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Journal of Physics: Conference Series

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To cite this article: D V Lyapunov *et al* 2016 *J. Phys.: Conf. Ser.* **741** 012097

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# Effect of a boron implantation on the electrical properties of epitaxial HgCdTe with different material composition

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**Abstract**. In this work the experimental results of investigations of the dynamics of accumulation and spatial distribution of electrically active radiation defects when irradiating epitaxial films of $Hg_{1-x}Cd_xTe$ (MCT) with different material composition (x). The films, grown by molecular beam epitaxy (MBE) were irradiated by B ions at room temperature in the radiation dose range $10^{12}$ –$10^{15}$ ions/cm$^2$ and with ion energy 100 keV. The results give the differences in implantation profiles, damage accumulation and electrical properties as a function of the material composition of the films.

## 1. Introduction

The semiconductor narrow-band material $Hg_{1-x}Cd_xTe$ (MCT) where the material composition (x) is the molar content of Cd is one of the main materials used for manufacturing inherent IR-photodetectors for the wavelength ranges of 3-5 and 8-14 micrometers [1]. At present the epitaxial MCT films grown by the method of molecular-beam epitaxy (MBE) present a promising material for creating multi-element semiconductor detectors of IR radiation providing signal processing directly in the focal region. One of the basic technological methods used to create photodiode structures is boron implantation [2 - 4]. For a precise control of the implantation, a strong insight is necessary into the processes of formation and evolution of radiation defects after ion implantation, which in the case of MCT determines all the electro-physical properties in the irradiated region [2 - 10]. It should be noted that in recent years to improve the operational characteristics of the device structures, the epitaxial material is used with different graded-band gap layers, in particular, in the surface region [11, 12]. Thus the study of the process of radiation defect formation in MCT, with a variable composition x, is important.

In the previous works of the authors concerning experiments about the effect of radiation using molecular nitrogen, Ar and boron ions on the electro-physical parameters of MCT epitaxial films [13, 14] showed that the observed differences due to ion implantation in heteroepitaxial MBE MCT as compared to the implantation in volume crystals of MCT can be explained by a different varied layer in the surface region. The authors make the assumption that the observed differences of ion

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implantation in the epitaxial films of MBE MCT with a variable composition in the region of implantation and in the volume material of MCT are mainly conditioned by various dynamics of accumulation of electrically active defects and the dependence of electro-physical characteristics on the MCT composition. But proof of this assumption requires more research.

The aim of this paper is to investigate the specific properties of the formation and accumulation of the spatial distribution of electrically active radiation defects after B ion implantation in MCT epitaxial films of different material composition in the region of introduction of the implant.

## 2. Samples and measurement procedure

The epitaxial films were grown at the Semiconductor Physics Institute of the Siberian Branch of the Russian Academy of Sciences in Novosibirsk, specifically with different mercury to cadmium ratios (x = 0.22, 0.3, 0.38, 057). After growth, the films had n-type conductivity, for conversion to p-type conductivity, the films were annealed in a neutral atmosphere of hydrogen or helium. Irradiation by B ions was made at room temperature for B ion radiation dose in the range $10^{12}$ –$10^{15}$ ions/cm$^2$ and with ion energy 100 keV.

Measurements of the electro-physical parameters of the samples before and after irradiation were made at the temperature of liquid nitrogen using the Hall Electromotive Force (EMF) method in the Van-der-Pau configuration. The electron concentration distribution as a function of semiconductor depth was determined by the method of differential Hall measurements using an etching process. Thin layers of material were removed by chemical etching in a 0.02% Br solution in dimethylformamide. The rate of etching was determined using a test sample with a step height measured by an electron microscope MII-4 after multiple cycles of material removal. The error in the Hall and conductivity measurements did not exceed 2-3%. The error in the volume concentration and mobility of charge carrier measurements is mainly determined by the accuracy in the measurement of the thickness of the removed layer and did not exceed 10-12%.

## 3. Experimental results and discussion

Measurement of the electro-physical parameters of the samples after implantation shows that B ion irradiation resulted in a conversion of the conduction type, with the formation of a highly alloyed n$^+$-layer in the surface of the material due to the generation of radiation defects. The dependence of the layer charge carrier concentration $N_S$ on the radiation dose Φ is shown in Figure 1.

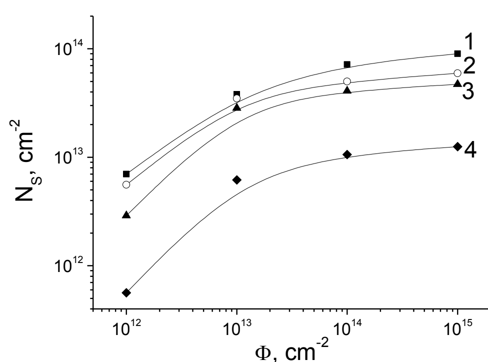


**Figure 1.** The dependence of the electron concentration $N_S$ plotted against radiation dose. The material composition (x): 1 – 0.22, 2 – 0.3, 3 – 0.38, 4 – 0.57.

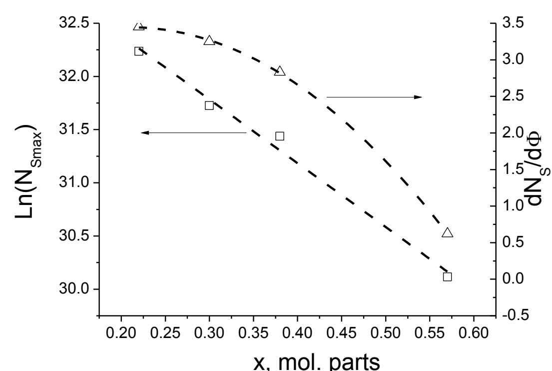


**Figure 2.** The dependence of the natural logarithm of the maximum layer charge carrier concentration $N_{Smax}$ and rate of introduction of electrically active radiation defects dNS/dΦ on the composition x of the MCT film

From the figures we can see that for all the samples, a monotonic increase of $N_S$ with radiation dose is observed. However, for the same radiation dose the value of $N_S$ depends strongly on the material

composition of the films. The dependence of $N_S$ on radiation dose shows a behavior typical of what would be expected in bulk MCT crystals. When attaining the radiation dose of $10^{14}$ ion/cm$^2$, the layer concentration is maximal $N_{Smax}$ and saturation takes place.

However, the magnitude of the maximum value $N_{Smax}$ in the saturation region dose depends strongly on the material composition of the films. With the increase in the value of the composition of the epitaxial film (x) the value of the $N_{Smax}$ decreases (Figure 2). The different behavior of $N_S$ on dose for the four series samples occurs because implantation take place in the region, where the material composition differs, the generated primary radiation defects in the metal sublattices of CdTe and HgTe will also differ. Using the software package SRIM2003 [15] a calculation was made of the total number of Hg interstitials that would form for a given number of collision cascades. The calculation shows that for sample 4 the number of primary shifts is 60% less than for sample 1. Because the number of generated interstitial Hg atoms decreases, we might expect a delay in the dynamics of formation of the secondary electrically active defects whose kinetics of accumulation is proportional to the primary radiation defect concentration. Therefore for samples of different series at doses $\Phi < \Phi sat$ the rate of introduction of electrically active radiation defects $dN_S/d\Phi$ was varied. With increasing composition x decreases the rate of defect introduction. Figure 2 shows the dependence of the rate of introduction of electrically active radiation defects on the composition of the epitaxial film.

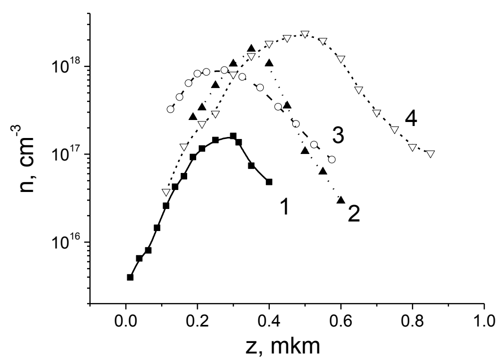


**Figure 3.** The electron concentration n plotted against depth z for the samples with material composition x = 0.22 after implantation by B ions. The radiation doses are : 1 – $10^{12}$ ion/cm$^{-2}$, 2 – $10^{13}$ ion/cm$^{-2}$, 3 – $10^{14}$ ion/cm$^{-2}$, 4 - $10^{15}$ ion/cm$^{-2}$.

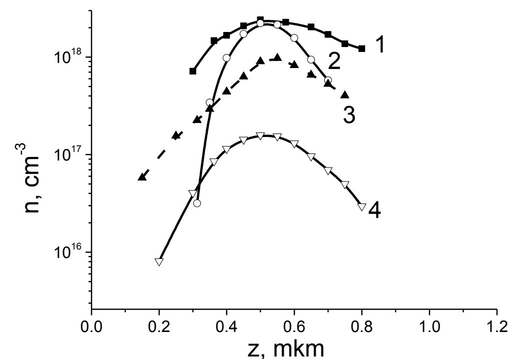


**Figure 4.** The electron concentration n plotted against depth z after implantation by B ions. The radiation doses are $10^{15}$ ion/cm$^{-2}$. The material composition (x): 1 – 0.22, 2 – 0.3, 3 – 0.38, 4 – 0.57.

The experimentally determined profiles of the volume electron concentration n as a function of the depth z show that at an irradiation dose of $10^{12}$ ion/cm$^2$ the maximum electron concentration is detected in the region of the mean free projection path of B ions. Increasing the irradiation dose up to $10^{14}$ ion/cm$^2$ results in an increase in the maximum value $n_{max}$. A further increase of irradiation dose results in a shift of $n_{max}$ deeper into the sample but the value of $n_{max}$ itself does not change, so electron concentration saturation takes place (Fig. 3). For a fixed dose the peak values of n occur at the same depth for all the samples considered. However the value of the volume electron concentration at the profile peak is determined by material composition (Fig. 2). The value of the $n_{max}$ is reduced by increasing the material composition.

According to experimental data the high-energy irradiation of the semiconductor (independence of irradiation condition and a previous history of a material) with increase of radiation dose lead to pinning of the electrochemical potential (Fermi level) in limiting state ($F_{lim}$). In the case of the material HgCdTe the pinning of a Fermi level is explained by coincidence of it energy with energy of radiation-induced defects ($E_R$), generating by irradiation. With increase of radiation dose the donor type defect concentration increase and accordingly an electron concentration increase down to

coincidence of Fermi level energy and a defect energy level ($E_F=E_{RD}$) is observed. At the further increase of radiation dose the electron concentration is invariable value that is shown by our experiments for irradiation HgCdTe by ions, protons, electrons and the relevant theoretical model is suggested [14, 16]. The energy position of the level $E_R$ is estimated to be 0.15 eV higher than the bottom of the conduction band.

In reference [18] it is shown that high energy radiation of semiconductors in the diamond structure and binary mixtures of group $A^{III}B^{V}$ leads to fixing the Fermi level in the limiting state $F_{lim}$ independent of the irradiation conditions and the previous history of the material. It was also shown that the stationary location of the Fermi level in an irradiated semiconductor coincided with the level of local electro-neutrality of a crystal, whose position can be calculated theoretically. Reference [19] uses such an approach applied for narrow-gap solid solutions of MCT.

A comparison of experimental data [2 - 14] and theoretical calculations [19] enables one to assume that the energy position of the level of radiation defects $E_R$ coincides with the position of local electro-neutrality of a crystal lattice of the material relative to the bottom of the conductivity band $E_C$. Within the limits this approach we have made the calculation of the energy position of the Fermi stationary level $F_{lim}$ and the corresponding limiting concentration of electrons $n_{lim}$ depending on the MCT composition. When calculating we took into account the results of reference [19] and the following.

1. The energy position of the level of local electroneutrality of the material relative to the level $E_C$ is linearly dependent on the MCT composition;

2. For the composition x = 0.5 the energy position of the level coincides with the edge of the bottom of the conductivity band;

3. For the composition x = 0.2 the level is located 0.15 eV higher than the bottom of the conductivity band $E_C$, i.e., it coincides with the energy position of the level $E_R$ determined from the experimental data [2 - 14].

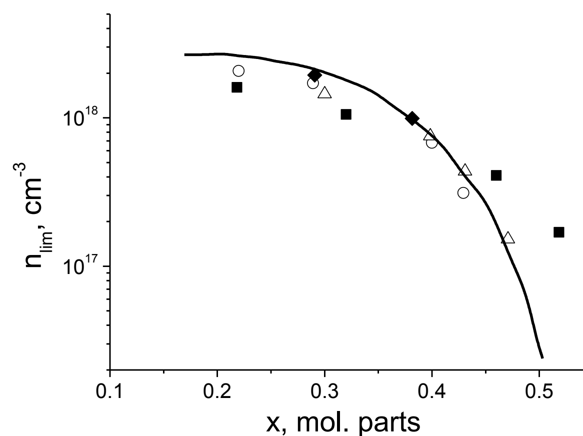


**Figure 5.** The maximum electron concentration $n_{lim}$ plotted as a function of the material composition x. The solid curve gives the calculated values and the symbols refer to experimental points obtained from figures 3-4.

The results of the calculation of the limiting (i.e. maximum) electron concentration $n_{lim}$ as a function of composition are shown in Figure 5. The symbols refer to the experimental values of the maximum electron concentration as determined from Figures 3-4. As seen from the figure the theoretical curve describes satisfactorily the experimental results.

## 4. Conclusion

Thus, in this work it is clearly shown that the material composition (x) of an epitaxial film significantly effect on boron implantation results and determine both the electrical parameters of the

implanted layer, and the spatial distribution of the donor type radiation defects. Practically the obtained results can be used for the optimization of ion implantation regimes in MBE MCT for producing diode structures.

**Acknowledgments**
This research was supported by grant (№ 8.2.10.2015) from "The Tomsk State University Academic D.I. Mendeleev Fund Program".

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