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GaAs resistor structures for X-ray imaging detectors

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Abstract

Unlike conventional GaAs detector structures, which operation is based on the use of a space charge region of a barrier structure, we propose to form a detector structure of resistor type. In this case, the electric field distribution, $\xi(x)$, is not screened by the ion concentration in the SCR but it is defined only by the uniformity of the resistance value distribution in the structure. The experimental results on charge collection efficiency for the detector irradiation with α, β, γ-radiation are presented. It is shown that the amplitude spectrum shape in the case of interaction with γ-radiation is defined mainly by the electron component of the charge. The simulation of the detector response function confirms it. It is established that, despite of hole trapping, it is possible to achieve high values of charge collection efficiency of γ-radiation. Explanation of the charge collection efficiency dependence on a type of ionizing radiation is made. Problems of design of the detector with high charge collection efficiency and low dark current are discussed.

Keywords: GaAs; Resistor structure; α; β; γ-radiation; Charge collection efficiency

1. Introduction

In this work, characteristics of the detectors fabricated on the base of semi-insulating (SI) GaAs resistor structures [1] have been investigated. The structures are made by means of high-temperature Cr diffusion into GaAs of n-type conductivity. The material feature is that for any type of metal contacts the electric field distribution through the whole detector structure thickness is uniform independently of the bias voltage polarity.

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2. Experimental technique

The detector experimental samples had a symmetric metal–semiconductor–metal structure and were made on the base of SI-GaAs resistor structures with the resistivity $\rho \approx 10^8 - 10^9\,\Omega\,\mathrm{cm}$. The samples area was $S \approx 0.3 \times 0.3\,\mathrm{cm}^2$, the high-resistive layer thickness was 800 μm. Ohmic contacts were made by step-by-step evaporation of metallic layers V, Au.

Investigations of amplitude spectra of the detector structures for γ photons of energy 60 keV from ^{241}Am radioactive source have been carried out. Low-energy component of γ-radiation,

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corresponding to the energy of 14 keV, was cut off by a GaAs filter 300 μm thick.

Current–voltage characteristics of the investigated structures are presented in Fig. 1. The characteristics are symmetric and obey Ohm's law up to bias voltages 400–500 V. The distribution of the resistivity through the high-resistive layer is uniform, as it is shown in Fig. 2. Therefore, the electric field distribution is supposed to be also uniform. It was confirmed experimentally by the potential distribution measured by means of a probe technique.

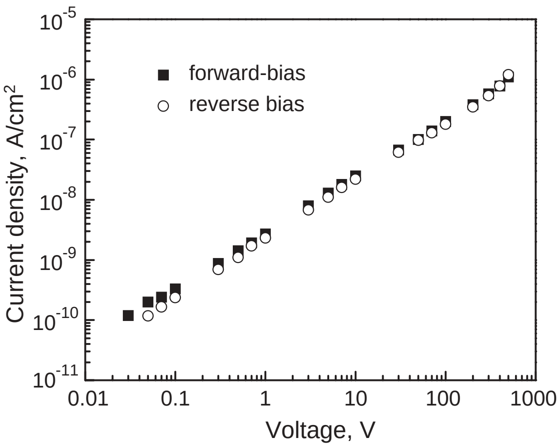

Fig. 1. Current–voltage characteristic of GaAs compensated by Cr.

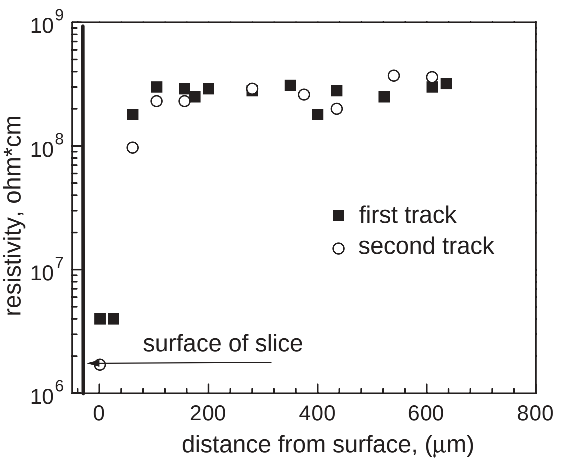

Fig. 2. Resistivity distribution through the sample thickness.

3. Analysis of the amplitude spectrum of the resistor structures

Modeling of the dependence of the amplitude spectrum shape and the charge collection efficiency (CCE) on bias voltage in the case of non-uniform absorption of γ photons has been carried out on the base of the expression [2]:

$$\frac{dN}{dE} = \int_0^d \frac{k \exp^{-kx}}{\sqrt{2\pi}\sigma_\Sigma(x)(1-\exp^{-kd})} \times \exp\left(\frac{-(E - E_{\gamma 0}\eta(x))^2}{2\sigma_\Sigma^2(x)}\right) dx \tag{1}$$

where $k \cong 10.98$ is the absorption coefficient of 60 keV X-rays in GaAs; $\eta(x)$ is a Hecht function, which is the CCE in dependence of a point of non-equilibrium charge carrier generation; dN/dE is the event intensity.

In the case of plane geometry and in the absence of charge carrier re-emission, when the photoelectron path is much lower than d, and without taking into account initial losses in the track, the function $\eta(x)$ is [2,3]

$$\eta(x) = \frac{l_n}{d}\left(1 - \exp\left(\frac{-(d-x)}{l_n}\right)\right) + \frac{l_p}{d}\left(1 - \exp\left(\frac{-x}{d}\right)\right) \tag{2}$$

where $l_n = v_n\tau_n$, $l_p = v_p\tau_p$, are drift lengths of electrons and holes, respectively; v_n, τ_n, v_p, and τ_p are drift velocities and lifetimes of electrons and holes, respectively.

The electron drift velocity dependence on the electric field strength ξ was approximated by the expression [4]:

$$v_n(\xi) = v_s\left(1 + \frac{\xi/\xi_s}{1 + A(\xi/\xi_s)^t}\right) \tag{3}$$

where $A = 0.6(\exp(10(\mu_n - 0.2)) + \exp(-35(\mu_n - 0.2)))^{-1} + 0.01$,

$$t = 4\left(1 + \frac{320}{\mathrm{sh}(40\mu_n)}\right), v_s = 0.6 + 0.6\,\mu_n - 0.2\,\mu_n^2$$

here the electron mobility, μ_n, is expressed in $m^2/V\,s$, v_s in 10^5 m/s.

It is easy to show that if $l_n, l_p \geqslant d$, $\eta \to 1$ and is independent of the point of γ photons absorption within the active region.

According to Ref. [2], the root-mean-square deviation in the case of independence of noise components is

$$\sigma^2_\Sigma(x) = \sigma^2_{st} + \sigma^2_{el} + \sigma^2_{col}(x) \tag{4}$$

where

$$\sigma_{st} = \sqrt{F\varsigma E_{\gamma 0}} \tag{5}$$

and

$$\sigma_{col}(x) = \sqrt{E_{\gamma 0}\varsigma\eta(x)(1-\eta(x))}. \tag{6}$$

In expressions (4)–(6) σ_{st} is a fluctuation of electron–hole pair creation; $\varsigma \cong 4.2\,\text{eV}$ is the average energy of the electron–hole pair creation in GaAs; F is the Fano factor; σ_{el} is electronics noise; σ_{col} (x) is a fluctuation conditioned by not full charge collection in dependence of the point of charge carrier generation.

Calculated amplitude spectra, according to expression (1), for γ-line $E_{\gamma 0} = 60\,\text{keV}$ of ^{241}Am radioactive source for different values of the bias voltage are presented in Fig. 3. It can be seen from the figure that there is no sharp peaks in the spectrum and a low-energy "tail" is observed. The behavior of the amplitude spectra can be explained by non-uniform absorption of γ-radiation through the high-resistive layer thickness according to the Bouguer's law:

$$J(x) = J_0 \exp(-kx) \tag{7}$$

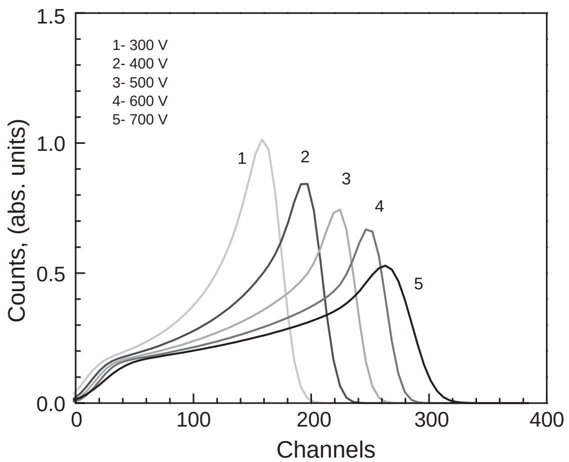

Fig. 3. Calculated shape of amplitude spectra from γ-radiation (60 keV) for different bias on the detector.

where $J(x)$, J_0 are γ-radiation intensity in the point x and near the detector structure surface respectively, Fig. 4. For the condition $l_p \ll d$ and $l_n \sim d$, the function $\eta(x)$ is defined mainly by the electron component of the charge and becomes dependent on the γ-photon absorption point:

$$\eta(x) \approx \eta_n(x) \approx 1 - \frac{x}{d}. \tag{8}$$

Consequently, events in the point $x \approx 0$, Fig. 4, in which the radiation intensity is maximum, will correspond to the maximum in the amplitude spectrum. l_n and l_p increase with the bias voltage due to the growth of electron and hole drift velocities. It results in the amplitude spectrum maximum shift towards $E_{\gamma 0}$ and its decrease in the absolute value.

Figs. 5 and 6 demonstrate the experimental electric field dependences of the response function and charge collecting efficiency in the case of the detector irradiation with γ-photons with the energy of 60 keV. It is interesting to note, that the area under the curve Fig. 7, which is defined by the relation (9):

$$S = \int_0^\infty \frac{dN}{dE}\,dE \tag{9}$$

where dN/dE is intensity of events in the energy range of dE, reaches saturation at sufficiently low values of the bias voltage (Figs. 5 and 7). This fact allows to state that the whole detector thickness (d) is active, keeping in mind a high value of CCE

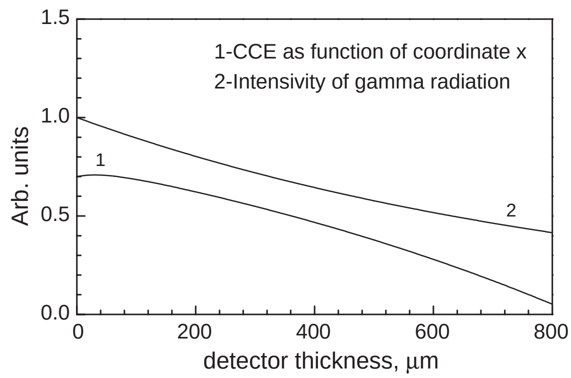

Fig. 4. Calculated values of charge collecting efficiency (1) and intensity of γ-radiation (2) dependences from point of interaction.

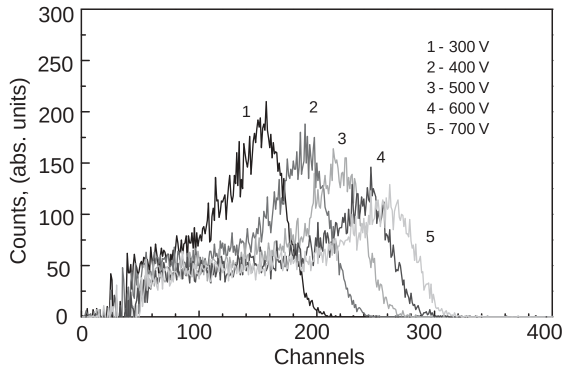

Fig. 5. Experimental amplitude spectra from γ-radiation (60 keV ^{241}Am source) for different bias on detector.

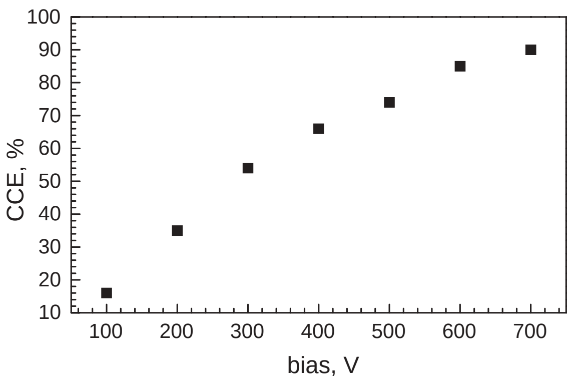

Fig. 6. Experimental charge collecting efficiency dependences for (60 keV) γ-radiation of the bias voltage.

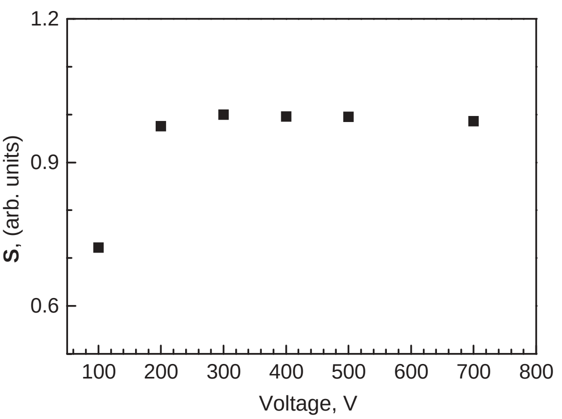

Fig. 7. Sum of event dependences for (60 keV) γ-radiation of the bias voltage.

(Fig. 7). It confirms the advantage of the proposed detector structures of resistor type in comparison with conventional structures manufactured on the basis of Schottky barrier and p–n junction.

Besides charge collecting efficiency dependence on the bias voltage for γ-radiation (CCE_γ), the investigations of similar dependences for α-, β-radiation are reported in the analysis (Fig. 8): the maximal value of CCE for α-radiation is 30–40%, for β-radiation is 50%, for γ-radiation it is 80–90%.

An average value of penetration for α-particle with energy 5.5 MeV in GaAs is about 25 μm. It is known that the changes generated by track filled of electron–hole plasma with density $10^{18}\,cm^{-3}$ with diameter 1–2 μm is a result of this interaction.

The plasma dissolving will take place during the time t_{pl} due to the diffusion of carriers to the periphery of the track. In our material the value of t_{pl} is about 30% or 50% of the electron lifetime.

Such a high density of charge carriers prevents electric field penetration into the track and results in the loss of charge because of carrier trapping on deep levels.

The CCE value for β-radiation of 50% is the effect of collection of electrons. According to the relation (2) the electron drift length l_n must be more than the detector thickness. This conclusion is confirmed by the value of $CCE_\gamma \sim 90\%$ in Fig. 6

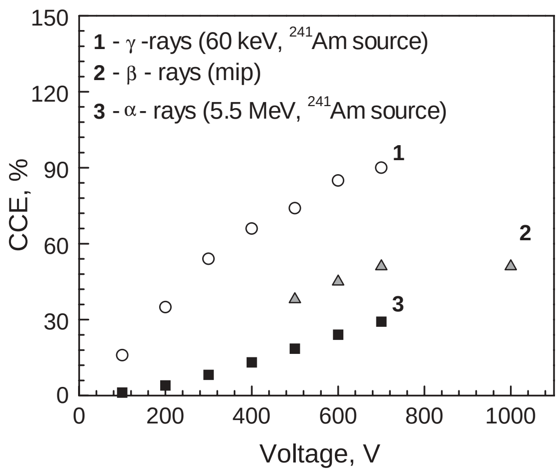

Fig. 8. Charge collecting efficiency dependences for α, β, γ-radiation of the bias voltage.

and the shape of the amplitude spectrum in Fig. 5. Thus, the value of $CCE_\beta \sim 50\%$ for β-radiation is limited by the hole lifetime but not by the sensitive layer width.

In our calculations we supposed that $l_p \ll l_n$. The fitting parameters μ_n, μ_p, τ_n, τ_p, $\sigma = 2$ keV were taken.

4. The features of multi-element detector design on the base of resistive structures

We have taken in account for multi-element detector design that the electron drift length is greater than the hole one. This experimental fact can be used for manufacturing of pixel and strip detectors to avoid "pixel effect" [5]. Calculations show that the bias voltage of positive polarity must be applied to the pixel contact in order to reach the high value of CCE due to the collection of electrons. It is confirmed by the calculated dependences of CCE for pixel matrix made out of our material. For different polarities of the pixel contact results are presented in Figs. 9 and 10. Application of the positive bias voltage to the pixel contact allows reaching the high value of CCE for a wide range of pixel matrix parameters.

Fig. 11 illustrates the image of the manufactured pixel matrix. The matrix has 170 μm pitch and the active region thickness 700 μm. The operating voltage for such matrix is 500 V. Experimental values of CCE are about 70% for γ-radiation with energy 60 keV.

In perspective, resistive structure can be made by Cr diffusion into GaAs vapor phase epitaxy (VPE) layers. Fig. 12 shows the amplitude spectra. The values of CCE for α- and γ-radiations for these detector structures are higher than for the detector structures fabricated by means of Cr diffusion into ingot GaAs. These differences can be explained by the greater value of charge carrier lifetimes due to higher purity and quality of the GaAs VPE layers.

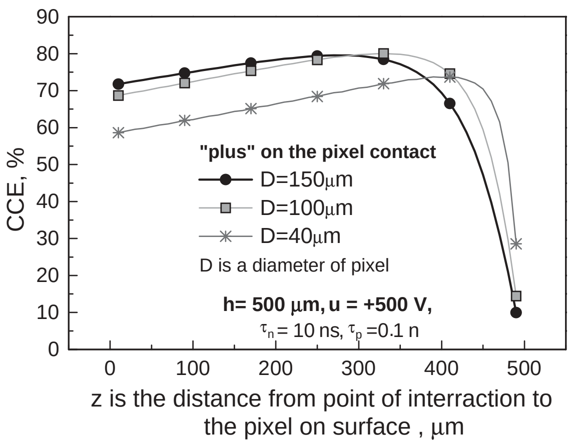

Fig. 9. Calculated dependences of charge collecting efficiency of the pixel matrix made of our material for positive polarities on the pixel contact.

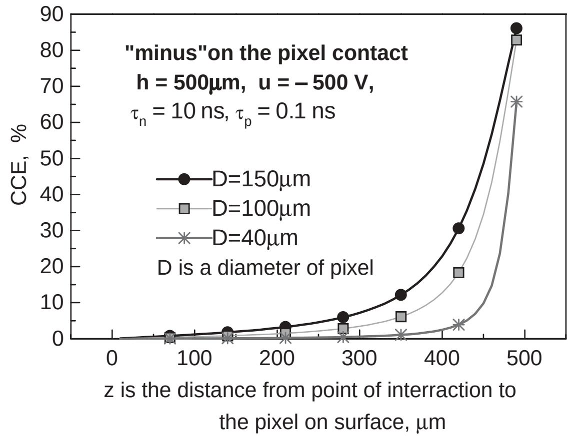

Fig. 10. Calculated dependences of charge collecting efficiency of the pixel matrix made of our material for negative polarities on the pixel contact.

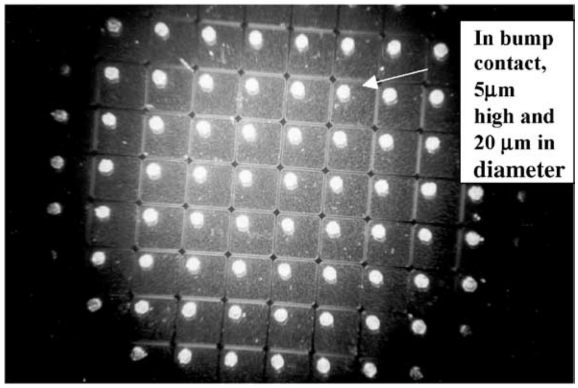

Fig. 11. Image of the manufactured pixel matrix.

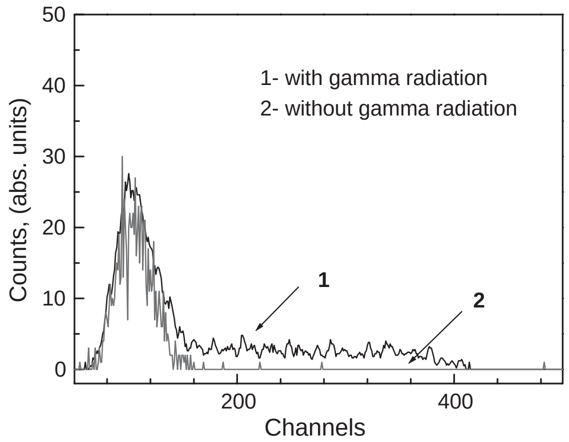

Fig. 12. The structures made by Cr diffusion in vapor phase epitaxy layers of GaAs γ-radiation (60 keV, source ^{241}Am). Bias voltage = −300 V.

5. Conclusion

Original resistive detector structures have been developed. They have high sensitivity to α-, β-, γ-radiations and their performance are independent of the bias polarity. The detector sensitive layer occupies the whole detector thickness. The detector lines and pixel matrix with the sensitive layer width up to 800 μm have been manufactured. The technique offers a perspective for the manufacture of multi-element detectors with high values of the CCE. Future development includes increase of the thickness of a sensitive layer up to 1 mm.

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