Distribution profiles of radiation donor defects in arsenic-implanted HgCdTe films

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Abstract. Mobility spectrum analysis and step-by-step chemical etching-based depth profiling have been employed for establishing distribution profiles of radiation-induced donor defects in an arsenic-implanted HgCdTe film grown by molecular beam epitaxy. Three electron species associated with specific defect layers in implanted material were detected, and defects responsible for these species were identified. The advantage of mobility spectrum analysis methodology over the use of traditional differential Hall effect-measurements with a single value of magnetic field was demonstrated for the ion-implanted HgCdTe.

1. Introduction

The mid-wavelength infrared (MWIR) part of the spectrum (2-6 μm) is a range with an increasing number of important applications, including molecular sensing, security, defence, energy conservation, etc. Among the materials used for the fabrication of MWIR devices, HgCdTe (MCT) alloy, the basic material for photodetectors operating in both long- and middle-wavelength parts of the IR range, stands out due to its unique properties [1, 2]. One of the current tasks of photodetector technology is related to increasing the operating temperature, as it allows for easier incorporation of detectors into commercial devices. Although relatively high-performance IR photodiodes can be implemented on the basis of p-type MCT by forming an n-type layer, modern MCT technology makes it possible to fabricate n-type material with concentration of deep centres much lower than that achievable for p-type material. As a result, dark currents turn out to be smaller for \( p^+\rightarrow n \) photodiodes than those for \( n^+\rightarrow p \) structures, and this is exactly what allows for increasing the device operating temperature [3-7]. For planar MCT technology, ion implantation is the most commonly used method for the fabrication of \( p-n \) junctions, and the impurity most widely used for producing \( p^+ \)-region in n-type material by implantation is arsenic.

Ion implantation brings a lot of damage to MCT and initiates defect reactions involving extended and point defects, such as dislocations, interstitial atoms, vacancies, etc. Defect structure of implanted...
measurements were used to monitor its composition and thickness [13]. The total thickness of the film was 9
radiation-induced donor defects in the film. In particular, low-mobility electrons (~5000 cm
carriers against the thickness of the etched material via differentiating the depth dependences of
Spectrum Analysis (DMSA) [14]. Distribution profiles of charge carriers were established with the use
It was established that as a result of ion implantation, an
region is usually investigated with the use of electron microscopy and optical measurements [8–11]. Electrical measurements are also very important, as they give detailed information on the transport properties of the implanted material and on the properties of the p-n junction, whose action is crucial for photodiode performance. Though general assessment of electrical properties of the implanted area can be done with the use of the standard Hall-effect measurements, the details of carrier mobilities and concentrations in a thin (less than 1 μm in thickness) multi-layer implanted region are not easy to get. To obtain such information, a mobility spectrum analysis in combination with step-by-step chemical etching can be applied, and this was effectively demonstrated for boron-implanted n-on-p junctions in MCT [12]. In this paper, we report on the results of profiling carrier mobilities and concentrations with the use of a similar approach as applied to an arsenic-implanted MCT film with a p+-on-n junction.

2. Experimental details

The film was grown with molecular-beam epitaxy (MBE) at the Rzhanov Institute of Semiconductor Physics (Novosibirsk, Russia) on (013) CdTe/ZnTe/Si substrate, and in situ ellipsometric measurements were used to monitor its composition and thickness [13]. The total thickness of the film was 9 μm. Its ‘absorber’ layer with uniform CdTe molar fraction (composition) x=0.22 was covered with a graded-gap protective layer with composition at the surface x=0.46. The thickness of the graded-gap layer was ~0.4 μm. The film was doped with indium during the growth, which rendered the material n-type conductivity with electron concentration and mobility at the temperature $T=77$ K, $n_{77}$≈3.9 $10^{14}$ cm$^{-3}$ and $\mu_{n}$=87500 cm$^2$ V$^{-1}$s$^{-1}$, respectively. After the growth the film was implanted with arsenic with energy 190 keV and fluence $\Phi=10^{15}$ cm$^{-2}$. Post-implantation activation annealing was not performed.

Arsenic concentration in the film $N_{As}$ was determined with Secondary Ion Mass–Spectroscopy (SIMS) using a Cameca IMS–6F machine with arsenic detection limit ~$1·10^{16}$ cm$^{-3}$. The electrical properties of the film were studied by measuring the Hall coefficient $R_H$ and conductivity $\sigma$ in the magnetic field $B$ of 0.01 up to 1.2 T at $T=77$ K. The measurements were performed on square-shaped van der Pauw structure, and the $R_H(B)$ and $\sigma(B)$ dependences were analysed with Discrete Mobility Spectrum Analysis (DMSA) [14]. Distribution profiles of charge carriers were established with the use of step-by-step wet chemical etching. The step heights were controlled by a shift of interference fringes in the IR absorption spectra, which were measured at the room temperature.

3. Results and discussion

It was established that as a result of ion implantation, an n+–n–p structure was formed, and its conductivity was contributed by three types of electrons with different mobilities (figure 1). In particular, the top n+–layer was represented by electrons with low and intermediate mobility.

It could be suggested that its properties were defined by extended and quasi-point donor defects formed as a result of implantation [15]. A ~1 μm-thick n–layer with electrons with high mobility, in its turn, was formed as a result of diffusion of interstitial mercury atoms and their annihilation with mercury vacancies, also typical of ion-implanted MCT [15]. On the basis of the values of averaged electron concentration $n_{av}$ and those of partial conductivity $\sigma_{pr}$, we calculated layered concentration $N_i$ and layered partial conductivity $\Sigma_i$ for each type of electrons at each etching step. The calculated values of $N_i$ and $\Sigma_i$ were used to plot the ‘bulk’ electron concentration and partial conductivity for each type of carriers against the thickness of the etched material via differentiating the depth dependences of $N_i$ and $\Sigma_i$ (figure 2).

The analysis of the obtained dependencies allowed for determining the detailed distribution of radiation-induced donor defects in the film. In particular, low-mobility electrons (~5000 cm$^2$ V$^{-1}$ s$^{-1}$), which gave dominating contribution to the conductivity, appeared to be located in a surface 400 nm-thick layer; this layer indeed corresponds to the area of localization of extended structural defects and to the profile of implanted arsenic ions [11], see also figure 1. These electrons are then likely related to donor defects formed when interstitial mercury is captured by the dislocation loops located in this layer. Intermediate-mobility electrons (~20000 cm$^2$ V$^{-1}$ s$^{-1}$) are located down to the depth of 700 nm.
They should be related to defect complexes formed by interstitial mercury with various point defects. High-mobility electrons (~90000 cm$^2$ V$^{-1}$ s$^{-1}$) are located in the $n$-layer extending beyond the depth of 700 nm.

![Graph](image1)

**Figure 1.** Distribution profiles for arsenic atoms according to SIMS (1), and averaged concentration of electrons $n_{av}$ with high (2), intermediate (3), and low (4) mobility.

![Graph](image2)

**Figure 2.** Distribution profiles for layered $N_i$ (1, 2 and 3) and ‘bulk’ $n$ (1′, 2′ and 3′) concentration of electrons with low (1′), intermediate (2′) and high (3′) mobility.

For comparison, figure 3 shows distribution of layered $N_i$ and ‘bulk’ $n$ concentration and ‘effective’ mobility of electrons ($N_{i}=1/(eR_{sn})$, $\mu_{n_{ef}}=R_{sn} \sigma_{sn}$, where $R_{sn}$ and $\sigma_{sn}$ are layered Hall coefficient and conductivity, respectively), which were obtained with the use of the commonly exploited method of a single-field (in this case, $B=0.05$ T) differential Hall-effect measurements with step-by-step etching. The values of ‘bulk’ electron concentration were obtained on the basis of those of layered concentration by differentiating.

Comparison of the results presented in figure 2 and figure 3 shows that the method of establishing the charge carrier distribution profiles with the use of a single-field differential Hall-effect does not give true representation of the profiles when a number of charge carrier types (electron species) contribute to conductivity. The distribution profiles for ‘bulk’ electron concentration and ‘effective’ mobility (higher than 28000 cm$^2$ V$^{-1}$ s$^{-1}$) shows that this method does not allow for revealing the
electrons with low mobility, while the latter actually give the dominating contribution to conductivity immediately after ion implantation and after the first two steps of chemical etching. The commonly used method only allows for accessing the fact that high-mobility electrons are located at the depth larger than 700 nm.

**Figure 3.** Distribution of layered electron concentration \( N_s (1) \), ‘effective’ mobility \( \mu_{\text{eff}} (2) \) and ‘bulk’ electron concentration \( n (3) \) obtained with the use of the common method of establishing the carrier distribution profiles via the differential Hall-effect measurements in a single magnetic field.

4. Conclusion
Discrete Mobility Spectrum Analysis (DMSA), a variety of mobility spectrum analysis methodology, in conjunction with step-by-step wet chemical etching was used to establish distribution profiles of radiation-induced donor defects in an arsenic-implanted HgCdTe film grown with molecular beam epitaxy on a silicon substrate. In the implanted sample, three electron species were detected, namely: i) low-mobility (~5000 cm\(^2\) V\(^{-1}\) s\(^{-1}\)) electrons in the top 400 nm-thick damaged layer, ii) intermediate-mobility (~20000 cm\(^2\) V\(^{-1}\) s\(^{-1}\)) electrons in the layer extending to 700 nm depth, and iii) high-mobility (~90000 cm\(^2\) V\(^{-1}\) s\(^{-1}\)) electrons in high-quality \( n \)-type layer below 700 nm. Radiation-induced defects responsible for the formation of each defect layer were identified. Comparison of the results obtained with the use of DMSA with those acquired with the commonly accepted method of establishing the profiles with the use of the differential Hall-effect measurements with a single value of magnetic field showed that the latter did not give true representation of the carrier profiles when a number of electron species contributed to the conductivity. The commonly used method allowed, nevertheless, for accessing the fact that high-mobility electrons were located deeper than 700 nm. The obtained results clarify the details of defect structure of arsenic-implanted MCT and can be useful for the developers of HgCdTe-based photo-electronic devices.

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