Temperature-dependent optical measurements of the dominant recombination mechanisms in InAs/InAsSb type-2 superlattices


Department of Physics and Astronomy and Optical Science and Technology Center, University of Iowa, Iowa City, Iowa 52242, USA
Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

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Temperature-dependent measurements of carrier recombination rates using a time-resolved optical pump-probe technique are reported for mid-wave infrared InAs/InAs1−xSbx type-2 superlattices (T2SLs). By engineering the layer widths and alloy compositions, a 16 K band-gap of ~235 ± 10 meV was achieved for five unintentionally and four intentionally doped T2SLs. Carrier lifetimes were determined by fitting lifetime models based on Shockley-Read-Hall (SRH), radiative, and Auger recombination processes to the temperature and excess carrier density dependent data. The minority carrier (MC), radiative, and Auger lifetimes were observed to generally increase with increasing antimony content and decreasing layer thickness for the unintentionally doped T2SLs. The MC lifetime is limited by SRH processes at temperatures below 200 K in the unintentionally doped T2SLs. The extracted SRH defect energy levels were found to be near mid-bandgap. Also, it is observed that the MC lifetime is limited by Auger recombination in the intentionally doped T2SLs with doping levels greater than n ∼ 10^{16} cm^{−3}. © 2015 AIP Publishing LLC.

I. INTRODUCTION

The minority carrier (MC) lifetime is an important parameter to assess the infrared photodetector performance in the narrow-bandgap absorber region. The photodetector dark current is inversely proportional to the MC lifetime for a diffusion limited photodetector, indicating that long carrier lifetimes are essential for low light-level detection. In previous studies, based on a variety of techniques, the MC lifetime has consistently been measured to be 75–100 ns for mid-wavelength IR (MWIR) and 15–30 ns for long-wavelength IR (LWIR) InAs/Ga(In)Sb type-2 superlattices (T2SLs). Ga-related Shockley-Read-Hall (SRH) recombination centers are suggested to be the cause of these short lifetimes. The recent observations of much longer MC lifetimes in Ga-free InAs/InAsSb T2SLs provide strong support for this suggestion. MC lifetimes of >6 µs in MWIR and >412 ns in LWIR T2SLs have been reported for this Ga-free T2SL material system. Furthermore, studies of InAs/InAsSb T2SLs using high resolution X-ray diffraction (HRXRD) and cross-sectional electron microscopy show excellent crystallinity, particularly for samples grown close to the strain-balanced condition at lower temperatures and those with higher Sb/As flux ratios. Due to a high sensitivity of carrier lifetime on electrically active defects, lifetime measurements can be used to characterize the material quality. Additionally, temperature dependent carrier lifetime measurements are a candidate for addressing the energy levels of the defect-related mid-gap SRH recombination centers. It has been recently shown that Ga-free T2SLs still have MC lifetimes that are SRH limited for low doping levels, which suggests that a temperature dependent study may lead to a fuller understanding of these materials. This in turn may lead to longer carrier lifetimes and better device performance.

Here, we present optical pump-probe measurements of the temperature- and density-dependent carrier lifetime in a set of InAs/InAsSb T2SLs. The nine samples in this set provide variation in the superlattice (SL) layer thickness, alloy composition, doping concentration, and dopant type, while maintaining a nearly constant bandgap energy of ~238 meV (5.2 µm wavelength). The measured carrier lifetime was fit using standard temperature-dependent models of Shockley-Read-Hall, radiative, and Auger recombination. The data indicate that the MC lifetime modestly increases with increasing Sb concentration and narrower SL periods. Radiative recombination is observed to be insignificant compared to SRH at temperatures below 200 K, while Auger recombination limits the MC lifetime at temperatures above 200 K.

II. InAs/InAsSb T2SLs AND EXPERIMENTAL METHODS

Samples were grown by molecular beam epitaxy using previously described techniques. For all samples, the epi-layers consist of a GaSb buffer layer, a 100 nm AlAsSb barrier layer, an unintentionally or intentionally doped and nominally 4-µm-thick T2SL absorber layer, a 100 nm AlAsSb barrier layer, and a 150 nm InAsSb cap layer. For the intentionally doped T2SLs, silicon and tellurium were used. The samples were first characterized through photoluminescence (PL) spectra at 16 K and results are shown in Fig. 1. At these temperatures, thermal effects are assumed to be minimal. Therefore, the effective T2SL bandgap energies can be obtained by fitting the PL spectra to extract the energy.
at which the PL reaches a maximum. HRXRD measurements were also taken in order to assess the quality of the T2SL layers, as well as determine the layer structures. These results are listed in Table I. Both the HRXRD and the PL measurements confirm the designed layer structure and bandgaps of ~5.2 μm wavelength for all nine samples. In addition, capacitance-voltage (C-V) measurements of these samples were used to determine the equilibrium carrier density (in this case, the majority carrier electrons) of the T2SLs and the results are listed in Table I. The C-V measurements were conducted and analyzed in a similar manner to those described previously.\(^{17,23}\)

A 14-band \(k\) \(p\) model\(^ {18}\) was used to calculate the absorption coefficient, band structure, and T2SL valence and conduction band edges at each temperature investigated. This model is optimized for the bowing of the InAsSb valance band (VB) by using the measured bandgap values and an InAsSb bandgap bowing parameter \(C_{\text{Egap}} = 0.67\).\(^ {11,19}\) The measured bandgap values obtained from the low-temperature PL measurements and the HRXRD data were introduced into the model for each sample in order to determine the correct InAsSb valence band energy required to match the T2SL bandgap energies. Once the theoretical bandgaps are matched to measurements, the model was extended to the higher temperature range reported for the measured carrier lifetimes. The calculated parameters for the T2SLs are listed in Table I for 77 K.

A time-resolved pump-probe technique, utilizing a subpicosecond MWIR pump, an electronically delayed \(\sim 3\) ns quantum cascade laser (QCL) probe, and differential transmission \((\Delta T/T)\) measurements, was used to investigate the non-equilibrium carrier dynamics of the T2SLs in the temperature range of 77 K to 293 K. Using difference frequency generation (DFG), 150 fs pulses at a wavelength of 3.55 μm (350 meV) were produced in an amplified Ti:sapphire pumped optical parametric amplifier (OPA) at a repetition rate of 1 kHz. This is used as a pump pulse to excite excess charge carriers in the sample under study. A low-power pulse from a QCL at wavelength of 9.3 μm \((\sim 133\) meV) was electronically synchronized to the pump using a precision, low-jitter delay generator. Notice that, for all the samples in this study, the probe photon energy is smaller than the bandgap of the devices, and therefore no change in excess carrier density due to the probe pulse is expected. For the measurements reported here, the pump and probe beams had radii \((e^{-1}\) of the intensity) of \(~1080\) μm and \(~182\) μm, respectively. The pump intensity was varied using a pair of Teflon polarizers, allowing for the pump fluence to be tuned from 2000 nJ/cm\(^2\) to 20 nJ/cm\(^2\), which is significantly larger than the probe fluence. The transient carrier population produces a change in sample transmission, which is monitored by electronically varying the time delay between pump and probe pulses. A low-vibration, closed-cycle, He-cooled cryostat was used to house the samples where the pump and probe beams were

TABLE I. Summary of the T2SL physical properties. The layer thicknesses and InAsSb compositions were determined from high-resolution x-ray diffraction. The T2SL bandgap energies \((E_g)\) were determined from 16 K PL measurements. The T2SL conduction \((E_c)\) and valence \((E_v)\) band edge energies, and absorption coefficient at the pump wavelength are obtained from a 14-band \(k\) \(p\) model and results are listed for 77 K. The band edge energies are listed relative to the valence band edge of InAs strained to GaSb. Notice that the intentionally doped samples are essentially structurally identical to the undoped sample C.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>(\text{InAs/InAs}_{1-x}\text{Sb}) Thicknesses (Å)</th>
<th>X (%)</th>
<th>Growth (n_0) (cm(^{-3}))</th>
<th>Measured (n_0) (cm(^{-3}))</th>
<th>(E_g) (meV)</th>
<th>(E_v) (meV)</th>
<th>(E_c) (meV)</th>
<th>(x) (cm(^{-1}))</th>
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<tr>
<td>A</td>
<td>49.1/29.1</td>
<td>26.1</td>
<td>Undoped</td>
<td>(1.5 \times 10^{15})</td>
<td>225.3</td>
<td>174.0</td>
<td>399.3</td>
<td>3300</td>
</tr>
<tr>
<td>B</td>
<td>43.1/20.0</td>
<td>30.5</td>
<td>Undoped</td>
<td>(1.0 \times 10^{15})</td>
<td>233.9</td>
<td>164.1</td>
<td>398.0</td>
<td>3606</td>
</tr>
<tr>
<td>C</td>
<td>41.9/15.5</td>
<td>33.5</td>
<td>Undoped</td>
<td>(1.0 \times 10^{15})</td>
<td>245.4</td>
<td>150.0</td>
<td>394.4</td>
<td>3603</td>
</tr>
<tr>
<td>D</td>
<td>40.7/12.9</td>
<td>40.0</td>
<td>Undoped</td>
<td>(9.3 \times 10^{14})</td>
<td>241.5</td>
<td>156.0</td>
<td>397.5</td>
<td>3730</td>
</tr>
<tr>
<td>E</td>
<td>40.7/10.0</td>
<td>49.0</td>
<td>Undoped</td>
<td>(9.3 \times 10^{14})</td>
<td>244.3</td>
<td>154.7</td>
<td>399.0</td>
<td>3707</td>
</tr>
<tr>
<td>F</td>
<td>41.9/15.5</td>
<td>34.4</td>
<td>(\text{Si}:1 \times 10^{15})</td>
<td>(1.9 \times 10^{15})</td>
<td>242.0</td>
<td>152.4</td>
<td>394.4</td>
<td>3603</td>
</tr>
<tr>
<td>G</td>
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<td>(\text{Si}:1 \times 10^{16})</td>
<td>(2.0 \times 10^{16})</td>
<td>246.0</td>
<td>148.4</td>
<td>394.4</td>
<td>3603</td>
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<tr>
<td>H</td>
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<td>34.2</td>
<td>(\text{Te}:1 \times 10^{15})</td>
<td>(4.1 \times 10^{15})</td>
<td>245.0</td>
<td>149.4</td>
<td>394.4</td>
<td>3603</td>
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<tr>
<td>I</td>
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<td>(\text{Te}:1 \times 10^{16})</td>
<td>(1.5 \times 10^{16})</td>
<td>248.6</td>
<td>145.8</td>
<td>394.4</td>
<td>3603</td>
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spatially overlapped. The initial optically injected excess carrier densities were calculated using the measured incident power, the measured spot sizes at the sample, and the absorption coefficient obtained from the 14-band $k\cdot p$ model taking into account losses due to optical windows and Fresnel reflections. Time-resolved $\Delta T/\Delta t$ decay curves for sample E and sample H for several injected excess carrier densities and temperatures are presented in Fig. 2. The data shown are representative of the other samples.

III. EXPERIMENTAL RESULTS AND LIFETIME THEORY

Using the data presented in Fig. 2, the recombination rate or inverse of the carrier lifetime, $R(\Delta n)$, as a function of excess carrier density is calculated as

$$R(\Delta n) = -\frac{1}{\Delta n} \frac{\partial \Delta n}{\partial t} = -\frac{1}{\Delta n} \frac{\partial \Delta n}{\partial (\Delta T/T)} \frac{\partial (\Delta T/T)}{\partial t},$$

(1)

where $\Delta n$ is the excess carrier density. These transformed data are shown in Fig. 3.

The carrier lifetime is a function of three main recombination mechanisms: SRH, radiative, and Auger recombination and can be expressed as

$$\tau^{-1} = \tau_{SRH}^{-1} + \tau_{Rad}^{-1} + \tau_{Auger}^{-1}.$$

(2)

The lifetime of SRH recombination for a single defect level is expressed as $^{20-22}$

$$\tau_{SRH}^{-1} = \frac{n_0 + p_0 + \Delta n}{\tau_{n}(n_0 + n_1 + \Delta n) + \tau_{p}(p_0 + p_1 + \Delta n)},$$

(3)

where $\tau_{n}$ and $\tau_{p}$ are the capture time constants and $n_0$ and $p_0$ are the equilibrium densities of electrons and holes, respectively. The excess carrier densities of electrons and holes are considered equal ($\Delta n = \Delta p$). The so-called SRH carrier densities are given by

$$n_1 = N_e \exp \left[ \frac{(E_t - E_c)}{k_B T} \right], \quad p_1 = N_e \exp \left[ \frac{(E_t - E_c)}{k_B T} \right],$$

(4)

where $k_B$ is Boltzmann’s constant, $T$ is the temperature, $E_t$ is the defect energy, and $E_c$ and $E_v$ are the T2SL conduction and valence band energies, respectively. Here, $N_e$ is the density of the defect state. For $n$-type material $n_0 > p_0$ and assuming a single defect level near the middle of the bandgap ($E_t = E_g/2$), Eq. (3) becomes $^{23}$

$$\tau_{SRH}^{-1} = \frac{n_0 + \Delta n}{\tau_{n}(n_0 + \Delta n) + \tau_{n}(\Delta n)},$$

(5)

which describes the density dependence of SRH recombination. Note that the density independent character of SRH

![FIG. 2. Time-resolved differential transmission decay curves illustrating carrier recombination for two of the MWIR InAs/InAsSb T2SL samples. Data are shown for both an unintentionally (sample E) and an intentionally (sample H) doped T2SL for multiple initial optically generated carrier densities and sample temperatures. Note the time scales are different at different temperatures.](image)
recombination can be obtained by assuming \( \tau_{p0} \gg \tau_{a0} \) or \( \Delta n \ll n_0 \). The SRH process is therefore limited by the hole recombination lifetime, \( \tau_{p0} \), in the minority carrier recombination regime for n-type material.

The lifetime associated with radiative recombination in a thick slab of absorbing material is\(^{20,21}\)

\[ \tau_{RAD}^{-1} = B \frac{(np - n_0^2)}{\Delta n}, \]

where \( B \) is the radiative coefficient. For a n-type material

\[ \tau_{RAD}^{-1} = B (n_0 + \Delta n). \]

The intrinsic radiative coefficient, \( B_r \), for a thin slab of material, is related to the measured radiative coefficient, \( B \), inversely as

\[ B = B_r / \phi, \]

where \( \phi \) is the photon recycling (PR) factor.\(^{12}\) PR enhances the radiative lifetime through the re-absorption of emitted photons and increases with absorption coefficient and thickness of the absorbing material. For example, if the sample thickness decreases to a single cell of the periodic absorbing layer, the PR factor trends to unity.

The lifetime associated with Auger recombination can be expressed as\(^{20}\)

\[ \tau_{Auger}^{-1} = \frac{C_n (np - n_0 p_0)n + C_p (np - n_0 p_0)p}{\Delta n} = C_n (n_0 + p_0 + \Delta n)n + C_p (n_0 + p_0 + \Delta n)p, \]

where \( C_n \) and \( C_p \) are the Auger coefficients associated with the Auger-1 and Auger-7 processes,\(^{20}\) respectively. For high level carrier injection (\( n_0, p_0 \ll \Delta n \)), the Auger lifetime becomes

\[ \tau_{Auger}^{-1} = (C_n + C_p)\Delta n^2, \]

which typically will limit the total carrier lifetime at high injection levels due to the inverse quadratic relation with excess carrier density. In the case of n-type material and low level injection, Eq. (12) has the limiting form\(^{24}\)

\[ \tau_{Auger}^{-1} \approx C_n n_0^2. \]

Overall, the Auger lifetime for n-type material can be written as

\[ \tau_{Auger}^{-1} = C_n (n_0 + \Delta n)^2. \]

Notice that the hole related Auger-7 recombination is neglected, and the total Auger recombination is assumed to be entirely due to the Auger-1 process.\(^{23}\) The Auger-1 coefficient, \( C_n \), for n-type material is defined as\(^{20,22}\)

\[ C_n = \frac{8(2\pi)^{5/2}q^4(m_e/m_0)|F_1 F_2|^2(k_BT/E_g)^{3/2}}{\hbar^2 \epsilon_\infty^2 n_0^2 (1 + \mu)^{1/2}(1 + 2\mu)} \times \exp \left\{ -\frac{1 + 2\mu E_g}{1 + \mu k_BT} \right\}, \]

where \( \epsilon_\infty \) is the high frequency dielectric constant and \( |F_1 F_2| \) is the Bloch function overlap integrals, and \( \mu = m_e m_0 / m_p \). The value of \( |F_1 F_2| \) is usually between 0.1 and 0.3, which can change the Auger lifetime by an order of magnitude.\(^{11,14}\)

Using Eqs. (2), (7), (9), and (14), the total lifetime can be written as
\[ R(\Delta n) = \tau^{-1} = \frac{n_0 + \Delta n}{\tau_{p0}(n_0 + \Delta n) + \tau_{s0}(\Delta n)} + B(n_0 + \Delta n) + C_n(n_0 + \Delta n)^2. \] (16)

The equilibrium majority electron concentration is implicitly handled in this fitting routine. This has been shown to be important when extracting radiative coefficients of materials with significant doping levels and/or Auger coefficients.\textsuperscript{24} The MC lifetime, including the contributions from SRH, radiative, and Auger processes, is determined using Eq. (16) under the assumption of low level injection as

\[ \tau_{MC}^{-1} = \tau^{-1}(\Delta n < n_0) = \tau_{p0}^{-1} + B(n_0) + C_n(n_0)^2. \] (17)

The total recombination lifetime, as described by Eq. (16), is fit to the measured lifetime data for each sample. Representative data for an undoped sample (E) are shown in Fig. 3, along with the overall fit, shown by the red curves. The contribution of each recombination process is identified by the fit coefficients, and the dominant recombination mechanism within a given injected carrier density range is therefore evident. SRH limited MC lifetimes are observed for sample E at excess carrier densities lower than the equilibrium density level. At higher excess carrier densities, the total recombination is Auger dominated at low temperatures. Furthermore, Auger recombination begins to dominate both at high and low excess carrier densities for temperatures above 200 K. Representative data and fits for a doped sample (H) are shown in Fig. 3(b). Due to the relatively high doping level, sample H was limited by Auger recombination at all excess carrier densities and temperatures.

Analysis of the temperature-dependent time-resolved data proceeds as follows. First, the density dependent carrier recombination rate data, at a specific temperature, are fit to the model given by Eq. (16). The recombination coefficients \( \tau_{p0}, B, \) and \( C_n \) are extracted from these best fits. The MC lifetime is then determined using Eq. (17). At this point, the MC lifetime includes the individual contributions of SRH, radiative, and Auger recombination rates in their low level injection forms. Second, MC lifetime values at each measured temperature are fit to the lifetime models\textsuperscript{20} for the low excess carrier density limit where the defect energy level, \( E_i \), capture probability, \( N_e \), and the Bloch overlap constant, \( |F_1F_2|^{12.14} \) are used as fitting parameters. Results of these temperature dependent MC lifetime analyses are shown in Fig. 4.

IV. DISCUSSION

A. SRH recombination

Deep SRH defect states have been suggested to inhibit longer MC lifetimes for MWIR and LWIR InAs/InAsSb T2SLs and InAsSb alloys at temperatures relevant to photodetector operation.\textsuperscript{2,4.12.20} Here, temperature dependent MC lifetime data are used to identify the limiting mechanism at low level excess carrier densities. At low temperatures, the MC lifetime weakly, but steadily, increases in the unintentionally doped samples as the Sb content is increased in the alloy layers (see Fig. 4). Specifically, it is observed to increase from 3.5 \( \mu \)s for the sample with 26% Sb (sample A) to \( \approx 5-6 \mu \)s for the samples with 40% and 49% Sb (samples D and E). Notice that the samples with higher Sb content in the alloy layer also have a thinner total SL period thickness. One possible explanation for the increased MC lifetime with increased alloy Sb content is that the number of SRH recombination centers is related to the total volume of InAsSb. By taking into account the number of SL layers and the InAsSb thicknesses, the fractional percentage of InAsSb in the absorber region decreases from 59.2% for sample A to 24.5% for sample E. Therefore, less InAsSb would provide fewer SRH recombination centers and the MC lifetime would increase. An alternative explanation is that the SRH defect energy shifts slightly relative to the T2SL band edges as the InAsSb composition is changed. This would be possible if the defect energy level is independent of the T2SL band edge energies. Varying the T2SL thicknesses and alloy composition can cause a shift of the absolute energy of the T2SL band edges relative to the absolute energy of the SRH defect energy, thereby modifying the SRH lifetime.\textsuperscript{25} However, the samples investigated here do not show significant shifts in the T2SL band edge energies on an absolute energy scale. From Table I, the T2SL VB edge for the unintentionally doped sample series changes by approximately 20 meV across the sample set, while the T2SL CB has effectively no change. Furthermore, the defect energies obtained from temperature dependent MC lifetime fits suggest that the energy level of SRH recombination centers is near mid-bandgap for all the samples tested, as compiled in Table II. Shown in Fig. 5 are the extracted SRH trap energies as well as the T2SL band edge energies and bulk InAs and InAsSb band edge energies, all plotted relative to the VB of InAs. The Sb content in the InAsSb alloy has a strong effect on the band offset of InAsSb with InAs across this compositional range. However, there is no relation observed between the SRH defect energy states and the bulk InAsSb band edges. Instead, the SRH defect remains relatively constant, as do the T2SL band edge energies. Unfortunately, as this sample set is engineered to keep the same 5.2 \( \mu \)m bandgap while spanning the most useful range of InAsSb compositions, it is unlikely that alternative 5.2 \( \mu \)m bandgap InAs/InAsSb designs would provide any sizable band edge shifts. The alternative now to increasing the minority carrier lifetime substantially is to identify and eliminate the parasitic SRH defects.

Lightly doped samples F and H also indicate a SRH limited MC lifetime at low temperatures. Sample F has an equilibrium density \( n_0 \approx 1.93 \times 10^{15} \text{ cm}^{-3} \) using Si as a dopant and sample H has \( n_0 \approx 4.17 \times 10^{15} \text{ cm}^{-3} \) using Te as a dopant, as listed in Table I. From the temperature-dependent MC lifetime analysis, the defect energy level of sample H is found to be \( \approx 2k_B T \) closer to the T2SL valance band edge relative to sample F. The MC lifetime of sample H is also found to be approximately 3 times shorter than sample F, while the experimentally determined doping level is only double. The doping level appears to be effective on the energies of the SRH recombination centers in the mid-bandgap. In this case, the factor of 2 increase of equilibrium carrier density could
cause a shallower SRH recombination center as shown in Table II. Therefore, the SRH lifetime becomes shorter for sample H than sample F due to a shorter $s_p^0$ at low excess carrier densities. With a small number of samples, caution must be applied, as these results might not be caused by SRH defect energy level or the type of dopant individually, but a combination of them. Overall, these temperature-dependent measurements demonstrate supporting evidence that the SRH process is indeed the limiting mechanism of the MC lifetime for unintentionally and lightly doped InAs/InAsSb T2SLs at low temperatures up to a doping level of approximately $4 \times 10^{15}$ cm$^{-3}$. As the equilibrium carrier density is increased through the intentional doping of the absorber, Auger recombination eventually begins to dominate instead of SRH recombination at all temperatures. This is noted in the doped samples G and I, which have MC lifetimes that are primarily limited by Auger recombination. As a consequence, the fitting procedure lost sensitivity to the SRH parameters ($E_t$ and $N_t$) and they could not be determined for these particular samples. The cause of this effect will be examined in Section IV C.

B. Radiative recombination

The radiative recombination coefficient, $B$, is obtained by fitting the excess carrier density dependent recombination rate data to the model described by Eq. (9). The measured radiative coefficient reported here (see Fig. 6(a)) includes the effects of PR, a process that can increase the apparent radiative lifetime through the re-absorption of emitted photons in the cavity of the device’s absorber region. The theoretical radiative recombination rates of a single SL cell, consisting
TABLE II. Summary of the temperature-dependent lifetime fitting results and the effective electron to heavy hole mass ratios are listed for vertical, \( \mu_{\text{vertical}} \), and horizontal, \( \mu_{\text{in-plane}} \), directions. Defect energy levels are reported as temperature independent and relative to the SL valence bands. Samples G and I were Auger limited and the SRH parameters could not be attained.

| Sample ID | \( E_i - E_v \) (meV) | \( \alpha N_i \) (cm\(^{-1}\)) | \(|F_1F_2|\) | \( \mu_{\text{in-plane}} \) | \( \mu_{\text{vertical}} \) |
|-----------|----------------|---------------------|--------|----------------|----------------|
| A         | 123.0          | 3.9                 | 0.14   | 0.0175/0.0348 | 0.0188/1.148   |
| B         | 118.4          | 5.1                 | 0.11   | 0.0175/0.0334 | 0.0189/1.538   |
| C         | 119.8          | 5.6                 | 0.11   | 0.0178/0.0336 | 0.0189/2.117   |
| D         | 122.6          | 4.7                 | 0.10   | 0.0176/0.0323 | 0.0191/2.724   |
| E         | 124.3          | 5.9                 | 0.09   | 0.0177/0.0323 | 0.0193/3.625   |
| F         | 125.3          | 4.3                 | 0.13   | 0.0178/0.0336 | 0.0189/2.117   |
| G         | ...            | ...                | 0.05   | 0.0178/0.0336 | 0.0189/2.117   |
| H         | 113.9          | 7.3                 | 0.11   | 0.0178/0.0336 | 0.0189/2.117   |
| I         | ...            | ...                | 0.08   | 0.0178/0.0336 | 0.0189/2.117   |

of a single InAs and InAsSb T2SL period, were obtained using the 14-band \( k \cdot p \) model, as shown in Fig. 6(b). These calculated values are then compared to the experimental values to determine \( \phi \). The recovered values of the PR factor vary from 1.5 to 15 over the temperature range investigated. The most recent findings of Hoang et al.\(^2\) and Höglund et al.\(^{26,27}\) suggest a PR factor of 2 for similar T2SL structures. However, in their comprehensive examination of carrier lifetimes in InAs/InAsSb T2SLs, Olson et al.\(^{23}\) concluded a PR factor of approximately 15, which is supported by Humphreys first-principles study of radiative lifetimes and PR in semiconductors.\(^{28}\) As shown in Figs. 6(a) and 6(b), the experimental \( B \) coefficient has a weak dependence on temperature, while the theoretical, \( B_{\text{in}} \), coefficient steadily decreases with increasing temperature. In general, radiative recombination increases with greater absorptivity.\(^{21}\) However, the case presented here shows decreasing \( B_{\text{in}} \) coefficients with increasing absorption coefficient (note the absorption is greater in the samples with greater Sb content as shown in Table I) due to the changes in the electronic band structure caused by the increasing strain with greater Sb concentration.

The radiative lifetime depends inversely upon the radiative coefficient as shown in Eq. (9). For unintentionally doped samples, the radiative lifetime at low injected carrier densities increases with increasing Sb. From the MC lifetime analysis, as shown in Fig. 4, the radiative lifetime is observed to increase by factor of 10 through samples A to E. Furthermore, the radiative lifetime at low nonequilibrium carrier densities is found to be shorter for increasing background carrier density,\(^{20}\) as illustrated for the intentionally lightly doped samples F and H in Fig. 4. These two samples have almost identical bandgaps, layer thicknesses, and Sb content in the InAsSb alloy. However, sample H exhibited a shorter radiative lifetime than sample F, which is attributed to the difference in the equilibrium carrier densities. On the other hand, as illustrated in Fig. 4, radiative recombination contributes weakly to the overall carrier lifetime at all temperatures reported here. These results are in agreement with those of Olson et al.\(^{23}\) who also reported minimal contribution of radiative processes, in this case for samples with ~4 \( \mu \)m absorber region thickness. Note that MWIR InAs/InAsSb T2SLs with thinner absorber region thicknesses have been shown to have radiative recombination dominated MC lifetimes for low excess carrier densities.\(^{27}\)

C. Auger recombination

Another goal of the present study was to measure the Auger recombination rates in a set of InAs/InAsSb T2SLs with fixed band gap and varied InAsSb composition.

![Fig. 5. Valence (VB) and conduction (CB) band edge energies for the unintentionally doped T2SL series (samples A through E), bulk InAs, and InAsSb are also shown as a function of Sb concentration relative to InAs valance band edge. Since InAs is independent of Sb content, it is simply a constant on this scale. The bulk band edges are listed as strained to GaSb. The extracted defect energy levels (\( E_i \)) from samples A-E are shown as green crosses.](image)

![Fig. 6. Radiative recombination rates of unintentionally doped samples are shown together as function of temperature. Here, (a) the extracted \( B \) coefficients from the measured recombination rate data and (b) the calculated \( B \) coefficients obtained from 14-band \( k \cdot p \) model are shown.](image)
Consideration of the Auger rate is crucial for the design of infrared detectors as this recombination mechanism can limit the best case performance of a device.\textsuperscript{16,24,25,29} In Fig. 4, the results for moderately ($>10^{16}$ cm$^{-3}$) doped samples G and I show that Auger recombination is the dominant process for minority carrier recombination at all temperatures in the range 77–293 K. For high excess carrier injection, the Auger process is observed to be the dominant mechanism in all nine samples due to the quadratic dependence of the Auger process is observed to be the dominant mechanism in all nine samples due to the quadratic dependence of the Auger process on excess carrier density. Auger recombination is also found to be the limiting mechanism in the low excess carrier density regime for temperatures greater than 200 K, corresponding to the intrinsic temperature range and large intrinsic carrier densities, which are greater than the doping levels.

The measured $C_n$ coefficients are shown as a function of temperature in Fig. 7. The experimental uncertainty of the reported Auger coefficients is approximately a factor of 2 to 3 for our pump-probe apparatus. While measured results are roughly within the bounds of experimental uncertainty, the Auger coefficients for the unintentionally doped InAs/InAsSb T2SLs appear to moderately decrease as the Sb content in the InAsSb layer increases and SL period thickness decreases as seen in Fig. 7(a). For example, at 77 K, the Auger coefficient for sample A is $2.75 \times 10^{-26}$ cm$^3$/s. This value gradually decreases to $2 \times 10^{-26}$ cm$^3$/s for sample C and to $1.75 \times 10^{-26}$ cm$^3$/s for sample E. It has been previously shown that by controlling the confinement and strain in the T2SL structure, the band structure can be engineered to eliminate the available final states in the Auger process. This feature of SL structures makes it possible to reduce Auger recombination in MWIR and LWIR T2SLs.\textsuperscript{13,24,29,30} The results from the unintentionally doped series (samples A to E), where the Sb content in the InAsSb alloy is increased and a reduction in the Auger coefficients by approximately a factor of 2, indicate that larger fractions of Sb may provide a more optimal band structure for Auger recombination reduction. The intentionally doped structures were found to have similar Auger coefficients with respect to the reference sample C, which is as expected since the T2SL structure was held constant for these samples and the doping, in all cases, is modest. While the SRH recombination rates have been shown to be considerably lower in the Ga-free T2SLs, the Auger coefficients for all the samples reported here are significantly larger than those measured in InAs/Ga(In)Sb T2SLs, which are as low as $10^{-23}$ cm$^3$/s.\textsuperscript{9}

The calculated Beattie, Landsberg, and Blakemore (BLB) Auger-1 lifetime for bulk material in low level injections is given as\textsuperscript{20}

$$
\tau_{BLB}^{A-1} = \frac{2n^2_e \tau_{A-1}}{(n_0 + p_0)n_0},
$$

where

$$
\tau_{A-1}^{j} = 3.8 \times 10^{-18} \epsilon_{\infty}^2 (1 + \mu)^{1/2} (1 + 2\mu) \left( \frac{E_g}{k_B T} \right)^{3/2} 
\times \exp \left[ \frac{1 + 2\mu}{1 + \mu} \frac{E_g}{k_B T} \right].
$$

This Auger lifetime is calculated using $\epsilon_{\infty} = 15.4$,\textsuperscript{23,31} and the electron and hole effective masses for the in-plane (parallel to the SL interfaces) and growth directions are obtained from the 14-band $k\cdot p$ model, which are listed in Table II. Notice that $\tau_{A-1}^{j}$ was evaluated using the vertical masses, since the most anisotropic masses will dominate the Auger rate, and the vertical masses are the most anisotropic. If final-state Auger optimization is not present, then the Auger recombination rate is a function principally of the band gap energies, the carrier densities, and the effective masses of the electrons and holes.\textsuperscript{29} Since the samples investigated here have nearly identical bandgaps, the primary difference is the majority carrier electron densities and the ratio of the effective masses (see Table II). The modest decrease in the Auger coefficients from samples A to E (see Fig. 7) is accompanied by an increase in antimony content (Table I) and a corresponding decrease in $|F_1F_2|$ (Table II).

V. SUMMARY

Time-resolved temperature-dependent differential-transmission measurements were used to investigate the nonequilibrium carrier dynamics in a series of MWIR InAs/InAsSb T2SLs. By altering the layer thicknesses and InAsSb alloy composition, a set of T2SLs with nearly constant 5.2 $\mu$m bandgap energy was designed and grown to investigate the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{Auger recombination rates of all samples are shown as a function of temperature. The extracted $C_n$ coefficients are shown as a function of Sb concentration in (a) and a function of temperature for undoped and doped samples in (b) and (c), respectively.}
\end{figure}
effects of Sb concentration on the carrier lifetime. Samples were initially tested by capacitance-voltage, photoluminescence, and high-resolution x-ray diffraction measurements to assess the optical and electrical properties of the devices. All nine samples demonstrated good agreement with the initial design and indicated a high structural quality. The results from time-resolved differential transmission measurements provided data indicating that the MC lifetime modestly increases with increasing Sb concentration and narrower SL periods. The data indicate that this increase in MC lifetime is related to a change in the SRH recombination lifetime at low temperatures, since it was determined that SRH recombination limits the MC lifetime at these temperatures. A fractional decrease in InAsSb alloy with increasing Sb content, resulting in fewer SRH recombination centers near mid-bandgap, is one possible explanation. It is also possible that the \( \sim 2 k_BT \) energy shift in the SRH defect energy relative to the band edges of the SLs could influence the SRH lifetime. In addition, by varying the Sb content, the band edges of strained InAsSb increase as more Sb is incorporated into the alloy. This larger valence band offset between the bulk constituents is found to not be effective in shifting the position of the SL bandgap in absolute energy. The SRH defect therefore stays near mid-bandgap of the SL regardless of the InAsSb composition. Radiative recombination is shown to be insignificant compared to SRH at temperatures below \( \sim 200 \) K and Auger processes dominate MC recombination at temperatures above \( 200 \) K. At higher temperatures, Auger recombination is the dominant MC recombination mechanism. Finally, the Auger coefficient is observed to weakly depend on Sb content in the InAsSb alloy, decreasing by approximately a factor of 2 as the antimony concentration increases from 26\% to 49\%. Note that the Auger coefficients reported here for InAs/InAsSb T2SLs are significantly larger than those found in InAs/Ga(In)Sb T2SLs.\(^6\)

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