Розглянуто технологічні аспекти використання надпровідних матеріалів та показано можливість виготовлення мішеней для магнетронного осадження плівок для формування кріопровідної розводки в структурах ВІС на основі GaAs. Визначені технологічні методи і режими осадження та розроблено високоефективну технологію виготовлення кріосплавів на основі Al, Nb, V з домішками Si, Ge та РЗМ та магнетронного формування надпровідних плівок із сплавів алюмінію, ніобію та ванадію

Ключові слова: комплементарні структури, епітаксія, інтегральні схеми, карбонові плівки, надпровідність, магнетронне осадження

Рассмотрены технологические аспекты использования сверхпроводящих материалов и показана возможность изготовления мишеней для магнетронного осаждения пленок для формирования криопровидноы разводки в структурах БИС на основе GaAs. Определении технологические методы и режимы осаждения и разработана высокоэффективная технология изготовления криосплавив на основе Al, Nb, V с примесями Si, Ge и РЗМ и магнетронного формирования сверхпроводящих пленок из сплавов алюминия, ниобия и ванадия

Ключевые слова: комплементарные структуры, эпитаксия, интегральные схемы, сверхпроводимость, магнетронное осаждение

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DEVELOPMENT OF TECHNOLOGY OF SUPERCONDUCTING MULTILEVEL WIRING IN SPEED GAAS STRUCTURES OF LSI/VLSI

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1. Introduction

The phenomenon of superconductivity was discovered in 1911 studying the properties of liquid helium. It turned out that the electrical resistance of mercury sample is extremely small at temperatures below 4.15 K. It is impossible to measure the resistance of the superconductor by traditional methods. New approaches are needed here. Today it is assumed that the resistance of the superconductor is at least 10^{18} times smaller than the resistance of high-conductivity metals: copper, silver, and gold.

If the temperature of the superconductor becomes less than so-called critical temperature T_c, then the phenomenon of superconductivity disappears, i.e. this material goes into the normal state from the superconducting one.

This phenomenon has become promising for the further growth of speed of the LSI/VLSI structures. It is known that today the wiring in the LSI structures takes up 60–68 % of the crystal, which consumes a significant proportion of the power of the energy supply. This is important for semiconductor materials with high mobility ($A^{III}B^{V}$ compounds). Therefore, the decision to increase the speed of the LSI structures due to the use of superconducting wiring in structures based on GaAs is relevant and requires further research.

2. Literature review and problem statement

Silicon has always played a decisive role in the technology of ICs as the main semiconductor material [1, 2]. In recent years, as an alternative, semiconductor compounds such as $AI^{II}B^{V}$ (for example, gallium arsenide) have been used [3]. Since 2010, the volume of commercial products of microelectronics based on gallium arsenide has increased several times [4]. This growth trend persists until now. One of the applications of GaAs electronic devices is microwave electronics. Typical values of the diameters of grown ingots are 100–150 mm. The commercial crystals of 200 mm in diameter have also appeared [5], but they are quite expensive.

The dielectric layers of Al_2O_3 are promising for GaAs structures. The main way of such layers obtaining at present is the atomic layer deposition method [6, 7]. Certain successes have been achieved for the creation of a field GaAs-transistor based on MOS-structures with Al_2O_3 [7].

The decreasing of geometric sizes of transistors results in decreasing of the crystal area, parasitic capacitances, LSI energy consumption and increasing of speed. Today, special attention is focused on the architecture of structures for the LSI of submicron range [8]. It is the architecture that qualitatively expresses the question of technology: the growth of epitaxial structures, the formation of functional layers and circuitry [9, 10].

Today, the existing technologies for the formation of high-speed LSI structures on GaAs are limited by the technological capabilities of gallium arsenide as a compound [8, 10] due to the high cost of GaAs ingots, its low thermal conductivity, which is 3–5 times less than the one for silicon. Also, technological problems in the manufacture of Czochralski' ingots over 75 mm in diameter with semiconductor purity are unresolved [8, 10]. Modern circuits are formed with a multilevel wiring with a top metal layer on the basis of aluminum alloys, which are not free of hillock-forming.

Also, considerable attention is paid to increasing the LSI speed, one aspect of which is the use of superconducting materials [11]. The use of cryogenic equipment allowed not only increasing the speed but also lowering their own thermal noise of the input circuits of electronic devices designed for operation at low signal-to-noise ratio [12]. The application of cryogenic temperatures in electronics on an industrial scale began in the 1950s. This was aided by the important practical results obtained from the research of low-temperature phenomena in solids and the achievements in the field of cryogenic technology for the development of small-volume, economical and reliable cooling systems [13].

Today, it is necessary to form high-speed LSIs on the GaAs epitaxial layers deposited on silicon substrates of large diameter, which allows combining gallium arsenide and silicon technology. The transition to cryogenic superconducting metallization will increase the speed of modern LSI/VLSI by 1–2 orders of magnitude.

It is known [14] that today the wiring in the LSI structures takes up 60–68 % of the crystal area, which consumes a significant part of the power of the energy supply, this is important for semiconductor materials with high mobility. Therefore, the development of the technology of superconducting multilevel wiring in high-speed GaAs-structures of the LSI structures is extremely promising, and will significantly improve their main characteristics.

3. The aim and objectives of the study

The aim of the work is to develop a technology for producing targets and magnetron deposition using films for multilevel wiring of GaAs structures on Si-substrates.

To achieve the goal, the following tasks were performed:

– to develop the technology of production of superconducting alloys of semiconductor purity using zone melting;

– to develop the technology for obtaining targets for magnetron sputtering in the sub-micron LSI technology for these superconducting alloys;

– to choose the necessary alloying admixtures for superconducting alloys to increase the cryotemperature on the basis of research;

– to design and develop the technology of LSI mounting on cryo-radiators, cryo-frames, cryo-tables for measuring the parameters of such systems in cryoregime.

4. Physical-technological aspects of superconductivity for use in multilevel wiring of LSI/VLSI structures

Superconducting properties are characteristic of many nonferromagnetic metals, in which the value T_c is different. In 1986, a whole class of rare-earth ceramic materials with the addition of copper ions was discovered, in which the critical temperatures are quite high (>77 K). For example, T_c=92 K for ceramics $YBa_2Ca_3O_7$, which is higher than the boiling point of liquid nitrogen (77 K). This feature radically proposed the technical use of the superconductivity phenomenon in the sub- and nanoelectronics in the formation of a multi-level wiring with low contact resistances.

According to the London superconductivity model, the substance in the superconducting state contains two types of charge carriers: normal carriers, which are subject to the usual laws of classical electrodynamics, and superconducting carriers that can move in a crystalline lattice of the test substance without any resistance. In the London theory of superconductivity, it is assumed [15] that the charge carriers responsible for the superconductivity phenomenon are electrons. The magnetic induction decreases e times compared with the initial value at a depth of 16 nm in metal. Therefore, we can assume that relative magnetic field is absent in the depth of the superconductor.

It was found later that electrons in a metal, in addition to the force of the Coulomb repulsion, undergo special forces of attraction. If the temperature of the substance becomes less than critical T_c, then the forces of attraction begin to dominate and part of the electrons are coupled together. As a result of this interaction, there are so-called Cooper pairs of electrons, which are already able to move between the nodes of the crystalline lattice of a substance like a superfluid. Hence the conclusion that the electrons are not true carriers of the superconducting current, but the so-called Cooper pairs, which essentially complements the London theory in terms of the interaction of electrons.

From a technical point of view, the Josephson's effect, the flow of a tunnel current through a very thin (1–2 nm) dielectric layer, is of great interest today. Josephson's effect makes it possible to build high-precision measuring instruments, to create elements of logic devices (resonant-tunnel transistors) for supercomputers (quantum computers).

Today, the London-Bardeen-Cooper-Schrieffer model is the basis of the superconductivity theory [15]. Cooper pairs of electrons are bosons and therefore are not subject to the Pauli principle and the Fermi-Dirac statistics, and are subject to the Bose-Einstein statistics. In superconducting metal, the Cooper pairs of electrons are condensed in an ordered set at one energy level below the Fermi level by the value of Δ.

As noted above, not all metals are characterized by superconductivity. It can be thought that substances with high electrical conductivity, as a rule, have weak electron-photon interactions. This leads to the fact that they do not form

Cooper pairs, and therefore superconductivity does not occur in them.

5. Practical implementation of the production of targets for magnetron formation of superconducting wiring in the arsenide-gallium LSI structures

In order to create a technology for the production of pure metals, alloys and targets for magnetron formation of layers of superconducting wiring of GaAs-LSI/VLSI structures at the first stage it is necessary to determine the metals and impurities with which alloys and targets for magnetron formation of superconducting films in GaAs-LSI structures can be made. Metals of niobium and vanadium are offered for taking as the basis, which are doped with various elements: metals and semiconductors, which help to raise the critical temperature.

The most actual question in the study of superconductivity is the question of raising the upper limit of the critical temperature T_c, which varies both with the impurity concentration (–15 %) and the pressure value of forming the alloy for the target (1–20 atm.).

Today, there are more than 35 superconducting metals and 1,000 superconducting alloys and chemical compounds of various elements. Superconducting properties of some semiconductors (Si, Ge, InSb), sulfur (S) are also established. At the same time, for many conductor materials (Ag, Cu, Au, Pt) even at rather low temperatures (He), it was not possible to reach the superconducting state.

Elementary superconductors by their physicochemical properties can be divided into two groups: light – Hg, Sn, Pb, In and hard – Ta, Ti, Zn, Nb, V. Light superconductors are characterized by low melting temperatures and the absence of internal mechanical stresses. The hard superconductors differ in higher melting point and the presence of significant internal stresses, but allow forming alloys and targets for magnetron deposition of superconducting films for the wiring of LSI/VLSI structures according to the unified technology.

Superconductor materials are divided into superconductors of the first, second and third kind from the standpoint of thermodynamics. First type superconductors are characterized by a jump-like change in specific heat capacity and a sufficiently defined transition temperature to the superconducting state, which is already collapsing at low critical temperatures and magnetic field strength about 1 kA/m, which makes it difficult to use these alloys in microelectronics. The second type superconductors are distinguished by the fact that the transition to the superconductive state in them is carried out not by a jump, but by a smooth transition. They are characterized by two critical values of the magnetic induction for the temperature $T_{cr}<T_0$. For second kind superconductors only niobium (Nb), vanadium (V) and technetium (Tc) are included of pure metals. Niobium and vanadium as process metals were selected to form targets from superconducting alloys. Third type superconductors include nonideal superconductors of the second kind (hard superconductors – alloys). They are already characterized by the presence of large inhomogeneities that arise in the allocation of the second phase or in plate deformation, which is based on the technology of targets manufacturing. Defects of the structure are nodes of fixing vortices (the phenomenon of pinning), which significantly increases the permissible currents. For example, currents with a density greater than 10^9 A/m^2 can be passed through the Nb_3Sb wire in fields with an induction about 10 T. The losses are hysteretic in nature and do not depend on the shape of the current at frequencies of no more than 10 kHz.

The high-temperature superconductors have a special status. The superconducting properties of the Y–Ba–Cu–O system depend on the ratio of bivalent and trivalent copper $Cu2^+/Cu^{3+}$. Today, superconductors have already been obtained with a transition temperature from –168 to –163 °C and a current density of 10^4 A/cm^2, which is slightly less than for metallic superconductors [16]. Currently, $Bi_2Sr_2Ga_2Cu_3O_4$ bismuth systems are interesting, whose transition temperature can reach –158 °C [17].

Such superconducting materials have been widely used in various fields of science and technology. The authors used superconductivity to create high-speed LSI/VLSI structures. Let's consider another category of superconducting materials – cryoconductors, which include such materials (alloys), which acquire high electrical conductivity on the verge of transition to the superconducting state during cryogen cooling (below –173 °C). The minimum resistance of especially pure metals (Al, Cu, Be) with the content of impurities <0.01 % is achieved at liquid nitrogen temperature 77 K. In addition, Be has a highly developed magnetoresistance effect. The use of Al in the role of conductor is more rational for alloys of niobium and vanadium, because it is more affordable, cheap and has low values of resistivity. For example, aluminum A9999, containing no more than 0.0001 % of impurities, has a specific resistance $(1–2)\cdot10^{-6}$ μΩ·m at the helium supply temperature. Si and Ge also deserve special attention here.

Cryoconductors are used today for the production of conductive cables and wires, which operate at temperatures of liquid hydrogen (–252.6 °C), neon (–245.7 °C) and nitrogen (–145.6 °C). This indicates the possibility of using niobium and vanadium in the formation of superconductors in microelectronics. The technology of AKG_0-1-1 aluminum alloy production was used for the formation of alloys and targets of magnetron sputtering. It should be noted that aluminum is also cryoconductor, in which the conductivity increases by almost two orders of magnitude at 77 K.

6. Industrial thin-film technology of cryoconductor metallization in the production of sub-micron structures on Si and GaAs

The industrial use of thin-film metallization for wiring of IC/LSI of lanthanum- containing aluminum alloys was carried out at first in [18, 19]. The test results are positive. However, the introduction and subsequent use of this alloy in the batch production of IC/LSI structures was curtailed due to the lack of industrial technology for the production of lanthanum-containing alloys of aluminum and targets on the basis of these alloys for the device of magnetron deposition of films on Si and GaAs. Therefore, the main attention is paid to research aimed at the development of industrial technology for the production of alloys of Al + 1 % Ho, Al + 1 % Ho + 1 % Si cryoconductors and proper targets for magnetron sputtering on silicon and gallium arsenide structures. This technology should become the main one for sputtering targets from superconducting alloys NbHo-1, NbSiHo-1-1, YHo-1, YGeHo-1-1 for the formation of superconducting wiring in GaAs-LSI structures.

6. 1. Development of industrial technology of manufacturing alloys for cryoconductors

Alloys AlHo-1, AlSiHo-1-1 were taken as the basis that became the main ones. There are such methods for the formation of Al-based alloys: induction alloying method, vacuum and vacuum-arc melting, zone recrystallization.

The main disadvantages of these methods are the complexity of obtaining alloys with uniformly distributed alloying components across the ingot due to the aggregation process.

The advantage of application of zone melting for the production of cryo-alloys, unlike other methods, is the possibility of obtaining a uniformly distributed alloying component, both in the section of the ingot, and in length, similar to that in the growing of doped ingots of mono-Si.

The theoretical substantiation of the zone introduction of the alloying impurity in metals was carried out in the late 1950's. It is known that if a zone melting is carried out several times along the ingot in one and the other direction (i. e. to carry out several cycles of recrystallization), then all variations in the uniformity of alloying will be eliminated by such process throughout its length. Zone recrystallization, in addition to the purification of materials, is considered today as a method that allows uniform distribution of one or another impurity in a single crystal, which for a long time remained an unresolved problem in the technology of metals and semiconductor materials. In addition, this method allows obtaining precision alloys based on especially pure materials (metals). Experimental works on the zonal growing of the conductor were carried out on an experimental industrial device UZPN-5. UZPN-5 is the device of zone melting of semiconductors of the fifth modernized variant, which consists of a graphite container for loading alloy components, a power supply unit, a mechanism for providing a movable melting area and a vacuum post for pumping the container to a vacuum of $10^{-2}\div10^{-3}$ mm Hg. The device also contains a working chamber in which the graphite crucible is placed so that its beginning is located inside the coils of the inductor installed between the refrigerators. Moving the crucible with the metal is provided by the wired mechanism with a given speed. A high-voltage thyristor converter LST-63-ZUM (power 60 kV at a working frequency of 2.5 kHz) is the power supply of the device.

The melting of doped alloys was carried out in carbon (graphite) crucible-containers containing Fe, Al, Cu, Mg ($\leq 3\cdot10^{-5}$ weight %), Ca, B, Mn ($\leq 1\cdot10^{-5}$ weight %), Si ($<9\cdot10^{-4}$ weight %). The pieces of silicon were loaded to the bottom of the container, on the top there was an aluminum ingot of A5N (Al≥99.999 weight %), then the holmium was loaded evenly from above. The initial amount of silicon and holmium injected into pure aluminum exceeded the specified concentration in the alloy by 20 %. Redistribution of holmium and silicon in the conditions of zone recrystallization was about 3.5 %. X-ray spectral analyzer ARL-72K00 was used for determination of holmium and silicon content. The results of chemical analysis for determination of rare-earth metals (REM) and Si in Al-based alloys are given in Table 1, and the microstructure of Al-Si-No-1-1 and Al-No-1 alloys is shown in Fig. 1.

Table 1

Distribution of alloying impurities of REM on the height of the ingot

No.	Alloy	Content of alloying elements (%) at a distance from the bottom							
		5 mm		20 mm		45 mm		60 mm	
		Ho	Si	Ho	Si	Ho	Si	Ho	Si
1	Al-Si-Ho-1-1	1.4	1.1	1.3	1.0	1.0	1.0	0.8	0.95
2	AlHo-1	2.1	–	1.9	–	1.2	–	0.78	–

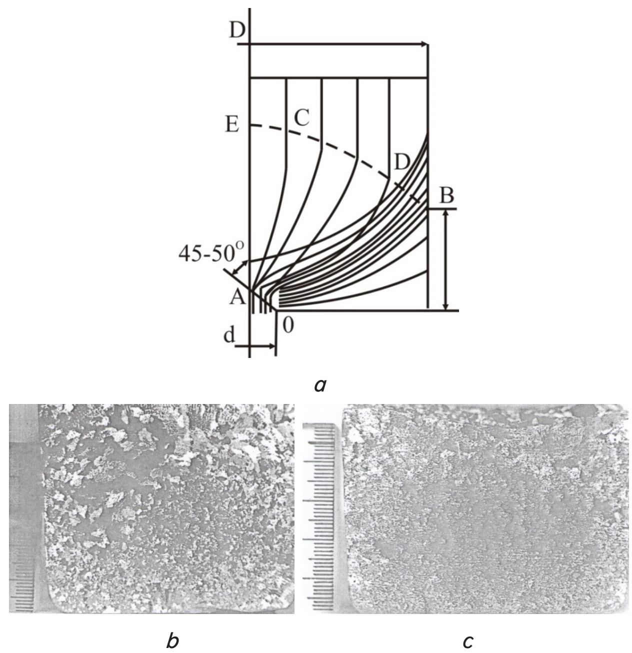


Fig. 1. Graphic (*a*) and structural (*b*, *c*) schemes of classical deformation of a circle of the workpiece.

As a result of the research, the specifications for ingots of Al-Ho-1,0 – AlHo-0.1-0.1 alloy on the basis of special purity aluminum (STU-0131-P/O-17), as well as on Al 0.5-2.0 Ho 0.1-1.0 alloy (STU18-0131-P/O-17) are developed. Technical specifications for specific Al, V, Nb alloys for targets and targets for magnetron deposition of cryo-alloys on the industrial device "Oratoria-5" with the planetary placement of substrates are designed.

6. 2. Development of industrial technology for the production of cryo-alloy targets for the deposition of superconducting metallization

In the manufacture of ingots of aluminum alloys with rare earth elements in the process of crystallization, the latter tended to precipitate in the bottom cleanliness. This leads to the fact that it is necessary to conduct zone cleaning of a large area in the ingot composition. Existing treatment of the melt does not eliminate the indicated heterogeneity. Therefore, it is expedient to use the so-called mechanical displacement of the layers in the process of forming the target workpiece, which is as follows.

The movement of metal layers of the target workpiece goes through complex trajectories in mechanical pressing. The scheme of layer moving is shown in Fig. 1. When using the flat-bottomed graphite matrix, there is a moving of molten metal from the central zone to the bottom one, which leads to the alignment of the chemical composition along the length of the pressed material. This is an important element of the technology of the formation of the target.

The technology of ingot recycling in the target includes the following operations:

– free forging;

– heating for forging up to 500±10°C (carried out in electronics without a protective atmosphere);

– forging was carried out in 5 stages.

As a result, rods of 80±2 mm in diameter were produced, which were then subjected to compression to a diameter of 37±1 mm. These operations provide chemical homogeneity in the content of alloying elements, which does not exceed 0.5 %.

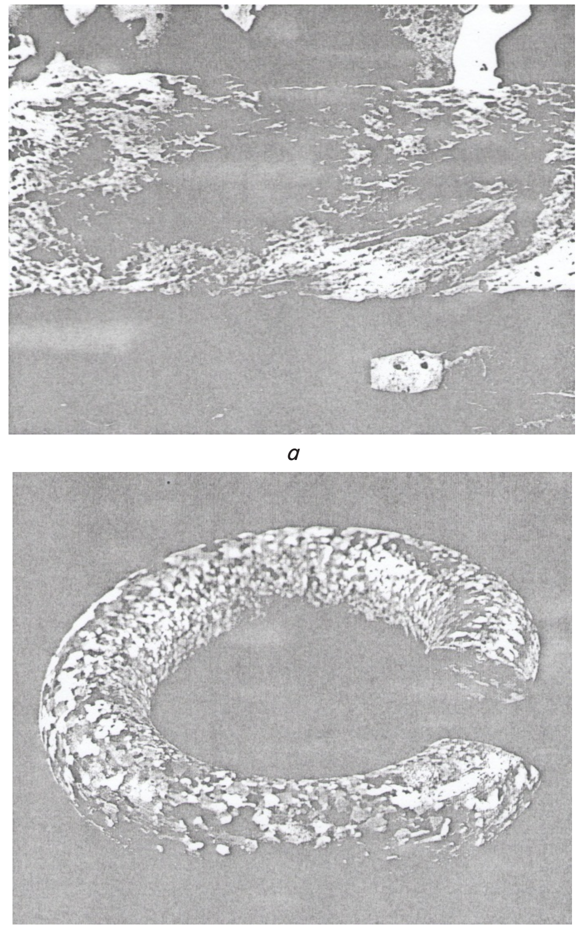
6. 3. Formation of a target for a magnetron from a pressed toroidal workpiece (on an example of aluminum one)

Let's consider first the process of pressure welding of the workpiece end-pieces, for which the corresponding technological process is developed that ensures the homogeneity of the toroid. In this case, the deformation in the interface zone varies from 21 to 39.6 % (almost 2 times). The authors of the work paid special attention to this process due to the lack of data in the technical literature on the research of welding modes. Strips of special purity materials (Al, Nb, Y) of 3 mm in thickness, 20 mm in width and 80 mm in length were used as initial models. The pressure welding was carried out by compression between flat plates, which simulated the real process that proceeded in the toroidal workpiece during stamping. To provide the necessary compression, the stops of different heights located between the stamps were used.

Experiments on welding of strips at room temperature yielded a negative result. A welding was not carried out in 80–85 % even during deformation. In the subsequent experiment, the welding of the toroid was carried out already by heating to 300 °C, which corresponded to the heating of the toroidal workpiece during stamping, when the plates were heated to 150 °C.

As a result of the research, it was found that there was a reliable grip of two parts of the model in the range of compression of 35–55 %, but the strength of the connection remained low and was within 25–75 % of the strength of the base metal.

From the practical experience of welding, it is known that a significant strengthening of the welded seam can be achieved by an introduction of diffusion annealing. In this case, in the zone of joint deformation, new grains are formed and grow, which sprout into the body of plate welding. Due to this phenomenon, the achievement of the high strength of the welded seam at the level of the weld metal is ensured. To check this possibility, an appropriate heat treatment of samples was selected, which was carried out in an electric furnace without a protective atmosphere for 2 h at 420–430 °C. This operation provides a sharp increase in the strength of the welded seam. In this case, the strength gain was 110-115 % in the range of small compressions, and only 25–35 % in the largest ones. This is due to the fact that high differential forces are accompanied by intense heat release. It was established that both recrystallization and diffusion processes in the seam proceed at 55–75 % deformation, which provides a given level of strength. Such a deformation provides a displacement that deviates from the horizontal plane at 17–21°. This demonstrates the microstructure of the welded seam of aluminum toroid (Fig. 2). Aluminum toroid was used to form the target on the magnetron deposition "Oratoria-5" device for magnetron formation of Al-Si-Ho-1-1 films.



a

b

Fig. 2. Microstructure: *a* — of zones of weld seam of Al-toroid; *b* — toroidal workpiece of the target for the "Oratoria-5" device

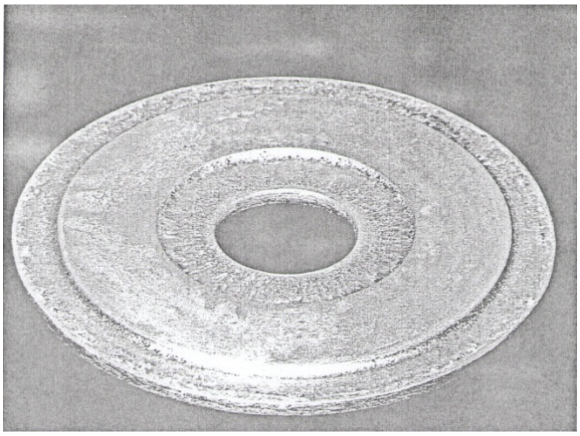
6. 4. Technological process of targets formation for superconducting wiring of LSI structures.

The production of a target (for example Al-Si-Ho-1-1) for magnetron deposition of superconducting films is carried out as follows.

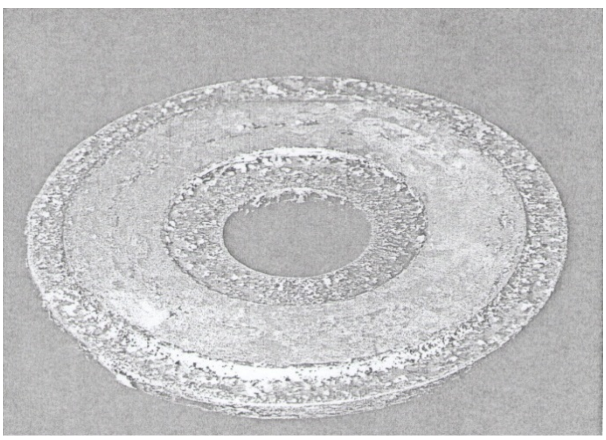
1. Removing a container with ingots of cryo-alloys.
2. Separation of the ingot into two equal weight parts.
3. Chemical treatment in aqua regia and washing in deionized water with bubbling.
4. Forging of the workpiece to 80 mm in diameter at 773 K (the maximum concentration should be at the bottom of the forging).
5. Pressing the workpiece of 34.5 mm in diameter at 773 K.
6. Formation of a workpiece in the "bagel" form.
7. Milling of the "bagel".
8. Chemical treatment of the "target" workpiece.
9. Formation of the target at 773 K by stamping at a pressure P=200 kPa/cm^2 2–5 times.
10. Turning of external and internal diameter with pressing and using of cooling liquid (alcohol).
11. Chip selection for chemical analysis from the working and reverse side of the target.

12. Chemical treatment of the "target" workpiece in aqua regia.

The general view of the target is shown in Fig. 3 and technical specifications are developed for parameters and technical characteristics of targets.



a



b

Fig. 3. Targets from cryometallic alloys for the formation of superconducting wiring in SiC or GaAs-based LSI structures. Targets made of aluminum alloys doped with holmium (*a*) and silicon and holmium (*b*)

7. Investigation of superconducting metallization and Schottky barriers of Nb and Y alloys on GaAs-structures

The increase in the speed of LSI/VLSI structures on GaAs is achieved by using thermostable cryomaterials as gate electrodes, conductors and contacts of source-drain regions of the Schottky field-effect transistors (ShFTs). The choice of gate material and deposition method determine the state of the interface boundary and the nature of the possible chemical interaction of the electrode material with the substrate, and the manufacture of short-channel ShFT with submicron interelectrode gaps provides the use of combined topological processes and cryoregimes.

Therefore, alloys of aluminum, niobium and vanadium were selected as the investigated materials of the Schottky barrier (ShB) electrodes. Magnetron deposition method characterized by low energy interaction on the substrate at high deposition rates was chosen as a method of application.

Insignificant thermomechanical stresses (about 1 kg/cm^2) and small grain size (~10 nm) will allow excellent adhesion of deposited films and formation of a topological pattern of submicron sizes by photolithography.

The advantage of niobium and vanadium alloys with silicides (polycytes) and nitrides of other metals (ZnN, TiN, NbN) is due to the ability to successfully combine the processes of the formation of strongly doped source-drain regions and submicron gaps in short-channel ShPTs. This provides a high level of conductivity of contacts and conductors in the cryoregimes, which became possible due to the saturation of the time dependence of the thicknesses of niobium, vanadium and gallium arsenide low-temperature alloys, the nearness of the optimal oxidation temperatures of these materials, and also due to the nearness of the temperatures of subsequent sublimation processes of GaAs oxides and annealing in the hydrogen atmosphere. At the same time, the reduction of niobium and vanadium oxides takes place during the process of hydrogen annealing, which significantly reduces the contact resistance of source-drain regions as the main parameters of ShPTs.

The results of electrophysical investigations of ShB parameters from Nb/n-GaAs and V/n-GaAs alloys obtained during magnetron sputtering of Nb-Si-Ho-1-1 and V-Ge-Ho-1-1 alloys respectively on the n-GaAs substrate in plasma argon are considered in this study. Partial pressure was set by precision runaways at a pressure of 1 Pa. The heating of the substrates was established and stabilized in the temperature range of 350–480 K, the rate of the film deposition varied by adjusting the discharge power and the choice of the argon plasma. Electrophysical studies of ShBs showed that the deposition rate of 0.35–1.45 nm/s is optimal. The choice of the technological mode of deposition at a fixed spray velocity was carried out in such a way that the films had the maximum critical temperature of transition to the superconducting state, indicating the formation of films close to the stoichiometric composition. Specific resistance of films of niobium and vanadium alloys was in the range of 18–22 μΩ·cm.

ShBs obtained in such way were burnt in the reducing atmosphere of hydrogen or arsenic and hydrogen to stabilize the surface charge. The quality of ShBs was estimated by the height of the barrier φ_b, the factors of the barrier non-ideality n, the saturation current I_s and the breakdown voltage U^*. In the framework of the generalized ShB model taking into account thermoelectron emission, diffusion and Schottky effect, the calculations made allowed obtaining the following values for the above parameters: the nonideal factor varies in the range of 1.02–1.05 in the temperature range 100–350 K, the saturation currents – in the interval $6\cdot10^{-6}$–$2\cdot10^{-2}$ A/cm^2, the breakdown voltage of inverse ShB was 25–35 V for niobium alloys and 20-30 V for vanadium ones.

Since the obtained values of the electrophysical parameters were calculated in order to prevent the chemical interaction of ShB electrode materials with the surface of the semiconductor GaAs substrate, as well as the absence of transition layers of surface oxides recovered in hydrogen, comparison of the calculated and experimental data of ShB parameters allows concluding about high efficiency of the use of Nb and V alloys for the formation of ShB electrodes of ShPT gates.

The dependencies of ShB parameters for the niobium (n-GaAs) and vanadium (n-GaAs) alloys on the annealing temperature under conditions of different conditions of preparation of GaAs substrate surface and deposition of ShPT gate electrode are presented in Fig. 4, *a*, *b*. Significant improvement of the electrophysical parameters of ShB in the conditions of reduction annealing of the structures has been achieved. Various metal-semiconductor junctions are formed in the region of annealing temperatures of 900–1,000 K, when the breakdown voltage increases by 5–10 V.

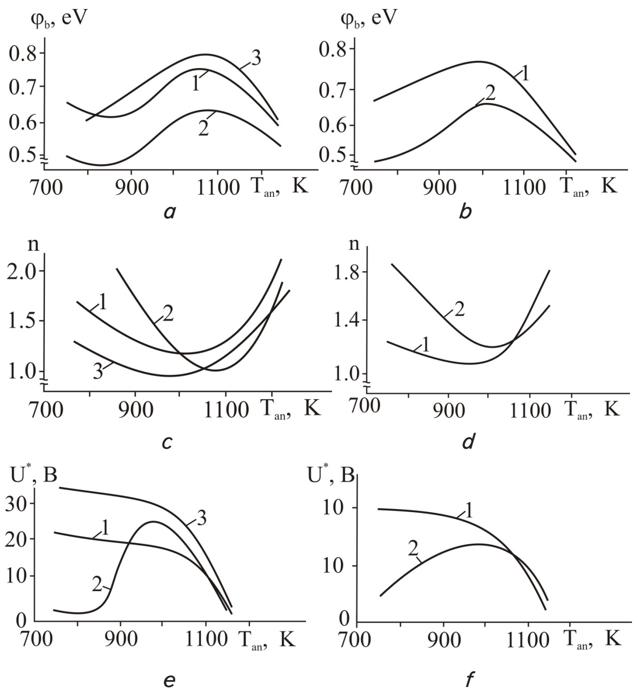


Fig. 4. The effect of annealing temperature on the Schottky barrier height φ_b, the factor of non-ideality n and the breakdown voltage U^* of the Schottky barrier:
a, *c*, *e* — Nb-Si-Ho-1-1 alloys (n-GaAs);
b, *d*, *f* — V-Ge-Ho-1-1 alloys (1 — without surface treatment; 2-3 — with treatment in Ar-plasma)

The value of the breakdown voltage approaches to certain stable value of 10-15 V with a decrease in the ShB area. The values of Richardson constant A^* for ShBs, formed at different temperatures of hydrogen annealing, are obtained from the processing of temperature dependence φ_b=f(T) in the coordinates $(\ln\left(\frac{I}{S}\right), -\frac{\varphi_b}{kT}+2\ln T)$ (Fig. 5). The Richardson constant reaches the value 9 A·cm^{-2}·K^{-2} in the region of optimal temperatures, which results in barrier formation of 1 eV for the rate of surface electron recombination $\sigma_t N_t(1-f_t)$. This may be due to some deterioration of the straightening ability of ShB due to a certain increase of an electronic component of the emission stream from the superconductor to the metal.

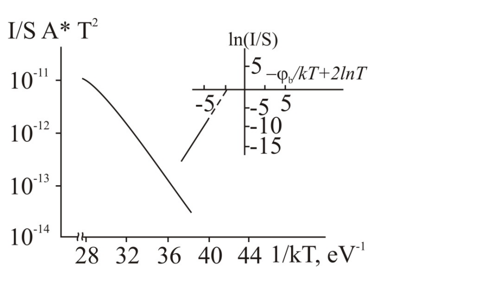


Fig. 5. Temperature dependence of the saturation current of the Schottky barrier Nb-Si-Ho-1-1 at an optimum temperature of hydrogen photon annealing at 1050 K for 10 s

8. Discussion of the research results and ways to increase the speed of field transistors on GaAs due to the formation of 2D-electron gas (2DEG) at the junction of semiconductors $Al_xGa_{1-x}As$-GaAs

The third factor that significantly influences the LSI speed on the ShFTs basis is the increase in the mobility of charge carriers (electrons) by almost an order of magnitude in cryoregime.

Another promising element of both digital ultra-fast chips and analog microwave range circuits is the heterostructured field-effect transistor with the control junction of the metal-semiconductor (HMES-transistor).

The properties of heterojunctions between thin monocrystalline layers of two semiconductor materials with similar crystalline structure, but different size of the gap are used in this transistor. Today, heterojunction between gallium arsenide (GaAs) and aluminum-aluminum arsenide ($Al_xGa_{1-x}As$) is most widely used, where x shows the relative content of aluminum. The width of the gap ΔE_g for gallium arsenide-aluminum linearly increases with x, i.e. this semiconductor is a varyzone one at x=0.2 (ΔE_g≈1.81 eV). The equilibrium energy diagram of the heterojunction between the undoped GaAs and doped by donor admixture (Si) $Al_xGa_{1-x}As$ is shown in Fig. 6, *a*.

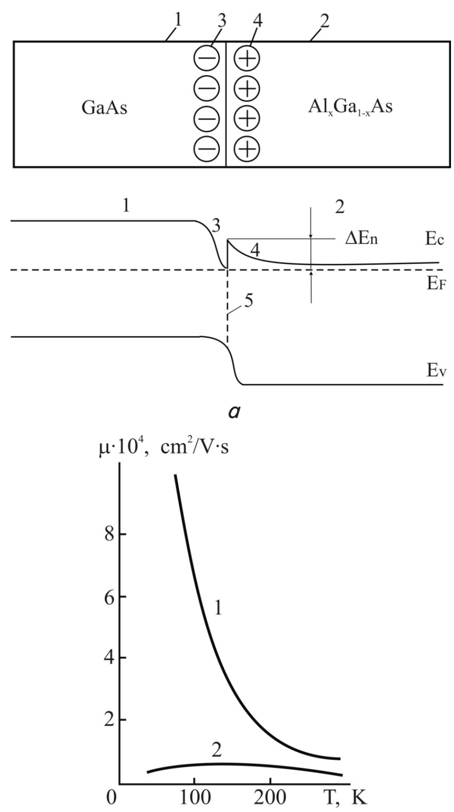


Fig. 6. Heterojunction on GaAs: *a* — structural and zone diagrams; *b* — temperature dependence of electron mobility in 2DEG for heterostructure GaAs-$Al_xGa_{1-x}As$ with the Ge-based buffer layer

The horizontal dashed line corresponds to the Fermi level E_F (in an equilibrium state its energy is the same for both semiconductors), E_v is the energy of the valence band boundary. Fermi level is located almost in the middle of the gap in undoped GaAs (region 1), which is practically an intrinsic semiconductor, and for $Al_xGa_{1-x}As$ doped by donors (Si) with a concentration of N=(1–20)·10^{17} cm^{-3} (region 2) it is located already near the bottom of the conduction band E_c.

The region 3 with minimum electron energy is formed in GaAs near the boundary 5 of these two semiconductors in the conduction band. In this region, the accumulation of electrons, passing from region 4 located in doped $Al_xGa_{1-x}As$, takes place. Region 4 is strongly depleted by electrons and is charged positively, since it contains uncompensated donor ions. Here, the split of the conduction band bottom E_c (energy jump ΔE_n) is 0.32 eV at the boundary 5 at x=0.3 (Fig. 6, *a*).

Therefore, the electrons, accumulated in region 3, are located in a deep potential well and can move in weak electric fields only along the interface 5 in the plane perpendicular to the plane of the figure. Such set of electrons accumulated in the region 3 is called a two-dimensional electron gas (2DEG), thus emphasizing that in the weak fields these electrons can not move in the third dimension, that is, to move, for example, from region 3 to region 4, since the potential barrier created by the split of the conduction band ΔE_n will already prevent this process.

The electrons that formed the 2DEG arise due to the thermal ionization of the donor impurities in AlGaAs, where the impurity concentration is large (>10^{17} cm^{-3}), and moves to the region 3, located in the undoped GaAs, where the impurity concentration is small (<10^{14} cm^{-3}). Thus, the spatial separation of free electrons (in region 3) and scattering centers (acceptor ions), concentrated in $Al_xGa_{1-x}As$ is achieved.

A low density of surface states and defects is provided in the heterojunction due to the good correspondence of crystalline lattice constants of two semiconductor materials. For the electrons, accumulated in region 1, very large mobility is achieved in weak electron fields, which is close to the bulk mobility of undoped GaAs of (8-9)·10^3 cm^2/V·s at 300 K [20]. Since the lattice arrangement predominates in the undoped layer of GaAs, the mobility sharply increases (by an order of magnitude), when the temperature decreases to the cryogenic one (77 K). This is a method for increasing the speed of both elements (field transistors) and LSI/VLSI structures.

For better spatial separation of 2DEG and scattering centres between undoped GaAs and donor-doped $Al_xGa_{1-x}As$, a thin (<10 nm in thickness) separating (buffer) layer of undoped gallium arsenide-aluminum or germanium is formed. The concentration of scattering centres in the buffer layer is much lower than in the doped one, therefore, the mobility of the electrons, accumulated in region 3, is increased additionally, which leads to an increase in the speed of field transistors on GaAs.

Temperature dependence of electron mobility for 2DEG in the heterostructure with the buffer layer is given in [20].

The mobility of electrons increases to 1.4·10^5 and 2·10^6 cm^2/V·s at a temperature of liquid nitrogen (77 K) and liquid helium (4 K), respectively. Fig. 6, *b* demonstrates for comparison the temperature dependence of electrons in GaAs containing donors with a concentration of 10^{17} cm^{-3}. This type of layer is used in the structures of field transistors (metal-semiconductor).

The mobility of electrons of 2DEG strongly depends on the technology of heterostructure formation especially at cryogenic temperatures of liquid nitrogen and helium. Different methods of epitaxial growth of thin semiconductor layers (so-called layered structure) are used to create a heterostructure. The best quality of the epitaxial structures for the formation of the heterostructure, the smallest defect density at the boundary and the greatest mobility are provided by the molecular beam epitaxy and the gas-phase epitaxy from the organometallic compounds.

The above-described heterojunctions are used in structures of field transistors with a metal-semiconductor control junction (Schottky barrier). Such a structure of the field transistor (normally open and normally closed) is given in [20]. In the formation of normally open structures, the undoped layer of p-type conductivity GaAs, undoped buffer layer of $Al_xGa_{1-x}As$, doped by silicon (Si) to the concentration N_σ=(5–9)·10^{17} cm^{-3} n^+-layer of $Al_xGa_{1-x}As$ are sequentially deposited on a doped semi-insulating GaAs substrate by the molecular-beam epitaxy. Aluminum alloys Al-Si-Ho-1-1 (or Al-Ge-Ho-1-1) are used to form the gate. These alloys are simultaneously used to form the wiring and contacts of source-drain regions. In a normally closed ShFT with an induced channel, the upper layer of arsenide gallium aluminum is partially etched to 50 nm in thickness (instead of 70 nm for a normally open transistor). This allows the formation of normally open and normally closed ShFTs (so-called complementary structure) on one substrate (structure).

The threshold voltage of such ShFT is determined by the expression:

$$U_T = \varphi_{eh} - \frac{\Delta E_n}{q} - qN_\sigma d^2 / 2\varepsilon_0 \varepsilon_{n2}, \quad (1)$$

where φ_{eh} – equilibrium height of the potential Schottky barrier of junction metal (gate) as Al-Si-Ho-1-1 – semiconductor n^+-$Al_xGa_{1-x}As$; d – total thickness of donor doped (Si) and undoped gallium arsenide-aluminum; ε_{n2} – its relative dielectric permittivity.

The principle of operation of the hetero-ShFTs (HShFTs) is similar to the principle of operation of the ShFTs on the homojunction. A metallic-semiconductor control barrier is formed between the metal gate and the underlying layer of gallium arsenide-aluminum. The depleted region of this junction is mainly located in the n-layer of gallium arsenide-aluminum.

The channel of the semiconductor transistor is formed at gate-source voltage U_{gs}<0 in the layer of undoped arsenide of gas (p-GaAs) at the boundary with the heterojunction in the region of accumulation of 2DEG. The thickness of the depleted metal-semiconductor junction region, the concentration of electrons in the saturation region and drain current are changed due to the influence of the gate-source control voltage.

The depleted region expands so much that it completely overlaps the accumulation region of electrons so that the flow current stops at a fairly large negative gate-source, which is equal to the threshold value U_T.

In a normally closed HShFT due to the lower thickness of the upper layer of doped n^+-$Al_xGa_{1-x}As$ at U_{gs}=0, the conducting channel is absent, because the accumulation region of 2DEG is blocked by an enlarged domain of the control junction (barrier). A channel in such HShFT occurs at a positive voltage equal to the threshold one, when the depleted region of the control junction is narrowed to such an extent that the lower limit falls into the saturation region of 2DEG.

Due to the high mobility of electrons in the whole range of gate voltage, the accumulation of the drift velocity of electrons in the channel is achieved and there is a linear dependence of the drain current [20]:

$$I_d = S'\left(U_{gs} - U_T - E_{cr} I_z\right), \quad (2)$$

where E_{cr} – critical field strength, $S' = \varepsilon_0 \varepsilon_{n2} \sigma_n b / d$. For equations (1) and (2), the great value of the steepness S' for normally closed ShFT is due to a smaller thickness of donor (Si) doped arsenide gallium-aluminum.

The important advantages of HShFTs (in comparison with homo-ShFTs) are the lower surface state density Q_{ss} at the boundary gallium arsenide-aluminum – dielectric and the rather high Schottky barrier (0.75 eV). Due to the lower surface states density, the negative surface charge and the thickness of the depleted region are reduced, which allows significantly decrease the parasitic resistance of these regions without using additional technological operations of selective ion multi-charge alloying, which are necessary for transistors with self-aligned structure. The multi-charge implantation of the source-drain regions is sufficient for this. The permissible direct gate-drain voltage reaches 0.7 V due to the increased height of the Schottky barrier for HShFTs. This is especially important for normally closed transistors, for which the working gate voltages can vary in a fairly narrow interval, limited by the barrier voltage of the control junction of metal-semiconductor of 0.7–1 V.

Pulse and frequency properties of HShFTs are determined mainly by the transit time of electrons t_{tr} through the channel of length L_g, where they are moving with the saturation speed $\upsilon_{sat}=L_g/t_{tr}$. $\upsilon_{sat}=2\cdot10^{17}$ cm/s at T=300 K. The saturation velocity increases according to the law $\upsilon_{sat}=1/T$ at low cryo-temperature, which reduces the transit time, leading to a significant increase in the electron speed.

HShFTs are very promising not only for digital LSI/VLSI structures, but also for use in the microwave range of analog circuits. The best parameters of these transistors are achieved at cryotemperatures. However, the basic parameters are better than for homo-ShFTs at room temperature. For example, ShFTs with a gate of 0.25 μm in length have a noise ratio of 1.8 dB and a gain of 9 dB in the frequency range 18–30 GHz. Similar values of these parameters for HShFTs are already achieved with a gate of 0.45 μm in length. Today, HShFTs with a gate of 0.2 μm in length are already certified and provide a working frequency of 180–220 GHz. To reduce the cost of these schemes, it is necessary to build an LSI/VLSI technology (serial in the Unified System of Technological Documentation) on GaAs layers epitaxially grown on Si substrates, namely:

– to develop the technology of production of superconducting alloys of semiconductor purity using zone melting;

– to develop the technology for obtaining targets for magnetron sputtering in the sub-micron technology of LSI-structures for these superconducting alloys;

– to choose the necessary alloying admixtures for superconducting alloys to increase the cryothermic temperature on the basis of research;

– to design and develop the technology of LSI mounting on cryo-radiators, cryo-frames, cryo-tables for measuring the parameters of such systems in cryoregime by the computer system.

9. Conclusions

1. A theoretical analysis was conducted to use superconducting materials for the formation of cryoconductive wiring in LSI-structures based on high-speed GaAs ones. The technology of making cryo-alloys based on Al, Nb, V with admixtures of Si, Ge and REM is developed on this basis. The originality of the alloys is that Si, Ge and REM admixtures are introduced in them, i. e. Si and Ge content ensures high solubility of the alloy in the contacts, and REM admixture eliminates the hillock formation, which increases the density of the wiring.

2. The possibility of making targets for magnetron deposition of films for the formation of superconducting wiring in GaAs-structures is investigated. Highly effective technology of magnetron formation of superconducting films from aluminum, niobium and vanadium alloys has been developed. In particular, technological regimes (ion current, accelerating voltage, deposition rate, plasma composition, uniformity of components per silicon substrate diameter) have been established, which provide a thickness of films at the level of 0.6–1 μm. This technology can be used in magnetron devices of continuous operation of "Magna" type.

3. The parameters and characteristics of the Schottky field GaAs transistors on homo- and heterostructures (Schottky barrier height 0.75–0.8 eV, non-ideality factor 1.2–2, breakdown voltage of Schottky barrier 15–30 V) are explored and methods for increasing the speed of the LSI-structures are defined.

4. The recommendations for the technology of formation of complementary LSI-GaAs-structures on HShFTs are presented. This allows the formation of normally open and normally closed ShFTs on the same substrate, which form complementary structures that consume energy only at moments of switching.

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