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GaAs X-ray coordinate detectors

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Abstract

GaAs coordinate detectors for X-ray systems of scanning type have been developed. Two modifications of the detectors have been constructed for ionizing radiation detection in parallel and perpendicular to the electric field direction in the detector bulk. The detectors have 64 active regions with 100 μm pitch. In order to reach the minimum value of coupling capacitance and resistance coupling between active regions, the latter is separated by narrow gaps on unit cells. The gaps are made by means of reactive ion etching. The detectors are fabricated on the base of vapor-phase epitaxial material 40–45 μm in thickness with free carriers concentration of $p_0 = 10^{12}\,\mathrm{cm}^{-3}$. Input capacitance of a detector cell is 0.25 pF, dark current is 30–50 pA per cell. The detectors have almost 100% charge collection efficiency for all types of ionizing radiation. High resolution of the detector allows to detect structures of a spectrum from the ^{241}Am source in the energy range of 14–17 keV. © 2001 Published by Elsevier Science B.V.

Keywords: Coordinate detector; GaAs; Epitaxial material; Dark current; Charge collection efficiency; Energy resolution

1. Introduction

During the last few years, progress has been made in the field of X-ray tomography. In Budker Institute of Nuclear Physics of SB RAS, a low dose digital radiographic device "LDRD SIBERIA – N" was developed which allowed to reduce a patient's radiation dose by a factor of 30–100. In the device, a multiwire proportional chamber of high efficiency is used instead of standard X-ray film for radiation detection. Detector parameters like spatial resolution, high-speed response, dynamic range, etc. define the parameters of the whole device. A semiconductor coordinate detector is a direct solid analog of the multiwire chamber. Coordinate detectors based on Si are widely used in nuclear physics but they are not as effective as X-ray detectors since the absorption coefficient of X-rays in Si is small. GaAs detectors, due to higher absorption coefficient, could be an alternative to proportional chambers if a spatial resolution in the range of 50–100 μm is required.

The aim of this work was to study a possibility of GaAs coordinate detectors fabrication for X-ray systems of scanning type for mammography.

2. The material for X-ray coordinate detectors

In this work, a material grown by means of vapor-phase epitaxy (VPE) in Tomsk Scientific

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and Production State Enterprise "Semiconductor Devices Research Institute" ("SDRI") was taken. The material structure and its main parameters are presented in Fig. 1.

The most interesting result regarding electrophysical characteristics of the VPE structures consists in the fact that the charge carrier concentration in the epitaxial active layer does not exceed $10^{12}\,cm^{-3}$. The result is illustrated by the device capacity dependence on the bias voltage shown in Fig. 2. As follows from the figure, the depletion region thickness is about 30 μm and completely occupies the p-region at zero bias. It means that the device is capable of operating at low voltages and currents. In our p-layers, the Hall mobility is $400 \pm 40\,cm^2/V\,s$. The deep center concentration in the layers has been measured to be less than $10^{13}\,cm^{-3}$, which allows to fabricate detectors more than 100 μm thick.

In Fig. 3, amplitude spectra from α particles (^{239}Pu, ^{238}Pu, ^{233}U) are presented. It is clear that

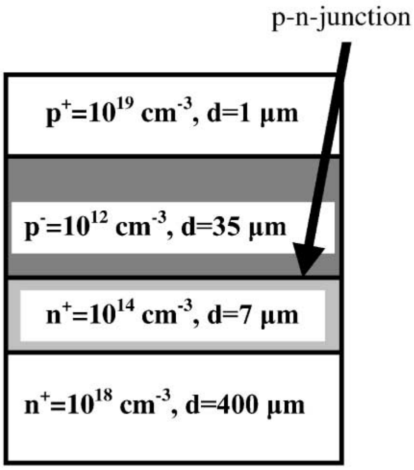

Fig. 1. Parameters of GaAs VPE structures.

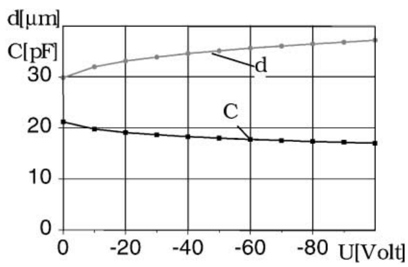

Fig. 2. The capacitance–voltage dependence of the detector ($S = 5.5\,mm^2$) and the depletion depth as a function of bias.

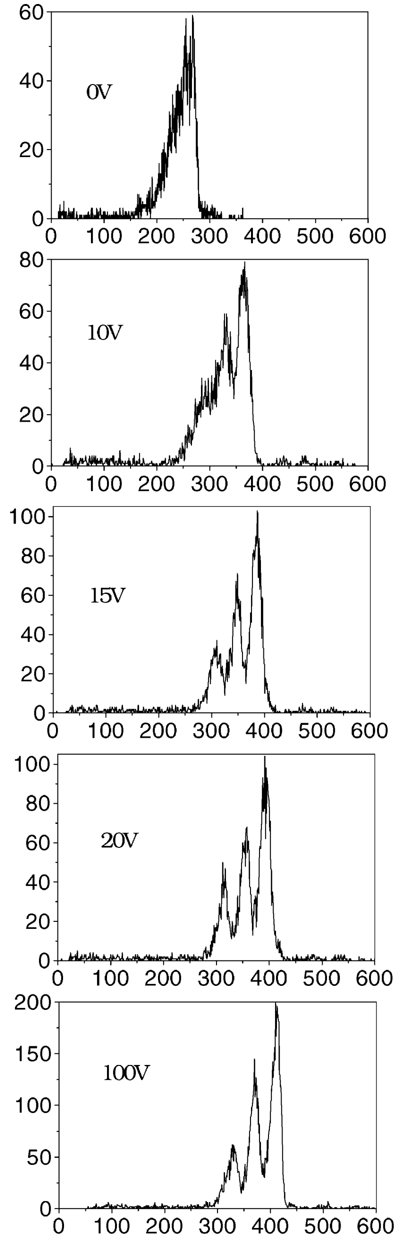

Fig. 3. α spectra obtained for detectors from (^{239}Pu, ^{238}Pu and ^{233}U sources).

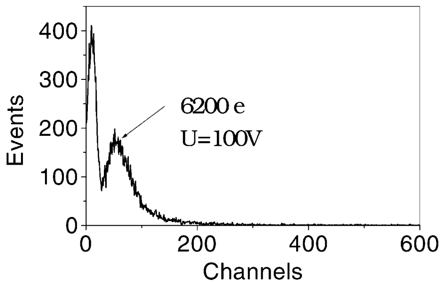

Fig. 4. The response of the detector to Sr^{90} electrons reverse biased at 100 V, measured at 20°C.

the detectors can operate at zero voltage and have good energy resolution at voltages of 15–20 V. A 100% charge collection efficiency (CCE) for X-ray photons of 14–100 keV energy range as well as for β particles has been obtained at voltages of 25–100 V. Charge collection of 6200 electrons at 100 V has been obtained in the case of the detector irradiating with β particles, Fig. 4. We would like to note that the charge collected by other authors from the best VPE structures was at a value of 5800 electrons at 200–400 V [1].

3. The detector construction and fabrication technology

For the selected material, we had to change the coordinate detector construction in order to exclude the coupling resistance between channels. The changes are explained by means of Fig. 5. A construction of the developed device is shown in Fig. 6 schematically. The detector channels are separated by narrow grooves. Due to this, the detector does not have interstrip capacities and regions of high electric field strength. Such a construction provides maximum charge collection and minimum current value. Output signals contain the information only about discrete regions of the investigated object.

Implementation of the proposed construction has been carried out on the basis of the developed process of reactive ion etching of GaAs. We have managed to make separation grooves of 15 μm thickness and 40–60 μm depth, as shown in Fig. 7.

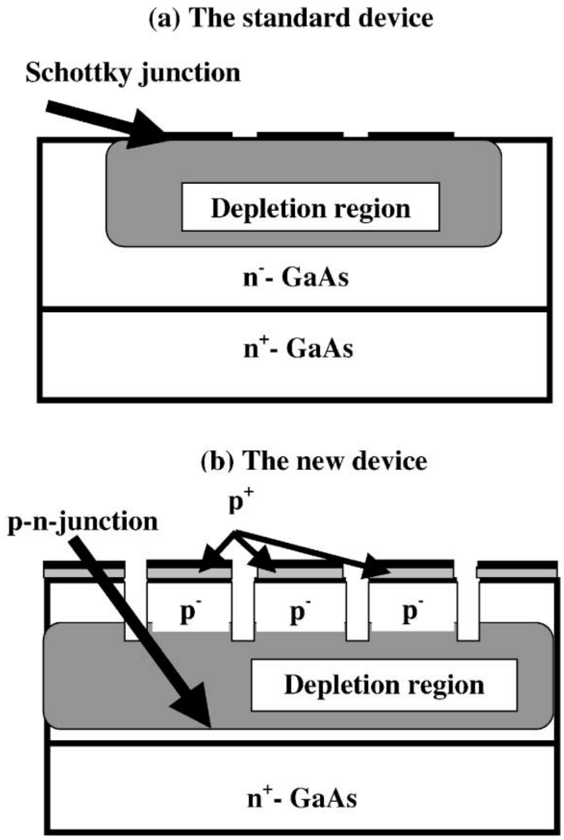

Fig. 5. Comparison of two designs of the device: (a) conventional and (b) new.

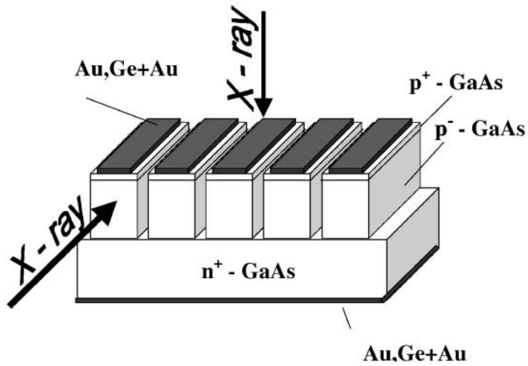

Fig. 6. The new developed device.

A form of a separation groove of 15 μm thickness and 40 μm depth is shown in the figure. Reactive ion etching of GaAs has been made in a medium containing chlorine and fluorine and through an

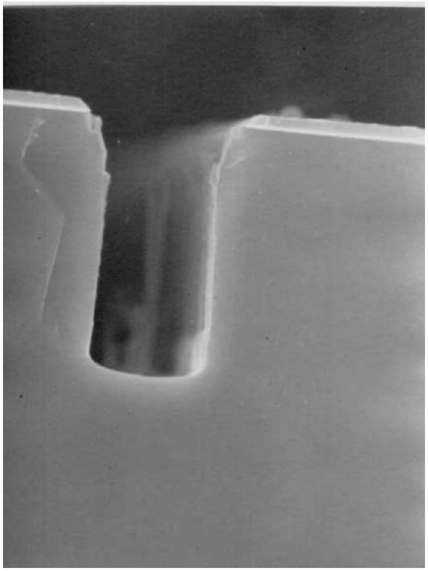

Fig. 7. The SEM cross-section showing 15 μm wide groove obtained by RIE.

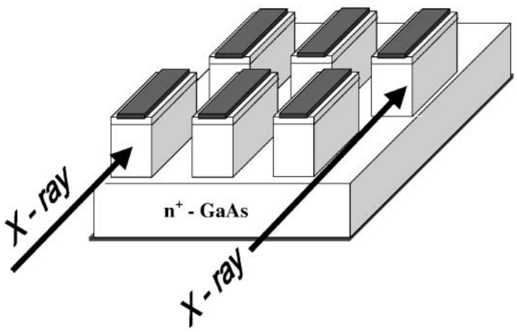

Fig. 8. A coordinate detector developed for registration of particles irradiating perpendicularly to the contact surfaces.

SiO_2 mask. The developed detectors have 64 strips and 100 μm pitch. Input capacitance of one strip is 0.25 pF. The developed detector construction was designed to be used for X-ray photons irradiation in parallel and perpendicular to the contact layers surface. Another coordinate detector construction specially developed for particles irradiating perpendicularly to the contact layers surface is presented in Fig. 8. An advantage of the construction is the absence of "dead regions" conditioned by separation grooves and by the implementation simplicity.

One of the main problems of detector fabrication was the problem of low currents achievement. In our work, we have tried to solve this problem by using different chemical treatments of the device surface. The results obtained are presented in Fig. 9 in the case of a reverse current–voltage characteristics of a detector of 5.5 mm^2 size. At a nominal supply voltage of 50 V, a record value of the dark current density of 70 pA/mm^2 has been obtained. For an average electric field of 10 kV/cm it is 100 times less than in semi-insulating GaAs (SI-GaAs) and at least 10 times less than in known epitaxial layers [1,2].

The obtained result is of principle interest because the measured value of the current density defines a potentiality of GaAs detectors. We would like to emphasize that this result is not only a material characteristic but an indicator of the technology level. During the development of the detector fabrication technology an original process of chemical oxidation of the detector crystal has been developed. The process is carried out in the presence of Au contacts and does not change their characteristics. Oxidation of GaAs occurs on the whole open crystal surface to the depth of 0.2 μm. This process sharply reduces surface leakage currents and eliminates time drift of the detector characteristics. A sharp decrease of surface currents after oxidation of the crystal treated by reactive ion etching and chemical etching is illustrated in Fig. 10. We have to note that chemical etching reduces the surface current effectively in the epitaxial material as well as in SI-GaAs.

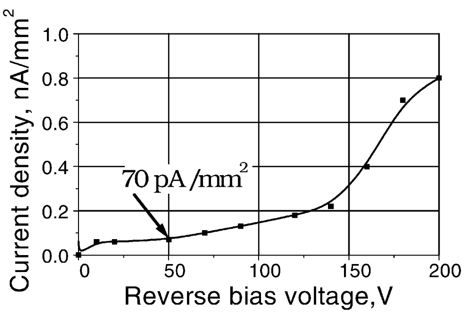

Fig. 9. Reverse current density–voltage characteristic of the detector.

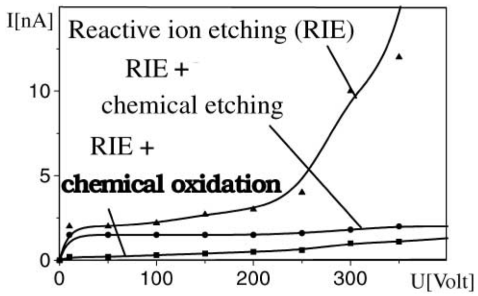

Fig. 10. The dependence of the device dark current on different ways of mesa-etching.

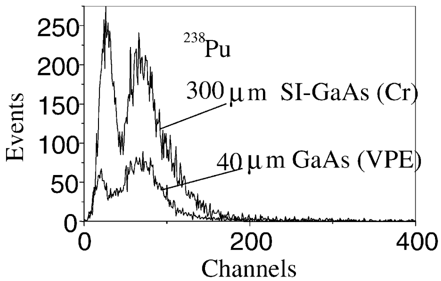

Fig. 12. A comparison of X-ray photons registration efficiency of two detectors: 300 μm SI-GaAs detector and 40 μm VPE-GaAs detector.

4. The detector parameters

An amplitude spectrum of one channel obtained from measurements with a Pu^{238} X-ray source is presented in Fig. 11. Peaks in the spectrum corresponding to energies 13.6 and 17 keV are well separated; energy resolution obtained with our detector is less than 1.6 keV. Such a resolution for room temperature can be obtained only for unique samples [3].

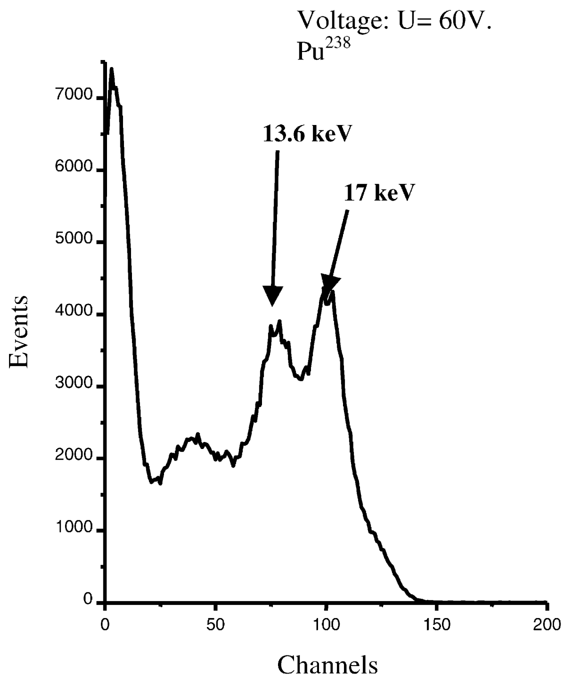

Fig. 11. The spectra obtained for detector with 60 V bias from an ^{241}Am source.

Photon registration efficiency is another important detector characteristic. In Fig. 12, amplitude spectra measured with detectors based on different materials such as epitaxial material (35 μm) and monocrystalline material (300 μm) are presented. Effective areas of the amplitude spectra in the range of 13–17 keV differ 3 times to the advantage of detectors based on monocrystalline material. Apparently, it is necessary to increase the active layer thickness at least 2 times in order to reach high registration efficiency of X-ray photons of 13–20 keV energy range. We are currently working on this problem.

Estimations show that minimum dark current values for epitaxial structures are 10–30 pA; for the diffusion structures are 2 orders of magnitude higher (the detector cell size is $100 \times 840\,\mu m^2$ in both cases).

5. Conclusions

The most important results of the work are the following:

1. Undoped epitaxial GaAs layers of p-type have been fabricated. The layers can be successfully used for ionizing radiation detectors. The use of this material is preferable since the equilibrium charge carriers concentration in GaAs VPE layers of p-type conductivity is lower than in layers of n-type and, consequently, the

depletion region thickness is larger for the same bias voltage.

2. Record values of current density—100 pA/mm^2 (for GaAs detector structures) have been obtained in VPE-layers.
3. A new construction of the detector separated by narrow grooves and its fabrication technology has been developed.
4. A technology of the detector chemical oxidation reducing surface leakage currents down to the limit has been developed.
5. The developed detectors have demonstrated high energy resolution for the 14–20 keV energy range.

Acknowledgements

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