Long-wave infrared InAs$_{0.6}$Sb$_{0.4}$ photodiodes grown onto n-InAs substrates

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Abstract. The results of a study of multilayer photodiodes based on InAs$_{1-x}$Sb$_x$ solid solutions (0.3 $<$ x $<$ 0.4), with a long-wavelength cut-off of $\lambda_{c1} \approx 11\mu$m at room temperature are presented. The current-voltage and spectral characteristics of photosensitivity and electroluminescence were analyzed in the temperature range of 80 $\div$ 300 K. Experimental samples of photodetectors are characterized by a quantum efficiency of 0.23 at 150 K and a diffusion mechanism of current flow at least in the 200-300 K range. The detectivity of the immersion lens PD at the maximum has values of at least $D*_{8\mu m} = 8 \cdot 10^9$ and $D*_{5.5\mu m} = 10^{10}$ cm·Hz$^{1/2}$W$^{-1}$ at 300 and 150 K, respectively.

1. Introduction
InAs$_{1-x}$Sb$_x$-based photodiodes (PDs) is a promising alternative to superlattice [1] and CdHgTe PDs in many photonic applications including (but not limited to) breath analysis [2], low temperature pyrometry [3], and near-field photonic cooling [4]. Depending on the chemical composition, the InAs$_{1-x}$Sb$_x$ based PDs can operate in the first ($\lambda = 3 - 5\mu$m) or second ($\lambda = 8 - 14\mu$m) atmospheric transmission “windows”, or, in other words, in the mid-wave (MWIR) or long-wave (LWIR) infrared spectral ranges, respectively [5]. Room temperature operating MWIR InAsSb PDs have already been evolved to the level of industrial application [2], while the LWIR ones usually require cooling and thus are mostly still at a research stage [6, 7].

In this paper, we study the photoelectric properties of p-n heterostructures with an InAs$_{1-x}$Sb$_x$ photosensitive region with x $\sim$ 0.4 and a long-wavelength cut-off at $\lambda_{c1} \approx 11\mu$m (300 K).

2. Experimental results
Epitaxial structures with the layout presented in table 1 were grown by the LPE method on undoped n-InAs (100) substrates ($n = 2 \cdot 10^{16}$ cm$^{-3}$).

A multi-stage photolithography process, including “wet” and “dry” (plasma-chemical) etching, was used for the fabrication of flip-chip diodes with a 40, 90, 180, or 270 $\mu$m wide sensitive areas. A similar chip design, as well as the composition of contacts, have been previously implemented for InAs DH PDs in [8]. The PDs on an n-InAs substrate were optically immersed with Ge lenses ($D = 3.5\mm$). Electroluminescence (EL) and photoelectric characteristics were measured in the temperature range of 80 - 350 K using a VERTEX 70v Fourier spectrometer, an HgCdTe (77 K) photodetector, a Keithley SourceMeter 6430 source meter and an LCR E4980A precision meter.
Table 1. Composition and parameters of the heterostructures.

| Layer number | Layer function             | Layer composition | $\Delta a/a_{InAs}$ | InSb concentration | Thickness, $\mu$m | Band gap (77 K), meV | Doping             |
|--------------|----------------------------|-------------------|---------------------|--------------------|------------------|-------------------|---------------------|
| 1            | Buffer region              | InAsSb$_x$        | 1.9                 | $X = 0.28$         | 2.8±3.0          | 240               | -                   |
| 2            | Wide gap region            | InAsSb$_x$        | 2.2                 | $X = 0.32$         | 1.5±1.7          | 225               | -                   |
| 3            | Photosensitive region      | InAsSb$_x$        | 2.6                 | $X = 0.38$         | 2.3±2.5          | 205               | -                   |
| 4            | Photosensitive region, contact/top layer | InAsSb$_x$ | 2.6                 | $X = 0.39$         | 2.0±2.5          | 200               | Zn, $p = (1\div2)\times 10^{18}$ cm$^{-3}$ |

Figure 1 shows the current-voltage ($I – V$) and light-current ($L – I$) characteristics of the 90 $\mu$m wide PD at room temperature. The PD resistance $R_o$ near zero bias is as small as 0.35 $\Omega$, and the forward $I – V$ characteristic is fairly close to a linear dependence, which is typical for many narrow band p-n junctions [9]. Such linearity, obviously, originates from the domination of contact/bulk resistance ($R_s > R_o$) at room temperature and could be taken into account when analysing the diode parameters [8]. As seen from figure 2, no full current saturation occurred under reverse bias due to the leakage current. Nevertheless, the saturation of the intensity of negative luminescence (NL, $I < 0$) took place at around -100 mA, which indicates efficient extraction of minor carriers by the electrical field within the p-n junction space charge region. It is worth mentioning that the modulus of the NL intensity exceeds the electroluminescent (EL) intensity at the same pumping current amplitude (say, $|I| = 100$ mA). The NL domination confirms Auger recombination suppression under reverse bias due to a reduction in the carrier concentration in the PD active zone.

![Graph of current vs. voltage and light intensity vs. current](image-url)

**Figure 1.** Room temperature $I – V$ and $L – I$ characteristics for a 90 $\mu$m wide PD.
Figure 2 shows the saturation current $J_o$ vs the mesa area $A$ (left panel) and the saturation current vs the reciprocal temperature (right panel). The saturation current values were defined at $U < 0$ as $J_o (I_o)$, at which $d^2I/d^2U = 0$. As seen in figure 2 (left panel), no significant dependence of surface leakage on the mesa diameter is observed. The variation in $J_o$ in figure 2 is most likely due to uncontrolled variations in properties over the wafer surface and from run to run. Figure 2 demonstrates the temperature dependence of the saturation current in a 40-µm wide PD, which is in good agreement with the exponential dependence with an activation energy close to the energy gap ($E_a = 0.2$ eV). This indicates the predominance of the diffusion current mechanism over surface leakage and tunneling in the samples under study.

Figure 3 shows the room temperature EL spectra under forward and reverse bias with a peak energy of 155 meV ($\lambda_{max} = 8$ µm). Taking into account the $1/2 \ h \nu$ difference between the energies of the $E_g$ and EL peaks ($h\nu_{max} = 155$ meV), the measured value of $\lambda_{max}$ corresponds to the InAs$_{1-x}$Sb$_x$ energy gap at InSb concentration $x = 0.4$. A slightly lower value $E_g = 0.12$ meV for the same InAsSb composition was extracted from photoconductivity measurements at several temperatures in [10]. We believe that the Joule effect and the dynamic Moss-Burstein effects compensate each other or, alternatively, have a negligible impact on the EL spectra, as no dependence of $\lambda_{max}$ on the pumping current ($I$) can be deduced from the data in figure 3. The obtained value of $\lambda_{max}$ is the longest reported room temperature EL value for InAsSb bulk p-n heterostructures; the previous close value of $\lambda_{max}$ has been measured in InAsSb multilayer structures without p-n junctions under optical pumping with a GaAs LED [11].

Figure 3. Room temperature EL spectra at several pumping currents.
Figure 4 presents the spectra of the photosensitivity $S_{I}(\lambda)$ (left panel) and specific detectivity (right panel) of the immersion lens PD at several temperatures in the 150 – 350 K range:

$$D^* = S_{I}(\lambda) \left( \frac{R_A}{4kT} \right)^{1/2}$$  \hspace{1cm} (1)

A dip at 4.3 μm is clearly seen, corresponding to absorption by CO$_2$ gas present in the atmosphere, as well as and a sharp short wavelength cut-off related to absorption in the n-InAs substrate, which filters out radiation with wavelengths shorter than ~ 3.2 μm.

The $D^*_{\text{max}}$ (300 K) value is in an order of magnitude higher than that reported in [6] for the InAs$_{0.12}$Sb$_{0.88}$ PD with $\lambda_{\text{max}} = 8$ μm. This is an adequate difference taking into account the absence of immersion in PDs described in [6]. Both the peak wavelength $\lambda_{\text{max}}$ and the long cut-off wavelength $\lambda_{0.1}$ exhibit a red shift with increasing temperature in accordance with the energy gap variation. The temperature dependence of the peak photon energy $h\nu_{\text{max}}$ has the same slope as the InAs energy gap variation reported by Fang et al in 1990 [12]:

$$E_g = 0.415 - \frac{2.76 \times 10^{-4} T^2}{(T + 83)} \text{ (eV)}$$  \hspace{1cm} (2)

Figure 4. Responsivity (left panel) and detectivity ($D^*$) spectra (right panel) of an InAs$_{0.6}$Sb$_{0.4}$ PD at several temperatures in the 150 – 350 K range.

Figure 5. Photoresponse and quantum efficiency at the maximum (left panel) and red cut-off wavelengths $\lambda_{0.5}$ and $\lambda_{0.1}$ (right panel) vs temperature $T$ in an InAs$_{0.6}$Sb$_{0.4}$ PD.
Figure 5 shows the photoresponse ($S_\lambda$) and quantum efficiency ($QE$) at the maximum and red cut-off wavelengths $\lambda_{0.5}$ and $\lambda_{0.1}$ vs temperature $T$. Both $S_\lambda$ and $QE$ exhibit fast growth during PD cooling in the 200 – 350 K range mostly due to an $R_c$ increase with respect to the serial resistance $R_s$. When approaching cryogenic temperatures, they both show saturation features as $R_c >> R_s$.

Both red cut-off wavelengths have a smooth variation with temperature (see the right panel of figure 5), which can be approximated by both Fang formula and the expression for the variation of the InSb energy gap (both shown analytically and graphically in figure 5).

![Figure 5](image)

**Figure 5.** Comparison of Fang formula and the expression for the variation of the InSb energy gap ($E_g$) with InSb composition ($X_{InSb}$) at 296 K. The numbers in brackets refer to the wafer process numbers.

![Figure 6](image)

**Figure 6.** Dependence of the room temperature energy of the photosensitivity red cut-off ($h\nu_{\text{cut-off}}$) on the InAs$_{1-x}$Sb$_x$ chemical composition $x$. The line represents the interpolation value of $E_g(\text{InAsSb})$ (300 K) (left panel) and the dependence of the dark current density on the PD red cut-off energy ($h\nu_{0.1}$) at 296 K. The numbers in brackets refer to the wafer process numbers (right panel).

Figures 6 presents a comparison of our results with previously published numbers. As can be seen, the data of the present research are in good agreement with the interpolation derived from the previous results. For example, the saturation current in this research is consistent with the exponential dependence of $I_o$ on $h\nu_{0.1}$ or, in other words, on the energy gap $E_g$ (see the dashed line in figure 7), which confirms the domination of the diffusion current in the developed InAs$_{0.6}$Sb$_{0.4}$ PDs:

$$J_o (T) \sim e^{-\frac{h\nu}{kT}}$$

(3)

3. Conclusions

Experimental samples of LWIR photodetectors with a photosensitive region InAsSb, ($0.35 < x < 0.4$) and a long-wavelength photosensitivity limit $\lambda_{0.1}$ of about 11 $\mu$m have been fabricated and studied, including the measurement of current-voltage and spectral characteristics in a wide temperature range. It is shown that: in the temperature range of 200 – 300 K, the p-n junction operation is determined by the diffusion mechanism of current flow; current sensitivity values reach more than 1 A / W at temperatures attainable with thermoelectric (TE) cooling; the temperature dependence of the long-wavelength edge is close to the temperature dependence of the band gap of the nearest binary compound InSb.
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