, to a shift in the Fermi level and to a change in the properties associated with the electronic subsystem. In structural modification at this level, the choice of the influencing factor is important. It should be chosen so that it mainly affects the defects, and not the entire structural grid as a whole. In the case of hydrogenated amorphous silicon films, for example, ultraviolet (UV) radiation is used as such a factor. When UV radiation is absorbed, phonons are generated near the surface of the $a - Si : H$ film. Diffusing deep into the semiconductor, phonons are localized mainly on defects, since the capture cross-section of the latter is larger than that of atoms with normal coordination. As a result of the release of phonon energy, the defects are rearranged. This is evidenced by the change in the peak areas in the IR absorption spectra corresponding to different forms of hydrogen entry into $a - Si : H$. The rearrangement of defects leads to a change in the density distribution of localized states in the band gap.

8. Application of non-crystalline semiconductors. Chalcogenide glassy semiconductors, hydrogenated amorphous silicon and its alloys, organic materials are widely used in many electronic devices and devices. The latter include:

- photovoltaic energy converters (solar panels) based on hydrogenated amorphous and microcrystalline silicon and its alloys;
- thin-film transistor arrays for controlling liquid crystal displays and television screens;
- devices for recording and processing optical and holographic information:
- vidicons (receiving TV tubes);
- optical disks;
- photothermoplastic media;
- photo -, electron-and X-ray resistors;
- devices for copying information and printers for computers (photocopying process);
- memory devices for phase transitions in chalcogenide alloys;
- sensors (detectors) for medical diagnostics;

- elements of infrared optics. The advantages of disordered semiconductors, which determine their use in these devices and devices, are as follows:

- the actual absence of restrictions on the area of the device;
- low (in comparison with single crystals), the cost of production, weak communication "the size – cost»;
- the possibility of manufacturing active electronic matrices on non-crystalline substrates;
- ratios of some electrophysical characteristics that are unattainable in crystals;
- the presence of a number of unique effects that are not present in the crystals and allow you to create devices on new principles.

Let's take a closer look at the listed advantages.

When they talk about the combination of "large area and low cost" properties, first of all they give examples of solar cells based on hydrogenated amorphous silicon. Indeed, with the efficiency achieved in industrial samples of 7 – 9% and the cost of electricity of 14 – 16 cents kW/h, such converters become economically feasible. As an example, a photovoltaic plant for an oil-producing enterprise, implemented in 2003 in California, USA, can be cited. The installed capacity of the station is 0,5 MW. It consists of 4,800 panels measuring 5.4 by 0.4 meters. The total area of the converters is approximately 2.5 hectares. However, powerful large-area photovoltaic plants are unlikely to become the main route of energy development, as they will not withstand competition from traditional methods of its production. Not to mention the environmental consequences.

However, the second parameter – low cost-determined the scope of application of FEP on $a - Si:H$: H. It is these energy sources, due to their low cost, that have entered consumer electronics. I mean solar panels for watches, calculators, children's toys, autonomous lighting sources, battery charging devices, and so on.

The possibility of obtaining photosensitive semiconductor films of large area and, in addition, on substrates of any shape has become one of the two main reasons for the monopoly of disordered semiconductors in electrophotography (copiers and printers based on the xerox process). The main element of these devices is an electrophotographic cylinder (EFC), which is a cylindrical conductive substrate with a layer of high-resistance semiconductor deposited on it. The height of the cylinder must not be less than the width of the original being copied.

The second reason for the monopoly of disordered semiconductors in electrophotography is as follows. The semiconductor layer in this group of devices must have a high photosensitivity in the visible region of the spectrum (to create the necessary potential relief during the exposure). On the other hand, it must have a high resistivity (to preserve the created potential relief during the visualization or reading of the image). In video cameras, where exposure and reading are carried out during the TV frame (0,04 seconds), the resistivity of the material must be at least 10^{11} ohmcm. In electrophotography, even higher resistance materials are needed in thermoplastic media. These requirements are very strict and contradictory. Indeed, the electrical conductivity (resistivity) of a semiconductor is determined by the concentration and mobility of charge carriers:

$$\sigma = 1/\rho = q \cdot n \cdot \mu_n + q \cdot p \cdot \mu_p$$

In turn, the minimum concentration of charge carriers in a proper semiconductor is determined by the width of its band gap:

$$n_i = p_i = A \exp(-\Delta E / kT).$$

Thus, to increase the resistivity of a semiconductor, it is necessary to choose semiconductors with a large band gap. On the other hand, the maximum photosensitivity of a semiconductor is observed when radiation with a quantum energy close to the band gap interacts with it. Since the visible region of the spectrum lies in the range of 0.4 – 0.7 microns to ensure photosensitivity in the red region of the spectrum, the band gap of the semiconductor should be $\Delta E = 1.7 - 1.9 \text{ eV}$ ($\lambda = 1.234 / \Delta E$).

However, traditional crystal semiconductors do not provide the necessary resistivity at such values of the band gap. It was possible to solve this contradiction by using non-crystalline semiconductors, which at the same band gap have a specific resistance of 4-5 orders of magnitude higher due to the lower mobility of charge carriers.

9. The possibility of manufacturing active electronic matrices on non-crystalline substrates. In all liquid crystal TVs and displays, the screen control matrix is created on thin-film transistors on $a-Si:H$. Why aren't single-crystal silicon transistors used?

By itself, creating a flat screen on liquid crystals of almost any area is not a big problem. The problem is the screen control. Indeed, if we proceed from the resolution of 10 points per millimeter, then the screen size of $10 \times 10 \text{ cm}$ should have 10^6 cells, each of which must be independently controlled. This means that there must be a million connections between the control system and the screen. The way out of this situation is to create a control system directly on the glass substrate of the liquid crystal screen. But this conclusion immediately determines the technology – it must be thin-film. With the help of single crystals, the problem cannot be solved, but it is solved by using transistors based on hydrogenated amorphous silicon. The electrical circuit of the liquid crystal screen is a matrix of thin-film transistors on $a-Si:H$, the sources of which are connected to vertical buses, the gates-to horizontal buses, and the drains - to the electrodes of the cells.

10. Switching effects and phase transitions in CSP. Chalcogenide glassy semiconductors have a unique property-the switching effect, that is, the rapid transition of a material from a high-resistance state to a low-resistance state when a voltage of a certain value is applied. In other words, the metal – XSP – metal structure has an S-shaped current-voltage characteristic with a negative resistance section. For the first time, the switching effect was discovered in CSP in 1963 by B. T. Kolomiets and his co-workers and S. Ovshinsky independently of each other. Despite the numerous studies conducted since that time, a unified theory of the switching effect has not yet been created. Only a number of models and hypotheses have been developed. However, on the basis of this effect, two groups of devices were created: monostable switches and switches with memory.

A typical switch is a film of CSP with a thickness of less than 1 micrometer, enclosed between two metal electrodes. The current-voltage characteristic of the threshold switch is symmetric and similar to the VAC of a symmetric silicon diode (Figure 3). Initially, the switch is in a high-resistance state. Its resistance is about 10^5 ohm . When a certain threshold voltage value (U_{th}) is reached, the device switches to the low-resistance state. Switching is caused by the formation of a current channel in the XSP film. The value of the threshold voltage corresponds to the value of the electric field of the order of 10^5 V/cm . In this case, the resistance of the device is reduced by 5 to 6 orders of magnitude. The dynamic resistance of the device in the low-resistance state is approximately 1 ohm . In the low-resistance state, when the current decreases to a certain value I_h , the device switches back to the high-resistance state.

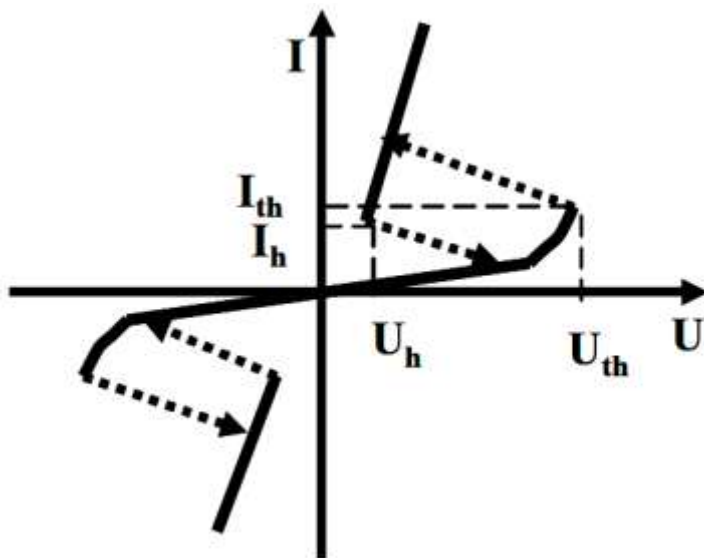


Figure 3-Volt-ampere characteristics of the threshold switch

The design of the switch with memory is completely similar to the previous one. Initially, the current-voltage characteristic of the memory switch repeats the VAC of the threshold switch. The initial resistance of the device is high, and when the threshold voltage is reached, the device quickly switches to a low state. If at this point the current through the device is reduced below the value of the holding current, the device will enter a high-resistance state, just like a threshold switch. However, if the low-resistance state is maintained for about 10^3 seconds, the device remains in the low-resistance state even after the voltage is removed. In this case, the conversion to a high-resistance state is performed by applying a "erasing" current pulse of any polarity,

but of a special form, to the device. Thus, this type of device makes it possible to store information without energy consumption. Two different types of behavior of devices of the same design are due to the different chemical composition of the CSP films included in the device.

The process of memorizing the low-resistance state is explained by the structural and phase changes of the material in the current channel: under the action of the electric current flowing through the channel, the material is heated and crystallized. On the basis of switches with memory in the late 70s of the last century, integrated circuits of reprogrammable permanent storage devices (RPMs) were created in the United States and in the USSR. However, it soon became clear that the new products have insufficient reliability. In the process of operation of a single cell spontaneously moved from one state to another. For this reason, the devices did not find further development, and the only positive result at that time was the use of the idea of recording information using phase transitions in optical disks. However, history shows that everything is developing in a spiral. In the early 2000s, the first reports appeared about a new type of memory devices based on the *Ge - Sb - Te* system, called **phase transition memory**. In 2004, such companies as Intel, Ovonyx, STMicroelectronics, Samsung, and Phillips participated in the development of integrated circuits on this basis. Created the first integrated circuits of this type of memory capacity of 64 and 512 Mb with the following characteristics: the cell size of 0,32 to 0,50 μm^2 (photolithography 0.18 μm), which corresponds to 64 Bitam memory 100 mm^2 ; time of entry in the cell of less than 10 NS; a retention time of 10 years at 110 – 130 $^{\circ}\text{C}$; number of write cycles 10^{13} ; electrical parameters: voltage to 3.3 V, currents up to 1 mA, the difference between resistances in Vysokomol and nizammam States – about 100 times. Developers believe that the new type of memory can successfully compete in flash memory devices, dynamic and static memory, and radiation-resistant special-purpose circuits.

What has fundamentally changed with the switches described above over the years? The matrix cell and the general structure of the switching element have not changed in principle. The element is a sandwich: a conducting electrode-a chalcogenide alloy-a conducting electrode (Figure 4).

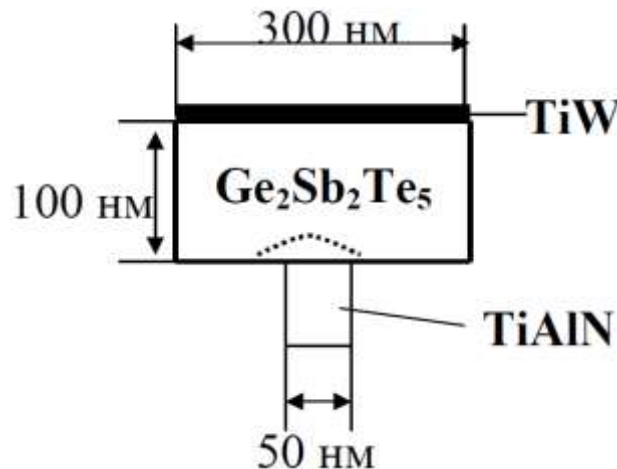


Figure 4 - Design of a memory cell at phase transitions

The difference is that the chalcogenide alloy is in a crystalline state, not in a glassy state. Therefore, the switch is initially in a low-resistance state. The next difference is in size.

As can be seen from Figure 4, the main dimensions are in the range of tens to hundreds of nanometers. This is fundamental not only from the point of view of increasing the density of information recording, but also from the point of view of the physics of the device operation. And, finally, another difference: the lower electrode is made of metal nitrides, and therefore has an increased electrical resistance.

Initially, the device is in a low-resistance state. When an erasing current pulse is applied (sufficiently large in magnitude and with a steep trailing edge), the chalcogenide material is heated. Moreover, the greatest heating will occur in the area adjacent to the lower contact, since in this area the current density is maximum and, in addition, additional heating occurs from the resistive electrode. As a result, the material in this region melts (dotted line in the figure) and at the abrupt end of the pulse passes into a glassy state. The thickness of the region in which the phase transition occurs does not exceed 50 nm. During the reverse switching, a longer, but smaller, current pulse is applied. As a result, the entire glassy region crystallizes, and the device goes into a low-resistance state. Thus, instead of crystallization and melting of the channel, which took place in the switches on the CSP, in these

devices, phase transitions occur in the volume, which significantly increases reliability. Integrated memory circuits on phase transitions are quite easily implemented using thin-film technology, which makes it possible to manufacture these circuits using the so-called 3D technology, when several integrated circuits are placed on a single substrate in several layers. This allows you to significantly increase the recording density.

The switching effect on phase transitions, in addition to its traditional use in memory elements, can find other applications, for example, as analog memory or controlled resistors. When switching an element from a low-resistance state to a high-resistance state, the volume of the material that has passed into the glassy phase and the resistance of the element depend on the current value. Therefore, by changing the programming current, you can change the resistance of the element in a wide range and instead of two states (high-resistance and low-resistance), write more than a dozen and a half states with different resistances.

The principle of recording information on optical disks is also based on phase transitions. In the case of multiple recordings, either the local crystallization of the amorphous chalcogenide film is used, or the amorphization process is used if the original film was in a crystalline state. The phase transition is initiated by a short pulse of laser radiation and leads to a change in the optical properties of the local region. The information is read by a low-power laser. The requirement to increase the recording density makes it necessary to reduce the size of the local regions in which phase transitions occur. The minimum size of the phase transition regions is determined mainly by the wavelength of the laser radiation that provides information recording. Reducing the wavelength from 780 to 405 nanometers, together with improving the optical system and reducing the distance from the disk surface to the recording layer, increased the disk capacity from 650 MB in 1997 to 23.3 GB in 2003 and 50 GB in 2004 [4].

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