Effects of absorption layer characteristic on spectral photoresponse of mid-wavelength InSb photodiodes

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Abstract

We report on 2D numerical simulations of photoresponse characteristic for mid-wavelength InSb infrared photodiodes. Effects of thickness of absorption layer on the photoresponse have been investigated for both front-side and back-side illuminated devices. Optimal thickness of absorption layers for different diffusion lengths are extracted theoretically. An empirical formula is proposed to predict a reasonable optimal thickness of absorption layer.

I. INTRODUCTION

InSb is the preferred material for fabrication of high-performance infrared detectors in the 3 to 5 μm region duo to superior fundamental properties and simple material growth and device fabrication processes. Applications of these infrared detectors include amongst others, thermal imagers, satellite IR cameras and heat seeking missiles. [1, 2] It is imperative to fully understand the inner physics mechanism of InSb infrared photovoltaic diode to successfully utilize this device to full potential. For thin film InSb infrared detector with epitaxial growth technology, the photo-response is limited by absorption layer characteristics, which is related to thickness of absorption layer, absorption length and diffusion length. In order to improve the device performance, a detailed analysis of structure-related photo-response mechanisms for the InSb infrared photo-detector is needed.

Numerical simulations, which can contain structural details such as layer thicknesses, doping profiles and trap concentrations, provide key insights into device design and the degradation mechanisms of the reliability. [2] Although numerical approaches have been employed in the design of InSb photodetectors, [3] few theoretical work has been performed to study effects of the thickness of the absorption layer on the photoresponse performance of the InSb photodetectors. In this paper, numerical simulations are used to optimize the device structure. Effects of thickness of absorption layer on the performance of the InSb photodetectors are theoretically investigated in detail.

II. SIMULATION MODELS

The structure that we have simulated consists of a n-doped InSb absorption layer with the doping density of N_d=9×10^{14} cm^{-3}, a p$^+$-doped InSb layer with the doping density of N_a= 1×10^{17} cm^{-3}. The p-doping layer thickness is 0.8μm. The thickness of the n-doping absorption layer is defined as d_{abs} in the simulations. The cross-sections of the simulated InSb photodetectors are shown in the left insets of Fig. 1 and Fig. 2.

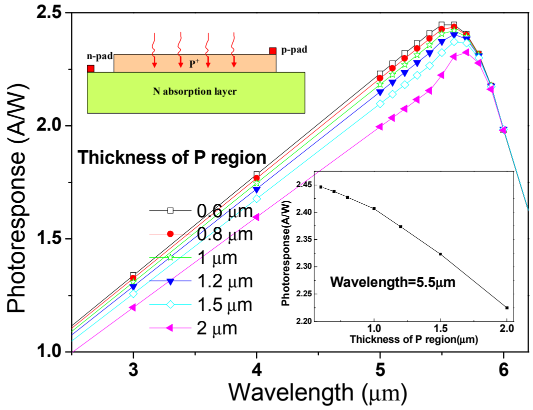

Fig. 1. Photoresponse vs. wavelength of incident light with P layer thickness changing from 0.6 to 2 μm. The right inset is photoresponse as a function of P layer thickness at the wavelength of 5.5μm. The left inset is cross-sectional structure of simulated InSb photodetector under front-side illumination.

Steady-state numerical simulations are performed using Sentaurus Device, a commercial package by Synopsys. For plain drift-diffusion simulation the well known Poisson equation and continuity equations are used. The carrier generation-recombination process consists of Shockley-Read-Hall, Auger, and optical generation-recombination terms.

III. RESULT AND DISCUSSION

Fig. 1 shows the photoresponse as a function of the incident light wavelength with the P layer thickness changing from 0.6 to 2 μm under the front-side illumination. The right inset is the photoresponse as a function of the P layer thickness at the wavelength of 5.5μm. The photoresponse monotonously decreases with the increase of the P layer thickness. When the incident light illuminates from the front-side, most of the lights are absorbed by the N absorption layer due to the thin P layer. With the increase of the P layer thickness, more incident lights are absorbed by the P absorption layer with more and more electron and hole pairs being generated in the P layer. However, the P-region minority carriers lifetime is very small (1-0.1ns),

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thus the photo-generated electron and hole pairs are easily recombinated in the P layer, inducing the decreases of the photoresponse.

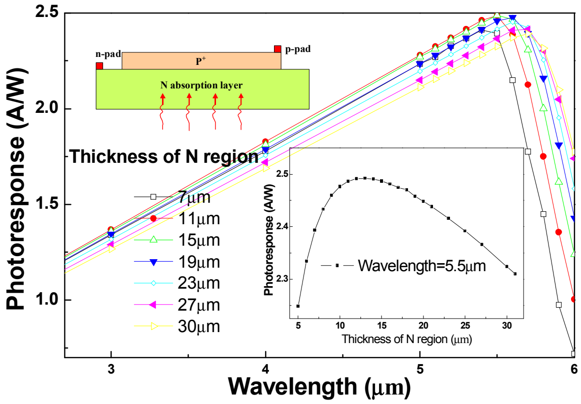

Fig. 2. Photoresponse vs. wavelength of incident light with N layer thickness changing from 7 to 30 μm. The inset (right) is photoresponse as a function of N layer thickness at the wavelength of 5.5μm. The inset (left) is cross-sectional structure of simulated InSb photodetector under back-side illumination.

Fig. 2 shows the photoresponse as a function of the wavelength of incident light (λ_{in}) with the thickness of absorption layer (d_{abs}) changing from 7 to 30μm under the back-side illumination. The right inset is the photoresponse as a function of the N layer thickness at λ_{in} = 5.5μm. At the short wavelength range, the photoresponse monotonously decreases with the increase of dabs. The absorption coefficient at the short wavelength range is bigger than that of the long wavelength range, thus the light is completely absorbed over a small fraction of the absorption layer. Here, the diffusion is the dominant mechanism of the photoresponse causing the monotonous decrease. When λ_{in} is bigger than the cut-off wavelength, it is found that the photoresponse monotonously increases with the increase of d_{abs}, and finally saturates. This is because the absorption coefficient in the long wavelength range is very small, so the absorption length is equal to d_{abs}. Here, the absorption is the dominant mechanism of the photoresponse causing the monotonous increase. When d_{abs} is close to the diffusion length of the minority carrier, the absorption out of one diffusion length distance from the p-n junction can not affect the photoresponse, consequently causing the gradual saturation. Near the peak-photoresponse wavelength as shown in the right inset of Fig. 2, the photoresponse increases with the increase of d_{abs} first, and then decreases. The maximum photoresponse, which is the consequence of competing effects of the absorption and diffusion, is at $d_{abs} \approx 12$μm.

Fig. 3(a) compares the photoresponse for different minority carrier lifetimes at λ_{in}=5.5 μm. Minority diffusion length can be calculated by:

$$L_d = \sqrt{D_p \cdot \tau_p} = \sqrt{\frac{kT}{q}\mu_p \cdot \tau_p} \qquad (1)$$

By substituting the InSb material parameters into Eq. 1, the corresponding minority diffusion length for each minority carrier lifetime is 25.7, 36.6, 57.5, 68.0, 81.2, 114.8, 140.6, 181.6, and 256.8μm, respectively. As shown in Fig. 3(a), the photoresponse increases with an increase of the minority carrier lifetimes. Therefore, the optimal d_{abs} increases with increasing of the diffusion lengths.

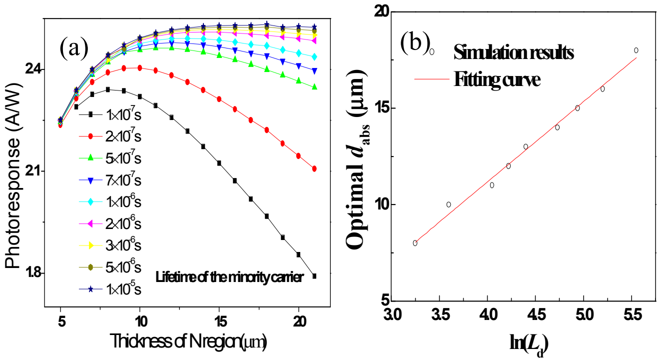

Fig. 3. (a) Photoresponse vs. d_{abs} with λ_{in} = 5.5 μm and $\tau_p = 5\times10^{-7}$-1×10^{-5}s, respectively; (b) Fitting curve of the optimal thickness of absorption layer as a function of diffusion length L_d.

To predict reasonable optimal thickness of absorption layer for InSb infrared photodetector, we calculate the corresponding optimal d_{abs} at the different diffusion lengths (L_d), as shown in Fig. 3(b). By fitting the curve of the optimal d_{abs} as a function of L_d, an empirical formula for predicting the optimal d_{abs} is obtained:

$$d_{abs} = 4.16 \times \ln(L_d) - 5.47 \qquad (2)$$

IV. CONCLUSION

In conclusion, the photo-response characteristics of mid-wavelength InSb infrared photodiodes have been simulated with a 2-D numerical simulator. Our theoretical work shows that the optimal thicknesses of absorption layers can be strongly affected by the minority carrier lifetimes. An empirical formula is proposed to predict a reasonable optimal thickness of absorption layer.

ACKNOWLEDGEMENTS

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