GALLIUM ARSENIDE STRUCTURES FOR IONIZING PARTICLES DETECTORS


a Siberian Physical Technical Institute, Tomsk, Russia
b Scientific & Production State Enterprise "Semiconductor Devices Research Institute", Tomsk, Russia
c Tomsk State University, Tomsk, Russia
d Scientific State Center "High Energy Physics Institute", Protvino, Russia

Fax: +7 3822 413828, E-mail: detector@mail.tomsknet.ru

Abstract

A comparable analysis of characteristics of the detector structures fabricated with the use of different technologies is presented in this work as well as advantages and disadvantages of each method proposed for high-resistive layers formation. Limit characteristics, which can be achieved by using a combination of the technological methods, are analyzed.

Keywords: charge collection efficiency, amplitude spectra

INTRODUCTION

A success in development of detectors for X-ray systems depends on progress in development and investigation of a semiconductor material capable to provide reliable registration of single X-ray photons. Traditionally used pure Si and Ge are not available for this aim. An intensive search for a material, which is more widegap than Si and Ge, is characterized by good dielectric properties and has a high absorption coefficient of X-rays is carried out at present. Among the materials with these requirements, a semi-insulating (SI) GaAs is of permanent concern of researchers. An attempt to create detectors based on GaAs and other binary wide-gap semiconductors is confronted by a serious obstacle and, namely, the impossibility of obtaining a pure material. Therefore, to achieve the required dielectric properties, GaAs is compensated with deep level impurities.

The thermodynamic conditions of growth of an ingot SI-GaAs do not allow decreasing the concentration of the EL2 centers less than $10^{15}$ cm$^{-3}$. The EL2 centers in...
The state electron capture cross section more than $10^{-13}$ cm$^2$, thus limiting the electrons lifetime up to these values [1]

$$\tau_{\text{max}} = 1/\sigma_{\text{EL2}}^n \cdot \nu_a \cdot N_{\text{EL2}} \approx 10^{-9} \text{ s.} \quad (1)$$

Most of investigators have found it necessary to reduce the EL2$^+$ concentration by all means [2-4]. It will allow increasing the non-equilibrium charge carriers lifetime in the track according to (1).

There are two ways of decreasing the concentration of the EL2$^+$ centers:

- By decreasing the growth temperature of undoped SI-GaAs; which causes a changeover to the epitaxial technology;

- By filling the centers with electrons when they are in the state of equilibrium $EL2^+ + e \rightarrow EL2^0$ which is possible by doping with shallow donors ($N_d$) of the concentration $N_d > N_{EL2}$, during growth followed by overcompensation with deep acceptor Cr impurity ($N_C$).

Alternative ways of fabrication of SI-GaAs and structures based on it, which can be used for the ionizing radiation detectors development, are presented in this work.

The work has been carried out in the following directions:

1. growth of “pure” (undoped) GaAs layers by means of vapor-phase epitaxy (VPE) in the chloride transport system;

2. doping GaAs wafers of n-type conductivity with Cr during the diffusion process.

SI-GaAs layers compensated with Cr during the process of liquid-phase epitaxy are of undoubted interest. Works in this direction are also carried out [5].

**UNDOPED GaAs EPITAXY LAYERS**

**VPE-GaAs characterization**

A growth of epitaxial GaAs layers from vapor phase is carried out under a temperature which is much lower than the temperature of bulk monocrystals growth ($T \leq 750 \text{ C}$). At this temperature a length of GaAs homogeneity region is small. Therefore, the equilibrium concentration of native point defects, caused by a deviation from stoichiometry, should be several orders lower in epitaxial layers than in the ingot GaAs. A great number of DLTS measurements have shown that the concentration of deep centers corresponding to native point defects or to their complexes with impurity atoms does not exceed $10^{13}$ cm$^{-3}$ in VPE layers including layers grown in the chloride transport system [6]. Only the concentration of the electron traps EL2 can reach $\approx 5 \cdot 10^{14}$ cm$^{-3}$ value when the relation As/Ga is high.
The level of background impurities in VPE GaAs depends on the used system and on particular growth conditions. In this regard the Ga-AsCl$_3$-H$_2$ system has the advantage over other VPE methods, since it assumes deep cleaning of initial components. Therefore, this method is expedient for fabrication of the ionizing radiation detectors material.

Epitaxial GaAs layers were grown in the Ga-AsCl$_3$-H$_2$ system on substrates of the orientation 2 from (100). GaAs wafers doped with Te with the electron concentration of $n^+\approx10^{18}$ cm$^{-3}$ were used as the substrates. The undoped epitaxial layers were (40-50)μm thick. For an electrophysical parameters control epitaxial layers on SI-GaAs substrates were grown under the same conditions. For these samples Hall constant was measured by means of Van der Pauw method. The parameters of the undoped epitaxial layers are presented in Table 1. Concentrations of ionized donors ($N_d$) and acceptors ($N_a$) and a compensation factor for an n-type GaAs sample have been calculated according to the Brooks-Herring formula. It can be seen that the undoped epitaxial GaAs layers are: of n-type conductivity with a free carriers concentration of $\approx10^{14}$ cm$^{-3}$ and high compensation factor; of p-type conductivity with a concentration of $\approx10^{11}$ cm$^{-3}$ and high resistivity. The nature of compensating acceptor centers is unspecified. Previous investigations have shown that in highly doped GaAs layers the effect of self-compensation occurs due to shallow acceptor centers, for example, complexes a donor-Ga vacancy or an impurity atom in the As node (for amphoteric impurities). For the low doping level the compensation is mainly due to deep centers. These centers are possibly conditioned by background deep acceptor impurities (Fe, Cr). The presence of these impurities is confirmed by our measurements made by means of the secondary ion mass-spectroscopy method.

Table 1. Electrophysical and charge collection efficiency of VPE-GaAs structures

<table>
<thead>
<tr>
<th>N-type</th>
<th>$d$, μm</th>
<th>Cond. type</th>
<th>$\rho$, Ohm-cm</th>
<th>$n$, cm$^{-2}$</th>
<th>$\mu_e$, cm$^2$/V·s</th>
<th>$\gamma_{90}^{\text{Sr}}$</th>
<th>$Q_{238}^{\text{Pu}}$</th>
<th>$Q_{241}^{\text{Am}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35-55</td>
<td>n</td>
<td>$&gt;10^2$</td>
<td>$&lt;10^{14}$</td>
<td>&gt;5000</td>
<td>6200</td>
<td>3250</td>
<td>13950</td>
</tr>
<tr>
<td>2</td>
<td>40-60</td>
<td>p</td>
<td>(0.8-2)$\cdot10^3$</td>
<td>(0.6-2)$\cdot10^{11}$</td>
<td>390-420</td>
<td>6700</td>
<td>3600</td>
<td>14250</td>
</tr>
</tbody>
</table>

The control of the parameters of the layers grown on n$^+$-substrates was carried out by means of C-V characteristics of a mercury probe or electrolytic profilometer as well as by means of measurement of the point probe breakdown voltage on angle laps. The results of this measurements indicate that the undoped epitaxial layers grown on n$^+$-substrates as well as on SI-GaAs substrates have the charge carriers concentration $\leq10^{14}$ cm$^{-3}$ and can be of both types of conductivity. In all cases there is a transition region of n-type near the layer-substrate interface (Fig.1) caused by the effect of auto-doping by impurities from the n$^+$-substrate. The electron concentration in this region decreases from the layer-substrate interface to the layer depth. A $\pi$-v junction is formed at the end of the layer.
Experimental results

High charge collection efficiency (CCE) has been obtained on the detectors fabricated on the base of the structures of p-type conductivity. Generalized experimental data on ionizing radiation detection is presented in Table 1. The typical amplitude spectra under γ-rays from the $^{238}$Pu and $^{241}$Am sources are shown in Fig.2 (a,b). The observed peaks positions on the X-axis correspond to almost 100% CCE for the average electric field strength in the structure of ~10 kV/cm. Energy resolution is ~1.6keV at the temperature of 300 K. An analysis of the C-V dependencies shows that the full depletion of the epitaxial layer occurs at the bias voltage of several volts. An amplitude spectrum under β-radiation from the $^{90}$Sr source is shown in Fig.2(c). The maximum position corresponds to the registered charge of $Q/e \approx 6200$. It means that the sensitive layer thickness (d) exceeds the 35 μm value.

![N-distribution](image_url)

**Fig.1.** Schematic distribution of the concentration of doping impurities in GaAs VPE structures

### DIFFUSION Cr COMPENSATED GaAs LAYERS

**Effects related to GaAs doping with d-impurities**

We used doped GaAs of n-type with the electron concentration $n \approx N_d \approx 10^{17}$ cm$^{-3}$ which is overcompensated into the p-type by means of Cr diffusion [7]. Cr diffuses like an internode atom Cr. Meeting with the gallium vacancy $\text{Cr}^+ + V_{Ga} \rightarrow \text{Cr}_{Ga}$ results in fixing chromium in the gallium node with the strongly localized potential which is a feature of impurities with the unfilled electron d-shell. Thus, allowed energy levels appears near the middle of the band gap [8]. For the concentration relation

$$N_C > N_d > N_f,$$

where $N_f$ is the total concentration of the background impurities and native defects, the background impurities partly compensate each other [9]. Electrons of the shallow donors fill deep EL2 centers according to (2) and partly compensate Cr centers.
Diffusion of the deep-level Cr impurity occurs at high temperatures. Therefore, compensation processes take place at the same time with the rearrangement of the native defects of a crystal. When we used the above technology we observed a formation of layers of dielectric type with a high level of compensation with deep centers. The resistivity of compensated layers reaches limit values \[10\]:

\[
\rho_i \equiv \rho_{max} = b^{1/2} / 2e \cdot \mu_n \cdot n_i,
\]

where \(n_i\) is intrinsic concentration, \(b = \mu_n / \mu_p \approx 15\), \(\rho_i > 10^9\) Ohm-cm.

A technology of formation of structures of two types is developed on the base of doping with Cr during the diffusion process. Structures of 1 type (n-v-n) are presented in Fig.3 schematically. The Cr distribution in the structure is nonuniform. Therefore, a double-layer structure is formed step-by-step on the n-GaAs substrate. The relation of concentration in the first layer is \(N_d \equiv N_{Cr} - N_f\). In this case the electrons of the

Fig.2. The typical amplitude spectra of GaAs VPE structures under γ-rays (a, b) and β-radiation (c).
donor centers completely fill the Cr centers and the high-resistive layer is of n-type conductivity (ν-layer). In the second layer the concentration relation $N_{Cr} > N_d - N_f$ takes place and the high-resistive layer is of p-type conductivity (π-layer), Fig.3. Structures of the second type (i-type) are formed by means of reach-through diffusion of Cr into n-GaAs with resistivity $\rho_t \approx \rho_{max}$. The structures have different contacts to the i-layer.

![Fig.3. Schematic distribution of the concentration of doping impurities in SI-GaAs structures compensated with Cr.](image)

**Electrophysical characteristics of compensated structures**

![Fig.4. A fragment of the energy diagram of highly compensated structures.](image)
In highly compensated crystals, and such are our structures, one can observe effects related to the random character of impurity distribution. Since in the equilibrium thermodynamic system (in a crystal) the chemical potential level is equalized, the energy diagram of the inhomogeneous crystal begins to look like goffer [11]. A fragment of the potential energy changes related to the random character of impurity distribution for the electrons photo-excitation from the valence band to the conduction band (transitions 1,2,3) is shown in Fig.4.

As a result, the electrons and holes in their gaps turn out to be spatially separated. Since for recombination they have to overcome an energy barrier of height \( \Delta E \), the electrons and holes can stay in the non-equilibrium state for a long time until they will be forcibly transited (transition 5) to the crystal point where a direct recombination can occur (transition 4). The non-equilibrium carriers lifetime \( (\tau) \) in the crystal with fluctuations of the bands edges increases according to the following law [12]:

\[
\tau = \tau_o \cdot \exp(\Delta E / kT),
\]

where \( \tau_o \) is the lifetime before compensation, \( \Delta E \) is the mean value of the height of the recombination barrier. Estimations show that in GaAs structures compensated with Cr \( \Delta \equiv 0,15\text{eV} \) and the lifetime increases up to \( 3 \cdot 10^7 \text{s} \).

![Graph](image)

**Fig.5.** The field dependence of charge collected by the \( \pi-v \) junction in the case of \( \alpha \)-particles detection.

The increase of the lifetime has been experimentally confirmed by means of two independent methods. In Fig.5 a field dependence of the amplitude of charge collected by the \( \pi-v \) junction (a structure of 1 type) registering \( \alpha \)-particles is presented. The dependence corresponds to the known expression [13]:

\[
Q = Q_o \cdot \frac{\mu_n \cdot \tau_n \cdot U_o}{d^2} \cdot \left[ 1 - \exp \left( -\frac{d^2}{\mu_n \cdot \tau_n \cdot U_o} \right) \right],
\]

- 370 -
where $Q_o/e = E_o/E$, is a number of electron-holes pairs created in the structure by a single $\alpha$-particle. The $\pi$-$\nu$ junction is reverse-biased and, therefore, we register the charge of electrons drifting through the high-resistive layer. In the region of low bias voltage the exponent in the expression (5) can be neglected, therefore, experimentally we observed a linear dependence $Q(U_d)$. The slope of the dependence corresponds to a value describing the non-equilibrium electron drift length in a low electric field when $\mu_n \cdot \tau_n \approx 10^{-4}$ cm$^2$/V. Parallel measurements have been made for a photoexcitation of non-equilibrium electron-holes pairs on the $\pi$-$\nu$-n structure surface by ultraviolet (UV) radiation of energy $h\nu \sim 6$ eV. Without applied bias voltage we have observed a photovoltaic effect in the $\pi$-$\nu$ junction due to non-equilibrium electrons and have defined the diffusion length which consists $\approx (10^2 + 10^1)$ cm. Estimations show that the non-equilibrium electrons lifetime in GaAs structures compensated with deep level impurities is in the range of $(10^{-7} + 10^{-6})$ s.

Investigations of electrophysical characteristics of the diffusion layers have confirmed the above model of the high-resistive compensated GaAs with the goffer energy diagram [11]: low values of Hall mobility of charge carriers ($\mu_n \leq 10^3$ cm$^2$/V·s, $\mu_p \leq 10^2$ cm$^2$/V·s) indicate the formation of drift barriers in the crystal.

Electric characteristics of the compensated structures

![Electric field distribution](image)

Fig.6. The electric field distribution in the diffusion structures of 1st type for different reverse bias voltages: 1-50V; 2-100V; 3-200V; 4-300V; 5-500V; 6-700V; 7-900V.

Electric characteristics essentially depend on the structure type. In the structures of 1st type, which contain a substrate, the electric field is always localized at the high-resistive layer-substrate interface with a maximum within the space charge region (SCR) of the $\pi$-$\nu$ junction. The electric field shifts towards the high-resistive $\pi$-layer with the increase of the bias voltage as it is shown in Fig.6. The dependence was
obtained by differentiating a curve of the potential distribution in the structure measured by means of a probe technique. In terms of the step distribution of the concentration of the deep compensating impurity within the SCR of the π-v junction a concentration of non-compensated Cr atoms at the edge of the π-region of the SCR has been evaluated: \( N_b \equiv (N_\text{Cr}^- - N_\text{Cr}^+) \equiv (3-5) \times 10^{13} \text{ cm}^{-3} \). It can be shown, by an analysis of the filling function of deep centers, that the decrease of the negatively charged deep centers concentration at the edge of the π-region of the SCR is related to the non-equilibrium holes trapping on the negatively charged deep Cr centers when the π-v-n structure is reverse-biased. In the structures of 2 type, which contain only the high-resistive layer, the distribution of the electric field is close to uniform along the whole high-resistive layer thickness. But a certain maximum is observed near the anode independently of the conductivity type, the contact layer properties and the bias voltage polarity, related presumably to the formation of a stationary domain of the electric field.

The structure type defines also the mechanism of current flow which is analyzed in previous works [14,15]. We would like to note only that because of the formation of high-resistive layers with the extremely high resistivity and formation of local barriers, the bulk current density in the structure doesn’t exceed \( (10^{-7}+10^{-6}) \text{ A/cm}^2 \) value for the average electric field strength \( \leq 10 \text{ kV/cm} \).

Experimental results on γ-rays detection

Structures for X-imaging detectors must satisfy the following:

- The condition of high (>95%) efficiency of detecting radiation can be written as \( \alpha \cdot d(\xi) > 3 \), where \( \alpha \) is the absorption coefficient of X-radiation, \( d(\xi) \) is the thickness of the sensitive layer depending on the distribution of the electric field strength. An ideal variant is fulfilled in the structures of 2 type (p-i-n) when the electric field is uniformly distributed in the thickness of the high-resistance layer, therefore we have \( d(\xi) \rightarrow d_0 \).

- The condition of complete collection of non-equilibrium charge carriers in the sensitive layer corresponds to the following relations

\[
L_{d_s} = \tau_n \cdot \nu_n(\xi) > d(\xi),
\]

\[
L_{d_p} = \tau_p \cdot \nu_p(\xi) > d(\xi). \quad (6)
\]

In the compensated structures the drift length of the charge carriers considerably increases, which is confirmed by the experimental data presented in 3.2 and, consequently, one can expect higher CCE.
In accordance with the above conditions the structures of 2nd type (p-i-n) with the high-resistive layer thickness \( d_l \geq 400 \mu m \) are the most promising for the X-ray imaging detectors development. In these structures it is possible to "lengthen" the electric field along the whole high-resistive layer and it provides the absence of "dead" regions in the structures. From the other side, the increase of the non-equilibrium charge carrier lifetime in the ionization track allows to achieve high CCE. The typical amplitude spectra under \( \gamma \)-rays from the \(^{238}\)Pu and \(^{241}\)Am sources are shown in Fig.7. Field dependencies of the CCE from \( \gamma \)-rays of different energy are presented in Fig.8. For \( \gamma \)-rays of low energy a 100\% charge collection is observed at the average electric field strength more than 5kV/cm. For a fixed value of the electric field strength, the CCE decreases with the increase of the \( \gamma \)-ray energy. Field dependencies of CCE from \( \beta \)-particles irradiation from the \(^{90}\)Sr source are presented in Fig.9, from what follows that properties of the contacts to the SI-GaAs layer compensated with Cr greatly influence the CCE.

![Fig.7. The typical amplitude spectra of diffusion Cr compensated GaAs structures under \( \gamma \)-rays (a,b) and \( \beta \) radiation (c).](image)
Fig. 8. Field dependencies of CCE of structures of 2 type under γ-rays.

Fig. 9. Field dependencies of the charge amplitude from β radiation of the structures of 2 type with different contact types: 1 Shottky contact-\(i-n-n^+\); 2 Ohmic contact-\(i-n-n^+\); 3 \(p^+-i-n^+\).

CONCLUSIONS

Different variants of the GaAs technology for X-ray detectors fabrication is proposed in this work. The technology allows decreasing the concentration of the \(EL2^+\) centers that are the efficient centers of electrons trapping. It is shown that epitaxial methods of formation of SI-GaAs layers, for example, a growth of undoped GaAs
layers by means of vapor phase epitaxy in the chloride transport system, are have future potential.

A fundamentally new diffusion technology of obtaining a promising SI-GaAs material of the p-type conductivity for X-ray detectors is suggested.

The main advantages of the above detector material as compared to the conventional ingot SI-GaAs are due to the following factors:

- a much greater drift length value both for electrons and holes;
- a larger value of the resistance of SI-GaAs, $\rho \rightarrow \rho_{\text{max}}$;
- a possibility to "lengthen" an electric field along the whole thickness of the high-resistance layer.

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