Time-resolved measurements of charge carrier dynamics in Mwir to Lwir InAs/InAsSb superlattices

Yigit Aytac
University of Iowa

Copyright 2016 Yigit Aytac

This dissertation is available at Iowa Research Online: https://ir.uiowa.edu/etd/2039

Recommended Citation
Aytac, Yigit. "Time-resolved measurements of charge carrier dynamics in Mwir to Lwir InAs/InAsSb superlattices." PhD (Doctor of Philosophy) thesis, University of Iowa, 2016.
https://ir.uiowa.edu/etd/2039. https://doi.org/10.17077/etd.djog2vn6

Follow this and additional works at: https://ir.uiowa.edu/etd
Part of the Physics Commons
TIME-RESOLVED MEASUREMENTS OF CHARGE CARRIER DYNAMICS IN MWIR TO LWIR INAS/INASSB SUPERLATTICES

by

Yigit Aytac

A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Physics in the Graduate College of The University of Iowa

August 2016

Thesis Supervisor: Professor Thomas F. Boggess
This is to certify that the Ph.D. thesis of

Yigit Aytac

has been approved by the Examining Committee for the thesis requirement for the Doctor of Philosophy degree in Physics at the August 2016 graduation.

Thesis Committee:

Thomas F. Boggess, Thesis Supervisor

Michael E. Flatté

John P. Prineas

David R. Andersen

Markus Wohlgenannt
Philosophy of science is about as useful to scientists as ornithology is to birds.

-Richard P. Feynman
ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Thomas Boggess, for helping me build this dissertation and for guiding me through all of the challenges in my academic journey. My former lab-mate and a great scientist Dr. Benjamin Olsons contributions were fundamental to this work and in helping me to look at things from a broader perspective. In addition, Dr. Michael Flatté from the University of Iowa and Dr. Zikri Altun from Marmara University have been very influential in my academic career and have helped shape the way I see things today. I am thankful to my collaborators at Sandia National Laboratories, including Dr. Kim, Dr. Klem, Dr. Hawkins, and Dr. Shaner, who were very helpful in completing this work. I am also grateful for the contributions of all of my current and former lab-mates, who have all left a mark on this dissertation.

My mothers support from the other side of the ocean and my extended familys support in the states during my pursuit of this Ph.D. degree has been wonderful. I am incredibly thankful to all of them.

My wife and love, Hannah, is possibly the strongest driving force in my academic growth. I am thankful for all of her help editing my academic journal papers and this dissertation. I also would like to thank our dogs Ozzy and Abby for keeping us entertained and helping me keep my sanity throughout.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under Contract No. DE-AC04-94AL85000. Research at Sandia was supported in part by the Department of Energys Office of Basic Research. Research at the University of Iowa was funded by the U.S. Government.
ABSTRACT

All-optical time-resolved measurement techniques provide a powerful tool for investigating critical parameters that determine the performance of infrared photodetector and emitter semiconductor materials. Narrow-bandgap InAs/GaSb type-II superlattices (T2SLs) have shown great promise as next generation materials, due to superior intrinsic properties and versatility. Unfortunately, InAs/GaSb T2SLs are plagued by parasitic Shockley-Read-Hall recombination centers that shorten the carrier lifetime and limit device performance. Ultrafast pump-probe techniques and time-resolved differential-transmission measurements are used here to demonstrate that ”Ga-free” InAs/InAs$_{1-x}$Sb$_x$ T2SLs and InAsSb alloys do not have this same limitation and thus have significantly longer carrier lifetimes. Measurements of unintentionally doped MWIR and LWIR InAs/InAs$_{1-x}$Sb$_x$ T2SLs demonstrate minority carrier (MC) lifetimes of 18.4 $\mu$s and 4.5 $\mu$s at 77 K, respectively. This represents a more than two order of magnitude increase compared to the 90 ns MC lifetime measured in a comparable MWIR and LWIR InAs/GaSb T2SL. Through temperature-dependent differential-transmission measurements, the various carrier recombination processes are differentiated and the dominant recombination mechanisms identified for InAs/InAs$_{1-x}$Sb$_x$ T2SLs. These results demonstrate that these Ga-free materials are viable options over InAs/GaSb T2SLs and potentially bulk Hg$_{1-x}$Cd$_x$Te photodetectors.

In addition to carrier lifetimes, the drift and diffusion of excited charge carriers through the superlattice layers (i.e. in-plane transport) directly affects the performance of photo-detectors and emitters. All-optical ultrafast techniques were successfully used for a direct measure of in-plane diffusion coefficients in MWIR InAs/InAsSb T2SLs using a photo-generated transient grating technique at various temperatures. Ambipolar diffusion coefficients of approximately 60 cm$^2$/s were reported for MWIR InAs/InAs$_{1-x}$Sb$_x$ T2SLs at 293 K.
PUBLIC ABSTRACT

Semiconductor type-II superlattices (T2SLs) are of prime interest for medium- and long-wavelength infrared photodetectors, and possibly as thermophotovoltaics. Their properties can be spoiled, though, by defect states with energies in the band gap, which promote carrier recombination. This optical study of a series of T2SLs reveals that the SRH defect state presents just one energy, nearly independent of the band gap or edges. Thus it seems possible to engineer T2SLs with no defect levels in the gap, for improved performance.
TABLE OF CONTENTS

LIST OF TABLES ............................................................... viii
LIST OF FIGURES ............................................................. ix

CHAPTER

1 INTRODUCTION ............................................................... 1
  1.1 Motivation ............................................................. 1
  1.2 Type-II Superlattices ................................................ 3
    1.2.1 Carrier Lifetime ............................................... 6
    1.2.2 Carrier Transport ............................................. 7
  1.3 Experimental Approach ............................................. 7
  1.4 Organization of Dissertation ..................................... 8

2 BACKGROUND .............................................................. 9
  2.1 Semiconductor Theory .............................................. 9
    2.1.1 The Band Structure of Solids ................................ 9
    2.1.2 Effective Mass ................................................ 12
  2.2 Optical Properties ................................................ 12
    2.2.1 Linear Optical Properties .................................. 13
    2.2.2 Nonlinear Optical Properties ............................... 16
  2.3 Semiconductor Nonlinearities .................................... 17
    2.3.1 Excited Carrier Relaxation ................................. 18
    2.3.2 Band Filling .................................................. 19
    2.3.3 Free-Carrier Absorption .................................... 22
  2.4 Equilibrium Charge Carrier Properties .......................... 23
    2.4.1 Intrinsic Semiconductors ................................... 25
    2.4.2 Extrinsic Semiconductors ................................... 26
  2.5 Non-equilibrium Carrier Dynamics ................................ 28
    2.5.1 Radiative Recombination ..................................... 30
    2.5.2 Shockley-Read-Hall Recombination ......................... 32
    2.5.3 Auger Recombination ......................................... 34
    2.5.4 Carrier Transport ............................................ 37

3 ULTRAFAST SPECTROSCOPY ............................................. 40
  3.1 Pump-Probe Measurements ......................................... 40
  3.2 Data Acquisition .................................................. 44
    3.2.1 Time-resolved Differential-Transmission .................. 44
    3.2.2 Photo-generated transient grating experiment ............ 47

4 CARRIER LIFETIME ...................................................... 54
  4.1 Samples of Interest ............................................... 54
  4.2 Set I: Varying the Sb Content ................................... 56
    4.2.1 Experimental Results ....................................... 58
    4.2.2 Discussion .................................................... 66
  4.3 Set II: Varying Bandgap from MWIR to LWIR ..................... 74
# 4.3 Experimental Results

- 4.3.1 Experimental Results ........................................... 76
- 4.3.2 Discussion ....................................................... 77

# 4.4 Set III: Varying the Superlattice Period Thickness

- 4.4.1 Experimental Results .......................................... 91
- 4.4.2 Discussion ....................................................... 93

# 4.5 Summary ............................................................ 96

# 5 Carrier Transport

- 5.1 Diffusion Model ................................................... 100
- 5.2 Experimental Results ............................................ 106
- 5.3 Discussion .......................................................... 109

# 6 Conclusions and Recommendations for Future Research

- 6.1 Conclusion .......................................................... 113
- 6.2 Recommendation for Future Research .......................... 115
  - 6.2.1 Metamorphically grown Ga-free InAsSbx/InAsSby T2SLs 116
  - 6.2.2 Vertical Transport Measurements of InAs/InAsSb T2SLs 117
  - 6.2.3 Proton Radiation Effect on Carrier Lifetime of InAs/InAsSb T2SLs 120
  - 6.2.4 Spin Relaxation in InAs/InAsSb T2SLs ..................... 124

## Appendix

- A Solution of the 2D Diffusion Equation with Gaussian Initial Conditions ........................................... 128
- B Efficiency of Light Diffracted from a Photo-Generated Transient Grating ........................................... 131
- C Experimental Arrangements ...................................... 136
- D Photon Recycling ................................................... 139

REFERENCES .................................................................... 142
LIST OF TABLES

Table

4.1 Summary of the T2SL set-I physical properties ........................................... 57

4.2 Summary of the temperature-dependent lifetime fitting results and the effective electron to heavy hole mass ratios are listed for the set-I samples. 69

4.3 Summary of the physical properties of the seven InAs/InAsSb type-II superlattice (T2SL) structures. ................................................................. 76

4.4 Summary the SRH defect energy, $E_t$, capture probability, $\sigma N_t$, and Auger recombination Bloch function overlap parameter, $|F_1F_2|$, determined from the temperature-dependent minority carrier lifetime fitting. ......................................................... 82

4.5 Summary of the physical properties of the three InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs structures. ................................................................. 92

4.6 Summary the SRH defect energy, $E_t$, capture probability, $\sigma N_t$, and Auger recombination Bloch function overlap parameter, $|F_1F_2|$, determined from the temperature-dependent minority carrier lifetime fitting. ......................................................... 95

5.7 Measured recombination and diffusion properties for samples GN0838, GN0837 and GN0835 at 293 K ................................................................. 111

6.8 Summary the SRH defect energy, $E_t$, capture probability, $\sigma N_t$, and Auger recombination Bloch function overlap parameter, $|F_1F_2|$, determined from the temperature-dependent minority carrier lifetime fitting for the pre- and post-rad. pieces of samples. ......................................................... 123
LIST OF FIGURES

Figure

1.1 Atmospheric absorption in the infrared spectrum for a 1 m path length at sea level. .................................................. 2
1.2 A plot of the low temperature energy bandgaps of a number of semiconductors with the diamond and zinc-blende structure versus their lattice constants. .................................................. 4
1.3 Type-I and type-II superlattice configurations are illustrated ..... 5
2.1 Simplified parabolic band structure ..................................... 11
2.2 77 K band structures for (a) 30/10 Å and (b) 75/25 Å InAs/InAs$_{0.7}$Sb$_{0.3}$ T2SLs .................................................. 11
2.3 Band-to-band absorption processes in a semiconductor ........... 15
2.4 Simplified schematic of the charge relaxation in a semiconductor as a function of time. .................................................. 20
2.5 Simplified schematic of the generation, cooling, and band filling of excess carriers .................................................. 20
2.6 Carrier density-dependent absorption spectra ........................... 22
2.7 Simplified illustration of the density-of-states for 3, 2 and quasi-2 dimensional quantum structures. .................................. 24
2.8 Recombination mechanisms in a semiconductor ...................... 29
2.9 Excess carrier density dependence of the SRH lifetime as a function of defect level position relative to the valence band-edge ......... 34
2.10 The three primary interband Auger recombination processes ...... 35
3.1 Cross-correlation of a 180 fs OPA pulse and the QCL pulse using two-photon absorption in HgCdTe. .............................. 41
3.2 A schematic diagram of the synchronized, two-color pump-probe .......................... 42
3.3 Measured OPA optical spectra across the signal ........................ 44
3.4 77 K time-resolved differential transmission data for multiple initial injected excess carrier densities ............................. 46
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>Schematic diagram of a typical transient grating arrangement</td>
<td>48</td>
</tr>
<tr>
<td>3.6</td>
<td>The grating period, Λ, given as a function of pump wavelength for a θₑ ≃ 10°.</td>
<td>48</td>
</tr>
<tr>
<td>3.7</td>
<td>The thin grating condition, Q, as a function of grating period Λ.</td>
<td>51</td>
</tr>
<tr>
<td>3.8</td>
<td>Diffracted probe angles outside of the sample for φ = 13°.</td>
<td>53</td>
</tr>
<tr>
<td>4.1</td>
<td>Intended superlattice layer sequence. Growth direction is from bottom to top.</td>
<td>55</td>
</tr>
<tr>
<td>4.2</td>
<td>Photoluminescence spectra of the five unintentionally doped (left panel) and four intentionally doped (right panel)</td>
<td>56</td>
</tr>
<tr>
<td>4.3</td>
<td>Time-resolved differential transmission decay curves illustrating carrier recombination for two of the MWIR InAs/InAsSb T2SL samples</td>
<td>59</td>
</tr>
<tr>
<td>4.4</td>
<td>Carrier recombination rates as a function of excess carrier density determined from intensity dependent time-resolved differential transmission measurements for a range of temperatures</td>
<td>63</td>
</tr>
<tr>
<td>4.5</td>
<td>Minority carrier lifetime results as a function of temperature, determined from the recombination rate data.</td>
<td>65</td>
</tr>
<tr>
<td>4.6</td>
<td>Valence and conduction band edge energies for the unintentionally doped T2SL series.</td>
<td>68</td>
</tr>
<tr>
<td>4.7</td>
<td>Radiative recombination rates of unintentionally doped samples are shown together as function of temperature.</td>
<td>70</td>
</tr>
<tr>
<td>4.8</td>
<td>Auger recombination rates of all samples are shown as a function of temperature.</td>
<td>72</td>
</tr>
<tr>
<td>4.9</td>
<td>Relative positions of the conduction and valence band edge energies.</td>
<td>75</td>
</tr>
<tr>
<td>4.10</td>
<td>Normalized photoluminescence spectra of the seven InAs/InAsSb T2SL samples at 80 K.</td>
<td>77</td>
</tr>
<tr>
<td>4.11</td>
<td>Influence of a) SRH defect energy, b) equilibrium carrier density, and c) capture probability on the SRH lifetime is shown for the sample GN0815 under low level injection conditions.</td>
<td>79</td>
</tr>
<tr>
<td>4.12</td>
<td>Minority carrier (MC) lifetime results as a function of temperature for the seven InAs/InAsSb type-II superlattice samples.</td>
<td>80</td>
</tr>
<tr>
<td>4.13</td>
<td>Valence and conduction band edge energies for the InAs/InAsSb type-II superlattice (T2SL) series (samples GN0815 through GN0832.</td>
<td>83</td>
</tr>
</tbody>
</table>
4.14 Time-resolved differential transmission decay curves and net recombi-
nation rate as a function of excess carrier density are illustrated for
samples GN0815, GN0824, and GN0826 at 77 K. The solid red curve is
the best fit to the measured data. 85

4.15 Measured (filled) and calculated (unfilled) Auger recombination rates
of all samples are shown as a function of temperature. 87

4.16 Calculated 77 K band structures of the MWIR and LWIR superlattice
structures. 88

4.17 Normalized photoluminescence spectra of the three InAs/InAsSb T2SL
samples at 18 K. 92

4.18 Net recombination rate as a function of excess carrier density are
illustrated for three type-II InAs/InAsSb T2SL samples at 77 K. 93

4.19 Minority carrier (MC) lifetime results as a function of temperature for
the three InAs/InAsSb type-II superlattice samples. 94

4.20 Minority carrier (MC) lifetime results as a function of temperature for
the three InAs/InAsSb type-II superlattice samples. 95

5.1 (a) Time-resolved differential transmission decay curves and (b) the
change in absorption coefficient with injection level are illustrated . 102

5.2 Two planar waves interacting in a sample body 105

5.3 Wavelengths of four pump beams and a probe beam is illustrated . 107

5.4 Calculated absorption coefficients as a function of energy is illustrated
for samples GN0838, GN0837, and GN0835 at 293 K. 107

5.5 Normalized diffraction efficiency (filled symbols) for various grating
period and carrier recombination 109

5.6 Grating decay rate, $\Gamma_G$ vs. $4\pi^2/\Lambda^2$ for the samples 110

5.7 A comparison of ambipolar diffusion coefficients in III-V binary . 112

6.1 Calculated band structure for the two different 135 meV bandgap T2SL
structures 117

6.2 (a) Simplified illustration the vertical transport measurement using
time-resolved $\Delta T/T$. Note, only the T2SL absorber layers are shown.
(b) Schematic of short-period grating technique for measuring vertical
transport. 118

6.3 Experimentally measured minority carrier lifetimes 122
CHAPTER 1
INTRODUCTION

The main goal of this dissertation is to advance our understanding of the optical and electrical properties of narrow bandgap group III-V InAs/InAsSb type-II superlattices (T2SLs) by applying ultrafast spectroscopic techniques. These structures are of interest for the design of mid-wave (MWIR) and long-wave (LWIR) infrared (IR) semiconductor photodiodes, which have various applications from 2 µm to 12 µm wavelength range. The carrier lifetime and transport measurements and analysis described in this dissertation are a part of a broader study incorporating band structure engineering, molecular beam epitaxy (MBE) growth, device processing, and material characterization, the goal of which is to develop the next generation of MWIR and LWIR photodetectors. This work utilizes a coordinated and iterative approach for enhancing the performance of MWIR and LWIR photodetectors: design, growth, optical measurement of key material properties, and redesign.

In this chapter, the motivation behind the interest in developing MWIR and LWIR photodetectors is introduced. The key issues associated with their development are discussed while introducing the terminology used in this dissertation.

1.1 Motivation

The superlattice infrared detector technology was initially studied by L. Esaki, R. Tsu and Sai Halasz et al. [1,2] to explore new infrared detector materials and technology. The first growth of Ga-free InAs/InAsSb T2SLs were demonstrated by Lee et al. [3] in 1985. The major goal is to enhance the IR photodetection capability and meet challenging requirements for various applications. In some of these applications, large format focal plane arrays (FPA) must be able to detect IR light and infrared signatures at LWIR wavelengths. Molecular and chemical absorption occurs in the atmospheric conditions; therefore it is important to take into account the spectral regions that
exhibit minimal absorption in the design of an IR device. In Fig. 1.1, the MWIR and LWIR wavelength ranges are indicated and will be associated with narrow bandgap semiconductors in this dissertation. In the past two decades, enormous progress has been made towards development of IR detectors with Ga-free materials [4–16]. This progress resulted in orders-of-magnitude reduction in detector dark-current density, a substantial increase in quantum efficiency (QE), and minority carrier (MC) lifetime, as well as the demonstration of high-quality MWIR and LWIR infrared FPAs. There are many technical challenges that must be tackled to realize the theoretical promise of superlattice IR materials [5,17–21]. Further reduction in dark current density and non-radiative recombination rates and make optically thick materials for high QE, and elimination of FPA processing-related performance degradation are just a few examples of which significant progress is still needed.

Figure 1.1: Atmospheric absorption in the infrared spectrum for a 1 m path length at sea level.

A simple empirical relationship that describes the dark current behavior with temperature and wavelengths called Rule 07 was first presented by William Tennant at
the 2007 U.S. Workshop on the Physics and Chemistry of II-VI Materials. The revised version was presented at the workshop of the same title held in 2009. The detailed description of Rule 07 and data used for deriving it can be found in Tennant et al. 2010 [22]. All diodes and arrays were grown with MBE and used double-layer planar heterostructure architecture. These layers’ diodes were among the best ever made, using a well-controlled HgCdTe photodiode process. In short, rule 07 is a convenient rule of thumb for estimating the dark current density for state-of-the-art HgCdTe photodiodes. It is valid for a cutoff wavelength and temperature product larger than 400 µm-K. Further efforts of building advanced photodetectors are currently in a race with this figure of merit.

The reduction of the non-radiative recombination rate in MWIR and LWIR InAs/InAsSb T2SL detector materials is a key limiting factor for realizing improvements in detectivity, which would lead to significant improvements over HgCdTe for FPA applications. Through design, growth and measurement iterations, our main goals are to optimize the Ga-free T2SL design, demonstrate larger than 2000 cm$^{-1}$ absorption coefficient at MWIR and LWIR bandgaps, reduce Auger coefficients to below $\times 10^{-27}$ cm$^6$/s, and achieve larger than 4 µm hole diffusion lengths at 77 K. By achieving all or some of these metrics, this effort will have an immediate impact on IR device technology, defining a path forward to greatly improve the current state-of-the-art. If all the objectives are not met, this effort will identify significant challenges or fundamental roadblocks that remain.

1.2 Type-II Superlattices

Using two distinct semiconductors with similar lattice constants, a superlattice is constructed by a periodic growth strategy. Selection of materials with similar lattice constants is an important task because the growth metrics are highly influenced by this structural criteria. The bandgap and lattice constant of the binary III-V
semiconductors and the 6.1 Å family compounds are illustrated in Fig. 1.2. In superlattice design, the barrier width of the alternating layers is thin enough that the electrons and holes can tunnel through. These carriers are affected by the alternating layers of superlattices as periodic potentials in addition to the crystal potential which makes superlattices so interesting and versatile [23,24].

Figure 1.2: A plot of the low temperature energy bandgaps of a number of semiconductors with the diamond and zinc-blende structure versus their lattice constants [25]. The shaded regions highlight several families of semiconductors with similar lattice constants. Semiconductors joined by solid lines form stable alloys. (Chen A.B., Sher A.: Semiconductor Alloys (Plenum, New York 1995) [26]) Note that the negative gap of HgSe is controversial [27]. Broken lines indicate that the bandgap is indirect.

The difference between two types of superlattices are shown in Fig. 1.3. In type-I configuration, the electrons and holes are confined to the same layer. The energy difference between valence and conduction band edges is called the bandgap. The type-II alignment occurs when the electrons and holes are confined in different
layers, such as in InAs/InAsSb superlattices. For the InAs/InAsSb T2SLs, the valence band edge of InAsSb is higher than the conduction band edge of InAs, which is called a broken-bandgap alignment. The confinement of carriers primarily in one layer is produced by the band offset potentials and will be discussed for T2SLs in later chapters of this proposal. The optical and electronic properties of the quantum confined materials presented here are governed by the band structure of these periodic crystal lattices.

Figure 1.3: Type-I and type-II superlattice configurations are illustrated. $E_v$ is the bulk valence band energy, $E_c$ is the bulk conduction band energy, and $E_g$ is the bandgap energy.

The InAs/Ga(In)Sb T2SL has been an important material system in recent years for infrared optoelectronic devices operating in the MWIR and LWIR infrared [28–33]. As a T2SL, they have various advantages over bulk HgCdTe IR photo-detectors, such as the ability to tune the bandgap energy by controlling the layer thicknesses and alloy composition, band engineered suppression of Auger recombination rates [34–36], more favorable effective masses, lower fabrication cost and lower predicted dark currents [37–39]. Single element detectors show high sensitivity at 80 K operating
temperatures [28], however, they underperform compared to bulk HgCdTe due to significantly shorter MC lifetimes that limit the overall performance of InAs/Ga(In)Sb T2SL detectors [40,41]. GaSb-related Shockley-Read-Hall (SRH) recombination centers are suspected to be the cause of these short lifetimes [37,42]. In fact, once the Gallium is removed from the material absorber layer, as for InAs/InAsSb structures, orders of magnitude improvement in MC lifetime was obtained [9, 43–45]. On the other hand, these Ga-free material structures have SRH limited MC lifetimes at cryogenic temperatures. Further studies are required for a fuller understanding of recombination process.

1.2.1 Carrier Lifetime

The MC lifetime in the narrow-bandgap absorber region is an important parameter to assess the infrared photodetector performance. The photodetector dark current is inversely proportional to the MC lifetime for a diffusion limited photodetector [16,39], 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 MWIR and 15 – 30 ns for LWIR InAs/Ga(In)Sb T2SLs [30,40,41,46,47]. Ga-related Shockley-Read-Hall (SRH) recombination centers are suggested to be the cause of these short lifetimes [28,37,48]. The recent observations of much longer MC lifetimes in Ga-free InAs/InAsSb T2SLs provide strong support for this hypothesis. For example, InAs/InAsSb T2SLs have been shown to have MC lifetimes of ~ 18 μs in the MWIR [43,44,49] and > 4.5 ns in LWIR [49] T2SLs have been reported for this Ga-free T2SL material system. These studies are included in this document. For materials that are not limited by SRH recombination, the Auger lifetime typically defines a photodetectors dark diffusion current, $J_{\text{diff}}$ [50]. This dissertation aims to demonstrate a comprehensive study of carrier lifetimes and various lifetime-killing mechanisms in narrow bandgap photodetectors.
1.2.2 Carrier Transport

Another factor that may provide information about the detector performance and quality is the in-plane carrier transport property. It is known, e.g., that doping reduces the dark current, but the diffusion length also shortens, necessitating a compromise between low dark current and high responsivity. Photo-generated transient-grating experiments have been performed for various semiconductors such as Ge [51], GaAs/AlGaAs quantum wells, SiGe alloys [52], Si [53], InSb [54] and InAs/GaAs SLs [55,56]. Measurement of the in-plane transport in the Ga-free InAs/InAsSb T2SLs is of interest due to their relatively light in-plane heavy-hole mass, which should lead to an enhancement of the in-plane transport. Here, the influence of SL period thickness on carrier transport is studied using a photo-generated transient-grating technique [52–56]. This technique can provide a direct measure of the ambipolar diffusion coefficient in InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs.

1.3 Experimental Approach

Although there are many variations of ultrafast semiconductor spectroscopy, one can generally think of the approach as using one short, intense, optical excitation pulse (pump) to create a non-equilibrium carrier distribution in the sample of interest, and a sub-nanosecond-delayed, synchronous and weaker probe pulse to sense the optically induced changes in the material. The changes in the optical properties (absorption and/or refractive index spectrum) are directly related to the optically-injected carriers, and the material returns to its equilibrium condition as the carriers recombine. By varying the arrival time of the probe relative to the pump, the time decay of the optically induced changes can be measured and transient properties of the carrier distribution can be inferred. Ultrafast optical techniques have previously been utilized at the University of Iowa to measure Shockley-Read-Hall (SRH) and Auger recombination rates in InAsSb alloys [43], InAs/GaSb [30] and InAs/InAsSb
T2SLs [17,43,44,56,57]. Other transient electronic processes in MWIR SLs include spin
dynamics in InAs quantum dots [58] and in-plane transport in InAs/GaAs short-period
T2SLs [56].

1.4 Organization of Dissertation

This dissertation is divided into six chapters. In Chapter 2, the relevant back-
ground on the electronic and optical properties of semiconductors are introduced.
Discussion of the ultrafast techniques is provided in Chapter 3, including the data
acquisition of time-resolved differential-transmission and photo-generated transient
grating techniques. Chapter 4 and 5 will cover the analysis of the experimental data
to determine the carrier recombination and in-plane diffusion dynamics, respectively.
Final thoughts and recommendations for future research are given in Chapter 6. In
addition, a number of appendices are included to cover specific topics in more detail
to supplement the main text.
CHAPTER 2
BACKGROUND

In this chapter, the fundamentals of optical and electronic properties of narrow bandgap semiconductors are briefly reviewed. First, the band structure and the density of the states in intrinsic semiconductors are introduced. This is followed by an explanation of optical properties of semiconductors, non-equilibrium states of semiconductors, carrier transport, and recombination processes in narrow bandgap semiconductors including SRH, Radiative, and Auger recombination. Multiple texts were used as general references for semiconductor theory, non-equilibrium charge carrier dynamics, and nonlinear optics.

2.1 Semiconductor Theory

2.1.1 The Band Structure of Solids

In order to understand optical absorption due to electronic transitions in the presence of an external incident optical pulse, one has to know the electronic band states including the energy bands and the corresponding wave functions. Since the structures under study (e.g. superlattices) have a periodic property, the electronic band structure can be derived from the Hamiltonian equation which satisfies the symmetry of the semiconductor crystals. Numerical methods such as the pseudo-potential, $k \cdot p$ method, and the tight-binding method are available to calculate the electronic band structure and the wavefunction. More information can be found in textbooks [25, 59, 60].

For an electron in periodic a potential,

$$V(r) = V(r + R), \quad (2.1)$$

where $R = n_1 a_1 + n_2 a_2 + n_3 a_3$, and $a_1$, $a_2$ and $a_3$ are the lattice vectors and $n_1$, $n_2$
and \( n_3 \) are integers. The electron wave function satisfies the Schrodinger Equation,

\[
\hat{H}\psi(\mathbf{r}) = \left[ -\frac{\hbar^2}{2m_0} \nabla^2 + V(\mathbf{r}) \right] \psi(\mathbf{r}) = E\psi(\mathbf{r}),
\]

(2.2)

here \( \hat{H} \) is the single electron Hamiltonian, which is invariant under translation by the lattice vectors, \( \mathbf{r} \rightarrow \mathbf{r} + \mathbf{R} \), therefore the solutions of \( \psi(\mathbf{r}) \) can be represented as,

\[
\psi_{nk}(\mathbf{r}) = e^{i\mathbf{k} \cdot \mathbf{r}} u_{nk}(\mathbf{r}),
\]

(2.3)

where \( u_{nk}(\mathbf{r}) \) is a periodic function over lattice constant \( \mathbf{R} \), \( u_{nk}(\mathbf{r}) = u_{nk}(\mathbf{r} + \mathbf{R}) \) and \( \mathbf{k} \) is the wavevector. By substituting Eq. 2.3 into Eq. 2.2, an equation in \( u_{nk}(\mathbf{r}) \) is derived as,

\[
\left[ \frac{p^2}{2m_o} + \frac{\hbar \mathbf{k} \cdot \mathbf{p}}{m_o} + \frac{\hbar^2 k^2}{2m_o} + V \right] u_{nk} = E_{nk} u_{nk}.
\]

(2.4)

At zone center (i.e. \( \mathbf{k} = (0,0,0) \)) this equation simplifies to,

\[
\left[ \frac{p^2}{2m_o} + V \right] u_{n0} = E_{n0} u_{n0},
\]

(2.5)

where \( E_{n0} \) and \( u_{n0} \) are the zone center band energies and block functions, respectively. The solution of this equation, beyond the zone center condition, can be found in [25].

In this \( \mathbf{k} \cdot \mathbf{p} \) method the perturbations from the zone center are the \( (\hbar \mathbf{k} \cdot \mathbf{p})/m_o \) and \( (\hbar^2 k^2)/2m_o \) terms. A 14-band \( \mathbf{k} \cdot \mathbf{p} \) model, developed by Dr. Jon Olesberg and Prof. Michael Flatté [61], was used with permission throughout this dissertation for the calculation of semiconductor optical and electronic properties.

The lowest conduction band is separated from the highest valence band, termed the heavy hole (HH) band, by a forbidden energy gap \( E_g \). Other significant energy bands are the light hole (LH) and split-off (SO) valence bands and are also shown in Fig. 2.1.

Note that the SL band structures are highly anisotropic and complex, compared to a simplified parabolic band structure of a direct bandgap semiconductor, as shown in Fig. 2.2. Band structures for an 30/10 Å and 75/25 Å InAs/InAs\(_{0.7}\)Sb\(_{0.3}\) T2SL are
Figure 2.1: Simplified parabolic band structure with lowest conduction band (CB), heavy hole (HH), light-hole (LH), split-off (SO) valence bands of direct gap semiconductor.

plotted in order to illustrate the versatility of the T2SL structure.

Figure 2.2: 77 K band structures for (a) 30/10 Å and (b) 75/25 Å InAs/InAs$_{0.7}$Sb$_{0.3}$ T2SLs. Zone center is denoted by the vertical black lines. Positive wavevectors indicate the in-plane direction while negative wavevectors indicate the growth direction.
2.1.2 Effective Mass

For a parabolic band, the energy dispersion in a semiconductor is described as,

\[ E = \frac{\hbar k^2}{2m_0}. \]  

(2.6)

Carriers properties are determined by the energy band that they reside and the details of the band structure, which also determines the carrier’s effective mass. In this case, the mass is calculated by,

\[ m^* = \hbar^2 \left( \frac{d^2E}{dk^2} \right)^{-1}, \]  

(2.7)

where \( m^* \) is referred to as the effective mass. The effective mass is inversely proportional to the curvature of the energy band that the carrier resides in. Notice that the effective mass is constant for a quadratic band and behaves as a free electron with a mass \( m^* \).

Throughout this dissertation the assumption is that at zone center energy bands are approximately parabolic. The simple solution of the time-independent Schrodinger equation, i.e. the parabolic band structure for a direct band gap material, is illustrated as in Fig. 2.1.

2.2 Optical Properties

To understand the interaction between radiation and material, Maxwell’s Equations must be applied. Therefore, before discussing the more complicated topic of nonlinear optics, a brief overview of light matter interactions will be developed. The light-matter interaction is governed by the wave equation [62],

\[ \nabla^2 \mathbf{E} - \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{1}{\varepsilon_0 c^2} \frac{\partial^2 \mathbf{P}}{\partial t^2}, \]  

(2.8)

where \( \mathbf{E} \) is the optical electric field, \( \mathbf{P} \) is the polarization of the material, and \( \varepsilon_0 \) is the permittivity of free space.
2.2.1 Linear Optical Properties

In conventional optics, the polarization of a material is related to the electric field through the linear relationship,

\[ P = \varepsilon_0 \chi E, \]  

(2.9)

where \( \chi \) is the linear susceptibility. Inserting Eq. 2.9 into Eq. 2.8 allows the wave equation to be re-cast solely in terms of \( E \) as,

\[ \nabla^2 E = \frac{\varepsilon}{c^2} \frac{\partial^2 E}{\partial t^2}, \]  

(2.10)

where \( \varepsilon = 1 + \chi \) is the relative permittivity or dielectric function of the material. Eq. 2.10 has solutions in the form of transverse waves and the electric field can, therefore, be assumed to have the form,

\[ E = E_0 e^{i[(q+i\kappa)z-\omega t]}, \]  

(2.11)

where \( q \) and \( \kappa \) are the real and imaginary part of the photon wavevector, respectively, and \( \omega \) is the photon frequency. Using this Equation with the wave equation yields,

\[ (q^2 + \kappa^2) = \frac{\omega^2}{c^2} (\varepsilon^2 + i\varepsilon^i), \]  

(2.12)

where \( \varepsilon = \varepsilon^r + i\varepsilon^i \), with \( \varepsilon^r \) and \( \varepsilon^i \) expressing the real and imaginary parts of the dielectric function, respectively. By separating the Eq. 2.12 into real and imaginary parts, the index of refraction can be introduced as a function of real and imaginary dielectric constants,

\[ \eta(\omega) = \frac{qc}{\omega} = \sqrt{\frac{1}{2} \left[ \varepsilon^r + \sqrt{(\varepsilon^r)^2 + (\varepsilon^i)^2} \right]}, \]  

(2.13)
Equation 2.13 can be separated into,

\[ \varepsilon^r = \left[ \eta(\omega) \right]^2 - \frac{k^2 e^2}{\omega^2}, \]  
\[ \varepsilon^i = 2\frac{kC}{\omega}\eta(\omega). \]  

(2.14a)

(2.14b)

Combining these two equations allows for the index of refraction to be solved solely in terms of the dielectric function as,

\[ \eta(\omega) = \sqrt{\frac{1}{2} \left[ \varepsilon^r + \sqrt{(\varepsilon^r)^2 + (\varepsilon^i)^2} \right]}. \]  

(2.15)

The linear absorption coefficient is defined using Eq. 2.12 as,

\[ \alpha(\omega) = 2\kappa = \frac{\omega}{c\eta(\omega)}\varepsilon^i, \]  

(2.16)

which can be related with the intensity of radiation as,

\[ I(z) = |E|^2 = |E_0|^2 e^{-2\kappa z} = I_0 e^{-\alpha(\omega)z}, \]  

(2.17)

where \( I(z) \) is the intensity of the optical field. Eq. 2.17 is called the Beer-Lambert law, and it frames the relation of the absorption and the total change in the magnitude of the radiation through the material.

When the excitation energy of a photon is above the bandgap, linear band to band absorption occurs. There are four different below bandgap excitations in semiconductors, as shown in Fig. 2.3.

1. The transitions between electronic states of impurity levels to the conduction or valence band, and from impurity levels into the valance or conduction bands:

As seen in Fig. 2.3, impurities in the semiconductor can create energy states that carriers can occupy. All the transitions from these states are included in this absorption process.

2. Indirect intraband excitations, also referred to as free carrier absorption (FCA):
Figure 2.3: Band-to-band absorption processes in a semiconductor, where (a) is single-photon interband absorption for a bulk semiconductor, (1) impurity related transitions, (2) indirect intraband excitation (free carrier absorption), (3) inter-valence band transitions of holes, and (b) is conduction subbands of a quantum well, (4) inter-subband transitions between different conduction subbands in quantum wells.

In this absorption process the electron or hole is promoted to the state of higher energy and both energy and momentum must be conserved. Since the excitation is vertical in k-space, this process requires a third particle e.g. a phonon or an impurity, of non-zero momentum.

3. Intervalance band transitions of holes: The transitions of holes from one valence band to states of higher energy in another valence band are the main mechanism in this process. Note that phonon absorption or emission are not necessary for this transition.

4. Inter-sub-band transitions of valance and conduction sub-bands in low-dimensional semiconductor nanostructures such as quantum dots, wires, wells and superlattices: A series of quasi two dimensional subbands with different energy and
effective masses can be created in low-dimensional semiconductors. Due to the geometry of the structure, the bands split into various subbands and inter-sub-band process can occur.

2.2.2 Nonlinear Optical Properties

As the intensity of the incident optical field is increased, the semiconductor may not respond in the linear fashion as described by Eq. 2.9. In this case, one typically expands the polarization in a power series, in $E$,

$$P = \varepsilon_0 \left[ \chi^{(1)}E + \chi^{(2)}EE + \chi^{(3)}EEE + \cdots \right], \quad (2.18)$$

where $\chi^{(1)}$ is the linear, first-order susceptibility, $\chi^{(2)}$ is the second-order susceptibility, $\chi^{(3)}$ is the third-order susceptibility and so forth. While $\chi^{(1)}$ is responsible for the linear optical properties described earlier, $\chi^{(2)}$ is responsible for such nonlinear processes as second-harmonic generation, sum- and difference-frequency generation and optical rectification. Second-order effects are nonresonant processes, also known as parametric processes, and are only found in non-centrosymmetric materials [62] or near surfaces of centrosymmetric materials [63]. Second-order processes are used extensively in ultrafast pulse characterization, optical frequency conversion, optical parametric oscillation or amplification, and surface studies. The third-order susceptibility, $\chi^{(3)}$, is responsible for such nonlinearities as third-harmonic generation, stimulated Brillouin scattering, Raman scattering, the AC Kerr effect, and two-photon absorption (2PA).

In general these susceptibilities are tensors, which for $\chi^{(3)}$ is rank four and written explicitly as,

$$\chi^{(3)} \rightarrow \chi^{(3)}_{ijkl} [\omega_4; \omega_1, \omega_2, \omega_3], \quad (2.19)$$

where $\omega_4 = \omega_1 + \omega_2 + \omega_3$. The indices $i, j, k,$ and $l$ reflect the three possible polarization directions: $\hat{x}$, $\hat{y}$, and $\hat{z}$. Using this new power series relationship the wave equation
can be re-written as,
\[ \nabla^2 E - \frac{\varepsilon^{(1)} \partial^2 E}{c^2 \partial t^2} = \frac{1}{\varepsilon_0 c^2} \frac{\partial^2 P^\text{NL}}{\partial t^2}, \]  
(2.20)

where \( \varepsilon^{(1)} \) is the linear relative permittivity introduced in Section 2.2.1 and \( P^\text{NL} \) are the nonlinear terms in Eq. 2.18. This is referred to as the nonlinear wave equation.

### 2.3 Semiconductor Nonlinearities

Semiconductor nonlinearities are the fundamental source of obtaining data from bulk or superlattice structures in this dissertation. The phenomena such as free carrier absorption (FCA) and band filling, arise from excited charge carriers, and are the focus of this section. Both the resonant and nonresonant absorption processes take the form,

\[ \alpha = \alpha_o + \Delta \alpha, \]  
(2.21)

where \( \alpha \) is the equilibrium absorption coefficient and \( \Delta \alpha \) is the intensity-dependent change in absorption. The total change in absorption coefficient can then be written as,

\[ \Delta \alpha = \Delta \alpha_{\text{NR}} + \Delta \alpha_{\text{R}}, \]  
(2.22)

where \( \Delta \alpha_{\text{NR}} \) are the nonresonant changes in absorption coefficient arising from the instantaneous electronic effects (e.g. multi-photon absorption (MPA)) and \( \Delta \alpha_{\text{R}} \) are the resonant changes in absorption coefficient arising from the slower excited carrier effects such as band filling and FCA. A major distinction between these two nonlinear absorption processes is that the excited carrier effects are devoid of information pertaining to the pump (i.e. wavelength, pulse width, etc.). The critical parameter for those effects is the density of excited carriers and not how they became excited. This is in contrast to MPA, where the absorption process is highly dependent on the properties of the pump.
2.3.1 Excited Carrier Relaxation

A dense population of nonequilibrium carriers is excited into the energy bands when an optical pulse is absorbed through resonances between valence and conduction band states. This initial population of excited carriers cannot be assigned a single temperature describing the entire population and is therefore different from a Fermi-Dirac distribution.

When a semiconductor system in equilibrium is excited by an ultrafast optical pulse, the new state of the semiconductor is nonequilibrium. This is followed by a complex relaxation process which partially occurs on ultrafast time scales [64,65]. The carrier relaxation process can be classified in four temporally overlapping regimes [66].

1. Coherent Regime ($\leq 200$ fs): The initial ultrafast pulse creates an excitation which has a well-defined phase relation between itself and the excited electronic system. Coherence in atomic and molecular systems and defect states in semiconductors have been already studied extensively, however the coherence of intrinsic states in semiconductors has been investigated only in last decade. The reason is the scattering processes that destroy the coherence are extremely fast in semiconductors so pico- and femtosecond techniques are required. The main processes can be identified as carrier-carrier scattering, intervalley scattering.

2. Non-Thermal Regime ($\leq 2$ ps): Shortly after the initial pulse, the excitation (free electron-hole pairs or excitons) distribution cannot be characterized by a temperature, as it is non-thermal. Investigation of this regime provides information about the carrier-carrier or exciton-exciton scattering processes.

3. Hot-Carrier Regime ($\sim 1 – 100$ ps): The injected energy is distributed into the system by mainly carrier-carrier (or exciton-exciton) scattering and can be characterized by temperature. The thermalization process highly depends on the number of the carriers in the system. In this hot regime, investigating the
cooling rate of carriers to the lattice temperature, provides various information about the system such as carrier-phonon, exciton-phonon, and phonon-phonon scattering processes.

4. Isothermal Regime ($\leq 100$ ps): Once the hot-carrier regime is mostly over, the population of carriers, phonons, and excitons achieve thermal equilibrium at the lattice temperature. However, there are still excess electron-hole pairs in the system compared to the thermodynamic equilibrium. Therefore, these excess carriers recombine either through radiative or non-radiative processes [65,67]. A primary focus in this dissertation is the investigation of these recombination processes.

It must be emphasized that initially all four physical processes leading to relaxation in different regimes are occurring almost simultaneously in a semiconductor. That means, the processes that destroy the coherence may also contribute the thermalization of carrier distribution [68].

In summary, on a time scale of 10’s to 100’s of femtoseconds the carriers thermalize with one another through carrier-carrier scattering and reach a common temperature. Typically, within 10’s of picoseconds (ps) these thermalized carriers cool to the lattice temperature through phonon emission and begin to occupy states near the band-edges. This process of carrier relaxation is illustrated in Fig. 2.4. Note that while only the electron density is shown in Fig. 2.4, a complementary plot is easily made for excited holes in the valence bands. How these excited carriers relax back to equilibrium through various recombination mechanisms is discussed in a later section.

2.3.2 Band Filling

As excited carriers cool, they fill previously unoccupied states near the band-edges, a phenomenon known as band filling [69]. Historically, the shift in bandgap energy to higher energies due to band filling has been referred to as the Moss-Burstein
Figure 2.4: Simplified schematic of the charge relaxation in a semiconductor as a function of time.

Figure 2.5: Simplified schematic of the generation, cooling, and band filling of excess carriers, where (a) illustrates these processes from a band structure point-of-view and (b) illustrates these processes from the point-of-view of the electron density in the conduction bands. The labels correspond to (I) the above-bandgap optical excitation of charge carriers, (II) the thermalization of the excited carriers through carrier-carrier scattering, and (III) the cooling of the carriers to the band-edges through phonon emission.
shift \cite{51,70}. When band-edge states are filled by excited charge carriers, a bleaching of the absorption coefficient occurs due to the optically coupled states being filled. This process is modeled as a carrier density dependent modification to the equilibrium absorption coefficient as,

\begin{align}
\alpha(\omega, N) &= \alpha(\omega) + \Delta \alpha(\omega, N), \quad (2.23a) \\
\Delta \alpha(\omega, N) &= -\alpha(\omega) [f_e(\omega, N) + f_h(\omega, N)]. \quad (2.23b)
\end{align}

where $\alpha(\omega)$ is the linear, equilibrium absorption coefficient at frequency $\omega$, $f_e(\omega, N)$ and $f_h(\omega, N)$ are the quasi-Fermi functions which describe the state occupations for the electrons and holes, respectively, and $\Delta \alpha(\omega, N)$ is the carrier-density dependent change in absorption. This has the same form as Eq. 2.21, where the absorption coefficient is dependent upon the incident optical excitation (i.e. the larger the pump fluence, the greater the excited charge carrier population). The band filling effect is shown in Fig. 2.5 for a MWIR InAs/GaSb T2SL, where $\alpha(\omega, N)$ is plotted as a function of energy for different excess carrier concentrations. The above bandgap absorption coefficient decreases with increasing excess carrier density, corresponding to the excited charge carriers bleaching the optical absorption. Below-bandgap, the absorption increases due to increased inter-subband absorption. For a large enough excess charge carrier density the band filling effect will saturate as no more states are available to fill.

As the quasi-Fermi functions can take values between 0 and 1, at large enough excess carrier densities band filling can counteract the fundamental absorption such that $\alpha = 0$ and the material becomes optically transparent near the band-edges. At larger excess carrier densities, the absorption coefficient can become negative ($\alpha < 0$) and optical gain occurs, which is an important effect for semiconductor lasers \cite{71}. Band filling is observed as an increase in transmission of an optical probe that is tuned to the semiconductor’s band-edge states, the magnitude of which is dependent on the
2.3.3 Free-Carrier Absorption

The absorption coefficient in direct gap semiconductors is also modified by excited charge carriers through FCA and phonon-assisted transitions, which lead to an increase in absorption. The FCA absorption coefficient is expressed as [72],

\[ \alpha_{\text{FCA}} = \frac{q^3 \lambda^2 N}{4 \pi^2 c^3 \varepsilon_0 m^* \mu} , \]  

(2.24)

where \( \lambda \) is the wavelength of the incident optical field, \( m^* \) is the effective mass of the involved carrier (either electrons or holes), \( \mu \) is the mobility of the carrier type, and \( N \) is the excess carrier density. Since \( N \) is dependent on the pump fluence, FCA is a nonlinear effect. Additionally, the squared dependence on wavelength makes FCA most noticeable for longer wavelengths, or in other words, low-energy, below-bandgap
2.4 Equilibrium Charge Carrier Properties

In order to determine the distribution of charge carriers throughout the allowed energy levels, it is first necessary to determine the probability that a particular state will be occupied. For a temperature \( T \) and an energy \( E \) this probability is given by,

\[
f_e(E) = \frac{1}{e^{(E-E_f)/k_B T} + 1},
\]

(2.25)

where \( E_f \) is the Fermi energy and \( k_B \) is Boltzmann’s Constant. This is the Fermi-Dirac distribution function which calculates the probability of a conduction band energy level being occupied by an electron. The Fermi energy defines the energy at which the probability of a level being occupied is precisely 50%. Similarly, the probability of a level being unoccupied by an electron is,

\[
f_h(E) = 1 - f_e(E) = \frac{1}{e^{(E_f-E)/k_B T} + 1}.
\]

(2.26)

This describes the probability that a valence band energy level is occupied by a positively charged hole. The density of electrons \( n \) and holes \( p \) is then found using,

\[
n = \int_{E_c}^{\infty} g_c(E) f_e(E) \, dE,
\]

(2.27a)

\[
p = \int_{-\infty}^{E_v} g_v(E) f_h(E) \, dE,
\]

(2.27b)

where \( g_c(E) \) and \( g_v(E) \) are the density-of-states for the conduction and valence bands, respectively. As the Fermi-Dirac functions tend to zero for energy levels far away from the Fermi energy, it is justifiable to set the integration limits to infinity. For a
nondegenerate, 3 dimensional semiconductor the density-of-states are,

\[ g_c(E) = \frac{1}{2\pi^2} \left( \frac{2m_e}{\hbar^2} \right)^{3/2} (E - E_c)^{1/2}, \] (2.28a)

\[ g_v(E) = \frac{1}{2\pi^2} \left( \frac{2m_h}{\hbar^2} \right)^{3/2} (E_v - E)^{1/2}. \] (2.28b)

In contrast to a 3 dimensional structure, the density-of-states for a 2 dimensional structure, such as a MQW, is a step function (e.g. Chu et al. [73]). This is due to the charge carriers being strictly confined to the in-plane direction of the potential wells. A SL, however, is a composite of these two quantum structures, with primary confinement of charge carriers to the in-plane direction and a small vertical component arising from the non-zero wavefunction overlap in that direction. This type of structure is neither 2 dimensional nor 3 dimensional and is referred to as quasi-2 dimensional. This effect is illustrated in Fig. 2.7.

Figure 2.7: Simplified illustration of the density-of-states for 3, 2 and quasi-2 dimensional quantum structures.
2.4.1 Intrinsic Semiconductors

An intrinsic semiconductor has a perfect crystal lattice with no defect or impurity atoms, and therefore no defect energy levels. For a nondegenerate semiconductor in thermal equilibrium, the carrier densities are constant and the Fermi-Dirac distribution functions are reliably replaced by Maxwell-Boltzmann distribution functions [74]. The equilibrium carrier densities are then,

\[ n_o = N_c e^{(E_f - E_c)/k_B T}, \quad \text{(2.29a)} \]
\[ p_o = N_v e^{(E_v - E_f)/k_B T}, \quad \text{(2.29b)} \]

where \( n_o \) and \( p_o \) are the equilibrium electron and hole concentrations and \( N_c \) and \( N_v \) are the effective conduction and valence band density-of-states, respectively, defined as,

\[ N_c = 2 \left[ \frac{2\pi m_e k_B T}{\hbar^2} \right]^{3/2}, \quad \text{(2.30a)} \]
\[ N_v = 2 \left[ \frac{2\pi m_h k_B T}{\hbar^2} \right]^{3/2}. \quad \text{(2.30b)} \]

The product of the equilibrium densities is equal to the square of the intrinsic carrier density \( n_i \) and is referred to as the law of mass action;

\[ n_o p_o = N_c N_v e^{(E_v - E_c)/k_B T} = n_i^2. \quad \text{(2.31)} \]

The intrinsic carrier density can then be written as,

\[ n_i = \sqrt{N_c N_v e^{(E_v - E_c)/2k_B T}}. \quad \text{(2.32)} \]

When this condition is perturbed by the injection of excess carriers, either optically or electrically, a non-equilibrium state is created such that,

\[ np > n_i^2, \quad \text{(2.33)} \]
where \( n = n_o + \Delta n \) and \( p = p_o + \Delta p \), with \( \Delta n \) and \( \Delta p \) representing the excess electron and hole carrier densities, respectively. Carrier recombination will then occur until the semiconductor has returned to equilibrium. An assumption routinely made in this dissertation is that \( \Delta n = \Delta p \), which is justifiable for band-to-band generation and recombination.

The Fermi energy is determined by requiring that the number of electrons in the conduction bands equals the number of holes in the valence bands, which for a 3 dimensional semiconductor is,

\[
E_f = \frac{E_g}{2} + \frac{3}{4}k_BT \ln \left( \frac{m_h}{m_e} \right). \tag{2.34}
\]

At zero temperature the Fermi energy lies in the middle of the bandgap. As the temperature increases the Fermi energy shifts towards a band-edge.

An important concept in semiconductor theory is degeneracy of the charge carriers. An intrinsic semiconductor is considered non-degenerate when the Fermi energy lies within the energy gap and is separated from the conduction and valence band-edges by a few \( k_BT \). More formally, the conditions for nondegeneracy are,

\[
E_v < E_f < E_c \quad \quad E_c - E_f \gg k_BT \quad \quad E_f - E_v \gg k_BT. \tag{2.35}
\]

When these conditions are no longer met, the charge carriers become degenerate in their respective energy bands. This can occur in both highly excited semiconductors and/or material that has been heavily doped with impurities to increase the background carrier population.

### 2.4.2 Extrinsic Semiconductors

A semiconductor that has impurities or defects in the crystal lattice is referred to as an extrinsic semiconductor. The impurity atoms create allowed energy states within the forbidden energy gap and can be present due to unintentional defects or
through intentional doping with specific impurities. When a semiconductor is doped with a donor impurity it is referred to as n-type as the impurities donate electrons to the crystal lattice and leave behind ionized donor atoms. Doping with an acceptor impurity will make a p-type semiconductor and results in an increased amount of holes in the valence bands as electrons occupy the impurity states. By including defect and impurity atoms, states are created in the energy gap which provide potential avenues for nonradiative recombination to occur.

In a doped (extrinsic) semiconductor, the Fermi energy level and the equilibrium electron and hole densities depend on the type and the concentration of the doping. The created doping concentration in the semiconductor creates impurities that are incorporated substitutionally on lattice sites that form and control shallow or deep energy levels in the forbidden bandgap. In a broader definition, a semiconductor that has impurities or defects in the crystal lattice is referred as an extrinsic semiconductor. The impurity atoms will create allowed energy states within the forbidden energy gap and can be present due to unintentional defects or through intentional doping with specific impurities. When a semiconductor is doped with a donor impurity it is referred to as n-type as the impurities donate electrons to the crystal lattice. Doping with an acceptor impurity will make a p-type semiconductor as there will be an increased amount of holes added to the semiconductor. Typical doping concentrations range from $10^{13}$–$10^{19}$ dopant atoms per cm$^3$. Since the dopant density is higher than $n_i$, it creates a distinction in electrons and holes into minority and majority carriers according to the law of mass action.

In the non-equilibrium case or when the semiconductor is heavily doped, the Fermi energy may intersect with the conduction or valence bands. When this happens, the semiconductor becomes degenerate. The degeneracy of bands is especially important when investigating Auger processes since it is proportional with the square of the excess and background carrier densities [65].
In general, the majority carrier concentration in a doped semiconductor is taken as temperature independent, which is a sufficient method to analyze systems at ambient temperatures. However, at low temperatures, the density of the ionized doping atoms reduces due to the reduced energy available for the thermal excitation in the system. As a result, the concentration of majority carriers decreases at low temperatures and this phenomena is called freeze-out [59].

2.5 Non-equilibrium Carrier Dynamics

For a system in thermal equilibrium with the lattice, the Continuity Equations 2.36 that govern the generation, recombination and transport of electrons and holes are,

\[
\frac{\partial n}{\partial t} = G_n - R_n + \frac{1}{q} \nabla \cdot J_n, \tag{2.36a}
\]

\[
\frac{\partial p}{\partial t} = G_p - R_p - \frac{1}{q} \nabla \cdot J_p, \tag{2.36b}
\]

where \( G \) is the net generation rate, \( R \) is the net recombination rate, \( J \) is the charge current, and \( q \) is the fundamental electronic charge. The charge currents are,

\[
J_n = nq\mu_n E + qD_n \nabla n, \tag{2.37a}
\]

\[
J_p = pq\mu_p E - qD_p \nabla p, \tag{2.37b}
\]

where \( \mu_n \) and \( \mu_p \) are the electron and hole mobilities, \( D_n \) and \( D_p \) are the electron and hole ambipolar diffusion coefficients, and \( E = -\nabla \phi \) is the electric field (with \( \phi \) being the electric potential). The diffusion coefficients are related to the carrier mobilities through the Einstein relations,

\[
D_n = \frac{k_B T}{q_e} \mu_n, \tag{2.38a}
\]

\[
D_p = \frac{k_B T}{q_e} \mu_p. \tag{2.38b}
\]
When restricted to one dimension and no electric fields, the Continuity Equations can be simplified using the charge currents to yield,

\[
\frac{\partial \Delta n}{\partial t} = G - U_n + D_n \frac{\partial^2 \Delta n}{\partial x^2},
\]

(2.39a)

\[
\frac{\partial \Delta p}{\partial t} = G - U_p + D_p \frac{\partial^2 \Delta p}{\partial x^2}.
\]

(2.39b)

The net recombination rates are related to the carrier lifetimes by,

\[
R_n = \frac{\Delta n}{\tau_n},
\]

(2.40a)

\[
R_p = \frac{\Delta p}{\tau_p},
\]

(2.40b)

where \(\tau_n\) and \(\tau_p\) are the electron and hole recombination lifetimes, respectively.

Figure 2.8: Recombination mechanisms in a semiconductor, where (a) is radiative, (b) is Shockley-Read-Hall, and (c) is Auger recombination.

In general, the generation and the recombination processes can be classified as radiative recombination and non-radiative recombination including SRH and Auger as mentioned earlier. While radiative processes involve the creation and annihilation of photons, non-radiative processes do not involve photons. They may involve the
interaction of phonons and the energy and momentum transformation of electrons and holes. The fundamental mechanisms can be described using Fermi’s golden rule with the energy and momentum conservation satisfied by these processes [25].

The processes contributing to the total carrier lifetime, including both radiative and non-radiative recombination mechanisms, are illustrated in Fig. 2.8. The total carrier lifetime, $\tau$, can be written as,

$$\tau^{-1} = \tau_{SRH}^{-1} + \tau_{rad}^{-1} + \tau_{auger}^{-1}, \quad (2.41)$$

or in terms of the carrier recombination rate, $R$, as,

$$R = R_{SRH} + R_{rad} + R_{auger}. \quad (2.42)$$

The next section provides a brief discussion of all three recombination processes for non-degenerate semiconductor systems.

### 2.5.1 Radiative Recombination

The band-to-band net radiative recombination rate as given by Hall [75] is,

$$B_{rad} = B_r (np - n_i^2), \quad (2.43)$$

where $B_r$ is the radiative coefficient. Notice that if there is not an external electrical or optical excitation, the total rate is zero. For the case, $\Delta n = \Delta p$, the radiative recombination rate can be written as,

$$R_{rad} = \tau_{rad}^{-1} = B_r (n_o + p_o + \Delta n). \quad (2.44)$$

For a direct gap semiconductor,

$$B_r = \frac{1}{n_i^2} \frac{1}{\pi^2 c^2 \hbar^3} \int_0^\infty \frac{\varepsilon \alpha E^2}{\exp(E/k_B T) - 1} \, dE, \quad (2.45)$$

where $\varepsilon$ is the dielectric function, $\alpha$ is the band-to-band absorption coefficient, $c$ is the
speed of light in vacuum, and $E$ is the photon energy. The band-to-band absorption coefficient in a direct-gap semiconductor is,

$$\alpha = \frac{2^{3/2} m_o q_e^2}{3 \sqrt{\varepsilon} \ h^2} \left[ \frac{m_e m_h}{m_o (m_e + m_h)} \right]^{3/2} \left( 1 + \frac{m_o}{m_e + m_h} \right) \left( \frac{E - E_g}{m_o c^2} \right)^{1/2}. \quad (2.46)$$

The radiative coefficient can then be calculated as,

$$B_r = \frac{(2\pi)^{3/2} h q_e^2 \sqrt{\varepsilon}}{3 \ m_o^2 c^2} \left( \frac{m_o}{m_e + m_h} \right)^{3/2} \left( 1 + \frac{m_o}{m_e + m_h} \right) \frac{E_g^2}{(k_B T)^{3/2} (m_o c^2)^{1/2}}. \quad (2.47)$$

In the case of low-excitation levels, where $\Delta n \ll n_o, p_o$,

$$R_{rad} \approx B_r (n_o + p_o). \quad (2.48)$$

For n-type semiconductors $n_o \gg p_o$,

$$R_{rad} \approx B_r n_o. \quad (2.49)$$

Likewise, for p-type semiconductors $p_o \gg n_o$,

$$R_{rad} \approx B_r p_o. \quad (2.50)$$

Therefore, for low-levels of excess carriers the radiative recombination is linearly dependent on the majority background carrier density. In the case of high-excitation levels $\Delta n \gg n_o, p_o$,

$$R_{rad} \approx B_r \Delta n, \quad (2.51)$$

where the radiative recombination rate is now linearly dependent on the excess carrier density. For the optically injected carrier density case, the photon recycling (PR) factor must be taken into account as well. The intrinsic radiative coefficient, $B_r$, for a thin slab of material, is related to the measured radiative coefficient, $B$, inversely as,

$$B = B_r / \phi, \quad (2.52)$$
where $\phi$ is the photon recycling (PR) factor [8]. 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 [8, 9, 57, 76–79].

2.5.2 Shockley-Read-Hall Recombination

The Shockley-Read-Hall recombination process involves four mechanisms between the carriers, phonons and trap states [75, 80]:

1. An unoccupied recombination center captures a single electron from the conduction band (electron capture).

2. An occupied recombination center emits an electron into the conduction bands (electron emission).

3. An occupied recombination center captures a hole from the valence band (hole capture).

4. An unoccupied recombination center emits a hole into the valence bands (hole emission).

For highly n- and p-type semiconductors, the SRH lifetime can be written as,

$$\tau_{no} = \frac{1}{\sigma_n \nu_n N_t}, \quad (2.53a)$$

$$\tau_{po} = \frac{1}{\sigma_p \nu_p N_t}. \quad (2.53b)$$

where $\sigma_n$ and $\sigma_p$ are the electron and hole capture cross-section, $\nu_n$ and $\nu_p$ are the electron and hole thermal velocity, and $N_t$ is the total trap density. The thermal velocities are,

$$\nu_n = \sqrt{\frac{3kBT}{m_e}}, \quad \nu_p = \sqrt{\frac{3kBT}{m_h}}. \quad (2.54)$$
Following the approach of Shockley and Read [80], the net SRH recombination rate is,
\[ R_{SRH} = \frac{np - n_i^2}{\tau_{no}(n + n_1) + \tau_{no}(p + p_1)}. \]  
(2.55)

The so-called SRH carrier densities are given by,
\[ n_1 = N_c \exp \left[ \frac{(E_t - E_c)}{k_B T} \right], \quad p_1 = N_v \exp \left[ \frac{(E_v - E_t)}{k_B T} \right] \]  
(2.56)

Here, \( N_v \) and \( N_c \) are the effective conduction and valence band density-of-states defined as,
\[ N_c = 2 \left[ \frac{2\pi m_e k_B T}{\hbar^2} \right], \quad N_v = 2 \left[ \frac{2\pi m_h k_B T}{\hbar^2} \right]. \]  
(2.57)

The carrier densities \( n_1 \) and \( p_1 \) are the electron and hole densities when the Fermi Energy overlaps the impurity energy level, \( E_t \). It’s important to note that this net recombination rate is an approximation. Shockley and Read argued that a ”steady state” occurs as the semiconductor returns to equilibrium from a small perturbation, which allowed the assumption that \( \frac{\partial n}{\partial t} = \frac{\partial p}{\partial t} \). This approximation implies that \( \tau_n = \tau_p \).

A low density of recombination centers is also assumed in their derivation.

Using Eq. 2.40 and \( \Delta n = \Delta p \),
\[ R_{SRH} = \tau_{SRH}^{-1} = \frac{1}{\Delta n} \left[ \frac{(n_o + \Delta n)(p_o + \Delta n) - n_i^2}{\tau_{po}(n_o + n_1 + \Delta n) + \tau_{no}(p_o + p_1 + \Delta n)} \right]. \]  
(2.58)

For low-level excitation \( \Delta n \ll n_o, p_o \) and \( \Delta n \ll n_1, p_1 \), which simplifies this to,
\[ R_{SRH} \approx \frac{n_o + p_o}{\tau_{po}(n_o + n_1) + \tau_{no}(p_o + p_1)}, \]  
(2.59)

which is independent of the excess carrier density. For n-type semiconductors \( n_o \gg n_1 \) and \( n_o \gg p_o, p_1 \), which further reduces \( R_{SRH} \) to,
\[ R_{SRH} \approx \frac{1}{\tau_{po}}. \]  
(2.60)

Similarly, for a p-type semiconductor \( p_o \gg p_1 \) and \( p_o \gg n_o, n_1 \), which reduces
Figure 2.9: Excess carrier density dependence of the SRH lifetime as a function of defect level position relative to the valence band-edge for a constant background carrier density of $n_0 \times 10^{15} \text{ cm}^{-3}$.

$$R_{SRH} \approx \frac{1}{\tau_{no}}. \quad (2.61)$$

In the low-level excitation limit the SRH recombination rate is almost equal to the inverse of the respective minority carrier lifetime if the system is dominated by this process.

2.5.3 Auger Recombination

Auger recombination occurs when an electron and hole recombine and the excess energy and momentum is used to excite a third particle to a higher energy state. There are four types of interband Auger processes that can occur and are denoted by CCCH, HSCH, HCHL, and CHHH where the C, H, L and S refer to the bands involved. The CCCH process tends to dominate in n-type semiconductors as the majority of carriers involved are electrons. The CHHS, CHHL and CHHH processes dominate in p-type,
reflecting the hole majorities. The CHHH process is usually negligible compared to the others due to the heavy masses of the two heavy holes involved. The three relevant Auger processes are shown schematically in Fig. 2.10.

![Figure 2.10: The three primary interband Auger recombination processes, where (a) is the CCCH, (b) is the CHHL, and (c) the CHHS recombination process.](image)

The band-to-band net Auger recombination rate as given by Hall [75] is,

\[
R_{\text{auger}} = C_n (n^2 p - n_o^2 p_o) + C_p (np^2 - n_o^2 p_o^2),
\]

(2.62)

where \(C_n\) and \(C_p\) are the electron- and hole-dominated Auger coefficients. Assuming \(\Delta n = \Delta p\),

\[
R_{\text{auger}} = \tau_{\text{auger}}^{-1} = C_n n^2 + 2(C_n + C_p)n_i^2 + C_p p^2.
\]

(2.63)

Under high-excitation levels \(\Delta n \gg p_o, n_o\),

\[
R_{\text{auger}} \approx (C_n + C_p) \Delta n^2,
\]

(2.64)

where the Auger recombination rate depends on the square of the excess carrier density, as well as the sum of the Auger coefficients. In the low-level limit, the Auger
recombination rate in an n-type semiconductor is,

\[ R_{\text{auger}} \approx C_n n_o^2. \quad (2.65) \]

Similarly, in a p-type semiconductor under low-level excitation,

\[ R_{\text{auger}} \approx C_p p_o^2. \quad (2.66) \]

In the low-level limit, the Auger recombination rate depends on the square of the respective majority carrier density and contributes a constant factor to the total recombination rate.

Additionally, consideration of the Auger recombination is crucial for the design of IR photodetectors and photoemitters as this process can limit the best case performance of a device at high injection levels. The possible final Auger transition states are approximately one bandgap energy above the conduction band edge or below the valence band edge. Because they increase rapidly with carrier density, Auger recombination rates are very sensitive to T2SL structure design, more specifically, the layer thicknesses and alloy compositions. Auger recombination can, however, be intentionally suppressed. For example, the ability to control the inter-sub-band transitions in a T2SL allows the reduction of Auger recombination rates by limiting the possible final, higher energy states of the electrons and holes [81]. If final-state Auger optimization is not present, then the Auger rate is a function principally of the bandgap energies and the effective masses of the electrons and holes [67]. In general, \( C \) is equal to the sum of the electron dominated Auger coefficient \( (C_n) \) and the hole-dominated Auger coefficient \( (C_p) \) as \( C = C_n + C_p \) [82,83]. The electron-dominated Auger-1 process involves an electron recombining with a hole across the bandgap and the excess energy being transferred to a second electron, which is excited to a higher lying state within the conduction bands. For hole-dominated Auger processes, the excess energy is instead transmitted to a second hole which is excited to a higher
energy state in the valence bands. Note that there are a total of nine hole-dominated Auger transitions labeled Auger-2 through Auger-10. One of the most probable hole-dominated Auger recombination processes is the Auger-7 transition which involves the light-hole band. Previous studies of the Auger recombination rates for MWIR and LWIR T2SLs indicated that the Auger-7 lifetimes are orders of magnitude longer than the Auger-1 lifetimes, as a consequence of large strain-induced splitting of the SLs valance sub-bands eliminating possible final Auger transition states [81].

2.5.4 Carrier Transport

One of the biggest strengths of the ultrafast spectroscopy is its ability for investigating the dynamics of carrier transport in semiconductors. The motion of carriers can be governed by two basic mechanisms. One is the drift due to an external excitation to the carriers and the other is the diffusion of carriers due to the inhomogeneous distribution of carriers in semiconductor. In experiments with no external field applied, the total conductivity in a semiconductor can be written as the summation of electron and hole conductivities,

\[ \sigma = \sigma_n + \sigma_p \]

\[ = e (n\mu_n + p\mu_p), \]

(2.67)

where \( \sigma_n \) and \( \sigma_p \) are the electron and hole conductivities, respectively. From Eq. 2.36 for one dimensional motion, the conductivity equation can be re-written as,

\[ \frac{\partial \Delta n}{\partial t} = G - U_N + D_{amb} \frac{\partial^2 \Delta n}{\partial x^2} - \mu_{amb} E \frac{\partial \Delta n}{\partial x}, \]

(2.68)

where \( \Delta n = \Delta p \). This Equation describes the united motion of electrons and holes with a mobility, \( \mu_{amb} \), and diffusion coefficient, \( D_{amb} \). The definition of the ambipolar
The in-plane ambipolar diffusion coefficient is,

\[ D_{amb} = \frac{\sigma_n D_p + \sigma_p D_n}{\sigma_n + \sigma_p} \]

\[ = \frac{n + p}{n/D_p + p/D_n}, \tag{2.69} \]

and the ambipolar mobility is,

\[ \mu_{amb} = \frac{\sigma_n \mu_p - \sigma_p \mu_n}{\sigma_n + \sigma_p} \]

\[ = \frac{n - p}{n/\mu_p + p/\mu_n}. \tag{2.70} \]

Under high excitation levels, where \( \Delta n \gg n_o, p_o \), or for near intrinsic material (i.e. \( n_o = p_o \)) the in-plane ambipolar diffusion coefficient reduces to,

\[ D_{amb} = \frac{2D_n D_p}{D_n + D_p} \]

\[ = \frac{2k_B T}{q} \frac{\mu_n \mu_p}{\mu_n + \mu_p}. \tag{2.71} \]

For InAs/InAsSb T2SLs, the effective electron masses are two orders of magnitude and an order of magnitude lighter than the hole masses in the vertical and in-plane directions, respectively. This makes the hole mobility slower than electrons and therefore the ambipolar diffusion coefficient becomes highly dependent on holes. The holes tend to be confined to the InAsSb layers, \( D_p \) is typically much less than \( D_n \), and carriers under high-excitation levels move with a diffusion coefficient that is equal to \( 2D_h \). Interestingly, for n-type semiconductors under low-level excitation, the diffusion coefficient reduces to,

\[ D_{amb} \approx D_p, \tag{2.72} \]

where the excess carrier pairs diffuse with a coefficient that is equal to the hole diffusion coefficient. Similarly, for p-type semiconductors in the low-level limit,

\[ D_{amb} \approx D_n, \tag{2.73} \]
where now the carrier pair motion is governed by the electron diffusion coefficient. It is therefore possible to investigate the individual transport properties of electrons and holes by measuring diffusion in doped semiconductors under low-level excitation.
CHAPTER 3
ULTRAFAST SPECTROSCOPY

The relaxation process of a material after a short optical (or electrical) excitation is introduced to the system was discussed in the previous chapter. Since we are ultimately interested in carrier recombination and carrier transport that persist for only sub-microseconds, there are undeniable advantages using ultrashort pulses to investigate these processes in low-dimensional semiconductors. In this chapter, ultrafast pump-probe spectroscopy equipment and methodology will be introduced, and the process of data acquisition for the proposed research will be discussed.

3.1 Pump-Probe Measurements

The pump-probe method is the main experimental technique that will be used in this research to investigate the electrical and optical properties of narrow band gap semiconductors at various temperatures, from cryogenic to room temperature. During pump-probe measurements, the sample structure is first irradiated with an intense optical excitation pulse that causes a change in the absorption due to the band filling process, and/or free carrier or intersubband absorption. This initial pulse is followed at a variable time later by a much weaker probe pulse that monitors the change of the transmission as the carriers return to their equilibrium condition. An amplified Ti-Sapphire laser generating 130 fs pulses at a repetition rate of 1 kHz is used to pump an optical parametric amplifier (OPA). In our setup, two synchronized OPAs can be used for pump-probe measurements. These OPAs can be tuned from the MWIR to LWIR and VLWIR with ~150 fs temporal width. Additionally, by using the digital time delay technique, a quantum cascade laser (QCL) is integrated into the system in order to probe in longer time delays between pump and probe. For more information, the reader is advised to see Dr. Olson’s Ph.D. thesis [17].

In carrier recombination rate measurements, the pulsed QCL, which is digitally
synchronized to the pump, is used as an optical probe to monitor the change in transmission of a sample. The maximum time delay between the pump and probe is limited only by the repetition rate of the pump pulse train which, for the QCL, is 1 ms. The digital time delay method eliminates the basic tracking problems of mechanical time delay stages and imperfections of the pump pulse beam collimation once they are initially set. The time resolution of the differential transmission data is set by the cross correlation between the $\sim 150$ fs pump pulse and the $\sim 3$ ns QCL probe, which is around $3 - 4$ ns at FWHM of the pulse as shown in Fig. 3.1 [17].

Figure 3.1: Cross-correlation of a 180 fs OPA pulse and the QCL pulse using two-photon absorption in HgCdTe. The red curve is a Gaussian fit to the data, providing a FWHM pulse width of 3.4 ns. The data are inverted for ease of viewing. (Credit: Dr. Olson [17])

A closed cycle, low vibration cryostat is used for housing the samples and controlling the lattice temperature from 10 K to 293 K. The pump and probe beams are spatially overlapped on the sample with a radius ($e^{-1}$ of intensity) of $\approx 1100 \pm 100 \mu m$ and $\approx 200 \pm 20 \mu m$, respectively, for the differential-transmission measurements covered in this dissertation. The optical energy injected into the system is attenuated
by a pair of teflon polarizers in the fluence range of 2200 nJ/cm² to 200 nJ/cm². The initial optically injected excess carrier density values are calculated using theoretical absorption coefficients. Time-dependent differential-transmission is obtained using a chopper at 500 Hz which is referenced by the pump clock. Therefore, the detector signal is processed using a gated integrator and lock-in amplifier and the QCL probe signal is collected with a cooled, single element HgCdTe detector. The homogenous distribution of excess carrier density at the probed region of the samples is ensured by having a considerably larger spot size of the pump relative to the probe pulse [17].

Figure 3.2: A schematic diagram of the synchronized, two-color pump-probe fs system is shown for traditional (a) and digital (b) delay options. Here, S refers to the ample and D refers to the detector.

OPAs are ideally suited to be pumped by amplified Ti:Sapphires as very large peak powers are required for efficient frequency conversion in a single pass through a crystal. A schematic diagram of the ultrafast laser system used in this work is shown in Fig. 3.2. The OPA process uses optical parametric generation [84,85], where in an appropriate nonlinear crystal a high-intensity pump beam at frequency $\omega_{pump}$ amplifies a low-intensity seed beam (the signal) at frequency $\omega_{signal}$. Due to energy conservation, a third beam (the idler) at frequency $\omega_{idler}$ must also be created such
that,  
\[ \hbar \omega_{\text{pump}} = \hbar \omega_{\text{signal}} + \hbar \omega_{\text{idler}}. \]  
(3.1)

where typically \( \omega_{\text{idler}} \leq \omega_{\text{signal}} \leq \omega_{\text{pump}} \). For efficiency considerations, the phase matching condition must be met and is expressed as,

\[ k_{\text{pump}} = k_{\text{signal}} + k_{\text{idler}} \]  
(3.2)

where \( k \) is the wavevector for the respective beam. The OPAs used in this research have a variable wavelength seed created by focusing a small portion of the pump into a sapphire plate to create a white-light continuum [86]. With this white-light continuum pre-amplifier, the OPAs are capable of creating signal and idler beams tunable from 1.1 – 1.6 \( \mu \)m and 1.5 – 2.6 \( \mu \)m, respectively, with combined average powers in excess of 200 mW from a fixed wavelength pump source. To extend the tuning range of the OPA deeper into the IR, the signal and idler are used for difference-frequency generation (DFG) [87], wherein the signal and idler are phase-matched in a suitable nonlinear crystal and the following conditions must be met,

\[ \hbar \omega_{\text{DFG}} = \hbar \omega_{\text{signal}} - \hbar \omega_{\text{idler}} \]  
(3.3a)

\[ k_{\text{DFG}} = k_{\text{signal}} - k_{\text{idler}}. \]  
(3.3b)

As the signal and idler are capable of reaching degeneracy \( (\omega_{\text{signal}} = \omega_{\text{idler}}) \) for this system, the tuning range of the DFG is limited by the material properties of the DFG crystal. The current set of DFG crystals are capable of producing efficient sub-picosecond pulses from 2.5 – 18 \( \mu \)m with pulse energies ranging from 1-15 \( \mu \)J as shown in Fig. 3.3.
3.2 Data Acquisition

Optical and electrical properties of narrow bandgap T2SLs are studied with time-resolved differential-transmission and photo-generated transient grating techniques. Optical properties such as density dependent changes in absorption and refraction as well as the electrical properties such as SRH and Auger recombination mechanisms can be understood by these two techniques.

3.2.1 Time-resolved Differential-Transmission

The time-resolved differential-transmission technique is used to study the electric and optical properties of narrow bandgap semiconductors. In this technique, as
explained for pump-probe spectroscopy, a pump pulse creates the nonequilibrium carrier distribution and then the relatively weaker probe beam monitors the change in transmission. This change in transmission can be express as,

$$\Delta T/T = \frac{T_{\text{on}} - T_{\text{off}}}{T_{\text{off}}}, \quad (3.4)$$

where $T_{\text{on}} = (1 - R_F)^2 e^{-\alpha_0 L e^{-\Delta \alpha L}}$, $T_{\text{off}} = (1 - R_F)^2 e^{-\alpha_0 L}$ are the transmission of the probe through the sample with the pump present and not present, respectively. Here also, $R_F$ is the Fresnel reflection coefficient and $L$ is the sample thickness. $\Delta T/T$ is then found to be,

$$\Delta \alpha L = -\log \left( 1 + \frac{\Delta T}{T} \right), \quad (3.5)$$

which for small changes in transmission is $\Delta T/T \approx -\Delta \alpha L$. Therefore, by varying the pump intensity and energy, $\Delta \alpha(N, \lambda)$ can be found. Other than measuring the density dependent optical properties, the time-resolved differential transmission technique provides an enormous amount of information about the carrier recombination. Once the pump pulses arrive on the sample surface, they are absorbed high in the energy bands creating a dense population of non-equilibrium. The expressions for the fluence and the excess carrier density are,

$$F_e = (1 - R_F) T_{\text{opt}} \frac{P_e}{\pi \omega_e^2 R_R}, \quad (3.6a)$$

$$\Delta n = \frac{F_e \lambda_e}{\hbar c L} \left[ 1 - e^{-\alpha_e L} \right], \quad (3.6b)$$

where $F_e$ is the measured pump fluence, $T_{\text{opt}}$ is the transmission of the cryostat window, $\omega_e$ is the pump radius ($e^{-1}$ intensity), and $R_R$ is the pump repetition rate. $P_e$ is the power which is measured directly in front of the sample by a broadband, high sensitivity thermal power-meter. As a consequence of various scattering processes, these photogenerated carriers thermalize in less than a picosecond, creating a hot-carrier electron-hole distribution. Within picoseconds, this hot distribution cools to
Figure 3.4: 77 K time-resolved differential transmission data for multiple initial injected excess carrier densities for a MWIR InAs/InAs$_{0.50}$Sb$_{0.50}$ T2SL structure. In (a) the initial development of band filling and (b) the full time range recovery of the differential transmission as the carriers recombine are plotted for initial injected carrier densities ranging from $1 \times 10^{16}$ cm$^{-3}$ to $8 \times 10^{16}$ cm$^{-3}$. In (c), the maximum values of differential transmission, which occur shortly after zero time delay, and corresponding initial carrier densities are demonstrated.

the lattice temperature (via phonon emission), leaving a nonequilibrium population of electrons (holes) in the conduction (valance) band. This band-filling process causes a change in the absorption coefficient and increases the probe transmission through the sample as mentioned in the previous chapter. The effect of band filling on absorption is $\Delta\alpha(N, \lambda) = -\alpha_0(\lambda) [f_e(N, \lambda) + f_h(N, \lambda)]$. Here, $f_e$ and $f_h$ are quasi-fermi functions for electrons and holes, respectively. $\Delta T/T$ data was taken for a range of initial photogenerated carrier densities, of which a subset is shown in Fig. 3.4.

As an example of this type of decay curve, an unintentionally-doped MWIR InAs/InAs$_{0.50}$Sb$_{0.50}$ T2SL ($E_g = 244$ meV) with an approximate thickness of 3.5 $\mu$m was characterized at 77 K. A pump wavelength of 3.55 $\mu$m was chosen to provide a large optical penetration depth. For this wavelength and structure, an absorption coefficient of 3707.6 cm$^{-1}$ at 77 K, was calculated using the $\mathbf{k} \cdot \mathbf{p}$ model. The pump and probe were spatially overlapped on the sample and measured to have radii ($e^{-1}$ of the intensity) of 1080 $\mu$m and 180 $\mu$m, respectively. A smaller probe spot size and a
large pump penetration depth relative to the T2SL thickness justifies the assumption that a homogeneous distribution carrier density was probed on the sample surface. A pair of teflon polarizers were used to attenuate the injected excess carrier densities shown in Fig. 3.4(c).

The $\Delta T/T_{\text{Max}}$ vs. $\Delta n_{\text{Max}}$ and $\Delta T/T$ vs. time-delay plots provide enough information to calculate the density dependent recombination rate using,

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

which is the recombination rate per electron-hole pair.

3.2.2 Photo-generated transient grating experiment

The photo-generated transient grating experiment can be seen as an extension of the pump-probe setup with an additional pump beam introduced into the system [53, 55, 56, 88]. These two pump pulses are used to create intensity modulation of charges in the sample through interference of the spatially and temporally overlapped pulses in the sample of interest.

In the simplest configuration, this interference produces a modulated irradiance in the sample of interest, which in turn produces a modulated change in both the absorption coefficient and refractive index [56]. This modulation of the optical properties acts as a grating, which will diffract a third time-delayed probe beam (see Fig. 3.5). The duration of the modulation depends on both the recombination of non-equilibrium carriers, as well as diffusion of carriers from the peak to the troughs of the modulation. Hence, this all-optical measurement allows one to obtain both the diffusion coefficient and the recombination dynamics. The period and efficiency of the intensity modulation can be controlled by the optical and geometric properties of pulses. For example, the period, $\Lambda$, can be controlled by the pump angles from sample normal, $\theta_e/2$, and pump wavelength, $\lambda_e$ as seen in Eq. 3.8 for the experimental setup
Figure 3.5: Schematic diagram of a typical transient grating arrangement.

shown in Fig. 3.5.

\[
\Lambda \simeq \frac{\lambda_e}{2 \sin \left(\frac{\theta_e}{2}\right)}
\]  

(3.8)

Figure 3.6: The grating period, \( \Lambda \), given as a function of pump wavelength for a \( \theta_e \simeq 10^\circ \).
Note that the interference modulation depth, $\mu$, is proportional to the injected carrier distribution into the sample,

$$\Delta n_0(x, t = 0) = N_0 \left[ 1 + \mu \cos \left( \frac{2\pi x}{\Lambda} \right) \right]$$

(3.9)

where $N_0$ is the average carrier density of the grating given by the summation of the individual contributions $N_0 = N_1 + N_2$ of the pump pulses along the x-axis, which is perpendicular to the growth direction (and the sample surface). The modulation depth is defined as $\mu = 2\sqrt{F_1 F_2} / (F_1 + F_2)$. Here $F_1$ and $F_2$ are the fluences (see Eq. 3.6) created by the first and second pump pulses, respectively. The modulation depth is useful to determine the peak-to-peak carrier density which is defined as $N_{pp} = 2\mu N_0$.

The diffraction efficiency at zero delay, when the absorption, $\alpha(\Delta n)$, and index of refraction, $n_{ind}(\Delta n)$, are linear functions of density, is given as,

$$\eta \simeq \frac{d^2}{4} \left[ \left( \frac{\pi \Delta n_{ind}}{\lambda_{probe}} \right)^2 + \left( \frac{\Delta \alpha_{pp}}{4} \right)^2 \right] .$$

(3.10)

where $\Delta n_{p-p}$ and $\Delta \alpha_{pp}$ refer to the peak-to-peak differences in refractive index and absorption, respectively (for more details see Appendix B). It must be noted that $\eta \ll 1$ in typical experiments. The approximation used to calculate the non-sinusoidal carrier distribution of the grating is covered in detail in the thesis of Dr. Anson [56].

The initial carrier distribution $\Delta n(x, t = 0) = N_0$ must be adjusted in the time domain form, $\Delta n(x, t)$. From the solution of continuity equations (Eq. 2.36) in one-dimension, the carrier distribution as a function of time can be expressed as,

$$\Delta n(x, t) = N_0 \left[ 1 + \mu \cos \left( \frac{2\pi x}{\Lambda} \right) e^{-t/\tau_D} \right] e^{-t/\tau_R}$$

(3.11)

where $\tau_D = \Lambda^2 / 4\pi^2 D_a$ is the diffusion lifetime, $\tau_R$ is the constant recombination lifetime. The constant recombination lifetime assumption is valid only for the low level injection densities where the MC lifetime becomes excess carrier density independent (as obtained from the previously described pump-probe measurement). The diffraction
efficiency decays according to,

\[ \eta \simeq \frac{d^2}{4} \left[ \left( \frac{\pi \Delta n_{pp}}{\lambda_{probe}} \right)^2 + \left( \frac{\Delta \alpha_{pp}}{4} \right)^2 \right] e^{-2t/\tau_G}, \]  

(3.12)

where \( \tau_G^{-1} = \tau_D^{-1} + \tau_R^{-1} \).

Therefore, by monitoring the diffracted probe signal as a function of time, the decay of the grating due to diffusion and recombination can be measured. From this set of expressions, the ambipolar diffusion coefficient can be obtained from,

\[ \tau_G^{-1} = D_a \frac{4\pi^2}{\Lambda^2} + \tau_R^{-1}. \]  

(3.13)

The geometry of incoming beams on the sample surface is crucial since it effects the modulation. The relation between pump and probe angles can be defined as, \( \phi = \theta_p + \theta_e/2 \), with respect to the normal of the sample surface. In order to predict the diffracted probe beam angle, the geometry of the experimental setup as well as the material parameters, must be specified.

For the refractive index value at the pump wavelength, \( n \), the period of modulation is given by,

\[ \Lambda = \frac{\lambda_e}{2n\sin\left[\frac{1}{2}\arcsin(1/n\sin(\theta_e))\right]} \simeq \frac{\lambda_e}{2\sin(\theta_e/2)}. \]  

(3.14)

Here, a small angle approximation is used for the \( \theta_e \).

The assumption of a thin grating will be made for the scale factor, \( Q \), which is given by,

\[ Q = \frac{2\pi d\lambda_p}{\Lambda^2 n_p} \ll 1 \]  

(3.15)

where, \( d \) is the active region thickness of the sample and \( n_p \) is the index of refraction at the probe wavelength. The condition that the scale factor is much smaller than 1 means that the phase difference between the diffracted waves is small enough that they interfere constructively. If not, the Bragg condition must be satisfied by controlling the incident beam angles. The dependence of \( Q \) on grating period is shown in Fig. 3.7.
The incident angle of the probe for a specific orientation of pump pulses must be defined so that the diffracted probe beam angle can be calculated. Therefore the Q factor must be controlled to ensure the validity of the thin grating assumption. It can be seen that the Q scale factor satisfies the condition of a 4 µm-thick sample at 3.5 µm probe wavelength for grating periods between 10 – 20 µm. In order to keep the grating period in this range, the pump angle must be approximately 5 – 15° relative to each other. Now we will derive the exit angle of the probe beam behind the sample using Snell’s law with the parameters set for the thin grating condition.

Due to the experimental setup geometry and limitations of focusing optics, the probe incident beam angle is chosen to be larger than the pump. The reflection from the front surface of the sample, especially for off-normal probe beam incidence, must be taken into account. Once the Fresnel reflection of the probe beam is calculated for normal and 20° off normal incidence, the reflection from the surface of the sample changes by approximately two percent. The angle of the probe beam inside of the sample, \( \theta_p' \), is determined using Snell’s law to be,

\[
\theta_p' = \text{ArcSin} \left[ \frac{1}{n_p} \text{Sin}(\theta_p) \right].
\]  

(3.16)
Inside of the sample, the momentum vectors of the photo-generated grating, \( \mathbf{K} \), and the probe beam, \( \mathbf{k}_1 \), are used to obtain the angle of the diffracted probe beam (also inside of the sample), \( \theta_{\text{diff}} \). The k-vector associated with the grating is given by,

\[
\mathbf{K} = |\mathbf{K}| \mathbf{x},
\]

(3.17)

where the magnitude of \( \mathbf{K} \) is given by,

\[
|\mathbf{K}| = \frac{2\pi}{\Lambda}.
\]

(3.18)

Also the k-vector of the probe inside of the sample is given by,

\[
\mathbf{k}_1 = |\mathbf{k}_1| \sin(\theta'_p) \mathbf{x} + |\mathbf{k}_1| \cos(\theta'_p) \mathbf{z}.
\]

(3.19)

The magnitude of \( \mathbf{k}_1 \) is given by,

\[
|\mathbf{k}_1| = \frac{2\pi n_p}{\lambda_p},
\]

(3.20)

therefore, the diffracted probe beam has an associated k-vector,

\[
\mathbf{k}_2 = \mathbf{k}_1 - m\mathbf{K},
\]

(3.21)

here, \( m \) is the order of diffraction. In our measurements, the case of \( m = 1 \) will be considered since higher order beams will not be able to exit the sample body due to total internal reflection. Therefore, \( \mathbf{k}_2 \), can be expressed as,

\[
\mathbf{k}_2 = (|\mathbf{k}_1|(\sin(\theta'_p) - K) \mathbf{x} + |\mathbf{k}_1|\cos(\theta'_p) \mathbf{z}
\]

(3.22)

The diffracted angle is,

\[
\theta_{\text{diff}} = \text{ArcTan}(k_{2x}/k_{2z}) = \text{ArcTan} \left[ \frac{|\mathbf{k}_1|(\sin(\theta'_p) - K)}{|\mathbf{k}_1|\cos(\theta'_p)} \right].
\]

(3.23)

Once the diffracted beam leaves the sample, once again the boundary conditions require satisfaction of Snell’s law. Therefore, the exiting angle with respect to normal
\[ \theta_{\text{out}} = \text{ArcSin} \left( n_p \sin(\theta_{\text{diff}}) \right). \]  

(3.24)

Figure 3.8: Diffracted probe angles outside of the sample for \( \phi = 13^\circ \).

For the range of our pump wavelength, the diffracted probe beam is expected to be in range of \( 2^\circ \) to \( 12^\circ \) as shown in Fig. 3.8.

In addition to the relations between the angles and wavelengths of the pump and probe beams, which are derived for this specific sample with known index of refraction and thickness, there are other properties to consider when planning the experimental setup. For example, the collection efficiency of the probe beam and specific consideration associated with femtosecond probe pulses must be addressed. A detailed model to understand the evolution of the carrier density in a transient-grating and the diffraction efficiency is presented by Dr. Anson in his Ph.D. thesis for InAs/GaSb T2SLs [56].
CHAPTER 4
CARRIER LIFETIME

Due to a high sensitivity of carrier lifetime on electrically active defects, lifetime measurements can be used to characterize the photodetector’s structural design. Temperature-dependent carrier lifetime measurements are a candidate for identifying the energy levels of the defect-related mid-bandgap SRH recombination centers. It has been shown that Ga-free InAs/InAs$_{1-x}$Sb$_x$ T2SLs have MC lifetimes that are SRH limited for low doping levels [8, 9, 41, 45, 49], 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.

In this chapter, a carrier lifetime study including 19 Ga-free MWIR to LWIR InAs/InAs$_{1-x}$Sb$_x$ T2SLs were presented in three sets. The first set covers a series of 5.2 $\mu$m wavelength bandgap structures with variations in Sb concentration and doping levels. In the second set, seven InAs/InAs$_{1-x}$Sb$_x$ T2SLs were studied that were designed to have specific bandgap energies between 290 meV (4.3 $\mu$m) and 135 meV (9.2 $\mu$m) in order to study the effects of the T2SL bandgap energy on carrier lifetime. The final set covers three samples with $\sim$ 5.2 $\mu$m bandgap and SL period thicknesses from 147 Å to 393 Å in order to understand the influence of SL period on carrier lifetime.

4.1 Samples of Interest

Materials were grown by a team led by Dr. Jin Kim at Sandia National Laboratories using molecular beam epitaxy (MBE) [13, 43, 57]. For all samples, the epilayers consist of a GaSb buffer layer, a 100 nm AlAsSb barrier layer, an unintentionally or intentionally doped and nominally 4 $\mu$m thick T2SL absorber layer, a 100 nm AlAsSb barrier layer and a 150 nm InAsSb cap layer as shown in Fig. 4.1. For the intentionally doped structures, Silicon (Si) and Tellurium (Te) were used as dopant.
The samples were first characterized through photoluminescence (PL) spectra at 16 K and 77 K. At these temperatures, thermal effects are assumed to be minimal. Therefore, the effective T2SL bandgap energies were obtained by fitting the PL spectra to extract the energy at which the PL reaches a maximum. High resolution X-ray Diffraction (HRXRD) measurements were also taken in order to assess the quality of the T2SL layers, as well as determine the layer structures. Both the HRXRD and the PL measurements confirm the designed layer structure and bandgaps for all 19 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, $n_0$) of the T2SLs. The C–V measurements were conducted and analyzed in a similar manner to those described previously [9, 89]. The results are listed under each section of this chapter in Tables 4.1, 4.3, and 4.5.

A 14-band $\mathbf{k} \cdot \mathbf{p}$ model [61] was used to calculate the absorption coefficient, band structure, effective masses of electron and holes, and T2SL valence and conduction band edges at each temperature investigated. This model is optimized for the bowing
of the InAsSb valence band by using the measured bandgap values and an InAsSb
bandgap bowing parameter \( C_{\text{gap}} = 0.67 \) [43, 45, 57, 90]. 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 [44, 45, 49, 57, 83].

4.2 Set I: Varying the Sb Content

The nine structures in this set provide variation in the superlattice alloy com-
position as well as layer thickness, doping concentration and dopant type, while
maintaining a nearly constant bandgap energy of \( \sim 235 \pm 10 \) meV. The results of PL,
HRXRD, and C–V measurements and the 14-band \( k \cdot p \) model calculation results are
listed in Table 4.1.

![Figure 4.2: Photoluminescence spectra of the five unintentionally doped (left panel)
and four intentionally doped (right panel) InAs/InAsSb T2SLs at 16 K.]

As discussed in Chapter 3, a time-resolved pump-probe technique, utilizing
<table>
<thead>
<tr>
<th>Sample ID</th>
<th>InAs/InAs$_{1-x}$Sb$_x$ Thicknesses (Å)</th>
<th>X (%)</th>
<th>Growth</th>
<th>Measured $n_0$ (cm$^{-3}$)</th>
<th>$E_g$ (meV)</th>
<th>$\alpha$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN0636</td>
<td>49.1 / 29.1</td>
<td>26.1</td>
<td>undoped</td>
<td>1.5E15</td>
<td>225.3</td>
<td>3300</td>
</tr>
<tr>
<td>GN0643</td>
<td>43.1 / 20.0</td>
<td>30.5</td>
<td>undoped</td>
<td>1.0E15</td>
<td>233.9</td>
<td>3606</td>
</tr>
<tr>
<td>GN0661</td>
<td>41.9 / 15.5</td>
<td>33.5</td>
<td>undoped</td>
<td>1.0E15</td>
<td>245.4</td>
<td>3603</td>
</tr>
<tr>
<td>GN0670</td>
<td>40.7 / 12.9</td>
<td>40.0</td>
<td>undoped</td>
<td>9.3E14</td>
<td>241.5</td>
<td>3730</td>
</tr>
<tr>
<td>GN0672</td>
<td>40.7 / 10.0</td>
<td>49.0</td>
<td>undoped</td>
<td>9.3E14</td>
<td>244.3</td>
<td>3707</td>
</tr>
<tr>
<td>GN0662</td>
<td>41.9 / 15.5</td>
<td>34.4</td>
<td>Si:1E15</td>
<td>1.9E15</td>
<td>242.0</td>
<td>3603</td>
</tr>
<tr>
<td>GN0663</td>
<td>42.0 / 15.5</td>
<td>34.5</td>
<td>Si:1E16</td>
<td>2.0E16</td>
<td>246.0</td>
<td>3603</td>
</tr>
<tr>
<td>GN0666</td>
<td>41.7 / 15.4</td>
<td>34.2</td>
<td>Te:1E15</td>
<td>4.1E15</td>
<td>245.0</td>
<td>3603</td>
</tr>
<tr>
<td>GN0667</td>
<td>41.4 / 15.3</td>
<td>32.6</td>
<td>Te:1E16</td>
<td>1.5E16</td>
<td>248.6</td>
<td>3603</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of the T2SL set-I 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 absorption coefficient at the pump wavelength are obtained from a 14-band $\mathbf{k} \cdot \mathbf{p}$ model and results are listed for 77 K. Notice that the intentionally doped samples are essentially structurally identical to the unintentionally doped sample GN0661.

A sub-picosecond MWIR pump, an electronically delayed pulsed quantum cascade laser (QCL) probe, and differential transmission ($\Delta T/T$) measurements were used to investigate the non-equilibrium carrier dynamics of the T2SLs in the temperature range of 77 K to 293 K. In this technique, 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 using difference frequency generation (DFG). This is used as a pump pulse to excite excess charge carriers in the sample under study. A low-power 3 ns 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 \( \sim 1080 \mu m \) and \( \sim 180 \mu m \), 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\(^2\). In all cases, the probe fluence was significantly smaller than the pump fluence. The transient carrier population produces a change in sample transmission, which is monitored by electronically varying the time delay between the 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 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 \( \mathbf{k} \cdot \mathbf{p} \) model. Losses due to optical windows and Fresnel reflections were also included into the analysis. Time-resolved \( \Delta T/T \) decay curves for sample GN0672 and sample GN0667 for several injected excess carrier densities and temperatures are presented in Fig. 4.3. The data shown are representative of the other samples.

4.2.1 Experimental Results

Using the data presented in Fig. 4.3, the recombination rate or inverse of the carrier lifetime, \( R(\Delta n) \), as a function of excess carrier density is calculated using Eq. 3.2.1,

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

where \( \Delta n \) is the excess carrier density. The transformed data are shown in Fig. 4.4.

The carrier lifetime is a function of three main recombination mechanisms: SRH,
Figure 4.3: 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 GN0672) and an intentionally (Sample GN0667) doped T2SL for multiple initial optically generated carrier densities and sample temperatures. Note the time scales are different at different temperatures.
radiative, and Auger recombination and can be expressed as in Eq. 2.41,

\[ \tau^{-1} = \tau^{-1}_{\text{SRH}} + \tau^{-1}_{\text{Rad.}} + \tau^{-1}_{\text{Auger}} \]

In Chapter 2, the net recombination rate of the SRH process was express as in Eq. 2.55. The lifetime of SRH recombination for a single defect level is \( \tau^{-1}_{\text{SRH}} = R_{\text{SRH}} \), and is expressed as \([65,67,75]\),

\[ \tau^{-1}_{\text{SRH}} = \frac{n_0 + p_0 + \Delta n}{\tau_{p0}(n_0 + n_1 + \Delta n) + \tau_{n0}(p_0 + p_1 + \Delta n)}, \]  

(4.1)

where \( \tau_{p0} \) and \( \tau_{n0} \) 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, \( n_1 \) and \( p_1 \), were previously given in Chapter 2.

The SRH lifetime is governed by two characteristic lifetimes (Eq. 2.53),

\[ \tau_{n0} = (\sigma_n \vartheta_n N_t)^{-1}, \quad \tau_{p0} = (\sigma_p \vartheta_p N_t)^{-1}, \]

where \( \sigma_n \) and \( \sigma_p \) are the electron and hole defect capture cross-sections, \( \vartheta_n \) and \( \vartheta_p \) are the electron and hole thermal velocities, and \( N_t \) 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 (\( E_t \approx E_g / 2 \)), Eq. 4.1 becomes \([9]\),

\[ \tau^{-1}_{\text{SRH}} = \frac{n_0 + \Delta n}{\tau_{p0}(n_0 + \Delta n) + \tau_{n0}(\Delta n)}, \]  

(4.2)

which describes the density dependence of SRH recombination. Note that the density independent character of SRH recombination can be obtained by assuming \( \tau_{p0} >> \tau_{n0} \) or \( \Delta n << n_0 \). 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 [67,75],
\[
\tau_{RAD}^{-1} = B \frac{(np - n_i^2)}{\Delta n},
\]
(4.3)
where \( B \) is the radiative coefficient. For a n-type material,
\[
\tau_{RAD}^{-1} = B(n_0 + \Delta n).
\]
(4.4)

The intrinsic radiative coefficient, \( B_r \), for a thin slab of material, is related to the measured radiative coefficient, \( B \), inversely as,
\[
B = B_r / \phi,
\]
(4.5)
where \( \phi \) is the photon recycling (PR) factor [8]. 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 [67],
\[
\tau_{Auger}^{-1} = \frac{C_n(np - n_0p_0)n + C_p(np - n_0p_0)p}{\Delta n} = C_n(n_0 + p_0 + \Delta n)n + C_p(n_0 + p_0 + \Delta n)p
\]
(4.6)
where \( C_n \) and \( C_p \) are the Auger coefficients associated with the Auger-1 and Auger-7 processes, respectively. For high level carrier injection \((n_0, p_0 \ll \Delta n)\), the Auger lifetime becomes,
\[
\tau_{Auger}^{-1} = (C_n + C_p)\Delta n^2,
\]
(4.7)
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. 4.7 has the limiting form [91],
\[
\tau_{Auger}^{-1} \simeq C_n n_0^2.
\]
(4.8)
Overall, the Auger lifetime for n-type material can be written as,

$$\tau_{\text{Auger}}^{-1} = \frac{C_n}{1 + \Delta n/N_s} (n_0 + \Delta n)^2,$$

where $N_s$ is a measure of the carrier density for the onset of saturated behavior in Auger recombination. At high excess carrier densities ($\Delta n \gg n_0$), Auger recombination is expected to saturate if the involved carriers become degenerate. In this case the rate approaches a linear dependence on the carrier density. The saturation can create a misleading result for the total radiative and Auger coefficients when it is not taken into account during the recombination rate analysis. The saturation term, $N_s$, must be taken into account for the samples indicating saturation of the conduction band due to the injected pump pulse. Note that the hole related Auger-7 recombination is neglected during this analysis, and the total Auger recombination is assumed to be entirely due to the electron dominated Auger-1 process [82]. The Auger-1 coefficient, $C_n$, for n-type material is defined as [65,67],

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

where $\epsilon_\infty$ is the high frequency dielectric constant, $|F_1 F_2|$ is the Bloch function overlap integrals, and $\mu = m_e/m_h$. The value of $|F_1 F_2|$ is usually between 0.1–0.3, which can change the Auger lifetime by an order of magnitude [12,43].

Using Eqs. 2.41, 4.2, 4.4, and 4.9 the total lifetime can be written as,

$$R(\Delta n) = \tau^{-1} = \frac{n_0 + \Delta n}{\tau_{\text{ld}}(n_0 + \Delta n) + \tau_{\text{rd}}(\Delta n)} + B(n_0 + \Delta n) + \frac{C_n}{1 + \Delta n/N_s} (n_0 + \Delta n)^2.$$  

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 [91]. The MC lifetime, including the contributions from SRH, radiative, and Auger processes,
Figure 4.4: Carrier recombination rates as a function of excess carrier density determined from intensity dependent time-resolved differential transmission measurements for a range of temperatures. Data are shown for unintentionally (Sample GN0672) and intentionally doped (Sample GN0667) T2SLs. The solid red curves are best fits to the measured data and represent the inverse of the total lifetime. The solid gray, blue, and green curves are the uniquely distinguished contributions of SRH, radiative, and Auger recombination to the total lifetime, respectively.
is determined using Eq. 4.11 under the assumption of low level injection as,

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

(4.12)

The total recombination lifetime, as described by Eq. 4.11, is fit to the measured lifetime data for each sample. Representative data for an undoped (GN0672) and a doped (GN0666) samples are shown in Fig. 4.4, along with the overall fits, 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 GN0672 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 (GN0667) are shown in Fig. 4.4. Due to the relatively high doping level, sample GN0667 (and GN0663) 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. 4.11. The recombination coefficients (\( \tau_p \), B, and \( C_n \), if necessary \( N_s \)) are extracted from these best fits. The MC lifetime is then determined using Eq. 4.12. 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 [67] for the low excess carrier density limit where the defect energy level, \( E_t \), capture probability, \( N_t \), and the Block overlap constant, \( |F_1 F_2| \) [8, 12] are used as fitting parameters. The best fit parameters are listed in Table 4.2, where the reported uncertainties are calculated by analyzing the Hessian matrices from the lifetime model.
results. Results of these temperature-dependent MC lifetime measurements and analyze are shown in Fig. 4.5.

Figure 4.5: Minority carrier lifetime results as a function of temperature, determined from the recombination rate data. The solid black curves are best fits to the measured data and represent the total MC lifetime. The solid red, blue, and green curves are the de-convolved low level injection contributions of SRH, radiative, and Auger recombination to the total lifetime, respectively.
4.2.2 Discussion

4.2.2.1 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 [8,16,40,67]. 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. 4.5). Specifically, it is observed to increase from $3.5 \, \mu s$ for the sample with 26% Sb (sample GN0636) to $\sim 6 \, \mu s$ for the samples with 40% and 49% Sb (samples GN0670 and GN0672). 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 GN0636 to 24.5% for sample GN0672. 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 [92]. However, the samples investigated here do not show significant shifts in the T2SL band edge energies on an absolute energy scale. From Table 4.1, the T2SL valence band edge for the unintentionally doped sample series changes by approximately 20 meV across the sample set, while the T2SL conduction band edge has effectively no change.
Furthermore, the defect energies obtained from temperature-dependent MC lifetime fits suggest the energy level of the SRH recombination centers is near mid-bandgap for all the samples tested, as compiled in Table 4.2. Shown in Fig. 4.6 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 valence band 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 µm bandgap while spanning the most useful range of InAsSb compositions, it is unlikely that alternative 5.2 µm 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 GN0662 and GN0666 also indicate a SRH limited MC lifetime at low temperatures. Sample GN0662 has an equilibrium density \( n_0 \simeq 1.93 \times 10^{15} \text{ cm}^{-3} \) using Si as a dopant and sample GN0666 has \( n_0 \simeq 4.17 \times 10^{15} \text{ cm}^{-3} \) using Te as a dopant, as listed in Table 4.2. From the temperature-dependent MC lifetime analysis, the defect energy level of sample GN0666 is found to be \( \sim 2k_B T \) closer to the T2SL valence band edge relative to sample GN0662. The MC lifetime of sample GN0666 is also found to be approximately 3 times shorter than sample GN0662, while the experimentally determined doping level is only double. The doping level appears to influence on the energies of the SRH recombination centers in the mid-bandgap. In this case the factor of 2 increase in equilibrium carrier density could cause a shallower SRH recombination center as shown in Table 4.2. Therefore, the SRH lifetime becomes shorter for sample GN0666 than sample GN0662 due to a shorter \( \tau_{\rho 0} \) at low excess carrier densities. With a small number of samples, caution must be
Figure 4.6: Valence and conduction band edge energies for the unintentionally doped T2SL series (samples GN0636 through GN0672), 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 ($E_t$) from samples GN0636 - GN0672 are shown as green crosses.

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 provide 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 GN0663 and GN0667, 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 the Auger analysis discussion section below.
Table 4.2: 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 GN0663 and GN0667 were Auger limited and the SRH parameters could not be obtained.

| Sample ID | $E_t - E_v$ (meV) | $\sigma N_t$ ($cm^{-1}$) | $|F_1F_2|$ | $\mu_{\text{in-plane}}$ | $\mu_{\text{vertical}}$ |
|-----------|------------------|-----------------|---------|-----------------|-----------------|
| GN0636    | 123.0            | 3.9             | 0.14    | 0.0175/0.0348   | 0.0188/1.148    |
| GN0643    | 118.4            | 5.1             | 0.11    | 0.0175/0.0334   | 0.0189/1.538    |
| GN0661    | 119.8            | 5.6             | 0.11    | 0.0178/0.0336   | 0.0189/2.117    |
| GN0670    | 122.6            | 4.7             | 0.10    | 0.0176/0.0323   | 0.0191/2.724    |
| GN0672    | 124.3            | 5.9             | 0.09    | 0.0177/0.0323   | 0.0193/3.625    |
| GN0662    | 125.3            | 4.3             | 0.13    | 0.0178/0.0336   | 0.0189/2.117    |
| GN0663    | -                | -               | 0.05    | 0.0178/0.0336   | 0.0189/2.117    |
| GN0666    | 113.9            | 7.3             | 0.11    | 0.0178/0.0336   | 0.0189/2.117    |
| GN0667    | -                | -               | 0.08    | 0.0178/0.0336   | 0.0189/2.117    |

4.2.2.2 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. 4.4. The measured radiative coefficient reported here (see Fig. 4.7 (a)) includes the effects of photon recycling (PR), a process which 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 of a single InAs and InAsSb T2SL period, were obtained using the 14-band $k \cdot p$ model, as shown in Fig. 4.7(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. [16] and Hoglund et al. [6,93] suggest a PR factor of \( \sim 2 \) for similar T2SL structures. However, in their comprehensive examination of carrier lifetimes in InAs/InAsSb T2SLs, Olson et al. [9] concluded a PR factor of approximately 15, which is supported by Humphreys first-principles study of radiative lifetimes and PR in semiconductors [78] (see Appendix D). As shown in Fig. 4.7 (a) and (b), the experimental \( B \) coefficient has a weak dependence on temperature while the theoretical, \( B_r \), coefficient steadily decreases with increasing temperature. In general, radiative recombination increases with greater absorptivity [75]. However, the case presented here shows decreasing \( B_r \) coefficients with increasing absorption coefficient (note, the absorption is greater in the samples with greater Sb content as shown in Table 4.1) due to the changes in the electronic band structure caused by the increasing strain with greater Sb concentration.

![Figure 4.7: 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 \( B_r \) coefficients obtained from 14-band \( \mathbf{k} \cdot \mathbf{p} \) model are shown.](image)

The radiative lifetime depends inversely upon the radiative coefficient as shown in Eq. 4.4. 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. 4.5, the radiative lifetime is observed to increase by factor of 10 through sample GN0636 to GN0672. Furthermore, the radiative lifetime at low nonequilibrium carrier densities is found to be shorter for increasing background carrier density [67], as illustrated for the intentionally lightly doped samples GN0662 and GN0666 in Fig. 4.5. These two samples have almost identical bandgaps, layer thicknesses and Sb content in the InAsSb alloy. However, sample GN0666 exhibited a shorter radiative lifetime than sample 2, which is attributed to the difference in their equilibrium carrier densities. On the other hand, as illustrated in Fig. 4.5, 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. [9] who also reported minimal contribution of radiative processes, in this case for samples with $\sim 4 \, \mu m$ 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 [93].

4.2.2.3 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. 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 [4, 5, 10, 91, 92, 94]. In Fig. 4.5, the results for moderately (>$10^{16} \, cm^{-3}$) doped samples GN0663 and GN0667 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 rate 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.

\[ C_n (10^{-26} \text{ cm}^6/\text{s}) \]

Figure 4.8: 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.

The measured $C_n$ coefficients are shown as a function of temperature in Fig. 4.8. 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. 4.8(a). For example, at 77 K, the Auger coefficient for Sample GN0636 is $2.75 \times 10^{-26} \text{ cm}^6/\text{s}$. This value gradually decreases to $2 \times 10^{-26} \text{ cm}^6/\text{s}$ for sample GN0661 and to $1.75 \times 10^{-26} \text{ cm}^6/\text{s}$ for Sample GN0672. 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 [5,44,81,91]. The results from the unintentionally doped
series (samples GN0636 to GN0672), 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 GN0661, 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 $10^{-28}$ cm$^6$/s [48].

The calculated Beattie, Landsberg, and Blakemore (BLB) Auger-1 lifetime for bulk material in low level injections is given as [67],

$$
\tau_{BLB}^{A-1} = \frac{2n_i^2 \tau_{i-1}^i}{(n_0 + p_0)n_0} \tag{4.13}
$$

where,

$$
\tau_{i-1}^i = 3.8 \times 10^{-18} \epsilon_{\infty}^2 (1 + \mu)^{1/2} (1 + 2\mu) \left( \frac{E_g}{k_BT} \right)^{3/2} \exp \left[ \frac{1 + 2\mu}{1 + \mu} \frac{E_g}{k_BT} \right]. \tag{4.14}
$$

This Auger lifetime is calculated using $\epsilon_{\infty} = 15.4$ [9,95], 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 $\mathbf{k} \cdot \mathbf{p}$ model, which are listed in Table 4.2. Notice that $\tau_{BLB}^{A-1}$ was evaluated using the vertical masses, since the most anisotropic masses will dominate the Auger rate, and the vertical masses are the most anisotropic [45]. If final-state Auger optimization is not present, then the Auger recombination rate is principally a function of the band gap energies, the carrier densities, and the effective masses of the electrons and holes [5]. 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 4.2). The modest decrease in the
Auger coefficients from sample GN0636 to GN0672 (see Fig. 4.8) is accompanied by an increase in antimony content (Table 4.1) and a corresponding decrease in $|F_1F_2|$ (Table 4.2).

4.3 Set II: Varying Bandgap from MWIR to LWIR

The mid-bandgap SRH recombination centers identified in MWIR InAs/InAsSb T2SLs have been previously reported to be at an energy approximately 250 meV below the valence band edge of bulk GaSb [8, 45]. One significant benefit of SL structures is that the position of the SL valence and conduction band edge energies, and hence the SL bandgap, on an absolute energy scale is determined by the layer thicknesses, compositions, and specific materials that make up the structure and can therefore be engineered. Recently, a method that utilizes this flexibility inherent to SL structures has been proposed to mitigate the effects of parasitic SRH recombination centers [92]. Essentially, if a mid-bandgap SRH defect is identified, the SL structure may be engineered such that the position of the SL bandgap on an absolute energy scale is shifted relative to the SRH defect. If this shift in SL bandgap position is on the order of $1/2 E_g$, the SRH defect state will then be near a SL band edge, or even within the valence or conduction bands, and rendered ineffective as a recombination center (see Fig. 4.9). This method of course assumes that the SRH defect state does not float with the T2SL band edge energies, but instead has an energy determined by the work function of the material-specific defect. For InAs/InAsSb T2SLs, this strategy involves engineering the SL structure using the layer thicknesses of InAs and InAsSb and the alloy composition to shift the T2SL band edge energies in absolute energy. In the previous section that focused on engineering the InAs/InAsSb structure, while keeping a constant bandgap near 5.2 $\mu$m, showed that an approximately $2 k_B T$ energy shift in the T2SL valence band energy is possible, which caused the MC lifetime to increase from $\sim 3 \mu$s to $\sim 6 \mu$s [45]. This result demonstrated the feasibility of
Figure 4.9: (a) Relative positions of the conduction and valence band edge energies for bulk GaSb, InAs, and InAs$_{0.7}$Sb$_{0.3}$ (solid lines), where InAs and InAs$_{0.7}$Sb$_{0.3}$ are strained to GaSb. The dashed lines in (a) correspond to the superlattice (SL) band edge energies of a strain-balanced 45.8 Å InAs/15.0 Å InAs$_{0.7}$Sb$_{0.3}$ SL. (b) Strain-balanced InAs/InAs$_{0.7}$Sb$_{0.3}$ SL band edge energies as a function of SL period thickness on an absolute energy scale. The solid curves in (b) correspond to three possible trends in recombination center energy level as the SL band edges are shifted in energy.

modifying the SRH lifetime through band structure engineering. A larger modification of the T2SL bandgap position is required, however, to fully remove the SRH defect from the bandgap and realize significantly longer MC lifetimes in this material system.

Here, time-resolved and temperature-dependent differential-transmission measurements and a MC lifetime analysis [8, 45] are used to determine the SRH defect energy level in a series of seven InAs/InAs$_{1-x}$Sb$_x$ T2SL samples engineered to have
<table>
<thead>
<tr>
<th>Sample ID</th>
<th>InAs/InAs(_{1-x})Sb(_x) Thickness (Å)</th>
<th>X (%)</th>
<th>% of SL Periods</th>
<th>(n_0) (cm(^{-3}))</th>
<th>(E_g) (meV)</th>
<th>(E_v) (meV)</th>
<th>(E_c) (meV)</th>
<th>(\alpha) cm(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN0815</td>
<td>57.7 / 13.1</td>
<td>38 ± 2</td>
<td>580</td>
<td>7.6 ×10(^{14})</td>
<td>203.9</td>
<td>-370.0</td>
<td>-167.0</td>
<td>3203</td>
</tr>
<tr>
<td>GN0822</td>
<td>72.2 / 16.1</td>
<td>39 ± 2</td>
<td>460</td>
<td>9.7 ×10(^{14})</td>
<td>161.6</td>
<td>-328.9</td>
<td>-167.0</td>
<td>2257</td>
</tr>
<tr>
<td>GN0824</td>
<td>85.6 / 19.1</td>
<td>39 ± 2</td>
<td>380</td>
<td>7.2 ×10(^{14})</td>
<td>134.5</td>
<td>-304.0</td>
<td>-170.0</td>
<td>2467</td>
</tr>
<tr>
<td>GN0826</td>
<td>30.1 / 9.8</td>
<td>31 ± 2</td>
<td>990</td>
<td>6.7 ×10(^{14})</td>
<td>289.6</td>
<td>-445.0</td>
<td>-155.0</td>
<td>3387</td>
</tr>
<tr>
<td>GN0828</td>
<td>45.8 / 15.0</td>
<td>30 ± 2</td>
<td>660</td>
<td>4.5 ×10(^{14})</td>
<td>240.2</td>
<td>-403.0</td>
<td>-164.0</td>
<td>3526</td>
</tr>
<tr>
<td>GN0830</td>
<td>61.9 / 20.2</td>
<td>31 ± 2</td>
<td>500</td>
<td>5.7 ×10(^{14})</td>
<td>185.2</td>
<td>-346.0</td>
<td>-161.0</td>
<td>2844</td>
</tr>
<tr>
<td>GN0832</td>
<td>76.5 / 25.0</td>
<td>30 ± 2</td>
<td>400</td>
<td>6.5 ×10(^{14})</td>
<td>155.2</td>
<td>-317.0</td>
<td>-226.0</td>
<td>2534</td>
</tr>
</tbody>
</table>

*Table 4.3: Summary of the physical properties of the seven InAs/InAsSb type-II superlattice (T2SL) structures. The layer thicknesses and InAsSb compositions are determined from high-resolution x-ray diffraction. The T2SL bandgap energies (\(E_g\)) are determined from 80 K photoluminescence spectra measurements. The T2SL conduction (\(E_c\)) and valence (\(E_v\)) band edge energies and absorption coefficients are obtained using a 14-band \(\mathbf{k} \cdot \mathbf{p}\) model at 77 K. The band edge energies are listed relative to the valence band edge of bulk GaSb.*

different absolute T2SL valence band energies.

### 4.3.1 Experimental Results

Photoluminescence (PL) spectra at 80 K are plotted in Figure 4.10 for the seven samples, showing the shifts in T2SL bandgap energy as the layer thicknesses and alloy composition are varied. The T2SL layer structures, determined using high-resolution X-ray diffraction (HRXRD) measurements, are listed in Table 4.3. Minority carrier lifetimes are measured using the time-resolved \(\Delta T/T\) data in a manner discussed previously. The resulting MC lifetime data for samples GN0815 to GN0832 are shown in Fig. 4.12, where the data are analyzed taking into account SRH, radiative, and
4.3.2 Discussion

4.3.2.1 SRH Recombination

The temperature dependent behavior of the SRH expression is illustrated in Fig. 4.11, for sample GN0815. The SRH defect state is more efficient as a recombination center when it is near the mid-bandgap, resulting in shorter SRH lifetimes as shown in Fig. 4.11(a). On the other hand, if the SRH defect state is instead closer to the VB edge (or CB edge) the SRH defect is less efficient, resulting in a longer SRH lifetime. In the first region (I) in Fig. 4.11(b), the SRH lifetime is limited by the capture of minority carriers and $\tau_{\text{SRH}} \rightarrow \tau_{\text{p}0}$. The SRH lifetime scales as $T^{-1/2}$ in this temperature range. The doping level ($n_0$) determines the onset position of increased SRH lifetime in the temperature regime where SRH recombination is least
efficient. For example, in region (II), the SRH lifetime increases exponentially as 
\[ \tau_{\text{SRH}}^{\mathrm{II}} \to \frac{N}{\tau_0 n_0} \exp\left[-E_r/k_B T\right], \]
where the onset of this increase is determined by \( n_0 \). At higher temperatures (region III), where the \( n_0 = p_0 = n_i \) condition is fulfilled, the SRH lifetime decreases exponentially due to increasing equilibrium carrier density and temperature. This is the intrinsic regime. The capture probability, defined as \( \sigma N_t \), acts as a scaling factor that primarily provides a vertical shift of the SRH lifetime at a particular temperature rather than a change in the overall temperature dependence (or shape as a function of temperature) as shown in Fig. 4.11(c). Notice that \( E_r \) and \( \sigma N_t \) are used as temperature independent fitting parameters in the analysis presented here. With these dependencies on temperature, the SRH defect energy can be uniquely identified based on the overall trend that the SRH-limited MC lifetime has with temperature, while the magnitude is primarily determined by \( \sigma N_t \).

Under the assumption of a static SRH defect, there are two possible interpretations of the measured MC lifetimes. First, the SRH defect state shifts from a deep to shallow level due to the engineered shifts in T2SL valence band edge energies, and the SRH lifetime is correspondingly affected as expressed previously. Second, the SRH defect energy level is near mid-bandgap for each sample and the variation in MC lifetimes is due instead to different SRH trap densities affecting \( \tau_{p0} \) and \( \tau_{n0} \). Since all samples have similar MBE growth parameters, the SRH defect density, \( N_t \), should not vary significantly from sample to sample. However, the cross section of carriers could vary with engineered layer thickness and bandgap value which can change the total capture probability. The best fit parameters are listed in Table 4.4, where the reported uncertainties are calculated by analyzing the Hessian matrices from the lifetime model results. In order to minimize the error attached to the extracted SRH defect energies, the SRH lifetime must dominate the MC lifetime over a broad range of temperatures. In addition, the Auger lifetime fitting parameter, \( |F_1F_2| \), is also extracted from temperature dependent MC lifetime data analysis, the results of which
Figure 4.11: Influence of a) SRH defect energy, b) equilibrium carrier density, and c) capture probability on the SRH lifetime is shown for the sample A under low level injection conditions. In each case, all other parameters are held constant while the specified values are varied.

are shown in Table 4.4.

Samples GN0815, GN0822, and GN0824, corresponding to Sb mole fractions of approximately 40 % in the alloy layer, are engineered to step the T2SL valence band edge with a valence band shift of approximately 70 meV. The MC lifetimes are correspondingly observed to be $\sim 4 \mu s$, $\sim 2 \mu s$, and $\sim 4.6 \mu s$ at 77 K for samples GN0815, GN0822, and GN0824, respectively. The substantially long MC lifetime in sample GN0824, despite is comparatively small bandgap energy, is attributed to the SRH defect being shifted closer to the T2SL valence band edge; in fact it is found to
Figure 4.12: Minority carrier (MC) lifetime results as a function of temperature for the seven InAs/InAsSb type-II superlattice samples. The solid black curves are the best fits to the measured data and represent the total MC lifetime. The red, blue, and green dashed curves are the deconvolved low level injection contributions of SRH, radiative, and Auger recombination to this total lifetime, respectively.
be $\sim 70$ meV closer than sample GN0822 and $\sim 93$ meV closer than sample GN0815 as shown in Fig. 4.13. The 93 meV shift in the SRH defect energy is significantly larger than the T2SL valence band shift of 70 meV realized in this series of samples. While some variation in the extracted SRH defect energy is found, this variation is relatively small compared to the sample-to-sample variation in the valence band edge. We therefore consider the SRH defect energy in the InAs/InAsSb T2SLs fixed at approximately -250 meV below the valence band edge of GaSb. Notice that the $\sigma N_t$ value also increases gradually with decreasing bandgap (as seen by the listed values in Table 4.4), which corresponds to a decreasing SRH lifetime.

It is therefore unlikely that the observed trends in the MC lifetimes are due to simply differences in capture cross section, since this would require $\sigma N_t$ to decrease from samples GN0815 to GN0824 to account for the long MC lifetimes. Samples GN0826 to GN0832 which have Sb mole compositions of 30 %, are similarly engineered to step the T2SL valence band edge, with the resulting as-grown structures realizing an approximately 128 meV shift in the T2SL valence band edge. The conduction band edge shifts less than 10 meV. Therefore, the defect energy is thus engineered to shift relatively closer to the T2SL valence band edge for samples GN0826 through GN0832, as shown in Figure 4.13. The SRH defect energy is found again to be approximately 250 meV below the GaSb valence band edge for these four samples. Even though the valence band edge shifts towards the SRH defect state and the SRH defect energy is quite shallow, we still find that the MC lifetime is limited by SRH recombination for the sample GN0832. The extracted capture probability values increase gradually from sample GN0826 to GN0832, but again cannot account for the observed trends in MC lifetime. A change in the SRH defect energy relative to the T2SL band edge energies is required to fully describe the results presented here. Overall, the SRH defect state is found to be at an energy of 250 $\pm$ 12 meV for the seven samples, as shown in Figure 4.13, determined from an average of the extracted SRH defect energies.
In group III-V semiconductors, the vacancies, antisites and interstitial defects are the most common point defects. Density functional theory (DFT) calculations [96] indicated that the vacancy of In-atoms produces a p-like T2-symmetry state, approximately 100 meV below the conduction band edge of InAs. In tensile strain, this vacancy state energy is located 37 meV below the strained InAs conduction band edge which is within 3 meV of the SRH recombination center energy reported here. Antisites occur in binary alloys when the electronegativity and size between two constituent atoms are small. In InAs binary alloy, it forms as the antibonding A1 state and is about 30 meV below the conduction band edge of InAs which holds the same position in strain. This state is within 4 meV of the reported SRH recombination energy. Between these two type of point defects, the antisites are more common in binary alloys which is most probably associated with the InAs region and registered
Figure 4.13: Valence and conduction band edge energies for the InAs/InAsSb type-II superlattice (T2SL) series (samples GN0815 through GN0832). The measured Shockley-Read-Hall (SRH) defect energy levels are also plotted as the dashed lines. The valence band edge of bulk GaSb is taken as zero energy on this scale.

to the (strained) bulk constituent. The Sb\textsubscript{As} antisites related to the Sb diffusion at the SL interfaces could cause localized defect states, however, the energy level of these antisites is more than an eV below the InAs valence band edge [97].

4.3.2.2 Radiative Recombination

The calculated radiative coefficients are in range of $1.5 - 3 \times 10^{-10}$ cm$^3$/s for the samples with 30 % and 40 % Sb content in their alloy layers at 77 K. These coefficients gradually decrease to $2 - 5 \times 10^{-11}$ cm$^3$/s at 200 K. The radiative recombination coefficients of all the InAs/InAsSb T2SLs examined in this sample set, were found to be essentially insignificant at high excess carrier densities for the temperatures ranging from 77 K to 200 K.

4.3.2.3 Auger Recombination

While MWIR and LWIR InAs/InAs$_{1-x}$Sb$_x$ T2SLs exhibit promising characteristics for infrared sensing, including very long minority carrier lifetimes (> 18 μs) [49],
low surface leakage [98], and high material quality [13], they unfortunately suffer from relatively high Auger recombination rates [9, 22, 45]. For materials that are not limited by Shockley-Read-Hall (SRH) recombination, intrinsic Auger recombination rates typically define a photodetectors maximum attainable carrier lifetime and, hence best case dark diffusion current [99]. MWIR InAs/InAsSb T2SLs intentionally doped to levels near $1 \times 10^{16}$ cm$^{-3}$ have been previously shown to exhibit Auger recombination-limited MC lifetimes at cryogenic temperatures stemming from these large Auger recombination rates [45], indicating that reduction of the Auger coefficient is critical for further potential improvement in photodetector performance [36, 45, 79, 82]. Reduction of the overall non-radiative recombination rate in MWIR and LWIR InAs/InAsSb T2SL detector materials could also lead to improvements in detectivity that would surpass HgCdTe for IR focal plane array applications [100].

Direct band-to-band Auger recombination processes can occur in a semiconductor under non-equilibrium conditions. These processes involve the recombination of an electron and a hole across the bandgap and the simultaneous excitation of a third particle (either an electron or a hole) to a higher energy state, from which it relaxes nonradiatively. The final Auger transition states are approximately one bandgap energy above the conduction band edge or below the valence band edge depending on whether the excited particle is an electron or hole. Auger recombination rates are very sensitive to the electronic band structure, which for T2SLs can be manipulated by physical factors, such as the InAs and InAsSb layer thicknesses, the alloy composition and, internal layer strain. The ability to suppress the inter-sub-band transitions in a T2SL allows the reduction of Auger recombination rates by limiting the possible final, higher energy states of the electrons and holes. However, suppression of Auger resonances remain a challenge due to the complicated nature of the recombination process and the dependence on states in the secondary zones of the electronic band structure. If final-state Auger optimization is not present, then the Auger recombination is
a function of the bandgap energies and the effective masses of the electrons and holes [4, 36, 45, 65, 67, 81, 82].

Figure 4.14: Time-resolved differential transmission decay curves and net recombination rate as a function of excess carrier density are illustrated for samples GN0815, GN0824, and GN0826 at 77 K. The solid red curve is the best fit to the measured data.

Using the data presented in Fig. 4.14 the net recombination rate (or inverse of the carrier lifetime), $R(\Delta n)$, as a function of excess carrier density is calculated using Eq. 2.41. Under the assumption of an n-type material, the total recombination rate
at high excess carrier densities could be simplified to the form below.

\[ R(\Delta n) = A(\Delta n) + B(n_0 + \Delta n) + \frac{C_n}{1 + \Delta n/N_s}(n_0 + \Delta n)^2 \]  

While more complicated fit functions are warranted when concerned about accurate extraction of doping, radiative, and MC lifetimes [9], for measurement of Auger coefficients this simplified equation suffices. The reason is that Auger coefficients are measured at very large excitation levels, such that \( \Delta n >> n_0 \), where Auger recombination is the limiting recombination mechanism and the functional dependence that SRH, radiative, and Auger recombination have with doping level is not important.

Multiple trends are readily observed in the experimental Auger coefficients, plotted as a function of bandgap in Fig. 4.15. The measured Auger coefficients generally increase with decreasing bandgap energy from \( 3 - 5 \times 10^{-27} \text{ cm}^6/\text{s} \) for the widest bandgap sample to \( 2 \times 10^{-25} \text{ cm}^6/\text{s} \) for the smallest bandgap sample at 77 K. This is expected, since in general Auger coefficients are exponentially dependent on the bandgap energy [67]. Sample GN0826, the sample with the widest bandgap, exhibited only a modest increase to \( 6 \times 10^{-27} \text{ cm}^6/\text{s} \) as the temperature is raised from 77 K to 200 K. Without considering the final state optimization in the T2SL structure design, the experimental Auger coefficients could be determined by the Beattie, Landsberg, and Blakemore (BLB) analysis [67] for a bulk material. Based on the Rule '07, which correlates the observed dark current in HgCdTe photodetectors to an Auger limited carrier lifetime [22], the Auger lifetime is calculated using the BLB Auger lifetime theory, recommended values for HgCdTe material parameters [100], and \(|F_1F_2|=0.2 \) [82, 101]. HgCdTe material parameters are treated as fully temperature dependent when available. The results of this analysis for HgCdTe are shown in Fig. 4.15 for comparison [100]. At temperatures lower than 150 K, InAs/InAsSb T2SLs are found to have smaller Auger coefficients than HgCdTe over the range
Figure 4.15: Measured (filled) and calculated (unfilled) Auger recombination rates of all samples are shown as a function of temperature. The solid curves are calculated Auger-1 coefficients for HgCdTd at each temperature.
Figure 4.16: Calculated 77 K band structures of the MWIR and LWIR superlattice structures. Negative wavevectors correspond to the superlattice in-plane direction and positive wavevectors to the superlattice growth direction. The gray horizontal dashed lines correspond to the superlattice band edge energies and the red dashed lines are zone center Auger-1 resonant energy, which occurs at one bandgap energy above the superlattice conduction band edge.
of bandgap energies measured. However, for temperatures greater than 150 K and for bandgap energies less than approximately 200 meV, the T2SL Auger coefficients trend towards being greater than HgCdTe. This result suggests that the benefit of n-type InAs/InAsSb T2SLs, in terms of intrinsic carrier lifetime limits, may not be significantly suppressed compared to HgCdTe at relatively high temperatures and small bandgaps. The widest bandgap T2SL material exhibits lower Auger coefficients across all temperatures tested, which suggests superior intrinsic limitations to HgCdTe in terms of attainable carrier lifetime.

Auger processes are highly sensitive to the electronic band structure, providing the ability to significantly alter the Auger coefficient in narrow bandgap SLs [102]. Calculated electronic band structures are shown in Fig. 4.16 for the T2SL structures discussed in this section. Positions of the Auger resonant energies occur approximately one bandgap above and below of the conduction and valence band edges, respectively, and are shown in Fig. 4.16. The importance of the electronic band structure, especially in the secondary zones away from zone center, are critical in determining the Auger recombination rate. For example, at 77 K, sample GN0824 ($E_g=135$ meV) has an Auger coefficient nearly identical to sample GN0815 ($E_g=204$ meV) even though the latter has a bandgap energy that is 66% larger than the former. Standard modeling with BLB Auger lifetime equations would suggest that Sample GN0824 would have a significantly larger Auger coefficient due to having a smaller bandgap. Furthermore, sample GN0832 has only a slightly ($\sim 15\%$) wider bandgap than sample GN0824, yet the 77 K Auger coefficient for sample GN0832 is approximately twice that of sample GN0824. These results suggest that sample GN0824, which has a SL structure of 85.6 Å InAs/19.1 Å InAs$_{0.61}$Sb$_{0.39}$, has a favorable band structure to suppress Auger recombination. The large band splitting in the valence band and smaller bandgap of sample GN0824 demonstrates that some degree of final state optimization has been achieved with this particular structure compared to the others. As the lattice
temperature increases, this favorable band structure condition diminishes, and the measured Auger coefficients for sample GN0824 increase more dramatically with temperature than in the other samples.

Additionally, a 14 band $\textbf{k} \cdot \textbf{p}$ model was used to calculate the Auger coefficients in these structures [61]. These calculated results are shown in Fig. 4.15 for 77 K, 150 K, and 200 K. The transition matrix elements used for the Auger calculations are evaluated using a statically screened Coulomb interaction and first-order $\textbf{k} \cdot \textbf{p}$ perturbation theory for the wave function overlaps. Only direct Auger processes are considered in the calculation. The lowest measured Auger coefficient is $3 \times 10^{-27} \text{ cm}^6/\text{s}$, which is nearly an order of magnitude larger than those measured in InAs/GaInSb, which are near $10^{-28} \text{ cm}^6/\text{s}$ [30]. However, InAs/GaInSb T2SLs remain plagued by significantly shorter MC lifetimes, hampering any attempt to attain Auger limited carrier lifetimes at reasonable doping levels and temperatures.

4.4 Set III: Varying the Superlattice Period Thickness

Previously in this chapter, carrier lifetime results for a set of $235 \pm 10$ meV bandgap samples were studied with a focus on the influence of various alloy concentrations and doping levels on carrier lifetime. In order to achieve a constant bandgap, the SL period were varied from 49 Å to 76 Å while the Sb content of the alloy layer increased from 25 % to 49 % from sample GN0636 to GN0672, respectively. Also in this study, MC lifetimes were shown to modestly increase for the samples with increasing Sb concentration and narrower SL periods. One possible explanation for this trend in MC lifetime was that a fractional decrease in InAsSb alloy thickness with increasing Sb content in the SL absorber layer resulting in fewer SRH recombination centers at (or near) mid-bandgap. If these mid-bandgap recombination centers were generated by the InAsSb alloy, this could be associated with the factor of two longer SRH limited MC lifetimes at cryogenic temperatures. In order to verify this hypothesis,
the SL period thickness, and therefore the InAsSb layer thickness, is increased to approximately three times larger than the previous set (GN0636 through GN0672). If the InAsSb alloy is responsible for the short MC lifetimes rather than the relative shift in the valence band offset to SRH recombination centers, then the MC lifetime is expected to be the shortest in the sample with the thickest SL period.

Another consideration was Sb diffusion from the InAsSb into the InAs layers, which would produce more pronounced effects in the high–Sb alloy content samples, especially for samples with thinner SL periods. An estimated 2-3 % Sb diffusion from the InAsSb to InAs layer was observed using TEM measurements by Wood et al. [13] for 200 nm SL period samples with 35 % Sb content in their alloy layers. When the Sb alloy content decreases, Sb diffusion into the InAs layer is expected to decrease as well. However, the MC lifetime is a factor of two longer for the thinner SL period samples GN0670 and GN0672 compare to the thicker SL period structure GN0636. If the SL period thickness could be increased by more than a factor of two, the change in MC lifetime should be more evident. This study aims to provide a comparison of 5.2 \( \mu \text{m} \) bandgap InAs/In\( \text{As}_{0.85}\text{Sb}_{0.15} \) materials with the higher Sb alloy content structures. By investigating the effect of Sb content on the MC lifetime, the Auger coefficient can be investigated.

4.4.1 Experimental Results

A set of three unintentionally doped nominally 4 \( \mu \text{m} \) thick InAs/In\( \text{As}_{0.85}\text{Sb}_{0.15} \) T2SLs are studied using differential-transmission measurements. The optical and structural characterization of these materials are done as previously explained in this document and are shown in Table 4.5. Additionally, the net recombination rate is obtained from a time- and temperature-dependent differential-transmission technique [45]. For the measurements reported here, the pump and probe beam spot sizes, pump wavelength, and optically injected excess carrier densities are also
Table 4.5: Summary of the physical properties of the three InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs structures. The layer thicknesses and InAsSb compositions were determined from high-resolution x-ray diffraction. The absorption coefficients at the pump energy and vertical effective mass ratios were obtained from a 14-band $k \cdot p$ model and the results are listed for 77 K.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>InAs/InAs$_{1-x}$Sb$_x$ Thickness (Å)</th>
<th>X (%)</th>
<th># of SL Periods</th>
<th>$n_0$ (cm$^{-3}$)</th>
<th>$E_g$ (meV)</th>
<th>$\alpha$ cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN0838</td>
<td>174/218.75</td>
<td>15 ± 2</td>
<td>580</td>
<td>7.6 $\times 10^{14}$</td>
<td>203.9</td>
<td>1990</td>
</tr>
<tr>
<td>GN0837</td>
<td>86.8/109.3</td>
<td>15 ± 2</td>
<td>460</td>
<td>9.7 $\times 10^{14}$</td>
<td>161.6</td>
<td>2278</td>
</tr>
<tr>
<td>GN0835</td>
<td>65.08/81.9</td>
<td>15 ± 2</td>
<td>380</td>
<td>7.2 $\times 10^{14}$</td>
<td>134.5</td>
<td>2185</td>
</tr>
</tbody>
</table>

consistent with the previous studies discussed in this dissertation.

Figure 4.17: Normalized photoluminescence spectra of the three InAs/InAsSb T2SL samples at 80 K.
4.4.2 Discussion

In this set of samples, GN0838 has the thickest SL period of 393 nm and exhibited the longest MC lifetime of 13.4 µs, while other two samples have 8 − 9 µs MC lifetimes at 77 K. The longer MC carrier lifetime of sample GN0838 suggests that the alloy layer might not be responsible for generating the SRH defect states in mid-bandgap because sample GN0838 has more than three times larger InAsSb layer thickness compared to samples GN0837 and GN0835. From the best fit of temperature-dependent MC lifetime data, the $\sigma N_t$ value was obtained and is smaller for sample GN0838 than for other two samples. These results were shown in Table 4.6. The structures studied here indicate SRH–limited MC lifetimes at cryogenic temperatures, and Auger limited lifetimes at temperatures above 200 K. The radiative lifetime at low excess carrier densities was found to have negligible effect on the overall lifetime at any temperature.

![Figure 4.18: Net recombination rate as a function of excess carrier density are illustrated for three type-II InAs/InAsSb T2SL samples at 77 K. The solid red curves are the best fit to the measured data.](image)

From the excess carrier density dependent recombination data analysis, such as that shown in Fig. 4.18, the Auger coefficients are obtained as a function of temperature. The measured Auger coefficients decrease with increasing SL period thickness, as shown in Fig. 4.20. Sample GN0838 has $C_n \simeq 10^{-27}$ cm$^6$/s at 77 K
Figure 4.19: Minority carrier (MC) lifetime results as a function of temperature for the three InAs/InAsSb type-II superlattice samples. The solid black curves are the best fits to the measured data and represent the total MC lifetime. The red, green, and blue dashed curves are the deconvolved low level injection contributions of SRH, radiative, and Auger recombination to this total lifetime, respectively.

while samples GN0835 and GN0837 have a factor of five larger coefficients than sample GN0838. This result is not predicted from the expression of $C_n$ as given in Eq. 4.10, since the SL band structure is not included in this analysis. Notice that in Eq. 4.10, Auger coefficient increases with decreasing bandgap value. However, sample GN0838, with 25 meV smaller bandgap than other two samples, has a significantly lower Auger coefficient suggesting that the band structural differences in the the SL design provide
Table 4.6: Summary the SRH defect energy, $E_t$, capture probability, $\sigma N_t$, and Auger recombination Bloch function overlap parameter, $|F_1F_2|$, determined from the temperature-dependent minority carrier lifetime fitting. Defect energy levels are reported relative to the valance band edge of each superlattice.

| Sample ID | $E_t - E_v$ (meV) | $\sigma N_t$ ($cm^{-1}$) | $|F_1F_2|$ |
|-----------|-------------------|--------------------------|------------|
| GN0835    | 127±6             | 1.4±0.1                  | 0.11±0.04 |
| GN0837    | 145±9             | 1.6±0.3                  | 0.10±0.04 |
| GN0838    | 135±5             | 0.95±0.15                | 0.04±0.01 |

Figure 4.20: Measured Auger recombination rates of MWIR InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SL (GN0838) as a function of temperature. The solid curve is calculated Auger-1 coefficients for HgCdTd for the same bandgap operation at each temperature.
4.5 Summary

By altering the layer thicknesses and InAsSb alloy composition, a set of T2SLs with nearly constant 5.2 μm bandgap energy was designed and grown to investigate the 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 in the first set 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 ~ 2 $k_B T$ 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 ~ 200 K and Auger processes dominate MC recombination at temperatures above 200 K. 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 [46].
The carrier lifetime measurements also indicate that the MC lifetime is limited by SRH recombination for all the unintentionally doped samples at temperatures below approximately 175 K, which allowed extraction of the SRH defect energy levels. The defect energy levels provides evidence that the SRH recombination center in InAs/InAsSb T2SLs is singular in nature and its energy position is nominally independent of the T2SL structure. Analysis of the MC lifetime data suggests that this parasitic SRH defect state is at an average energy of 250 ± 12 meV below the valence band edge of bulk GaSb. These results provide evidence that the MC lifetime in InAs/InAsSb T2SLs can be substantially altered by engineering the electronic band structure. For instance, a T2SL sample with a bandgap of 134 meV (∼ 9.2 µm wavelength) is observed to have a MC lifetime of 4.6 µs at a temperature of 77 K. This enhanced SRH lifetime is a direct consequence of the T2SL structure being engineered such that the T2SL valence band edge is shifted up in energy, effectively shifting the SRH defect state away from mid-bandgap and closer to the valence band edge. This suggest that additional improvement to the carrier lifetime in InAs/InAsSb T2SLs can be achieved through electronic band engineering of the T2SL structure to render parasitic defect states ineffective as SRH recombination centers.

Auger recombination coefficients of the InAs/InAsSb T2SLs in set II were measured using a time- and temperature-resolved differential-transmission technique. A LWIR structure with 135 meV bandgap energy is found to have an Auger coefficient of $7 \times 10^{-26}$ cm$^6$/s at 77 K, which when compared to the other structures measured suggests some degree of optimization of the electronic band structure to suppress Auger-1 recombination has been attained. The MWIR samples are found to have an order of magnitude smaller Auger coefficient relative to calculated coefficients for HgCdTe using the Rule ’07 with comparable bandgaps, indicating superior intrinsic limitations to the maximum attainable nonradiative lifetime.

In set III, three MWIR InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs were studied to understand
the influence of SL period thickness on carrier lifetime. In set I, one of the explanations for the increasing SRH limited MC lifetime at low temperatures from sample GN0636 to GN0672 was the decrease in the fractional percentage of InAsSb alloys layer. In this section’s results, thicker SL period samples demonstrated a factor of two longer MC lifetime than the thinner SL period samples, suggesting that the alloy thickness is not directly related to the SRH limited MC lifetime for MWIR InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs.
CHAPTER 5
CARRIER TRANSPORT

Photo-generated transient-grating experiments have been performed for various semiconductors such as Ge [51], GaAs/AlGaAs quantum wells, SiGe alloys [52], Si [53], InSb [54], and InAs/GaAs SLs [55, 56]. Measurement of the in-plane transport in Ga-free MWIR InAs/InAsSb T2SLs is of interest due to their relatively light in-plane heavy-hole mass, which should lead to an enhancement of the in-plane transport. Carrier transport studies of InAs/InAs$_{0.65}$Sb$_{0.35}$ T2SLs have previously been carried out using the Hall measurement setup for Be-doped structures at 10 K. Carrier mobility of 4200 cm$^2$/Vs was reported [11] for p-type ($p_0 \approx 3 \times 10^{16}$ cm$^{-3}$ doped) detectors InAs/InAsSb T2SLs.

The photo-generated transient grating technique employed in this dissertation has several advantages over the Hall measurement technique which is commonly used to determine carrier mobility in semiconductor materials [53, 55, 56]. For example, it is not necessary to grow an intentionally doped sample for the mobility measurement, resulting in time and cost savings. Also, the photo-generated carrier density can be easily manipulated during the experiment so that a comparison of carrier diffusion and mobility in different samples at the same carrier density is possible. On the other hand, the optical method also has some drawbacks. For example, since photo-excitation creates carriers in electron-hole pairs, the electron and hole mobilities cannot be measured separately. The ambipolar diffusion coefficients measured with the optical method are dominated by the heavier species and therefore usually provide information on the hole mobility. Also note that in Ga-free InAs/InAsSb T2SLs the in-plane effective mass asymmetry of electrons and holes are smaller than other semiconductors, so it is more challenging to make assumptions about the carrier type.

In Chapter 4, the thicker SL period sample ($L_{SL}=393$ Å) was shown to have a factor of two longer MC lifetime than the thin SL layer samples ($L_{SL}=147$ Å and
$L_{SL} = 197 \, \text{Å}$ at 77 K. The samples GN0835, GN0837, and GN0838 are studied here to assess the quality of the SL structure and estimate the influence of SL period thickness on carrier mobility. To achieve this goal, photo-generated transient-grating experiments are performed to provide a direct measure of in-plane carrier transport properties in InAs/InAs$_{0.85}$Sb$_{0.15}$ [52–56]. In this chapter, a brief discussion of this approach and experimental results of the study are presented.

### 5.1 Diffusion Model

The experimental methodology outlined in Chapter 3 works well as long as the recombination lifetime, $\tau_R$, can be considered constant. This is the case for the Ga-free InAs/InAsSb T2SLs at room temperatures. At these excess carrier density levels, the Auger recombination limits the carrier lifetime. For example, if the Auger coefficient is approximately $C_n = 10^{-26} \text{ cm}^6/\text{s}$ and the injected carrier density is $\Delta n = 10^{17} \text{ cm}^{-3}$ then the Auger lifetime, $\tau_A \simeq 1/C_n^2 \Delta n$, is approximately 10 ns according to Eq. 4.8. This value is an order of five times longer than the pulse width and at least an order of magnitude longer than the transient grating decay lifetime. Under these conditions, a simple analysis procedure is used which is based on the assumption that the amplitude-phase grating profile remains sinusoidal during the evolution of the grating. A brief explanation of the diffusion model is presented in this section to clarify the grating evolution over time.

Once the ultrafast pulse is introduced into the system, the change in absorption coefficient, $\Delta \alpha$, can be obtained by measuring the differential transmission of a weak probe pulse as,

\[
\Delta \alpha = -\frac{1}{L} \log \left( 1 + \frac{\Delta T}{T} \right),
\]

where $L$ is the total absorber layer thickness of the structure. For small changes in differential transmission, this expression can be simplified to $\Delta T/T \simeq -\Delta \alpha L$, where
the change in absorption is linearly proportional to the injected excess carrier density,
\[ \Delta \alpha = \sigma_{eh} \Delta n. \quad (5.2) \]

Here, \( \sigma_{eh} \) is defined as the absorption cross section which is the total change of absorption coefficient per photo-generated electron-hole pair. The absorption cross section can be extracted from Eqs. 5.1 and 5.2 as shown in Fig. 5.1.

The spatial distribution and temporal evolution of the non-linearity in a structure are determined by the density of photo-generated carriers in the unsaturated region. Assuming that the pump pulse is much shorter than the lifetime of photo-generated carriers upon excitation of the system by an ultrafast excitation, is,
\[ \frac{d \Delta n(x, y, t)}{dt} + \frac{\Delta n(x, y, t)}{\tau_R} - D_a \nabla^2 \Delta n(x, y, t) = 0, \quad (5.3) \]

with
\[ \Delta n(x, y, t = 0) = \frac{\alpha F(x, y)}{h \nu} = N_0 \exp \left( -\frac{x^2 + y^2}{\omega_e^2} \right). \quad (5.4) \]

Here \( D_a \) is the ambipolar diffusion coefficient of the host material, \( F \) is the total fluence of the pump pulse, \( \omega_e \) is the spot size \( (e^{-1}) \), and \( \alpha \) is the linear absorption coefficient at the pump energy, \( h \nu \). The solution of Eq. 5.3 is shown in Eq. 5.5 and the detailed solution can be found in Appendix A,
\[ \Delta n(x, y, t) = \frac{N_0}{1 + 4D_a t/\omega_e^2} \exp \left( -\frac{x^2 + y^2}{\omega_e^2 + 4D_a t} \right) e^{-t/\tau_R}. \quad (5.5) \]

The changes in the absorption coefficient caused by the optically injected excess carriers are accompanied by refractive index modification. In this case, the change in the refractive index, \( \Delta n_{ind.} \), is linearly proportional to the density of the photo-generated electron hole pairs for an unsaturated semiconductor,
\[ \Delta n_{ind.} = n_{eh} \Delta n, \quad (5.6) \]

with \( n_{eh} \) is the nonlinear refraction coefficient, which is the change of refractive
Figure 5.1: (a) Time-resolved differential transmission decay curves and (b) the change in absorption coefficient with injection level are illustrated for the MWIR InAs/InAsSb T2SL sample GN0838. (c) Calculated $\Delta \alpha$ values as a function of excess carrier density demonstrated for the sample GN0838 at 77 K.

index per photo-generated electron-hole pair. The value of $n_{eh}(\omega)$ can be obtained from $\sigma_{eh}(\omega)$ via the Kramers-Kronig relation which relates the refractive index and
the absorption coefficient of materials containing a fixed number of carriers. The absorption coefficient and the refractive index of a photo-excited semiconductor are therefore also related by the Kramers-Kronig relations. The change of refractive index associated with the change of absorption coefficient is given by,

$$\Delta n_{\text{ind.}}(\omega) = \frac{c}{\pi} P \int_0^\infty \frac{\Delta \alpha(\omega') d\omega'}{\omega'^2 - \omega^2},$$

(5.7)

where P indicates that the principle value of the integral must be evaluated.

For differential-transmission experiments, the $\Delta \alpha$ spectra can be obtained by tuning the pump wavelength. The measurements are therefore not made at fixed carrier density, since both linear absorption coefficient and laser output power are functions of wavelength. In order to use the Kramers-Kronig relations, it is necessary to convert the $\Delta \alpha(\omega)$ and $\sigma(\omega)$ by using the definition given in Eqs. 5.2 and 5.6. Both $\Delta \alpha(\omega)$ and $\sigma_{eh}(\omega)$ are independent of carrier density over the range of interest and are therefore related by Kramers-Kronig relations,

$$n_{eh}(\omega) = \frac{c}{\pi} P \int_0^\infty \frac{\sigma_{eh}(\omega') d\omega'}{\omega'^2 - \omega^2}. $$

(5.8)

Information on $\sigma_{eh}$ and $n_{eh}$ can also be obtained from the transient-grating diffraction efficiency spectrum of the sample [56].

The geometry of the transient grating measurement was shown in Fig. 3.5. Two identical pump pulses separated by an angle $\theta_e$ are spatially and temporally coincident at the sample. The interference between the two pump pulses modulates their intensity, and hence the fluence experienced by the sample along the in-plane direction (perpendicular to the vertical or growth direction). Under the plane wave approximation, assuming plane wave fronts and a uniform spatial intensity distribution of the incident pump pulses as shown in Fig. 5.2, the intensity distribution along the in-plane direction can be determined. The fluence of each pump beam (identical in this case) and the modulation efficiency ($\sim 1$) is given by Eqs. 5.9(a) and 5.9(b),
respectively,

\[ F_e = (1 - R_F)T_{opt} \frac{P_e}{\pi \omega_F^2 R_R^2}, \]  

\[ \mu = \frac{2\sqrt{F_1 F_2}}{F_1 + F_2} \]  

where \( F_e \) is the measured pump fluence, \( T_{opt} \) is the transmission of the cryostat window and \( R_R \) is the pump repetition rate as discussed in Chapter 3. \( P_e \) is the power measured directly in front of the sample by a broadband, high sensitivity thermal power meter. The \( F_1 \) and \( F_2 \) terms are the individual pump fluences injected into the system by pump-1 and pump-2 as in Fig. 3.5. The modulation depth is used to define the peak to peak carrier density \( N_{p-p} \) of the grating as \( N_{p-p} = 2\mu N_0 \). Therefore the total excess carrier density injected into the system at \( t = 0 \) is

\[ \Delta n(x, t = 0) = N_0 \left[ 1 + \mu \cos \left( \frac{2\pi x}{\Lambda} \right) \right]. \]  

(5.10)

Note that the modulation depth was chosen to be near 1 by controlling the degenerate pump fluences to be approximately the same for all measurements presented here. The expression for the grating decay rate, \( \Gamma_G \), is defined in Chapter 3 as,

\[ \Gamma_G = \Gamma_D + \Gamma_R, \]  

(5.11)

here, \( \Gamma_D \) is the diffusion rate,

\[ \Gamma_D = \frac{4\pi^2 D_a}{\Lambda^2}. \]  

(5.12)

The carrier density distribution given by Eq. 5.3 will modulate the absorption and refractive index, according to Eqs. 5.1 and 5.5, forming a diffraction grating. The efficiency, \( \eta \), with which a weak probe pulse is scattered from a thin sinusoidal grating is given by (see Appendix B):

\[ \eta = \frac{1}{4} \exp \left( -\alpha L - \sigma_e e^{-t/R} N_0 L - 2t/\tau_G \right) \left[ \left( \frac{2\pi n_e e}{\lambda_p} \right)^2 + \left( \frac{\sigma_e e}{2} \right)^2 \right] N_0^2 L^2. \]  

(5.13)
When $t \ll \tau_G$ and the condition $\Delta \alpha = \sigma_{eh} N_0 \ll \alpha$, Eq. 5.13 becomes,

$$
\eta = \frac{1}{4} e^{-\alpha L} \left[ \left( \frac{2\pi n_{eh}}{\lambda_p} \right)^2 + \left( \frac{\sigma_{eh}}{2} \right)^2 \right] N_0^2 L^2. \tag{5.14}
$$

The diffraction efficiency, measured before significant decay by in-plane diffusion has occurred, can be used as a check on the consistency of the measured $\sigma_{eh}$ and $n_{eh}$ calculated from the $\Delta T/T$ measurement and the Kramers-Kronig transformation.

It should be emphasized that Eq. 5.13 was derived, and will only be valid, under the following approximations and conditions:

1. Plane wave approximation, which assumes that the pump pulses have plane wave-fronts, uniform spatial intensity distributions and infinite cross sections. These assumptions are appropriate when the sample is set at the beam waist, only the central $e^{-1}$ part of the pump laser spot is probed and the laser spot is sufficiently large that the effects of carrier diffusion out of the photo-excited area are negligible.
2. The fluence of the pump pulses are sufficiently low, i.e. within the unsaturated region of the nonlinearity, so that sinusoidal modulations of $\alpha$ and $n_{ind}$ will be produced.

3. The active sample is thin enough that the thin grating condition is satisfied ($Q \ll 1$).

4. The duration of the pump pulses are much shorter than the carrier recombination time and the diffusion decay time.

5. Measurements are made a few ps after the optical excitation, when photo-generated carriers have been thermalized.

Care was taken to ensure that all these conditions were fulfilled in the experiments.

5.2 Experimental Results

The in-plane carrier transport properties of a set of three MWIR InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs were studied at 293 K. The duration of the intensity modulation depends on both the recombination of non-equilibrium carriers and diffusion of carriers from the peak to the troughs of the modulation. Hence, this all-optical measurement allows one to obtain both the diffusion and the recombination dynamics. The period and efficiency of the intensity modulation were controlled by the optical and geometric properties of the pulses. The pump wavelength was varied from 2.5 $\mu$m to 3.4 $\mu$m to control the modulation period from approximately 15 $\mu$s to 22 $\mu$s according to Eq. 5.1. For the measurements reported here, the pump and probe beams had radii ($e^{-1}$ of the intensity) of $\sim$ 1200 $\mu$m and $\sim$ 400 $\mu$m, respectively. The pump intensity was varied using a pair of Teflon polarizers, resulting in identical pump fluences from 2000 nJ/cm$^2$ to 20 nJ/cm$^2$, values that are significantly larger than the probe fluence.

If the grating decay rate is measured for a given grating period, the ambipolar
Figure 5.3: Wavelengths of four pump beams and a probe beam is illustrated. The long-pass (LP) filter is used to block pump beams while measuring the diffracted probe beam.

Figure 5.4: Calculated absorption coefficients as a function of energy is illustrated for samples GN0838, GN0837, and GN0835 at 293 K.

diffusion coefficient can be determined from Eqs. 5.11 and 5.12. Here, a three dimensional excess carrier density of $2.3 \times 10^{17}$ cm$^{-3}$ was injected into the samples. During this process, the calculated absorption coefficients, as shown in Fig. 5.4, were
taken into account at each incident pump energy. The modulation depth was chosen near 1, meaning pump fluences were almost equal. The angle between two pumps beams was approximately $9^\circ$ and the incident probe beam is oriented at $18^\circ$ to the normal of the sample surface. The thin grating condition of $Q = \frac{2\pi d \lambda_p}{\Gamma^2 n_p} \ll 1$ was satisfied, where $n_p$ is the index of refraction at the probe wavelength, $\lambda_p$. Therefore, the phase difference between the diffracted waves is small enough that they interfere constructively. Note that if this condition is not satisfied then the Bragg condition must be taken into account by controlling the incident beam angles as discussed in Chapter 3.

The decay of the normalized diffraction efficiency for each sample with grating period from 15.1 $\mu$m to 22 $\mu$m is shown in Fig. 5.5. The results of the pump-probe measurement with similar injected carrier densities are also shown in Fig. 5.5. The carrier recombination lifetimes were obtained using the differential-transmission technique discussed in Chapter 4. Notice that the Auger process in InAs/InAsSb T2SLs is responsible for limiting the carrier recombination at high carrier densities resulting in orders of magnitude smaller recombination rates compared to the decay rate of the transient-grating, confirming that the Auger process did not influence the extraction of the ambipolar diffusion coefficients.

Multiple grating periods of the intensity modulation were used to ensure each ambipolar diffusion coefficient was accurately extracted at a given grating period. Eq. 3.13 is used to correlate $\Gamma_G$ and $4\pi^2/\Lambda^2$ with a linear fit as shown in Fig. 5.6. Notice that the y-intercept of this line is the carrier recombination rate as extracted from pump-probe measurements. The grating decay rate increases with decreasing grating period as predicted from Eq. 3.13. Ambipolar diffusion coefficients of $56\pm3$ cm$^2$/s, $60\pm3$ cm$^2$/s, and $61\pm3$ cm$^2$/s were extracted for samples GN0838, GN0837 and GN0835, respectively, as shown in Fig. 5.6.
Figure 5.5: Normalized diffraction efficiency (filled symbols) for various grating period and carrier recombination rate (unfilled dots) as a function of probe delay for samples GN0838, GN0837 and GN0835 at 293 K. The solid red curves are the best fit to the measured data.

5.3 Discussion

Table 5.7 outlines the results of transient-grating measurements that reveal an obvious correlation between the carrier lifetimes and the measured ambipolar diffusion coefficients. The longer MC lifetime sample GN0838 has the smallest diffusion coefficient of $56 \pm 3 \text{cm}^2/\text{s}$ among the samples at 293 K. This results also suggests that
Figure 5.6: Grating decay rate, $\Gamma_G$ vs. $4\pi^2/\Lambda^2$ for the samples GN0838, GN0837 and GN0835 at 293 K. The solid red curves are the best fit to the measured data where the slope is the $D_a$ and the y-intercept is the $\tau_R^{-1}$.

the ambipolar diffusion coefficients of these three samples could differ more at the cryogenic temperatures where the carrier lifetime difference is a factor of two.

For equal electron and hole densities, the relation between the ambipolar diffusion
Table 5.7: Measured recombination and diffusion properties for samples GN0838, GN0837 and GN0835 at 293 K.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$\tau_{MC}$ (ns) at 293 K</th>
<th>$D_a$ (cm$^2$/s)</th>
<th>$\mu_a$ (cm$^2$/Vs)</th>
<th>$m_e/m_h$ (Vertical)</th>
<th>$m_e/m_h$ (In-Plane)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN0838</td>
<td>292 ± 3</td>
<td>56 ± 3</td>
<td>2220 ± 120</td>
<td>0.040 / 0.999</td>
<td>0.019 / 0.029</td>
</tr>
<tr>
<td>GN0837</td>
<td>260 ± 3</td>
<td>60 ± 3</td>
<td>2380 ± 120</td>
<td>0.017 / 0.999</td>
<td>0.016 / 0.032</td>
</tr>
<tr>
<td>GN0835</td>
<td>222 ± 3</td>
<td>61 ± 3</td>
<td>2420 ± 120</td>
<td>0.016 / 1.000</td>
<td>0.016 / 0.031</td>
</tr>
</tbody>
</table>

The measured recombination and diffusion properties for samples GN0838, GN0837, and GN0835 at 293 K are summarized in Table 5.7.

The recombination coefficient and ambipolar mobility is given as,

$$D_a \simeq \frac{2k_BT}{e} \frac{\mu_n\mu_p}{\mu_n + \mu_p},$$

where $\mu_n$ and $\mu_p$ are the electron and hole mobility, respectively, $k_B$ is Boltzmann’s constant, $e$ is the magnitude of the fundamental electronic charge, and $T$ is the carrier temperature. Notice that if the electron’s effective mass is significantly smaller than the hole effective mass along the in-plane direction, then this expression reduces to $D_a \simeq \frac{2k_BT\mu_p}{e}$, which allows an estimate of the lower limit for the minority carrier mobility. However, the effective electron and hole masses do not differ enough in the in-plane direction to make this estimate for the MWIR InAs/InAsSb T2SLs studied here. Considering that all the materials are grown in the same molecular beam epitaxy system, the major structural difference is expected to be the SL period thickness. Therefore, the trend of increasing $D_a$ values with narrowing SL period thickness could be related to the amount of SL disorder and their influence on carrier localization. This explanation may also be supported by the inverse relation of MC lifetime and ambipolar diffusion coefficients.

It should be noted that the effective electron masses are approximately 60% of the effective hole masses for the in-plane direction. Therefore, the measurements presented...
Figure 5.7: A comparison of ambipolar diffusion coefficients in III-V binary compounds, InAs/InAsSb T2SL and a four-layer-superlattice structures.

here are not sensitive to electron or hole transport particularly. Previous measurements of electron mobility in unintentionally doped (n-type) InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs demonstrate that the electron mobility is approximately 206,000 cm$^2$/Vs at 10 K. The ambipolar diffusion mobilities of InAs and InSb at 293 K are approximately 66 % and 4 % of the T2SLs, respectively. The results of these previous studies are shown in Fig. 5.7 for comparison.

In summary, ambipolar diffusion coefficients of unintentionally doped MWIR InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs have been measured for the first time and the results compared with the similar Sb-based photodetector materials. The influence of SL period thickness on ambipolar diffusion was studied to understand the SL disorder related to alloy scattering, interface roughness. Less than 10% faster diffusion for the thinner SL period samples were observed at 293 K. However, the results suggest that the difference could be larger at lower temperatures where the MC lifetimes differ by a factor of two.
CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Conclusion

Time-resolved temperature-dependent differential-transmission measurements were performed to investigate the non-equilibrium carrier dynamics in a series of MWIR and LWIR InAs/InAs$_{1-x}$Sb$_x$ T2SLs. The carrier lifetime and transport properties were studied by varying the alloy Sb content, doping concentration, SL layer thickness, and SL bandgap. Samples were initially tested by capacitance-voltage, photoluminescence, and high-resolution X-ray diffraction measurements to assess the optical and electrical properties. These measurements confirmed the designed layer structure and bandgaps for all samples. A 14-band $k \cdot p$ model [61] was used to calculate the electrical and optical properties of these SL structures at each temperature investigated.

The carrier lifetime study was based on three sets of InAs/InAs$_{1-x}$Sb$_x$ T2SLs with the aim to individually understand the influence of SL alloy concentration, SL bandgap, and SL period thickness on carrier lifetime. The highlights of the first set and the results are listed as follows [44,45,57].

- 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 effects of Sb concentration on the carrier lifetime.

- The MC lifetime was found to modestly increasing with Sb concentration and narrower SL periods (from 3 $\mu$s MC lifetime for 26 % Sb content sample to 6 $\mu$s MC lifetime for 49 % Sb content sample.)

- One possible explanation for this variation is a fractional decrease in InAsSb alloy with increasing Sb content, resulting in fewer SRH recombination centers near mid-bandgap. It is also possible that the $\sim 2 k_B T$ energy shift in the SRH
defect energy relative to the band edges of the SLs could influence the SRH lifetime.

- The SRH defect states stays near mid-bandgap of the SL regardless of the InAsSb composition for these MWIR samples.

- The Auger coefficient is observed to weakly depend on Sb content in the InAsSb alloy, decreasing by approximately a factor of 2 as the Sb concentration increases from 26% to 49%. The Auger coefficients reported here for the InAs/InAs$_{1-x}$Sb$_x$ T2SLs are in range of 1-5 $\times 10^{-26}$ cm$^6$/s and significantly larger than those found in InAs/Ga(In)Sb T2SLs.

This study utilizes a coordinated and iterative approach including: design, growth, optical measurement of key material properties, and redesign. Based on the results of the first set, two additional sets were designed to better understand the influence of SL bandgap and SL period thickness on carrier lifetime.

In set II, seven InAs/InAs$_{1-x}$Sb$_x$ T2SLs were designed to have specific bandgap energies between 290 meV ($4.3 \, \mu\text{m}$) and 135 meV ($9.2 \, \mu\text{m}$) [49,83]. The third set has three MWIR InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs, which were designed with various SL period thicknesses from 147 Å to 393 Å. The conclusions of this study are summarized as follows.

- The defect energy levels provide evidence that the SRH recombination center in InAs/InAsSb T2SLs is singular in nature and its energy position is nominally independent of the T2SL structure and bandgap.

- By varying the bandgap from 290 meV to 135 meV, a shallow defect state has been observed to enhance the SRH limited MC lifetime. The minority carrier lifetime was measured to be 4.5 $\mu$s at 77 K in an LWIR T2SL. This is an order of magnitude longer MC lifetime than the previously reported results [12].
A MWIR structure with 290 meV bandgap energy and 40 % Sb alloy content was found to have approximately 18 µs MC lifetime at 77 K.

A LWIR structure with 135 meV bandgap energy was found to have an Auger coefficient of $7 \times 10^{-26} \text{ cm}^6/\text{s}$ at 77 K. When compared to the other structures measured, this suggests some degree of optimization of the electronic band structure to suppress Auger-1 recombination has been attained.

The thickest SL period sample was observed to have a factor of two longer MC lifetime than the thinnest SL period samples, suggesting that the alloy thickness is not directly related to the SRH limited MC lifetime for MWIR InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs.

Additionally, the photo-generated transient grating measurements were performed on nominally 4–µm–thick InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs to measure the in-plane ambipolar diffusion coefficient at 293 K. The experimental ambipolar diffusion coefficients of $\sim 60 \text{ cm}^2/\text{s}$ were reported for a set of three InAs/InAs$_{0.85}$Sb$_{0.15}$ T2SLs with various SL period thicknesses. Significantly lower heavy hole masses in these SLs due to the strain on the Sb-based structures causes a larger ambipolar diffusion coefficient compared to the group III-V binary alloys in 6.1 Å family. An inverse relation between MC lifetime and ambipolar diffusion was found at room temperature.

6.2 Recommendation for Future Research

The nBn device structures employing Ga-free InAs/InAsSb T2SLs exhibit promising characteristics for infrared sensing, including long minority carrier (MC) lifetimes, low surface leakage, and high material quality, but they also suffer from three key limitations:

1. The optical absorption strength becomes low at longer wavelengths as T2SL period increases and electron-hole overlap decreases.
2. The operating temperature is limited by high Auger recombination rates.

3. The quantum efficiency is limited by short minority hole diffusion length due in part to the large effective mass of minority holes in these structures.

In this chapter, suggestions for better device performance in Sb-based MWIR and LWIR photodetectors are discussed.

6.2.1 Metamorphically grown Ga-free InAsSb\textsubscript{x}/InAsSb\textsubscript{y} T2SLs

A promising avenue to overcome present limitations in InAs/InAsSb T2SLs is a new approach using metamorphically grown Ga-free InAsSb\textsubscript{x}/InAsSb\textsubscript{y} T2SLs [28, 103, 104]. These T2SLs have recently been shown to achieve bandgaps out to the VLWIR using superlattice periods of less than half that required by the lattice matched InAs/InAsSb\textsubscript{y} system [103]. In addition to the dramatic increase in absorption strength afforded by the reduced period in metamorphic modulated-Sb (MM-Sb) T2SLs, the hole effective mass can be reduced by a factor of five or more, greatly improving hole transport. The additional degrees of freedom with respect to lattice constant and alloy composition of MM-Sb T2SLs provide wide latitude for band structure engineering to suppress Auger processes.

The band structures of 135 meV bandgap 100 Å InAs/15 Å InAsSb\textsubscript{0.45} and 23 Å InAsSb\textsubscript{0.65}/23 Å InAsSb\textsubscript{0.45} were calculated using a 14-band $\mathbf{k} \cdot \mathbf{p}$ model [61] and results are shown in Fig. 6.1. One of the most important result of using an InAsSb\textsubscript{x}/InAsSb\textsubscript{y} design is that the SRH recombination centers could be forced below the valence band edge, which can effectively increase the SRH limited MC lifetime. Another important advantage is that the band splitting in valence and conduction bands eliminates the final states for Auger processes, leading to a smaller Auger coefficient.
Figure 6.1: Calculated band structure for the two different 135 meV bandgap T2SL structures at a lattice temperature of 77 K. Negative wavevectors correspond to the vertical or growth direction, while positive wavevectors correspond to the in-plane direction.

6.2.2 Vertical Transport Measurements of InAs/InAsSb T2SLs

There is still no consensus in the InAs/InAsSb T2SL photodetector community regarding the SL structural disorders that occur during MBE growth (e.g. Sb segregation). Previously, MWIR InAs/InAsSb T2SLs have been studied using multiple electron microscopy methods to estimate the interface chemical diffusion caused by Sb segregation [13, 20, 105]. The measurement of local Sb compositional profiles across the superlattices using electron energy-loss spectroscopy and 002 dark-field imaging revealed asymmetric Sb distribution, with the InAs-on-InAsSb interface being chemically graded. However, the InAsSb-on-InAs interface showed a small intrinsic interface width. Segregation dominated over the sigmoidal growth at the InAs-on-InAsSb interface, and a segregation probability of approximately 81% was obtained from the two microscopy techniques. Thus, 81% of Sb atoms from the topmost layers
segregated into the next layer during growth, causing the interfaces to be broadened over a length of approximately 3 nm. Additionally, the MBE growth simulations by Dr. Grein suggest that the material specific defects and localized states can result in carrier localization in InAs/InAsSb T2SLs [106].

Figure 6.2: (a) Simplified illustration the vertical transport measurement using time-resolved $\Delta T/T$. Note, only the T2SL absorber layers are shown. (b) Schematic of short-period grating technique for measuring vertical transport.

It is important to understand how the carrier transport properties in the growth direction are influenced by SL structural disorders. There are two techniques that can be implemented to answer this question by using an all-optical approach at the University of Iowa’s research facilities. In the first technique, an ultrafast optical pulse with a higher energy than the bandgap of the studied SL can be introduced to the system to excite carriers from the top layer of the device. In roughly 10s of ps, these excited carriers cool down to the lattice temperature. Next, these carriers will diffuse to a narrower band gap (lower energy) marker SL where they relax to the band edges. At this point, a lower energy pulse will be used to probe the band filling process of the marker SL as shown in Fig. 6.2. Due to the band filling process, the absorption in this band is dependent on the number of initially injected excess carriers.
It is possible to detect the change of the differential-transmission over time by using pump-probe technique. The transport time of generated electron-hole pairs will be different due to the SL active region thickness, and the ambipolar diffusion coefficient can be calculated from the continuity equation 2.36.

Such an experiment for MWIR InAs/GaSb superlattice with an LWIR superlattice marker region was performed by Dr. Benjamin Olson in 2013 [17, 32]. The experimental differential transmission was measured as a function of delay between the pump and the probe for a MWIR InAs/GaSb T2SLs with an LWIR superlattice marker region grown below it. The measurements were made at 77 K and the band gap of the MWIR SL in both samples was measured to be 3.8 μm (325 meV). The LWIR marker SL has a band gap of ∼ 10 μm (124 meV). The 392 nm pump was derived from a frequency doubled Ti:Sapphire laser with an estimated peak carrier density of ∼ 8 × 10^{17} cm^{-3}. The probe was an 8.7 μm pulse produced by frequency conversion of the fundamental Ti:sapphire output in an OPA followed by the generation of the DFG signal. From a best fit to the data, the recombination rate and D_a were found to be 20 ns and 0.3 cm^{2}/s, respectively. The knowledge gained from these measurements and analysis can be applied to the design of a series of InAs/InAsSb superlattices with differing SL period and absorber layer thicknesses. This would lead to a better understanding of the carrier localization and the correlation between carrier lifetime and Sb segregation.

The photo-generated transient grating technique is also applicable to measuring the carrier transport properties in vertical direction. The in-plane ambipolar diffusion coefficients were already obtained using the approach discussed in Chapter 3 and Chapter 5. Instead of creating the intensity modulation in the in-plane direction, a similar charge intensity modulation could be created along the vertical axis (or growth direction). For this measurement, the pump beams would be incident from opposite sides of the investigated sample (as illustrated in Fig. 6.2(b)). To optimize the
measurement, a grating period much smaller than the absorber layer thickness would be used. In a previous study, a short-period transient grating technique was used to study the vertical transport as a function of lattice temperature in a GaAs/Al\(_{0.3}\)Ga\(_{0.7}\)As multiple quantum wells [107, 108]. This experimental approach could be adapted to the Sb-based T2SLs discussed in this dissertation.

6.2.3 Proton Radiation Effect on Carrier Lifetime of InAs/InAsSb T2SLs

Ga-free MWIR InAs/InAsSb T2SLs are a growing technology demonstrating long carrier lifetimes and low dark current densities, making them good candidates for astronomical applications [38, 100, 109, 110]. Infrared detectors and focal plane arrays are used in numerous instrumentation developed by NASA for Earth and Planetary Science missions in which HgCdTe IR detectors are most frequently used [111]. The search for bio-signatures around Earth-like exo-planets requires extremely sensitive measurements of faint systems, resulting in photon limited observations. Even using large collecting areas of > 8 m, the study of bio-signatures requires ultra-low background noise or prohibitively long observation times to fully characterize each exoEarth candidate [109]. Another application for Sb-based SLs of particular interest is IR detectors on satellites to detect mid-range ballistic missiles whose temperatures in space, even without an exhaust plume, are well above ambient [112, 113]. To maximize the science yield of future missions, IR photodetectors operated in the MWIR and LWIR with high quantum efficiency and minimal noise (optimally zero read noise, ultra-low dark current, and ultra-low spurious count rate) are necessary. Due to the very low input signal, dark current and readout noise are currently the limiting factors [114]. In this regime, Ga-free InAs/InAsSb T2SLs become good candidates to provide high absorption coefficients and low dark current in IR range [113].

One challenge is that photodetectors used in space-based instrumentation are
required to be radiation hard, meaning that they need to exhibit only a minor performance degradation after exposure to radiation. In the last decade, SL detectors based on InAs/GaSb material layers have demonstrated significant performance improvements over HgCdTe due to their low interband tunneling and suppressed Auger recombination rates [5,81,82,102,115]. A set of LWIR InAs/GaSb T2SLs based on a Np complementary barrier IR detector (CBIRD) device design was previously studied to understand the effect of proton irradiation on the device performance [116,117]. The results showed that, irradiation of the samples with 68 MeV protons caused a significant increase in dark current from $J_{d}^{\text{pre-rad}} = 5 \times 10^{-5}$ A/cm$^2$ to $J_{d}^{\text{post-rad}} = 60 \times 10^{-5}$ A/cm$^2$ after the first irradiation, with a fluence of $19.2 \times 10^{11}$ H$^+$/cm$^2$. Overall, this change in the dark current mechanism was attributed to an onset of surface leakage current.

At the University of Iowa, a set of measurements has been initialized to investigate the effect of irradiation on Ga-free InAs/InAsSb T2SLs with bandgaps from 135 meV to 290 meV (set II and set III as in Chapter 4). These structures were tested using time-resolved temperature-dependent differential measurements and the results were discussed in Chapters 4 and 5. These samples were initially $0.5 \times 1 \text{ cm}^2$ and each sample was cleaved into to $0.5 \times 0.5 \text{ cm}^2$ pieces. One piece was used as a control and the other was irradiated with 100 kRad (65 MeV) at Sandia National Laboratories.

After irradiation, the MC lifetime was observed to decrease at low temperatures due a higher rate of SRH events. The $\sigma N_t$ term for the irradiated samples was foud to be larger. This suggests an increase in either the cross section or the density of the SRH recombination centers. Assuming that the band structures, effective carrier masses, and bandgaps were unchanged after irradiation, the change in the cross section value must be small compare to the change in SRH recombination center density. Therefore, it can be concluded that the $N_t$ values are higher for the samples that are SRH limited for the post-radiation condition. If the sample is not strongly SRH limited, e.g. sample GN0826, the MC lifetime was almost unchanged. As shown
Figure 6.3: Experimentally measured minority carrier lifetimes for pre-radiation (black squares) and post-radiation (red circles) as a function of temperature for the unintentionally doped InAs/InAs$_{1-x}$Sb$_x$ T2SLs.
Table 6.8: Summary the SRH defect energy, $E_t$, capture probability, $\sigma N_t$, and Auger recombination Bloch function overlap parameter, $|F_1F_2|$, determined from the temperature-dependent minority carrier lifetime fitting for the pre- and post-rad. pieces of samples. Defect energy levels are reported relative to the valence band edge of each superlattice.

| Sample ID | $E_t^{\text{post-rad}}$ (meV) | $E_t^{\text{pre-rad}}$ (meV) | $(\sigma N_t)^{\text{post-rad}}$ (1/m) | $(\sigma N_t)^{\text{pre-rad}}$ (1/m) | $|F_1F_2|^{\text{post-rad}}$ | $|F_1F_2|^{\text{pre-rad}}$ |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| GN0815    | 133±9           | 111±8           | 10.2±0.6        | 4.1±0.3         | 0.13±0.04       | 0.16±0.04       |
| GN0822    | 99±9            | 99±16           | 13.2±3.0        | 8.2±2.0         | 0.20±0.08       | 0.15±0.04       |
| GN0826    | 166±25          | 170±30          | 0.5±0.2         | 0.4±0.2         | 0.15±0.09       | 0.13±0.10       |
| GN0828    | 164±6           | 145±11          | 11.7±1.0        | 1.9±0.9         | 0.14±0.09       | 0.14±0.05       |
| GN0830    | 111±11          | 111±8           | 8.0±0.9         | 4.0±0.3         | 0.14±0.08       | 0.14±0.09       |

in Fig. 6.3, the sample GN0815 displays the most drastic decrease in MC lifetime, which was attributed to its strong SRH limited MC lifetime. The energy level of the SRH recombination centers for the samples GN0815, GN0822, and GN0826 indicated almost no change for the post- and pre-rad. conditions as shown in Table 6.8.

In these measurements and analyses, the background carrier density, band structure, effective masses, and valence and conduction band edges were assumed identical for the post- and pre-radiated pieces of samples. The change in the density of SRH recombination centers due to the proton radiation do not strongly influence the Auger process as evidenced by the fact that the C coefficients of the post-rad. samples were comparable to the pre-rad. samples.

In summary, up to a 50 % drop in the MC lifetimes was observed in the post-radiated samples compared to the pre-radiated samples as shown in Fig. 6.3. These results suggest that InAs/InAsSb T2SLs are quite tolerant of proton irradiation and may be suitable for space infrared detector arrays. Tests over a larger range of
temperatures are necessary to better understand these effects and will be carried out at the University of Iowa.

6.2.4 Spin Relaxation in InAs/InAsSb T2SLs

Due to the unique characteristics of T2SL systems, including the strong spin orbit interaction [118] and the high ambipolar diffusion coefficients, as discussed in this dissertation, it may be possible to realize a variety of novel high-speed, spin-sensitive, electronic devices in the future [58,119–122]. An important parameter in the design of any spin-sensitive electronic device is the electron spin relaxation time ($T_1$), which must be long enough to allow for transport and/or processing of the spin-polarized electrons [123]. In addition, the spin lifetime properties are strongly influenced by the asymmetric barrier potentials at the interfaces, referred to as native interface asymmetry (NIA). NIA can be used to evaluate the structural disorders at the SL interfaces regarding the SL period thickness or Sb content of the alloy.

The spin manipulation schemes shown in Fig. 6.4 do not require an external magnetic field. The non-magnetic spin control exploits the Rashba effect [124]: An applied electric field is experienced by the charged carriers spin as an effective magnetic field though the spin-orbit interaction. The Rashba effect was previously utilized in a variety of related experiments [58,120,121] at the University of Iowa. The photo-generated, spin-polarized electrons alter the absorption coefficient of the associated interband transition through state filling. $T_1$ can be determined by monitoring the transmission of a weaker, delayed probe pulse that has the same (SCP) or opposite (OCP) circular polarization as the pump pulse. In the measurements presented here, an excess carrier density of approximately $5 \times 10^{16}$ cm$^{-3}$ was initially injected. A 76 MHz operation frequency Ti:Sapphire pump laser was used to generate idler and signal beams in an optical parametric oscillator (OPO) with an idler beam energy of $\sim 420$ meV and a 120 fs pulse width. The delay between pump and probe pulses was
Figure 6.4: Schematic diagram of a polarization-sensitive pump-probe measurement. In (a), (b), (c), and (d) same linear polarized (SLP), same circular polarized (SCP), opposite linear polarized (OLP), and opposite circular polarized (OCP) pump-probe measurement configurations are illustrated, respectively.

created using a 60 cm delay stage which can create a 4 ns delay.

Figure 6.5: Results of differential transmission experiments on doped InAsSb$_{0.09}$ alloy. On the left panel, data for conditions of same circular (SCP) and opposite circular (OCP) polarization geometries are indicated by black and red lines, respectively. On the right panel, the data and single exponential fit to the difference between the decay curves for SCP and OCP is shown.
Figure 6.6: Results of differential transmission experiments on undoped InAsSb\textsubscript{0.09} alloy. On right panel, data for conditions of same circular (SCP) and opposite circular (OCP) polarization geometries are indicated by black and red lines, respectively. On left panel, the data and single exponential fit to the difference between the decay curves for SCP and OCP is shown.

Here, the spin lifetime of an InAsSb\textsubscript{0.09} alloy and an unintentionally doped MWIR InAs/InAs\textsubscript{0.70}Sb\textsubscript{0.30} T2SL were measured using a time- and polarization-resolved differential-transmission technique at 293 K. The results are presented in Figs. 6.5, 6.6, and 6.7. The peak in first 100s of femtoseconds is related to non-thermal process which was excluded during the spin lifetime analysis. The doped and undoped alloy structures were measured to have 27.7 ps and 25.7 ps \( T_1 \) lifetimes, respectively, which is approximately 10 ps longer than the InAs/InAs\textsubscript{0.70}Sb\textsubscript{0.30} T2SL structures spin relaxation lifetime. The electron spin relaxation time was measured previously in MWIR InAs/GaSb T2SLs where native interface asymmetry process was found to strongly dominate the spin relaxation lifetime [118,125]. While the \( T_1 \) values of the unintentionally doped MWIR InAs/InAs\textsubscript{0.70}Sb\textsubscript{0.30} T2SL was comparable to MWIR InAs/GaSb T2SLs, a study specifically targeting the influence of Sb concentration of the alloy layer and the SL period thickness on spin lifetime could aid further understanding of these Ga-free materials.
Figure 6.7: Results of differential transmission experiments on undoped InAs/InAs$_{0.70}$Sb$_{0.30}$ alloy. On right panel, data for conditions of same circular (SCP) and opposite circular (OCP) polarization geometries are indicated by black and red lines, respectively. On left panel, the data and single exponential fit to the difference between the decay curves for SCP and OCP is shown.
APPENDIX A
SOLUTION OF THE 2D DIFFUSION EQUATION WITH GAUSSIAN INITIAL CONDITIONS

A Gaussian spatial intensity distribution was assumed during pump-probe experiments in which the duration of the pump pulse is much shorter than the lifetime of photo-generated carriers. After the ultrafast photo-excitation, the carrier density in quasi-2D systems, such as the superlattice samples studied here, can be described by,

\[
\frac{\partial \Delta n(x, y, t)}{\partial t} + \frac{\Delta n(x, y, t)}{\tau_R} - D_a \nabla^2 \Delta n(x, y, t) = 0, \tag{A.1}
\]

with,

\[
\Delta n(x, y, t = 0) = \frac{\alpha F(x, y)}{h \nu} = \Delta n_0 \exp \left( -\frac{x^2 + y^2}{\omega_e^2} \right). \tag{A.2}
\]

Here \( \Delta n \) is the density of the photo-generated electron hole pairs, \( \Delta n_0 \) is the density at the center of the laser spot at \( t = 0 \), \( \tau_R \) is the recombination lifetime of the photo-generated electron-hole pairs, \( D_a \) is the ambipolar diffusion coefficient of the host material, \( F \) is the fluence of the pump pulse, \( \omega_e \) is the \( e^{-1} \) intensity spot size, and \( \alpha_e \) is the linear absorption coefficient at the pump energy, \( h \nu \).

Assuming that the recombination lifetime is not a function of carrier density,

\[
\Delta n(x, y, t) = U(x, y, t) e^{-t/\tau_R}, \tag{A.3}
\]

and substituting Eq. A.3 into Eq. A.1,

\[
\frac{\partial U(x, y, t)}{\partial t} - D_a \nabla^2 U(x, y, t) = 0, \tag{A.4}
\]

is obtained. If the variables in \( U(x, y, t) \) are separable,

\[
U(x, y, t) = X(x)Y(y)T(t), \tag{A.5}
\]

\( U \) can be represented by a product of three single variable functions. Substituting
Eq. A.5 into Eq. A.4 and dividing it by $D_aU$, we have

$$\frac{T''}{D_aT} = \frac{X''}{X} + \frac{Y''}{Y}. \quad (A.6)$$

Since both sides of the equation have different variable(s), they can be equal only if they are both equal to a constant, e.g.,

$$\frac{T''}{D_aT} = \frac{X''}{X} + \frac{Y''}{Y} = 2\omega^2. \quad (A.7)$$

Considering the symmetry of the problem, we also have,

$$\frac{X''}{X} = \frac{Y''}{Y} = \omega^2. \quad (A.8)$$

The solutions for Eq. A.6 are,

$$T(t) \sim e^{-2\omega^2 D_a t}, \quad (A.9a)$$

$$X(x) \sim e^{i\omega x}, \quad (A.9b)$$

$$Y(y) \sim e^{i\omega y}. \quad (A.9c)$$

Therefore, the solution corresponding to constant $\omega$ is,

$$U(x, y, t, \omega) = A(\omega) e^{-2\omega^2 D_a t} e^{i\omega(x+y)}. \quad (A.10)$$

Considering the independence of $X(x)$ and $Y(y)$, and again the symmetry of the problem, we can write,

$$U(x, y, t, \omega) = X(x, t, \omega) Y(x, t, \omega) \quad (A.11)$$

and

$$X(x, t, \omega) = A_x(\omega) e^{-\omega^2 D_a t} e^{i\omega x}, \quad (A.12a)$$

$$Y(y, t, \omega) = A_y(\omega) e^{-\omega^2 D_a t} e^{i\omega y}. \quad (A.12b)$$
The final solution is the superposition of all the possible solutions,

\[ X(x, t) = \int_{-\infty}^{+\infty} A_x(\omega)e^{-\omega^2D_at}e^{i\omega x}d\omega, \tag{A.13} \]

where \( A_x(\omega) \) is the Fourier transform of \( X(x, t = 0) = \sqrt{\Delta n_0}e^{-x^2/\omega_e^2} \).

\[ A_x(\omega) = \frac{\sqrt{\Delta n_0}}{2\pi} \int_{-\infty}^{+\infty} A_x(\omega)e^{-\zeta^2/\omega^2}e^{-i\omega \zeta}d\zeta. \tag{A.14} \]

Substituting Eq. A.14 into Eq. A.13,

\[ X(x, t) = \int_{-\infty}^{+\infty} \sqrt{\Delta n_0}e^{-\zeta^2/\omega^2} \left[ \frac{1}{2\pi} \int_{-\infty}^{+\infty} e^{-\omega^2D_at}e^{i\omega(x-\zeta)}d\omega \right] d\zeta. \tag{A.15} \]

Using the integration formula of,

\[ \int_{-\infty}^{+\infty} e^{\omega^2\alpha^2}e^{\beta\omega}d\omega = \frac{\sqrt{\pi}e^{\beta^2/4\alpha^2}}{\alpha}, \tag{A.16} \]

Eq. A.15 becomes,

\[ X(x, t) = \int_{-\infty}^{+\infty} \sqrt{\Delta n_0}e^{-\zeta^2/\omega^2} \left[ \frac{1}{2\sqrt{D_a}\pi t} \frac{1}{\omega_e\alpha^2} \right] e^{-\frac{(x-\zeta)^2}{\omega_e\alpha^2}} d\zeta = \frac{\sqrt{\Delta n_0}}{1 + 4D_at/\omega^2_e e^{-x^2/(\omega_e^2+4D_at)}.} \tag{A.17} \]

In the same way we can get,

\[ Y(y, t) = \frac{\sqrt{\Delta n_0}}{1 + 4D_at/\omega^2_e} e^{-y^2/(\omega_e^2+4D_at)}. \tag{A.18} \]

Combining these equations together gives

\[ \Delta n(x, y, t) = \frac{\Delta n_0}{1 + 4D_at/\omega^2_e} Exp \left( -\frac{x^2 + y^2}{\omega^2_e + 4D_at} \right) e^{-t/\tau_R}. \tag{A.19} \]
Efficiency of Light Diffracted from a Photo-Generated Transient Grating

In this appendix, a theory of the evolution of photo-generated transient gratings in a semiconductor superlattice is presented, based on the work of H. J Eichler [53,88] and S. Anson [56].

Using plane-wave and thin grating approximations, the efficiency of the diffracted probe beam will be derived here. In our transient grating measurement, two pump pulses separated by an angle, $\theta_e$, were temporally and spatially coincident on the sample. The interference between the two pulses modulated the intensity across the sample. The direct absorption of the two interfering pump pulses produced a transient free-carrier grating, as described by Eq. B.1,

$$\Delta n(x, t = 0) = \Delta n_0 \left[ 1 + \mu \cos \left( \frac{2\pi x}{\Lambda} \right) e^{-t/\tau_D} \right] e^{-t/\tau_R}, \quad (B.1)$$

where $\Delta n$ is the number density of photo-generated electron-hole pairs, $\Delta n_0$ is the number density at the center of the laser spot at $t = 0$, $\tau_R$ is the recombination lifetime of the photo-generated electron-hole pairs, and $\tau_D$ is the diffusive decay time. As discussed in Chapter 5, the change of absorption and the accompanying change of refractive index are the result of phase-space filling of the photo-generated carriers. When the carrier density is sufficiently low, the change of absorption coefficient, $\Delta \alpha$, and the change of refractive index, $\Delta n_{ind}$, are linearly proportional to the carrier density,

$$\Delta \alpha = \sigma_{eh} \Delta n, \quad (B.2a)$$
$$\Delta n_{ind} = n_{eh} \Delta n. \quad (B.2b)$$

where, $\sigma_{eh}$ is defined as the nonlinear absorption cross section, and $n_{eh}$ is defined as the nonlinear refraction coefficient. Therefore, the free-carrier grating can be described
Figure B.1: Grating geometry of a thin grating induced by two pump beams separated by an angle $\theta_e$.

in terms of a transmission grating and a phase grating. Using Eqs. B.1, B.2(a) and B.2(b), the photo-generated grating can be described by a spatially periodic amplitude transmittance, $T_a$, where,

$$T_a = \exp[-(\alpha + \Delta\alpha)L] \times \exp\left[\frac{i2\pi(n_{ind} + \Delta n_{ind})d}{\lambda e}\right], \quad (B.3)$$

or, using Eq. B.1

$$T_a = \exp[-\alpha L + \frac{i2\pi nd}{\lambda_e} - \left(\sigma_{eg}\Delta n_0 L - \frac{i2\pi n_{eh}\Delta n_0 d}{\lambda} \right) + \left(1 + e^{-t/\tau_D}\cos\left(\frac{2\pi x}{\Lambda e}\right)e^{-t/\tau_R}\right]. \quad (B.4)$$

here, $\alpha$ is the linear absorption coefficient of the sample, $n_{ind}$ is the linear refractive index of the sample, $\lambda_e$ is the pump wavelength, and $L$ is the sample thickness.

For simplicity, we treat the grating as being thin by neglecting the effects of
finite grating thickness. A thin photo-generated carrier grating with fringe spacing $\Lambda$ is shown schematically in Fig. B.1 which is determined by the angle between two the pump beams and the pump wavelength as in Eq. 3.8.

Let us assume a probe beam propagates perpendicular to the grating surface with the electric-field,

$$E_j = \frac{A_j}{2} e^{i(\omega t - k_2 z)} + c.c. \quad (B.5)$$

The field strength at $z = 0$ is,

$$E_j = \frac{A_j}{2} T(x) e^{i\omega t} + c.c. \quad (B.6)$$

The amplitude of the incident beam just behind the grating, $A_j T(x)$, can also be described by a superposition of plane waves (each of which corresponds to a diffracted partial wave) with amplitudes $A_m$,

$$A_j T(x) = \sum_m A_m e^{-ik_m x}. \quad (B.7)$$

Because $T(x)$ is periodic with $\Lambda$, Eq. B.7 corresponds to a Fourier series development of $T(x)$ if $k_m$ is chosen as,

$$k_m = \frac{m2\pi}{\Lambda}; m = 0, \pm 1, \pm 2, \ldots, \quad (B.8)$$

The amplitude $A_m$ of a diffracted partial wave is given by the $m$th Fourier coefficient of the transmittance $T(x)$,

$$A_m = \frac{A_j}{\Lambda} \int_0^{\Lambda} t(x) e^{im \pi x/\Lambda} dx. \quad (B.9)$$

The direction of the $m$th order diffraction is determined by,

$$\sin(\phi_m) = \frac{k_m}{k} = \frac{\frac{2\pi m}{\Lambda}}{\frac{2\pi}{\Lambda}} = \frac{m\lambda}{\Lambda} = 2m\sin(\lambda/2). \quad (B.10)$$
Substituting Eq. B.4 into Eq. B.9 gives,

\[ A_m = \frac{A_j}{\Lambda} \int_0^\infty \exp\left[-\alpha L + i \left( \frac{i\sigma_{eh}}{2} + \frac{2\pi n_{eh}}{\lambda} \right) \Delta n_0 L \right. \]

\[ \left. \left( 1 + e^{-t/\tau_D} \cos \frac{2\pi x}{\Lambda} \right) e^{-t/\tau_R} - \frac{im2\pi x}{\Lambda} \right] dx, \]  

(B.11)

where we neglected the term \( e^{i2\pi m/\lambda} \) in Eq. B.1 since it only creates a constant phase shift. Defining,

\[ \phi = \left( \frac{i\sigma_{eh}}{2} + \frac{2\pi n_{eh}}{\lambda} \right) \Delta n_0 d, \]  

(B.12)

Eq. B.11 becomes,

\[ A_m = \frac{A_j e^{-\alpha d/2}}{\Lambda} \exp \left( i\phi e^{-t/\tau_R} \right) \int_0^\infty \exp \left( i\phi e^{-t/\tau_R} \cos \left( \frac{2\pi x}{\Lambda} \right) + \frac{im2\pi x}{\Lambda} \right) dx. \]  

(B.13)

Defining the dimensionless variable,

\[ \zeta = 2\pi x/\Lambda, \]  

(B.14)

de the amplitude can be expressed as,

\[ A_m = A_j e^{-\alpha d/2} \exp \left( i\phi e^{-t/\tau_R} \right) \left[ \frac{1}{2\pi} \int_0^\infty \exp \left( i\phi e^{-t/\tau_R} \cos(\zeta) \right) \cos(m\zeta) d\zeta \right], \]  

(B.15)

which can be further reduced to,

\[ A_m = A_j e^{-\alpha d/2} \exp \left( i\phi e^{-t/\tau_R} \right) \left[ i^m J_m \left( \phi e^{-t/\tau_R} \right) \right]. \]  

(B.16)

Here, \( J_m \) is the \( m \)th order Bessel function defined in the square bracket in Eq. B.15. For the case of \( |\phi e^{-t/\tau_R}| \ll 1 \), the following approximations are valid,

\[ J_0(\phi e^{-t/\tau_R}) = 1, \]  

(B.17a)

\[ J_1(\phi e^{-t/\tau_R}) = J_{-1}(\phi e^{-t/\tau_R}) = \frac{1}{2} \phi e^{-t/\tau_R}. \]  

(B.17b)
The efficiency of the first order diffracted beam is,

\[ \eta = \left| A_{m=1} \right|^2 \]

(B.18a)

\[ \eta = \frac{1}{4} \exp \left( -\alpha L - \sigma_{eh} e^{-t/\tau_G} \Delta n_0 L \right) |iJ_1(\phi e^{-t/\tau_G})|^2, \]

(B.18b)

\[ \eta = \frac{1}{4} \exp \left( -\alpha L - \sigma_{eh} e^{-t/\tau_R} \Delta n_0 L - 2t/\tau_G \right) \left[ \left( \frac{2\pi n_{eh}}{\lambda_e} \right)^2 + \left( \frac{\sigma_{eh}}{2} \right)^2 \right] \Delta n_0^2 L^2. \]  

(B.18c)

Eqs. B.18(a)-(c) describe the first order diffraction efficiency of a photo-generated transient-grating for the thin grating condition as a function of material non-linearity, photo-generated carrier density, and time. Care should be taken not to use this equation at \( t = 0 \). As we have discussed in Chapter 2 and Chapter 6, it takes a few picoseconds for the photo-generated carriers to thermalize, and \( \sigma_{eh} \) and \( n_{eh} \) have different values before the thermalization of the carriers. Therefore, if \( t \ll \tau_G \), Eq. B.18 can be simplified as,

\[ \eta \simeq \frac{1}{4} \exp \left( -\alpha L - \sigma_{eh} \Delta n_0 L \right) \left[ \left( \frac{2\pi n_{eh}}{\lambda_e} \right)^2 + \left( \frac{\sigma_{eh}}{2} \right)^2 \right] \Delta n_0^2 d^2. \]  

(B.19)

If the excess carrier density is low enough so that the \( \sigma_{eh} \Delta n_0 \ll \alpha L \), we have,

\[ \eta \simeq \frac{1}{4} e^{-\alpha d} \left[ \left( \frac{2\pi n_{eh}}{\lambda_e} \right)^2 + \left( \frac{\sigma_{eh}}{2} \right)^2 \right] \Delta n_0^2 L^2. \]  

(B.20)

Note again that all the results in this section were obtained under the plane wave approximation, which assumes plane wave fronts and uniform intensity across the beam. This approximation is appropriate as long as the sample is placed at the beam waist, the spot size of the pump beam is large enough so that the effect of carriers diffusing away from the excited area can be neglected, and the size of the probe beam is much smaller than that of the pump beam.
APPENDIX C
EXPERIMENTAL ARRANGEMENTS

The experimental scheme and optical components are illustrated in this appendix.

In Fig. C.1, the beam path for the electronic and digital pump probe measurements are demonstrated. More information of alignment procedure can be found in Dr. Olson’s [17] and Dr. Anson’s [56] Ph.D. thesis.
Figure C.1: Schematic diagram of the two color and electronic delay pump-probe apparatus. M: gold mirror, FM: flip up mirror, AM: HeNe alignment mirror, L: lens, I: iris, D: detector, CC: corner cube, P wire grid polarizer, BS: beam splitter.
Figure C.2: Schematic diagram of the two color and electronic delay pump-probe apparatus designed for four-wave-mixing measurements. M: gold mirror, FM: flip up mirror, AM: HeNe alignment mirror, L: lens, I: iris, D: detector, CC: corner cube, P: wire grid polarizer, BS: beam splitter.
APPENDIX D
PHOTON RECYCLING

A brief analysis of Humphreys’ study [77] is discussed in this appendix to provide a more profound understanding of the photon recycling (PR) phenomena. The basic theory of radiative recombination takes into account both the black body photon flux inside a material, as well as the free carriers. This approach satisfies the microscopic lifetime [78] without including the photon recycling within the material. However, if the active region is thick enough, the photon recycling appears as an enhancement in radiative lifetime. There are two main interactions to consider when the re-absorption is included in the calculations. First, the interaction between carriers and photons within the material is discussed and second, the interaction between photons within the material and in the cavity surrounding it will be considered.

First, consider the interchange between carriers and photons within the sample. The carrier generation rate per unit volume is,

\[
g = \int_{E_g}^{\infty} \frac{q(\nu) \alpha(\nu) c}{\mu(\nu)} d\nu, \quad (D.1)
\]

where \(q\) is the photon density in the sample at a photon frequency \(\nu\), \(\alpha\) is the absorption coefficient for inter-band transitions, \(c\) is the the velocity of light, \(\mu\) is the refractive index and \(E_g\) is the bandgap of the structure. As was shown by van Roosbroeck and Shockley (VRS) [126], the photon density \(q\) is given by,

\[
q(\nu) = \frac{8\pi\nu^2\mu^3}{c^3(e^u - 1)}, \quad (D.2)
\]

where \(u = h\nu/k_B T\).

If the carrier and photon distribution are taken to be characteristic of the sample temperature, then deviations from equilibrium can be expressed by a simple multiplicative factor. Therefore, the integrals can be simplified and the quantities
replaced by appropriate averages without further loss of generality;

\[ q(v) = \int_{E_g}^{\infty} q(v)dv, \quad (D.3a) \]

\[ \alpha = \frac{1}{q} \int_{E_g}^{\infty} \alpha(v)q(v)dv, \quad (D.3b) \]

where the dispersion of the refractive index is neglected.

Therefore the recombination rate is given by,

\[ r = g_0 \frac{np}{n_i^2}, \quad (D.4) \]

where \( n_i \) is the intrinsic carrier concentration and \( g_0 = qac/\mu \) is the equilibrium generation rate. From these equations, the rate of change in excess carrier density is,

\[ \frac{d\Delta n}{dt} = -\frac{\mu}{qac} \frac{(p + n)}{n_i^2} \Delta n + \frac{ac}{\mu} \Delta q. \quad (D.5) \]

Now, we can identify the lifetimes. The VRS lifetime ignores the term \( \Delta q \) for thin materials. Therefore, the expression becomes,

\[ \tau_{micro} = \frac{\mu n_i^2}{qac(n + p)}; \tau_{micro}^i = \frac{\mu n_i}{2qac} \rightarrow \text{in intrinsic material}. \quad (D.6a) \]

The time required to reach equilibrium between excess carriers and photon density is found from Eq. D.5 by taking \( \Delta n = -\Delta q \),

\[ \tau_{cp}^{-1} = \frac{1}{\tau_{micro}} + \frac{ac}{\mu}. \quad (D.7) \]

This is dominated by the photon lifetime \( \mu/ac \), which is significantly short compared to \( \tau_{micro} \).

An equilibrium state between carriers and photons inside the material is rapidly reached very fast and this equilibrium is characterized by,

\[ \frac{(p + n)}{n_i^2} \Delta n = \frac{\Delta q}{q}, \quad (D.8) \]

under the assumption of \((d\Delta n)/dt \rightarrow 0\) in Eq. D.5.
Let us now consider the exchange of photons between the sample and the cavity surrounding it. The sample is taken to be a thin slab of material of surface $A$ and volume $V$. The number of photons with energy greater than $E_g$ incident on its surface from the cavity per unit time is given by Planck’s distribution,

\[
\int_{E_g}^{\infty} \frac{A2\pi v^2 dv}{c^3(e^v - 1)} = \frac{qcA}{4\mu^3}.
\]  

(D.9)

In equilibrium, an equal amount of flux must leave the sample as was initially absorbed. The net rate of change of photon density is,

\[
\frac{d\Delta q}{dt} = -\frac{\Delta q cA}{4\mu^3 V} - \frac{d\Delta n}{dt}
\]  

(D.10)

where the first term on the right hand side comes from Eq. D.9 and is representing the photons emitted to the cavity. The second term is due to the radiative recombination of excess carriers. If the sample is sufficiently thin such that the area contributed by the edges is small, then the sample thickness $L = 2A/V$. The equilibrium within the sample from Eq. D.8 gives $\Delta q << \Delta n$.

\[
\tau_{Bulk} = \frac{2\mu^3 d_n^2}{q(p + n)c},
\]  

(D.11)

\[
\tau_{i Bulk} = \frac{\mu^3 d_n^2}{qc}
\]  

(D.12)

The bulk radiative lifetime is thus $2\mu^2 \alpha d$ times the microscopic lifetime. For $\alpha d \sim 1$, the PR factor is expected to be larger than 20 for a typical refractive index of a semiconductor.
REFERENCES


[59] N. W. Ashcroft and N. D. Mermin. There is no corresponding record for this reference.


