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Development of technology for creating high-voltage p⁰ – n⁰ junctions based on GaAs

An optimal solution has been found to the problem of obtaining p⁰-n⁰ junctions based on lightly doped GaAs layers with high values of electrical parameters and specified thicknesses of base layers to create ultra-fast high-voltage pulsed three-electrode switches with a photon injection mechanism of minority charge carriers. A technology has been developed for the formation of high-voltage, powerful subnano-second photonic injection switches based on gallium arsenide and its solid solutions. The dependence of the current rise time, switching voltage and switching stability relative to the control pulse of high-voltage photonic injection switches in a wide current and frequency mode of their operation, its sensitivity to various external influences, as well as dependence on the thickness of the p⁰-layer, on the transmission coefficient, on breakdown voltage U_{probe} of the high-voltage p⁰-n⁰ junction. The carried out studies and the obtained results indicate the prospects of using the developed high-voltage pulsed semiconductor devices in picosecond optoelectronics for pumping high-power laser and LED structures.

Keywords: Liquid-phase epitaxy (LPE), heterostructures, high-voltage p⁰-n⁰ transition, Hall effect, background doping, solution-melt.

Introduction

As is known, to create subnano- and picosecond photon-injection switches based on GaAs and Al-GaAs heterostructures, the main need is:

1. Determination of the optimal temperature-time regime for the reproducible production of an n⁺-p⁰-n⁰ transistor structure with a high-voltage p⁰-n⁰ junction, in liquid-phase epitaxy (LPE), formed due to background doping with specified parameters and the creation of subnano-second powerful switches based on them.
2. Study of the influence of the main technological factors: the temperature of the onset of crystallization $t_{n.cr.}$, the thickness of the solution-melt h , the hydrogen flow rate F , the static turn-on voltages U_{on} , the control current $I_{up.}$, and the dynamic parameters — current rise time, turn-on delay time relative to the control impulse, the stability of switching-on-switching structures [1-5].

Conducting research on the creation of high-power high-voltage switching device structures based on lightly doped gallium arsenide is associated with the need to search for alternative principles for switching electrical power in the subnano- and picosecond time ranges. Since modern laser, accelerator and location technology, thermonuclear energy, picosecond spectroscopy of liquids and solids, topography, radio engineering, digital technology and a number of areas of converter technology require the creation of semiconductor switches of this power range, which have the traditional advantages of semiconductor devices: long service life, reliability, high efficiency and, which is extremely important for a number of applications, resistance to external influences (radiation, temperature) and instant readiness for operation.

Due to the need for location technology, defense, digital technology, two new switching principles have been developed — using a control plasma layer and using a delayed shock-ionization wave, which made it possible to increase the power switched by devices in the nanosecond range by almost two to three orders of magnitude and in the picosecond range by almost four orders of magnitude [6–8].

The speed, the magnitude of the absolute and specific power switched by semiconductor devices largely depends on the processes of filling the region with electron-hole plasma, which has a high resistance in the initial state and blocks the applied external voltage. Such a region is the region of the space charge, depleted by the strong field of the reverse-shifted p-n junction.

Powerful semiconductor devices developed on the basis of silicon, such as pulse sharpeners of diode, transistor and thyristor types, operating on the principle of switching using a delayed shock-ionization wave, required the development of new circuitry, a new direction of research using new materials, primarily GaAs and heterostructures on its basis [9, 10].

Currently, epitaxial methods for obtaining single-crystal layers are widely used for the manufacture of various semiconductor devices. Epitaxial growth methods make it possible to combine in time the process of crystallization of a semiconductor material and the production of a device structure. Gas-transport, molecular-beam and liquid-phase epitaxy have received the main distribution.

When developing high-voltage diodes, transistors and thyristors, it is necessary to use GaAs with a concentration of the main charge carriers of $\sim 10^{15} \text{ cm}^{-3}$ or less. A fairly common technology for obtaining such a material is LPE, carried out in a quartz container with forced cooling of a solution-melt of GaAs in Ga [11–13]. This method, in comparison with other methods for growing epitaxial layers, makes it possible to obtain efficiently injecting junctions. This is due to the fact that, when GaAs is grown by this method, the internal quantum yield of radioactive recombination is much higher than when GaAs is grown from stoichiometric melts [14, 15]. This opens up the possibility of an unconventional approach to the design of high-voltage devices based on heterostructures. In addition, this method has the following advantages over gas-transport and molecular epitaxy: simplicity of equipment, higher growth rates, the possibility of reducing the impurity background, etc. The physicochemical foundations of LPE are well described in a number of monographs [16–18].

Methods

LPE is an oriented crystallization of single-crystal layers of semiconductor materials from solutions of these materials. There are several methods of epitaxial growth from a solution-melt: growth from a limited volume and growth from a semi-limited volume of a solution-melt. The method of growing epitaxial layers from a limited volume of a solution-melt has received the main distribution.

Under conditions of crystallization from limited volumes of solutions-melts, both a significantly higher reproducibility of obtaining layers with a given thickness is achieved compared to crystallization from semi-limited volumes, as well as a higher degree of their planarity. In addition, the growth of layers from a limited volume of a solution-melt makes it possible to control the crystallization rates and conduct the process under conditions closer to quasi-equilibrium.

Thanks to the development of technology for obtaining high-voltage p-n junctions based on lightly doped GaAs, it became possible to create pulsed transistors and thyristors based on GaAs-AlGaAs heterostructures. Studies have shown the prospect of using photon-injection mechanisms of coupling between p-n junctions in high-voltage multilayer structures, the possibility of switching high powers by three-electrode semiconductor devices in the subnano-second range of durations [9].

Therefore, the improvement of the main parameters and characteristics (increasing the operating voltage, improving the speed, reproducibility and dependence of the temperature effect, radiation) of switches is associated with an understanding of the technological processes for the formation of high-voltage p-n structures, the choice of the optimal geometry and the search for new designs [10, 13].

The analysis of the literature data shows [1, 13, 16-19] that the production of lightly doped GaAs layers and the formation of high-voltage p-n junctions in the process of growth have not been clarified, the nature of residual impurities is not entirely clear, the influence of technological factors on the electrical properties has not been studied, which makes it difficult to create high-voltage switches with subnano- and picosecond speed.

The static and impulse characteristics of such device structures obtained under various technological conditions have not been studied at all.

The aim of our work is to obtain high-voltage p-n junctions based on lightly doped GaAs layers, to study the influence of technological factors on their main dynamic parameters and characteristics, to create powerful photon-injection pulse switches based on them with subnano- and picosecond speed, to elucidate the possibility of increasing the power of the switched gallium arsenide transistors and thyristors in the subnano-second range.

Experimental

The proposed technologies for obtaining high-voltage p-n junctions based on lightly doped GaAs allowed the creation of pulsed transistors and thyristors based on GaAs-AlGaAs heterostructures. We have optimized technologies for obtaining high-voltage p-n junctions based on lightly doped GaAs layers and creating subnano- and picosecond speed photon-injection switches based on the principle of photon transfer of no equilibrium charge carriers. The main attention is paid to the features of obtaining device structures, the influence of technological factors on the static and dynamic parameters of switching structures in the mode of high currents and voltages.

Liquid-phase epitaxy is the method of growing epitaxial layers from a limited volume of a solution-melt to obtain and fabricate device structures. Under conditions of crystallization from limited volumes of solutions-melts, both a significantly higher reproducibility of obtaining layers with a given thickness is achieved compared to crystallization from semi-limited volumes, as well as a higher degree of their planarity. In addition, this method makes it possible to control the crystallization rates, conduct the process under conditions closer to quasi-equilibrium, and obtain “pure” and doped layers of high-quality p-n junctions and multilayer device structures with specified electrophysical parameters with sufficiently high reproducibility.

The main problem in creating subnano- and picosecond switches based on GaAs is to obtain layers with a given thickness of the base regions and a low dopant concentration. A study was made of the influence of technological factors on the properties of epitaxial layers and p⁰-n⁰ junctions.

To ensure the optimal impurity distribution profile in a quartz container, from a limited volume of an arsenic melt solution in gallium on n⁺ - GaAs substrates oriented in the [100] plane, p⁰- and n⁰- GaAs layers with specified thicknesses were grown, which are the basic regions of the structure. The position of the p-n transition, the concentration profile in the p⁰- and n⁰-layers, the thickness of the p⁰-region in depending on the conditions for the formation of an impurity background in the solution-melt were obtained in advance planned limits. The lifetime of minority charge carriers (NCC) is an important dynamic characteristic of a semiconductor device. In lightly doped GaAs, the NCC lifetime is determined mainly by the concentration of deep levels. Its value in lightly doped regions of transistor and thyristor structures was determined by measuring the dissipation time of the charge accumulated in these regions and was 50–500 ns. Such a scatter in the values of the CC lifetime is due to the concentration and capture cross section of uncontrollably introduced recombination centers. The concentration of carriers in the p⁰- and n⁰- regions ranged from $1.0 \cdot 10^{15} \text{ cm}^{-3}$ to $0.1 \cdot 10^{15} \text{ cm}^{-3}$, the mobility of charge carriers was, $\mu_n = (5 - 6) \cdot 10^3 \text{ cm}^2 / \text{V}\cdot\text{s}$ in the n⁰-layer and $\mu_p = (400 - 450) \text{ cm}^2 / \text{V}\cdot\text{s}$ at 300 K. The charge carrier mobilities were determined by measuring the Halle effect in the grown epitaxial layers [19].

The thickness of the n⁰-layer, exceeding the dimensions of the space-charge layer at zero mixing of the p-n junction, was (30–35) μm and provided the possibility of effective separation of electron-hole pairs created by absorbed radiation. The control of the position of the p-n transition, the estimation of the size of the space charge region was carried out by a method based on the observation of the electro-optical effect in gallium arsenide during the passage of plane polarized infrared light through the crystal.

For the efficient operation of thyristors and transistors, the thickness of the p⁰-part should be as small as possible, therefore, for them manufacturing can only be used n⁺- p⁰-n⁰ structures with certain thicknesses p⁰ - areas that provide high transfer coefficient values. Defined temperature dependence of p⁰-layer on temperature the beginning of crystallization (Fig. 1), and coefficients segregation of fine acceptor and donor impurities the level of concentration and the degree of compensation [19].

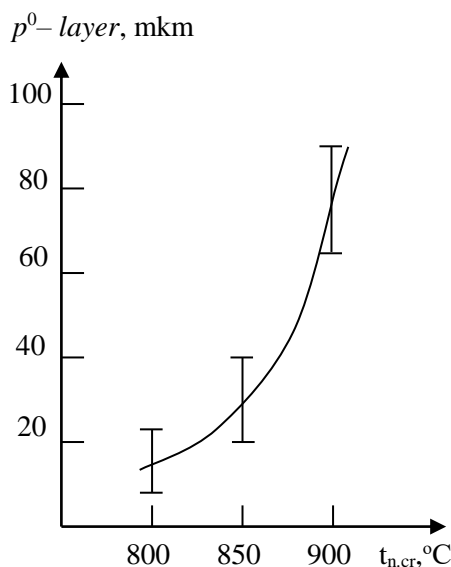


Figure 1. DependenceK of the thickness of the p⁰-layer on temperature.

In order to optimize the growth technology and the design of thyristors, the dependences of the transfer coefficients of structures on the thickness of the low-resistance part of the p^0 -region and on temperature were studied (Fig. 2).

It can be seen that the transfer coefficient α of transistor $n^+ - p^0 - n^0$ structures drops sharply already at a thickness $p^0 = 30 \mu\text{m}$ regardless of the temperature on set crystallization. At the same time, the thickness of the high-resistance parts h_i — areas up to $h_i - 120 \mu\text{m}$ do not have a significant impact on the value transmission coefficients.

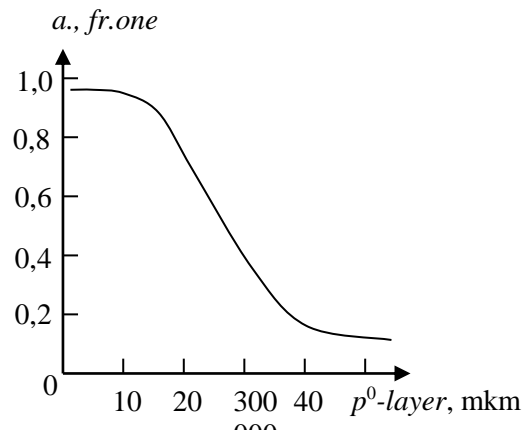


Figure 2. The dependence of the transfer coefficient on the thickness p^0 – layer.

In the region of low values of α and large thicknesses of p^0 – layer, there is a connection between α and production technology. It can be seen that the choice of liquid phase annealing is preferable, which is justified due to the higher values of the transfer coefficient. This is especially important for technological control of p^0 . Figure 3 shows dependence of the transfer coefficient $n^+ - p^0 - n^0$ structures on temperature. It can be seen that α decreases with increasing temperature.

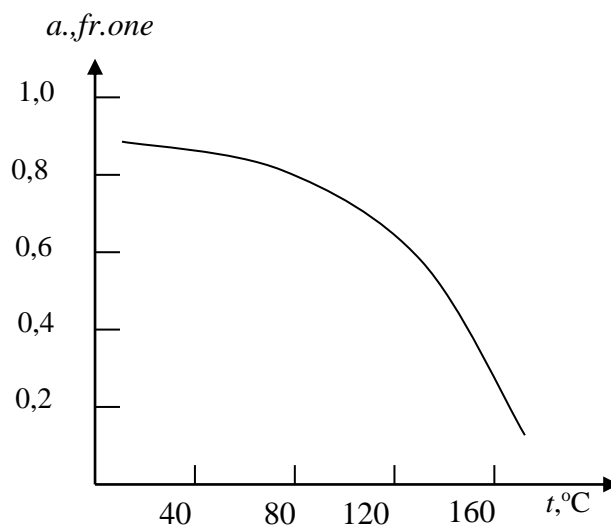


Figure 3. The dependence of the transfer coefficient $n^+ - p^0 - n^0$ structure on temperature.

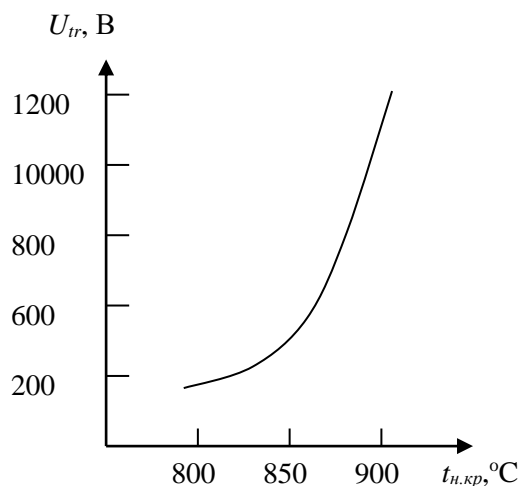


Figure 4. The dependence of U_{tr} , high voltage p^0-n^0 transition on temperature

The decrease in α with increasing temperature can be explained by the temperature dependence of the capture cross section G_n^A and G_n^B , which increase in this temperature range by factors of 5 and 20, respectively.

The effect of temperature at the beginning of crystallization and growth technology on the breakdown voltages ($U_{trial.}$) of a high-voltage p^0-n^0 junction was studied in $n^+-p^0-n^0$ structures for the possibility of obtaining maximum voltages at the collector junction (Fig. 4). The breakdown voltages increased significantly when p-n junctions turned out to be displaced from the metallurgical boundary and formed during growth. From Figure 4 it can be seen that the values of $U_{trial.}$ increase when using a higher temperature, the onset of crystallization. The growth of $U_{trial.}$ is explained. A decrease in the carrier concentration gradient in the region of the p-n junction. However, with an increase in the temperature of the onset of crystallization, the transfer coefficient of the resulting $n^+-p^0-n^0$ structures decreases. In high-voltage p^0-n^0 junctions, the allowable voltages are determined by the impurity concentration gradient in the space charge region (SCR) of the junction and the thickness of the n^0 region. Therefore, the carrier concentration gradient and the thickness of the n^0 region determine the breakdown voltages of the p-n junction. The use of semiconductor structures based on A3B5 is associated with the possibility of a significant increase in performance, which is due to higher mobilities and short lifetimes of minority charge carriers (NCCs). The estimates made by the authors of [19] show that, due to the significantly shorter lifetime of the NCC in gallium arsenide high-voltage devices, it is possible to reduce the total duration of the power switching process by at least an order of magnitude compared to silicon ones. The first experimental results also testify to the high potential capabilities of key devices. For example, for gallium arsenide thyristors of a traditional design, which has three p-n junctions (collector and two emitter) interacting with minor charge carriers, the following record parameters were achieved when switched on through the control circuit: rise time no more than — 10 ns, turn-on delay relative to the control pulse — 100 ns at an operating voltage of up to 1000 V and a pulsed current of 100 — 120 A.

Conclusions

Thus, the above features of obtaining lightly doped layers and p-n junctions based on them show a real possibility of creating high-speed pulse transistors and thyristors. Optimization of the technology for obtaining high-voltage p-n junctions based on lightly doped GaAs layers, development of new principles for the generation and transport of charge carriers in semiconductor structures based on materials with a high proportion of radiative recombination made it possible to obtain high-voltage three-electrode switches with sub-nano-second turn-on times. The studies carried out and the results achieved indicate broad prospects for the use of gallium arsenide and its solid solutions in the development of high-speed transistors and thyristors with a photon-injection coupling mechanism between p-n junctions.

References

- 1 Alferov, Zh.I., Grekhov, I.V., & Korolkov, V.I. (1987). Formation of high-voltage voltage drops in the picosecond range on gallium arsenide diodes. *Letters to JTF, Vol. 13(18)*, 1089-1093.
- 2 Alferov, Zh.I., Andreev, V.M., Korolkov, V.I., Portnoy, E.L., & Tretyakov, D.N. (1968). Injection properties of heterojunctions n (Al_xGa_{1-x}As) - p (GaAs). *FTP, 2*.
- 3 Soldatenkov, F.Yu. (2011). Subnanosecond switches based on heterojunctions in the GaAs (InGaAs)-AlGaAs cuctem. *Doctor's thesis*. Russia. St. Petersburg. Physics-Technical Institute named after A.F. Ioffe.
- 4 Alferov, Zh.I., & Korolkov, V.I. (1986). Electrically Controlled Three-Electrode High-Voltage Subnanosecond Switches Based on Multilayer GaAs – AlGaAsHeterostructure. *Letters to ZhTF, Vol. 12(21)*, 1281-1285.
- 5 Bowers, H.C. (1967). Space-charge-induced negative resistance in avalanche diodes. *IEEE Trans/ EI.Devices*, ED. 15.
- 6 Solovieva, E.V., Milvidsky, M.G., Sabanova, L.D., Berman, L.V., Kolobova, G.A., Sharonov, B.N., Morgulis, L.M., & Surf, J. (1977). The role of impurities and defects in the formation of properties of undoped gallium arsenide layers. *Growth and doping of semiconductor crystals and films*, Part 11, 248-252. Novosibirsk: Science.
- 7 Ya, L. (1979). Distribution of impurities in large area gallium arsenide structures grown by liquid epitaxy. Materials of the report. At the All-Union Coordinators. *Meeting Sections "Semiconductor. Heterostructures"*, 66-73. Tallinn.
- 8 Voitovich, V., & Dumanevich, A. (2009). How to replace SiC Schottky diodes. *Power Electronics*, 5.
- 9 Grekhov, I.V., & Serezhkin, Yu.N. (1980). Avalanche breakdown of the p-n junction in semiconductors. *L., energy*, 151 p.
- 10 Grekhov, I.V., & Smirnova, I.A. (1985). Semiconductor Powerful Subnanosecond Switches with a Long Hold Time. *Letters to ZhTF, Vol. 11(15)*, p. 901.
- 11 Hur, J.H., Hadirad, P., Hummel, S.G., Dzusko, K.M., Dfrkus, P.D., Fetterman, H.R., & Gundersen, M.A. (1990). GaAs-Based Opto-Thyristor for Pulsed Pioneer Applications. *Electron's devices, Vol. 37(12)*, 2520-2525.
- 12 Kyurenyan, A.S. (1975). Investigation of impact ionization and avalanche breakdown in high-voltage p-n junctions. *Extended abstract of candidate's thesis*. Moscow, All-Russian Electrotechnical Institute named after V.I. Lenin.
- 13 Ya, L. (1979). Distribution of impurities in large area gallium arsenide structures grown by liquid epitaxy. *Materials of the report. At the All-Union Coordinators. Meeting Sections "Semiconductor. Heterostructures"*. Tallinn, 66-73.
- 14 Vainshtein, S.N., Yuferev V.S., Kostamovaara J.T., Kulagina, M.M., & Moilanen, H.T. (2010). Significant Effect of Emitter Area on the Efficiency, Stability and Reliability of Picosecond Switching in a GaAs Bipolar Transistor Structure. *IEEE Transactions on Electron Devices, Vol 57(4)*.
- 15 Sarkat, T., & Mazumder, S.K. (2007). Epitaxial Design of Direct Optically Controlled GaAs/AlGaAs –based Heterostructure Lateral Superjunction Power Device for Fast Repetitive Switching. *IEEE Transactions on Electron Devise, Vol. 54(3)*.
- 16 Mamatkarimov, O.O., Khamidov, R., & Abdukarimov, A.A. (2019). The relative current change, concentration, and carrier mobility in silicon samples doped nickel and at pulse hydrostatic pressure. *Materials Today: Proceedings 17*, 442–445.
- 17 Voitovich, V., Gordeev, A., & Dumanevich, A. (2009). GaAs - diodes for PFC, SMPS, UPS, IPM Solar Inverters and replacement of synchronous rectifiers. *2 Power Electronics*, 6.
- 18 Karimov, M., Makhkamov, Sh., Makhmudov, Sh.A., Muminov, R.A., Rakhmatov, A.Z., Sulaymanov, A.A., & Tur-sunov, N.A. (2010). Peculiarities of influence of radiation defects on photoconductivity of silicon irradiated by fast neutrons. *Applied Solar Energy, Allerton Press, Inc., Vol. 46(4)*, 298-300.
- 19 Zadiranov, Yu.M., Korolkov, V.I., Ponomarev, S.I., Rozhkov, A.V., & Tsvilev, G.I. (1987). High-voltage impulse thyristors based on lightly alloyed gallium arsenide. *JTF. Vol. 57(4)*, 771-777.

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GaAs негізіндегі жоғары вольтты р⁰ – n⁰ өтулерін құрудың технологиясын дамыту

Негізгі емес заряд тасымалдаушылардың фотонды-инъекциялық механизмі бар аса тез әсер ететін жоғары вольтты импульсті үш электродты коммутаторды жасау үшін электрфизикалық параметрлердің жоғары мәндері және берілген базалық қабаттардың қалыңдығы бар GaAs әлсіз легирленген қабаттары негізінде р⁰-n⁰ өтулерін алудың оңтайлы шешімі табылды. Галлий арсениді және оның қатты ерітінділері негізінде жоғары вольтты, қуатты субнаносекундтық фотонды инъекциялық қосқыштарды қалыптастыру технологиясы әзірленді. Токтың өсу уақытының, кернеуді қайта қосу және қайта қосудың тұрақтылығы оларды пайдалануда кең ток және жиілік режиміндегі жоғары вольтты фотонды-инжекциялық коммутаторлардың басқару импульсіне тәуелділігі, оның әртүрлі сыртқы әсерлерге сезімталдығы, сондай-ақ р⁰-кабатының қалыңдығына, беріліс коэффициентіне, жоғары вольтты р⁰-n⁰ өтулерінде U сынағасының тесілуі кернеуге байланысты екендігі зерттелді. Жүргізілген зерттеулер мен алынған нәтижелер жоғары қуатты лазерлік және жарықдиодты құрылымдарды айдау үшін пикосекундтық оптоэлектроникада әзірленген жоғары вольтты импульстік жартылай өткізгіш құрылғыларды пайдалану перспективаларын көрсетеді.

Кілт сөздер: сұйық фазалық эпитаксис (LPE), гетероқұрылымдар, жоғары вольтты p^0-n^0 өтулері, Холл эффектісі, фондық легирлеу, ерітінді-балқыма.

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Разработка технологии создания высоковольтных p^0-n^0 -переходов на основе GaAs

Найдено оптимальное решение проблемы получения p^0-n^0 -переходов на основе слабелегированных слоев GaAs с высокими значениями электрофизических параметров и заданными толщинами базовых слоев для создания сверхбыстродействующих высоковольтных импульсных трехэлектродных коммутаторов с фотонно-инжекционным механизмом неосновных носителей заряда. Разработана технология формирования высоковольтных мощных субнаносекундных фотонно-инжекционных коммутаторов на основе арсенида галлия и его твердых растворов. Изучена зависимость времени нарастания тока, напряжения переключения и стабильности переключения относительно импульса управления высоковольтных фотонно-инжекционных коммутаторов в широком токовом и частотном режиме их эксплуатации, ее чувствительность к различным внешним воздействиям, а также зависимости от толщины p^0 -слоя, от коэффициента передачи, от напряжения пробоя U проб высоковольтного p^0-n^0 -перехода. Проведенные исследования и полученные результаты указывают на перспективность применения разработанных высоковольтных импульсных полупроводниковых приборов в пикосекундной оптоэлектронике для накачки мощных лазерных и светодиодных структур.

Ключевые слова: жидкофазная эпитаксия, гетероструктуры, высоковольтный p^0-n^0 -переход, эффект Холла, фоновое легирование, раствор-расплав.