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High-ohmic GaAs-AlGaAs structures for power electronics

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Abstract
The original method of manufacturing of high impedance p-i-n structures based on GaAs-AlGaAs system by liquid phase epitaxy is proposed. It allows to receive power diodes, significantly in excess of the aggregate basic parameters of the best silicon counterparts.

Key words: power electronics, liquid phase epitaxy, p-i-n diode, A^3B^5 compounds.

The intensive energy saving solution improvement over the world makes ever-more-hard requirements to power electronics devices and equipment. It can't be realized by usage of the traditional silicon-based components in any case. The silicon as the current electronics base material has been at the end of its resources for lots of applications. The silicon diodes have the low cost, wide range of operating current and voltage, acceptable dynamics and high workability. But its high temperature dependence of switching characteristic cuts down the field of diodes application. Non-optimal silicon diodes reverse recovery process causes the switching loss and the higher power dissipation of the device at high frequencies as a consequence [1]. That is why there is growing interest to wide-gap materials including GaAs and GaAs-AlGaAs based system of solid solutions. Such GaAs properties as direct gap, high electron mobility, low lifetime of minor carriers, high lattice perfection, possibility to form the hetero-compositions in GaAs-AlGaAs system makes possible to design the wide range of unique devices.

The perfect GaAs technology is widely used in the current electronics. The GaAs boules are produced by standard equipment with high yield to provide the necessary reliability level for industry application.

Due to technical and economic parameter dominance GaAs devices are able to oust quickly the silicon analogue from segment of HF power devices potentially. Nevertheless GaAs as the power electronics material doesn't attract the focused attention by reason of the valid method absence to make the high-ohmic epitaxial material that could provide the high breakdown voltages. The epitaxial p-i-n structure on the base of GaAs-AlGaAs system with extended low impurity concentration layers and high carrier mobility are required to achieve high breakdown voltages and low switching loss [2].

This problem can be solved most efficiently by means of liquid phase epitaxy technique which is not able for low processing cost, simplicity of equipment and the growth of multi-layer high thick compositions possibility. It has great potential capabilities in the structures properties control by means of dopant and growing parameters adjustment.

The principal framework of the GaAs p-i-n structures making technology had been provided by developments of the Ioffe Institute [3]. The usage of quartz growing fixture and specially humidified hydrogen in growth process was the specific feature of this technology. Within these investigations the possibility in principle of high-voltage high-speed GaAs p-i-n structures and power diodes based on them making had been shown. The set of its parameters is superior to the best silicon analogue. But this technology hadn't been carried up to industry application because of a lot of typical for quartz growing fixture technical limitations. The principal problem of this technology is that making of a number of epitaxial layers in one fabrication cycle is impossible since the quartz growing fixture doesn't provide the solution-melts replacement. It doesn't allow realizing the finite multi-layer structure with buffer and ohmic layers, which in turn reduces to the need for usage of two- or three-stage epitaxy. That is unjustified not only economically but in relation to structural perfection of produced epitaxial composition. The epitaxial process interruption causes every time to additional defects at the interface from stage to stage.

The application of high-capacity graphite growing unit of pumping type permits to get over these restrictions. It provides the making of the ready multi-layer semiconductor GaAs structure or GaAs-AlGaAs heterostructure in one epitaxial process by means of successive solution-melts replacement. Then the standard design of GaAs-AlGaAs based p-i-n heterostructure consists of three epitaxial layers.

1). The buffer layer, that reduces the effect of GaAs substrates structural defects and impurities on the p-i-n heterostructure parameters.

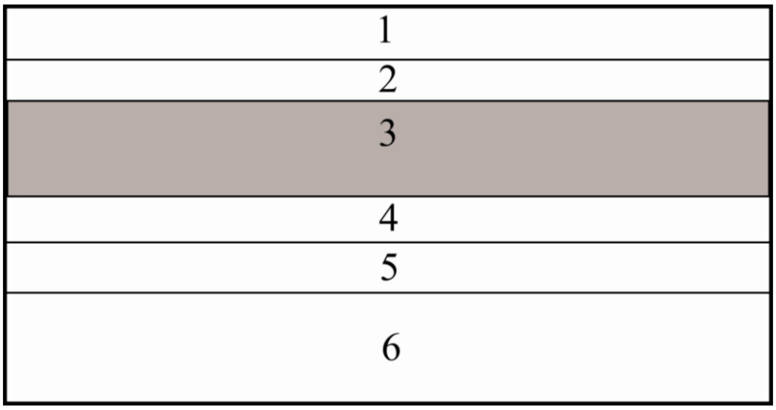
2). The base p-i-n layer, that contains the extended i-region of high-ohmic GaAs with the carrier concentration less than $1\cdot10^{13}$ cm^{-3} and with thickness up to several tens of microns. This layer is grown from one solution-melt in the epitaxial process when the temperature is reduced within growing range and the conductivity inversion takes place. In reality the base layer is the sequence of three different regions with p-, i- and n-conductivity.

3). The ohmic n+-layer, that provides the ohmic contact with the structure surface at the finite device manufacture.

The base design of structure and the epitaxial layers parameters are presented at Picture 1 and in Table 1.

Table 1 — The parameters of the epitaxial regions in GaAs-GaAlAs p-i-n structure

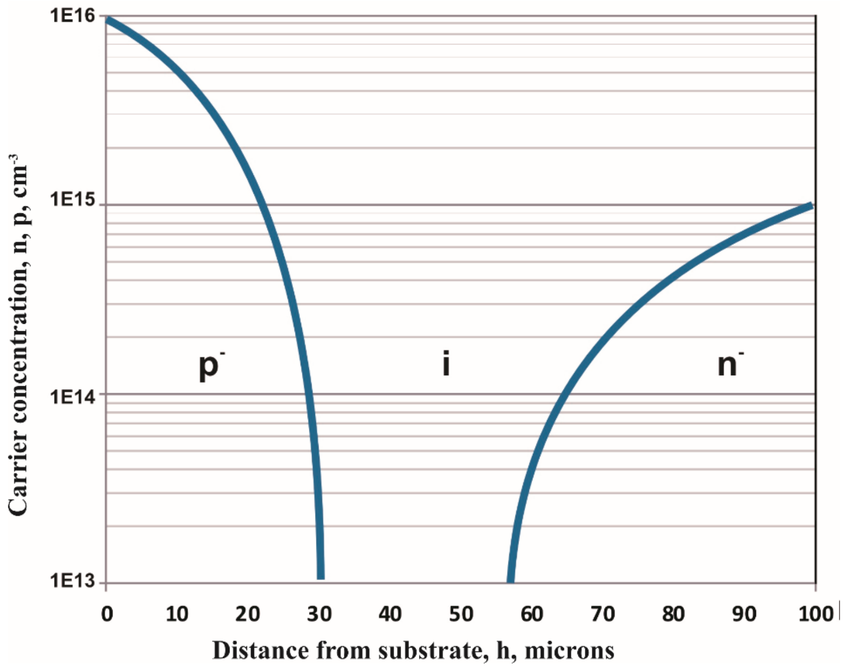
No	Epitaxial region type	Carrier concentration, cm^{-3}	Region thickness, μm
1	High-impurity n^+- layer of GaAs (AlGaAs)	$n=(1—5)\cdot10^{18}$	5—7
2	Low-impurity n-layer of GaAs	$n=1\cdot10^{13}—5\cdot10^{15}$	15—20
3	High-ohmic i-layer of GaAs	$n<5\cdot10^{13}$	25—50
4	Low-impurity p^-- layer of GaAs	$p=1\cdot10^{13}—10^{15}$	15—25
5	Buffer p-layer of GaAs	$p=(1—7)\cdot10^{16}$	3—5
6	High-impurity p^+-substrate of GaAs	$p=(0,8—2)\cdot10^{19}$	280—320



Picture 1. — The base design of GaAs-AlGaAs p-i-n structure. The layer number corresponds to Table 1 data.

The main problems of high-ohmic GaAs structures making at the graphite growing unit usage are the solution-melt contamination by carbon and the graphite porosity. The first problem is solved by means of the original method application [4], such as doping by the special oxides that interact intensively with the solution-melt background impurities and to put it into inactive state. As a result, the possibility emerges to grow the epitaxial layers with extremely low background impurities concentration, that means there is the possibility to grow the extended high-ohmic region by usage of the graphite growing unit. The problem of the graphite porosity is connected with the impurities capture by woids and then its release within the next epitaxial process. The special schedule of interstage annealing in vacuum and in hydrogen atmosphere allows to minimize this undesirable effect.

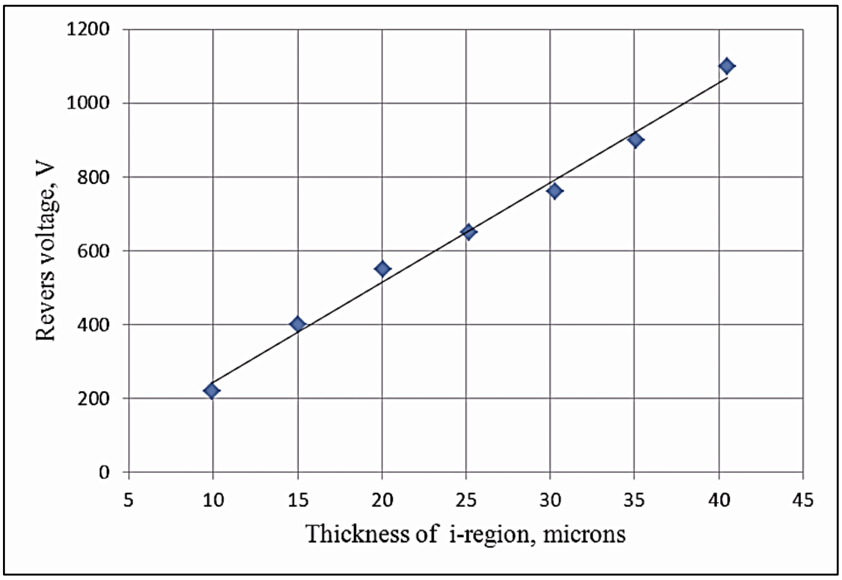
The dopant profile in base p-i-n layer is presented in Picture 2. Its key feature is the soft carrier concentration changing in low-impurity p- and n-region.



Picture 2 – The dopant profile in base p-i-n layer

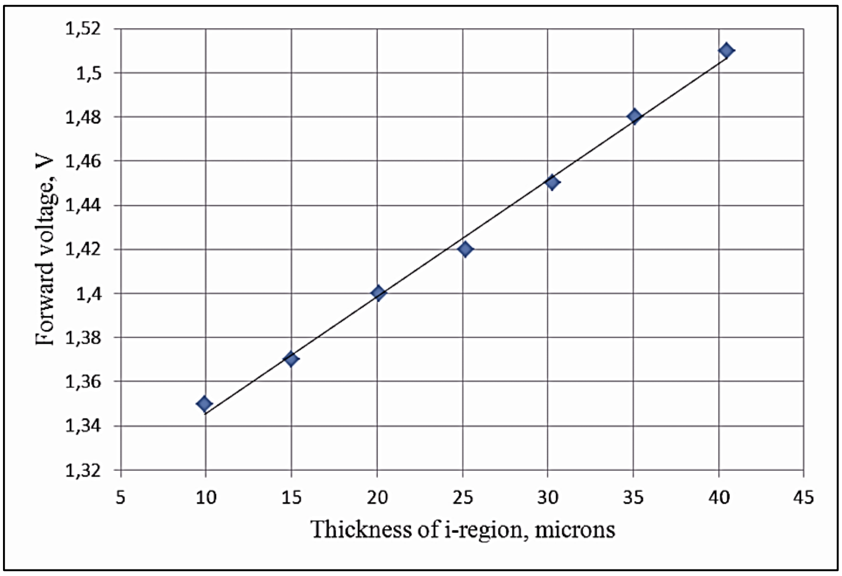
Key parameters of p-i-n structures, such as the reverse voltage, speed characteristic, the softness of reverse recovery process and the temperature dependence of current-voltage curve mainly are a function of separate base p-i-n layer regions parameters such as thickness, doping level and carrier concentration gradient which can be adjustable effectively by growth schedule variation.

The value of the reverse break-down voltage is determined by the thickness of high-ohmic i-region. The dependence is linear according to Picture 3.



Picture 3 – The dependence of reverse break-down voltage vs. thickness of high-ohmic i-region

The forward voltage drop at the current density of 150A/cm^2 rises weakly under the i-region thickness increase and the dependence is linear too according to Picture 4.



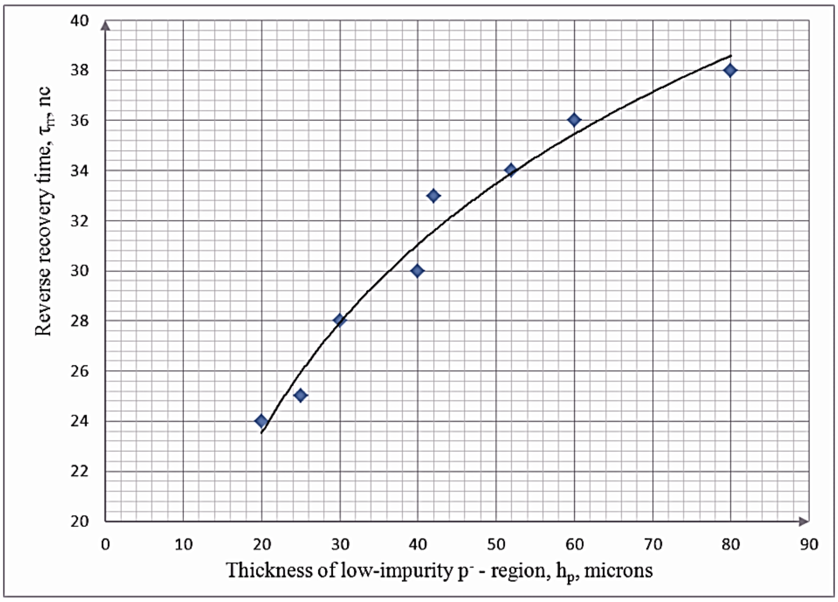
Picture 4 – The dependence of forward voltage drop at the current density of 150A/cm^2 vs. thickness of high-ohmic i-region

The speed characteristic of p-i-n structures is mainly determined by the thickness of the low-impurity p- region. The increase of this region thickness results to rise of the reverse recovery time always. This dependence is presented at Picture 5.

Non-standard distribution of internal field in base region at backward-bias potential is the specific feature of GaAs-based p-i-n structures. The location and length of i-layer and the field distribution over the structure thickness are determined by means of electron-beam induced current technique in the structure cleaved sample scanning.

The induced current measurements were made on the electron probe micro-analyzer “CAMECA” at the several voltage of reverse polarity applied to sample.

The results of induced current measurements on p-i-n structures at voltage of reverse polarity within 0—160V range are presented at Picture 6.



Picture 5 – The dependence of the reverse recovery time vs. thickness of low-impurity p- region. I_f = 0.5A, dI_f/dt = 200A/μs, U_r = 40V

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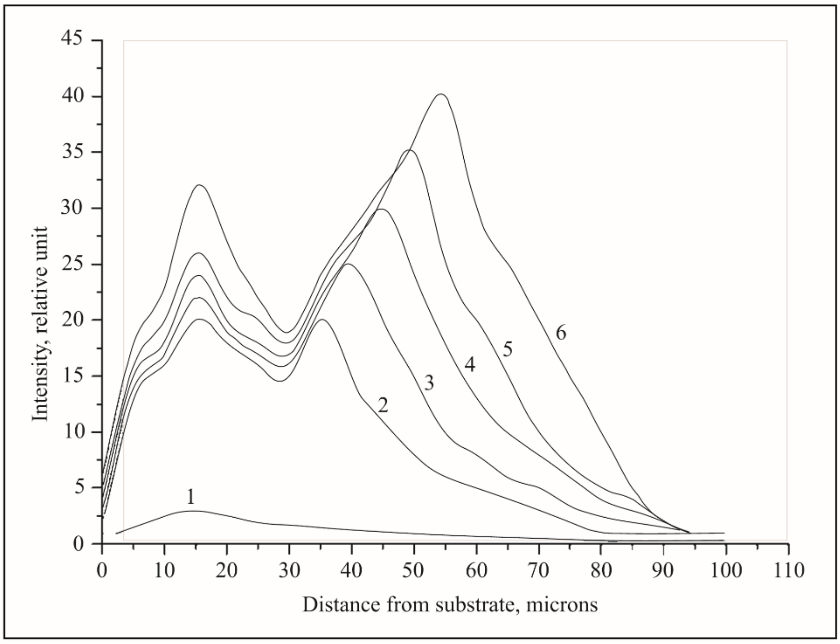

Picture 6 – The profile of induced current over p-i-n structures thickness at voltage of reverse polarity within 0—160V range

There is only one maximum in curve of induced current without backward-bias. This maximum is attributable to the location of p-n heterojunction. In view of this maximum location and shape it can be said that p-region has short length and big carrier concentration gradient.

At the same time the field propagates in n-region over all its length. It can be said that the small donor impurity concentration gradient spreads over all of n-region.

At the backward-bias application the second maximum appears due to i-region appearance, that is charge-depletion region. There has been observed the strong n-i junction shifting to positive electrode under the backward-bias voltage increase. But the p-i junction location doesn't change. At the backward-bias voltage value of 160V the i-region thickness rises to 40 μm when the total thickness of structure is 100 μm.

The similar investigations of p-i-n structures by the method of electric field optical viewing on the base of Franz–Keldysh effect have been made in the paper [5]. The authors have observed two maximums in electric field distribution over structure thickness at the backward-bias voltage value of 60V too. At high backward-bias voltage there has been observed one broad maximum. In present paper there hasn't been achieved the voltage for one maximum appearance.

We associate such dependence of internal field at backward-bias voltage with specific profile of carrier concentration distribution in base region in stationary state, were carrier concentration gradient variation vs. coordinate takes place.

There has been developed the stable industry-standard technology of GaAs-AlGaAs p-i-n structures growing with reverse break-down voltage of 600-1200V on the base of making research results. The achieved physical parameters p-i-n structures have provided the production of the power diodes pilot batch with following base characteristics:

- the forward current, I_f — 1—50A;
- the forward voltage drop, U_f –1,3—1,8V;
- the reverse break-down voltage, U_r — 400—1200V;
- the reverse recovery time, t_{rr} — 20—70 nc, independently of working temperature;
- the max operating chip temperature — up to 250ºC.

Conclusion

There have been investigated the high-ohmic p-i-n structures design and technology of making by liquid phase epitaxy in GaAs-AlGaAs system. The typical p-i-n structures design contains three epitaxial layers: the p-type buffer layer, the base p-i-n layer with extended i-region of high-ohmic GaAs, and the ohmic n+-layer. It has been shown that key parameters of p-i-n structures, such as the reverse voltage, speed characteristic, the softness of reverse recovery process and the temperature dependence of current-voltage curve mainly are a function of separate base p-i-n layer regions parameters such as thickness, doping level and carrier concentration gradient which can be adjustable effectively by growth schedule variation. There has been developed the stable industry-standard technology of GaAs-AlGaAs p-i-n structures growing with reverse break-down voltage of 600-1200V on the base of making research results.

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