Auger Suppression in MWIR InSb Photodiode for Ambient Temperature Operation

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at George Mason University

by

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DEDICATION

This is dedicated to my parents and my husband for their endless love, also my advisors for their unlimited support.

ACKNOWLEDGEMENTS

I would like to thank the many friends, relatives, and supporters who have made this happen. My loving husband, Aaron, assisted me in my paper writing. My advisor Dr. Li, and the other members of my committee were of invaluable help.

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ABSTRACT

AUGER SUPPRESSION IN MWIR INSB PHOTODIODE FOR AMBIENT TEMPERATURE OPERATION

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A primary goal for infrared photon detection systems is to increase their operating temperature without sacrificing performance. Auger process is the most significant component that contributes to the dark current. In this thesis a non-equilibrium Auger suppression InSb infrared detector is designed and studied to achieve the ambient temperature operation. We investigated the mechanisms that contributes to dark current and simulate the device under various conditions. The dark current is largely decreased and performance at room temperature is optimized.

INTRODUCTION

Infrared (IR) technology has progressed a lot during past 30 years, and throughout all the applied areas the role of the IR technology has been irreplaceable. In military use, for example, IR is used in missile guidance and warning systems, target detection, object recognition, location tracking, etc. For civil use, applications are even wider, such as high voltage circuit troubleshooting, medical imaging, night vision, short-range wireless communication weather forecasting, and navigational aids. [1] IR technology increases our quality of life and efficiency, and also opens new possibilities for various research area like astronomy and medical science.

In different application cases, different types of infrared detectors are required to sense different infrared windows. The IR optical sensors can be confined to two classes: thermal detectors and photodetectors. [2] Thermal detectors absorb the energy of the optical IR radiation and elevated temperatures caused by the radiation. This temperature change will result in an electrical characteristic changing, most commonly seen as resistance change. However, thermal detectors have a very high response time compared to photodetectors. When the application requires a high sensitivity and response time, thermal detectors will be unqualified. Photodetectors can be divided into different types: intrinsic extrinsic, photoemissive and quantum well and quantum dot intraband detectors.

Intrinsic infrared detectors are built with a direct band gap semiconductors like InSb, MCT, PbSe, etc. Photovoltaic (PV) effect and photoconductive (PC) effect are also two main schemes of intrinsic IR detectors. PV devices are used as a reverse biased photodiode and PC devices are used as a conductor that will change conductivity when it receives the target wavelength infrared signal.

Photodiodes are one of the most common detectors, as well as one of the best performing. The photodiode is made of photo sensitive semiconductors and will react to certain wavelengths of radiation. For intrinsic photodiodes, the semiconductors should have an energy band gap of Eg close to the energy of the target infrared light frequency. When the specific light shines on the diode, electrons in the valance band absorb the energy and move to the conduction band, creating an electron-hole pair. Figure 1 illustrates this process. [3] This process results in a higher carrier concentration in the diode. When the diode is applied with a reverse bias voltage, the minority in diffusion length are swept to the depletion region and create a distinct larger reverse biased current (light current) compared to the situation when there is no photon excitation (dark current), shown as in Figure 2. [3]

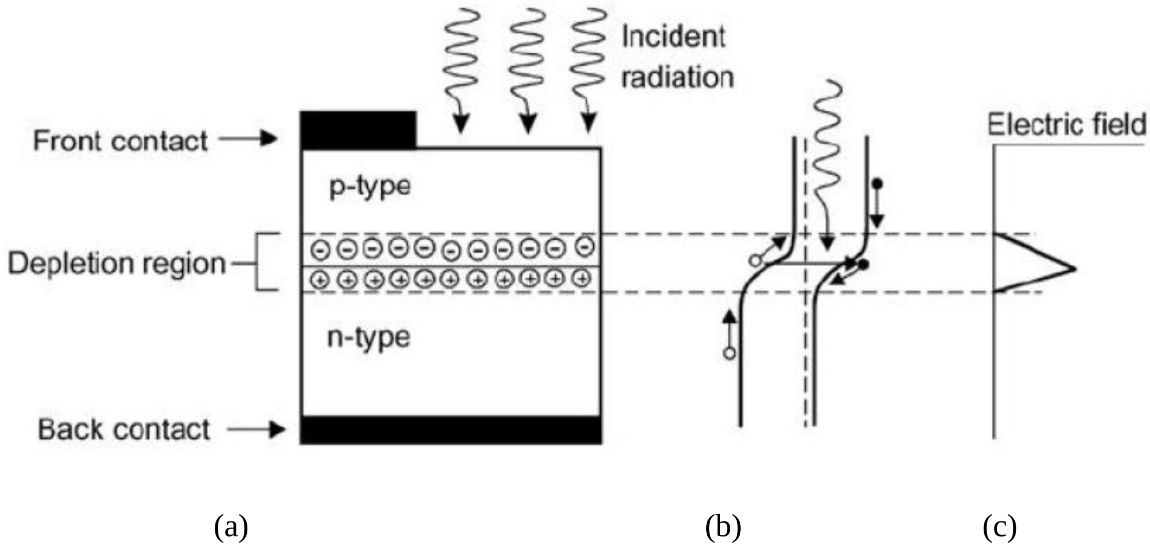

FIG 1. (a) Cross-section of photondiode. (b) Photon excitation process in band gap. (c) The electric field of depletion region.

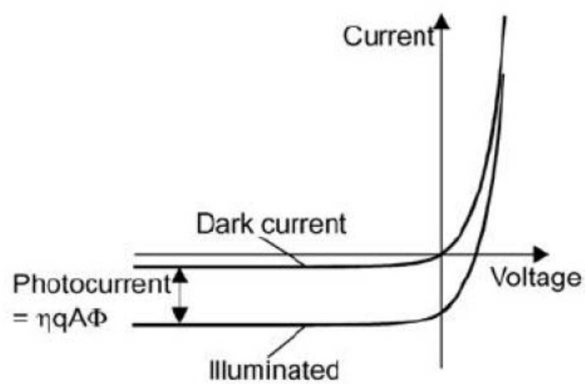

FIG 2. The I-V curve of device with and without infrared radiation.

However, to optimize the quantum efficiency, frequency response since the capacitance is decreased and spectral response. We construct an advanced PIN structure which has an intrinsic or nearly intrinsic layer between P and N layer. This will enlarge the depletion region which means the volume of the absorption region increased. [2]

Lots of intrinsic infrared detectors are largely limited by operating temperature since they are built with narrow-band semiconductor. For mid-wavelength or long-wavelength infrared radiation detection, narrow band gap semiconductor device has provided high-response speed, low noise, high-specific directivity, and robustness. However, to maintain high performance, products are required to cool down to cryogenic temperature to limit the thermal noise by working with bulky liquid nitrogen cooling system. Main reason behind this is the thermal generation recombination process is greatly marked under ambient-temperature operation, which leads to a high dark current and introduces lots of noises to the device. The primary goal for improving infrared detector is to increase the operation temperature. In my thesis, a nonequilibium InSb intrinsic PIN photodiode is studied in order to minimize the cooling requirements without sacrificing the performance.

MATERIAL PROPERTY

InSb is very well developed and used for mid wavelength infrared detector. The fabrication technology are mutual and easy to control compared to MCT and the bulk crystalline solid-state properties are great for infrared detector design compared to PbSe. Indium antimonide is an intrinsic semiconductor with direct band gap, lowest point of conduction band and highest point of valence band are both at the center of Brillouin zone. The Energy gap of InSb is temperature dependent. [3] The Eg fits the following formula [4]:

$$Eg = 0.24 - \frac{6\times10^{-4}T^2}{500-T}eV \quad (1)$$

Where T is the device operating temperature (kelvin).

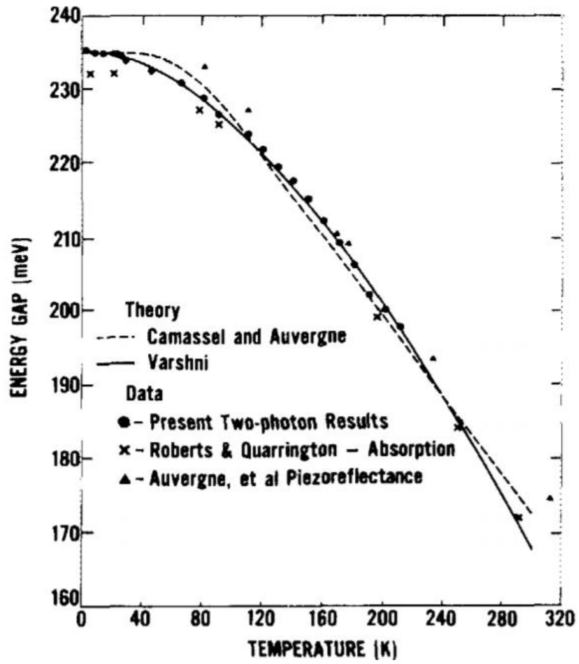

FIG 3. Dependence of the energy gap of InSb upon temperature.[4]

InSb intrinsic photodiode can detect around 7um at room temperature (300K), and at liquid nitrogen temperature it can detect around 5.5um from equation:

$$Eg = \frac{hc}{\lambda}\ eV \quad (2)$$

Where h is Planck Constant and c is the speed of light, λ is the wavelength of the light.

InSb's intrinsic carrier concentration is temperature dependent too. The ni fits the formula below [4] [5]:

$$ni = (Nc \times Nv)^{0.5} e^{\frac{-Eg}{2kT}} \quad (3)$$

$$Nc = 8 \times 10^{12} T^{1.5} \quad (4)$$

$$Nv = 1.4 \times 10^{15} T^{1.5} \quad (5)$$

The FIG 4 is the plot of InSb ni value versus the temperature. [6]

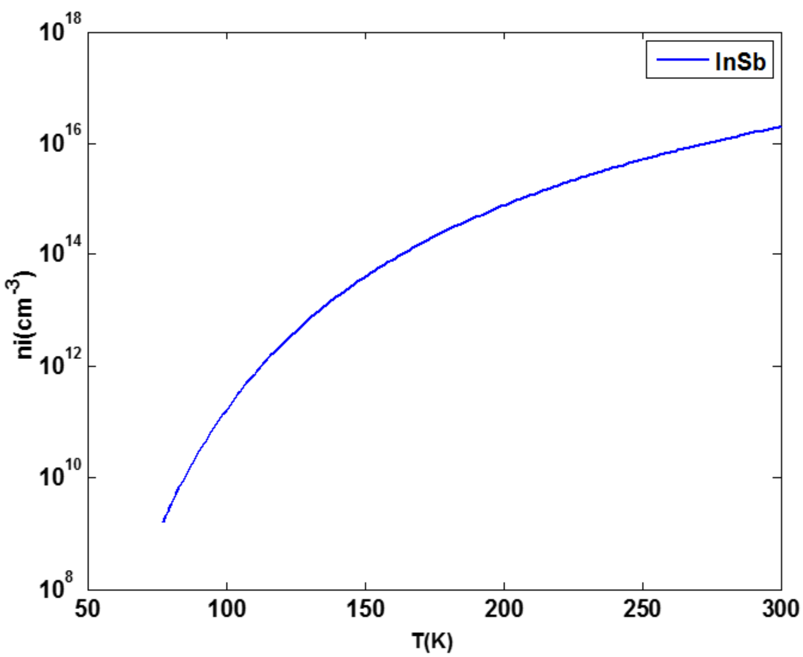

FIG 4. Dependence of the intrinsic carrier concentration of InSb upon temperature. [4] [5]

As early as the 1960s, the processing of high quality pure single crystals of InSb have been studied and developed. The fabrication of high-purity (0.999999) InSb is very commercially available compared to the HgCdTe alloy when it comes to band gap engineering, since it’s very difficult to control the growth of HgCdTe to acquire the exact alloy ratio.

THEORETICAL ANALYSIS OF DARK CURRENT

For an intrinsic PIN infrared detector, the understanding of the dark current mechanism (reverse bias current of diode) is very important, since the high dark current brings low detectivity and big noise. Similar to the PN junction diode, PIN photodiode's dark current is mainly a diffusion current at high temperature. There are also several mechanisms that are involved when determining the dark current: generation-recombination (g-r) current in the depletion region, band-to-band (B-B) tunneling, trap-assisted (TAT) tunneling, surface recombination (surf). The figure below shows those different mechanisms [3]:

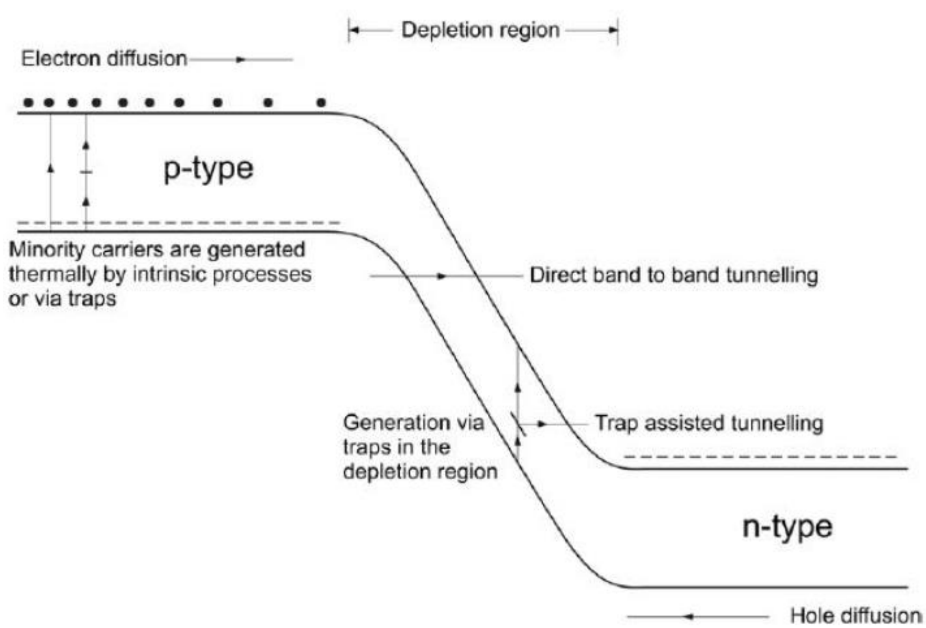

FIG 5. Mechanisms that contribute to dark current.

The generation-recombination mechanisms are basically thermal generation. The electron and hole pairs are generated in the depletion region and under the affection of electrical field in the depletion region, the electrons on the p-side will drift to n-side and holes will drift to the p-side. In this case a current flowing from N region to P region is formed up as drift current. Also at P side minority carriers, which are electrons in this case, will diffuse into the depletion region.

Band to band tunneling is dependent on the band gap and the electrical field, which is caused by the reverse biased voltage. In this case keeping the voltage applied as low as possible is one of our goals. Trap-assisted Tunneling is mainly related to the impurities and defects in the device, which will add more energy bands (Etrap) in between the conduction band and valence band. This kind of tunneling typically occurs when the fabrication is poor and a lot of the impurities and defects are introduced. Also, surface recombination is basically caused by defects too, since on the surface it is more likely to leave unsaturated chemical bonds and defects. Those bonds and defects might react and trap ambient chemicals which changes the characteristics of the device. However, we can coat the device with a protection layer to protect it from the affection from surface recombination. In this case the bulk g-r process attracts the most attention.

The g-r recombination limits the carrier life time in the depletion region. When the recombination is high, and diffusion length will be short which will result a large dark diffusion current. In the bulk of the device, the total minority lifetime is mainly depends on three types of recombination: Auger recombination, radiative recombination and Shockley-Read-Hall (SRH) recombination: [7]

$$\frac{1}{\tau bulk} = \frac{1}{\tau A} + \frac{1}{\tau R} + \frac{1}{\tau SRH} \quad (6)$$

Where $\tau bulk$ is the total minority carrier life time, τA is the Auger lifetime, τR is the radiative lifetime and τSRH is SRH lifetime.

There are two ways for electrons and holes pairs to combine. First is the direct band to band process, which is happened when electron in the conduction band drop to an unoccupied state in conduction band. The second one is indirect process, where electron first drop to an energy state between conduction and valence band, then recombine with a hole. When an electron and a hole recombine, there will be energy equal or less than Eg released from this process. If energy released as a photon, then this process is radiative recombination. Another way is the energy get transferred to another mobile electron, this process will be Auger recombination, which is also the reverse process of impact ionization. The third type will be the energy is dissipated in the lattice. To study each of the process's contribution to the dark current, we will calculate the lifetime for each recombination. For Auger lifetime, to simplify the analysis we consider the Auger 1 only [8]:

$$GA1 = \frac{1}{2\times ni^2\times\tau A1i} = \left[\frac{2ni^2\times3.8\times10^{-18}\mathcal{E}s^2(1+\frac{me^*}{mh^*})^{0.5}(1+2\frac{me^*}{mh^*})\times e^{\left(\frac{(1+2\frac{me^*}{mh^*})}{(1+\frac{me^*}{mh^*})}\frac{Eg}{kT}\right)}}{me^*|F1F2|^2(\frac{Eg}{kT})^{1.5}}\right]^{-1} \quad (7)$$

Where ni is the intrinsic carrier concentration (cm^{-3}), me* and mh* are the electron and hole effective mass respectively (m_0) and Eg is the energy band-gap (eV). The |F1F2| value here is 0.3. Use MABLAB to plot the Auger 1 lifetime at temperature range from 77K to 300K:

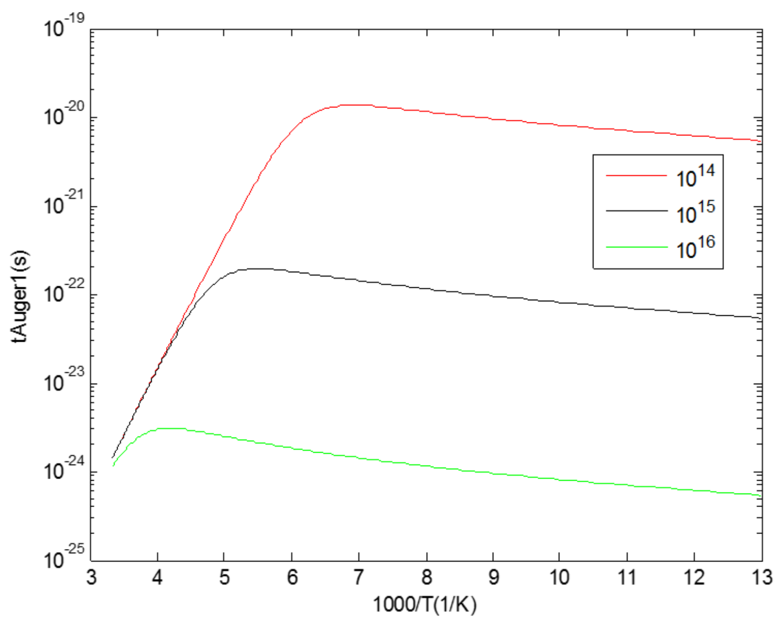

FIG. 6 Calculated Auger-1 lifetime for InSb versus temperature for different doping concentration.

The lifetime of radiative recombination is [9]:

$$GR = 5.18 \times 10^{-13} \mathcal{E}s^2 \left(\frac{\mathrm{m0}}{me^* + mh^*}\right)^{1.5} \left(1 + \frac{m0}{me^*}\right) \left(\frac{300}{T}\right)^{1.5} (Eg^2 + 3kTEg + 3.75k^2T^2)\ , \tag{8}$$

$$\tau R = \frac{1}{GR(n+p)}\ . \tag{9}$$

The graph below is the MATLAB plot from the formula (8)(9).

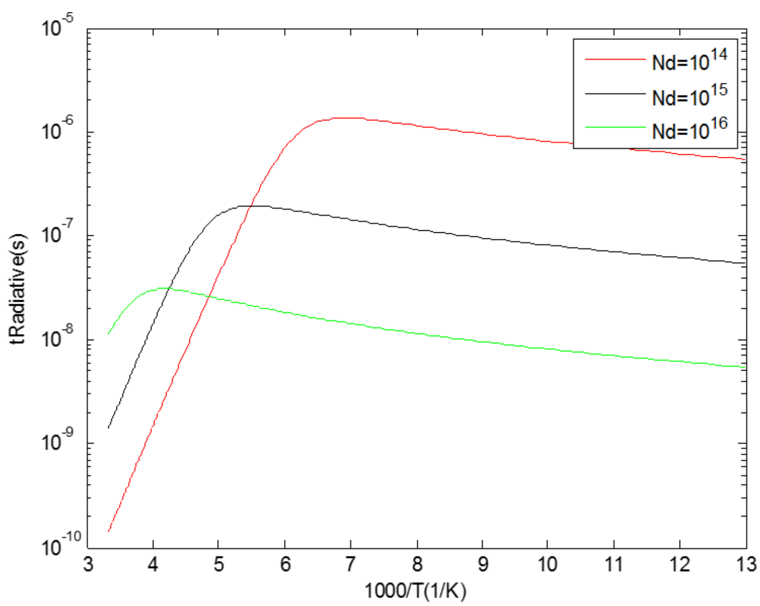

FIG. 7 Calculated radiative lifetime for InSb versus temperature for different doping concentration.

The lifetime of SRH recombination is:

$$n1 = Nc \times e^{-\frac{Etrap}{kT}}\ , \tag{10}$$

$$p1 = Nc \times e^{\frac{(Eg - Etrap)}{kT}}, \tag{11}$$

$$\tau SRH = \frac{\tau n0(p+p1)+\tau p0(n+n1)}{n+p}, \quad (12)$$

Where Etrap is the defect level below the conduction band, n1 and p1 are the electron concentration (cm-3) and the hole concentration (cm^{-3}) respectively when the Fermi level is coincident with the trap level, τn0 (s) is the electron characteristic SRH lifetime in p-type InSb, τp0 (s) is the hole characteristic SRH lifetime in n-type InSb. To simply the calculation τn0 = τp0 =1μs. The figure below is the plot result from formula (10),(11),(12).

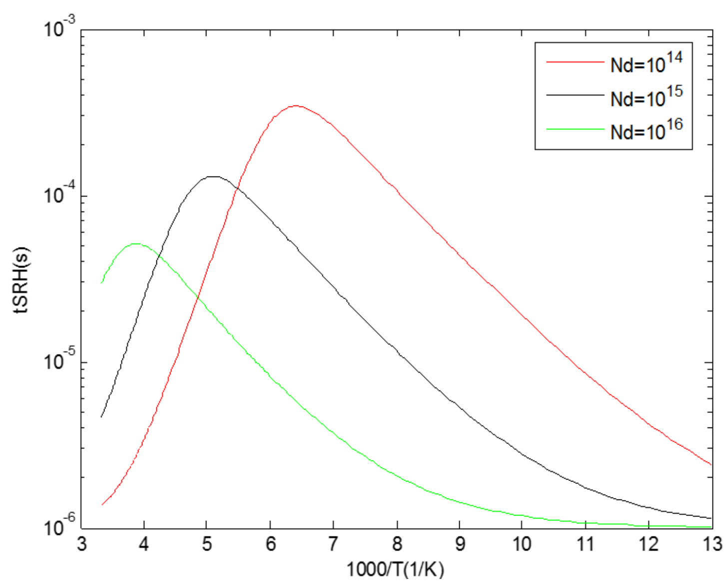

FIG. 8 Calculated radiative lifetime for InSb versus temperature for different doping concentration.

The figure below is the plot of all recombination lifetime at 10^{14} doping concentration level along with the total lifetime. It is obvious that the Auger1 lifetime dominates among all other recombination lifetime. Since the lower minority lifetime is, the more diffusion dark current will occur in the photodiode, the larger the noise is. In this case, suppressing Auger recombination and increasing Auger lifetime will largely improve the performance of the device under the high temperature operation.

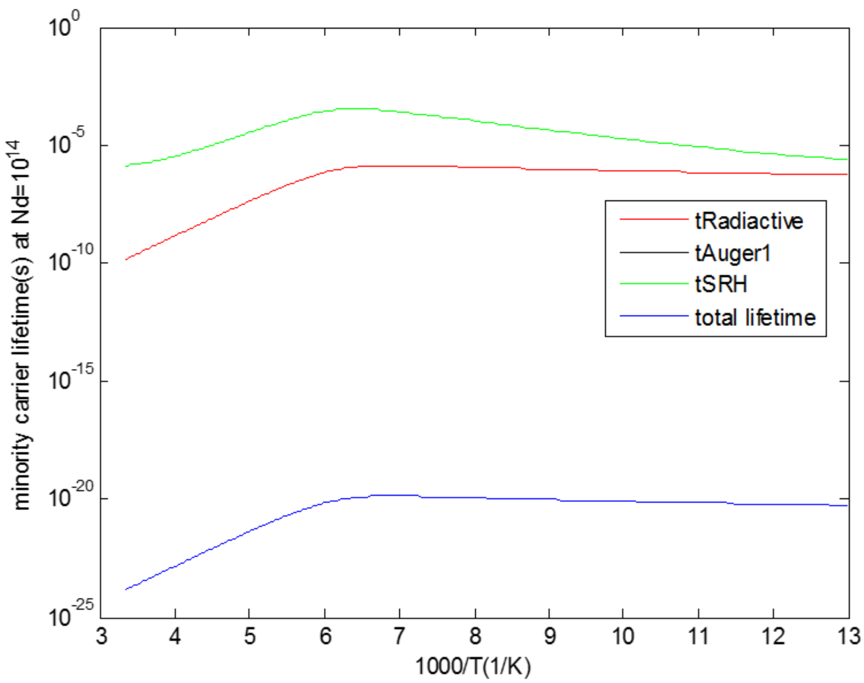

FIG. 9 Calculated lifetimes for InSb versus temperature at Nd = 10^{14}.

SILMULATION RESULTS

In Senturaus TCAD Simulation tool, we construct a 2D model for our PIN structure photodiode. The cross-section and doping concentration is shown as below. The red region is represented as N-type region and blue region is P-type. The middle region is lightly doped 10^{14} cm^{-3}, and at room temperature the middle region is nearly intrinsic. The length of heavily doped N and P region is 2μm and the length of intrinsic region is 8μm. The middle absorber layer is intentionally undoped. However, during the practical fabrication period, the unintentional doping will always exist.

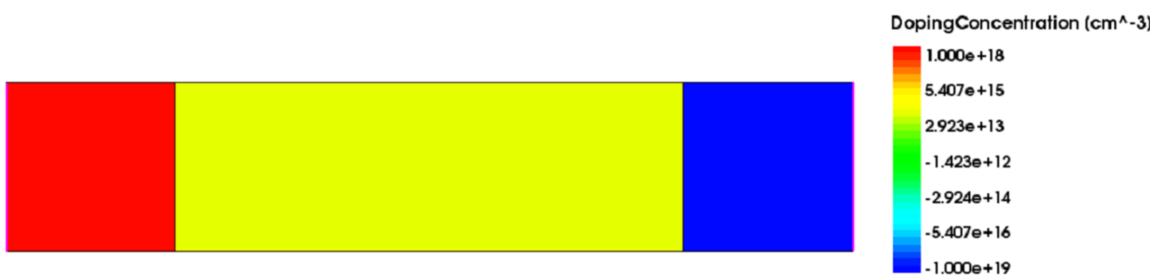

FIG.10 Device structure.

To suppress Auger recombination, we apply a reverse bias on the structure and observe the changing of the device. The FIG.11-13 reflect the carrier concentration change of the device at 300K. The left contact would be cathode connection and the right contact is anode.

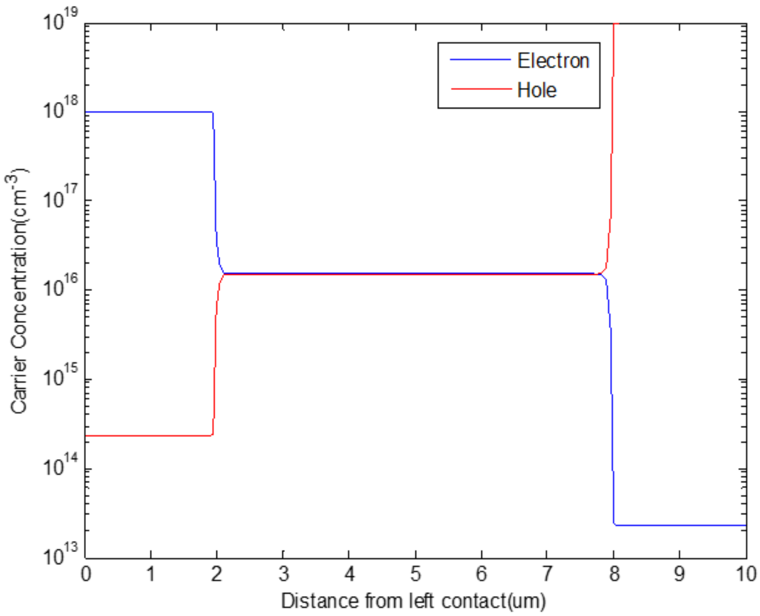

FIG. 11 Carrier concentration in the device at zero bias.

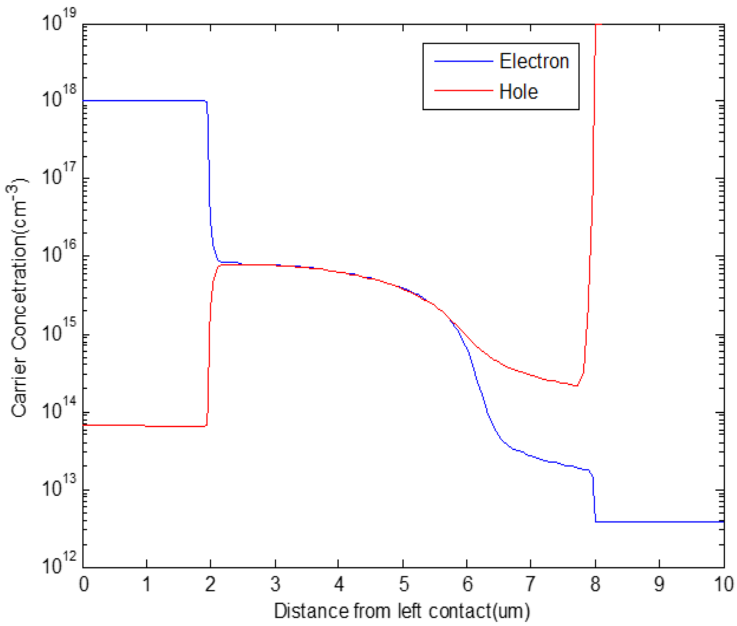

FIG. 12 Carrier concentration in the device at reverse bias voltage equal to 0.3V.

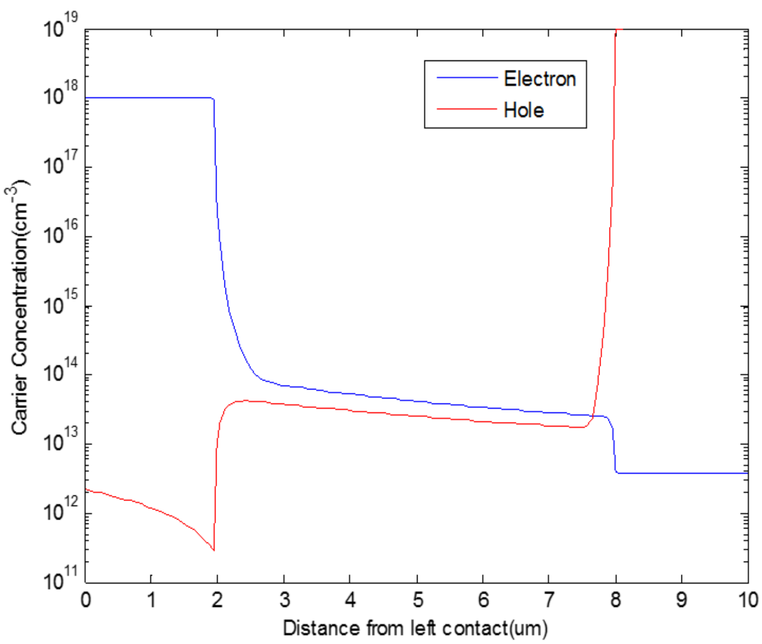

FIG. 13 Carrier concentration in the device at reverse bias voltage equal to 0.5V.

We can see that the carrier concentration in the intrinsic area decreased by the magnitude of two and in this case, and from FIG.14 we can see the Auger recombination drops from 10^{25} cm^{-3} to 10^{22} cm^{-3}.[12]

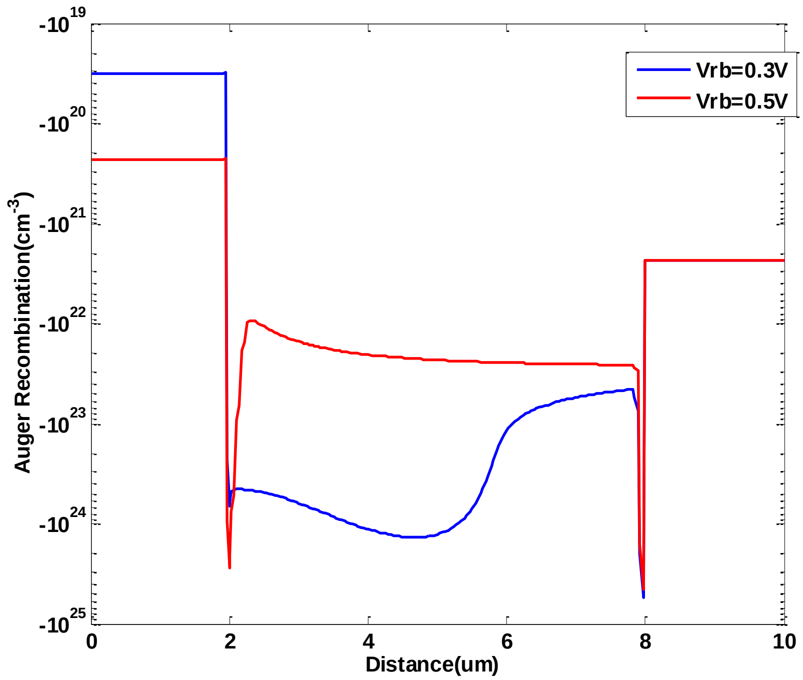

FIG. 14 Auger Recombination comparison in the device before and after application reverse bias voltage.

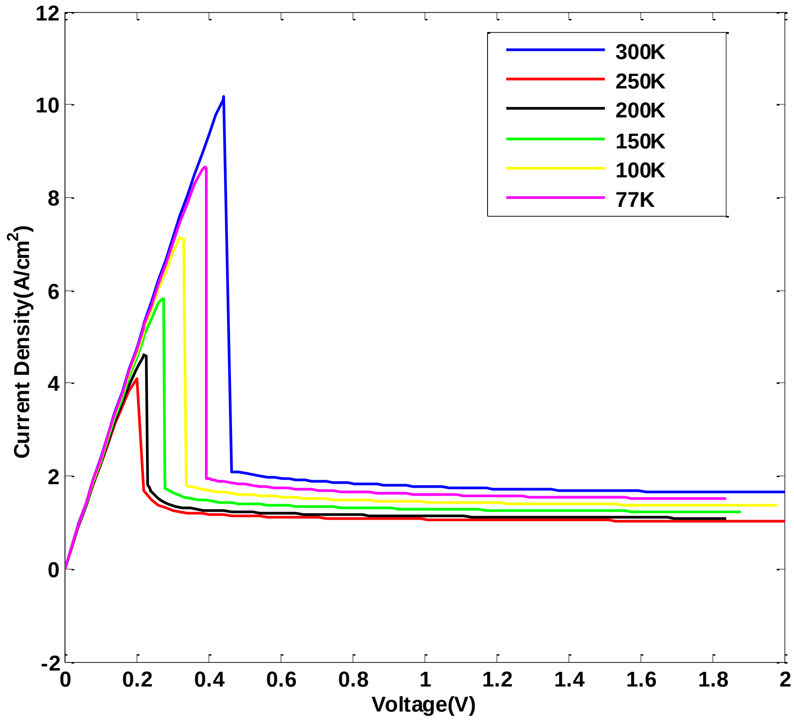

FIG. 15 I-V curve of the InSb PIN infrared photodiode under different operation temperatures.

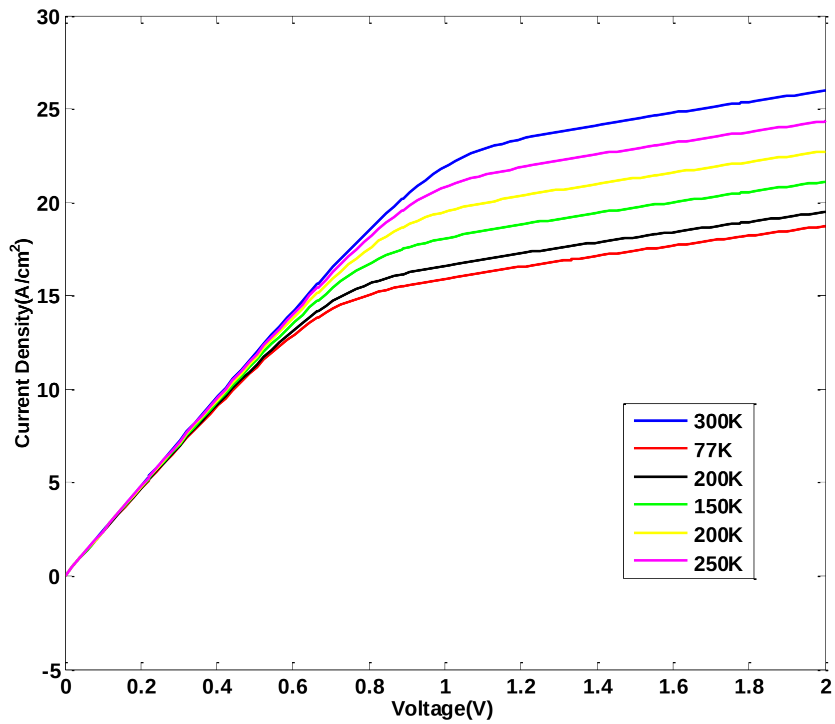

FIG. 16 I-V curve of the InSb PN infrared photodiode under different operation temperatures.

In the graph above we can see that when reverse bias voltage is small, the current keeps increasing. At this moment the device is acting very ohmic. And when the reverse bias voltage keeps increasing, we can see a big drop when it reaches on point. This is happened due to the device is under the non-equilibrium operation and the Auger process is largely suppressed. [11]The minority lifetime is increased greatly so that the diffusion current, which is the main component of the dark current decreases. We compared this result with the same size PN junction, where we could observe a great advantage of PIN over PN structure.

Also we would like to study the effect of different doping concentrations in the absorber layer. The FIG.17 shown below is the I-V curve of the device with different absorber doping. It is obvious that the more intrinsic it is, the more auger suppression we observe. When absorber is doped with very high concentration, it is acting like a pure PN junction, and could not observe that current drop caused by auger suppressing.

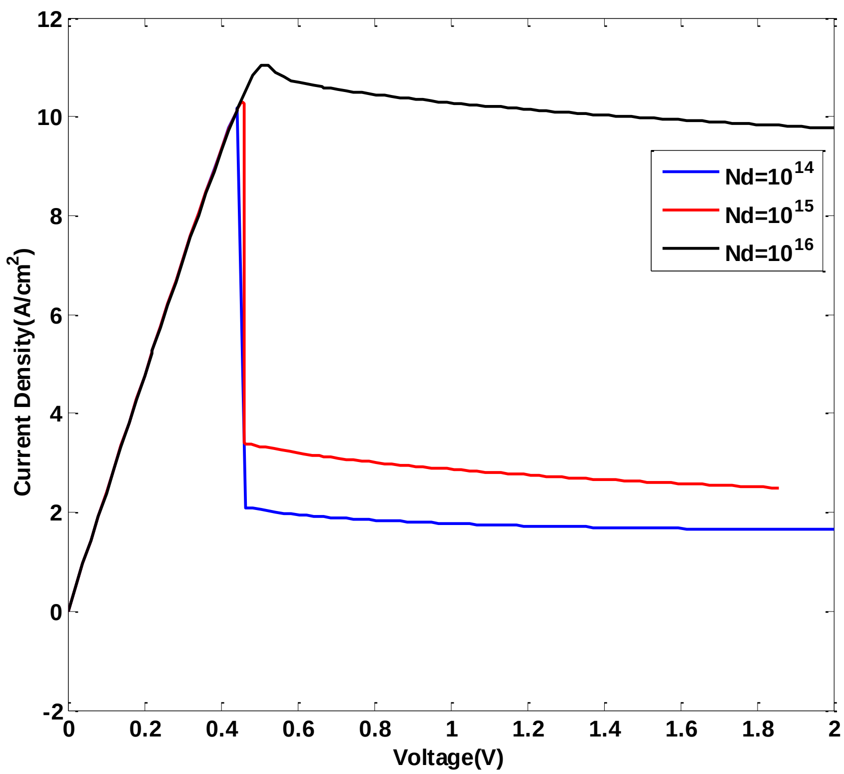

FIG. 17 I-V curve for different absorber concentration

The last simulations are testing out the I-V curve of our device with light and without light. From the result we can see, the reverse bias voltage largely decreased the dark current and even in the 300K operation the light current versus dark current ratio is still very high. Compared to the conventional PN junction device, the PIN structure has smaller dark current and smaller noise. At 300K operation, we can see a great advantage of PIN Auger suppressed photodiode over PN photodiode.

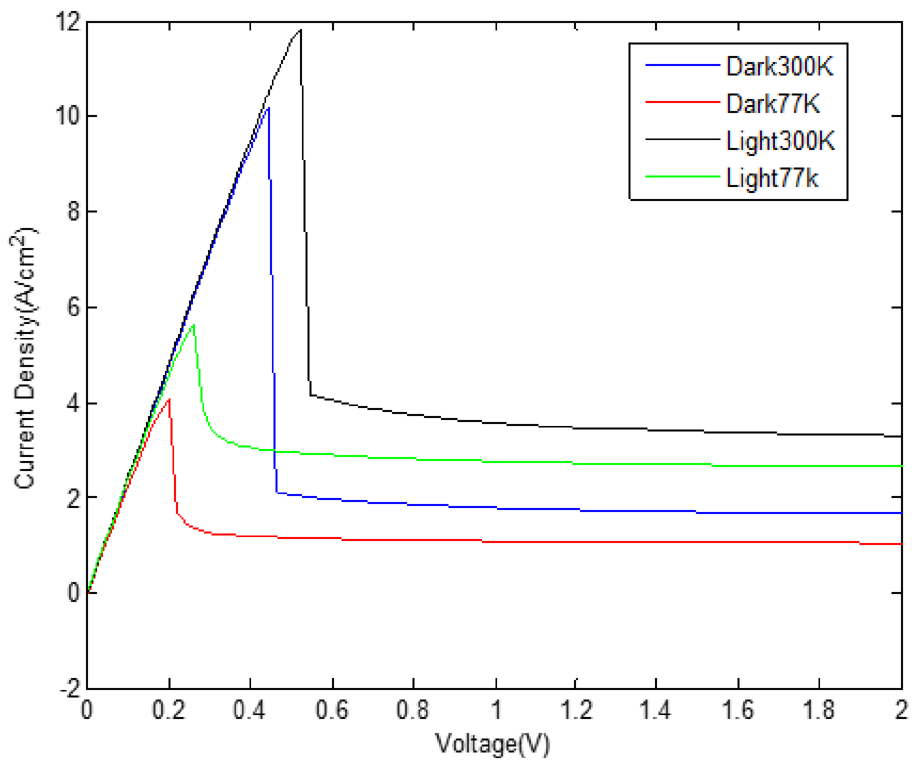

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FIG. 18 IV curve for PIN structure with and without light at 300k and 77k

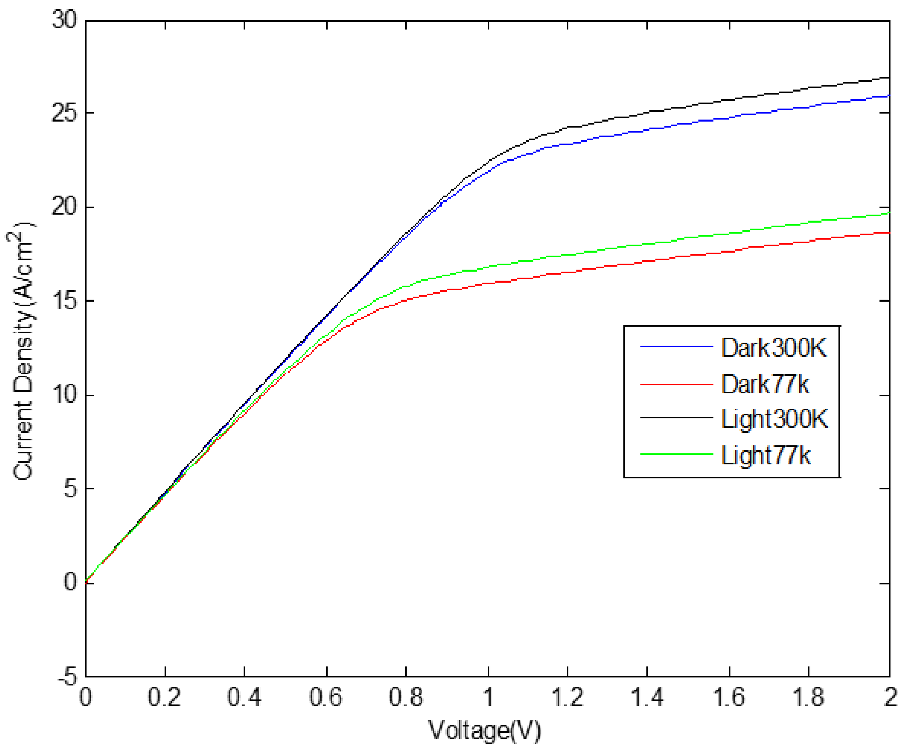

FIG. 19 IV curve for PN structure with and without light at 300k and 77k.

CONCLUSION

In my thesis a new PIN structure InSb infrared detector is studied to improve the operation temperature. Non-equilibrium operation was simulated in three-layer (P+/v/N+) photodiodes, also referred as Auger-suppressed or HOT photodiodes. Firstly the different recombination model for dark current is studied and calculated. Among all the recombination mode, Auger recombination dominates the dark current of the high temperature operation. Then we use TCAD simulation tools to study the carrier concentration distribution in the device under different reverse bias. We also study the doping concentration in the v layer (absorber) will leads to different IV curve. Too high doping made the device not able to have Auger suppression effect at any large reverse bias voltage, so it is important to keep the absorber layer lightly doped.

In the end we simulate the device under light and without light at different temperature, which gave us a very well worked device. Even under 300K temperature, the device can still keep the dark current as low as possible have a high light to dark current ratio.

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BIOGRAPHY

Yu Dong graduated from George Mason University, Fairfax, Virginia, in 2015, where she received her Bachelor of Science of Electrical Engineering. She studied and work with Dr. Qiliang Li's research group for 1 years at George Mason University under the supervision of his advisors in the field of Microelectronics.