InAsSbP/InAs$_{0.9}$Sb$_{0.1}$/InAs DH photodiodes ($\lambda_{0.1} = 5.2$ $\mu$m, 300 K) operating in the 77–353 K temperature range

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Double heterostructure back-side illuminated photodiodes with a 10-$\mu$m thick InAs$_{0.9}$Sb$_{0.1}$ active layer have been fabricated, studied and characterized in the 77–353 K temperature range. Spectral response peculiarities and temperature induced peak shift ($\lambda = 4–4.8$ $\mu$m) were explained within simple phenomenological model based on proximity of the active layer thickness and hole diffusion length while reasons for a sensitivity decrease at low temperatures are still less evident. Transition from a generation-recombination to a diffusion current flow mechanisms with temperature increase appeared to be close to that for the InAs based diodes.

Because of high segregation coefficient at growth temperature the phosphorus concentration diminished at the surface of a 50–80 $\mu$m thick InAs$_{0.9}$Sb$_{0.1}$ layer providing the energy gap decrease along the growth direction with $\nabla E_g = -1–2$ meV/$\mu$m in both previously mentioned cases [8,9]. InAs$_{0.9}$Sb$_{0.1}$ lattice constant at heterojunction was nearly the same as for InAs substrate ($\Delta a/a < 0.05\%$) while distant from the substrate alloy had negligible phosphorus content and was thus lattice mismatched with InAs substrate ($\Delta a/a < 0.5\%$). When back-side illuminated the afore-mentioned heterostructures showed relatively narrow photorepsonse spectral band (FWHM < 0.7 $\mu$m) evidently due to finite diffusion length of the photogenerated holes.

For many years we believed that high $S_{\text{max}}$ values in [8,9] resulted from low threading dislocations density ($N < 10^6$ cm$^{-2}$) in curved InAs$_{0.9}$Sb$_{0.1}$ graded structures used for these particular PDs. Low dislocation density in [8,9] was achieved by implementing peculiar growth procedure accompanied by stress relaxation process via substrate plastic bending ($R < 10$ cm). Data on this relaxation process (or in other words “inversion deformation process”) can be found elsewhere [10,11]. The authors of [10,11] stated that plastically deformed (bent) InAs substrate ($N_{\text{max}} > 10^7$ cm$^{-2}$) was incorporated with the bent InAs$_{0.9}$Sb$_{0.1}$ graded layer of high crystalline quality ($N_{\text{max}} < 10^5$ cm$^{-2}$). Similar data supporting general properties of the “inverse defect formation process” was traced also during the growth of GaAs$_2$/GaAs [12] and InGaAsSb/InAs [13] graded heterostructures.

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1. Introduction

In the past there have been quite sufficient number of research efforts aiming at design efficient photodiodes (PDs) with peak sensitivity at wavelengths of $\lambda_{\text{max}} = 4.6–4.8$ $\mu$m (or $\lambda_{0.1} \sim 5.2$ $\mu$m). These PDs is important for use in low temperature pyrometry [1] as well as in non-dispersive infrared (NDIR) gas analysis of carbon oxide gas that has strong absorption band near the 4.7 $\mu$m wavelength [2,3]. Together with spectrally matched light emitting diodes (LEDs) these PDs can be used for ultra low power consumption gas sensors and portable gas analyzers [2–5].

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On the other hand an impact of dislocation density in InAs substrates [14] and in InAsSb buffer layer [15] onto PD performance in “flat” heterostructures has been recently revealed. The authors of [15] suggested that increasing the buffer layer thickness from 1 to 9 μm resulted in sufficient dislocation density decrease that was accompanied by a 4-fold increase of the detectivity (D*) value. The “buffer layer” approach described in [15] is evidently attractive for PD fabrication especially when growth of large format matrix PD structures (or FPA) is considered. Alternatively curved structures with “thick” InAsSbP or InGaAsSbP buffers with R < 50 cm like those in [10–13,16] could hardly be integrated into large area wafer growth, photolithography and assembling procedures.

Additional motives for investigation InAsSb based PDs include a desire to improve electrical design of PD chip that could enhance device performance. Most known InAsSbP PDs with Δv_{max} = 4.6–4.8 μm suffer from poor collection efficiency of photogenerated carriers that originate from current crowding effects in front surface illuminated (FSI) structures with small area anodes formed onto low conductivity cladding [17] or substrate [16]. As a result most FSI PDs exhibit low sensitivity with a typical value of S_{100X} = 0.2–0.3 A/W (see, e.g. [18]). Let us also note that relatively high R_A product values in many published FSI PDs originated from the abovementioned current crowding effect. Electrically active area in such PDs approximately amounted to that of the anode area [17].

Although the InAsSb barriod structures with background-limited performance (BLIP) at 160 K were already used for matrix fabrication [19] they need sufficient bias for operation. Alternatively conventional InAsSb double heterostructure (DH) p–n structures can operate in a photovoltaic mode, however no PL peak difference constituted to Δhν_{77 K} = hν_{InAsSbP} – hν_{InAs} = 47 meV which correlated with the interpolated energy gap difference at the 2-nd heterojunction where ΔE_{2-3}g = E_g(x_1, y_1) – E_g(x_2, y_2) = 390–335 = 55 meV. The expected PL peak energy for the InAsSb alloy at T_2 = 300 K is close to hν_{InAsSb} = hν_{InAs} + ΔE_{2-3}g – ΔE_{3-100 K} + k(T_2 – T_1)/2 = 270 meV temperature variation of the energy gap being the same as for the InAs binary (ΔE_{2-3}g = 55 meV [20,21]). The expected InAsSb PL peak energy hν_{InAsSb} is in a good agreement with the electroluminescence peak (EL) value of 263 meV measured at 296 K in a transmission mode (see the insert in Fig. 2). We didn’t analyze agreement between PL and EL spectra at 77 K as the measurements were carried out in the presence of normal atmosphere (0.03 vol% of CO₂, total optical path of ~2 m) and both spectra were distorted by the CO₂ gas absorption at 4.3 μm. As seen from the graph in Fig. 2 there was no shortwave EL radiation coming from the broad band gap p-InAsSbP layer evidently due to efficient absorption in the InAsSb narrow gap layer.

Standard optical photolithography and wet chemical etching processes developed by Ioffe Institute together with IoffeLED, Ltd. have been implemented to obtain 26 μm high circular mesa (Φ_m = 190 μm) and 55 μm deep grooves for separation of the 580 × 430 μm rectangular chips. Circular Au- or Ag-based reflective anode (Φ_a = 170 μm) and cathode contacts were formed on the same chip side by sputtering and thermal evaporation in vacuum followed by thick (3 μm) gold plating deposition as described elsewhere [22,23]. Preliminary evaluation showed no radical difference between reflection properties in the above contact types. Flip-chip bonding/packaging procedure has been implemented using the 1800 × 900 μm submount made from semiinsulating Si wafer with Pb-Sn bonding pads. PD chips were mounted up-side down, n-InAs side being an “entrance window” for the incoming
radiation as shown in the insert in Fig. 7. TO-18 standard case was chosen for bare chip PDs package while some chips were equipped with aplanatic hyperhemispherical Si immersion lenses (Ø = 3.5 mm) with antireflection coating using a chalcogenide glass as an optical glue between Si and n"-InAs (or n-InAs) as described elsewhere [1,3–6,8].

As seen from Fig. 3 bare PD chips exhibited broad spatial sensitivity suggesting that an optical area was sufficiently larger than the mesa one. Having in mind abovementioned enhanced optical activity suggesting that an optical area was sufficiently larger than elsewhere [1,3–6,8].

Fig. 3. Distribution of the photosignal along two orthogonal directions (1 and 2) intersecting the mesa center projection onto n"-InAs surface in bare chip PD.

In Fig. 4 one can find typical I–V characteristics together with the $I = I_0 \exp (eV/kT)$ function presented by straight dashed lines. Good matching of the above exponent and the forward bias (FB) I–V curves for $T < 220$ K is evident. “High temperature” ($T > 220$ K) I–V data has poor matching with exponents at high currents probably due to series resistance impact. On the other hand current leakage at a reverse bias (RB) is progressively decreasing as temperature grows leading to nearly ideal Shockley I–V characteristics near room temperature with current saturation at high RB. The same conclusion comes from analysis of the $\beta$ and $I_0$ temperature dependences shown in Fig. 5. As seen from Fig. 5 the ideality factor $\beta$ approaches unity at 300 K and approaches 2 at $\sim 110$ K suggesting transition from diffusion (at high $T$) to generation–recombination (at low $T$) current flow mechanism. Low temperature data ($T = 77$ K) evidently suggests domination of the tunneling mechanism as $\beta \to 3$.

The above transformation of the current flow mechanism can be also traced from the Arrhenius plot in Fig. 6 with where temperature dependence of zero bias resistance (defined as $R_0^{0}$ and $R_0^{\infty}$) is presented. The $R_0^{0}$ values were extracted from low bias measurements ($|U| < 0.005$ V), while the $R_0^{\infty}$ values were understood as $R_0^{\infty} = V^2/\epsilon \overline{\mu}_n$, where $\overline{\mu}_n$ is the zero bias current – parameter derived from interpolation. As seen from Fig. 6 both $R_0^{0}$ and $R_0^{\infty}$ values exponentially grow on temperature decrease, whereas growth rate is sufficiently different at low and high temperatures. The energy parameter $E$ in the above exponent ($\exp (–E/kT)$) for both $R_0$ values is fairly close to InAsSb energy gap value ($E = 0.3$ eV) which confirms diffusion current domination at least in the 200–350 K temperature interval. At low temperatures the $R_0^{0}$ and $R_0^{\infty}$ values split as additional leakage takes place (see deviation from ideal I–V characteristic at small forward bias in Fig. 4). Meanwhile a guess that generation–recombination current dominates at low temperatures ($\beta = 2$) is true for fairly small temperature interval as seen from comparison of low temperature data.

3. Results and discussion

In Fig. 4 bare chip and immersion lens PD I–V characteristics at several temperatures. Straight dashed lines in the forward bias region correspond to the modified Shockley formula.

Fig. 4. Bare chip and immersion lens PD I–V characteristics at several temperatures. Good matching of the above exponent and the forward bias (FB) I–V curves for $T < 220$ K is evident. “High temperature” ($T > 220$ K) I–V data has poor matching with exponents at high currents probably due to series resistance impact. On the other hand current leakage at a reverse bias (RB) is progressively decreasing as temperature grows leading to nearly ideal Shockley I–V characteristics near room temperature with current saturation at high RB. The same conclusion comes from analysis of the $\beta$ and $I_0$ temperature dependences shown in Fig. 5. As seen from Fig. 5 the ideality factor $\beta$ approaches unity at 300 K and approaches 2 at $\sim 110$ K suggesting transition from diffusion (at high $T$) to generation–recombination (at low $T$) current flow mechanism. Low temperature data ($T = 77$ K) evidently suggests domination of the tunneling mechanism as $\beta \to 3$.
immersion lens PDs have similar numbers at least in the measurement accuracy (±5%) sensitivities in bare chip and "natural diaphragm" formed by a 3.2 mm wide open lens part. With diaphragm (see Section 1) and in immersion lens PDs contain different temperatures measured in bare chip PDs equipped with diaphragm (Fig. 6). At low temperatures tunneling seems to prevail – a confirmation for this assumption nicely meets our previous estimations of diffusion to generation–recombination current flow mechanisms. Proximity of layer thickness d and \( L_{diff} \) values could explain broad spectral response in our BSI PDs. Alternatively in BSI PDs based on thick graded band gap PDs with InAsSb active zone [8]. Proximity of layer thickness d and \( L_{diff} \) values could explain broad spectral response in our BSI PDs. The latter assumption nicely meets our previous estimations of \( L_{diff} \) in InAsSbP graded band gap PDs with InAsSb active zone [8]. Proximity of layer thickness d and \( L_{diff} \) values could explain broad spectral response in our BSI PDs. Alternatively in BSI PDs based on thick graded heterostructures with d \( \gg \) \( L_{diff} \) photoresponse is narrow due to large distance for hole traveling from broad band InAsSb absorbing region to the p–n junction.

Fig. 6. Temperature dependence of the zero bias resistance derived from direct measurement at |U| < 0.005 V (filled squares) and from the \( I_x \) values shown (open symbols). Straight lines correspond to \( \exp(0.3/kT) \) and \( \exp (0.3/2kT) \) functions.

Fig. 7. Response spectra in n-InAs (upper graph) and n'–InAs (bottom graph) based PDs with InAsSb absorbing layer at 77, 155, 245, 296 and 353 K.

Fig. 8. Detectivity spectra in n-InAs and n'–InAs based PDs with InAsSb absorbing layer at –20, 0, 20, 40, 60 and 80 °C.

As seen from Figs. 7 and 8 the responsivity spectra bears four distinct regions: the cut-off region (4.7 < \( \lambda \) < 5.5 \( \mu \)m) (1), sharp longwave response decline region (2), smooth response decline region (3) and finally fast shortwave response decline region (4). The latter region is evidently due to transmission degradation in heavily doped n'–InAs substrate with degeneration of electrons in the conduction band. In our case the Moss-Burstein associated absorption edge shift in n'–InAs is as large as 1 \( \mu \)m (compare data for PD with heavily doped (#878 sample) and undoped (#877 sample) substrates in Fig. 7).

Sharp response decline in region 2 (in Fig. 7) is a consequence of the absorption coefficient increase and corresponding decrease of the number of photogenerated electron-hole pairs in a vicinity of a p–n junction. We assume that the hole diffusion length \( (L_{diff}) \) is of the same order or larger than the InAsSb thickness and thus subsequent absorption coefficient increase (at a wavelength decrease – region 3) leads to more or less stable portion of carriers that can reach p–n junction by diffusion. Large absorption means that the majority of photons are absorbed near the n (n')–InAs/n'–InAsSb interface, that is, at fixed distance from the p–n junction. The latter assumption nicely meets our previous estimations of \( L_{diff} \) in InAsSbP graded band gap PDs with InAsSb active zone [8]. Proximity of layer thickness d and \( L_{diff} \) values could explain broad spectral response in our BSI PDs. Alternatively in BSI PDs based on thick graded heterostructures with d \( \gg \) \( L_{diff} \) photoresponse is narrow due to large distance for hole traveling from broad band InAsSb absorbing region to the p–n junction.

It is worth mentioning that there is no 100% coincidence of the spectra shape in region (2) and (3) for the PDs grown onto n-InAs and n'–InAs substrates. At the moment we are not able to erect the verdict “who is guilty” for that discrepancy but are willing to get knowledge on that in our future work.

Fig. 7 states that PDs response reaches its maximum at temperatures close to 300 K and degrades at elevated and low temperatures. Sensitivity degradation for PDs with "entrance window" made from heavily doped n'–InAs at elevated temperatures was already explained by substrate transmission changes [6,8], while reasons for sensitivity degradation at low temperatures and in PDs with n–InAs substrate are still unclear. The above degradation at low temperatures could be explained by a diffusion length decrease in InAsSb. However, there is no strong experimental evidence for that so far save data in [7] where statement of \( L_{diff} = 5.5 \mu \)m at 77 K for the BSI PDs has been made.

Superposition of \( R_x \) (Fig. 6), \( S_x \) (Fig. 7) values and Johnson detectivity formula \( (D' = S_x(R_{Ap} \lambda /4kT)^{1/2}) \) provides \( D'_{max} \) values shown in Figs. 8 and 9. Temperature variation of sensitivity and peak
position were taken into account using graphs in Figs. 7 and 10. In
all simulations including internal quantum efficiency calculation the
A_{p-n} number (the p–n junction area) was substituted by the mesa area value. For the immersion lens PDs the D^*_m values are
generally about decade higher than those for bare chip PDs [8];
the same tendency was confirmed in our current measurements
(see Fig. 8).

As seen from Fig. 9 the developed PDs are not superior to those
in [15] at room temperature but exhibit better D^*_m values than
published ones for InAsSb/InAs DH [18,25] or GaSb/InGaAsSb type
II heterostructure PDs [26]. Moreover PDs in this study are charac-
terized by higher internal quantum efficiency/current sensitivity
(see Figs. 7 and 10) than all abovementioned PDs save the “old
ones” in [9]. At low temperature the developed PDs remain “quan-
tum efficient” while the simulated D^*_m values are higher than
that for the graded band gap PDs [27] and fairly close to those
displayed by InAs_{0.85}Sb_{0.15}/InAs_{1-x}Sbx/InAs/GaAs [28] and InAsSb/GaSb lattice matched heterostructure PDs [29]. However former PDs
have several times smaller R_A value; in the latter case as well in
[19] the PDs need electrical bias for appropriate operation – a
feature that creates certain difficulties in some kind of applica-
tions. At the same time we were not able to achieve the R_A value as high as in [7]; PDs in [7] are still champions among
all 4 μm PDs known to us.

The simulated D^*_m values in our bare chip PDs at 77 K are
close to the 2π BLIP numbers defined in [30] for the 300 K
environment. Our future work will be concentrated on noise
measurements to confirm high InAs/InAs_{0.9}Sb_{0.1}/InAsSbP DH PD performance at low temperatures.

4. Conclusion

Broad band DH BSI PDs with 0.19 mm wide active layers made
from InAs_{0.9}Sb_{0.1}/InAs showed diffusion current flow and negligible leakage current flow mecha-
nisms at T > 190 K, while at lower temperatures generation–recom-
bination at high bias and tunneling at low bias prevail. Internal quantum efficiency peaked at 270 K (η = 0.6) and appeared higher
in many close analogues with the result that the bare chip current sensitivity and simulated detectivity reached values
acceptable for many applications: S^*_{min} = (0.6–1.5)A/W D^*_m\mu m = 8 \times 10^8 and D^*_m\mu m = 6 \times 10^{11} cm Hz^{1/2} W^{-1} at 300 and 77 K corre-
spondingly. Immersion lens PD options (Θ_{open} ≈ 3.2 mm) offer similar S^*_{min} and a decade higher D^*_m values.

Conflict of interest

There is no conflict of interest.

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