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Optical and electrical studies of arsenic–implanted HgCdTe films grown with molecular beam epitaxy on GaAs and Si substrates

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HIGHLIGHTS

- HgCdTe films grown on GaAs and Si substrates were implanted with arsenic.
- Implantation into *p*-type material resulted in formation of n^+–*n*–*p* structure.
- 100%-activation of arsenic implanted into *n*-type material was achieved.
- Influence of graded-gap surface layer on concentration of radiation defects was noted.

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ABSTRACT

A defect study was performed on arsenic-implanted $Hg_{1-x}Cd_xTe$ (x = 0.23–0.30) films with graded-gap surface layers, grown with molecular-beam epitaxy on GaAs and Si substrates and designed for fabrication of 'p^+–n'-type photodiodes. First, formation of n^+–p structure was investigated in *p*-type material, in order to study radiation-induced donor defects. Next, formation of p^+–n structure was investigated in the course of implantation in *n*-type material and arsenic activation annealing. Influence of the graded-gap surface layer was found to be expressed in the degree of saturation of the concentration of radiation-induced defects, with results obtained on arsenic- and boron-implanted material differing due to the difference in the ion masses.

1. Introduction

Ion implantation remains to be the most widely used method for *ex situ* fabrication of *p-n* junctions for photodiodes based on $Hg_{1-x}Cd_xTe$ (MCT), an important material for infrared photoelectronics. A popular photodiode technology is based on implantation of arsenic with fabrication of p^+-type implanted region in *n*-type base [1–8]. Dark currents in *p-n* junctions of the 'p^+–n'-type are believed to be substantially lower than those in 'n^+–p'-type structures. This provides higher working temperature or longer wavelength cut-off sensitivity threshold of photodiodes and is due to the fact that *n*-type MCT typically has lower concentration of deep traps that limit carrier lifetime and thus, the device performance.

Ion implantation creates much damage in the subsurface layer of MCT and initiates defect reactions involving extended and point defects: dislocations, interstitial mercury atoms Hg_I, mercury vacancies V_{Hg}, etc. The effect of the damage is investigated with the use of electron microscopy, optical and electrical measurements, and combinations of various methods [9–13]. Electrical properties of as-implanted MCT are governed by the damage rather than by the implanted species, and irrespective of the nature of the latter, the implanted region typically has *n*-type conductivity. To achieve *p*-type conductivity, the number of the defects should be reduced and implanted dopant must be activated electrically. For

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this purpose, activation annealings are performed. In general, doping of MCT with ion implantation is a complicated task, as one need to anneal radiation-induced defects, activate the dopant and control the position of the *p-n* junction, all at the same time. The presence of protective graded-gap surface layer on the surface of the structure makes this task even more difficult.

The purpose of this work was to investigate defects in arsenic-implanted MCT films grown with molecular-beam epitaxy (MBE) on GaAs and Si substrates. The studies were performed with the use of Secondary-Ion Mass Spectroscopy (SIMS), optical reflectance and the Hall effect measurements. Studied were samples with initial *n*– and *p*-type conductivity, with and without graded-gap surface protective layer, as-implanted and after post-implantation activation annealing.

2. Experimental

The films were grown at A.V. Rzhanov Institute of Semiconductor Physics (Novosibirsk, Russia) on (013) CdTe/ZnTe/GaAs or CdTe/ZnTe/Si substrates with the growth cycle controlled *in situ* by means of an ellipsometer [14]. The active ('absorber') layers had constant composition (CdTe molar fraction) x_a ranging from 0.23 to 0.30 and was covered with graded-gap protective surface layers with composition at the surface approaching $x_y = 0.45$. The thickness of the graded-gap layers did not exceed 0.4 μm. As-grown films had *n*–type conductivity with electron concentration as measured at the temperature $T = 77$ K $n_{77} = (0.2–8) \times 10^{14}$ cm^{-3}. Samples with *p*–type conductivity were obtained via annealing *n*–type samples in helium atmosphere with low mercury pressure (220 °C, 24 h). The parameters of the films before the implantation are given in Table 1, where μ_{77} is carrier mobility at $T = 77$ K. The films were implanted with As^+ or As^{++} ions with energy $E_{As} = 190$ keV or 350 keV, respectively; ion dose ranged from 10^{13} cm^{-2} up to 10^{15} cm^{-2}. The implantation was performed using IMC200 (Ion Beam Services, France) system. After the implantation, some samples were subjected to two-stage thermal activation annealing in saturated mercury vapours (360 °C, 2 h, and 220 °C, 24 h). Arsenic SIMS profiles were recorded using Cameca IMS-6F (France) machine with As detection limit $\sim 1 \times 10^{16}$ cm^{-3}.

Optical reflectance spectra were recorded in 300–800 nm wavelength range with step 0.5 nm at $T = 300$ K using Shimadzu UV-3600 (Japan) spectrometer. Electrical parameters were determined with measurements of the magnetic field dependence of the Hall coefficient R_H and conductivity σ at $T = 77$ K. The experimental dependences were analyzed using discrete mobility spectrum analysis [15].

3. Results

3.1. Ion implantation damage

To study ion implantation damage, we used films with *p*-type conductivity, as in such films it was possible to follow formation of implantation-induced donor centres in the clearest way. Fig. 1 shows SIMS arsenic profiles in films grown on GaAs and Si substrates. Implantation (As^+ ions with $E_{As} = 190$ keV) was performed both in samples with graded-gap surface layer and in samples with this layer removed after the growth with the use of chemical etching. As can be seen in Fig. 1, irrespective of the type of the substrate and of the presence or the absence of the graded-gap layer, the experimental profiles for dose 10^{15} cm^{-2} at low implantation depths looked very similar (curves 1–4). They could be fitted with profiles obtained with the use of the free TRIM software, which calculates the stopping and range of energetic ions into matter using a quantum-mechanical treatment of ion-atom collisions [16]. Film M4 grown on GaAs substrate appeared to have very high background concentration of arsenic ($\sim 5 \times 10^{17}$ cm^{-3}); the reason for this remains unknown. Nevertheless, disregarding the arsenic distribution 'tail', which was strongly affected by the background doping starting from 300 nm and deeper, in general we obviously dealt with typical results of ion implantation in MCT. Concentration of arsenic at the peak of the distribution profile increased with the implantation dose and equalled 4×10^{18} cm^{-3}, 1×10^{19} cm^{-3}, and 8×10^{19} cm^{-3} for doses 10^{13} cm^{-2}, 10^{14} cm^{-2}, and 10^{15} cm^{-2}, respectively, as shown in the inset in Fig. 1, curves 1′, 2′, and 3′, respectively (high arsenic surface concentration seen in curve 1 was, most likely, caused by accidental impurity adsorption at the

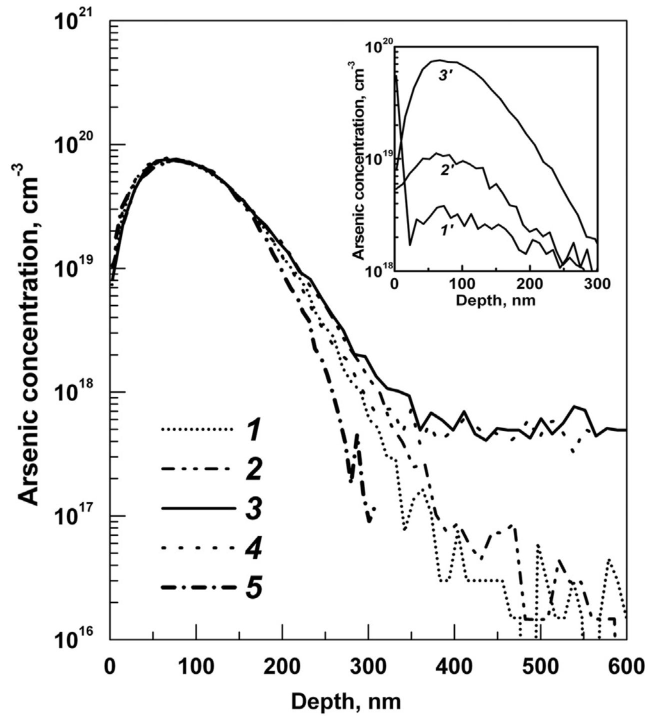

Fig. 1. SIMS arsenic profiles for samples M7, M6, M4, and M5 (curves 1, 2, 3, and 4, respectively) implanted with ion energy 190 keV and implantation dose 10^{15} cm^{-2}. Curve 5 shows calculated TRIM profile. Inset shows SIMS profiles for sample M4 implanted with doses 10^{13}, 10^{14}, and 10^{15} cm^{-2} (curves 1′, 2′ and 3′, respectively).

Table 1
Parameters of the films studied.

Sample	M1	M2	M3	M4	M5	M6	M7
x_a	0.30	0.23	0.29	0.23	0.23	0.23	0.23
Substrate	Si	Si	Si	GaAs	GaAs	Si	Si
Variable-gap surface layer	Yes	Yes	Yes	Yes	No	Yes	No
Conductivity type	*n*	*n*	*n*	*p*	*p*	*p*	*p*
n_{77},p_{77}, cm^{-3}	1.5×10^{13}	4.5×10^{13}	2.1×10^{13}	1.1×10^{16}	1.2×10^{16}	1.5×10^{16}	1.6×10^{16}
μ_{77}, cm^2 V^{-1} s^{-1}	2.1×10^4	4.6×10^4	3.2×10^4	470	440	440	440
Post-implantation activation annealing	Yes	Yes	Yes	No	No	No	No