MODELING & SIMULATION FOR PARTICLE RADIATION DAMAGE TO ELECTRONIC AND OPTO-ELECTRONIC DEVICES

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Final Report

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**Modeling & Simulation for Particle Radiation Damage to Electronic and Opto-Electronic Devices**

In this effort, we have undertaken fundamental studies on vertical transport in an antimonide-based semiconductor superlattice structure. For this purpose, we used theoretical expressions based on Hovel model to extract the minority carrier diffusion length of a unipolar nBp type-II superlattice (T2SL) mid-wave infrared detector. Combining these results with the lifetime via Time-Resolved Photoluminescence (TRPL) data, we were able to additionally determine the minority vertical mobility and diffusivity, providing a comprehensive picture of vertical transport characteristics of the excited carrier in the nBp T2SL detectors. Finally, we performed dark current modeling and investigated the dominant dark current mechanisms at different temperatures. Our next step is to investigate the origin, types, and effects of radiation damage on this structure.
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1.0 SUMMARY

We present a model for the spectral external quantum efficiency (EQE) to extract the minority carrier diffusion length ($L_n$) of a unipolar nBp InAs/GaSb Type-II superlattice (T2SL) mid-wave infrared (MWIR) detector. The detector consists of a 4 µm thick p-doped 10 monolayer (ML) InAs/10ML GaSb superlattice (SL) absorber with a 50% cut-off wavelength of 5 µm at 80 K and zero bias. The n-type doped InAs/AlSb SL barrier in the structure was included to reduce the generation-recombination dark current. By fitting the experimentally measured EQE data to the theoretically calculated quantum efficiency (QE) based on the solution of the drift-diffusion equation, the p-type absorber was found to have $L_n = 10 \pm 0.5$ µm at 80K, and $L_n = 12 \pm 0.5$ µm at 120K and 150K. We performed the absorption coefficient measurement at different temperatures of interest. Also, we estimated the reduced background concentration and the built-in potential by utilizing a capacitance-voltage measurement technique. We used time-resolved-photoluminescence (TRPL) to determine the lifetime at 80K. With the result of the model and the lifetime measurement, we calculated the diffusion coefficient and the mobility in the T2SL detector at various temperatures. Also, we studied the behavior of different dark current mechanisms by fitting the experimentally measured and simulated dark current density under different operating temperatures and biases.

2.0 INTRODUCTION

Semiconductor superlattices with type-II band alignment have been shown to be versatile materials for their applications in infrared (IR) optoelectronic devices. Type-II Superlattice (T2SL) based detectors were the focus of research in the last couple of decades with promising improvements demonstrated in their manufacturing, fabrication, and performance. However, the theoretically predicted advantages have not been achieved yet in these structures because of a high level of dark current. Different design structures using heterostructures and including a higher band-gap barrier have been proposed to reduce the dark current while leaving the photo-generated carriers unimpeded [1]. On the other hand, the effect of the physical phenomenon such as transport mechanisms and its relation to design and growth parameters in T2SLs are still unknown. Transport through the SL growth layers (i.e., vertical transport) has especially high importance in the design of IR detectors, since the carrier conduction via this path is the typical mode of operation and it affects the collection efficiency in the device.

Different groups have investigated transport in T2SLs using different theoretical and experimental techniques [2-7]. With the help of different semi-parametric modeling techniques, these methods can contribute to characterize the drift and diffusion parameters. Among these methods, the spectral QE measurement has proved useful in investigating the effect of different design parameters, such as absorber thickness [5] and background doping [7] on the performance of the T2SL IR detectors.

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In this technical report, we report the result of spectral QE modeling on an InAs/GaSb T2SL $nBp$ detector incorporating a hole-barrier (h-barrier). The analytical expressions derived for quantum efficiency of $pn$ junction photodetectors by Hovel [8] have been utilized to extract different transport parameters in the model. Capacitance-voltage characterization has been performed to obtain information about the built-in potential and reduced carrier concentration. Also, TRPL has been measured to estimate the lifetime in the material at 80 K. Moreover, we used the dark current modeling to evaluate the performance of the photodiode and determine different parameters, such as reduced effective mass, trap energy states, and concentration of the material.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Materials

In this work, we studied a MWIR T2SL heterostructure as illustrated in Figure 1. The structure was grown by solid source molecular beam epitaxy on a GaSb: Te (001) epi-ready substrate. The epi structure consists of a 250-nm non-intentionally doped GaSb buffer layer, followed by 1.5-$\mu$m thick $p$-doped ($5 \times 10^{17}$ cm$^{-3}$) bottom contact layer with a bandgap of 0.250 eV composed of 10 ML InAs/10 ML GaSb T2SL, a 4-$\mu$m thick $p$-doped ($5 \times 10^{16}$ cm$^{-3}$) absorber region composed of a 10 ML InAs /10 ML GaSb T2SL with a bandgap of 0.250 eV, a 250-nm thick lightly $n$-doped ($5 \times 10^{15}$ cm$^{-3}$) hole barrier (h-Barrier) with a bandgap of 0.650 eV composed of a 12 ML InAs/ 6 ML AlSb T2SL, and a 200-nm thick $n$-doped ($5 \times 10^{17}$ cm$^{-3}$) top contact layer with a bandgap of 0.360 eV composed of a 5 ML InAs/ 4 ML GaSb T2SL. The h-Barrier helps minimize the dark current generation, while at the same time allows photo-generated carriers to flow unimpeded to the contacts. We then processed the wafer into variable area single-pixel devices for further characterizations, the details of which have been discussed in Reference 9.

Contact Layer (200 nm $n^+$ InAs/GaSb)

h-Barrier (250 nm $n^-$ InAs/AlSb)

Absorber (4 $\mu$m $p^-$ InAs/GaSb T2SL)

Contact Layer (1.5 $\mu$m $p^+$ InAs/GaSb T2SL)

Buffer Layer (250 nm NID GaSb)

Substrate (GaSb)

Figure 1. (Left) Design Structure of the $nBp$ T2SL Photodetector. (Right) Calculated Equilibrium Band Alignment of the $nBp$ Structure

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3.2 Quantum Efficiency Modeling

We have used a simple analytical model based on the Hovel expressions [8] to simulate the quantum efficiency in an nBp photodiode under optical illumination. This model has been tested on T2SLs, previously [5],[7],[10]. It is based on some simplifying assumptions that when fulfilled, it can be used as the first principle approximation for estimating a device’s performance. These assumptions include: 1) Low-level injection: $n_{p0} \ll p_{p0}$ (p-type) or $n_{n0} \gg p_{n0}$ (n-type), 2) Uniform material: spatially invariant parameters, 3) Zero excess minority carriers at the depletion edges, 4) Uniform absorption coefficient ($\alpha$) in each region of the diode, 5) Negligible recombination in the depletion region, and 6) Negligible majority carrier current. Using these assumptions, the nonlinear drift-diffusion equation can be solved, and the analytical solution for quantum efficiency in n-, p-, and depletion regions can be obtained using a set of boundary conditions [8]. Figure 2 shows the cross-section of the photodiode that we used in this model. The n-region of the diode consists of the top-contact layer and the h-barrier with different absorption properties. The p-region consists of the absorber region and the bottom contact. $W$ is the thickness of depletion region, $x_j$ is the junction depth, $H$ is the total thickness of the diode, $x_n$ and $x_p$ are the depletion width in n- and p-regions, respectively.

![Figure 2. Schematic of the Device Cross-Section for the nBp Diode](image)

Assuming the light is incident on the n-side of the photodiode, the drift-diffusion equation for the minority electron of the p-type material can be written as

$$D_n \frac{\partial^2 (\delta n)}{\partial x^2} + \mu_n E \frac{\partial (\delta n)}{\partial x} + g - \frac{\delta n}{\tau_{n0}} = \frac{\partial (\delta n)}{\partial t}$$

where $D_n$ is the electron diffusion coefficient, $\mu_n$ is the electron mobility, $E$ is the applied electric field, $g$ is the generation rate, and $\tau_{n0}$ is the electron recombination lifetime. Upon optical illumination, electron-hole pairs (EHPs) are produced in the material. The EHPs then contribute to the current measured in the external circuit if they reach the depletion edges before they recombine, from where they will be swept out by the electric field.

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The generation rate associated with the optical excitation in the device is given by [8].
\[ g(\lambda) = \alpha(\lambda)\Phi(\lambda)[1 - R(\lambda)]e^{-\alpha(\lambda)x}, \]
where \( \alpha(\lambda) \) is the wavelength-dependent absorption coefficient of the material, \( \phi(\lambda) \) is the total number of incident photons per unit area per second per unit bandwidth, and the \( R(\lambda) \) is the power reflectivity.

Under steady state conditions, and considering zero-applied electric field, Equation (1) can be solved using two boundary conditions for each region: (a) A perfect collector condition at the junction edge \((p_n - p_{n0} = 0, \text{ for the } p\text{-region})\), and (b) The boundary between the material and vacuum, at which the surface recombination occurs, characterized by its recombination velocity \( S \) with the dimension of cm-s\(^{-1}\) \((D_p \frac{\delta(p_n-p_{n0})}{\delta x} = S_p(p_n - p_{n0}), \text{ for the } p\text{-region})\). The result will be the density of minority carriers \( N_\delta(x) \), in the \( p\)-side of the photodiode, which is used to calculate the diffusion photocurrent densities \( J_{ph} \). The same calculation can be done for the minority holes in the \( n\)-region. The total QE in the device can then be written as
\[ QE = \frac{1}{qQEE_{ph-n} + J_{ph-SCR} + J_{ph-p}} = QE_n + QE_{SCR} + QE_p. \]

The quantum efficiency components, \( QE_p, QE_n \) and \( QE_{SCR} \) (corresponding to the photocarrier generation in the \( p\)-, \( n\)-, and space-charge regions, respectively) can be defined as
\[ QE_p = (1 - R) \frac{\alpha_p L_n}{\alpha_p^2 L_n^2 - 1} e^{-\alpha_n x_j + \alpha_{nb} W_1 + \alpha_p W_2} \times \left[ \frac{\alpha_p L_n}{L_n^2 + \alpha_p^2 L_n^2 - 1} \right], \]
where \( \alpha_n, \alpha_{nb}, \text{ and } \alpha_p \) are the absorption coefficients of the \( n\)-type top-contact, the \( n\)-type h-barrier, and the \( p\)-type absorber, respectively. \( x_j \) is the thickness of the \( p\)-region, \( L_n \) is the electron diffusion length, and \( S_n/D_n \) is the electron surface recombination velocity to diffusion coefficient ratio.

\[ QE_n = (1 - R) \frac{\alpha_n L_p}{\alpha_n^2 L_p^2 - 1} \left[ \frac{\alpha_n L_p + L_p D_p}{L_p^2 D_p} e^{-\alpha_n x_j} \left( \frac{L_p}{L_p} \frac{S_p}{D_p} e^{-\alpha_n x_j} \left( \frac{x_j}{L_p} \right) + \sinh \left( \frac{x_j}{L_p} \right) \right) - \alpha_n L_p e^{-\alpha_n x_j} \right], \]
where \( x_j \) is the junction depth, \( L_p \) is the hole diffusion length, and \( S_p/D_p \) is the hole surface recombination velocity to diffusion coefficient ratio.

\[ QE_{SCR} = (1 - R) e^{-\alpha_n x_j} \left[ 1 - e^{-\alpha_{nb} W_1 + \alpha_p W_2} \right], \]
where \( W_1 \) and \( W_2 \) are the depletion widths in the \( n\)- and \( p\)-region, respectively.
The total quantum efficiency is dependent on the absorption coefficient ($\alpha$), the background doping concentration, the minority-carrier diffusion lengths ($L_n$ and $L_p$), and the surface velocity recombination to diffusion coefficient ratios ($S/D$ at the two interfaces). The latter can be assumed to be zero since it does not change the shape of the curve. However, it can affect the absolute magnitudes when the junction depth of the diode and the effective minority carrier diffusion length become comparable [7]. With this assumption, the results should be considered as a lower bound on $L_n$ [5]. Other methods, such as Electron Beam Induced Current (EBIC) can be used to extract $S$ and $L$ simultaneously and to verify the results of this model. So, by choosing $L$ as a fitting parameter, while providing the information about other parameters, one can fit the model to the experimentally measured quantum efficiency to extract $L$.

### 3.3 Dark Current Modeling

We also performed dark current modeling to characterize the photodiode further. For this purpose, we fit the experimentally measured dark current to analytically simulated dark current. Assuming a neutral center and a constant electric field across the depletion region, and a triangular barrier, the simulated dark current is expressed as the sum of the diffusion current ($I_{diff}$), generation-recombination current ($I_{gr}$), tunneling current (including the trap-assisted ($I_{TAT}$) and band-to-band components ($I_{BTB}$)) as [11-12].

\[
I_{diff} = A\sqrt{qk_BT} \frac{n^2_i}{N_A} \left[ \mu_e \tanh\left( \frac{x_p}{L_p} \right) \right] \exp\left( \frac{qV_i}{k_BT} \right) - 1
\]

\[
I_{gr} = \frac{2An_i\omega k_BT}{(V_{bi}-V_i)\tau_{gr}} \sinh\left( \frac{-qV_i}{2k_BT} \right) f(b)
\]

\[
I_{TAT} = \frac{Aq^2m_t^2N_iV_i}{8\pi\hbar^3(E_g-E_\ell)} \exp\left( -\frac{4\sqrt{m_t(E_g-E_\ell)^3}}{3qE_h} \right)
\]

\[
I_{BTB} = \frac{Aq^2E_n^2\sqrt{2m_{red}}}{4\pi^2\hbar^2\sqrt{E_g}} \exp\left( -\frac{4\sqrt{2m_{red}E_g^3}}{3qE_h} \right)
\]

where $A$ is the device area, $q$ is the electron charge, $k_B$ is the Boltzmann constant, $T$ is the temperature, $n_i$ is the intrinsic carrier concentration, $N_A$ and $N_D$ are the absorber’s and barrier’s doping concentrations, respectively, $\mu_e$ is the electron mobility, $\tau_e$ is the electron lifetime, $V_i$ is the bias voltage, $V_{bi}$ is the built-in potential, $W$ is the depletion width, $\tau_{gr}$ is the generation-combination lifetime, $\hbar$ is the Planck constant, $m_t$ is the effective tunneling mass, $N_t$ is the trap density, $E_\ell$ is the trap energy location, measured from the valence band edge, $M^2$ is a matrix element associated with the trap potential, assumed to be $10^{-23}$ eV-cm$^3$, $E_g$ is the absorber’s band gap, $E$ is the electric field, $m_{red}$ is the reduced effective mass and

\[
f(b) = \begin{cases} 
1 & b > 1 \\
\frac{1}{2\sqrt{b^2-1}} \ln(2b^2 + 2b\sqrt{b^2 - 1} - 1) & b = 1 \\
\frac{1}{\sqrt{1-b^2}} \arctan\left( \frac{\sqrt{1-b^2}}{b} \right) & b < 1
\end{cases}
\]

where, $b = e^{\frac{qV_i}{k_BT}}$. 

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The total voltage \( (V_{app}) \) applied to the structure can be expressed as the sum of the voltage drops on an ohmic series resistance and the effective applied bias on the depletion region

\[
V_{app} = V_I + R_s I,
\]  

for which we extracted \( R_s \) from the forward bias voltage region of the differential resistance-voltage characteristic to be 0.5 Ohms for all temperatures of interest. We estimated \( V_{bi} \) to be 0.16 V from capacitance-voltage (C-V) measurement. Also, we defined the depletion widths in the barrier and absorber, and the electric field at the barrier–absorber heterojunction as [12-13].

\[
W_n^2 = \frac{2\varepsilon_n\varepsilon_p N_A (V_{bi}-V_I)}{qN_A(\varepsilon_n N_D + \varepsilon_p N_A)}, \tag{13}
\]

\[
W_p^2 = \frac{2\varepsilon_n\varepsilon_p N_D (V_{bi}-V_I)}{qN_D(\varepsilon_n N_D + \varepsilon_p N_A)}, \tag{14}
\]

\[
E = \frac{\varepsilon_n + \varepsilon_p}{2} \sqrt{\frac{2q(V_{bi}-V_I) N_A N_D}{\varepsilon_n \varepsilon_p (\varepsilon_p N_A + \varepsilon_n N_D)}}, \tag{15}
\]

### 4.0 RESULTS AND DISCUSSION

#### 4.1 Quantum Efficiency Measurement and Modeling

The knowledge of the wavelength dependence of the absorption coefficient \( (\lambda(\alpha)) \) is required to extract diffusion length from the spectral quantum efficiency model. In this work, we determined the absorption coefficient through IR transmission measurements using a Fourier transform infrared (FTIR) spectrometer. The T2SL epi-layers were etched off to different thicknesses on three separate pieces, in which the top contact, the h-barrier, and the absorber were removed, respectively, to measure the transmission spectra of each layer separately. The samples were mounted side-by-side in the cryostat with ZnS windows and transmission spectra at 80 K, 120 K, and 150 K were measured using reflective optics. The same sized apertures on each sample were used in the measurement to ensure the identical radiant flux for each sample. The result of the transmission at each layer was compared directly to the transmission of its underlying layers. The absorption coefficients for the top-contact, the h-barrier, and the absorber were then calculated using the model [11],[14] and the effect of the reflection in normal incidence configuration was considered in the calculation.

Figure 3 shows the result of the measured absorption coefficient of the absorber layer with the thickness of 4 \( \mu \text{m} \) at 80 K, 120 K, and 150 K, which increases slightly with temperature.
For quantum efficiency measurements, we used a standard setup consisting of a calibrated blackbody, narrow band filters (centered at 3.4 and 4.5 µm), a current pre-amplifier, and a lock-in amplifier. Measurements were performed using front-side illumination geometry with no anti-reflection coating. The results for quantum efficiency at 3.4 and 4.5 µm were used to calibrate the spectral photoresponse, which was obtained using an FTIR spectrometer and was normalized to a reference detector’s response.

Figure 4 shows the results of the quantum efficiency under zero and 200 mV applied bias at 80 K, 120 K, and 150 K. The insets show the trend of the QE at \( \lambda = 4.5 \) µm with temperature. The device used for this measurement was 500 µm in size. The CO\(_2\) absorption at 0.295 eV is visible in the experimental data. The dependence of quantum efficiency with applied bias was also measured at the same temperatures. It revealed that the turn-on bias increases with temperature, most probably due to the presence of a barrier at the heterojunction interface, which changes with the temperature. As a result, the quantum efficiency at 0 V decreases with temperature. However, it stays nearly constant at 200 mV bias. For this reason, the data for 200 mV applied bias was chosen for use in the model. The inclusion of bias affects the simulated quantum efficiency only through changing the depletion region width.
The fitting of the simulated and measured spectral quantum efficiency at various temperatures was done using the diffusion length as the fitting parameter. For this purpose, we used the spectral area primarily around the band edge as the main focus of the fitting, where the absorber (p-region) has the most profound effect. It should be noted that we neglected the contribution of the $QEn$ and $QESCR$ in the simulation since they are mostly effective at the higher energy regions of the quantum efficiency spectra.

Figure 5 shows the comparison of the measured and simulated spectral quantum efficiency at three different temperatures under applied bias of 200 mV. The simulated quantum efficiency is in good agreement with the experimental results in the region near the band edge. The difference at higher energy indicates that the carriers excited by the incoming radiation have some loss due to absorption in the top contact region. Also, other factors might be responsible such as the error in the absorption measurement used in the model.
Figure 5. Comparison Between Experimental (Solid Lines) and Calculated (Dashed lines) QE Spectra for the nBp Photodetector at V = 0.2 V for T = 80 K, 120 K, and 150 K

We estimated the diffusion lengths that correspond to the best fits between experimental and calculated quantum efficiency. Moreover, we calculated the diffusion coefficient using the diffusion length and lifetime at each temperature. Having the diffusion coefficients, we also calculated the mobility at each temperature using the Einstein relation \( \mu = \frac{Dnq}{k_BT} \). We used the lifetime from TRPL measurements for the calculation at 80 K, while the lifetime at other temperatures was inferred from the dark current modeling as will be discussed later. Table 1 summarizes the results of different parameters for several operating temperatures at \( V_{\text{applied}} = 0.2 \text{V} \).

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>Diffusion Length [μm]</th>
<th>Diffusion Coefficient [cm²s⁻¹]</th>
<th>Mobility [cm²V⁻¹s⁻¹]</th>
<th>Lifetime [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>10</td>
<td>33.33</td>
<td>4826.08</td>
<td>30</td>
</tr>
<tr>
<td>120</td>
<td>12</td>
<td>53.33</td>
<td>5149.75</td>
<td>27</td>
</tr>
<tr>
<td>150</td>
<td>12</td>
<td>60.00</td>
<td>4637.68</td>
<td>24</td>
</tr>
</tbody>
</table>

Depletion Width (W): 0.3 μm  
Junction Depth (xj): 0.28 μm  
SL Thickness (H): 5.95 μm
4.2 Dark Current Modeling

For this part, we used \( m_{\text{red}}, m_t, E_t, N_t, n_i, N_A, \) and \( N_D \) as the fitting parameters in equations (7-10). We used the TRPL result for \( \tau_e \) and \( \tau_{gr} \), which were taken to be similar (\( \tau \)), at 80 K. We then used \( \tau \) as a fitting parameter at higher temperatures. Table 2 summarizes the results for 80 K, 120 K, and 150 K. It is evident that the trap state’s energy increases with temperature. Moreover, \( \tau \) decreases gradually with temperature. All the other parameters except for \( n_i \) were fit using 80 K data and were kept the same for other temperatures.

Table 2. Summary of Different Fitting Parameters from Dark Current Modeling

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>80</th>
<th>120</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\text{red}} / m_0 )</td>
<td>0.011</td>
<td>0.011</td>
<td>0.011</td>
</tr>
<tr>
<td>( N_t [\text{cm}^{-3}] )</td>
<td>( 1 \times 10^{11} )</td>
<td>( 1 \times 10^{11} )</td>
<td>( 1 \times 10^{11} )</td>
</tr>
<tr>
<td>( E_t / E_{\text{absorber}} )</td>
<td>0.800</td>
<td>0.845</td>
<td>0.865</td>
</tr>
<tr>
<td>( m_t / m_0 )</td>
<td>0.055</td>
<td>0.055</td>
<td>0.055</td>
</tr>
<tr>
<td>( \tau [\text{ns}] )</td>
<td>30</td>
<td>27</td>
<td>24</td>
</tr>
<tr>
<td>( n_i [\text{cm}^{-3}] )</td>
<td>( 2 \times 10^{12} )</td>
<td>( 7 \times 10^{12} )</td>
<td>( 5.5 \times 10^{13} )</td>
</tr>
<tr>
<td>( N_A [\text{cm}^{-3}] )</td>
<td>( 3.9 \times 10^{16} )</td>
<td>( 3.9 \times 10^{16} )</td>
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<td>( N_D [\text{cm}^{-3}] )</td>
<td>( 7.2 \times 10^{15} )</td>
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Figure 6 shows the variation of measured and simulated dark current densities with applied bias at different temperatures. Also, Figure 7 demonstrates various dark current mechanisms versus bias at 80 K, 120 K, and 150 K. The device used for the dark current modeling was 200 \( \mu \text{m} \) in size. Under all operating temperatures, we found \( I_{\text{TAT}} \) and \( I_{\text{BTB}} \) to be dominant at higher biases, while \( I_{\text{BTB}} \) was leading at 80 K and this fact was used to determine the reduced effective mass in the material. On the other hand, \( I_{\text{diff}} \) and \( I_{\text{gr}} \) contributions were more significant in the lower bias regime with \( I_{\text{diff}} \) leading at 150 K.
Figure 6. Measured (Circle) and Simulated (Solid Line) Dark Current Density at 80K, 120K, and 150K

Figure 7. Different Dark Current Mechanisms, the Total Simulated, and Experimentally Measured Dark Current Density for T=80K, 120K, and 150K

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5.0 CONCLUSIONS

In summary, we report the result of a set of analytical models to evaluate the performance of T2SL detectors based on the InAs/GaSb T2SL $nBp$ photodiode, including spectral quantum efficiency and dark current modeling. The quantum efficiency model, based on the Hovel expressions was presented. We measured the absorption coefficient at different temperatures and used its result to fit the model to the experimental quantum efficiency data and to extract the diffusion length of the minority electrons in the absorber layer under applied bias of 200 mV. We found the diffusion lengths to be longer than the absorber thickness at all temperature of interest. We used TRPL measurements to estimate the lifetime at 80 K and calculated the diffusion coefficient and mobility at different temperatures. Moreover, we performed dark current modeling to investigate the dominant dark current mechanism at different bias regimes and temperatures. Various parameters such as the reduced effective mass, trap energy state, trap concentration, and the lifetime at all the operating temperatures was determined.
REFERENCES

### LIST OF ACRONYMS

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<td>Time-Resolved Photoluminescence</td>
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