CHARACTERIZATION ANALYSIS AND DESIGN OF MID-WAVE INFRARED III-V-BASED TYPE-II SUPERLATTICE nBn PHOTODETECTORS FOR SPACE APPLICATIONS

Alexander Timothy Newell

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CHARACTERIZATION ANALYSIS AND DESIGN OF MID-WAVE INFRARED III-V-BASED TYPE-II SUPERLATTICE $nBn$ PHOTODETECTORS FOR SPACE APPLICATIONS

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ABSTRACT

The performance of the mid-wave infrared InGaAs/InAsSb $nBn$ photodetector is investigated and its viability for space applications is assessed. Three structures are grown with unique absorber layer doping profiles via molecular beam epitaxy. Material and device characterizations are performed and analyzed to determine the effects of doping on fundamental material parameters and detector performance. Noise-equivalent irradiance is calculated to be a factor of 4x that of an ideal detector exhibiting Rule 07 dark current and 100% quantum efficiency, demonstrating high sensitivity. The structures are then irradiated with 63 MeV protons to evaluate the extent of performance degradation over the course of mission lifetime within the space environment. The graded doping profile structure exhibits high sensitivity and resiliency to performance degradation, thereby demonstrating viability to satisfying the growing demand of a scalable mid-wave infrared sensor for space applications.
In-depth characterization analysis and development of fitting tools offer insight into the properties of the InGaAs/InAsSb superlattices and their evolution with proton fluence. This allows for a fundamental perspective into the mechanisms driving the observed trends in detector performance, providing a path forward to further technological improvement.
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1. Infrared Detection

1.1 Introduction

Our eyes are remarkable feats of biological engineering. Generations of evolution have resulted in a photodetector array and built-in lensing system, fine-tuned, and optimized sensing earth-based events. As the sun radiates the largest percentage of its photons of wavelengths around 640 nm, we have adapted a high degree of sensitivity to the spectral range covering 400 to 750 nm. In fact, some studies report the ability for our eyes to detect less than 5 photons [1]. Our reliance on eyesight stems from the advantages of photon detection. Light can transfer huge amounts of information with high spatial resolution at great speeds. This allows us to react to events quickly and decisively. However, our eyes are incapable of detecting an overwhelming majority of the electromagnetic spectrum, which can be of great value.

This was discovered in 1800 by William Herschel in an attempt to measure the amount of energy carried by each color of light. For this experiment, Herschel used a prism to separate the individual colors of sunlight and placed a thermometer within the constituent bands to record changes in temperature. By means of insight, curiosity, or perhaps luck, Herschel also placed the thermometer outside the range of visible light, in which he found that the thermometers readings rose most swiftly a few inches away from the termination of the red band. Herschel coins this region the “thermometrical spectrum” [2].

Centuries later, the detection of the thermometrical spectrum, or infrared (IR) radiation as we now know it, is used in a wide range of applications. The absorption of this relatively low energy light by certain molecules and compounds allows for the detection and identification of various gases and surface contaminants [3]. Water vapor profiles in the
atmosphere can be determined, helping inform our understanding of global weather patterns and climate change [4]. In the medical field, infrared detection is used for in-vivo mapping of skin tissue, allowing for the detection of early-stage cancer which is critical for the effectiveness of potentially life-saving procedures [5]. While each of these applications demonstrates the utility of infrared detection, the topic of this dissertation regards thermal sensing.

1.2 Thermal Sensing

In contrast to our vision, in which the photons generated by visible light sources are reflected by the objects we view, thermal sensors detect photons that are emitted by the objects themselves, therefore being of great practicality in applications where no external light source is present, such as night vision. Generally, objects are significantly cooler than the sun, and therefore emit relatively low numbers of visible photons. Even a rocket plume at its peak temperature moments after ignition, reaches 2200 K [6], exhibiting a peak photon exitance of 1.6 µm and radiating only 2.3% of its total energy as visible light. The effective detection for these thermal bodies therefore requires detection of IR.

The spectral photon exitance of an object can be modeled by Planck’s equation for blackbody radiation as given in Equation 1.

\[
M = \frac{2\pi c}{\lambda^4 \left( e^{\frac{hc}{\lambda kT}} - 1 \right)}
\]

Here, \(c\) is the speed of light in a vacuum, \(\lambda\) is the wavelength of the photon in µm, \(h\) is Planck’s constant, \(k\) is Boltzmann’s constant, and \(T\) is the temperature of the blackbody. Units of Equation 1 are given in \(\frac{\text{photons}}{\text{cm}^2 \text{s} \mu\text{m}}\) in which the unit of cm² represent the area of the blackbody
and the unit of µm represents the unit of wavelength of emitted light. The spectral exitance for targets of various temperatures is shown in Figure 1.

![Spectral Exitance Diagram](image)

Figure 1. Spectral photon exitance of objects with various temperatures. Horizontal lines indicate the defined spectral ranges: ultra-violet, visible, short-wave infrared, mid-wave infrared, long-wave infrared, and very-long-wave infrared.

Here it is observed that visible detectors such as our eyes are extremely useful for the thermal sensing of the sun’s radiation, but of little use for detecting the photons emitted by low-energy bodies like the Earth, which require long-wave infrared detection (LWIR) or very-long-wave infrared detection (VLWIR). The short-wave infrared (SWIR) regime is seen to be practical for hotter objects such as the peak temperature of a rocket’s exhaust, while the mid-wave infrared (MWIR) exhibits strong alignment with the peak thermal signature of objects such as a typical missile plume or jet engine exhaust.
Although the spectral photon exitance is useful to inform the appropriate wavelengths for detection of a target based on its temperature, the more pertinent metric for detection is the photon irradiance. This is defined as the photon flux incident on the detector \( \phi_p \), which is attained by factoring the photon exitance of the target by its projected solid angle, as described in Eq. 2 [7].

\[
\phi_p = M \frac{\Omega}{\pi} = M \sin^2(\theta/2) \approx M \frac{A_{\text{target}}}{r^2}, \text{for small } \theta
\]

Here, a circular aperture is assumed such that the field of view is conical. \( M \) is the spectral photon exitance of the thermal body, as given by Equation 1, and \( \Omega \) represents the projected solid angle of the target, which depends on the angular field of view \( (\theta) \), and the distance between the emitter and detector \( (r) \) as shown in Figure 2. The right side of the equation is a commonly used approximation for small targets at large viewing distances where the angular FOV is small. A diagram of the viewing distance and angular FOV is shown in Figure 2.

![Diagram of viewing distance and angular FOV](image)

Figure 2. A simple geometric depiction of a space-based missile detection system. The grey ellipse represents the circular area of earth within the FOV of the detector, determined by the angular FOV \( (\theta) \), and the viewing range \( (r) \). The red point within the FOV represents the target missile.
The total photon irradiance on the detector generally originates from both the target and the background. If the detector is looking down, the photon flux from Earth can occupy the entire FOV of the detector. Therefore, despite Earth’s relatively small photon exitance, its integration over a large area can result in photon irradiances far greater than the signal from the target. To reduce this background photon flux, the wavelength and angular FOV must be considered. The 3 to 5 µm MWIR band allows for the detection of a large fraction of the missile’s photon exitance, while overlooking the majority of the Earth’s.

Shown in Figure 3 is the estimated photon irradiance of a missile plume as a function of viewing distance calculated with the small angle approximation for various spectral ranges spanning 1 to 9 µm. The right plot shows the angular FOV required such that the target’s photon irradiance is equal to the background photon irradiance from Earth for a single detector. Although this represents an oversimplification due to the neglection of optical lensing, non-normal incident angles, detector area, and many more factors, it serves to evaluate the relative efficacy of each spectral regime for missile detection purposes.
Figure 3. Left: Filtered photon irradiance of a 5 m² target at 1300 K as a function of viewing range under the small angle approximation for various spectral ranges. Inset (a) depicts the target’s photon exitance as a function of wavelength. Colored lines correspond to the spectral range depicted in the inset. The 3-5 MWIR spectral range is depicted by the pink dashed lines. Right: Angular FOV required such that the photon irradiance from Earth is equal to the photon irradiance from the target. Inset (b) depicts the Earth’s spectral exitance in which it is assumed that the Earth is at an effective temperature of 288 K and exhibits minimal reflection from the sun.

Here, it is observed that the photon irradiance within the MWIR spectral range is the highest, thereby offering the highest optical signal. The SWIR, however, is seen to offer similar signal intensities, with a much larger angular FOV of the detector due to Earth’s smaller photon exitance at shorter wavelengths as seen in the inset. However, it is noted that this approximation neglects the contribution of the reflection of sunlight, which is most problematic for shorter wavelengths. Regardless, it is found that the detection of this target is achievable from long viewing ranges at most wavelengths with proper design of the optical system and
sufficient detector sensitivity. However, another important consideration for long-range detection is atmospheric effects.

Photon scattering and absorption can result in significant attenuation of the optical signal, depending on the wavelength. The atmospheric transmission as a function of wavelength is shown in Figure 4 for various weather conditions.

![Figure 4. Normalized photon transmission as a function of wavelength for three weather conditions, clear, rain and fog. Plots taken from Ref. [8]](image)

Here it is seen that there exist several windows of relatively high atmospheric transmission, allowing for long-range detection. The LWIR regime is seen to exhibit the highest atmospheric transmission as well as the least reduction with degrading weather conditions while the SWIR regime exhibits the most. The MWIR regime is seen to exhibit high atmospheric transmission as well as the relatively low signal attenuation due to weather conditions compared to the SWIR.

Although each spectral regime may be capable of space-based thermal imaging, detection of MWIR radiation offers the most favorable alignment to the thermal signatures of a wide variety of missiles and other lower temperature aircraft exhaust, while exhibiting low responsivity to the background Earth’s radiation. It is therefore generally used for the long-
range detection of these targets. It is critical however that the sensitivity of the detector be sufficiently high for the detection of small signals characteristic of long-range viewing.

1.3 Detector Sensitivity

Sensitivity is a metric that gauges the detector’s ability to discern a signal. For high sensitivity required for long-range detection, two conditions must be satisfied. First and foremost, the detector must exhibit responsivity to the optical signal, which requires detection of the signal and the subsequent output from the detector. The most critical metric of the photodetector to maximize its responsivity to an optical signal is the quantum efficiency (QE). QE is defined as the fraction of incident photons that become collected carriers. Although QE is ideally equal to unity, it is typically smaller due to reflections off surfaces, parasitic absorption within inactive regions of the detector, and imperfect collection of photogenerated charge carriers. The signal of the photodetector, given by the output photo current, is proportional to the QE as shown by Equation 3.

\[ I_{\text{photo}} = q \Phi_p \eta A \]  

Here \( q \) is the electronic charge, \( \eta \) is the QE of the detector and \( A \) is the area of the detector. Although a low QE can drastically reduce the output photocurrent, it may not necessarily impede the ability to distinguish it. This condition only requires that photocurrent be discernable from noise.

Noise in a photodetector consists of deviations from the average output, which can obscure small signals, as shown in the inset of Figure 5. Conventionally, noise is quantified by the root-mean-square of the deviation in average output, however, due to its multitude of sources and random nature, it is notoriously difficult to describe. In fact, Rogalski states that a
general theory of noise that is applicable to all sources has not been developed [9]. The sources of noise considered here are attributed to variance in both photo current and dark current, otherwise known as shot-noise [7].

Dark current is the output current of the detector when there are no photons incident on the detector. Every detector at a non-zero bias and temperature exhibits some level of current output due to the prevalence of thermally generated carriers within the material. Although the average dark current may be subtracted from the total current to help isolate the signal, the variance in dark current may not. Deviations in dark current are attributed to local fluctuations in generation rates as well as arrival rates of carriers at the electrode terminals. Due to the discrete nature of electrons, the variance in dark current may be assessed with Poisson statistics as given by Equation 4.

\[
I_{n,dark} = \sqrt{\frac{qAJ_{dark}}{\tau_{int}}} \tag{4}
\]

Here, \( J_{dark} \) is the dark current density, \( \tau_{int} \) is the integration time and \( A \) is the area of the detector.

In a similar fashion, fluctuations in the photon arrival rate also results in variation in the photo current output. Photon shot noise may be calculated by Equation 5.

\[
I_{n,photo} = \sqrt{\frac{q^2\eta A\phi_p}{\tau_{int}}} \tag{5}
\]

Shown in the inset of Figure 5 is an illustration of the current output of a detector before and after the incidence of an optical signal. Two signal conditions are depicted here, one in which the signal is equal to 5 times the magnitude of noise, and one in which the signal is equal to
the noise, more commonly known as a signal to noise ratio (SNR) of one. The noise is simulated via a random number generator ranging from $\pm 0.5$ and factored such that its range is equal to the noise contribution calculated via Equations 4 and 5, then added to the average current value.

![Diagram](image)

Figure 5. Output current as a function of photon flux for a typical MWIR detector, exhibiting a dark current density of 1 $\mu$A/cm$^2$ and a QE of 100%. The shot noise associated with dark current and photo current is calculated by assuming the integration time is 10 ms and the pitch of the detector is 10 $\mu$m. The inset illustrates the output current by the detector as a function of time in which the incoming optical signal is equal to the noise (blue) and 5$\times$ greater than the noise (green).

It is observed in Figure 5 that the optical signal is significantly more distinguishable from the noise when it is greater than the magnitude of the noise. An SNR of 1 is loosely defined as the minimum discernable signal, and the photon flux at which this occurs is known as the noise-equivalent irradiance (NEI), which occurs in Figure 5 at around $2 \times 10^{10}$
photons/cm²s. By using the aforementioned definitions of signal and noise, the NEI of a detector is given by Equation 6.

\[
NEI = \frac{1}{\eta} \sqrt{\frac{q\eta \Phi_p + J_d}{qA\tau_{int}}}
\]

Although other sensitivity metrics may be used, NEI is preferred as it allows for a simple assessment of the detectability of a signal. If the NEI of the detector is known, the viewing range, as shown by Figure 3 may be estimated. Furthermore, if both the signal photon irradiance and NEI are known, then SNR may easily be calculated.

Noticeably in Equation 6, NEI may be decreased by increasing both \( A \) and \( \tau_{int} \). Since thermal sensors generally count the number of output electrons provided by the detector over a given time-frame, the number of collected carriers approaches the true average value, as shown by the solid lines in the inset of Figure 5, as the integration time increases. However, increasing the integration time is not always possible, especially when considering the detection of short time scale events such as objects that travel quickly across the FOV of the detector. Increasing the detector area is also found to reduce NEI, however this increases the size of the focal plane array (FPA), and in turn the optical lensing system and other components necessary for the sensor system. This is also undesirable especially for space applications in which the size and weight of the detector system must be kept as low as possible. The best strategy for the sensitivity enhancement of detectors purposed for space-based sensing is to maximize QE and minimize dark current density.
1.4 Space-Based Missile Detection

The tactical advantages provided by high vantage points and large FOV are critical for the purpose of missile detection, which is of increasing importance as international tensions rise and missile technologies advance. Currently, radar is predominantly used as it offers high resolution detection and tracking capabilities of missiles. However, its range is limited by the radar horizon, which is dependent on the altitude of both the missile and the detector [10]. While radar is sufficient for the timely detection of most missiles, some advanced long-range missiles remain a significant threat.

An intercontinental ballistic missile (ICBM) spends the majority of its time-of-flight in space, allowing it to go tremendous speeds without impediment from air resistance. In fact, Ref [10] cites that the speed of an ICBM can achieve Mach 20, or about 4.25 miles per second. Therefore, the duration that it’s within the line of sight of radar is severely limited, making its detection in this phase nearly futile. The ICBM is most easily detected in its booster phase where it burns the majority of its fuel, thereby exhibiting a strong thermal signature. However, this phase only lasts for up to 5 minutes and may occur at any location from mobile launching systems [10]. Constant global coverage is therefore necessary for the timely detection of these missiles, which encourages the utilization of a mega-constellation of low-earth orbit (LEO) satellites. Additionally motivating the deployment of such a sizable fleet is the significant reduction in detrimental impact of a single satellite’s malfunction or potential damage from a foreign adversary.

Supporting the feasibility of this project is the recent trend in satellite launches. Advances in satellite technology as well as decreasing launch costs have resulted in unprecedented levels of satellite deployment. Additionally, the significant increase in space-
based expenditures motivated by the advantages offered by satellites have led to an exponentially increasing rate of satellite launches across the past decade, as shown by Figure 6.

![Figure 6](image)

Figure 6. Number of objects launched per year as reported by the United Nations [11]. The green bar represents the current year, which constitutes an incomplete dataset.

This exponential increase in satellite deployment has shifted the development of satellite components towards low-cost, and manufacturable implementations. Therefore, the development of a high-yield and low-cost MWIR detector solution that is effective for space-based detection is of great importance.

One complication however, unique to space applications, is the prevalence of damaging radiation in the space-environment. The Earth’s magnetosphere traps high energy protons and electrons in regions known as the Van Allen Belts which are frequently encountered by space vehicles [12]. Outside of the magnetosphere, higher energy particles originating from solar flares and galactic rays are prevalent [13]. Space-based detectors must therefore be resilient to radiation-induced performance degradation to maximize their mission lifetime.
1.5 Materials for Mid-wave Infrared Detection

Currently two photodetectors are predominantly used for MWIR detection, InSb and HgCdTe. InSb is currently the most commonly used MWIR detector [14], owing to both its high sensitivity and low-cost. Its manufacturability is attributed to its group III-V elemental composition. III-V material solutions are relatively cheap and easily producible because of the large industrial infrastructure used for the telecommunications industry. Low-cost large format substrates and advanced growth capabilities allow for the scalable growth of devices, thus optimizing production efficiency.

One major drawback of the InSb detector, however, is the lack of other III-V materials that share the same lattice constant, as shown by Figure 7. This limits the possibilities for strain-balanced growth of devices to a homojunction structure. The InSb photodetector is therefore utilized in the form of a $pn$ junction in which a depletion region constitutes a large portion of the device’s volume, as shown by the inset of Figure 8. Although the electric field in the depletion region offers maximum collection efficiency of photogenerated electron-hole pairs, it is similarly responsible for high dark currents from thermally generated carriers. It is therefore necessary to reduce the operating temperature of this detector for the sufficient suppression of the thermal generation rate. This typically requires cryogenic coolants such as liquid nitrogen and is therefore unfavorable for more portable applications such as space-based detection.
The other photodetector technology predominantly used for MWIR detection is the HgCdTe (MCT) detector. This detector exhibits high sensitivity at high operating temperatures, allowing for operability using simple active cooling components. Interestingly, these MCT detectors function via pin junctions, similar to the InSb detector. In contrast however, this device’s dark current is dominated by the diffusion current mechanism rather than depletion current, which is attributed to the material’s intrinsic high minority carrier lifetime. Whereas the highest reported minority carrier lifetime of InSb is around 1 µs, the highest minority carrier lifetime of MWIR MCT is around 60 µs [14], thereby suppressing the generation rate within the intrinsic depletion region and allowing for diffusion limited behavior. Diffusion current has a more favorable temperature dependence which allows for higher temperature operation, as shown by Figure 8. The dark current density of MCT detectors as a function of detector cutoff wavelength and temperature is document and modeled using Rule 07. For detectors with cutoff wavelengths above 4.6 µm, Rule 07 dark current density is calculated via Equation 7 [16].

Figure 7. Lattice constant vs bandgap energy of III-V materials with HgCdTe. Figure taken from Ref. [15]
\[ J_{07} = J_0 e^{c \left( \frac{1.24 \Phi}{kT \cdot \lambda_{\text{cut-off}}} \right)} \]

Here \( J_0 \) and \( C \) are empirically derived quantities which are equal to 8367 and -1.162 respectively.

Figure 8. Dark current density as a function of temperature for Rule 07 and a typical InSb detector. Inset shows a PN junction band structure modeled by Silvaco at -200 mV, which serves as a basic illustration for the devices. The grey region represents the depletion region within the structure.

As seen by Figure 8, the MCT detector exhibits similar dark current densities at significantly higher temperatures compared to the InSb detector, which is beneficial for reducing the size, weight, and power consumption of the active cooling components of the detector system. Generally, an increase of 10 K in operating temperature reduces the power required for cooling in half [17] which is highly favorable for utilization on space-vehicles. Because of MCT’s high operating temperature, sensitivity, as well as observed resilience to
damage from space radiation, this technology is used for the MWIR imaging of the universe on the James Webb Space Telescope [18].

However, the growth and fabrication of MCT devices is subject to numerous difficulties. High interdiffusion coefficients make the growth of a compositionally uniform structure challenging [15]. In turn, the bandgap, which exhibits high sensitivity to material composition as seen in Figure 7, can vary significantly across the structure. Additionally, as the III-V material system is more robust compared to the II-VI material system due to its less ionic chemical bonding [19], a higher rate of dislocation formation is prevalent in MCT, furthering inconsistencies in the material growth. The MCT detector is therefore a high-cost, low yield solution that is unfavorable for satisfying the increasing demand of a MWIR detector solution required for the growing space industry.

1.6 III-V based Type-II Superlattice \(nBn\) Photodetector

The III-V based type-II superlattice (T2SL) \(nBn\) photodetector offers high manufacturability as well as high operating temperature and is therefore a promising candidate to satisfy the growing demand of a space-based MWIR detector component. The \(nBn\) was first demonstrated in 2006 as a high operating temperature device due to its unique ability to suppress the current mechanisms that typically dominate in III-V narrow-bandgap \(pn\) junction detectors [20]. In particular, the formation of surface shunt paths in InAs-based materials due to Fermi-level pinning caused by surface states was highly problematic. Due to the lack of passivation strategies to mitigate this issue, the integration of InAs-based \(pn\) junction photodetectors into focal plane arrays was severely limited [20]. As it was known that these surface states caused degenerately n-type surfaces [21], the barrier layer was designed to extend into the conduction
band to block the flow of electrons, thereby eliminating surface currents and removing the need for passivation methods. Additionally, the majority of the potential drop from the applied bias falls across the wide-bandgap barrier layer, thus suppressing the formation of a depletion region and the resulting depletion current mechanism, as shown by Figure 9. This limits the total current of the $nBn$ to the minority carrier diffusion current, allowing for higher temperature operation similar to the MCT device shown in Figure 8.

Figure 9. Energy band diagram of an $nBn$ MWIR detector structure with a uniformly-doped absorber at a reverse bias of -200 mV, including direction of electron and hole transport under normal operation, and the electron quasi-Fermi level indicated as the dotted black line. The left most layer is the n-type top-contact layer (150 nm), followed by an undoped barrier layer (200 nm), and then the n-type InGaAs/InAsSb superlattice absorber layer (4 µm) and n+ bottom contact. The center inset shows the cross-section schematic of the mesa structure, direction of incident light, and reverse bias polarity. The right inset shows the spectral QE of the graded doping structure at 130 K in which the 5.5 µm cutoff wavelength is shown by the vertical dashed grey line.

Although the initial $nBn$ used InAs as the absorber material, exhibiting a cut-off wavelength of 3.4 µm [20], the structure can be used for any material system. To gain full
coverage of the 3 to 5 µm atmospheric transmission window for space-based detection, an absorber material with a smaller bandgap is required (< 250 meV). This is achievable with III-V materials via a T2SL.

A T2SL consists of thin layers of alternating materials whose bandgaps align to form potential wells for holes and electrons in each layer. The quantum confinement of these charge carriers allows for control over the ground-state energies by means of changing the potential barrier height and well thickness. The effective bandgap of the material, which is equal to the difference in the ground-state energies as shown by Figure 10, is then tunable via modifications to the layer composition and layer thickness. Furthermore, the growth of superlattices on conventional substrates is achievable by strain-balancing.

![Figure 10. NRL Multibands simulation of an InAs/GaSb T2SL. Solid black lines correspond to the conduction and valence band of the constituent materials and the dotted lines represent the ground-state energies of the electrons (blue) and holes (red). The right axis corresponds to the wavefunction squared, or the probability density of the electron (blue solid line) and hole (red solid line)】
Another encouraging aspect of the T2SL is that the spatial separation of the electrons and holes, seen in Figure 10, theoretically suppresses the Auger recombination rate by several orders of magnitude compared to MCT materials [22]. As this is the dominant recombination mechanism responsible for Rule 07 dark current density, it is predicted that the T2SL-based detectors may be capable of outperforming MCT in terms of dark current. In practice this has yet to be achieved. Further research of these materials and their implementation into the \( nBn \) structure is needed.

1.7 Summary
The increasing demand of satellite components needed for space-based imaging and early missile and jet detection and tracking systems requires a low-cost and highly manufacturable detector solution. A MWIR detector is favored as the MWIR regime exhibits relatively little signal attenuation due to atmospheric effects, heightened responsivity to the thermal signature of missile and jet plumes, and relatively low responsivity to the background photon flux from earth. For the effective detection of small signals characteristic to long-range applications, the detector must exhibit very high sensitivity. However, the operating temperature of the detector must be kept as high as possible to minimize size, weight and power consumption requirements of the active cooling components which is of considerable interest to the design of a component for a space-vehicle.

The manufacturability and high operating temperature offered by a III-V based T2SL \( nBn \) detector make it a highly promising solution. Further research into maximizing the
detector’s sensitivity as well as an understanding of the effects of radiation on performance degradation are required before its effective implementation on space-vehicles.
2. Sensitivity Optimization of III-V Based Type-II Superlattice $nBn$ Detectors

2.1 Abstract

An analytical model of the $nBn$ detector is derived from carrier continuity equations such that dark current density, QE and NEI may be determined. Structural parameters of an InAs/InAsSb-based $nBn$ detector are optimized for minimum achievable NEI and compared to an ideal detector, defined as exhibiting Rule 07 dark current density and 100% QE. Results of the analytical model’s dark current density and spectral QE under both topside and backside illumination configurations are compared to Silvaco TCAD simulations. An investigation into the limitations of the minimum achievable NEI of the MWIR InAs/InAsSb-based $nBn$ detector is performed, illuminating relevant material parameters for further improvement of detector sensitivity. The novel InGaAs/InAsSb material, which is reported to exhibit heightened absorption and mobility, is then compared to the InAs/InAsSb demonstrating a higher performance potential when implemented into a diffusion-limited $nBn$ detector.

2.2 Dark Current

2.2.1 Thermally Generated Carriers

For the detection of small signals, noise in a photodetector must be sufficiently low. Noise, due to dark current variance, becomes increasingly sizeable as cutoff wavelength increases due to the exponential dependence of the thermally generated carrier concentration on bandgap. The concentration of thermally generated carriers that can participate in conduction at equilibrium is known as the intrinsic carrier concentration ($n_i$), and given by Equation 8.
\[ n_i = \sqrt{N_c N_v} e^{-E_g / 2kT} \]

Here \( N_c \) and \( N_v \) are the density of states in the conduction and valence band, respectively, \( E_g \) is the bandgap of the material, \( k \) is the Boltzmann constant and \( T \) is the temperature of the material. Although the intrinsic carrier concentration for a given material may only be decreased through a reduction of temperature, the degree to which these carriers contribute to dark current can be modified.

2.2.2 Depletion Current

Depletion current is directly proportional to the intrinsic carrier concentration as each thermally generated carrier gets swept out by the electric field, thus contributing to current. Depletion current density is given by Equation 9.

\[ J_{dep} = q n_i \frac{W_d}{\tau_g} \]

Here, \( W_d \) is the width of the depletion region and \( \tau_g \) is the generation lifetime of carriers within the region. Although some materials such as MCT exhibit large generation lifetimes, most semiconductor materials exhibit significantly smaller generation lifetimes and thus the magnitude of depletion current can be quite large. Furthermore, the effectiveness of decreasing the dark current density with temperature is limited to a half-bandgap activation energy due to depletion current’s proportionality to the intrinsic carrier concentration.
2.2.3 Diffusion Current

The appeal of the $nBn$ detector stems largely from its high operating temperature, which is achievable through its diffusion-limited dark current. Diffusion current can be understood as being proportional to the product of the diffusion coefficient of the minority carrier and its gradient at the junction interface, as seen by Equation 10.

\[ J_{diff} = qD_p \nabla p|_{x_j} = q(\mu_p V_{th}) \nabla p|_{x_j} \tag{10} \]

Here, $D_p$ is the diffusion coefficient of the minority carrier hole which is equal to the product of the thermal voltage $\left(V_{th} = kT/q\right)$, and the vertical hole mobility $\left(\mu_p\right)$ as seen by the substitution of the right-hand side of the expression. $\nabla p|_{x_j}$ represents the gradient of minority carriers at the junction interface, which in the case of the $nBn$ represents the barrier layer, as shown by Figure 11.
Figure 11. Silvaco TCAD simulated band diagram of a MWIR nBn detector structure at 130 K with an applied bias of -0.2 V (solid blue curve, left-hand vertical axis). The dotted blue curve represents the Fermi energy. The right-hand vertical axis plots the minority hole concentration profile which shows that the hole concentrations predicted by the analytical model (hollow circles) are consistent with the hole concentration profile calculated by Silvaco (solid black curve). The dashed black line depicts the slope at the barrier interface, denoted $\nabla p\big|_{x_j}$. The pink circle depicts the minority carrier hole, and the arrow indicates direction of transport.

The formation of the minority carrier profile gradient is seeded by the prevalence of an electric field at the edge of the quasi-neutral region. Due to thermal motion, some carriers inevitably fall into the depletion region where they are swept across the junction by the electric field. Thus, the carrier concentration nearest to the junction is lower than the carrier concentration further away. The concentration of minority carriers at the edge of the depletion region may be calculated by the Boltzmann approximation, which is given by Equation 11 for an $n$-type region.
\[
p(x_j) = \frac{n_i^2}{n_0} e^{-\frac{[V_{bi}+V_a]}{V_{th}}} = p_0 e^{-\frac{[V_{bi}+V_a]}{V_{th}}}
\]

Here, \(n_0\) is the equilibrium majority carrier electron concentration, which is typically set by the doping density, and \(p_0\) is the equilibrium minority carrier hole concentration. \(V_{bi}\), \(V_a\), and \(V_{th}\) are the built-in voltage, applied voltage, and thermal voltage respectively. Although the \(nBn\) typically has no substantial built-in voltage, modifications to the structure such as a \(p\)-type top contact gives rise to a built-in voltage, allowing for the formation of the minority carrier gradient at zero applied bias.

Equation 11 constitutes one of the boundary conditions required to solve for the minority carrier profile in the quasi-neutral region, which is required to solve for its gradient at the junction interface \( \nabla p|_{x_j} \), as found in Equation 10. The other boundary condition is a Neumann-type boundary condition, as detailed by Equation 12 [23].

\[
\nabla p(L_a) = S[p(L_a) - p_0]
\]

Here, \(\nabla p(L_a)\) is the gradient of holes at the edge of the absorber region, \(S\) is the surface recombination velocity, and \(p(L_a)\) is the concentration of holes at the at the edge of the absorber region. Generally, the surface recombination velocity is assumed to be zero. While this may or may not be valid, it is seen in Figure 11 that the prevalence of a highly doped \(n\)-type contact region results in a local maximum of minority carriers near the edge of the absorber region. This causes the gradient of holes to be zero, effectively mimicking the \(S = 0\) condition, thereby resulting in nearly perfect agreement between the minority carrier profile predicted by both the analytical model and Silvaco. It is worth noting that without this highly doped contact region, the ohmic contact used in the Silvaco model acts as an infinite surface recombination velocity, causing both electron and hole concentrations at the contact interface
to be always equal to their equilibrium values at any bias. This can result in significantly
different behavior of diffusion dark current and QE and should be kept in mind.

Given the apparent validity of the $S = 0$ assumption however, the boundary condition
defined by Equation 12 is established, allowing for the calculation of the minority carrier
profile. The gradient at the junction interface and thus the diffusion current may then be
attained, which is given by Equation 13 [23],

$$J_{diff} = q \frac{D_p n_i^2}{L_p n_0} \tanh \left( \frac{L_a}{L_p} \right) = q D_p \frac{p_0}{L_p} \tanh \left( \frac{L_a}{L_p} \right)$$

13

Here, $L_p$ represents the vertical diffusion length of holes, which is equal to the square root of
the product of the diffusion coefficient and the minority carrier recombination lifetime ($\tau_p$) as
shown by Equation 14.

$$L_p = \sqrt{D_p \tau_p} = \sqrt{V_{th} \mu_p \tau_p}$$

14

Notably, unlike depletion current, which is proportional to the intrinsic carrier
concentration, diffusion current is proportional to the equilibrium minority carrier
concentration, which can be orders of magnitude less than the intrinsic carrier concentration
depending on the doping density ($p_0 = \frac{n_i^2}{n_0 \approx N_d}$). Furthermore, the proportionality of diffusion
current on the square of the intrinsic carrier concentration results in a full-bandgap activation
energy with temperature, which is highly favorable compared to the half-bandgap activation
energy characteristic of depletion current. This is the fundamental difference that allows the
diffusion-limited $nBn$ structure to operate at significantly higher temperatures compared to a
deployment-limited $pn$ junction detector.
2.3 Diffusion Quantum Efficiency

The implication of a fully quasi-neutral absorber region is that photo current is also determined by diffusion mechanics. Photogenerated holes must diffuse past the junction at the barrier to contribute to photo current, implying that collection efficiency is highly dependent on the hole’s vertical diffusion length. The geometry of the device and direction of incident light is therefore an important factor in the determination of the detector’s QE.

Topside illumination is the typical configuration for process-evaluation chips (PECs) due to the conventional growth strategy of an $nBn$ and the simple fabrication process for reticulated devices. $nBn$ structures are generally grown with their absorber layer first due to the high absorber material quality required for a high-performance detector. Although an inverted design is achievable [24], growth quality is facilitated by smooth interfacial transitions. Thus, growth above the barrier may be subject to higher defect densities. After growth, the fabrication of a fully reticulated mesa devices only requires etching through the barrier region and subsequent metal deposition as illustrated in Figure 12 (a). A topside illuminated geometry accurately describes all structures studied in this work.

In contrast to the PEC, a more complicated fabrication process involving flip-chip bonding and substrate lapping is generally required for the hybridization of an $nBn$ onto a fanout chip for its integration into an FPA. Thus, the geometric configuration of a typical FPA is the backside illuminated condition, as shown in Figure 12 (b).
Figure 12. (a) Fabrication schematic and geometric configuration of a fully reticulated nBn structure. From left to right depicts; a conventionally grown nBn structure, mesa structure after lithography, wire-bonded structure after contact placement. Hollow black circle represents photogenerated hole and arrow depicts shortest route for photo collection. (b) Schematic of an nBn structure hybridized to a fanout chip. Direction of incident light is depicted by the red squiggly lines. Not shown is the ~11 steps required for fabrication of this device.

The significance of these geometrical configurations is the location of photon absorption. For the topside illuminated geometry, as shown by Figure 12 (a), the majority of photon absorption occurs nearest to the junction, such that the photogenerated holes need only travel short distances for their arrival to the junction. The opposite is true for the backside illuminated geometry, as shown by Figure 12 (b), in which photons are predominantly absorbed at the opposite end of the absorber region, thereby requiring photogenerated holes to
travel the entire length of the absorber region to reach the junction. This distinction may result in significant differences in each configuration’s QE.

Photo current from a quasi-neutral region is calculated in a similar manner to dark current with the aforementioned boundary conditions. In contrast however, the addition of a generation source representing the photon irradiance results in a photogenerated hole profile. Mathematically, this photogenerated hole profile is entirely independent of the dark hole profile, conveniently allowing for the separation of diffusion dark current and diffusion photo current. Diffusion partial QE may then be attained by dividing photo current by the photon irradiance factored by the charge of the electron. For the topside illuminated geometry, diffusion partial QE is given by Equation 15.

$$\eta_{diff, top} = F \left( \frac{L_p^2 \alpha^2}{1 - L_p^2 \alpha^2} \right) \left[ \frac{\sinh \left( \frac{L_a}{L_p} \right) + \alpha L_p e^{-\alpha L_a}}{\alpha L_p \cosh \left( \frac{L_a}{L_p} \right)} - 1 \right]$$

Here, $F$ represents the fraction of light that makes it to the absorbing region in which losses occur due to reflection and parasitic absorption in the contact region, $\alpha$ represents the absorption coefficient of the absorbing material. The diffusion partial QE of a backside illuminated geometry is given by Equation 16

$$\eta_{diff, bot} = F \left( \frac{L_p^2 \alpha^2}{1 - L_p^2 \alpha^2} \right) \left[ e^{-\alpha L_a} - \frac{\alpha L_p - e^{-\alpha L_a} \sinh \left( \frac{L_a}{L_p} \right)}{\alpha L_p \cosh \left( \frac{L_a}{L_p} \right)} \right]$$

Here, $F$ also represents the fraction of photons that make it to the absorbing region, however losses are only attributed to reflections off the surface.
A demonstration of the dependence of both cases of diffusion partial QE on absorber length is shown in Figure 13.

![Figure 13](image-url)

Figure 13. Diffusion partial QE as a function of absorber length for both illumination configurations with varying absorber diffusion lengths.

Here, QE tends to the total percentage absorbed within the absorber region only when the diffusion length is infinite, implying perfect collection efficiency. For structures exhibiting finite diffusion lengths however, the maximum QE is limited by imperfect collection efficiency. It is seen that both topside and backside illuminated detectors benefit from higher diffusion lengths, however while the partial diffusion QE of a topside illuminated detector suffers nearly no reduction in QE from increased absorber lengths, the QE of a backside illuminated detector does. This is especially true for materials with small diffusion lengths, due to the higher likelihood of carrier recombination before arrival at the junction. This implies
that the optimal absorber length for maximum QE is dependent upon the illumination configuration.

2.4 Diffusion-Limited Noise-Equivalent Irradiance Under Low-Light Conditions

The effective optimization of a detector requires an evaluation of the detector’s sensitivity, which considers both dark current and QE. For simplicity, photon shot noise is assumed to be negligible compared to dark current shot noise, which is generally known as the low-light condition. Under low-light conditions, NEI may be approximated by Equation 17.

\[
NEI = \frac{1}{\eta} \sqrt{\frac{J_d}{qA \tau_{int}}} 
\]

For the analysis here, a 10 µm pitch and 10 ms integration time are always assumed. Substituting the equation for dark current and the appropriate QE expression into Equation 17 results in an analytical model for device sensitivity of a diffusion-limited \( nBn \) detector under low-light conditions. This model offers a prediction of performance potential for any given absorber material system, as well as an evaluation of the optimal structural parameters required to maximize sensitivity.

2.5 Structural Considerations of the Superlattice \( nBn \) Detector

The advantages of a T2SL include the capacity for bandgap tunability along with strain-balanced growth on conventional substrates for low-cost and scalable growth. However, this material also exhibits a few drawbacks. The potential wells required for miniband formation in the T2SL confine charge carriers, resulting in their spatial separation and therefore relatively low wavefunction overlap compared to bulk material as shown in Figure 10. Although this is
theoretically beneficial for reducing the Auger recombination mechanism, it also decreases the absorption coefficient, which is proportional to the wavefunction overlap squared [25]. Consequentially, large absorber lengths are generally required for photon absorption.

T2SLs, however, also typically exhibit low vertical mobility. The confinement of charge carriers in the constituent layers of the superlattice limits the vertical movement of the carriers to phonon-assisted hopping transport mechanisms [26], thereby hindering mobility. Whereas the lateral hole mobility in the InAs/InAsSb T2SL is reported to be \( \sim 4,000 \text{ cm}^2/\text{Vs} \) at 130 K, its vertical mobility is only \( \sim 10 \text{ cm}^2/\text{Vs} \) [26]. Since photogenerated holes must travel vertically to reach the barrier to contribute to photo current, the vertical mobility is the relevant parameter for the detector’s QE. The resulting low vertical diffusion length therefore limits the capacity of QE improvement via increasing absorber length, as shown by Figure 13. Furthermore, absorber length plays an important role in diffusion dark current and is therefore one of the optimizable structural parameters for detector sensitivity.

Another optimizable parameter is the absorber doping density. Increasing the doping density reduces the equilibrium minority carrier concentration, which benefits sensitivity by decreasing diffusion dark current density, as shown by Equation 13. However, the inclusion of donor impurities also leads to minority carrier lifetime degradation in T2SLs, thereby negatively affecting both dark current and QE. The optimization of the absorber doping density for maximum sensitivity of the \( nBn \) is therefore non-trivial and requires an understanding of the influence that doping has on each recombination mechanism that factors into the effective minority carrier lifetime. These recombination mechanisms are illustrated in Figure 14.
The Shockley-Read-Hall (SRH) recombination mechanism is a trap-assisted process involving the capture or emission of a single carrier [27]. For an n-type material, the traps are assumed to be filled with electrons such that the recombination rate’s limiting factor is the spatial coincidence of a hole, allowing the trapped electron to fall into the valence band, as depicted in Figure 14. This is known as hole capture and is the dominant SRH process which limits the minority carrier hole’s lifetime in the valence band within n-type materials. The SRH lifetime is given by Equation 18 as

$$\tau_{SRH}^{-1} = \sigma_p v_p N_t$$

in which $\sigma_p$ is the capture cross-sectional area of the defect, $v_p$ is the thermal velocity of minority carrier holes, and $N_t$ is the defect concentration. As the SRH recombination rate is dependent on both the defect’s concentration and characteristics, the total SRH recombination rate requires a summation over all relevant defects in the material. For the purpose of attaining the functional form of the SRH lifetime on doping density, it is sufficient to consider two defect...
types, one pertaining to the native defects prevalent in the intrinsic material \((\tau_{SRH_0})\), and one associated with the donor impurities introduced by doping \((\tau_{SRH_1})\) [28]. The intrinsic SRH lifetime is independent of doping density whereas \(\tau_{SRH_1}\) scales inversely with the dopant concentration \((N_e = N_d)\), causing the total SRH lifetime to decrease with increased doping density.

The radiative recombination process is the direct band-to-band transition of an electron in which a photon is emitted. As this requires both an electron and a hole, it is a two-carrier process, implying that the recombination lifetime scales with the majority carrier concentration. In contrast to the SRH recombination mechanism, which is dependent on defects within the material, the radiative recombination mechanism is inherent to the fundamental parameters of the material and can therefore not be suppressed. Typically, however, the radiative recombination lifetime in a T2SL is long compared to the SRH and Auger recombination lifetimes, as shown in Figure 15, and does not significantly affect the performance of the detector.

The Auger-1 recombination, which is the dominant Auger process in the narrow-bandgap n-type material [29], is a three-carrier process involving two electrons and a hole. The Auger lifetime therefore scales with the square of the majority carrier concentration. Similar to the radiative recombination mechanism, the Auger coefficient is a fundamental parameter that is inherent to the material system. However, Auger recombination tends to play a more significant role in the effective minority carrier lifetime of a material, which then may act as a fundamental limitation to the performance potential of a detector, such as in the MCT detector.
The total recombination rate is then equal to the sum of each individual recombination rate mechanism. The functional form of total minority carrier lifetime on doping density is given by Equation 19.

\[
\tau_p^{-1} = \tau_{SRH}^{-1} + \tau_{rad}^{-1} + \tau_{Aug}^{-1} = \sum_i \tau_{SRH_i}^{-1} + \frac{B_r}{\phi} n_0 + C_n n_0^2. \tag{19}
\]

Here, \( C_n \) denotes the Auger coefficient for the dominant Auger-1 process, \( B_r \) is the radiative coefficient, and \( \phi \) is the photon recycling factor, which considers the probability that an emitted photon is reabsorbed in the material, effectively increasing the radiative lifetime. This factor is calculated to be 15 by Ref. [29], however it is completely dependent on the geometry of the absorber material, and therefore only serves as an estimate. Although a more precise value may be determined for the structures studied here, the radiative lifetime is not found to play a significant role in the material’s total minority carrier lifetime.

Shown in Figure 15 is the minority carrier lifetime corresponding to each recombination mechanism as a function of doping density along with the resulting total minority carrier lifetime, as calculated with the recombination rate parameters defined by Ref. [28] and listed in Table 1.
To summarize the effects of doping on minority carrier lifetime, an increase in doping density results in the increase of both the Auger and radiative recombination rates due to the increase of the majority carrier concentration, as well as the increase of the SRH recombination rate due to higher defect densities. The optimization must therefore consider both the beneficial effects of minority carrier concentration reduction as well as the drawback of the minority carrier lifetime reduction.
2.6 \(N_d \tau_p\) Product

This trade-off between the minority carrier concentration and the minority carrier lifetime on diffusion dark current is reflected in the widely known \(N_d \tau_p\) metric [28], which should be maximized to minimize diffusion dark current. However, this is only strictly true for materials exhibiting the thin-base limit, in which the vertical diffusion length is \textit{significantly} larger than the absorber length. More specifically, this approximation is accurate to 95% when the diffusion length is roughly 2.5x the absorber length.

The doping density corresponding to minimum diffusion dark current in materials with diffusion lengths equal to, or less than the absorber length can differ significantly from the doping density corresponding to the maximum \(N_d \tau_p\) product. This is exemplified in Figure 16, which depicts the dark current density as a function of doping density alongside the \(N_d \tau_p\) product for two materials. One material is given a mobility of 100 cm\(^2\)/Vs such that the diffusion length is greater than the absorber length for all values of doping density, and one material is given a mobility of 5 cm\(^2\)/Vs such that the diffusion length is smaller than the absorber length near the \(N_d \tau_p\) maximum.
Figure 16. Dark current density as a function of doping density for two materials with mobilities of 5 cm$^2$/Vs (blue line) and 100 cm$^2$/Vs (red line). The right axis corresponds to the black line which shows the $N_d\tau_p$ product, which is the same for both devices.

Noticeably, the minimum dark current of the detector exhibiting a high mobility aligns well with the $N_d\tau_p$ maximum due to the validity of the thin-base limit approximation. The structure exhibiting a lower mobility, however, does not share the same agreement as its minimum dark current density occurs at significantly higher doping densities compared to the $N_d\tau_p$ maximum. Given that many T2SL materials do not exhibit diffusion lengths that are significantly larger than their absorber length, the $N_d\tau_p$ product may not be accurate in its prediction of optimal doping density.

Moreover, reduction of the active region’s minority carrier lifetime has deleterious effects on the detector’s diffusion QE, especially in materials exhibiting diffusion lengths less than or equal to the absorber length. Thus, the optimization of the absorber doping density is
only properly assessed by examining detector sensitivity using full analytic expressions and minimizing the usage of approximating limits.

2.7 Structural Optimization Process

Optimal structural parameters and corresponding NEI are entirely dependent on the material parameters of the absorber region, consisting of the recombination rate parameters \((\tau_{SRH0}, B_r, C_n)\) required for the functional form of minority carrier lifetime on doping density, the vertical hole mobility \((\mu_p)\), the absorption coefficient \((\alpha)\), and the intrinsic carrier concentration \((n_i)\). In order to assess the optimal values of absorber length and doping density in which minimum NEI, and hence maximum sensitivity, is achieved for any given absorber material system, a two-dimensional array is created such that each cell represents a unique combination of absorber length and doping density, which are permitted to range from 0.1 to 10 \(\mu\text{m}\) and \(1\times10^{14}\) to \(1\times10^{16}\) \(\text{cm}^{-3}\), respectively. A contour plot illustrating this approach is given in Figure 17.
Figure 17. Example contour plot of NEI as a function of absorber length and doping density. Contour lines are plotted in increments of 0.1 on the log scale. The red star corresponds to the structure design with minimum NEI.

2.8 Optimization of the Structural Parameters for an InAs/InAsSb-Based nBn

The InAs/InAsSb material system has recently been the subject of extensive study due to the material’s relatively high minority carrier lifetime [30]. Minority carrier lifetime is an especially important parameter for the absorber material of an nBn due to its beneficial impact towards both QE and dark current. The high minority carrier lifetime observed in the InAs/InAsSb superlattice is attributed to its intrinsic defect energy level existing above the conduction band, thereby acting as an inefficient SRH recombination center [31]. For reference, the intrinsic SRH lifetime has been reported to be 10 µs by Ref [28].
To evaluate the ideal absorber doping density and absorber length for an InAs/InAsSb-based detector with a bandgap of 215 meV, resulting in a cutoff wavelength above 5 µm, material parameters have been assumed from previous literature which are listed in Table 1.

Table 1. Material parameters used in the model of the InAs/InAsSb T2SL at 130 K.

<table>
<thead>
<tr>
<th>Bandgap Energy [meV]</th>
<th>Intrinsic Carrier Concentration [cm(^{-3})]</th>
<th>Mobility [cm(^2)/Vs]</th>
<th>(\tau_{SRH,0}) [µs]</th>
<th>(B_r) [cm(^3)/s]</th>
<th>(C_n) [cm(^6)/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>215</td>
<td>1.38x10(^{13})</td>
<td>10(^{(a)})</td>
<td>10.0(^{(b)})</td>
<td>1.01x10(^{-10})(b)</td>
<td>1.60x10(^{-26})(b)</td>
</tr>
</tbody>
</table>

(a) Ref. [26], (c) Ref. [28]

The absorption coefficient of the material is determined through NRL Multibands [32] simulations of a structure optimized for maximum wavefunction overlap as described in [25] and shown in Figure 18. This T2SL structure consists of 4.626 nm of InAs followed by 1.062 nm of InAs\(_{0.495}\)Sb\(_{0.505}\).
Since the optimal structural parameters are highly dependent on the absorption coefficient of the absorber material, which is observed to vary from 900 to 3,700 cm$^{-1}$ over the MWIR atmospheric transmission window, the optimization process for the 3 to 5 µm band is non-trivial. Some characteristics for the detector may be preferred, such as spectral uniformity of the detector’s response, minimum NEI at particular wavelengths within the band, or lowest average NEI across the spectral range. To explore the variety in structural optimization, a detector structure is optimized for each wavelength within the MWIR atmospheric transmission window.
transmission window. Additionally, optimization is performed for both illumination types to evaluate differences in design considerations for each geometrical configuration.

Shown in Figure 19 (a) is each optimized structure’s spectral NEI, represented by separate lines. Each line intersects as each structure exhibits the lowest attainable NEI at the wavelength it’s optimized for.

![Figure 19](image)

Figure 19. (a) Spectral NEI for InAs/InAsSb $nBn$ detectors optimized at each wavelength for the topside (top plot (a)) and backside (bottom plot (a)) illuminated geometries. (b) Average spectral NEI for the detectors as functions of the wavelength for optimization. Vertical dashed line indicates the wavelength at which the minimum average spectral NEI occurs for both illumination configurations.

As seen by Figure 19, the detectors optimized for 5 µm, as represented by the black lines in both top and bottom plots, exhibit the smallest range in NEI across the MWIR atmospheric transmission window, thereby constituting the best spectral uniformity. In contrast, the detectors exhibiting the lowest NEI within the MWIR atmospheric window are the devices optimized for 3 µm. The topside illuminated configuration exhibits a minimum NEI within the 3 to 5 µm range of $4.05 \times 10^{10}$ photons/cm²s while the backside-illuminated geometry exhibits a minimum of $4.12 \times 10^{10}$ photons/cm²s. This enhancement in sensitivity of
the topside illuminated geometry is exhibited at all wavelengths as observed in the average NEI by Figure 19 (b). Both illumination configurations are found to exhibit the lowest average spectral NEI for the detector optimized for 3.9 µm, nearly exactly equal to the middle of the spectral range. This metric indicates the highest signal output for an input optical signal exhibiting uniform spectral irradiance, and therefore may be the most appropriate for the optimization of a structure designed for the detection of an entire spectral range.

The optimal structural parameters corresponding to the wavelength for optimization are found in Figure 20.

![Figure 20](image.png)

Figure 20. Optimal structural parameters, absorber length (solid lines, left axis) and absorber doping density (dashed lines, right axis) for topside (red lines), and backside (blue lines) illuminated configurations.

As seen in Figure 20, similar trends in structural parameters are required for optimization for both geometrical configurations. As the absorption coefficient decreases, the optimal absorber length increases to minimize the extent of photon transmission. Consequentially, the diffusion length must also increase to maintain sufficient collection
efficiency of the photo generated carriers. Thus, a higher minority carrier lifetime is favored over a lower minority carrier concentration which is observed by the decrease in the optimal doping density. Both detectors are found to exhibit similar optimal doping densities, which decrease by about $4 \times 10^{14} \text{ cm}^{-3}$ as the wavelength for optimization increases from 3 to 5 $\mu$m.

In contrast to the similarity between each geometrical configuration’s optimal doping densities, the optimal absorber length for each illumination geometry varies more significantly, especially at 5 $\mu$m. This implies that a detector optimized for a conventional PEC geometry may exhibit significant differences in performance when implemented into an FPA. To further investigate these differences, both structures optimized for 5 $\mu$m are examined under both topside and backside illuminated configurations.
Figure 21. Spectral QE of two \( nBn \) detectors at 130 K optimized for 5 \( \mu m \) for backside illumination with an absorber length of 6.2 \( \mu m \) (blue circles and squares) and topside illumination with an absorber length of 8.2 \( \mu m \) (red lines) shown for both illumination configurations. Squares indicate the spectral QE of the structures under topside illumination and circles depict the spectral QE under backside illumination. The solid semi-transparent lines are calculated using Silvaco TCAD simulations and the points are calculated using the analytical model. The dashed line represents the Spectral QE of the ideal detector, with 100\% QE at wavelengths less than the cutoff wavelength of 5.36 \( \mu m \). Inset depicts the simulated dark current density for both structures using Silvaco. The dashed blue and red lines represent the diffusion dark current of each structure at 130 K calculated via the analytical model. The black dashed line represents Rule 07 dark current density for the given cutoff wavelength.

The QE values of these structures are found to be less than 80\% for all wavelengths. Moreover, the dark current densities are significantly higher than Rule 07 dark current. The resulting NEI of these structures is therefore considerably higher than the ideal MWIR detector implying that further modifications, such as changes to the absorber material may be necessary for further improvement.
It is also observed that the 6.2 µm structure, optimized for backside illumination and depicted by blue lines, exhibits significantly less variation in spectral QE compared to the 8.2 µm structure, depicted by red lines. Additionally, it is observed that the topside illuminated spectral QE of the 8.2 µm absorber length detector is only marginally better than the 6.2 µm absorber length detector under topside illumination. Moreover, due to the lower dark current of the 6.2 µm detector, as shown in the inset to Figure 21, the spectral sensitivity of both devices are remarkably similar. In fact, the 8.2 µm device, which is optimized for minimum NEI at 5 µm under topside illumination, only exhibits a difference in NEI of 1.31x10^9 photons/cm^2s compared to the 6.2 µm detector, optimized for backside illumination. For reference, this implies that the 6.2 µm detector would require an operating temperature of 129.84 K to achieve the same level of sensitivity as the 8.2 µm detector at 130 K. Considering the costs of growth and fabrication, the 6.2 µm absorber length is certainly preferable over the 8.2 µm detector.

Although the minimum achievable sensitivity under topside illumination for a given wavelength is determined to require long absorber lengths, this is observed to exhibit significant differences in performance when subject to backside illuminated conditions. Furthermore, the overall improvement in sensitivity is found to be small when compared to detectors with significantly shorter absorber lengths. A more practical absorber length may be informed through an evaluation of the function of NEI on absorber length, as shown in Figure 22.
Figure 22. NEI as a function of absorber length of both topside illumination (dashed lines) and backside illumination (solid lines) configurations for varying absorber hole diffusion lengths as labeled. Circular points on these lines indicate the position in which the absorber length is equal to the diffusion length. Vertical dashed grey line corresponds to the penetration depth of the material.

The NEI shown in Figure 22 is calculated for a structure with a doping density of $4 \times 10^{15}$ cm$^{-3}$, an intrinsic carrier concentration of $1.38 \times 10^{13}$ cm$^{-3}$, and a mobility of 10 cm$^2$/Vs. Here, the absorption coefficient is set to 2,500 cm$^{-1}$ in which the penetration depth is equal to 4 µm, as shown by the grey vertical dashed line. Five different values of minority carrier lifetime are used such that the diffusion length is equal to $\frac{1}{4}$, $\frac{1}{2}$, 1, 2, and 4 times that of the penetration depth, defined as the inverse of the absorption coefficient.

There are several remarkable features shown in Figure 22. First, NEI exhibits the most considerable reduction with increased absorber length when absorber length is smaller than the diffusion length. In this region, QE is limited by the photon transmission through the absorber...
region rather than the collection efficiency of photogenerated carriers, and therefore both geometrical configurations exhibit identical performance as shown by Figure 13. This is observed to diverge at absorber lengths equal to either the diffusion length of the material, or the penetration depth.

If the diffusion length of the material is less than the penetration depth, then the topside illuminated detector’s NEI has no appreciable change after the absorber length increases past its diffusion length. This is attributed to both QE and dark current. The QE of a topside illuminated detector exhibits a diminishing benefit as absorber length increases past diffusion length. Additionally, as the detector approaches the thick-base limit \( L_a > L_p \), its dark current density becomes independent of absorber length. Although the backside illuminated detector shares the same dark current, its QE begins to degrade when the absorber length exceeds its diffusion length, thereby increasing the NEI.

A more interesting condition occurs if the diffusion length of the material is greater than the penetration depth. When the absorber length is less than the penetration depth, the increase in QE with increased absorber length outweighs the increase in dark current, thus beneficially reducing NEI. However, after the absorber length exceeds the penetration depth, the improvement in QE due to increased absorber length is severely reduced. On the other hand, as the detector has not yet achieved the thick-base limit, its dark current is still strongly dependent on absorber length. The NEI therefore increases until it reaches the thick-base limit, in which it is no longer exhibits dependence on absorber length for topside illumination conditions. The backside illuminated detector exhibits both a reduction in QE and increase in dark current, resulting in the highest degree of NEI degradation with increased absorber length in this region.
Through the evaluation of Figure 22, it is generally determined that the optimal absorber length for any material should be roughly equal to either the material’s diffusion length or penetration depth, whichever is smaller. Although the minimum achievable NEI typically requires longer absorber lengths, this metric offers similar sensitivity along with more comparable performance between the topside illuminated configuration typical of PECs and backside illuminated configurations generally used in FPAs. Additionally, it reduces material requirements of the detector, thereby being favorable from a manufacturing perspective.

2.9 The Impact of Material Parameters on Detector Sensitivity

The diffusion-limited MWIR InAs/InAsSb $nBn$ is determined to be incapable of outperforming the sensitivity of an ideal detector. Given that this limitation is fundamental to the material parameters of the InAs/InAsSb absorber region, an investigation of the impact that each material parameter has on minimum achievable NEI is conducted.

To evaluate the capacity for sensitivity enhancement through modifications to material parameters of the absorber region, the InAs/InAsSb T2SL material parameters, as found in Table I, are designated as default values. To avoid the limitations in sensitivity improvement seeded by structural design and evaluate the minimum achievable NEI corresponding to the input material parameters, a device is optimized as each parameter is varied in which doping density may range from $10^{14} - 10^{16}$ cm$^{-3}$ and absorber length may range from 0.1-10 µm as shown by Figure 17. The baseline structure is optimized for the 4 µm wavelength under topside illumination with an absorption coefficient of 1900 cm$^{-1}$, consisting of a 5.2 µm absorber length and doping density of $2.1 \times 10^{15}$ cm$^{-3}$ following Figure 20. Each material parameter is then varied by multiplication of a factor ranging ±2 orders of magnitude from unity, and the
The corresponding device is optimized for minimal NEI. The resulting NEI value is plotted as a function of the multiplicative factor for a direct comparison of each material parameter’s influence on achievable sensitivity. Although any modification to superlattice design realistically results in further complications than variation in any single material parameter, insight towards each parameter’s impact on sensitivity is still of great value.

![Graph](image)

Figure 23. Minimum attainable NEI, defined as the NEI of an optimized structure for the input material parameters, as a function of multiplicative factor, which the parameter is multiplied by. At a multiplicative factor of 1, all devices are equivalent and thus share the same value of NEI. Each parameter is varied independently and lines corresponding to that variance is labeled with the appropriate parameter name. A power law of 1 and -0.5 is shown by the purple and pink lines, respectively. The horizontal black dotted line represents the ideal detector corresponding to Rule 07 dark current density for a 5.3 μm cutoff wavelength, and unity QE.

It is seen in Figure 23 that the three material parameters with the most influence on sensitivity for diffusion-limited devices under low-light conditions are the intrinsic carrier concentration \(n_i\), minority carrier lifetime \(\tau_p\), and absorption coefficient \(\alpha\), with power law relationship dependencies on the multiplicative factor of 1, -0.5 and -0.5, respectively. It
is noted that these findings are in line with expectations from the normalized thermal generation rate reported in Ref. [33], which shows that the background photon flux required to achieve background limited performance is strictly related to these parameters. Mobility, in contrast, is seen to exhibit minimal benefit to sensitivity for the diffusion-limited InAs/InAsSb-based MWIR detector due to its simultaneous increase of dark current as well QE despite its low value. It is noted however, that the competition between dark current and QE with increasing mobility leads to asymptotic behavior in NEI only at high diffusion lengths. However, an increase in mobility is demonstrated to be beneficial towards radiation tolerance of the detector as described in later sections.

The intrinsic carrier concentration, which exhibits a power law relationship of 1 with NEI due to the dependency of diffusion dark current on intrinsic carrier concentration, is observed to be highly impactful for diffusion-limited NEI. However, since the bandgap is held constant, any manipulation of the intrinsic carrier concentration at a given temperature must come from modifications to the density of states effective masses, which is a complicated by anisotropic superlattice band structures and hole subband splitting [34]. It is noted however, that the effects of the intrinsic carrier concentration pertain only to dark current density, thus being most relevant in low-light conditions, in which dark current shot noise is dominant.

Minority carrier lifetime on the other hand, benefits both QE and dark current density and is thereby a more comprehensive parameter for sensitivity enhancement in a wider range of applications. It is seen however, that no modification to a single recombination mechanism allows for drastic improvement of device sensitivity in the InAs/InAsSb T2SL. This is due to the limitations imposed on the effective minority carrier lifetime by other recombination
mechanisms as shown by Figure 15. Both the Auger and SRH lifetimes relative to the InAs/InAsSb must improve for more substantial enhancement of detector sensitivity.

Lastly, the absorption coefficient exhibits significant impact on sensitivity as it allows for smaller absorber lengths for absorption, thus beneficially reducing the dark current density of the device and improving collection efficiency for a given diffusion length.

2.10 Performance Potential of an InGaAs/InAsSb nBn Detector

The InGaAs/InAsSb material was developed in part to mitigate the issues of low vertical hole mobility and low wavefunction overlap in InAs/InAsSb by creating a more symmetric strain balancing profile about the GaSb lattice constant. This allows for similar layer thicknesses to achieve strain-balanced growth, reducing the confinement of holes in the relatively thin InAs layer and thereby promoting both mobility [35] and absorption properties [36]. Although minority carrier lifetimes of the InGaAs/InAsSb were initially low [37], recent progress in material quality has resulted in more comparable lifetimes to the InAs/InAsSb material system [38] demonstrating the potential for InGaAs/InAsSb to act as a higher sensitivity drop-in replacement as the absorber material.

The absorption coefficient of the InGaAs/InAsSb T2SL is calculated via NRL Multibands and compared to the absorption coefficient of the InAs/InAsSb material in Figure 24.
Figure 24. Absorption coefficient of the InAs/InAsSb (red) and InGaAs/InAsSb (blue) as functions of wavelength at 130 K as calculated by NRL Multibands simulations.

It is observed that the absorption properties of the InGaAs/InAsSb T2SL exhibit significant improvement compared to the Ga-free superlattice. This pushes the penetration depth to shorter lengths, thereby requiring shorter absorber lengths for optimal sensitivity, as shown by Figure 22. By assuming a vertical hole mobility of $30 \text{ cm}^2/\text{Vs}$, as determined by Ref. [37], and identical recombination rate parameters as the InAs/InAsSb T2SL, the minimum average spectral NEI is calculated and shown in Figure 25.
Figure 25. Averaged spectral NEI as a function of wavelength for optimization for the InGaAs/InAsSb based nBn detector under topside (red) and backside (blue) illumination configurations.

Here it is seen that the minimum average NEI is achieved when optimizing for wavelengths near the middle of the spectral range, similarly to the InAs/InAsSb nBn. However, the minimum average NEI is found to be $4.19 \times 10^{10}$ photons/cm$^2$s for the topside illuminated configuration, which constitutes a 26% decrease compared to the minimum average NEI of the InAs/InAsSb nBn optimized for topside illumination. Furthermore, this is achieved with a 3.1 μm absorber length, which is nearly 2 μm less than the absorber length of the InAs/InAsSb nBn optimized for minimum average NEI, thereby being highly favorable for cost and manufacturability. These advantages lend considerable motivation for the research and development of a MWIR InGaAs/InAsSb nBn detector.
2.11 Conclusions

Sensitivity of a diffusion-limited MWIR detector under low-light conditions is evaluated using an analytical model derived from carrier continuity equations. Structural optimization is performed for an InAs/InAsSb \( nBn \) detector with a bandgap of 215 meV for both topside and backside illumination conditions. Due to the dependence of optimal structural parameters on the absorption coefficient, the optimization is performed as a function of wavelength across the entire MWIR atmospheric transmission window. The best spectral uniformity in NEI is achieved by the detectors optimized for the lowest absorption coefficient at 5 µm, while the minimal attainable NEI is achieved for the detector optimized for the highest absorption coefficient at 3 µm. The minimum average spectral NEI is found to be the lowest for the detectors optimized at wavelengths near the middle of the spectral range. This value is found to lower for the topside illuminated structure compared to the backside illuminated structure, illustrating an expectation of performance reduction when implemented into a backside illuminated FPA.

Similar trends in optimal structural parameters are observed for both illumination configurations as the wavelength for optimization varies. However, whereas the optimal doping densities are comparable, the optimal absorber lengths become significantly different as the absorption coefficient decreases. An investigation towards variations in the performance of these structures when subject to the opposite illumination type reveals that the larger absorber length structure, optimized for topside illumination, exhibits more significant differences in spectral QE compared to the smaller absorber length structure. Additionally, the NEI of the thinner structure under topside illumination is found to be marginally higher than the optimal structure, despite its significantly smaller absorber length. Thus, a more
generalized metric for the optimal absorber length is established, in which it is determined that an absorber length equal to the lesser of the material’s diffusion length or penetration depth allows for nearly maximal sensitivity as well as mitigates performance variation when implemented into an FPA under backside illuminated conditions.

The limitations of sensitivity of diffusion-limited nBn detectors are then evaluated from the fundamental perspective of the material parameters of the absorber region. By using the InAs/InAsSb material parameters as default values, each parameter is modified, and a structure is optimized for minimum NEI such that the impact of each material parameter on minimum attainable NEI may be assessed. This reveals that absorption coefficient, total minority carrier lifetime, and intrinsic carrier concentration are the three parameters most capable of significantly improving the sensitivity of an nBn detector.

The InGaAs/InAsSb T2SL, which is reported to exhibit higher absorption and mobility is then compared to the InAs/InAsSb T2SL. Assuming identical recombination rate parameters, the InGaAs/InAsSb-based detector is observed to achieve higher sensitivity with less absorber material than the InAs/InAsSb detector. Further research into the material parameters of the InGaAs/InAsSb T2SL is required for its optimal implementation into the nBn device structure for the realization of a high sensitivity, manufacturable MWIR detector solution needed by the space-industry.
3. Effects of Absorber Doping on Fabricated InGaAs/InAsSb nBn Detectors

3.1 Abstract

The effects of absorber doping on majority carrier concentration and minority carrier lifetime are evaluated and the resulting performance of MWIR ($\lambda_{\text{cutoff}} = 5.5 \mu m$) nBn detectors with variably-doped InGaAs/InAsSb T2SL absorbers are investigated. The detector structures are grown by molecular beam epitaxy such that their absorbing layers are either undoped, uniformly-doped with a target density of $4 \times 10^{15} \text{ cm}^{-3}$, or doped with a graded profile, and variable-area mesa detector arrays are fabricated. Recombination rate parameters are assessed via temperature-dependent minority carrier lifetime, as determined by time-resolved photoluminescence. Majority carrier concentration is extracted by the fitting of each device’s capacitance-voltage profile through a model derived from Poisson’s equation. Detector performance is then evaluated with dark current and photocurrent measurements, from which QE and shot-noise-limited NEI are calculated. Analysis of temperature-dependent dark current results in the determination of a defect energy level contributing to high levels of SRH generation rates.

3.2 Introduction

Due to the evaluated limitations in sensitivity of InAs/InAsSb nBn detectors, the inclusion of Ga in the InAs layer is proposed for further improvement of the MWIR nBn photodetector. InAs/InAsSb is known to exhibit lower vertical hole mobility [26] and absorption properties [39] relative to bulk material due to the constraints imposed by the strain-balance condition to the GaSb substrate. To strain-balance the superlattice, the InAs layer must be $\sim 3 \times$ thicker than the InAsSb layer to balance the relatively small degree of tensile strain in
the InAs with the ~3× higher compressive strain of the InAsSb compositions needed to achieve MWIR cutoffs [25]. This leads to a high degree of localization of the heavy holes in the relatively thin InAsSb layers, and consequently poor electron-hole wavefunction overlap and hole transport. Inclusion of Ga in the InAs reduces the In(Ga)As layer’s lattice constant, establishing a more symmetric strain-balance profile with the InAsSb layer in an InGaAs/InAsSb superlattice. This allows for strain compensation to be achieved with similar layer thicknesses which in turn broadens the hole miniband, which is reported to increase the hole mobility [36].

Recent advances leading to high minority carrier lifetime in strain-balanced InGaAs/InAsSb superlattices have led to it being considered as a higher absorption, higher mobility drop-in replacement for the InAs/InAsSb superlattice in a MWIR nBn detector structure [38]. However, like the InAs/InAsSb superlattice [28], the minority carrier lifetime of InGaAs/InAsSb is also a function of doping, and its impact on device performance has yet to be studied.

3.3 Growth and Fabrication of InGaAs/InAsSb detectors

The nBn detectors studied in this work are grown in a Veeco Gen 930 molecular beam epitaxy system on 3” undoped GaSb substrates. A lattice-matched InAs,91Sb,09 layer is first grown with a Si doping density of 1×10^{18} cm^{-3} that acts as the bottom contact layer. This is followed by 4 µm of the absorber InGaAs/InAsSb T2SL material. In this work, three different absorber doping profiles are evaluated. One absorber is uniformly-doped with Si to a target doping density of 4×10^{15} cm^{-3}. Another structure is left undoped to examine trends as well as extract the unintentional doping density and majority carrier type of the InGaAs/InAsSb T2SL.
A third structure is grown with a graded doping profile, designed to impart a modest potential drop across the absorber region for the promotion of collection efficiency. For the implementation of a constant electric field within the absorber region, the Fermi-energy is designed to exhibit a linear dependency on depth into the absorber. The dependence of Fermi-energy on doping density for an n-type material is given in Equation 20 as

$$E_f = E_c - kT \ln \left( \frac{N_c}{n_0 \approx N_d} \right)$$

Where $E_c$ represents the conduction band of the material. It is seen here that a linear change in the Fermi-energy requires an exponential change in doping density. Due to the exponential dependence of the Si dopant flux on source temperature, this is achieved via linearly decreasing the Si source temperature during the growth of the absorber region. For the promotion of hole transport to the barrier junction, the highest doping density occurs nearest the contact region, as shown by Figure 26.
Figure 26. Band diagram of the graded absorber region. Solid lines indicate the conduction and valence band, and dashed line represents the Fermi-energy of the material. The hollow circle depicts the minority carrier hole and arrow represents the direction of transport. The grey arrow shows the direction of the imparted electric field. The red line corresponds to the doping density, which is given by the right axis.

The electric field is represented by the slope of the conduction and valence band, which is roughly equal to 40 V/cm in this structure.

After the growth of the absorber layer, a growth interrupt is performed such that the substrate temperature may be increased for optimal growth of the barrier layer. The barrier used here consists of Al$_{0.77}$Ga$_{0.23}$As$_{0.04}$Sb$_{0.96}$, which was previously found to minimize the valence band offset between absorber and barrier layers. A valence band offset is detrimental to the sensitivity of an $nBn$ photodetector as it impedes the collection of photogenerated holes thereby requiring larger operating biases to overcome the potential barrier, which may result in larger depletion and tunneling dark current components. After the growth of the barrier, the substrate temperature is brought back to the optimal superlattice growth temperature and 70 nm of
undoped superlattice material is grown before another 80 nm of material doped to $1 \times 10^{18}$ cm$^{-3}$ is grown, which serves as the top contact. After the growth of the structures, material characterizations are performed to gauge the structural and optical quality of the material.

3.4 Material Characterizations

Nomarski interference contrast imaging allows for an assessment of the surface quality of the material, which acts as a simple evaluation of the general quality of the grown material in which a rough surface indicates high defect densities within the material. X-ray diffraction is additionally utilized to evaluate the strain-balancing of the superlattice as well as interface quality.

Optical characterization of the material includes steady-state photoluminescence (SSPL) and time-resolved photoluminescence (TRPL). SSPL is used to assess the bandgap of the structures as a function of temperature. Here, a 785 nm laser is used to excite carriers in the material and the photoluminescent signal is coupled into a Bruker vertex 80v Fourier transform infrared spectrometer (FTIR) for high spectral resolution of the photoluminescence signal. A 0.87 µm long-pass filter is used to remove any reflection from the pump laser before the signal is detected by a 15.5 µm cutoff MCT detector. The materials are held in a closed-cycle helium cryostat such that photoluminescence spectrum may be measured from 4 to 300 K. The temperature-dependent photoluminescence spectrum of the undoped structure is shown in Figure 27.
Figure 27. Photoluminescence spectrum of the undoped structure at temperatures ranging from 300 (black line) to 77 K (blue line). Inset shows the measured bandgap energy as a function of temperature in which blue circles represent the undoped structure, red squares represent the uniformly doped structure, and green triangles represent the graded structure. The black line corresponds to the Einstein-single oscillator model fit in which the fitting parameters are given by Table 2.

The material’s bandgap, which is shown in the inset of Figure 27, is determined by the first derivative maximum of an exponentially modified Gaussian fit to the data, corrected for CO2 absorption. The undoped structure’s photoluminescence spectrum is taken in small temperature increments for accurate fitting of the material’s temperature dependent bandgap energy. The two doped structures photoluminescence spectrums are taken at 4, 77, and 130 K, to ensure consistency in bandgap between structures. At 130 K each structure exhibits a bandgap energy of 215 meV (5.7 µm). An Einstein single oscillator model is used to fit the
bandgap as a function of temperature, which is required for the temperature dependent dark current analysis and given by Equation 21 [40].

\[ E_g = E_0 - \left( \frac{S_0 kT_e}{e^{T_e/T} - 1} \right) \]

Here, \( E_g \) is the temperature-dependent bandgap of the material, \( E_0 \) is the zero-kelvin bandgap energy, \( S_0 \) is a dimensionless coupling parameter, and \( T_e \) is the Einstein temperature. The values used for fitting the InGaAs/InAsSb temperature dependent bandgap as shown in Figure 27 may be found in Table 2. As observed in Figure 27, good agreement is attained for temperatures above 50 K, however below this temperature, the localization of carriers results in an effective decrease in the material’s bandgap energy, which is characteristic of a superlattice material.

<table>
<thead>
<tr>
<th>( E_0 ) [meV]</th>
<th>( S_0 )</th>
<th>( T_e ) [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>225.429</td>
<td>2.423</td>
<td>222.260</td>
</tr>
</tbody>
</table>

TRPL is performed on the samples mounted in a liquid nitrogen cooled cryostat. A 1535 nm wavelength pump laser with 3.5 ns pulse duration is used to excite the samples, and a quarter-waveplate compensator and polarizing beam splitter are used to reduce the optical intensity for low-injection conditions. A <1% optical pick diverts the beam to a power meter.
which is used to determine the photon irradiance of the pump laser, which is calculated to be roughly $10^{11}$ to $10^{12}$ photons/cm$^2$ per pulse, verifying the low-injection condition. The photoluminescence signal passes through a 2.4 µm long-pass filter to ensure exclusion of the pump laser and is detected using a 6 µm wavelength cutoff VIGO Systems PVI-4TE detector. The TRPL setup is illustrated in Figure 28.

50,000 acquisitions are averaged by a Teledyne Lecroy HD 4096 oscilloscope to attain one time-resolved photoluminescence decay. The resulting decay is then fit with a single exponential over at least 2.5 lifetimes to accurately extract the slope of the characteristic decay and the effective minority carrier lifetime, as seen in the inset of Figure 29. Four separate data sets and their corresponding minority carrier lifetimes are then averaged, and standard deviations calculated to assess the uncertainty in measurement. At 130 K, the undoped structure exhibits the highest lifetime of 2.10 µs while the graded and the uniformly-doped
structures exhibit lifetimes of 0.65 and 0.62 µs, respectively. The temperature-dependent minority carrier lifetimes for all three samples are shown in Figure 29.

![Minority carrier lifetime graph](image)

Figure 29. Minority carrier lifetime of the three MWIR InGaAs/InAsSb structures as a function of temperature; blue circles, red squares, and green triangles depict the undoped, uniform doping, and graded doping structures, from left to right respectively. The blue, red and green line correspond to the radiative, Auger, and SRH minority carrier lifetime components and the resulting fit is depicted by the black line.

The black curves in Figure 29 are a recombination rate fit of the Auger, radiative, and SRH recombination lifetimes, which show that each structure is Auger-limited above 225 K and is SRH-limited below 225 K. Radiative recombination is not found to play a significant role in the total minority carrier lifetime for any structure.

3.5 Electrical Characterizations of Devices
After material characterization, devices are processed into variable-area mesa arrays in a cleanroom using standard lithography in which a deep-etch process shown in Figure 12 is used to produce the square mesa structures, which are shown in Figure 30. Ti/Pt/Au contacts are placed via metal deposition and each mesa is wire bonded to a 68-pin leadless-chip carrier. Electrical characterizations are then performed in a temperature-controlled vacuum-sealed Dewar.

![Figure 30](image)

Figure 30. Normarski image of processed variable-area mesa array. Gold areas are the deposited Ti/Pt/Au contacts, and dark green shows the exposed nBn structure. Mesa structures are all square shaped with side lengths ranging from 100 to 1,000 µm.

3.5.1 Capacitance Voltage Measurements and Analysis

CV measurements are used extensively for the non-destructive determination of doping profiles in semiconductor materials due to its accuracy in assessing low doping concentrations and relative simplicity compared to alternative methods such as secondary ion mass
spectroscopy or energy-dispersive X-ray spectroscopy [41]. However, the application of traditionally developed analysis methods in the assessment of doping profiles within the $nBn$ are often prone to error.

Fundamentally, the capacitance of a material is inversely proportional to its depletion width, as seen in Equation 22.

$$ C = \frac{\varepsilon A}{W_d} \quad 22 $$

Here, $\varepsilon$ is the permittivity of the material in which the depletion region exists, which is calculated to be $15.3\varepsilon_0$ by NRL Multibands for the InGaAs/InAsSb T2SL, $A$ is the area of the device, and $W_d$ is the depletion width, which is a function of the doping density and bias as shown by Equation 23.

$$ W_d = \sqrt{\frac{2\varepsilon}{qN_d(V_{bi} + V_a)}} \quad 23 $$

By evaluating the change in capacitance as a function of applied bias, the doping density may be assessed, as shown by Equation 24.

$$ N_d = \frac{2}{q\varepsilon A^2} \frac{d}{dV} \left( \frac{1}{C^2} \right) \quad 24 $$

This is known as the Schottky approximation, which is valid for abrupt junctions in which the entire voltage drop and depletion width is contained within the material whose doping
profile is being probed, such as a Schottky junction. This analysis is used for the determination of doping density of the $nBn$ in Ref [42]. Applying this method to the CV profile measured of the uniformly doped structure results in an extracted doping density value of $7 \times 10^{15} \text{ cm}^{-3}$.

As observed in Figure 11 however, the barrier region is also typically depleted, and thus the measured capacitance includes at least these two capacitance sources summed in series. This effect is accounted for in the analysis provided by Ref [43]. The relevant capacitance associated with the depletion width within the absorber region may be isolated through Equation 25.

$$\frac{1}{C_{abs}} = \frac{1}{C_{nBn}} - \frac{1}{C_{bar}} = \frac{1}{C_{measured} - C_{par}} - \frac{\varepsilon_{bar} A}{t_{bar}} \tag{25}$$

Here, $C_{par}$ is the parasitic capacitance of the measurement setup, $\varepsilon_{bar}$ is the permittivity of the barrier region which is calculated to be $12.795\varepsilon_0$ by NRL Multibands, and $t_{bar}$ is the thickness of the barrier layer. This expression assumes that the barrier is fully depleted, which is generally true of thin barriers at low temperatures. By substitution of $C_{abs}$ for $C$ in Equation 22, the depletion width of the absorber region may be isolated. However, substitution of $C_{abs}$ for $C$ in Equation 24 results in a value of $1.3 \times 10^{16} \text{ cm}^{-3}$ for the uniformly doped structure, which is nearly two times greater than that attained by the simple Schottky approximation.

This method approaches a more realistic interpretation of the depletion behavior within the $nBn$ structure, which is useful for a more accurate assessment of the depletion.
width within the absorber region. However, the doping density attained from this analysis method tends to stray further from the true value. This error is attributed to the neglecting of the voltage drop that falls across the barrier region. As shown in Figure 11, a non-negligible potential drop falls across the barrier layer. To illustrate the effect of this on the extracted doping density, Figure 31 depicts $\frac{1}{C^2}$ as a function of potential drop across the absorber region, in which the slope is inversely proportional to the doping density, for each analysis method.

![Figure 31](image_url)

Figure 31. Inverse capacitance squared as a function of applied bias for the uniform doping structure at 80 K. Each line corresponds to a different analysis method in which the slope is inversely proportional to the doping density.

Here, the blue line depicts the simple Schottky approximation in which the absorber capacitance is taken to be the measured capacitance and the potential drop across the absorber region is taken to be the applied bias. The green line depicts the analysis method of Ref [43], in which the absorber capacitance is isolated, but the entirety of the applied bias is
assumed to fall across the absorber region. Additionally included is the red line, which depicts the isolated absorber capacitance under an assumption that half of the applied bias falls across the absorber region to illustrate its effects towards the extracted doping density.

It is observed that each analysis method yields a different doping density value which highlights the importance of using a proper analysis method to attain an accurate doping profile within an nBn structure. However, this requires an evaluation of the functional form of the potential drop that falls across the absorbing region on applied bias. To demonstrate this, the band diagram of the nBn is simulated at three biases, as shown in Figure 33.

![Band diagram of the nBn structure under -0.5, -1.0 and -1.5 V from left to right. Vertical dashed line indicates the edge of the depletion region. Purple and blue solid lines depict the potential drop across the barrier and absorber layer.](image)

Figure 32. Band diagram of the nBn structure under -0.5, -1.0 and -1.5 V from left to right. Vertical dashed line indicates the edge of the depletion region. Purple and blue solid lines depict the potential drop across the barrier and absorber layer.
As shown in Figure 32, the distribution of potential across all three layers of the nBn is dependent on the applied bias. The solution to this potential distribution may be derived from using Poisson’s equation and imposing a charge neutrality condition on the structure. This work has been recently published and is detailed Ref. [44]. The resulting model can then be used to fit the CV profile of an nBn and extract the doping density of both the absorber region as well as the barrier, as shown by Figure 33.

Figure 33. Capacitance as a function of applied bias for the uniformly doped structure. The black hollow circles represent the measured data, and the red line depicts the model’s fit to the curve. The inset depicts the distribution of potential as a function of the magnitude of applied bias as calculated by the model.

Here, it is observed that the model accurately captures the reverse bias regime, offering high accuracy in the determination of the absorber doping density in which the depletion region extends into. However, the same level of agreement is not found in the forward bias regime.
This is attributed to the complex doping profile and small thickness of the contact region. The model assumes a semi-infinite contact and absorber region such that the depletion region may continually grow. However, only small positive biases are required to fully deplete the 70 nm of the undoped portion of the top contact layer. After this is achieved, the depletion region no longer increases appreciably, and the capacitance no longer decreases as the model would expect. This deviation limits the model’s accuracy in determining the contact region’s doping profile.

CV measurements are performed on the three fabricated structures by a Keithley 590 CV Analyzer at 100 kHz and 80 K. The parasitic capacitance of the Dewar is accounted for by analyzing the measured capacitance density \( C_d \) as a function of device area \( A \), which yields the linear relationship in which parasitic capacitance is the slope as seen in Equation 26 and in the inset to Figure 34.

\[
C_{d, measured} = C_{d,nBn} + C_{par} \left( \frac{1}{A} \right)
\]

Characterization and correction for the parasitic capacitance is critical to accurately extract the \( nBn \) capacitance from the measured capacitance. Additionally, since the parasitic capacitance has the greatest effect on the smallest devices, the largest devices (1000 \( \mu \)m) are used for determination of the majority carrier concentration.
Figure 34. Inverse of capacitance density squared versus voltage for largest devices (1000 µm) of each structure at 80 K; blue circles, red squares and green triangles represent the undoped, uniform doping, and graded doping structures, respectively. The solid lines are fits to the data. Inset shows the capacitance density as a function of inverse area for one of the variable-area mesa arrays and the resulting parasitic capacitance.

A fitting window from 0.3 to -2 V is used in which the admittance phase angle is sufficiently large [43]. Figure 34 plots the inverse capacitance density squared as a function of applied bias which shows that the model captures both the low and high reverse bias regimes, the latter of which converges to the linear trend expected in the traditional $pn$-junction depletion limit. The background majority carrier concentration of the undoped InGaAs/InAsSb is found to be $1.7 \times 10^{15} \text{cm}^{-3}$, while the doping density of the uniformly-doped structure exhibits $5.9 \times 10^{15} \text{cm}^{-3}$, consistent with the sum of the target $4 \times 10^{15} \text{cm}^{-3}$ doping density and the background level. The graded structure is found to have an effective doping density of $3.2 \times 10^{15} \text{cm}^{-3}$, as the aforementioned fitting method assumes a uniform doping. Increasing reverse bias pushes the depletion interface deeper into the active region from the barrier/active
region interface, thus the effective doping density extracted from the graded active region is representative of the majority carrier concentration within $0.7 \, \mu m$ of the barrier interface, which constitutes the lower-doped region of the grade, as shown by Figure 26.

3.5.2 Dark Current Measurements and Analysis

The determination of minority carrier lifetime and majority carrier concentration of each structure allows for a more fundamental understanding and analysis of the detector’s dark current density.

Dark current density is first examined as a function of perimeter to area ratio (P/A), to ensure the suppression of surface conduction pathways, as shown by Figure 35.

![Figure 35. Dark current density as a function of the perimeter to area ratio at -200 mV and 130 K. Blue circles, green triangles and red squares depict the undoped, graded and uniformly doped structures, respectively. Solid lines depict linear fits to the data.](image-url)
The slightly negative slope observed in Figure 35 is still under investigation, however, the lack of a distinct positive slope indicates that surface currents are negligible in each structure. This implies that the barrier successfully blocks the surface conduction pathway as no surface passivation procedures were performed.

Dark current is then measured as a function of bias and temperature ranging from 77 to 295 K and shown in Figure 36.

![Graph showing dark current density as a function of bias for all structures ranging from 77 to 300 K.](image)

Figure 36. Dark current density as a function of bias for all structures ranging from 77 to 300 K.

The interpretation of Figure 36 may be made by the understanding of each dark current mechanism’s dependencies on both temperature and applied bias. Diffusion current is mostly independent of voltage and is most easily observed at high temperatures due to its proportionality to the square of the intrinsic carrier concentration, as shown by Equation 13. Depletion current, which is proportional to the depletion width in the absorber region, as shown...
by Equation 9, is then proportional to the square root of the applied bias, as found in Equation 23. Tunneling current, is independent of temperature and is typically the dominant current mechanism at low temperatures. These individual current mechanisms are more easily resolved through the examination of dark current as a function of temperature, or specifically as a function of $1/kT$.

The Arrhenius plot is widely used to determine the dominant current mechanism in a detector. However, its analysis is often misleading, especially at temperatures near the transition points from one dominant current mechanism to another. This is exemplified by an examination of the Arrhenius plot for the undoped structure as shown Figure 37.

![Figure 37. Arrhenius plot of the undoped structure at -200 mV fitted with a full bandgap activation energy as depicted by the grey line. Inset depicts the dark current density as a function of applied bias at 130 K.](image-url)
Here, it is observed that the dark current density at -200 mV exhibits a full bandgap energy until the onset of tunneling at temperatures below 100 K. This may be interpreted as a diffusion-limited structure, in which depletion current plays no significant role. However, as seen by the inset, there is a clear dependency of dark current on the applied bias, which is uncharacteristic of the diffusion current mechanism. A more detailed evaluation requires a more rigorous model than a simple linear slope fit. To fit the Arrhenius plot of the \( nBn \), three current mechanisms are included, tunneling, diffusion, and depletion.

The modelling of tunneling is quite complicated [45] [46] [47], however the assumption that the lowest temperature dark current measurement is equal to the tunneling current component is sufficient to fit the Arrhenius plot of the \( nBn \). Although tunneling current is theoretically independent of temperature, an associated activation energy of the mechanism is observed at low temperatures in the Arrhenius plot. This is attributed to temperature dependent band parameters of the heterojunction structure. As the primary source of tunneling within the \( nBn \) device under reverse bias is determined to be associated to electrons in the valence band of the barrier layer tunneling into the conduction band of the absorber region, the increase in tunneling with higher temperatures indicates a shifting of the valence band of the barrier region towards the conduction band of the absorber region (or vice-versa), thereby reducing the spatial separation of the two bands at a given bias. For the purpose of fitting the Arrhenius plot however, the tunneling current mechanism is simply assumed to be constant.

The modeling of diffusion current requires a precise knowledge of the structure’s temperature-dependent bandgap, as extracted by SSPL and shown in Figure 27, temperature-dependent minority carrier lifetime, as attained from TRPL and shown in Figure 29, the mobility, which is assumed to be equal to 10 cm\(^2\)/Vs, and the majority carrier concentration,
which is evaluated via CV. The intrinsic carrier concentration required to attain the minority carrier concentration, however, is subject to uncertainty in the superlattice density of states effective masses. NRL Multibands predicts that the effective masses of the InGaAs/InAsSb superlattice are equal to $0.197m_0$ for holes and $0.021m_0$ for electrons, however using these parameters to calculate the uniformly doped structure’s dark current density results in a value that is nearly 2x lower than observed. To avoid complications stemming from the superlattice effective masses and retain consistency in device modeling, the density of states effective masses of InAs are used, such that the hole effective mass is $0.333m_0$ and the electron effective mass is $0.026m_0$.

The modeling of depletion current requires knowledge of the depletion width in the absorber region, which is attained from CV measurements and an evaluation of the generation lifetime ($\tau_g$) as found in Equation 9. The generation lifetime is related to the recombination lifetime as shown by Equation 27.

$$\tau_g = \tau_r e^{\frac{|E_i - E_T|}{kT}}$$

Here, $E_i$ is the intrinsic Fermi-energy, and $E_T$ is the defect energy level. It is seen that the most efficient defects for lowest thermal generation lifetime have energy levels equal to the intrinsic Fermi-energy. This results in the highest possible depletion current, in which the generation lifetime is exactly equal to recombination lifetime.

The generation lifetime may be assessed through an evaluation of dark current density as a function of depletion width in the absorber region as described by Ref [43]. Since depletion current is directly proportional to this depletion width, the plot appears linear, as shown by the inset of Figure 38, until the onset of tunnelling current, which appears to occur at biases corresponding to a depletion width of around 600 nm.
Figure 38. Defect energy level as a function of temperature for each structure. Green triangles, red squares, and blue circles represent the graded doping, uniform doping and undoped structure, respectively. Inset depicts the undoped structure’s dark current density as a function of absorber depletion width.

The slope of dark current density as a function of absorber depletion width ($m$) is inversely proportional to the generation lifetime within the material as shown by Equation 28.

$$\tau_g = \frac{q n_i}{m}$$  \hspace{1cm} 28

The relationship between the recombination lifetime obtained from TRPL and the generation lifetime then allows for determination of the defect energy ($E_{\tau}$) as described by Equation 27 and plotted in Figure 38 for each structure. The defect energy level is most accurately assessed at temperatures between 120 and 180 K. At lower temperatures, the early onset of tunneling obscures the characteristic slope of the depletion current mechanism, and at higher...
temperatures the dominance of diffusion current causes the fitting of slope to be subject to higher uncertainty.

One interesting observation is the dissimilarity between the defect energy level extracted from the uniform structures (doped and undoped) and graded structure. This is determined to be due to the depth-dependent recombination rate, characteristic of the graded structure. Via TRPL, the recombination lifetime of the graded structure is found to be 0.65 µs at 130 K, which is comparable to the uniformly doped structure with a target doping density of 4×10^{15} cm^{-3}. However, the depletion width in the graded structure only extends roughly 0.35 µm into the absorber region before the onset of tunneling current, in which the intentional doping density does not exceed 1×10^{15} cm^{-3}. Therefore, the relevant recombination lifetime in this region should be more comparable to the recombination lifetime attained of the undoped structure, rather than the recombination lifetime attained by TRPL. This underestimation of recombination lifetime within the depletion region for the generation lifetime analysis artificially increases the defect energy level. In contrast, using the recombination lifetime of the undoped structure, which is an overestimation of the recombination in the depletion region of the graded structure, results in an artificially low defect energy level of 5.8 meV from the intrinsic Fermi-energy. The defect energy level is therefore determined to be roughly 12 meV from the intrinsic Fermi-energy, which is seen to be consistent between the undoped and uniformly doped structures between the temperatures of 120 to 180 K and is used in the Arrhenius fitting model.

The only unknown fitting parameter required to accurately model the Arrhenius plot of each structure at any given bias is a parameter herein referred to as \( W_{d,offset} \). Although the depletion width of the absorber region is primarily isolated by removing the parasitic
capacitance of the measurement system as well as the barrier capacitance, other capacitance sources within the \( nBn \) include depletion or accumulation in the contact region, and diffusion capacitance from the free-carrier charge stored within the quasi-neutral region of the absorber [48]. Further research is required to resolve more precise capacitance values, however summing them into an associated depletion width is sufficient for the Arrhenius fitting. The resulting fits for each structure at varying biases is shown in Figure 39.

![Figure 39. Arrhenius plot of each InGaAs/InAsSb \( nBn \) device at biases of -200, -400 and -600 mV (left to right). The purple, red, and blue lines depict the tunneling, depletion, and diffusion components of total current density, while the black line is the result of the total fit to the measured data.](image-url)
Here, the defect energy level is set to 12 meV for the uniformly doped and undoped structures and 20 meV for the graded structure to account for its measured recombination lifetime. $W_{d,offset}$ is set to 75 nm for each structure, which results in a depletion width of 23 nm at -200 mV in the undoped structure, 9 nm of depletion width in the graded doping structure, and no depletion width in the uniform doping structure, as seen by the lack of the red line corresponding to the contribution of depletion current. Although these depletion widths are relatively small compared to the 4 µm absorber region, the efficient generation centers with energy levels near the intrinsic Fermi-energy, result in significantly high levels of current. Further substantiating these defect energies is the agreement to the measured Arrhenius plots at higher reverse biases.

Although the undoped structure’s dark current is found to be mostly diffusion current, the simple Arrhenius analysis fails to recognize the contribution of the depletion current mechanism, which is calculated to constitute the majority of the difference in dark current density between the undoped and uniform doping structures. This result highlights the importance of the suppression of the depletion region at the operating bias, which is determined to be effectively achieved via doping of the barrier/absorber interface region.

3.5.3 Photo Current Measurements and Analysis

With an assessment of device dark current as a function of absorber layer design, an assessment of QE must follow to address the effects of absorber doping profiles on sensitivity. To measure photo current ($I_{photo}$), a 900 K blackbody is placed in front of the devices. Photons pass through a cold bandpass filter, centered at 3 µm wavelength (0.1 µm full-width at half-max), yielding a photon flux of $4.7 \times 10^{13}$ photons/cm²s incident on the entire mesa array. An
optical chopper and lock-in amplifier isolate the photo current from the total current. Reflections from the metal contact are accounted for by dividing the measured photo current by the fill factor, which is defined as the fraction of mesa area occupied by the contact, as seen in Figure 30. QE is then assessed via the relationship between photo current and mesa side length as detailed in Equation 29 to account for any potential lateral optical collection from the flood illumination conditions [49].

\[
\sqrt{I_{\text{photo}}} = \sqrt{q\eta\phi(L + 2L_{\text{LOC}})}
\]

Equation 29

Here, \( \phi \) is the photon irradiance, \( \eta \) is the QE, and \( L_{\text{LOC}} \) is the lateral optical collection length, which is found to be negligible due to the deep etch fabrication geometry. The structures do not possess anti-reflection coatings and experience parasitic absorption in the top contact, resulting in a maximum external QE expectation of 64%. Figure 40 depicts the QE of each structure as a function of bias.
Figure 40. QE as a function of applied bias for each structure at 3 µm and 130 K. The vertical dashed line depicts the operating bias of the detectors. Inset depicts the spectral QE of the graded doping structure, which is normalized such that the QE at 3 µm (green triangle) is equal to the measured value from photo current measurements. The vertical dashed line depicts the detector’s cutoff wavelength, defined as the first derivative maximum of spectral QE.

At the -200 mV operating bias, the QE of the uniformly doped structure is 44% and the QE of the undoped structure is 56%. The observed enhancement in QE is consistent with the undoped sample’s longer minority carrier lifetime and correspondingly longer hole diffusion length. On the other hand, despite its lifetime being comparable to that of the uniformly doped structure, the graded structure exhibits a high QE of 57%. Even despite the evidence that the minority carrier lifetime extracted via TRPL does not accurately reflect the minority carrier lifetime nearest the barrier junction, the expected lifetime is still less than the undoped structure’s at any point in the material due to the prevalence of doping. Thus, the higher QE exhibited by the graded structure indicates that the doping grade is effective in enhancing the collection efficiency of photogenerated carriers within the quasi-neutral absorber region of an nBn. This
effect is simplified to an effective mobility enhancement, however it is noted that the prevalence of the electric field is unlikely to have any physical alterations towards the mobility of the material. The fundamental reasoning behind the heightened QE is still under investigation.

3.6 Noise-Equivalent Irradiance

NEI is calculated via Equation 6 From the QE and dark current measurements obtained at -200 mV, to compare the detectors’ sensitivities. Figure 41 plots the NEI of the three detectors as a function of the background photon flux ($\Phi_b$) alongside the ideal detector, exhibiting Rule 07 dark current and 100% QE for comparison.
Figure 41. Shot-noise-limited noise-equivalent irradiance as a function of background photon flux at 130 K for each nBn structure. Dotted green lines depict the transition from dark current-limited to background-photon flux limited performance regimes of the graded structure. The dashed grey line corresponds to the shot-noise-limited noise-equivalent irradiance of a device exhibiting Rule 07 dark current density and unity QE. Inset plots NEI as a function of applied bias. The vertical dashed line indicates the detector’s operating bias, set at the bias in which minimum NEI is achieved.

The undoped and graded structures yield the lowest NEI in the $\Phi_B$-limited regime where QE drives NEI, while the doped and graded structures yield the lowest NEI in the dark-current-limited regime where NEI goes by the square root of dark current over the QE. In either case, the graded structure provides the best NEI performance across the entire range of $\Phi_B$ with a transition from $\Phi_B$-limited to dark-current-limited performance occurring at $2\times10^{13}$ photons/cm$^2$s.
Table 3. Material parameters and device performance metrics at operating voltage and temperature (-200 mV, 130 K) for each nBn structure.

<table>
<thead>
<tr>
<th>Absorber Doping Profile</th>
<th>$n_0$ [10$^{15}$ cm$^{-3}$]</th>
<th>$\tau_p$ [µs]</th>
<th>$J_d$ [µA/cm$^2$]</th>
<th>$\eta_{3\mu m}$ [e$^{-}$/photon]</th>
<th>NEI [10$^{10}$ photons/cm$^2$s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undoped</td>
<td>1.7</td>
<td>2.10</td>
<td>3.48</td>
<td>56.2</td>
<td>8.3</td>
</tr>
<tr>
<td>Uniform Doping</td>
<td>5.9</td>
<td>0.62</td>
<td>1.27</td>
<td>43.7</td>
<td>6.4</td>
</tr>
<tr>
<td>Graded Doping</td>
<td>3.2</td>
<td>0.65</td>
<td>2.10</td>
<td>57.2</td>
<td>6.3</td>
</tr>
</tbody>
</table>

The dark-current-limited shot noise NEI ($\Phi_B = 0$) of each sample is provided in Table 3 alongside the other measured material and device parameters for comparison. For reference, the minimum achievable NEI of the theoretical InAs/InAsSb nBn detector at 3 µm was found to be 4.1x10$^{10}$ photons/cm$^2$s. However, this assumes an $F$ of 1. The application of anti-reflective coating on these devices is expected to reduce the NEI by a factor of $(1 - R)$, or by roughly 66%, resulting in an NEI value of 4.3x10$^{10}$ photons/cm$^2$s for the unoptimized uniform doping structure. Additionally, this detector exhibits a larger cutoff wavelength and uses significantly less absorber material compared to the optimal InAs/InAsSb nBn structure. Thus, a higher performance potential of the uniformly doped MWIR InGaAs/InAsSb nBn is expected. Further investigation is necessary to realize a fully optimized detector. The graded doping strategy is found to further heighten detector sensitivity, which is not considered in the sensitivity optimization model.

In addition to improving the detector performance characteristics here, the effective mobility enhancement imparted by the graded doping profile, or alternatively a graded bandgap [50] may also reduce the rate at which QE degrades with irradiation [51]. This doping-grade strategy may also be employed for long-wave infrared devices, to gain the beneficial effects of the electric field without the absorption and dark current trade-offs that come with a graded
bandgap. Such a detector with an optimized graded absorber profile for minimum NEI as well as improved radiation hardness would be of great value for space sensing applications.

3.7 Conclusions

In conclusion, high minority carrier lifetime InGaAs/InAsSb superlattice \( nBn \) photodetectors are produced exhibiting shot-noise-limited NEI within a factor of \( 4 \times \) of the NEI expected of an ideal detector with 100% QE and Rule 07 dark current density. Analysis of the minority carrier lifetimes, majority carrier concentrations, dark current, and QE in these detectors resulted in the determination of fundamental material parameters of the InGaAs/InAsSb T2SL, which are used in the analysis of the diffusion and depletion current. Insight towards the driving mechanisms of device performance was gained from this fundamental approach, allowing for a more rigorous understanding of the diffusion and depletion current processes as a function of temperature and bias.

Doping is found to reduce the minority carrier lifetime at the detriment of QE in the uniformly doped structure, but not in the graded structure which exhibits a comparable QE to the higher lifetime undoped structure. Although all devices are diffusion-limited at the operating conditions of 130 K and -200 mV reverse bias, the difference in dark current density between doped and undoped structures is attributed mostly to the depletion current mechanism, facilitated by defects with energy levels near the intrinsic Fermi level. Ultimately, the graded structure exhibits the best NEI performance across the entire range of background photon flux due to the effective mobility enhancement imparted by the graded doping profile, allowing for high QE and reduced dark current density while also potentially enhancing its tolerance to radiation damage.
4. Effect of Proton Irradiation on InGaAs/InAsSb nBn Detectors

4.1 Abstract

An investigation into the effects of 63 MeV proton irradiation on high-sensitivity MWIR InGaAs/InAsSb nBn devices is performed. Three different structures with various absorber region doping profiles are irradiated and characterized to assess its impact on performance degradation. Minority carrier lifetime is measured as a function of proton fluence using TRPL and lifetime damage factors are assessed. Majority carrier concentration is determined via CV measurements and dopant introduction rates are calculated. An analysis of dark current density is performed using these material parameters, revealing a reduction in mobility with proton fluence and the emergence of a proton-induced defect energy level. QE is calculated at each proton fluence, and QE damage factors are assessed, which show the graded doping structure exhibits the least reduction of QE with dose, attributed to its effective mobility enhancement. Conclusively, detector sensitivity, assessed via shot-noise limited NEI, shows that the graded doping structure is the least susceptible to high-energy proton irradiation-induced performance degradation.

4.2 Introduction

The demonstration of high sensitivity MWIR InGaAs/InAsSb detectors at high operating temperatures provides encouragement for their utilization in space applications. It is necessary to evaluate the extent of performance degradation due to proton irradiation to assess these detector’s expected mission lifetime.
Space vehicles in orbit around Earth are subject to various sources of damaging radiation such as solar flares, cosmic rays, and high energy protons trapped within Van Allen belts [13]. High energy proton irradiation can be especially destructive to crystalline semiconductor materials [52] as it induces displacement damage within the lattice [53], as well as ionization damage. The former has been reported to affect material properties such as majority carrier concentration [54], carrier mobility, and minority carrier lifetime [55] [56]. As these parameters determine the performance of detectors [57] [51], it is necessary to evaluate how the InGaAs/InAsSb T2SL is affected by high energy proton irradiation and how this degrades the resulting performance of the nBn detector.

4.3 Methods

Three InGaAs/InAsSb nBn structures with varying absorber doping profiles are grown via molecular beam epitaxy and irradiated with 63 MeV protons to study the effect of high energy proton irradiation on device performance and explore strategies to reduce performance degradation. Material and detector samples are positioned in vacuum-sealed temperature-controlled Dewars where they are held at the operating temperature and bias while being subjected to a collimated beam of 63 MeV protons produced by the cyclotron at Crocker Nuclear Laboratory at the University of California, Davis [58]. Irradiation occurs in step-doses, and the devices are characterized in-situ between doses to avoid thermal annealing effects that would not occur in space.

To achieve accurate dose levels, the proton fluence is first measured using a faraday cup within the beam line while a secondary emission monitor (SEM) outside of the beam takes an indirect measurement. The SEM is then calibrated by the ratio of these two measurements such that it may take in-situ measurements of the beam current during testing which is
determined to exhibit a maximum of 2% uncertainty in proton fluence [58]. TRPL, CV, photo current, and dark current measurements are taken of the \( nBn \) structures during the irradiation process to determine the material and device characteristics as functions of the proton fluence.

4.4 Minority Carrier Lifetime

Unprocessed pieces of the as-grown materials are characterized via TRPL to evaluate the minority carrier lifetime degradation as a function of proton fluence. TRPL is performed in the same manner as previously described, in which a pulsed laser excites the material under low-injection conditions such that a single exponential decay, characteristic of the minority carrier lifetime may be assessed. This single exponential decay is shown in Figure 42. The minority carrier lifetime is measured \textit{in-situ} between doses of proton irradiation and the reciprocal of the measured minority carrier lifetime, defined as the recombination rate, is plotted as a function of proton fluence in Figure 42.
Figure 42. Recombination rate of each structure at 130 K as a function of proton fluence. Blue circles, red squares, and green triangles correspond to the undoped, uniformly doped, and graded structure respectively. The solid lines represent linear fits to the data where the slope is the lifetime damage factor. The inset depicts the photoluminescence decay for the undoped structure in which blue points correspond to the unirradiated decay and red points correspond to the decay of the material after a proton fluence of $3.05\times10^{11}$ H$^+/\text{cm}^2$.

As each structure exhibits SRH-limited recombination dynamics, the linear dependency observed in each sample as a function of proton fluence corresponds to an expected constant SRH recombination center introduction rate with proton irradiation [59]. The lifetime damage factor, defined as the rate at which the recombination rate increases with proton fluence [57], is labeled in Figure 42. The undoped structure, with the highest unirradiated lifetime of 2.1 µs, exhibits the lowest lifetime damage factor of $4.4\times10^{-6}$ cm$^2$/H$^+$s, while the uniformly doped and graded doped structures exhibit damage factors of $6-7\times10^{-6}$ cm$^2$/H$^+$s. For comparison, lifetime damage factors on the order of $5\times10^{-6}$ cm$^2$/H$^+$s are typical.
for the InAs/InAsSb superlattice, while damage factors are closer to $1 \times 10^{-5} \text{ cm}^2/\text{H}^+\text{s}$ in bulk InAsSb [56].

4.5 Majority Carrier Concentration

Electrical characterizations are performed on fully reticulated variable-area mesa arrays, ranging in pitch from 100 to 1,000 µm, fabricated using standard lithography techniques with a deep-etch geometry. Ti/Pt/Au contacts are placed via metal deposition and the mesa devices are packaged in and wire-bonded to a 68-pin leadless-chip carrier and placed in vacuum-sealed temperature-controlled Dewars for in-situ characterization between doses. CV measurements are performed on each structure and fit using the aforementioned model described in Ref [44] to assess the majority carrier concentration profile as a function of the proton fluence, as shown in Figure 43.
Figure 43. Squared inverse capacitance density of each structure as a function of applied bias at 85 K. The solid red, green and blue curves correspond to the unirradiated data of the uniformly doped, graded, and undoped structures respectively. The dotted black points represent the measured data for each structure after a proton fluence of $6.1 \times 10^{11} \text{ H}^+/\text{cm}^2$. The inset shows the change in majority carrier concentration in the absorber layer of each structure as a function of proton fluence, with error bars indicating the standard deviation across several mesa devices.

The majority carrier concentration within the absorber region of each structure is observed to exhibit a positive trend with proton fluence. Linear fits to the data provide the dopant introduction rates for the uniformly doped, undoped, and graded structures, which are 92, 89, and 60 cm$^{-1}$ respectively. Large standard deviations in the extracted majority carrier concentration, shown in the inset of Figure 43, arise from the minimal change in capacitance-voltage profiles after irradiation, as shown by the dotted lines in Figure 43. Despite these relatively large standard deviations, the dopant introduction rates are found to be comparable to the rate of 142 cm$^{-1}$ reported by Ref. [54] in an InAs/InAsb $nBn$ device. In contrast to Ref
[54], however, the initial majority carrier concentration is two orders of magnitude larger than the assessed change in majority carrier concentration, and thus the most severe percentage increase between majority carrier concentration pre- and post-irradiation is only \( \sim 3.5\% \) for the undoped structure with the smallest majority carrier concentration of \( 1.7 \times 10^{15} \text{ cm}^{-3} \), resulting in minimal effect on the change in dark current density.

4.6 Dark Current Density

Dark current density is measured as a function of voltage at 130 K for each device at each proton fluence. Perimeter-to-area analysis of dark current density reveals that surface currents are negligible before and after irradiation for each structure as expected [60]. Pre-irradiation data and analysis show that diffusion current is the dominant current mechanism for each structure, however depletion current is found to have a significant contribution to the total dark current density of the undoped structure at the operating conditions of 130 K and -200 mV [61]. An investigation into the effect of proton irradiation on both diffusion current and depletion current is therefore necessary for a complete understanding of the relationship between dark current density and proton fluence. Although an Arrhenius analysis would be informative towards the changes in each current mechanism, the detectors are held at the operating temperature to avoid thermal annealing that would compromise this study.

To examine the effect of proton irradiation on depletion current, dark current density is plotted as a function of depletion width, determined by the CV measurements, as previously described, in which the slope of the linear portion of this plot is inversely proportional to the generation lifetime. This analysis reveals that the SRH level shifts further from the intrinsic
level with increasing proton fluence, as shown in the inset of Figure 45. Understanding that this analysis method reduces a spectrum of SRH energy levels to a single weighted average [62], this behavior can be interpreted to indicate that proton irradiation introduces one or more new defects that are further from the intrinsic Fermi energy compared to the SRH energy level prevalent prior to irradiation, causing $|E_t - E_i|$ to increase with proton fluence. This effect may be replicated via a two-level defect introduction model in which recombination lifetime and generation lifetime are given by Equations 30 and 31 respectively.

$$R_r(\phi_p) = \frac{1}{\tau_r(\phi_p)} = \frac{1}{\tau_r(0)} + \frac{1}{\tau_r(0)} = \frac{1}{\tau_r(0)} + K_{1/\tau} \phi_p,$$  

$$R_g(\phi_p) = \frac{1}{\tau_g(\phi_p)} = \frac{1}{\tau_g(0)} + \frac{1}{\tau_g(0)} = \frac{1}{\tau_g(0)} + K_{1/\tau} \phi_p e^{\frac{|E_{t2} - E_i|}{kT}}.$$  

Here, $\tau_r(0)$ corresponds to the measured unirradiated recombination lifetime, $K_{1/\tau}$ is the extracted lifetime damage factor, $\tau_g(0)$ is the extracted unirradiated generation lifetime, $\phi_p$ is the proton fluence, and $E_{t2}$ is the defect level of the proton-induced defect. The only fitting parameter is $E_{t2}$, which is found to be 30 meV from the intrinsic fermi energy to best fit the unintentionally doped structure’s data shown in the inset of Figure 44. This energy level, relative to the intrinsic Fermi energy, is equivalent to 55 meV below the conduction band which is consistent with the result in Ref. [63]. Through this analysis, the proton-induced displacement damage is observed to results in less efficient SRH generation centers relative to the intrinsic defects prevalent in the as-grown InGaAs/InAsSb T2SL, thereby increasing the magnitude of depletion current less significantly than anticipated. Shown in Figure 44 is the
defect energy as a function of proton fluence for the uniformly doped and undoped structures, and the inset depicts a diagram of these energy levels.

Figure 44. Defect energy level as a function of proton fluence for each structure at 130 K. Inset depicts a diagram of bandgap energy and expected defect level positions.

Although the uniformly doped defect levels are also displayed, the lower depletion volume due to the intentionally doping results in a narrow window of linearity in the plot of dark current density as a function of depletion width before the onset of tunneling, making it difficult to distinguish the slope corresponding to depletion current. Due to this uncertainty, only the unintentionally doped structure is fit for the purpose of extracting the proton-induced defect level.
Further confirmation of the introduced defect energy behavior is observed in the undoped structures’ recombination rate, which increases by $6.4x$ following proton irradiation while depletion current only increases by $1.9x$, constituting roughly 20% of the total dark current across all doses. This calculation is performed by using the depletion width in the absorber region as determined by CV, which is not appreciably impacted by proton fluence, as well as the extracted generation lifetime as a function of proton fluence.

The remainder of the dark current density under low-bias conditions is attributed to diffusion current which is given in terms of recombination rate ($R_r$) by Equation 32.

$$J_{diff} = qP\sqrt{V_{th}\mu_pR_r} \ast \tanh \left( L_a \frac{R_r}{V_{th}\mu_p} \right)$$

In the limiting case of the diffusion length being much longer than the absorber layer thickness ($L_p \gg L_a$), diffusion current is proportional to the recombination rate, while in the other limit ($L_a \gg L_p$), it is proportional to the square root of the recombination rate. Since the majority carrier concentration is found to exhibit minimal change with proton fluence, the relationship between dark current density and recombination rate ($R_r$) will exhibit a power law relationship ($n$) between 0.5 and 1.0 if only the minority carrier lifetime is changing with proton irradiation. Notably, examining the power law relationship between dark current density and proton fluence, which is the approach in Ref. [54], may result in a power law relationship between 0 and 1.0 due simply to the presence of the constant term accounting for the unirradiated lifetime in Equation 30. Thus, it is advantageous to separately determine recombination lifetime degradation with proton irradiation alongside dark-current degradation as it permits a clearer analysis of the device behavior.
It is observed that the uniformly doped and undoped structures exhibit power laws of 0.32 and 0.34 respectively, as shown in Figure 45. Although the undoped structure’s analysis is complicated by the prevalence of depletion current, its calculated constant fractional percentage of the measured total current density would not influence its power law dependency on recombination rate. The uniformly doped structure on the other hand, which exhibits clearly diffusion dominated behavior until the onset of tunneling below 100 K, as shown by Figure 39, is also found to have a comparable power law. Therefore, it is concluded that the vertical carrier mobility must also be reduced by high energy proton irradiation in the InGaAs/InAsSb T2SL to account for this power law behavior. The extent of mobility degradation, however, is
tied strongly to the intrinsic carrier concentration of the material, as seen in Equation 32. To rule out the possibility for this trend to be attributed to uncertainty in the intrinsic carrier concentration, the mobility required to achieve each structures’ diffusion current density is calculated for a range of intrinsic carrier concentrations, ranging from $7 \times 10^{12}$ to $1.38 \times 10^{13}$ cm$^{-3}$, which constitute the values attained by using the effective masses from NRL Multibands and of bulk InAs, respectively, as shown in Figure 46.

![Figure 46. Mobility required to attain each structures estimated diffusion dark current density as a function of proton fluence for varying values of intrinsic carrier concentration. Diffusion dark current is estimated to be roughly equal to total dark current for the uniform and graded doping structures and equal to 80% of the dark current of the undoped structure.](image-url)
Although the uncertainty in the effective masses of the T2SL impedes confidence in the extraction of an absolute value of mobility, an inverse trend with proton fluence is observed for each structure regardless of the intrinsic carrier concentration. The undoped and graded structures, are subject to further uncertainty due to the prevalence of other current mechanisms, as well as spatial variability of carrier concentration and recombination rate inherent to the doping grade, however, similar trends with proton fluence are exhibited by all three.

Additionally, it is observed that the graded doping structure exhibits a lower mobility compared to the uniform structures, which contradicts the sentiment of the graded doping strategy. Since the graded structure shares a comparable lifetime to the uniform structure, yet exhibits a significantly lower doping density, the required mobility to attain its measured dark current density is observed to be small. This hints towards the misconception of a mobility enhancement and suggests that the actual benefits of the doping grade extend beyond what an increase in mobility would provide.

While the power law relationship between dark current density and recombination rate lends insight towards the driving mechanisms behind dark current density increase due to proton irradiation, it is of more practical importance to discuss the resulting change in dark current density. Despite the graded structure exhibiting the highest power law relationship with recombination rate, its change in dark current density is nearly half that of the undoped structure. In fact, the change in dark current density is observed to trend with the unirradiated dark current density; the undoped structure, exhibiting the highest unirradiated dark current density also exhibits the largest change in dark current density, whereas the uniformly doped structure, exhibiting the lowest unirradiated dark current density exhibits the least change. This observation may be substantiated by the proportionality of diffusion dark current density on
the equilibrium minority carrier concentration. Given that the carrier concentration is assessed to exhibit minimal change with proton fluence, the overall change in diffusion dark current density also scales with the equilibrium minority carrier concentration. Therefore, intentional doping of the absorber region is found to not only reduce unirradiated dark current density, but also the rate at which dark current density increases with proton fluence. This trend is also assessed to agree with other studies [54].

Notably however, this observation neglects the impact of recombination rate on dark current density. As seen in Figure 42, as doping increases so does both recombination rate and lifetime damage factor, thereby reducing the beneficial effects that the reduction in equilibrium minority carrier concentration has on both unirradiated diffusion dark current and the overall change in diffusion dark current post-irradiation. Although this limits potential improvement via increased absorber doping, the effects of this compromise are not found to substantially modify the trends observed in the samples studied here. Values of each structure’s equilibrium minority carrier concentration as well as change in dark current density may be found in Table 4.

4.7 Quantum Efficiency

After dark current measurements, photo current is measured for each device as a function of proton fluence to evaluate QE. Photo current is measured in the same method as previously described and QE is calculated via Equation 29. QE damage factors are then defined by the rate of change in inverse QE as a function of proton fluence, as described in Ref [51] and shown in Figure 47.
Figure 47. Inverse QE for 3 µm wavelength light as a function of proton fluence for each structure at 130 K and -200 mV. The uniformly doped, undoped and graded structures data is represented by red squares, blue circles, and green triangles respectively. Solid lines correspond to linear fits to the solid data points in which the slope is represented by the QE damage factor, labeled in units of cm$^2$photon/H$^+\cdot$e$. The hollow green point, corresponding to the graded doping structure at 1.22×10$^{11}$ H$^+/\text{cm}^2$, is excluded from fitting due to its unexpectedly low QE along with its dissimilar functional form with voltage compared to other proton fluences. The inset depicts the theoretical diffusion partial QE for a topside illuminated device with an F value of 0.65 at 130 K. Solid points indicate measured QE before irradiation and hollow points represent the measured QE after a proton fluence of 3.05×10$^{11}$ H$^+/\text{cm}^2$.

Here it is observed that the graded structure exhibits the smallest QE damage factor while the uniformly doped structure exhibits the highest. Although the original intention was to dose the samples to a proton fluence of 6×10$^{11}$ H$^+/\text{cm}^2$, the final QE measurement exhibited an uncharacteristically low value for each structure. The origins of this are still unknown, however due to the lack of foundation and justifiable physical explanations of this result, it is interpreted as an experimental error. In addition, the hollow triangle seen in Figure 47 at 1.22×10$^{11}$ H$^+/\text{cm}^2$ corresponds to a measurement that is uncharacteristically low, and exhibits
significant deviation in bias dependency compared to the other QE measurements of the structure and is therefore also excluded from fitting. This exemplifies the difficulties of experimental measurement under the influence of proton irradiation, in which measurements may not be taken again after a full data assessment.

To verify the trends in QE damage factor between structures, separately processed nBn devices fabricated from the undoped and graded materials are remeasured and shown in Figure 48.

![Figure 48](image.png)

Figure 48. Inverse QE at 130 K, -200 mV and a wavelength of 3 µm as a function of proton fluence for the second set of processed devices fabricated from the graded structure (green triangles) and undoped structure (blue circles). Solid lines indicate best linear fit to all data points.

Here it is verified that the graded doping structure does in fact exhibit the lowest QE damage factor. Unfortunately, the relative magnitudes of QE varied between processed devices by roughly 7%. The reason for this is still not currently known, however some theories include
potential reduction in material quality from the center to the edge of the wafer, differences in surface roughening between processes, or possibly reduction in effective device area due to oxidation of the barrier layer and subsequent chipping of the top contact layer during wire-bonding. The consistency of increase in QE damage factor observed in both structures may support the location-dependent material quality hypothesis, as lower unirradiated minority carrier lifetimes are found to exhibit higher lifetime damage factors, which in turn would increase the QE damage factor. Location dependent TRPL may help further substantiate this theory. Regardless, Figure 48 verifies the beneficial impact of a graded doping profile towards the reduction of QE degradation, prompting an investigation of its efficacy.

Although there exists a small depletion width in the undoped structure which contributes to dark current density under standard operating conditions, the estimated percentage of photon absorption within this region is comparatively small and thus the QE of each device may be approximated by the partial diffusion QE for a topside illuminated geometry as given by Equation 15 and depicted in the inset of Figure 47.

Notably, the first term in parentheses in Equation 15, \( (L_p^2 \alpha^2 / (1 - L_p^2 \alpha^2)) \), is also present in the expression for the diffusion partial QE of a backside illuminated geometry, as given by Equation 16. This term was previously found to drive a linear relationship between inverse QE and proton fluence which allows for the QE damage factor by Ref [51]. Although subtle differences in the bracketed term for the topside illuminated QE equation results in a non-linear dependence of inverse QE over a wide range of proton fluence, similar trends arise. Taking the inverse of the first term \( (1/L_p^2 \alpha^2 - 1) \), expressing the diffusion length in terms of proton fluence via Equation 30, and differentiating with respect to proton fluence reveals that
the QE damage factor is dependent on the ratio of lifetime damage factor \( K_{1/\tau} \) to vertical carrier mobility \( K_{1/QE} \propto K_{1/\tau} / \mu_p \). This result is substantiated by the experimentally observed trends shown in Figure 47.

Comparing the uniformly doped and undoped structures, which are expected to have roughly similar values of vertical hole mobility, shows that a significantly higher QE damage factor is exhibited by the uniformly doped structure, which is a consequence of its larger lifetime damage factor. The graded structure, on the other hand, exhibits the smallest QE damage factor despite its largest lifetime damage factor, which is indicative of the structure’s higher effective mobility. This effective mobility enhancement from the doping grade is further confirmed by the unirradiated QE, as the highest QE and therefore the longest diffusion length, as seen in the inset to Figure 47, corresponds to the graded structure despite its substantially lower minority carrier lifetime. It is therefore assessed that the effective mobility enhancement exhibited by the graded doping approach not only enhances unirradiated QE, but also reduces the rate of QE degradation due to proton irradiation.

Similar to the analysis of mobility from dark current measurements, an analysis of mobility from QE may be performed. Whereas values of mobility from the dark current analysis was limited by uncertainty in the intrinsic carrier concentration, the QE analysis is limited by uncertainty in QE. Error in QE is upwards of \( \pm 5\% \) due mostly to complications in radiometry and imperfect emissivity from the blackbody source. Although this constitutes a systematic error, thereby allowing for the evaluation in trends between structures, the difference between a photon irradiance of \( +5\% \) and \( -5\% \) of what is calculated may change the trend of mobility as a function of proton fluence. Therefore, QE is set to range \( \pm 5\% \) for a more
rigorous investigation. The mobility required to attain the resulting QE values as a function of proton fluence is shown in Figure 49.

Figure 49. Mobility as a function of proton fluence for each structure. The dashed lines depict the mobility values required to attain the measured QE, while the lines above and below depict the mobility required to attain the measured QE with an additional ±2.5% and ±5%, reflecting the potential error in radiometry.

Here, unlike the mobility analysis from dark current measurements, the graded structure exhibits the highest mobility, which reiterates the fact that the effective mobility enhancement of the doping grade seems to benefit photo current without the same level of detriment to dark current. It is also observed that the trend in mobility is dependent upon the uncertainty in QE. If the actual QE is greater or equal to the measured value, mobility exhibits a negative trend with proton fluence. The undoped structure exhibits an increase in mobility if
the actual QE is less than the measured value. This analysis method therefore requires further investigation before any conclusions about mobility degradation can be drawn.

4.7.1 Differences in Quantum Efficiency Degradation Under Backside Illuminated Conditions

It is also important to evaluate the effects of proton irradiation on the QE of a backside illuminated configuration to gain insight towards how these detectors would fare in space when implemented into the traditional FPA. For this investigation, $F$ is set to 0.65, the absorption coefficient is set to $6,660 \text{ cm}^{-1}$, the mobility is held constant at $10 \text{ cm}^2/\text{Vs}$ for the uniform structures and $30 \text{ cm}^2/\text{Vs}$ for the graded structure and each structure exhibits identical lifetime damage factors as measured.
Figure 50. Inverse QE as a function of proton fluence for a topside illuminated geometry (solid lines) alongside a backside illumination (dashed lines). The green, blue, and red lines correspond to the measured lifetimes as functions of proton fluence for the graded, undoped, and doped structures, respectively. Green triangles, blue circles, and red squares depict the measured data of the graded, undoped, and doped structures, respectively.

Figure 50 demonstrates that each structure exhibits significantly higher QE damage factors when subjected to backside illumination as opposed to topside. It is calculated that the expected rate of $1/QE$ increase is $5.1 \times$ higher in the uniformly doped structure, $3.6 \times$ higher in the undoped structure and $3.0 \times$ greater in the graded structure. This indicates that the graded doping structure, with comparable pre-irradiation sensitivity to the uniformly doped structure, may be significantly more favorable for space-based applications, especially when implemented into a FPA under the backside illumination configuration. This conclusion, however, is drawn with the assumption that the graded doping structure exhibits a constant
mobility 3x that of the uniform structure. The physical evaluation of an InGaAs/InAsSb nBn under backside-illumination conditions will be the subject of future research.

4.8 Noise-Equivalent Irradiance

To evaluate the effect of proton irradiation on the sensitivity of the devices, NEI under low-light conditions, as given by Equation 17, is calculated at each proton fluence and shown in Figure 51.

![Figure 51. Shot-noise limited noise-equivalent irradiance as a function of proton fluence for each device at \( \lambda_{\text{peak}} = 3 \ \mu\text{m} \), 130 K and -200 mV. Blue circles, red squares and green triangles correspond to the undoped, uniformly doped, and graded structure respectively. The solid lines represent linear fits to the solid data points in which \( K_{\text{NEI}} \) is labeled in units of photons/H{\textsuperscript{+}}s.](image)

Notably, the graded structure exhibits smaller increase in NEI after proton irradiation compared to the uniform structures. Given the apparent linearity of NEI with proton fluence,
NEI damage factors are calculated using the best linear fit, as labeled in Figure 51. While a comparable pre-irradiation NEI is attained for the uniformly doped and graded structures, the NEI damage factor of the graded structure is lower than that of the uniformly doped structure, resulting in a significantly lower post-irradiation NEI. Future work will explore varying degrees of doping grades for further evaluation of its effects on device performance as well as its influence towards performance degradation due to proton irradiation.

4.9 Conclusions

Table 4. Lifetime damage factor \( (K_{1/\tau}) \), estimated equilibrium minority carrier concentration \( (p_0) \), change in dark current density after \( 6.1 \times 10^{11} \text{ H}^+ / \text{cm}^2 \) proton fluence \( (\Delta J_d) \), QE damage factor \( (K_{1/\eta}) \), and shot-noise limited NEI damage factor \( (K_{\text{NEI}}) \) for each structure under operating conditions -200 mV and 130 K. Best structure for each category is marked in bold.

<table>
<thead>
<tr>
<th>Absorber Doping Profile</th>
<th>( K_{1/\tau} ) ( [10^{-6} \text{ cm}^2/\text{H}^+\text{s}] )</th>
<th>( p_0 ) ( [10^{10} \text{ cm}^{-3}] )</th>
<th>( \Delta J_d ) ( [\mu\text{A/cm}^2] )</th>
<th>( K_{1/\eta} ) ( [10^{-12} \text{ cm}^2\text{photon/\text{H}^+\text{e}^-}] )</th>
<th>( K_{\text{NEI}} ) ( [\text{photon/\text{H}^+\text{s}}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undoped</td>
<td>4.4</td>
<td>11.2</td>
<td>2.95</td>
<td>1.16</td>
<td>0.14</td>
</tr>
<tr>
<td>Uniform</td>
<td>5.8</td>
<td>3.0</td>
<td>0.60</td>
<td>2.34</td>
<td>0.10</td>
</tr>
<tr>
<td>Graded</td>
<td>6.8</td>
<td>5.9</td>
<td>1.58</td>
<td>0.68</td>
<td>0.07</td>
</tr>
</tbody>
</table>

In conclusion, a study on the effects of 63 MeV proton irradiation on MWIR InGaAs/InAsSb \( nBn \) devices is performed. Dark current density and QE are measured at each proton fluence and NEI is calculated to compare performance degradation between structures. Measured values of minority carrier lifetime and majority carrier concentration from TRPL
and CV measurements are used in the analysis of dark current density and QE to evaluate proton-irradiation induced defect energy level, generation lifetime, and assess trends in mobility. Changes in the material parameters in the InGaAs/InAsSb T2SL reveal the underlying physics behind performance degradation, illuminating strategies towards further improvement. Reduction in the rate at which the dark current density increases with irradiation is found to be achievable through intentional doping of the absorber region, which reduces the equilibrium minority carrier concentration. QE degradation, attributed to changes in diffusion length, is found to be effectively lessened through a high effective mobility, and low lifetime damage factor. The graded doping structure, exhibiting moderate dark current density increase due to the intentional doping as well as low QE degradation due to its high effective mobility is found to have the smallest increase in shot-noise limited NEI after proton irradiation. Additionally, the graded structure is expected to exhibit significantly less performance degradation under the backside illumination configuration compared to the uniform structures. Therefore, a graded doping profile in the absorber region of the nBn device is determined to be an effective strategy towards the improvement of the resiliency of performance degradation due to high energy proton irradiation and thereby the most viable for space applications.
5. Conclusions and Future Work

The MWIR InGaAs/InAsSb nBn detector is demonstrated to be a promising candidate to satisfy the growing demand for a MWIR sensor for the space-industry. The combined manufacturability of this detector as well as its high operating temperature, owing to its effective implementation into an nBn structure, allow it to satisfy the low-cost, weight, and power requirements of a detector solution needed for effective implementation on space vehicles. Additionally, this detector is theoretically determined to exhibit enhanced sensitivity relative to the InAs/InAsSb nBn while requiring significantly smaller absorber lengths for its optimization, offering considerable motivation for its research and development.

To investigate this novel material and its performance when implemented into a MWIR nBn detector structure, three strain-balanced InGaAs/InAsSb nBn structures with bandgaps of 215 meV at 130 K are grown with unique absorber doping profiles to evaluate the effects of doping on detector performance. A minority carrier lifetime of 2.1 µs is achieved in the undoped structure at 130 K and evaluated to decrease with intentional doping due to the increase of the SRH recombination rate. The accurate determination of doping profiles within the absorber layer is achieved via the development of an analytical model of the CV profile of an nBn structure, to which the intrinsic majority electron concentration of the InGaAs/InAsSb material is evaluated to be $1.7 \times 10^{15}$ cm$^{-3}$. Further investigation of the CV measurements resulted in an estimation of absorber depletion width as a function of applied bias, which is used for the extraction of intrinsic defect energy level. This energy level is found to be near the intrinsic Fermi-energy in each structure, resulting in high levels of depletion dark current density. The validity of this defect energy level as well as other
extracted material parameters from characterization analysis is verified via the development of an Arrhenius model of the dark current density for each structure. Moreover, the extent of depletion within the absorber region is more accurately determined via the fitting of each structure’s Arrhenius plot, in which a more sizable depletion width is observed in the undoped structure compared to the doped structures at the operating bias. This allows for the determination that intentional doping of the absorber region of the MWIR InGaAs/InAsSb \( nBn \) reduces the total dark current density through reduction of the minority carrier concentration as well as effective suppression of the depletion region.

The relatively low minority carrier lifetime of the uniformly doped structure is found to significantly reduce its QE, while the graded structure achieves the highest measured QE of 57% despite its comparable minority carrier lifetime. The resulting NEI of each structure substantiates that the implementation of a graded doping profile is an effective strategy for the enhancement of sensitivity of diffusion-limited \( nBn \) detectors.

Following the successful demonstration of high sensitivity MWIR InGaAs/InAsSb \( nBn \) detectors, an assessment of the effects of radiation on performance degradation is performed. The detectors are irradiated with 63 MeV protons and characterized between doses to evaluate changes in material properties and detector performance. The CV model is utilized to assess a positive trend of majority carrier concentration with proton fluence, which is found to be small compared to its pre-irradiated values. Recombination rate is evaluated to increase at a comparable rate as the InAs/InAsSb material, which is attributed to a constant rate of defect introduction from its linear dependency on proton fluence. This is observed to drive an increase in dark current as well as a decrease in QE.
Further analysis of dark current density reveals that a mobility degradation is necessary to account for its behavior with proton fluence in each structure. Additionally, the dark current and CV is used to assess the defect energy with respect to the intrinsic Fermi level, which is observed to increase with proton fluence. The development of a defect introduction model is used for the fitting of the extracted defect energy level as a function of proton fluence, revealing a high energy proton-induced defect energy level existing roughly 30 meV from the intrinsic Fermi-energy. This defect is significantly less effective for the SRH generation process compared to the defect energies intrinsic to the material, such that the resulting increase in depletion current with proton irradiation is found to be less severe than anticipated. The overall change in dark current is found to trend with doping density to which it is evaluated that a reduction in the equilibrium minority carrier concentration is effective towards the reduction of dark current density increase with high energy proton irradiation.

An analysis of the fundamental QE equations and their relationship with recombination rate reveals that the QE damage factor is essentially dependent on the vertical hole mobility and the lifetime damage factor. This assertion is substantiated by the measured trends, which show that the graded doping structure exhibits the smallest QE damage factor, attributed to its effective mobility enhancement, whereas the uniformly doped structure exhibits the largest, attributed to its lifetime damage factor. Additionally, a high mobility is demonstrated to significantly reduce the rate at which QE degrades in a diffusion-limited $nBn$ when subjected to backside illumination conditions.

Finally, NEI as a function of proton fluence is assessed, which demonstrates the superiority of the graded doping profile strategy at reducing sensitivity degradation due to
high-energy proton irradiation. It is therefore demonstrated that the MWIR graded doping profile InGaAs/InAsSb $nBn$ is a highly promising candidate to satisfy the accelerating demand for a MWIR sensor component for space applications. Future work will investigate varying degrees of graded doping profiles for an assessment of further performance enhancement and its role in resiliency to performance degradation. Additionally, an evaluation of detector performance after hybridization to fanout chips for integration into an FPA is currently underway.
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