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FEATURES OF FORMATION OF MICROWAVE GaAs STRUCTURES ON HOMO AND HETERO-TRANSITIONS FOR THE SUBMICRON LSIC STRUCTURES

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Розглянуто особливості технології формування надвисокочастотних (НВЧ) GaAs структур та проведено комплекс досліджень для створення серійної технології структур великих інтегральних схем (ВІС), в тому числі НВЧ на епітаксійних шарах GaAs, осаджених на монокремнієвих підкладках.

Досліджено умови формування двомірного електронного газу в гетероструктурах з визначенням рухливості електронів в залежності від орієнтації поверхні. Для гетеростуктур на поверхні напівізольованої GaAs-підкладки, розорієнтованої від площини (100) на кут 6–10° із вмістом кисню на вихідній поверхні C0=10–50 % по відношенню до піку галію Оже-спектру, виявлена сильна анізотропія рухливості за рахунок збільшення кута розорієнтації та неповного відпалу вуглецю з вихідної поверхні GaAs-підкладки.

Для осадження шарів арсеніду галію на монокремнієвих підкладках застосована епітаксійна технологія, яка дозволяє значно підвищити чистоту отриманого матеріалу, а саме суттєво понизити рівень ізоконцентраційних домішок кисню і вуглецю, які сильно впливають на зарядовий стан міжфазної межі.

Для формування конструктивних шарів на GaAs розроблена і досліджена технологія формування нітридних шарів Si_3N_4, AlN, BN магнетронним методом при низьких температурах підкладки та заданою стехіометрією. Суміщення арсенід галієвої епітаксійної технології на монокремнієвих підкладках реально стало можливим тільки при розробці технології магнетронного осадження буферних шарів германію.

Розроблена технологія формування логічних елементів НЕ, АБО-НЕ, І-НЕ високої швидкодії з низькою пороговою напругою, яка дозволяє будувати високошвидкісні мікросхеми комбінаційного і послідовних типів на комплементарних структурах.

Ключові слова: комплементарні структури, низькотемпературна епітаксія, інтегральні схеми, буферний шар, магнетронне осадження

1. Introduction

Today's Schottky-barrier field-effect transistor (SBFET) is in fact the main active elements of gallium-arsenide microwave circuits. The main goal of their development is increasing a speed. Digital gallium arsenide LSICs belong to the class of super-fast, and analog, as a rule, are designed to work in the microwave range.

When developing SBFET-based microcircuits, the following advantages of gallium-arsenide are used as compared to monosilicon: higher electron mobility in weak electric fields and saturation rates in strong fields, a large band gap. In this regard, as a result, the resistivity of undoped GaAs is much larger, which allows the formation of semi-insulating layers (local and interlayer) in the LSIC structures. But gallium arsenide is inferior to monosilicon in a number of parameters that are important for the formation of transistors and microcircuit structures. Thus, the high density of surface layers in a metal-dielectric semiconductor (MDS) GaAs-based structure today does not allow the formation of high-quality MDS transistors and microcircuits. The low hole mobility and short lifetime of minority charge carriers complicates the development of bipolar complementary transistors. For these reasons, the optimal active element, which makes it possible to realize the advantages of GaAs compared to mono-Si in IC/LSIC structures, is precisely the SBFET metal-semiconductor.

The technology of obtaining high-purity GaAs crystals is rather expensive, therefore, the actual problem is the development of epitaxial technologies for the formation of GaAs structures on Si substrates.

2. Literature review and problem statement

Silicon-based semiconductor technologies have played an important role in integrated circuit technology in recent decades [1, 2]. Recently, semiconductor $A^{III}B^{V}$ type compounds, for example, gallium arsenide, have been used as an alternative [3]. In [4], it is noted that since 2010 the volume of commercial microelectronics products based on gallium arsenide has increased several times. This growth trend continues to this day. One of the areas of application of electronic devices GaAs is microwave electronics. Typical diameters of grown ingots are 100–150 mm, commercial crystals with a diameter of 200 mm [5] and more have also appeared.

As dielectric layers for GaAs structures, Al_2O_3 is promising, the main method for obtaining which at the moment is the atomic two-layer deposition method [6, 7]. Some progress has been made in creating a field GaAs transistor based on MDS structures with Al_2O_3 [7].

With a decrease in the geometrical dimensions of the transistors, the crystal area decreases, the parasitic capacitances decrease, the speed increases and the power consumption of the LSIC decreases. Today, special attention is focused on the architecture of structures for the LSIC submicron range [8, 9]. It is through architecture that the technology issue is expressed qualitatively: the growth of structures, the formation of functional layers and circuit design [10, 11]. Integrated on-chip systems are also being actively developed using sensors of various physical quantities [12], which imposes additional requirements on the creation of route technology for forming such systems.

The authors of [8, 11] note the limitations of the existing technology for forming high-speed LSICs on GaAs with the technological capabilities of gallium arsenide as a compound due to the high cost of gallium ingots to arsenicum, low thermal conductivity gallium to arsenicum, which is 3–5 times less than thermal conductivity of silicon. There are also unsolved technological problems of manufacturing Czochralski ingots with a diameter of more than 75 mm with semiconductor purity [8, 11]. In particular, the unsolved problem of cleaning GaAs ingots from isoconcentration impurities of oxygen and carbon, which negatively affect the charge state of the semiconductor-insulator interface. Modern schemes are formed with multilevel layout with the upper metal layer based on aluminum alloys are not devoid of hillock pattern, that is, the formation of protrusions-needles due to different thermal expansion coefficients.

Today, it is necessary to develop a technology for forming high-speed LSICs on epitaxial layers of GaAs deposited on large-diameter silicon substrates, which makes it possible to combine arsenide-gallium and silicon technologies [13]. The epitaxial technology and the effect of technological parameters on the properties of semiconductor films are considered in [14]. It is shown that one of the main technological factors is the substrate temperature. In [15], the features of the SBFET formation with a self-mixing gate based on tungsten nitride or silicide are considered. It is shown that the use of SBFET on GaAs for the formation of high-speed LSIC has a great prospect. Therefore, it is expedient to develop methods that allow the formation of complementary structures of transistors for the combined silicon and arsenide-gallium technology.

Today, the problem of the formation of dielectric capsule-blue layers to provide highly stable submicron-like LSIC structures on both silicon and gallium arsenide is also becoming urgent. For silicon ICs/LSICs, this problem is solved by using the oxide and nitride layers of silicon. At the same time, for the LSIC on the basis of $A^{III}B^{V}$ compounds, the necessary research and development of low-temperature methods for obtaining dielectric films of high thermal field stability.

The paper presents the features of the formation of submicron structures of microwave SBFET on GaAs homo- and hetero-transitions, which are formed on Si-substrates using Ge buffer monolayer. And this allows to create complementary structures of transistors for the combined silicon and arsenide-gallium technology. This technology, in combination with non-destructive methods of electrophysical diagnostics of reliability even at the stage of crystal manufacturing, allows to significantly reduce the cost of C production.

3. The aim and objectives of research

The aim of research is development of a technology for manufacturing self-aligned LSICs on complementary SBFET on epilayer of GaAs deposited on Si substrates. This will make it possible to switch to large diameters of the substrates, which will bring the cost of GaAs LSIC technology to silicon technology, as well as reduce energy consumption and improve the LSIC thermal characteristics.

To achieve this aim, the following objectives were solved:

– determination of technological regimes and implementation of low-temperature epilayer of GaAs and Ge on Si substrates;

– the study of silicide and nitride technologies for the formation of spacers and interlayer insulation of SBFET on GaAs;

– the choice of the necessary structural and technological options for the structures of the first-class technical infrastructure on the GaAs epilayers on Si substrates;

– design and development of technology for the formation of buffer and encapsulate layers for self-aligned LSIC on the SBFET, formed on the epilayer GaAs, deposited on monosilicon substrates.

4. Two-dimensional electron gas (2DEG) in the n-$Al_xGa_{l-x}As$/GaAs system on disoriented oxygen-containing substrate

The prospect of the development of modern digital circuitry is associated with the submicron technology for the formation of IC/LSIC structures on the SBFET on a hetero-transition, as well as with low-dimensional electronic systems. Restrictions on the degree of freedom (1D and 0D states) are accompanied by the appearance of a new quality in electrons, which is expressed in increased mobility during the formation of a two-dimensional electron gas.

The originality of the developed technology is that in a single process of low-temperature epitaxy, n-$Al_xGa_{l-x}As$/GaAs hetero-transitions are formed where areas of accumulation of two-dimensional electron gas with high mobility are created, which is an order of magnitude larger than GaAs. This is the basis of the technology for the formation of complementary structures of the first-stop technical equipment on monosilicon substrates.

High-resolution electron and submicron photolithography implemented quasi-one-dimensional states in selectively doped hetero-structures with 2DEG). It is an alternative solution for creating 2DEG quasi-one-dimensional conductivity on the profiled surface of the interface of the hetero-transition.

Such a growth mechanism by epilayers of mono-Si on Si-substrates, which is disoriented in angle of 3–4.5°, makes it possible to implement bipolar technology for the formation of IC/LSIC structures.

Measurement of carrier concentration and mobility and processing of results were carried out according to the test electrophysical control method described in [16], using automated computer systems T45-03 and AIK-TEST.

A strong anisotropy of mobility is found due to an increase in the angle of reorientation and incomplete annealing of carbon from the initial surface of the GaAs substrate. The effect of isoconcentration impurities of oxygen and carbon on the getter effect in silicon LSICs was also studied.

In particular, hetero-structures on the surface of a semi-isolated GaAs substrate rotated from the (100) plane to an angle of 6–10° with the oxygen content on the initial surface C_0=10–50 % relative to the Auger gallium peak were investigated. The effect of isoconcentration impurities of oxygen and carbon on the epitaxial growth of hetero-layers, and their effect on mobility were studied. Grown structures with carrier surface concentration n_s=(1–6.7)·10^{12} cm^2 and mobility μ=(2.7–6) m^2/V·s at T=77 K for various oxygen concentrations (10–60 %), what is shown in Fig. 1. It is seen that with increasing concentration of oxygen impurity, the concentration of electrons significantly decreases, and their mobility increases. This is due to the getter effect of oxygen acceptors.

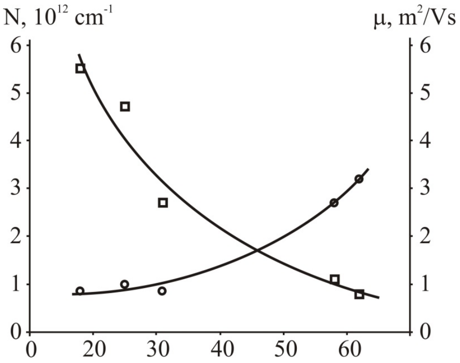


Fig. 1. Dependence of the mobility (♦) and concentration (■) of electrons in GaAs hetero-structures on the oxygen concentration

The anisotropy of the properties of this hetero-structure was measured on narrow and long sample-test structures (TS) with a ratio of length and width 3–7 and orientations [110] and $[1\bar{1}0]$. For this, the characteristics of conductivity, magnetoresistance in a classical and quantized magnetic field were measured. Fig. 2 shows the results of the determination of the magnetoresistance anisotropy of samples of a hetero-structure with 2DEG on oxygen-containing GaAs substrates (1–4 – direction [110], 1′–4′ – direction $[1\bar{1}0]$). This is based on the method of measuring the longitudinal and Hall resistances described in [15]. It should be noted here that the degree of mobility anisotropy: $\gamma = \mu^{(110)}/\mu^{(1\bar{1}0)}$, characterizing samples of hetero-structures with strong reorientation, which have a sufficiently large value γ=1.4~2.6, indicates the dependence of mobility on the orientation of the structure. This result is presented in Fig. 2, on which two characteristic features of these models are visible: the first is a decrease in anisotropy with a decrease in the electron mobility (2DG) – curves 1,1′ and 4,4′. The second feature is that the mobility in the [110] direction is greater (by an order) than in the direction. This result was confirmed, both at the measurement at T=77 K and at T=4 K.

Such observed anisotropy is explained by highly mobile extended states in the two-dimensional channel of the hetero-structure in the [110] direction.

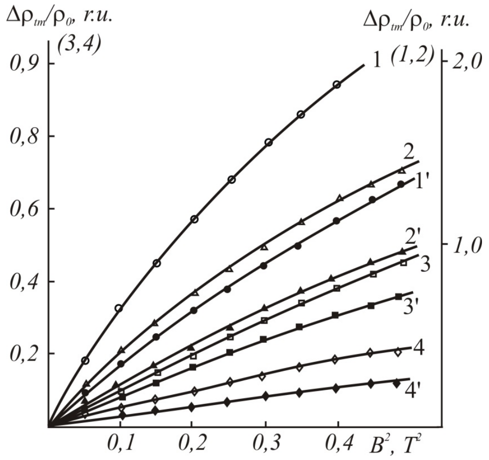


Fig. 2. Dependence of the relative transverse magnetoresistance of GaAs hetero-structure samples with 2 DEG on capsule-free GaAs substrates on the square of the magnetic field B^2: orientation on the substrates, direction [110] — curves 1—4; direction $[1\bar{1}0]$ — curves (1′-4′)

Then, based on the relation $\mu^{-1} = \mu_{\mathrm{I}}^{-} + \mu_{\mathrm{II}}^{-1}$, where $\mu_{\mathrm{I}}=\mu^{(110)}$, $\mu_{II} = \mu^{(\bar{1}\bar{1}0)}$, and the value γ=1.41 for sample 1, let's have μ_n=13.2 m^2/V·s and μ_{I}=9.4 m^2/V·s at T=77 K, which significantly (by an order of magnitude) exceeds the value of the integral mobility μ=5.47 m^2/V·s, measured at the van der Pauw (Hall) TS. These experiments show the need for a significant reduction in the concentrations of these impurities of oxygen and carbon in GaAs substrates. The obtained results allow to determine the technological regimes and realize low-temperature $Al_xGa_{1-x}As/GaAs$ epitaxy on Si substrates.

The studies of the quantum Hall effect indicate the great promise of the hetero SBFET technology using the molecular beam epitaxy (MBE) method for the synthesis of selectively doped hetero-systems containing 2DEG with high mobility and anisotropy of their electrophysical properties. It is possible to expect an increase in the anisotropy effect on substrates from disorientation 4–6° and localization of 2D electrons in quasi-one-dimensional states. Such a realization of quasi-one-dimensional leading channels in LSIC heterosystems, accompanied by a sharp increase (by several orders of magnitude) of mobility, will become the basis for the formation of a new generation IC/LSIC. As well as microwave circuits with new unique properties, where the analog and digital microwave signal will be combined on the same LSIC structure.

5. Silicide and nitride technologies for the formation of encapsulating layers on GaAs for spacers and interlayer insulation

One of the main criteria for a dielectric coating to gallium arsenide is its capsule quality. Silicon dioxide (SiO_2) can't be a reliable sealing coating when heated, since there is a significant diffusion of gallium and arsenic atoms through the dielectric layer. AlN and Si_3N_4 compounds are thermally stable diffuse barriers for Ga and As, but the possibility of using these compounds as capsule-based coatings for GaAs is limited due to the large difference in thermal expansion coefficients [15].

Formation of aluminum nitride films, which has a thermal expansion coefficient closest to GaAs, and silicon nitride films on GaAs when spraying a flat aluminum (silicon) target with a directed beam of nitrogen ions with a small content of argon ions (3–5) %, which regulates the rate of magnetron deposition. When microwave magnetron sputtering aluminum (silicon) target nitrogen ions are neutralized and, falling on the substrate, form a nitride mask. The addition of heavier argon ions to the nitrogen plasma increases the rate of sputtering of the target and thereby changes the ratio of metal (semiconductor) and active nitrogen in the film, changing its stoichiometric composition. And the use of doped Al and Si targets changes the coefficients of thermal expansion within the specified limits. This is where aluminum targets made of AKG_0-1-1 or AGG_0 alloys are used (other metals can be used instead of REM), as well as silicon targets of the KDB-10 or KDB-80 substrate (the boron content changes both the refractive indices and thermal expansion).

When using ion-beam (magnetron) sputtering, it is also possible to significantly reduce the temperature of deposition of high-quality layers when using rotating magnetic blocks that are cooled with deionized water. Such a decrease in temperature is extremely necessary, since at $T>720$ K, the destruction of the GaAs surface already takes place. Such a process also causes the formation of thermoradiation defects. The chemical composition and stoichiometry of the forming films were studied using Auger spectroscopy with ion sputtering and ellipsometry to determine the refractive index.

The processes of formation of nitrides of aluminum and silicon are very critical to the oxygen content, as the more active gas can be the first to react.

For the formation of such capsule layers of AlN and Si_3N_4, the "Oratorio-5" or "Oratorio-11" magnetron sputtering units were used. The deposition rate of aluminum nitride films (and their alloys) is in the range of 0.01–0.05 nm/s. With an increase in the deposition rate due to an increase in the Ar content, the dielectric parameters deteriorate somewhat, since much excess aluminum (silicon) remains in these films and did not have time to react with active nitrogen (semiconductor purity 10^{-4} % with a dew point of –72 °C). Therefore, it is important to carry out annealing of the spray system under high vacuum (10^{-6} mm Hg) and temperature (300–400 °C) before the deposition process.

To study the thermal stability of the AlN and Si_3N_4 films on the GaAs substrate, films were deposited on both sides with a thickness of 500 nm. After the Auger spectra were taken before and after annealing at a temperature of 850 °C 15 min. (Fig. 3), which showed that the stoichiometry of the GaAs interface did not change, which indicates the sufficiency of fast photon annealing.

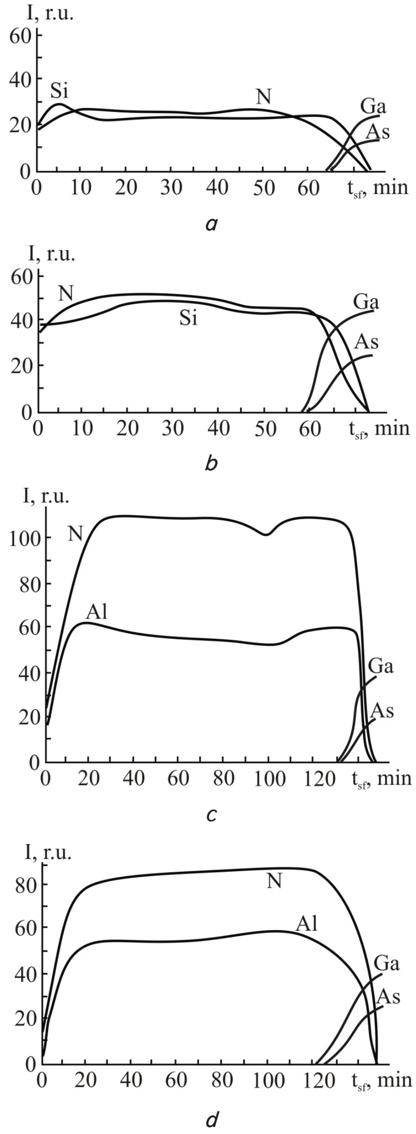


Fig. 3. Stoichiometry of Si_3N_4 and AlN films deposited by the magnetron method: *a*, *b* – without annealing; *c*, *d* – with photon annealing

The films of aluminum and silicon nitrides obtained at a temperature of 100–150 °C had a stoichiometric composition, low pore density, high breakdown voltage (>$5\cdot10^6$ V/cm).

The key coefficients of thermal expansion of films and GaAs substrates, high thermal stability and adhesion allows them to be used as masks for multiply charged ion implantation, photon annealing and diffusion and as protective coatings, ensuring high radiation resistance of the LSIC structures. This allows them to use such nitride films as gate dielectrics and interlayer insulation. This technology has received a patent for the formation of boron nitride films by gas-phase nitrolysis of $B_3N_3H_6$, which can be successfully used as solid-state planar sources of boron diffusion and gate dielectric for GaAs LSIC [17].

6. Discussion of the research results and the formation of germanium buffer layers on GaAs using the MBE method

The epitaxial growth of Ge films on gallium arsenide seems to be a very important technological task due to the proximity of the parameters of the crystal roller and the thermal expansion coefficients of materials for the formation of hetero-transitions. These are essentially buffer separation layers. It also creates conditions for testing using the Ge/GaAs hetero-transitions using models of physical processes in h hetero-transitions, as well as implementing new semiconductor devices and LSIC structures using the Ge/GaAs and AlGaAs–Ge–GaAs hetero-transitions.

The production of high-quality hetero-epitaxial buffer layers of germanium on gallium arsenide is rather difficult due to uncontrolled doping during epitaxial growth. And one of the possible ways to reduce the level of uncontrolled doping is the use of low-temperature epitaxy processes of MBE and microwave epitaxy in electron cyclotron resonance (ECR) reactors. The MBE was chosen for research because in this process it is believed that, at low epitaxy temperatures (320–400 °C), the hetero-diffusion process of As and Ga to germanium somewhat slows down, which creates the conditions for obtaining ultrapure germanium films. But these experiments have shown that there are other uncontrolled diffusion mechanisms: evaporation, MBE structural materials, vacuum and residual gases of the MBE installation. Experimental samples obtained at the UE.PMA-12.5-001 MBE installation (Vekshinsky Research Institute for Vacuum Technologies, Zelenograd, USSR) with a limit pressure of residual gases $1{\cdot}10^{-8}$. The installation itself is equipped with a built-in electronic Auger spectrum, a fast electron diffractometer, a quadrupole mass spectrometer. In addition, the unit was a block of molecular sources: one electron-beam evaporator and 4 crucible molecular sources.

A source of germanium GDG-40 with an impurity concentration close to its own concentration of electrons and holes in germanium (10^{13} cm^{-3}) was used as a source for evaporation. Comparison of the actually obtained level of non-controlling doping of epitaxial films (>10^{15} cm^{-3}) with the concentration of impurities in evaporative germanium showed that non-controlling doping is not determined by the purity of the source material itself, but by the internal chamber equipment of the MBE installation. The main elements of the structure of the crucible type molecular source are: crucible, insulators with pyrolytic boron nitride, microwave heaters. Gas emission from nitride also provides a concentration of background impurities in the epilayer at the level of 10^{14} cm^{-3}. Therefore, for experiments, the Auger spectra of a pure substrate were studied: Ge films grown with BN, from a graphite (UHP) crucible, sapphire crucible, from a silicon crucible of an electron-beam evaporator (EBE). All this is shown in the spectra presented in Fig. 4:

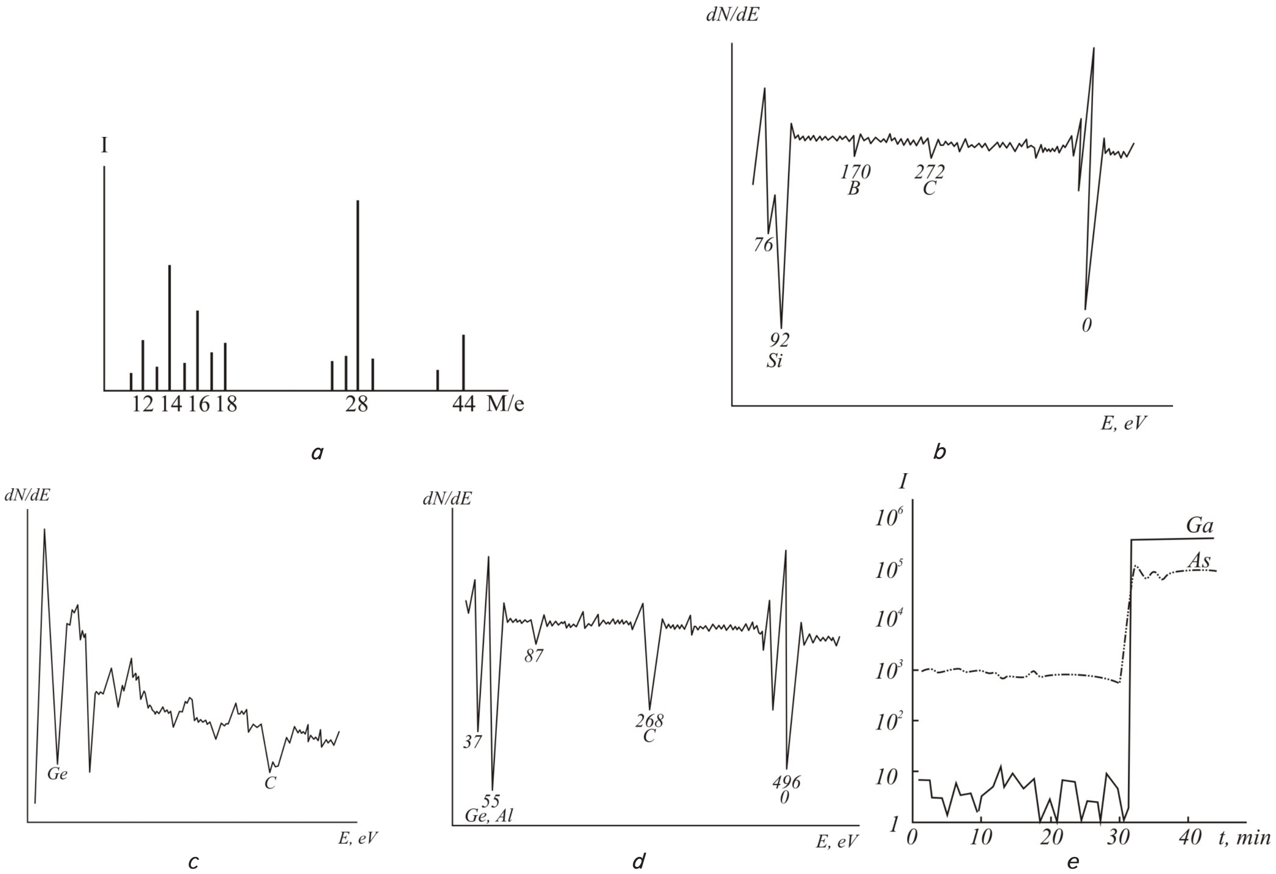
– spectral composition of residual gases of the MBE process chamber during evaporation of Ge from the crucible with boron nitride (Fig. 4, *a*);

– Auger spectrum of the clean substrate (GaAs) after exposure (~10 h.) sources with crucible with BN (Fig. 4, *b*);

– Auger spectrum of Ge films grown from a graphite crucible (Fig. 4, *c*);

– Auger spectra of germanium films grown from sapphire crucible (Fig. 4, *d*);

– composition of Ge films grown on a GaAs substrate from an electron beam source (Fig. 4, *e*).



a *b* *c* *d* *e*

Fig. 4. Residual gas spectra: *a* — pure GaAs substrate; *b* — Auger spectrum of a Ge film; *c* — Ge films deposited from a graphite crucible; *d* — sapphire; *e* — EBE

To substantially reduce the level of non-controlling doping in Ge epilayers, the electron beam evaporation method Ge was also used for comparison. Here, the electron beam evaporator (EBE) is an electron gun with electrostatic focusing of the beam and turning the beam 270° using an electromagnet. The EBE crucible was cooled with deionized water at a temperature of 4 °C.

The electron beam evaporation method gave the best results on the purity of the deposited Ge films in the auto-flash mode. The latter was very easily realized with EBE from a silicon crucible with a melting point of 1423 °C. Here, the contamination level of Ge films was lower than when using crucible molecular sources. This was confirmed experimentally: using EBE, p-germanium films with hole concentrations of $(1–2)\cdot 10^{16}$ cm^{-3} and mobility of 1300–1600 cm^2/V s were obtained on GaAs substrates, which was not achieved when using crucible evaporators with boron nitride, graphite and sapphire crucibles. Measurement of the distribution profile of impurities in p-Ge by the *VIPS* method also showed (Fig. 4, *e*) low compared with the crucible evaporators of the type of contamination such as B and Al.

Such germanium epilayers are reliable buffer separation layers during the formation of GaAs/Si and AlGaAs/GaAs hetero-transitions, since the germanium lattice constant is closest to GaAs.

It is for these purposes that an electron beam evaporator of refractory metals (Ti, Mo, W) and semiconductors (Ge, Si) with an impacting positioning unit is developed in Rodon (JSC, Ivano-Frankivsk, Ukraine). This EBE provides alternate evaporation as a sequence of three samples of refractory metals (Ti, Mo, W) or two semiconductors (Ge, Si) and is designed to work in high vacuum installations. Therefore, high-vacuum materials are used in its construction, and all joints and seals are all-metal. Such an EBE can be used both in the metallization modules of the LSIC structures and as part of the MBE installations.

To control the LSIC structure at extreme temperatures, the thermal cryostat for a substrate of 150 mm has been developed and allows technological diagnostics of the vehicle in the temperature range from 77 K to +400 K and is the basis of technological CAD systems for submicron LSIC structures.

On the basis of this technology logical elements were formed, the parameters of which are shown in Fig. 5, normally open and normally closed transistors, which can be used as a complementary pair of submicron LSICs.

The inverter circuit (Fig. 5, *a*) contains the input active transistor VTa (normal-closed-enriched) and the loading passive transistor VT (normal-open-depleted). The load serves as several static inverters, which in static mode can be changed by an equivalent circuit containing a Schottky diode VD and a resistor R_n. The diode corresponds to the Schottky barrier (between the gate and the channel of the input load transistors, and the resistor R_n takes into account the leakage resistance of these transistors).

Typical values of the threshold voltage of an active transistor U_{TT}=0.1–0.2 V, and passive U_{TT}= –(0.2–0.4) V. The power supply voltage U_{Fg}=1.5–2 V. Circuits of inverters on the Schottky transistor and n-channel MDS transistors are similar, except for the fact that using SBFETs that form on a semi-insulating GaAs substrate, but a second power supply is no longer needed.

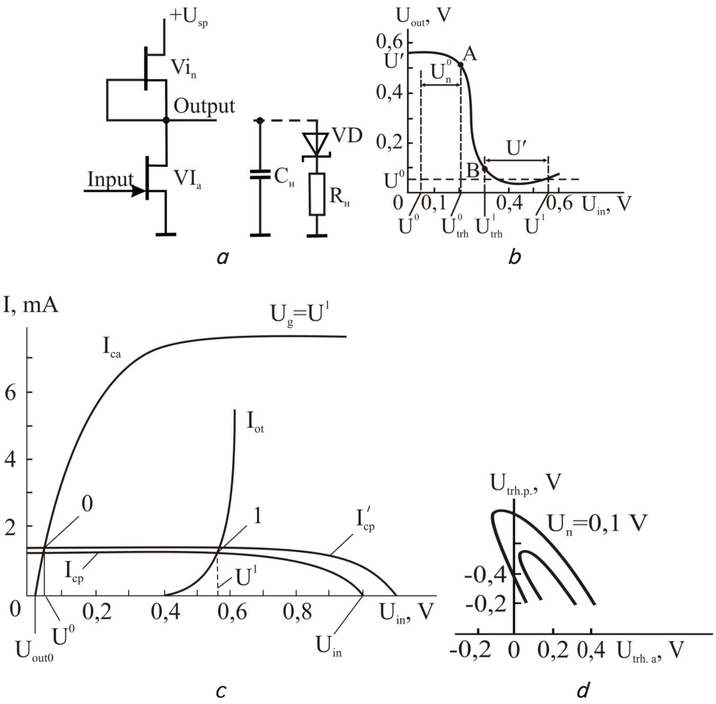


Fig. 5. Inverter on SBFET: *a* — scheme; *b* — its dynamic characteristic; *c* — transfer characteristic; *d* — noise immunity graphs

The results are aimed at improving the speed of submicron LSICs and reducing the cost of the gallium arsenide technology. The solutions described are provided by the implementation of heterostructural SBFET on monosilicon substrates of large diameter (over 150 mm).

Further development of this technology requires the development of epitaxial units for the gas-phase growth of GaAs layers using organometallic compounds of high purity at a temperature of 770–870 K.

This technology expands the possibilities of implementing high-speed low-power microprocessors, microcontrollers of memory circuits, but for the further development of this technology it is necessary to implement a bipolar-field two-gate transistor for high-speed submicron LSIC.

7. Conclusions

1. Technological regimes were determined and low-temperature $Al_xGa_{1-x}As$/GaAs and Ge epitaxy on Si substrates for high-speed LSIC structures was implemented. In particular, the optimum temperature for epitaxial growth is 820–870 K.

2. The features of the formation of 2DEG on the reorientations of the GaAs substrate using the quantum Hall effect are investigated. It has been established that at the $Al_xGa_{1-x}As$/GaAs interface, 2DEG is formed with a high electron mobility of 8200 cm^2/V s, which exceeds the electron mobility in GaAs by an order of magnitude.

3. For the implementation of the MDS technology and GaAs, a highly efficient technology has been developed for the formation of spacer-like and capsule layers of AlN, $Si_3N_4$and BN nitride films by magnetic sputtering of the target in active nitrogen plasma.

4. For the implementation of reliable hetero-transitions, a technology has been developed and investigated for the formation of epitaxial buffer layers of germanium to align the

permanent crystal lattices of semiconductor materials silicon, gallium arsenide, gallium-aluminum arsenide. The formation of high-quality germanium buffer layers is achieved by using a special design of crucibles using electron-beam evaporation in MBE installations; this makes it possible to form precision GaAs epilayers on a Si substrate.

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