Acceptor states and carrier lifetime in heteroepitaxial HgCdTe-on-Si for mid-infrared photodetectors

S V Zablotsky[1,2], N L Bazhenov[1], K D Mynbaev[1,3], M V Yakushev[4], D V Marin[4], V S Varavin[4] and S A Dvoretsky[4]

[1] Ioffe Institute, 194021 Saint-Petersburg, Russia
[2] Saint Petersburg Electrotechnical University 'LETI', 197376 Saint-Petersburg, Russia
[3] ITMO University, 197101 Saint-Petersburg, Russia
[4] Rzhanov Institute of Semiconductor Physics, Siberian Branch of Russian Academy of Sciences, 630090 Novosibirsk, Russia

E-mail: zablotcky@yandex.ru

Abstract. Temperature dependences of the carrier lifetime and photoluminescence (PL) spectra in $Hg_{1-x}Cd_xTe$ ($0.3< x <0.4$) epilayers grown on Si substrates (HgCdTe-on-Si) and intended for fabrication of p^+-n photodiodes have been studied. It is shown that the as-grown material has a high concentration of recombination centres with energy $30 \div 40$ meV, which reduces the lifetime. The post-growth annealings, both that converting the material to the p-type and that imitating the activation of an implanted impurity, reduce the concentration of the centres. This manifests itself in an increase in the lifetime, which is especially noticeable after 'activating' annealing and is confirmed by results of the PL studies.

1. Introduction

Recently, the increasing attention in technology of photodiodes based on $Hg_{1-x}Cd_xTe$ (MCT), one of the basic materials of infrared photo-electronics has been given to a method of fabrication of p^+-n junctions in which a p^+-layer is formed in the initially n-type material [1]. Typically, in such structures, as compared to n^+-p structures, dark currents are considerably smaller which provides a higher working temperature of photodiodes. It is believed that this is due to the fact that n-type MCT has a greater minority carrier lifetime τ than that in the p-type material, because the n-type material has a smaller concentration of deep recombination centres.

Determination of the density and energy position of such centres, as well as reduction of their concentration, are among major tasks in the technology of high-quality MCT [2]. As a rule, in order to elucidate the effect of recombination centres on parameters of the material, the experimentally measured τ values are compared with those limited by the fundamental band-to band recombination mechanisms. If the experimental τ values are much smaller than those calculated, the slope of the temperature dependence $\tau(T)$ allows evaluation of the energy position of the centres.

Fabrication of MCT-based devices includes, in addition to the growth, one or several annealings performed in order to obtain the desirable type of conductivity, improve the homogeneity of the material and reduce the number of defects. It is of interest to monitor the concentration of recombination centres at each technological step.


Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

This paper reports on a study of the nonequilibrium charge carrier lifetime in MCT epilayers, intended for fabrication of p^+-n junctions and grown by molecular beam epitaxy (MBE) on Si substrates (HgCdTe-on-Si), one of the most promising substrate material for coupling of photodetectors with readout systems [3]. The data obtained are compared with the results of photoluminescence (PL) experiments carried out on similar epilayers.

2. Experiment

Experimental structures were grown at Rzhanov Institute of Semiconductor Physics with ZnTe and CdTe buffer layers. The $Hg_{1-x}Cd_xTe$ chemical composition x in the photosensitive layers of the structure (with thickness of 5 to 6 μm) was 0.3 to 0.4, which corresponds to cut-off wavelengths of the photo detectors of 4.9 to 2.9 μm at T=77 K. The carrier lifetime τ was studied using photoconductivity decay technique.

As-grown samples demonstrated n-type conductivity with a carrier concentration of $4 \cdot 10^{14} \div 2 \cdot 10^{15}$ cm^{-3} at $T = 77$ K. Parts of the samples were subjected to a two-stage annealing in a saturated Hg vapour (2 hours at $T = 360$ °C and 24 hours at $T = 225$ °C). This annealing was used as an imitation of the 'activating' annealing performed after ion implantation in order to create p^+-areas and fabricate p–n junctions (the samples studied were not implanted). After such an annealing, the samples remained n-type with a carrier concentration of $5 \cdot 10^{14} \div 5 \cdot 10^{15}$ cm^{-3}. Parts of some samples were annealed to convert the as-grown material to p-type conductivity in the He atmosphere and low-pressure Hg-vapour (15 hours at T=260 °C): this procedure is common in fabrication of n^+-p photodiodes. After this annealing, the hole concentration in the material was $8 \cdot 10^{15} \div 2 \cdot 10^{16}$ cm^{-3}.

3. Results and Discussion

3.1. Lifetime

The results of lifetime measurements are shown in Fig. 1, 2 and 3.

Figure 1 shows temperature dependences of the lifetime for as-grown samples. For samples with the composition $x = 0.31$ at high temperatures τ typically decreases with increasing temperature, which is due to the contribution of the intrinsic conductivity and the domination of the band-to-band recombination. Therefore, the curves have a maximum; however the curve for the sample with $x = 0.4$ has no maximum of this kind up to 300 K. As the temperature decreases below 200 K, τ becomes smaller, with an exponential (linear in the chosen coordinate axes) section being clearly visible; then the $\tau(T)$ dependence for samples with $x = 0.31$ becomes nonmonotonic. Figure 2 shows temperature dependences of the lifetime for samples after their annealing into p-type material. The $\tau(T)$ dependences are qualitatively similar to those shown in Fig. 1, but τ becomes about ten times smaller after the annealing. Figure 3 shows $\tau(T)$ for samples after the 'activating' annealing, when the material remains n-type. As before, the $\tau(T)$ dependence is similar to that in Fig. 1, but τ becomes about ten times greater.

On the whole, Figs. 1, 2 and 3 indicate that τ in the samples studied is governed by the Shockley-Read recombination via local centres and the annealings significantly affect the concentration of these centres. To evaluate the effect of recombination centres, let us compare experimental data with the calculated lifetimes, governed by the band-to-band recombination mechanisms: radiative and non-radiative. In MCT, the main non-radiative mechanisms are the follows: in an n-type material, Auger recombination involving two electrons and a heavy hole, with the excitation of an electron into a higher energy state (CHCC or A1 process); and for a p-type material, Auger recombination involving two heavy holes and an electron, with the conversion of a heavy hole into a light hole (CHHL or A7 process). The most rigorous calculations of τ with consideration for these mechanisms can be carried out using expressions from [4]. The radiative recombination in MCT of the compositions studied is of importance at

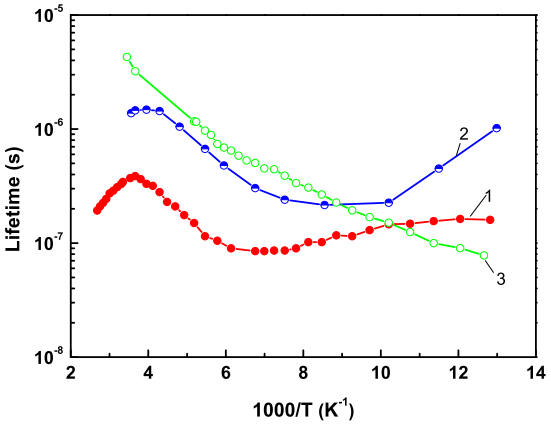


Figure 1. Temperature dependences of the lifetime for as-grown samples. The composition x is equal to 0.31 (*1*, *2*) and 0.4 (*3*).

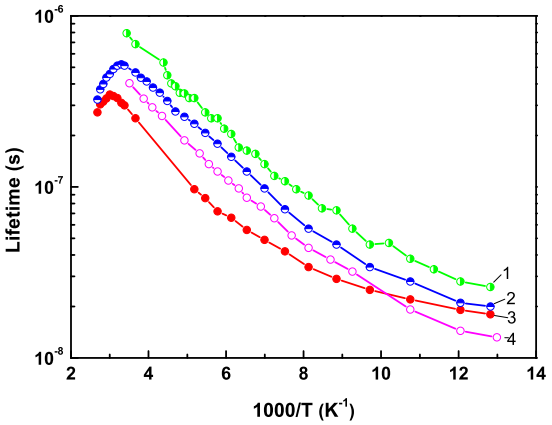


Figure 2. Temperature dependences of the lifetime for samples after annealing into p-type. The composition x is equal to 0.31 for all the samples.

temperatures below 200 K. To calculate τ governed by the radiative recombination, we used expressions from [5].

Figure 4 combines experimental and calculated τ for a sample with $x = 0.31$. The carrier concentration at $T = 77$ K was $n = 4.1{\cdot}10^{14}$ cm^{-3} in the as-grown sample, $p = 1{\cdot}10^{16}$ cm^{-3} after the annealing with conversion into p-type and $n = 1{\cdot}10^{15}$ cm^{-3} after the 'activating' annealing. It can be seen that in the as-grown sample τ determined by the band-to-band mechanisms is about an order of magnitude greater than the experimental data. After the annealing with conversion into p-type, τ decreases due to the increase in the equilibrium carrier concentration; however, experimental τ values become closer to those calculated. This relative closeness of the experimental and calculated τ values holds after the 'activating' annealing, which unambiguously indicates that the concentration of recombination centres decreases.

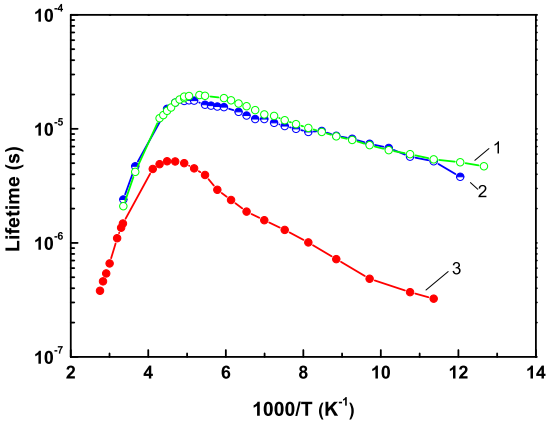


Figure 3. Temperature dependences of the lifetime for samples after the activation annealing. The composition x is equal to 0.31 for all the samples.

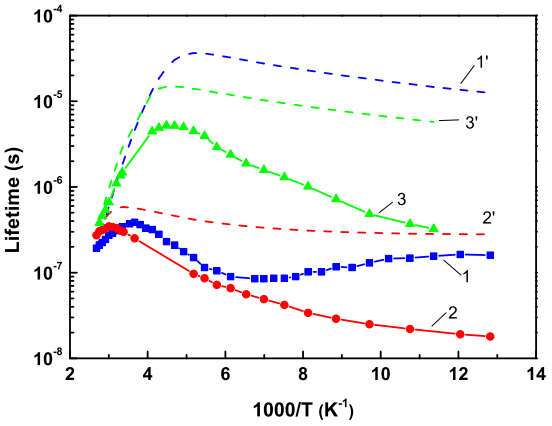


Figure 4. $\tau(T)$ dependences for a sample with x=0.31: as-grown (*1*), p-type (*2*) and after activation annealing (*3*). Dashed curves were calculated for band-to-band recombination.

The energy position E_t of the centres was estimated using the linear section of the $\tau(T)$ curves at temperatures below 200 K. The values obtained were within the range $30 \div 40$ meV.

3.2. Photoluminescence

$\tau(T)$ data were compared with those of photoluminescence (PL) measurements. The PL signal was excited by a pulsed semiconductor laser with wavelength $\lambda = 1.03$ μm and detected by a cooled InSb photodiode and a lock-in amplifier. Figure 5 shows PL spectra for a sample with $x = 0.4$ at $T = 4.2$ K (as-grown and after the 'activating' annealing). The discrete band corresponds to band-to-band recombination (band A), while an additional structure in the long-wavelength part of the spectrum can be attributed to transitions to local centres (B, C and D). The annealing slightly modified the composition x and shifted the spectrum to higher energies. Note, that after the annealing the long-wavelength structure in the PL spectrum disappeared (except for line D'), which indicated that concentration of the recombination centres involved in the radiative recombination decreased. Thus, PL data confirmed the decrease of the density of states in the energy gap after the annealing, which was observed in the lifetime study.

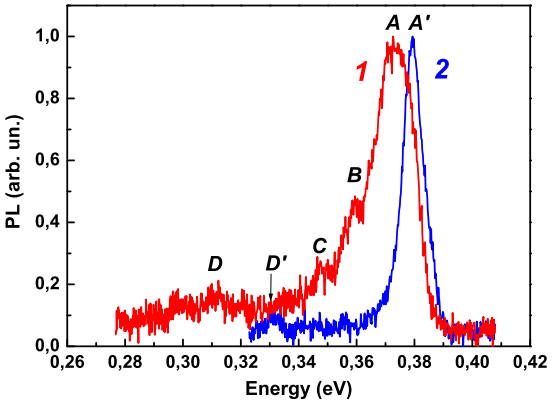


Figure 5. PL spectra of as-grown (1) and annealed (2) HgCdTe-on-Si samples.

4. Conclusion

Studies of temperature dependences of the carrier lifetime and PL spectra in HgCdTe-on-Si grown by MBE have shown that the as-grown material has a considerable concentration of recombination centres, which reduces the lifetime in the material. The conversion of the initial n-type material into that of p-type through an appropriate annealing leads to a decrease in the recombination centre concentration. An even greater decrease was provided by the 'activating' annealing, which imitates that performed to fabricate implanted p^+-n photodiode structures.

Acknowledgments

The study at Rzhanov Institute of Semiconductor Physics was supported by the Ministry of Education of the Russian Federation (Grant RFMEFI60414X0134).

References

[1] Mollard L, Bourgeois G, Lobre C, Gout S, Viollet-Bosson S, Baier N, Destefanis G, Gravrand O, Barnes J, Milesi F, Kerlain A, Rubaldo L and Manissadjian A 2014 *J. Electron. Mater.* **43** 802–807
[2] Edwall D D, DeWames R E, McLevige W V, Pasko J G and Arias J M 1998 *J. Electron. Mater.* **27** 698–702
[3] Simingalam S, Brill G, Wijewarnasuriya P and Rao M 2015 *J. Electron. Mater.* **44** 1321–1326
[4] Bazhenov N L, Mynbaev K D and Zegrya G G 2015 *Semiconductors* **49** 432–436
[5] Gel'mont B L and Zegrya G G 1991 *Sov. Phys. Semicond.* **25** 1216–1218