GaAs P-I-N structures as detectors of x-ray radiation

L. M. Fedorov, D. I. Mikulik, T.A.Orlova, N.K. Panteleev, N.A. Poletaev, C. A. Snytkina and Yu.V.Zhilyaev

A.F.Ioffe Physico-Technical Institute, RAS, 194021, Russia, Saint-Petersburg, Polytekhnicheskaya, 26
dmitry.mikulik@gmail.com

Abstract. Novel epitaxial growth regimes have been identified to grow thick layers of pure GaAs (up to 250 mcm) of large area in a single growth experiments by gas phase epitaxy. Characteristics of semiconductor epitaxial p-i-n structures based on GaAs have been studied. The obtained layers of i-GaAs have residual impurity concentration $< 10^{12} \text{cm}^{-3}$. Pilot samples of x-ray radiation detector have been fabricated and energy resolution of the devices was about 600 eV at the absorbed photons energy of 60 keV and 200 eV at 5.9 keV, respectively.

1. Introduction

There are two types of semiconductor devices for detection of x-ray radiation: p-i-n diodes and Schottky diodes. Also, photovoltaic detector needing no reverse bias, in contrast to the above two device types, had been reported [1]. At present, silicon, germanium and gallium arsenide are mainly used as semiconductor detector materials for the energy range of $10 - 100 \text{keV}$. The choice of semiconductor detector material determines the specific efficiency of x-ray quanta registration. This parameter is much higher for GaAs and Ge compared with Si. Device characteristics for GaAs and Ge are close; however, gallium arsenide detectors can be operated at room temperature without cooling. Special mention should be made of the potential of $A_2B_6$ semiconductor compounds for fabrication of uncooled semiconductor detectors of X-ray, $\gamma$-ray and other types of nuclear radiation. Single crystal CdTe-detectors proved their advantages compared to other semiconductor detectors in efficiency of registration of x-ray quanta; however the presence in them of large concentrations of various impurities significantly affects characteristics of these devices. Besides, GaAs is superior to wide-gap $A_2B_6$ materials regarding charge carriers kinetic parameters (mobility and lifetime), as well as the perfection of many techniques of planar integral technologies [2].

On the strength of the above considerations we have chosen GaAs p-i-n diodes as the most promising and competitive devices from the viewpoint of eventual commercial production. Currently, the main objectives in the fabrication technology of GaAs p-i-n diodes are: achievement of high structure quality, growth of large area structures and approach to ideal device characteristics. The carrier concentration in the pure epitaxial layer should be as low as possible in order to allow the use of the entire thickness of the epitaxial layer as the sensitive detector area. One more problem of the technology is the drastic increase of the reverse current in detectors of large active area (greater than 6 mm$^2$) [2]. Thickness of the detector active area determines the energy range in which effective registration of x-ray quanta takes place. For our purposes the required active area thickness should be at least 200 mcm, which is a serious challenge for the current growth technology of high-quality gallium arsenide layers.

This study aimed at fabrication of high-quality gallium arsenide p-i-n structures suitable for subsequent manufacture of detectors of x-ray radiation in the range energy 10-100 keV.

2. Experiment

All the semiconductor structures have been grown in a custom made quartz reactor by the method of Chloride Vapor Phase Epitaxy (CVPE) in its standard form [3]. CVPE is a quite well developed
technology for fabrication of GaAs layers enabling to achieve high growth rates and good layer quality. In our experiments we used a horizontal flow reactor with resistive heating system capable of maintaining the required temperature regime both in the source zone (800ºC) and in the growth zone (730 – 760ºC). AsCl$_3$ was used as arsenic source carried to the reactor with a H$_2$ flow. In the source zone a boat with metallic Ga was placed.

Epi-ready substrates of n$^+$-type GaAs doped with Si to $10^{18}$ cm$^{-3}$ had dimensions of 5x10 cm$^2$ (rectangular) and a thickness of 300 mcm. The growth process in the reactor was a two-stage one: 1) growth of the thick (up to 200 mcm) high-resistivity basic layer of GaAs with majority carriers concentration of $10^{11}$ - $10^{13}$ cm$^{-3}$; 2) growth of p$^+$-GaAs layer doped with Zn of a thickness 1-3 mcm and concentration in the range of $10^{18}$ cm$^{-3}$. Doping with acceptor was accomplished as follows – metallic Zn was heated to T=500ºC and carried with H$_2$ flow to the growth zone.

For elimination of longitudinal thickness wedge occurring in the growth in a horizontal reactor an additional flow of AsCl$_3$ was applied, which at high temperature is interacting with H$_2$ producing hydrogen chloride shifting the useful gas mixture toward the end of the growth zone. This process serves to equalize deposition at the beginning and the end of the growth zone.

For characterization of the obtained layers and structures various methods have been used requiring application of ohmic contacts. The contacts were formed by vacuum deposition simultaneously onto both sides of the structures: on n$^+$-layer Ge/Au film was deposited, on p$^+$-layer – Zn/Au film. Then a top layer of Ni was deposited to strengthen the Au films.

3. Result and discussion
In a series of experiments structures with specular surface have been grown. The thickness of the samples was measured on the cleaved edge using optical microscope. The thickness of the active i-layer varied from 150 to 250 mcm depending of the growth conditions, the thickness of p$^+$-layer of GaAs was on the order of 1 mcm. The use of additional flow of AsCl$_3$ allowed to practically completely eliminate the longitudinal thickness wedge: the thickness reduced by 10 – 20 mcm over 10 cm of the wafer length.

For controlling the electrophysical parameters of pure GaAs layers p$^+$-layer was etched away for subsequent photoluminescence and voltage-capacitance measurements.

Photoluminescence from the i-layer was measured at 2 K using He-Ne laser (see fig. 1). This diagnostic technique proved useful in previous studies [4]. The measurement data provide information on the purity of i-layers and the presence of acceptors and donors there. D$^k$x broadening, as a rule, is caused by layer nonhomogeneity and high impurity content. Intensity ratio of the spectral lines makes it possible to estimate residual impurity concentration in the material [4] and gives a value of $N_{D^k}^x-N_A^x=10^{11}$ - $10^{12}$ cm$^{-3}$.

For estimating the free carrier concentration in the layer of n$^+$-GaAs voltage-capacitance measurements were performed. The values obtained by this method were $<10^{12}$ cm$^{-3}$, which agrees with photoluminescence measurements and meets requirements to the active layer purity of the chosen x-ray detector type.

Current-voltage characteristics of the obtained structures are similar to those of typical diode structures. Of particular interest are reverse branch of CVC because semiconductor detector predominantly operate at reverse bias. In all samples breakdown occurred at reverse voltage not lower than 500 V, which is an evidence of the high purity of the i-layers.

From electroluminescence intensity distribution in the direction perpendicular to the p-n-junction plane the charge carrier diffusion length can be determined. Fig. 2 shows typical electroluminescence pattern from the p-n junctions. From the fact that the electrical field created at the p-n junction boundary (at zero point on the Ox axis) exists throughout the low-doped i-layer thickness it can be concluded that the space charge region extends over the entire i-layer. Thus, the entire n$^+$-GaAs layer represents the detector active layer, in which efficient registration of x-ray radiation quanta takes place. The calculated diffusion lengths of charge carriers were in the range from 70 to 100 mcm.

One of the main problems in the fabrication of x-ray detectors based on p-i-n structures is the
The obtained gallium arsenide p-i-n structures have been used to fabricate pilot samples of x-ray radiation detector. Energy resolution of the devices was about 600 eV at the absorbed photons energy of 60 keV and 200 eV at 5.9 keV, respectively.

Besides, prospects exist for manufacture of pixel matrices based on p-i-n structures described above. X-ray radiation detectors have been fabricated with matrices of 256x256 pixels, the pixel size being 55x55 mcm.

An important outcome of this research is that due to the very high quality of the obtained structures in some areas of scientific research it will be possible to operate x-ray detectors without any external power supply, as mentioned above, making use of the photovoltaic effect – separation of electron-hole pairs generated by x-ray photons in the built-in electrical field.

This study has been supported by Russian Foundation for Fundamental Research. (Grant № 10-08-00782)

References
[1] R.A. Akhmadullin, V.F. Dvoryankin, G.G. Dvoryankina, Yu.M. Dikaev et al., Letters to ZhTF, 2002, v. 28, no.1, p.p.34-38
[2] V.M. Zaletin, Yu.V. Tuzov. Uncooled semiconductor radiation detector on epitaxial gallium arsenide for spectral and radiographic analysis, Electronic scientific publication “GEORAZREZ”, 2008, Issue #2
[3] M.L. Cardwell, Journal of Crystal Growth 70 (1984) 97
[4] Yu. V. Zhilyaev, N. K. Poletaev, V. M. Botnaryuk T.A. Orlova, L. M. Fedorov, Sh. A. Yusupova, A. Owens, M. Bavdaz, A. Peacock, B. O’ Meara, H. Helava. Optical characterization of ultra-pure GaAs. - Phys. Stat. Sol., (c), v. 0(3), p.1024–1027 (2003)
[5] V.F. Dvoryankin, G.G. Dvoryankina, Yu.M. Dikaev et al., ZhTF, 2007, v. 77, no..10, p.p.121-124
Figure 1. Photoluminescence spectrum of a pure layer of GaAs, concentration $N_D - N_A \sim 5 \times 10^{11}\text{cm}^{-3}$. 

FWHM($D^0_{\text{X}}$) = 0.124 meV, $T=2\text{K}$, HeNe
Figure 2. Electrical field distribution in an asymmetric p-n junction obtained from induced electrical current, $d_\text{inh-GaAs} = 213$ mcm.