ABSTRACT
Numerical computation has been carried out for theoretical characterization of a p'-InSb/n⁺-InSb/n⁻-InSb photodiode at 300 K for operation in 4.0 μm to 4.5 μm wavelength region. The different components of the dark current and the R/A products have been calculated using the theoretical model discussed above. In present work the the R/A product as well as the other major parameters of the p'-InSb/n⁺-InSb/n⁻-InSb gas detectors such as quantum efficiency, responsivity and detectivity have been estimated quantitatively. The peak detectivity has been estimated to be ~ 6.8 × 10⁵ mHz⁴/W and efficiency obtained on the basis of this model with their peaks at 4.2 μm wavelength, which reveals that this detector is best suited for detection of CO₂ gas.

Index Terms
Detectivity, Responsivity, Efficiency, Gas detector

1. INTRODUCTION
The presence of any toxic gas and its amount needs to be monitor for different applications such as safety alarm for toxic gases in mines, CO and CO₂ monitoring in car exast, environmental monitoring etc. Every material and gas has a unique fundamental fingerprint in terms of their characteristic absorption band. An emission spectrum of a particular gas and its intensity measurement quantifies the amount of gas present at a particular space. A number of pollutant combustible/toxic gases and liquids such as hydrocarbons like NH₃ (2.3 μm), H₂S (2.7 μm), CH₄ (3.3 μm), CO₂ (4.2 μm), CO (4.6) etc having their characteristic absorption band located in the infrared IR region. So a photodetector can be modeled for obtaining best performance about characteristic wavelengths of a particular gas and are best suited for monitoring that gas. Several photodetector models are proposed by several researchers [1]-[10] for monitoring various toxic gases

The structure under consideration is p'-InSb/n⁺-InSb/n⁻-InSb photo-diode grown on a GaAs substrate as shown in Fig. 1. The top p' layer receives the incident light and the lightly doped n⁺ region acts as the active layer. The incident light is absorbed in the neutral p', n⁺ regions as well as in the space charge region formed at the p'-n⁻ junction. The carriers generated in the neutral p' and n⁺ regions beyond their respective diffusion lengths will recombine before reaching the junction and fail to contribute to the net photocurrent.
The net or the effective value of zero bias resistance area product \((R_0A)_{Net}\) is given by

\[
\left(\frac{1}{R_0A}\right)_{Net} = \left(\frac{1}{R_0A}\right)_{Diff} + \left(\frac{1}{R_0A}\right)_{GR} + \left(\frac{1}{R_0A}\right)_{Tun}
\]

### 2.3 Quantum Efficiency And Specific Detectivity:

The quantum efficiency \((\eta)\) of a p–n junction photodetector has generally three major components. These components arise from the contribution of the three regions e.g., neutral n-region \((\eta_n)\), neutral p-region \((\eta_p)\) and the depletion region \((\eta_{dep})\). The net quantum efficiency can be obtained by

\[
\eta = \eta_n + \eta_p + \eta_{dep}
\]

The quantum efficiency components contributed by the neutral n\(^{th}\) and p\(^{th}\) regions can be obtained finally as [4],[7]

\[
\eta_p = \frac{(1-r_p)\alpha_pL_n}{\alpha_pL_n+1} \left[ \gamma_p \cosh \left( \frac{t-x_p}{L_n} \right) + \sinh \left( \frac{t-x_p}{L_n} \right) \right] - \alpha_pL_n \exp \left( -\alpha_p(t-x_p) \right)
\]

\[
\eta_n = \frac{(1-r_n)(1-r_p)\alpha_nL_p}{\alpha_nL_p+1} \exp \left( -\alpha_n(t-x_n) \right)
\]

\[
\eta_{dep} = \left( 1 - r_n \right) \left( 1 - r_p \right) \exp \left( -\alpha_p(t-x_p) \right) \exp \left( -\alpha_n(t+\alpha_n x_n) \right)
\]

### 2.4 Responsivity

The photoresponse is

\[
\mathcal{R} = \frac{q\eta\lambda}{hc}[9]
\]

Where, \(\eta\) is the quantum efficiency, \(\lambda\) is the operating wavelength.

### 2.5 Specific Detectivity

The specific detectivity of the photodetector under consideration can be written as

\[
D^* = \frac{q\eta\lambda}{hc} \sqrt{\frac{(R_0A)_{Net}}{4kT}}[10]
\]

where, \(\eta\) is the quantum efficiency, \(\lambda\) is the operating wavelength and \((R_0A)_{Net}\) is the net or effective value of the zero-bias resistance area product arising out of various components (e.g. diffusion, generation-recombination and tunneling) from references [7],[10]

### 3. Results and Discussion

Numerical computation has been carried out for theoretical characterization of a p\(^{+}\)-InSb/n\(^{+}\)-InSb/n\(^{-}\)-InSb photodiode at 300 K for operation in 4.0 \(\mu\)m to 4.5 \(\mu\)m wavelength region. The parameters used for computation are taken from ref [1],[6]. The different components of the dark current and the \(R_0A\) products have been calculated using the theoretical model discussed above. In present work the the \(R_0A\) product as well as the other major parameters of the p\(^{+}\)-InSb/n\(^{+}\)-InSb/n\(^{-}\)-InSbGaAs detectors such as quantum efficiency, responsivity and detectivity have been estimated quantitatively. Various other parameters used in the theoretical computations are taken from references [7]-[9].

Fig. 2 shows the current-voltage characteristics of the detector in the dark condition.

![Figure 2 Variation of the net dark current & its component with applied voltage](image-url)

The components constituting dark current e.g. diffusion, generation-recombination and tunneling (including the
combined effect of trap-assisted and band-to-band components) and their variations with the applied voltage are also shown in the figure. It is seen that the tunneling component of current density dominates over the net current density. Computations also reveal that the generation-recombination component also slightly affected net current density in forward bias. In Fig. 3, the variation of net zero bias area product ($R_0A_{net}$) and its component is shown with applied voltage.

In Fig. 5, the variation of the responsivity of the gas detector with operating wavelength ranges 4.1 µm to 4.30 µm, its maximum value 2.8 (A/W) at the wavelength 4.2 µm and decreases sharply on the both side.

The detectivity falls rapidly near the long wavelength cutoff. The peak detectivity has been estimated to be $\sim 6.8 \times 10^7$ mHz$^{1/2}$/W at the wavelength $\lambda_c = 4.2$ µm.

Fig. 6 depicts the variation of the detectivity of the device with the wavelength of operation. It is seen that detectivity of the device at room temperature increases with increase in wavelength which reaches a peak value at $\lambda = 4.2$ µm.

4. CONCLUSION
In this paper a generic model of an infrared photodetector has been carried out for theoretical characterization of a p$^+$-InSb/n$^-$-InSb/n$^-$-InSb photodiode at 300 K for operation in 4.0 µm to 4.5 µm wavelength region. The model has been applied to characterise theoretically an InSb homojunction photodetectors such as quantum efficiency, responsivity and detectivity have been estimated for operation at 4.2 µm. The peak detectivity has been estimated to be $\sim 6.8 \times 10^7$
mHz$^{1/2}$/W and efficiency obtained on the basis of this model with their peaks at 4.2 µm wavelength, which reveals that this detector is best suited for detection of gases such as CO$_2$.

Using the same modelling procedure and considering the characteristic wavelength of the selected gas one can develop model for other toxic gas monitoring. Such model would reduce the experimental cost and time of developing the gas detector for toxic gas sensors. Also II-VI materials such as HgCdTe can also be selected for some toxic gas detectors for LWIR region.

5. REFERENCES