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Analysis of optical properties of InGaSb PIN photdiodes

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Abstract—This paper represents the optical characteristics of InGaSb PIN photodiodes, grown on metamorphic layers of InGaSb, through the modeling of responsivity, quantum efficiency and detectivity. The modeling is based on the wavelength dependent models of absorption coefficient and reflectivity. Theoretical results are fitted with experimental data obtained for these photodiodes. The cut-off wavelength is found to be 2271nm, which is within ±5nm of the experimentally obtained data. The detectivity of the photodiodes is found to be $1.5(\pm0.1)\times10^9$cmHz$^{1/2}$W^{-1} and quantum efficiency 28±3% through the analysis. Such modeling can be used to optimize the detection performance of InGaSb PIN photodiodes.

GaSb and related materials have achieved growing interest in recent times for potential new device applications originating from their excellent optical and electronic properties. One particular GaSb-based easy-to-grow ternary is InGaSb, which is finding ever increasing applications in photodetectors and lasers operating adequately well in the 1.7-6.9μm wavelength range, and which has interesting biomedical and security applications [1]. For such applications, spectral response and hence optical characteristics become crucial for defining the performance of a photodiode. These characteristics include the responsivity, quantum efficiency and detectivity of the photodiode. The photodiode responsivity, defined as generated photocurrent per unit optical power variation with a wavelength, is primarily dependent on the device material, structure, and operating conditions in terms of bias voltage, temperature, and wavelength of the incident radiation. Thus, it becomes essential to have a detailed understanding of the effects of these parameters to design and fabricate an optimal photodetector. The quantum efficiency of such diodes can be optimized by varying the composition to tune the detection wavelength. The detectivity is the key parameter characterizing normalized signal-to-noise performance of photodiodes. Various noises are caused by the current passing through the device because of the statistical nature of the generation and recombination processes. So one critical aim is to suppress all kinds of noise and thus improve the detectivity. A theoretical model for these optical parameters is particularly useful to accomplish such a task. In this paper, a model is developed for the responsivity of InGaSb PIN photodiodes. The developed models are fitted to the experimental data [2-3] obtained for the fabricated InGaSb PIN photodiode devices.

All the layers of the metamorphic samples were grown in a Gas Source Molecular Beam Epitaxy (GSMBE) system manufactured by SVT Associates (SVTA). A complete experimental detail is depicted in Ref. [2-3].The epitaxial layer structure for the metamorphic sample starts with a GaSb buffer (0.1 to 0.25μm) on the GaSb substrate, followed by a sequence of four buffer layers of $In_yGa_{1-y}Sb$ grown at various temperatures (450°C to 540°C), where y was varied in equal increments of y=0.03. Each buffer layer had a thickness of 250nm. The step-graded buffer layers were terminated by the final metamorphic layer with the composition y=0.15. The thickness of the top metamorphic layer was between 1.1 and 1.5μm. Finally, a fully strained 40 nm GaSb cap-layer was grown on top of the metamorphic layer to simplify x-ray characterization. The samples were nominally 2×10^{18}cm^{-3} p-doped by a beryllium solid-source cell operating at 785°C and 1.5×10^{18}cm^{-3} n-doped by a tellurium source. The undoped InGaSb is unintentionally p-type and has a doping concentration of 2.4×10^{16}cm^{-3}. InGaSb PIN homojunction diodes, lattice-matched to the underlying top metamorphic layer, were epitaxially regrown. Samples were designed for light detection at wavelengths of 2.0μm and beyond.

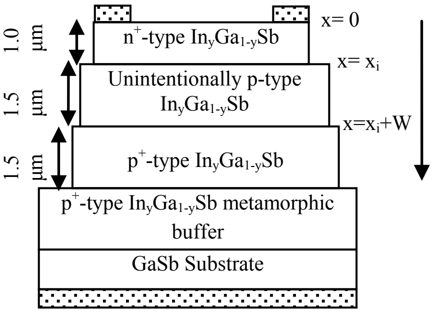

Fig. 1. Device schematic structure.

The observed variation in the measured power density causes an estimated error of ±0.05 in responsivity values, ±3% in values of quantum efficiency and $\pm0.1\times10^9$ in detectivity.The device schematic along with the device

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dimensions, used for the calculation, is shown in Fig. 1. We have considered an n-i-p diode. For the modeling of absorption and reflection coefficients we have followed the model developed by González-Cuevas *et al.* [4].

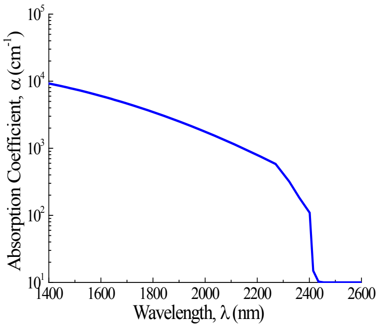

Fig. 2. Variation of absorption coefficient with the incident light wavelength for $In_{0.182}Ga_{0.818}Sb$ at 300K.

The wavelength dependent complex dielectric function can be expressed as:

$$\varepsilon(\lambda) = \varepsilon_1(\lambda) + i\varepsilon_2(\lambda) \tag{1}$$

The absorption coefficient can be expressed as:

$$\alpha(\lambda) = \frac{4\pi}{\lambda}\left[\frac{\varepsilon_1(\lambda)^2 + \varepsilon_2(\lambda)^2 - \varepsilon_1(\lambda)}{2}\right]^{1/4} \tag{2}$$

and the reflectivity can be expressed as:

$$R(\lambda) = \frac{\sqrt{\varepsilon_1(\lambda)^2 + \varepsilon_2(\lambda)^2} - \sqrt{2\varepsilon_1(\lambda) + 2\sqrt{\varepsilon_1(\lambda)^2 + \varepsilon_2(\lambda)^2}} + 1}{\sqrt{\varepsilon_1(\lambda)^2 + \varepsilon_2(\lambda)^2} + \sqrt{2\varepsilon_1(\lambda) + 2\sqrt{\varepsilon_1(\lambda)^2 + \varepsilon_2(\lambda)^2}} + 1} \tag{3}$$

Using (3), the minority carrier optical generation rate $G(x,\lambda)$ along the device depth x direction according to [4] is given by:

$$G(x,\lambda) = \frac{\lambda P_{opt}(\lambda)\alpha(\lambda)\left[1 - R(\lambda)\right]}{hc\ \exp\left[\alpha(\lambda)x\right]} \tag{4}$$

where $P_{opt}(\lambda)$ is the total optical power incident on the photodiode per unit area, h is Planck's constant, c is the speed of light, and λ is the wavelength of the incident light. The drift current expression in the photodiode is:

$$J_{dr} = -q\int_{x_i}^{x_i+W} G\left(x,\lambda\right)dx \tag{5}$$

We then consider the diffusion component of the photocurrent assuming negligible absorption and production in the top n^+-layer for PIN photodiodes. The continuity equation for electrons in the p^+-layer beyond the i-layer (unintentionally p-doped) at steady state, including generation and recombination, is given by:

$$D_n\frac{\partial^2\Delta n}{\partial x^2} - \frac{\Delta n}{\tau_n} + G(x,\lambda) = 0 \tag{6}$$

where D_n is the electron diffusion coefficient, related to the carrier mobilities by Einstein's relation, τ_n is the electron lifetime and Δn is the excess electron density in the p^+-region. Solving this equation with the boundary conditions $\Delta n(\infty)=\Delta n(0)$ and $\Delta n(x_i+W)=0$, we get the solution for an excess minority carrier as:

$$\Delta n = C\left[\exp\left\{-\alpha(\lambda)\cdot x\right\} - \exp\left\{(x_i + W)\cdot\left(\frac{1}{L_n} - \alpha(\lambda)\right) - \frac{x}{L_n}\right\}\right] \tag{7}$$

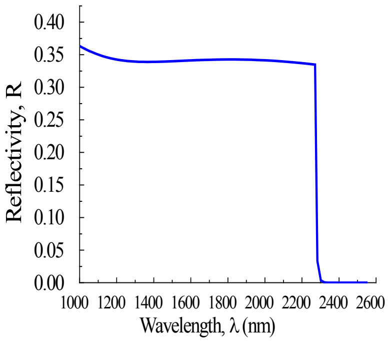

Fig. 3. Reflectivity as a function of incident light wavelength for $In_{0.182}Ga_{0.818}Sb$ at 300K.

Here, C is the parameter obtained after solving the differential equation and using the boundary conditions given as:

$$C = \frac{P_{opt}(\lambda)\cdot[1 - R(\lambda)]\cdot\alpha(\lambda)\cdot\lambda}{D_n hc\left[\frac{1}{L_n^2} - \alpha(\lambda)^2\right]} \tag{8}$$

The electron diffusion current can be expressed as follows:

$$J_n = qD_n\frac{\partial\Delta n}{\partial x} \tag{9}$$

The expression for a diffusion current is then given by (7) to (9) as:

$$J_{diff} = qD_nC\left[\frac{1}{L_n} - \alpha(\lambda)\right]\exp\left[-\alpha(\lambda)\cdot(x_i + W)\right] \tag{10}$$

where L_n is the electron diffusion length obtained from [5]. The total photocurrent then can be expressed as the summation of the drift and diffusion currents by:

$$J_{ph} = J_{dr} + J_{diff} \tag{11}$$

The responsivity $\Re$ is then obtained from the expression given as:

$$\Re(\lambda) = \frac{J_{ph}(\lambda)}{P_{opt}(\lambda)} \tag{12}$$

The quantum efficiency η of the photodiode can be calculated from:

$$\eta = \frac{hc}{q\lambda}\frac{J_{ph}(\lambda)}{P_{opt}(\lambda)} \tag{13}$$

Finally, the detectivity D^* is obtained from the equation given in [6] as:

$$D^* = \Re(\lambda)\sqrt{\frac{R_0A}{4kT}} \tag{14}$$

where R_0A is the zero-bias resistance area product obtained from [5, 7] and k is Boltzmann's constant.

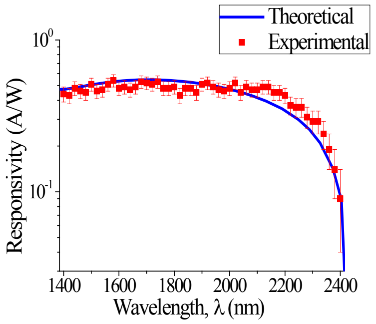

Fig. 4. Variation of responsivity as a function of wavelength.

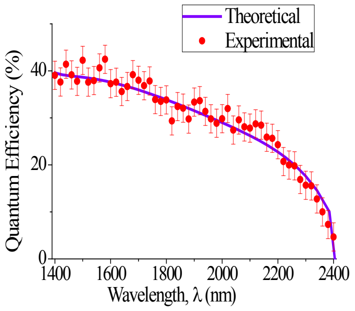

Fig. 5. Variation of quantum efficiency as a function of wavelength.

For the calculation 100μm square mesa $In_yGa_{1-y}Sb$ (y=0.182) PIN-diode is used. The carrier mobilities μ_p and μ_n are equal to 468 and 2164 cm^2/V-s, respectively. Figure 2 shows the absorption coefficient (2) of $In_yGa_{1-y}Sb$ as a function of the wavelength of incident light per unit area at room temperature, 300K. Figure 3 shows the variation of reflection coefficient (3) with the incident light wavelength for the same material at the same condition. The spectral response of the InGaSb PIN photodiode is shown in Fig. 4. The solid curve shows the resulted responsivity obtained from (11). The model fits well with the experimental data at room temperature shown with the error bars. The quantum efficiency as a function of incident light wavelength is shown in Fig. 5. The experimentally obtained quantum efficiency is shown with the error bars within ±3%. The solid curve shows result obtained from the modeling using (11) which fits with the experimental values as well. Theoretically predicted detectivity variation with a wavelength, using (13), is plotted in Fig. 6 for InGaSb PIN photodiodes. Experimental data is also plotted with error bars within $\pm 0.1\times10^9$cmHz$^{1/2}$W^{-1}. According to the calculation, for the present InGaSb PIN photodiodes, the cutoff wavelength is 2271nm, which is close to the experimentally found cutoff wavelength 2270±5nm [2]. So the developed model fits adequately well with the experimental results obtained for InGaSb PIN photodiodes. The experimental results show a low value in room-temperature detectivity of the photodiodes due to the surface leakage originating from fabrication issues [2, 5].

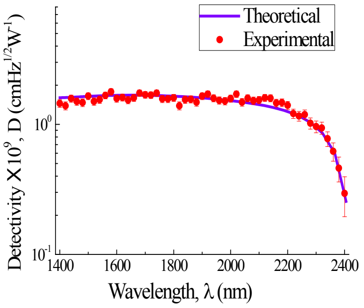

Fig. 6 Variation of detectivity as a function of wavelength.

InGaSb photodetectors working in the near infrared range find useful applications in various fields. In this paper, we have studied the optical characteristics of InGaSb PIN photodiodes by considering the responsivity, quantum efficiency and detectivity. The spectral response of a InGaSb n-i-p infrared photododetector has been analyzed using a theoretical model based on the continuity equations of the minority carriers different regions. The quantum efficiency and detectivity of the photodiode are also modeled. All the results obtained from modeling are fitted with experimental data and a satisfactory match is found. For further study, the effects on the spectral response due to the variation of temperature, dislocations, photon energy, diffusion depth, and carrier concentration can also be analyzed [6]. The electron and hole ionization coefficients for InGaSb PIN photodiodes [8] can also be modeled in a similar fashion. These models can be utilized to combine the aforementioned parameters appropriately and thus optimize the device performance.

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