

Photo- and electroluminescence in strong electric fields in Sb-containing narrow gap semiconductor materials

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Abstract. Spectra of the mid-infrared interband luminescence under interband optical pumping and impact ionization in strong electric fields are experimentally studied in the InAsSb epilayer and in the monocrystalline InSb in the temperature range from 10 K to 85 K. The recombination radiation anisotropy in InSb arising due to electron heating and drift in strong electric fields is observed.

1. Introduction

The narrow band semiconductors, semiconductor alloys and superlattices allow to develop mid-infrared photodetectors, detector arrays and light sources [1, 2]. Such materials as a HgCdTe and Sb-based A3B5 alloys are rivals in this field. On the characterization stage of the semiconductor material, the information about its fundamental properties can be obtained from a luminescence study. In the present work we report on the spectral study of interband photoluminescence (PL) under interband optical pumping and electroluminescence (EL) under strong electric fields due to impact ionization in the InAsSb epilayer and in the InSb monocrystalline samples. The luminescence spectra obtained under optical excitation gave information about fundamental bandgap value. Electroluminescence spectra allow us to study the nonequilibrium electron heating phenomena in strong electric field as well as electric field induced luminescence polarization anisotropy observed earlier in ref. [3] on integrated over the spectrum luminescence.

2. Samples and experimental details

Our first sample is bulk 1 μm InAs_{0.6}Sb_{0.4} MBE-grown, unintentionally doped epilayer. Details of the sample structure could be found in ref. [4]. The second sample is monocrystalline InSb with low donor impurity concentration of about $6 \cdot 10^{13} \text{ cm}^{-3}$ and electron mobility of about $6 \cdot 10^5 \text{ cm}^2/(\text{V} \cdot \text{s})$ at the lattice temperature $T = 77 \text{ K}$. Electric field was applied using contacts created on the surface of the samples: the InAs_{0.6}Sb_{0.4} epilayer sample had a gold contacts; the InSb sample had an indium contacts annealed at 300°C. In order to increase the quantum efficiency of luminescence we have performed optical and photoelectrical studies at low lattice temperatures (from 10 K to 85 K) using the closed cycle cryostat. To prevent sample overheating, the electric field was applied in short pulse regime (250 ns / 10 Hz). For PL studies, we used interband optical pumping of the sample surface with radiation wavelength of 1064 nm (peak power up to 30 W in 100 ns pulse regime [5]). The mid-



infrared PL and EL spectra were studied using FTIR-based setup described earlier in ref. [6] supplemented with lock-in amplifier.

3. Experimental results and discussion

The PL spectrum of the $\text{InAs}_{0.6}\text{Sb}_{0.4}$ epilayer obtained at the lattice temperature $T = 10$ K is presented in figure 1. It shows luminescence band lying in the spectral range 100 - 240 meV with the maximum near the photon energy of about 160 meV. The EL spectra of the sample studied at the $T = 10$ K at different applied electric fields F are presented in figure 2. Long-wavelength edges of the PL and EL spectra are similar and correspond well to the calculated $\text{InAs}_{0.6}\text{Sb}_{0.4}$ bandgap value $E_g = 136$ meV [1] (this value is marked in figures 1 and 2 with arrows). Thus, we suppose, that the emission bands observed on the EL and PL spectra are related to a direct interband electron-hole recombination. In case of EL the nonequilibrium electrons and holes were generated due to an impact ionization in strong electric field. Probable due to low carrier mobility, the intensive impact ionization was observed on measured current-voltage characteristics of the $\text{InAs}_{0.6}\text{Sb}_{0.4}$ sample in strong electric fields near 1000 V/cm. The EL spectrum measured at the electric field $F = 600$ V/cm shows a luminescence band lying in the spectral range 100 - 190 meV with the maximum near 145 meV (see figure 2). The increase of the electric field up to 1000 V/cm leads to broadening of the EL spectrum till 300 meV and to the change in a slope of the high-energy part of the spectrum. The luminescence band broadening could be connected with the increase of the nonequilibrium carrier concentration due to impact ionization with the increase of electric field. A slope change could be a result of the electron temperature increase in electric field.

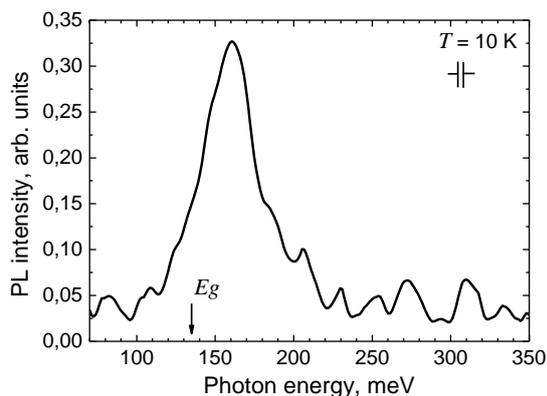


Figure 1. Interband PL spectrum of the $\text{InAs}_{0.6}\text{Sb}_{0.4}$ sample.

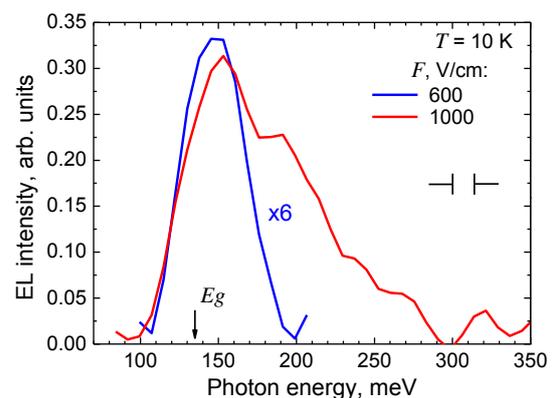


Figure 2. Interband EL spectra of the $\text{InAs}_{0.6}\text{Sb}_{0.4}$ epilayer under different applied electric fields (please, see the legend on the plot). The EL intensity at the $F = 600$ V/cm is multiplied by 6.

The n -InSb sample current-voltage characteristic (CVC) studied at $T = 77$ K is presented in figure 3. In figure 3, one can observe the impact ionization threshold (marked with arrow) at the electric field F of about 200 V/cm when the Ohmic behaviour of the CVC changes to the sharp current density increase with F (like F^3). In the electric fields stronger than 600 V/cm, the current increase is slowing down because of the mobility decrease due to rise of polar optical phonon scattering.

The EL spectra of the InSb sample were measured in the range of electric fields from 300 V/cm to 1125 V/cm ($T = 85$ K). They also shows the emission band related to direct interband electron-hole recombination (see figure 4). As the electric field rises, the luminescence band of the InSb sample is broadening and a change in a slope of the high-energy part of the EL spectrum can be observed as well as for the $\text{InAs}_{0.6}\text{Sb}_{0.4}$ sample. Analysis of this shortwave slope can give information about the hot carrier temperature.

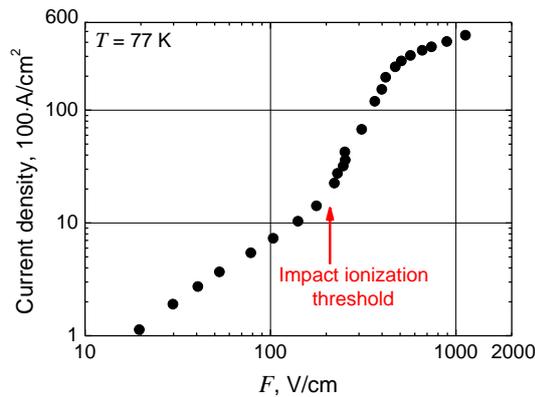


Figure 3. Current-voltage characteristic of the n -InSb sample.

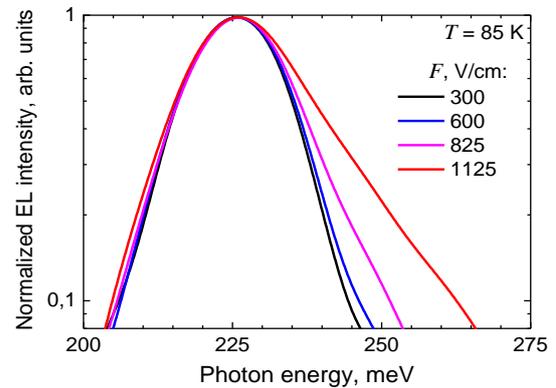


Figure 4. Interband EL spectra of the n -InSb sample under different applied electric fields F (please, see the legend on the plot).

Dependence of the spontaneous emission intensity I on the photon energy $\hbar\omega$ is determined by the following expression [7]:

$$I(\hbar\omega) \sim (\hbar\omega)^2 \cdot \alpha(\hbar\omega) \cdot f_e(\hbar\omega) \cdot f_h(\hbar\omega), \quad (1)$$

where $\alpha(\hbar\omega)$ is the absorption coefficient, f_e and f_h are electron and hole distribution functions. For large photon energies $\hbar\omega$ one can simplify expression (1) using Maxwell-Boltzmann electron and hole distribution functions:

$$I(\hbar\omega) \sim \frac{(\hbar\omega)^2 \cdot \alpha(\hbar\omega)}{\exp(\hbar\omega/kT_c)}, \quad (2)$$

where k is the Boltzmann constant, T_c is the effective carrier temperature [7]:

$$\frac{1}{T_c} = \frac{m_h}{m_e + m_h} \frac{1}{T_e} + \frac{m_e}{m_e + m_h} \frac{1}{T_h}, \quad (3)$$

where m_e and m_h are the effective masses of the electron and hole, T_e and T_h are the electron and hole temperatures, respectively. As far as m_e is much smaller than m_h , the equation (3) can be simplified to

$$T_c = T_e \quad (4)$$

Thus, electrons temperature T_e could be determined from fitting the high-energy tail of luminescence spectra (figure 4) with expression (2). The dependence of the hot electron temperature change $\Delta T = T_e - T$ (where T is the lattice temperature) on the applied electric field F determined from the EL spectra for the n -InSb sample at the $T = 85$ K is presented in figure 5 by black squares. The values of ΔT obtained for the different electric fields are much lower than ones calculated from ref. [8]. This could be explained with a distortion of the EL spectra by self-absorption. Self-absorption occurs when we collected the emission from deep layers of the sample (deep in comparison with penetration depths of light with photon energy comparable with the InSb bandgap). The distortion is as large, as sample thicker, if we take into account the pinch effect [9]. To demonstrate the significant influence of self-absorption on measured EL spectrum, we plot in figure 6 both corrected spectrum taking into account self-absorption for 60 μm thick sample and original measured spectrum. We have performed as well the self-absorption correction for all curves from figure 4 and have determined the corresponding electron temperatures. Dependence of the hot electron temperature change for self-

absorption corrected spectra is plotted by red squares in figure 5. Finally, after self-absorption correction for 60 μm thick sample we have obtained significantly higher values of hot electron temperature.

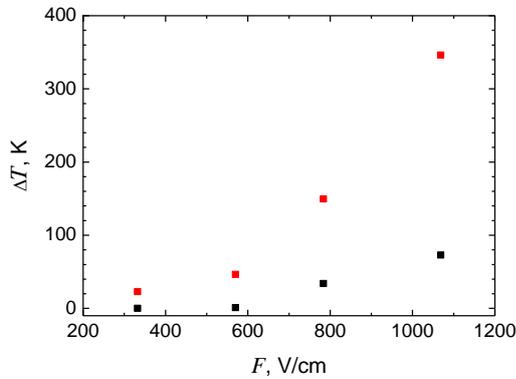


Figure 5. Dependence of the hot electron temperature change ΔT on the applied electric fields F for the n -InSb sample at the $T = 85$ K without self-absorption correction (black squares) and with correction for 60 μm thick sample (red squares).

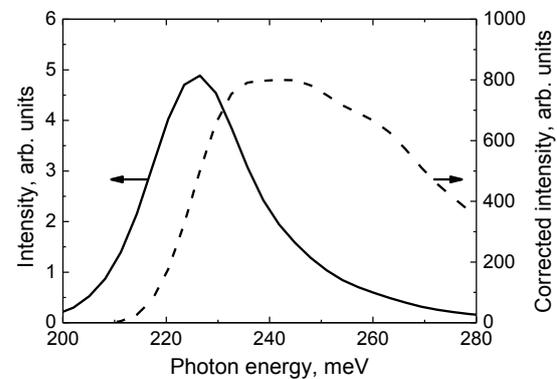


Figure 6. The comparison of the original measured spectrum of the n -InSb sample at the $T = 85$ K and $F = 1125$ V/cm (solid curve) and the results of self-absorption correction of the measured spectrum (dashed curve).

It should be mentioned that in our conditions the main mechanism of charge carrier energy loss in InSb is the polar optical phonon scattering (electron-electron scattering and impurity scattering are negligible unless the impurity or carrier concentrations are more than 10^{16} cm^{-3}). Acoustic phonon scattering times are much longer (approximately two orders of magnitude) than those for optical phonon scattering [10]. The probability for the polar optical phonon scattering $W_{kk'}$ is given by

$$W_{kk'} \sim \frac{1}{|\mathbf{k} - \mathbf{k}'|^2}, \quad (5)$$

where \mathbf{k} and \mathbf{k}' are the wave vectors of the initial and final carrier states, respectively. From this equation, one can conclude that small-angle scattering is more likely than large-angle scattering. In strong electric field the energy gained by electron from the electric field will be partially dissipated with the emission of polar optical phonons, but after each collision the electron will continue to move close to the direction of electric field. Therefore, the distribution of electrons in \mathbf{k} -space will be focused along the direction of the electric field. The squared module of the optical matrix element for electron transitions from conduction band to heavy holes subband $|M_{e \rightarrow hh}|^2$ depends on the angle between polarization vector of the electromagnetic wave \mathbf{e}_ω and electron wave vector [11]:

$$|M_{e \rightarrow hh}|^2 \sim \sin^2(\widehat{\mathbf{e}_\omega, \mathbf{k}}). \quad (6)$$

Consequently, the difference between interband luminescence intensity for light polarized along applied electric field and perpendicular to it should appear.

The EL spectra for the n -InSb sample measured for light polarized along applied electric field (I_{\parallel}) and perpendicular to it (I_{\perp}) are presented in figure 7. Comparing these spectra measured at strong electric field ($F = 1000$ V/cm) when electron heating and drift are significant (see figure 5), one can observe a difference between them. This polarization anisotropy is related to nonequilibrium electron distribution function anisotropy and angle dependence of the interband optical matrix element in \mathbf{k} -space discussed above. For greater clarity we also presented in figure 7 the interband luminescence

anisotropy as the difference $\Delta I = I_{\perp} - I_{\parallel}$ related to the I_{\perp} (black curve). In accordance with the model of luminescence anisotropy discussed in ref. [3], anisotropy increases with photon energy increase.

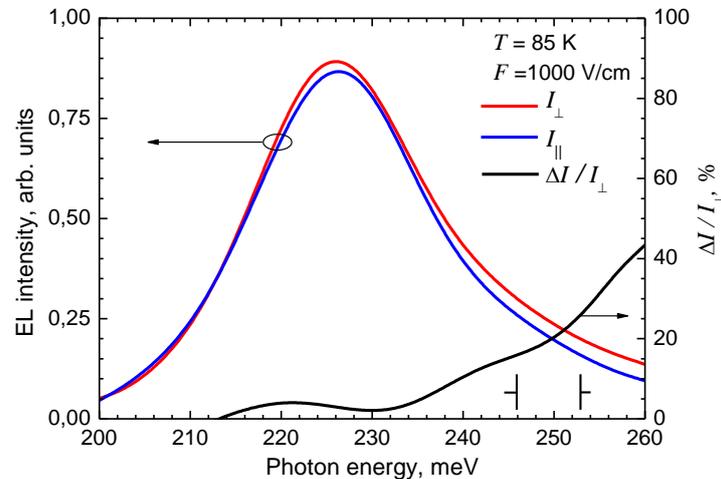


Figure 7. Polarized EL spectra of the n -InSb sample (I_{\perp} and I_{\parallel}) and relative change in the EL intensity $\Delta I/I_{\perp}$ (please, see the legend on the plot).

4. Summary

It is shown that $\text{InAs}_{0.6}\text{Sb}_{0.4}$ epilayer can be used as mid-infrared ($\sim 10 \mu\text{m}$) light sources with electrical pumping. Significant influence of the self-absorption on interband luminescence spectra excited by a strong electric field, inherent to the “thick” samples, is demonstrated. The polarization anisotropy of electroluminescence spectra in strong electric fields was studied in InSb monocrystalline sample.

Acknowledgments

The reported study was funded by the Russian Foundation for Basic Research (grant 16-02-00863), Russian Federation President grant for young scientists No MK-4616.2016.2 and the Ministry of Education and Science of the Russian Federation (state assignment).

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