Investigation of the effects of harmful radiation on type-II strained layer superlattice focal plane arrays operated in the long wave infrared

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INVESTIGATION OF THE EFFECTS OF HARMFUL RADIATION
ON TYPE-II STRAINED LAYER SUPERLATTICE
FOCAL PLANE ARRAYS OPERATED IN THE LONG WAVE INFRARED
INVESTIGATION OF THE EFFECTS OF HARMFUL RADIATION
ON TYPE-II STRAINED LAYER SUPERLATTICE
FOCAL PLANE ARRAYS OPERATED IN THE LONG WAVE INFRARED

A Dissertation Presented to the Graduate Faculty of the
Dedman College
Southern Methodist University
in
Partial Fulfillment of the Requirements
for the degree of
Doctor of Philosophy
with a
Major in Electrical Engineering
by
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May 19, 2018
In-situ exposure of InAs/InAsSb strained layer superlattice focal plane arrays to gamma-rays revealed the possibility of a detector capable of imaging through a total ionizing dose event. Two long wave infrared focal plane arrays were exposed to a Co\textsuperscript{60} source at dose rates of 60 Rads/s and 70 Rads/s in incremental steps up to a total accumulated dose of 30 kRads. The first device showed no degradation in dark current density with accumulated dose while the second device tested showed a small increase up to 1 kRad and minimal increases with subsequent dose steps. The primary imaging defect in the focal plane arrays with exposure to high energy photons was the appearance of bright pixels. A correlation was made between the number and magnitude of ionization events seen in the material and detector bias. The silicon read-out integrated circuit used with the detector material tested in these experiments began to show significant deterioration near 30 kRads.

Two long wave infrared InAs/InAsSb strained layer superlattice focal plane arrays were subjected to several exposures from the fast burst reactor at White Sands Missile Range in NM, with a max fluence of 1 x 10\textsuperscript{12} neutrons/cm\textsuperscript{2}. The primary effect from a neutron event contributing to a degradation in image quality was an increase in the distribution of dark current density values, which blurs the features of an image. Standard deviation of dark current density measurements for the array increased by 6 x 10\textsuperscript{-5} A/cm\textsuperscript{2} which constitutes a 406 % increase in pixel-to-pixel variation. Following an accumulated fluence of 1.6 x 10\textsuperscript{12} neutrons/cm\textsuperscript{2} there was an absolute decrease in quantum efficiency of 2 % and an relative increase in noise equivalent differential temperature of 64 ± 225 %.

A single long wave infrared focal plane array was operated in a 200 MeV proton beam with dark current density measurements performed at incremental steps for a total accumulated
fluence of $2.5 \times 10^{11}$ protons/cm$^2$. The degradation seen in the focal plane array when exposed to protons confirmed the effects seen with gamma-rays and fast neutrons.
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Chapter 1

INTRODUCTION

Infrared (IR) focal plane arrays (FPA) have applications in which imaging capability in a radiation environment provides an advantage, such as nuclear power plant maintenance, high energy physics experiments, and targeting systems. Radiation environments are often hostile places for electronic components to reside and therefore it is important to know how devices will behave once they are exposed to such an environment. Type-II strained layer superlattice (T2SLS) devices have emerged in recent years as the main competitor to the mercury cadmium tellurium (MCT) material system for cooled IR detection. First proposed in 1984 in a journal entry by G. C. Osbourn [25], T2SLS material systems have been developed predominantly for applications in the mid-wave infrared (MWIR 3-5 $\mu$m), and the long wave infrared (LWIR 8-15 $\mu$m). The HgCdTe material system covers the entire IR spectrum from 0.8 $\mu$m to 30 $\mu$m and is the ideal material system for IR detection. However, the ionic nature of its chemical bonds makes the material brittle, which creates challenges in producing uniform large format arrays [2]. Because T2SLS devices are constructed from III-V semiconductor compounds as opposed to a II-VI compound they have advantages in several key areas such as; a larger manufacturing base, full-size wafers resulting in a higher yield at a reduced cost, a theoretically calculated longer Auger lifetime which predicates a lower dark current density and higher operating temperatures, and greater flexibility when designing for a particular operating wavelength. Whereas the absorption edge of MCT is controlled through the mercury to cadmium ratio, with T2SLS both the material composition and the thickness of the layers that make up the superlattice structure contribute to the absorption characteristics.

Other bulk materials that have bandgaps in the infrared spectrum are InSb and InAsSb. The direct bandgap relation of these alloys, along with MCT, coincides with strong absorp-
tion leading to high quantum efficiency [2]. The bandgap of InSb does not cover the LWIR and InAsSb has a maximum effective band edge of 9 \( \mu m \) leading to other solutions for LWIR photodetection utilizing a III-V material system [40]. Quantum well infrared photodetectors (QWIP) are produced from III-V alloys which gives them added control and reproducibility in the growth process resulting in consistent spatially uniform large format arrays [2]. Low conversion efficiency in QWIP devices due to an inability to absorb surface-normal incident radiation has prohibited them from becoming a viable solution [40].

The following study characterizes the effects from displacement damage and total-ionizing-dose in state-of-the-art LWIR T2SLS FPAs. Performance of IR FPAs is primarily determined by three parameters, quantum efficiency (QE), noise equivalent differential temperature (NEDT), and dark current density. QE is a measure of a detectors ability to convert radiant energy into electrical energy dependent on the minority carrier lifetime of the detector material. As trap sites are introduced in the detector material through displacement damage the minority carrier lifetime of the material will be reduced lowering the detectors QE. NEDT is a measure of a detectors sensitivity and determines the minimum resolvable temperature difference. NEDT measurements are a function of the detectors temporal noise and will increase with exposure to ionizing radiation and the addition of dislocations in a detector material. Dark current density is a measure of the amount of signal generated in the detector material in the absence of photo-generated minority carriers. It will determine the operating temperature of the detector and the background limited performance with larger F-number optics [42]. Displacement damage increases the amount of dark current generated through the Shockley-Read-Hall (SRH) effect and trap-assisted-tunneling (TAT) [34] [5]. Ionizing radiation will cause the dark current density to increase as oxides on the surface of the detector absorb charge and create surface leakage currents [43] [48]. Measurements of these parameters were performed prior to irradiation, directly following exposure to either gamma-rays, fast neutrons, or protons, and after an annealing period. Video was captured at 60 frames-per-second (fps) throughout each exposure utilizing custom hardware and software developed by the author for the purposes of this experiment. It was discovered that
although damage to the detector material did occur with exposure to all three radiation sources, the imaging capability of the FPAs tested was intact.
The principle goal in the design of a T2SLS IR detector is to create an indirect bandgap from materials whose bulk bandgaps lie outside of the infrared spectrum. The valence and conduction band edges of a T2SLS device can be set to a desired energy level by taking advantage of the effects of strain between alternating layers of material in a type-II bandgap alignment. Charge transport in a T2SLS device is achieved through quantum tunneling with the transport properties being decided by material composition and the thickness of the layers.

The alloys used in T2SLS systems to produce MWIR detectors are composed of elements whose compounds can be tailored to share a common lattice constant around 6.1 Å, such as; InAs, InSb, GaSb, InAsSb, GaInSb. To produce a bandgap in the LWIR and V LWIR requires a larger amount of strain in the layers of the superlattice [30]. Popular SLS material systems that can operate in both the MWIR and the LWIR are the binary-binary InAs/GaSb system, the binary-ternary InAs/InGaSb system, and the binary-ternary InAs/InAsSb system. Recently, InAs/InAsSb has become the favorite material system choice for the LWIR while InAs/InGaSb is predominantly used in the VLWIR and InAs/GaSb is almost exclusively used in the MWIR [1] [12] [30]. Use of the InAs/InAsSb material system in both the MWIR and LWIR is driven by high Shockley-Read-Hall (SRH) recombination rates believed to be caused by defect levels introduced during the growth process associated with gallium [6] [21]. The Ga-free binary-ternary InAs/InAsSb system has the advantage of having a higher minority carrier lifetime, high electron mobility, and reduced dark current in both the MWIR and the LWIR [23] [1] [7]. Minority carrier lifetime measurements performed on the InAs/InAsSb system and on the InAs/GaSb system of comparable bandgap energies, around 5 µm, found that carrier lifetime increased by two orders of magnitude for
the Ga-free material system [9]. The drawback of a Ga-free system is a lower absorption coefficient due to the thicker layers required for strain balancing. It has been predicted that the ternary-ternary InGaAs/InAsSb system could be both strain balanced and maintain its electrical properties while at the same time feature a higher absorption coefficient than the InAs/InAsSb system [24]. Quantum efficiency measurements performed on InAs/InAsSb devices in the LWIR have shown comparable results to those designed with InAs/GaSb [1].

Figure 2.1: III-V infrared alloys.

Type-II band alignment refers to a staggered or broken bandgap arrangement in which the conduction band of one of the materials is lower in energy than the valance band of the other (broken) or is just above the valence band (staggered). The different types of band alignments used for creating the absorbing regions, contact areas, and heterostructures associated with a type-II SLS IR device are shown in Figure 2.2. The common SLS material systems InAs/GaSb, InAs/InAsSb, and InAs/InGaSb that make up the absorbing region of a device, fall under both type-II broken gap and type-II staggered band offset. A disadvantage of the band alignment compared to bulk semiconductor materials is the spatial separation of electrons and holes into localized quantum wells affecting the absorption coefficient of the material [14]. An advantage to the confinement of electrons and holes into separate layers is that it has the effect of limiting Auger recombination mechanisms and enhancing carrier lifetimes [38].
T2SLS devices are grown on both GaSb or InSb substrates. They can be grown using either molecular beam epitaxy (MBE) or metalorganic chemical vapor deposition (MOCVD) [21]. When growing an SLS device it is important to maintain strain balance between alternating layers of material. This requires accurate models for predicting alloy compositions and layer thicknesses in order to achieve a high quality material with minimal dislocations [21]. Dislocations are defined as large defects in an ordered structure and are made up of many interstitial or vacancy sites within a crystal lattice. A single defect can create a trap site or non-uniform energy state. An ordered structure of defects can create an energy band, know as a miniband. Crystallographic defects, such as those formed when layers of semiconductor material are not exactly lattice matched, creates strain resulting in the formation of minibands. When SLS alloys are grown in an alternating fashion with a constant period and thickness the discrete energy states formed, as a result of the type-II band alignment and the strain present in the layers of the superlattice, can be tailored to produce a bandgap in the infrared.

The minibands of an SLS structure are defined by an overlap in the electron and hole wavefunctions of the material compounds [14] [40]. The magnitude of the wavefunction overlap between the layers of the superlattice determines the minority carrier lifetime of optical transitions. It is dependent on the molar fraction of antimony and the thickness of the alternating layers, with the period thickness being the dominant factor [55]. The
thicker the layers of the superlattice are the weaker the wavefunction overlap will be which results in strong carrier localization [55]. Carrier localization is an effect caused by the alignment of valence and conduction bands in a type-II arrangement that is used to describe the separation of electrons and holes [55]. For a superlattice composed of InAs/InAsSb the electron wavefunction has a maximum in the InAs layer while the hole wavefunction has a maximum in the InAsSb layer [55] [40] [26]. Carrier localization enhances minority carrier lifetime, which is usually beneficial to charge collection, but can also negatively effect carrier transport properties by raising the tunneling threshold in the layers of the superlattice [55]. Because the minority carrier lifetimes of the InAs/InAsSb and InAs/GaSb material systems are much longer than their scattering times vertical miniband transport becomes a favorable mechanism for removing optically generated electron-hole pairs [17].

The magnitude of the wavefunction overlap along with determining minority carrier lifetime also determines the absorption coefficient of the structure. An increase in the wavefunction overlap can be thought of as a widening of the allowed energy states within the miniband which corresponds to an increase in the absorption coefficient [1] [41] [26] [22]. Considering the InAs/InAsSb material system, an increase in strain will have the effect of lowering the conduction band in the InAs layers and a raising of the heavy hole valence band in the InAsSb layers leading to the absorption edge being extended [14] [26]. Increased strain in the InAs/InAsSb system, for a constant period thickness, is achieved through a larger percentage of antimony which reduces the wavefunction overlap and brings down the materials absorption coefficient [25] [41]. The decrease in absorption coefficient for an increasing cutoff wavelength can be attributed to a reduction in the density of states [16]. Decreasing the bandgap of an SL system to the VLWIR region requires increasing the period of the SL layers and increasing the percentage of antimony to maintain a favorable strain balance. As the period thickness is increased and the wavefunction overlap is reduced, the ground state transition energy is affected extending the absorption edge [41].

The cutoff wavelength of the InAs/GaSb material system can be lengthened by increasing the thickness of the InAs layer and holding the GaSb layer thickness constant [16]. The cutoff
wavelength of the InAs/InAsSb material system can be extended by increasing the thickness of both the InAs layers and the InAsSb layers while maintaining a constant ratio between them [16]. In both cases a shrinking of the bandgap increases carrier localization which has the effect of reducing the diffusion length of minority carriers leading to shorter absorbers and lower conversion efficiency. For all wavelengths the InAs/GaSb material system has an advantage over the InAs/InAsSb material system in the magnitude of its absorption coefficient, due to thinner layers and an increased wavefunction overlap.

Varying the layer thicknesses of the superlattice requires that the strain experienced at the interface between subsequent layers is balanced. Strain balancing is achieved through the molar fraction of antimony which has the opposite effect on the wavefunction overlap as adjusting the layer thickness [1] [41]. Figure 2.3, provided by QmagiQ, LLC, depicts a plot of a T2SLS band edge diagram and its resulting wavefunction. Plots such as those in Figure 2.3 are produced through complex software algorithms for the simulation and design of T2SLS structures. Methods for estimating band structures of T2SLS are based on the envelope-function approximation Hamiltonian model which takes into account coupling between electrons, light holes, and spin-orbit split-off holes [22] [26] [21].

The strain experienced by the layers of a superlattice structure alternates between tensile and compressive and has the effect of splitting the valence band into light and heavy hole components [25] [14]. The biggest difference between the energy band diagram of a superlattice structure and a typical bulk semiconductor is the splitting of the highest heavy hole (HH1) and the highest light hole (LH1) bands at the Brillouin zone center [19]. In this configuration the electron effective mass is determined by the conduction band to light hole bandgap while the infrared absorption edge is determined by the conduction band to heavy hole bandgap [14] [19]. The degree of valence band splitting is dependent on the amount of strain experienced by the layers of the superlattice structure. Separation of the HH1 and LH1 bands with increased strain results in a longer Auger recombination lifetime, improved detectivity, and a higher operating temperature [30].
Another important feature of the band diagrams for InAs/GaSb and InAs/InAsSb type-II SLS material systems is the anisotropy of the valence band, which is to say that the valence band energy level is dependent on direction [19] [8] [18]. As a result, holes have a greater mobility in the plane vectors than in the growth direction which leads to poor electrical transport properties for an n-type absorber [18]. For this reason, most absorbers are doped p-type to take advantage of the near isotropic conduction band which has a slightly lower band edge effective mass in the growth direction than in the plane direction [19] [17]. The larger electron effective mass is favorable for reducing band-to-band tunneling as well as trap-assisted-tunneling (TAT) thereby limiting diffusion dark current and at the same time not being so large that carrier mobility is significantly affected [14] [38] [19].

However, it has recently been reported by Ting, Soibel, and Gunapala, that hole mobility in the growth direction has been grossly underestimated [16]. The authors site a journal entry, Ref. [1], in which it was reported that an nBn device with a cutoff wavelength of 10 μm demonstrated 54 % QE. In their 2016 paper entitled, *Hole effective masses and subband splitting in type-II superlattice infrared detectors*, Ting, Soibel, and Gunapala attempt to
explain the high QE associated with n-type absorbers operating in the LWIR fabricated from the InAs/InAsSb material system, as a product of a small hole conductivity effective mass. They propose that the conductivity effective mass is a better candidate for describing hole mobility in type-II SLS devices than is the band edge hole effective mass which is typically used. They also postulate that devices with n-type absorbers in the LWIR exhibiting large hole subband splitting will benefit from suppressed inter-subband scattering due to a smaller hole conductivity effective mass and a mitigated momentum relaxation time.

In summary, the bandgap of the material system is dependent on both the percentage of antimony and the period of the layers in the superlattice. Increasing the percentage of antimony causes an increase in strain which results in a greater splitting of the light hole and heavy hole valance bands while at the same time driving down the conduction band energy level. The wave function overlap, which determines the absorption coefficient, can be increased by decreasing the period thickness of the superlattice. To achieve the minimum thickness in the layers of the superlattice in order to maximize the absorption coefficient requires adding large amounts of antimony to strain balance the system. This has the adverse effect of increasing carrier confinement. The more lattice matched the layers of the superlattice are the less strain there will be at the interface between layers resulting in an increased wavefunction overlap. In order to keep the system in strain balance at a constant operating wavelength the period thickness cannot be adjusted without also adjusting the antimony percentage. The optimization variable for a given absorption edge then becomes the minority carrier lifetime which varies inversely with wavefunction overlap.
Chapter 3

UNIPOLAR BARRIERS

The ability to adjust the positions of the conduction band and valence band edges of type-II material systems give them a distinct advantage over bulk infrared materials in the variety of heterostructures that can be implemented. The fundamental heterostructure used with type-II SLS devices is the unipolar barrier which has the ability to reduce the charge collected from dark current mechanisms. Unipolar barriers are designed to allow the unimpeded movement of one type of charge carrier while blocking the other. This constitutes having a zero-band offset in either the valence band (electron barrier) or in the conduction band (hole barrier) and a significant offset in the alternative energy band.

The simplest T2SLS device structure that incorporates a unipolar barrier is the nBn configuration which uses an n-type contact layer on one side of a barrier and an n-type absorbing region on the other, depicted in Figure 3.1. The barrier separating the two n-type regions is known as an electron barrier as it is meant to block majority carrier electrons from diffusing from the n-type contact into the absorbing region while allowing minority carrier holes an unobstructed path from the absorbing region to the contact layer [38] [12]. III-V semiconductor compounds generally have large dark currents associated with depletion regions formed under bias [15]. The unipolar barrier is used to reduce the electric field in the small bandgap absorbing region by requiring a significant drop across a wide bandgap barrier region. This leads to a minimal depletion region in the absorbing layers eliminating generation-recombination depletion dark currents and reducing SRH and TAT currents [38]. A useful consequence of the unipolar barrier is that the strong electric field at the barrier helps to collect photogenerated carriers from the absorbing region before they can recombine [38].

When creating electron and hole barriers it is important that the lattice mismatch between neighboring regions be less than 0.1% to avoid strain induced defect states [23]. If
the layers of an SLS structure are not in strain balance at the interface between a contact layer and barrier or between a barrier and absorber region the effectiveness of the device structure will be compromised. This is avoided by the flexibility of III-V SLS material systems where the conduction band and valence band offsets can be adjusted by varying layer thickness and composition. Barriers have also been realized in bulk material compounds however band edges can only be varied through changes in composition limiting the number of unique solutions available [38].

A variety of heterostructure combinations can be constructed with the III-V family of infrared alloys (AlAs, InAs, InAsSb, GaAs, GaSb, GaInSb, AlGaInSb, AlSb, InSb) due to the fortunate coincidence that they can be lattice matched around 6.1 Å. Figure 2.1 depicts the bandgap energies of the different binary and ternary III-V infrared material compounds with respect to their lattice constants. A proven device design that incorporates both a hole barrier and an electron barrier is the Complementary Barrier Infrared Detector (CBIRD) [38] [19] [18]. The structure consists of a p-type absorber region between both
a hole barrier and an electron barrier. The barriers are designed to have zero conduction and valence band offsets with respect to the absorber. By carefully engineering the electron barrier to be slightly n-type and the hole barrier to be slightly p-type the CBIRD design enables the majority of the applied electric field to be dissipated in the barrier layers. This leads to a weak electric field in the absorption region and the result is a reduction in SRH and TAT dark current mechanisms approaching the "Rule 07" [38] [19].

The "Rule 07" was developed in 2007 by Teledyne imaging sensors as a way of comparing dark current density versus cutoff wavelength for state-of-the-art photovoltaic MCT detectors [15] [2]. The common empirical fit of the collected data is expressed as, 

\[ J = J_0 \exp \left( \frac{C}{\lambda kT} \right) \]

where \( J_0 = 8367.00019 \text{A/cm}^2 \), and \( C = -1.162972237 \) [15]. The "Rule 07" has since served as a convenient measuring tool for indicating the progress of the type-II SLS technology.

The advantages of heterostructures such as those employed in the CBIRD design have a significant effect on the operating temperature of a device. For cooled IR detectors the dark current associated with background radiation known as background-limited infrared photodetection (BLIP) will set the maximum operating temperature of the device. Thermally generated carriers in the active region of a detector with energies close to the bandgap, known as generation-recombination current, are suppressed by cooling of the detector material. The temperature at which the dark current component of the total current becomes smaller than the measured photocurrent is when the device is operating at BLIP conditions [45]. The generation-recombination current for a typical pn-junction diode varies with operating temperature, \( T \), as \([\text{const. } T^{-3/2}] \exp(-E_{g0}/2kT)\), where \( E_{g0} \) is the bandgap energy of the diode at absolute zero. SLS detectors that implement electron and hole barrier layers suppress dark current contributions that are dependent on temperature and support the goal of warmer operating temperature devices [38].

There have been a number of heterostructure designs tested with varying success that take advantage of the properties associated with type-I, type-II broken, and type-II staggered band alignments. Different heterostructure configurations allow for increased wavefunction overlap, increased absorption, reduction in dark currents, and greater control for modifying
conduction and valence band energy levels [38]. With the numerous heterostructures that can be implemented as absorbers, electron barriers, and hole barriers there are expectations that a novel device configuration can solve the high dark current and short minority carrier lifetimes that plague T2SLS devices. Advancements in the types of unipolar barriers incorporated with type-II SLS devices has been the primary reason for alternative technologies to HgCdTe becoming competitive in the MWIR and LWIR markets.
Chapter 4
DARK CURRENT MECHANISMS

Dark current in photoconductive devices takes on three primary forms which include; generation-recombination currents associated with the SRH process, radiative recombination, and Auger generation-recombination currents. The different mechanisms are depicted in Figure 4.1. Studies performed on dark current density mechanisms for the InAs/InAsSb material system concluded that the dominant generation-recombination mechanism was highly sensitive to the active region thickness and carrier concentration [33].

![Figure 4.1: Generation-recombination mechanisms.](image)

4.1. Shockley-Read-Hall

The SRH effect describes the process by which a defect site in the crystal lattice creates a trap site or energy level that can be used as a stepping stone to facilitate the promotion of electrons from the valence band to the conduction band (generation) or vice-versa (recombination). It is commonly believed that dark currents due to SRH generation and short minority carrier lifetimes due SRH recombination, in the InAs/GaSb material system are a result of Ga-mediated defect states generated during SL growth [40] [23]. This limitation has led to short absorber regions resulting in low QE. The SRH lifetimes reported for
InAs/InAsSb are significantly longer [13]. The expression for SRH lifetimes in both material systems can be written as follows.

\[
\tau_{SRH} = \frac{\tau_{p0}(n + n_1) + \tau_{n0}(p + p_1)}{n_0 + p_0 + \Delta n}
\] (4.1)

Where \(\tau_{p0}\) and \(\tau_{n0}\) are the defect capture time constants for electrons and holes which represent the average time for a defect site to capture an electron or hole. The capture time constants can be written as, \(\tau_{p0} = (N_t \sigma_p v_p)^{-1}\) and \(\tau_{n0} = (N_t \sigma_n v_n)^{-1}\), where \(N_t\) represents the defect concentration, \(\sigma_n\) and \(\sigma_p\) are the cross sectional areas, and \(v_n\) and \(v_p\) are the thermal velocities of electrons and holes respectively. The concentrations \(n_1\) and \(p_1\) represent the carrier densities occupying the energy state \(E_t\) and are expressed as, \(n_1 = N_c \exp\left[\frac{E_t - E_c}{k_B T}\right]\), and \(p_1 = N_v \exp\left[\frac{E_v - E_t}{k_B T}\right]\), where \(E_t\) is the SRH defect energy level [53]. A defect energy level near a band edge will be less effective than a defect energy level at the mid gap energy level and have a longer capture time constant [53]. In an entry in Physical Review Applied in 2016 by Y. Aytac it was proposed that for a known defect energy the valence and conduction band edges of the absorber could be tailored in order to shift the defect site closer to one band or the other [53] [7]. Assuming that the defect site is not dependent on the valence or conduction band energy levels the dominant defect capture time \((\tau_{p0}, \tau_{n0})\) could then be controlled. Shifting the defect site either towards the conduction band or towards the valence band would limit its effectiveness to trap minority charge carriers in the opposite band resulting in a longer SRH time constants [53].

Defect energy levels are identified through temperature dependent minority carrier lifetime measurements. Assuming that \(E_t\) and by extension \(\sigma N_t\) are temperature independent by fitting the resulting minority carrier lifetimes to lifetime models in the low injection regime the SRH defect energy can be determined from the minority carrier lifetimes dependence on temperature. In Aytac’s paper entitled “Evidence of Shockley-Read-Hall Defect State Independent of Band-Edge Energy in InAs/InAsSb Type-II Superlattices” it was reported that the SRH recombination centers position in InAs/InAsSb is independent of the band edges allowing for the possibility of eliminating its impact as a dominant recombination mechanism.
in the low injection regime [53]. It is shown through temperature dependent measurements of minority carrier lifetime performed on samples with varying antimony concentrations that the SRH process is the limiting recombination mechanism at low temperatures below 175 K [52] [7].

Another method of limiting the dark current density and extending the minority carrier lifetime of an SLS device by reducing the impact of the SRH effect is by constraining the thickness of the absorbing region. It is predicted that the number of trap sites in a superlattice structure is directly dependent on the total volume of the absorbing layers [52]. As previously discussed reducing layer thickness can be achieved by raising the percentage of antimony in the hole confinement layer. This method of reducing the effect of SRH trap sites has the adverse effect of shifting the band edges of the structure.

4.2. Radiative

Radiative recombination is the reverse process of absorption by which an EHP recombining through either direct or indirect means releases energy in the form of a photon or phonon respectively. The radiative recombination lifetime of a semiconductor device can be shown to be proportional to the occupied states in the conduction and valence bands.

\[
\tau_{\text{Radiative}} = \frac{\phi}{(B_r(n_0 + p_0 + \Delta n))} \quad (4.2)
\]

The variable \(\phi\) is known as the photon recycling factor and represents the fraction of photons emitted from radiative recombination that are reabsorbed enhancing the radiative lifetime [52]. The constant \(B_r\) is a material parameter that represents the ability to release energy in the form of photons during of EHP recombination known as the radiative coefficient [52].

4.3. Auger
A third recombination mechanism that effects the minority carrier lifetime of optically generated EHPs is Auger generation-recombination, of which the Auger-1 and Auger-7 processes are of primary interest. Auger-1 is an electron dominated process in which excess energy from an electron recombining with a hole promotes a second electron to higher lying state within the conduction band. Auger-7 is a hole dominated process in which excess energy from an electron recombining with a hole promotes a second hole to a higher energy state within the valance band. Auger recombination rates are highly sensitive to carrier densities in the high-injection regime [51]. However, with type-II SLS devices in the [1, 0, 0] growth orientation, because the separation in energy levels between the LH1 and HH1 bands is greater than the separation between the conduction and HH1 bands Auger-7 events can be suppressed resulting in a long Auger lifetime [19]. The degree of Auger suppression is controlled by the splitting of the LH1 and HH1 bands which is dependent on the amount of strain in the layers of the superlattice structure [7]. Higher percentages of antimony increase the splitting of the LH1 and HH1 valence bands which acts to further suppress tunneling and Auger-7 processes [16]. The suppression of Auger-7 events along with a higher electron mobility provides incentive to use a p-type absorber as there will be less chance of Auger-1 events occurring. The Auger lifetime can be expressed as follows.

$$\tau_{\text{Auger}} = C_n \cdot n(n_0 + p_0 + \Delta n) + C_p \cdot p(n_0 + p_0 + \Delta p)$$  (4.3)

$C_n$ and $C_p$ are the Auger coefficients corresponding to the Auger-1 and Auger-7 processes respectively. For a n-type absorber Auger-1 events will dominate and $C_p \rightarrow 0$ [7]. Auger recombination mechanisms are primarily a thermal effect which scale quadratically with carrier density dominating SRH mechanisms in the high injection regime and at high temperatures [7] [52]. Auger coefficients as a general rule are exponentially increasing with decreasing bandgap energy [50]. It has been previously reported for several InAs/InAsSb devices utilizing n-type absorbers that at temperatures below 150 K the Auger coefficients over a range of bandgap energies from the MWIR to the LWIR were found to be smaller than traditional values reported for HgCdTe Auger coefficients [50]. However, for temper-
atures greater than 150 K and bandgap energies less than 200 meV the Auger coefficients were greater than those of HgCdTe devices suggesting the benefits of a larger carrier lifetime associated with an n-type absorber region are outweighed by a shorter Auger coefficient [50].
Chapter 5
CHARACTERIZATION OF IR FPAs

Infrared (IR) focal plane arrays (FPAs) have several qualities that can be quantified to examine the detectors performance as an imaging sensor. These include; noise equivalent differential temperature (NEDT), quantum efficiency (QE), dark current density ($J_d$), activation energy ($E_a$), and minority carrier lifetime ($\tau_{mc}$). QE is a measure of a detectors ability to convert radiant energy into electrical energy. NEDT provides an evaluation of an IR detectors sensitivity and determines the minimum detectable difference in temperature. Dark current density is a measure of the amount of signal generated in the detector material in the absence of photo-generated minority carriers. Activation energy represents the bandgap energy and cutoff wavelength of the photodiode. Minority carrier lifetime is the time an optically generated electron-hole pair exists before recombining and sets the upper limits of a detectors performance. The following sections describe a typical laboratory setup for the characterization of IR FPAs and illustrates the correct methods for measuring these qualification factors. Experimental data is provided for NEDT, QE, $J_d$, and $E_a$ measurements using an InAs/InAsSb type-II strained layer superlattices detector operating in the long wavelength infrared (LWIR) with a 12 $\mu$m cutoff. The device used in following sections was designed and manufactured by QmagiQ, LLC and designated FPA QF6-HLW12-35 to distinguish it from other FPAs used in subsequent chapters.

5.1. Cryogenic Cooling of FPAs

Due to the small bandgap of infrared detectors it is necessary that they be cooled to prevent thermally generated carriers from filling the conduction and valence bands. There are a number of different cooling methods employed for IR semiconductor detectors, including; liquid nitrogen (LN2), liquid hydrogen, thermoelectric, and Sterling cryocoolers. For
laboratory testing of IR FPAs LN2 is the most popular choice as it is cheap and available in most laboratory settings. To prevent the LN2 from evaporating it must be insulated from air using a vacuum as close to zero atmosphere as possible. A dewar is a double walled vessel for containing the LN2 with a vacuum between the walls reducing its thermal conductivity. Laboratory dewars are typically constructed using aluminum with the size of the dewar and the vacuum achieved determining the holding time of the liquid. With a vacuum near 10 millitorr a LN2 pour filled dewar is capable of holding at a temperature of 77 K for several hours. When using liquid hydrogen, which has to be cooled to 20 K, a vacuum around 1 millitorr is necessary to achieve an adequate holding time.

Photodiode arrays are grown using molecular beam epitaxy (MBE) or metal organic chemical vapour deposition (MOCVD) and are then flip-chip bonded to silicon ROICs using an indium bump bonding technique. Leadless chip carriers (LCC) are used to hold the hybridized FPAs and provide a contact surface for cooling the detector material to cryogenic temperatures. The LCC is made from a high thermal conductive material such as aluminum nitride with connections to the ROIC being made up of gold wire bonds. The LCC is mounted to a cold finger inside a thermally insulated dewar with electrical connections routed to the outside using coaxial cable and hermetic feedthroughs. A cold shield at the same temperature as the detector sits above the FPA inside of the dewar to restrict its field-of-view and prevent exposure of the FPA to background radiation. In the LWIR range, room temperature background radiation is centered around 10 microns. The dewar is hermetically sealed with an IR window such as germanium or zinc selenide through which the FPA detects incoming radiation. Often it will be necessary to cool the detector material to a temperature above LN2 temperatures when analyzing the generation-recombination mechanisms at work in the material. For these applications a resistive heater element is placed in the dewar behind the LCC and in front of the cold finger. A PID temperature controller and resistive temperature detector (RTD) or diode sensor is used to control the exact temperature of the device.
Figure 5.1: Hybridized focal plane array wirebonded to leadless chip carrier.

For systems used in field applications active coolers are required which contain reciprocating pistons for compressing and expanding a fluid such as helium. The moving parts in an active system are of considerable concern as they can cause vibrations that can be picked up by the detector disrupting the image. Active systems often contain vibration suppression systems increasing their size and cost as well as power output. Operating a device at a higher temperature helps to reduce much of the power requirements of an active system but the trade-off is higher dark currents in the detector material.

5.2. Experimental Setup

In order to capture in-situ data the ROIC needed to be able to be operated remotely from a control room. Custom electronics were designed in two stages with shielded twisted pair cabling separating them. The first stage electronics are connected to the back of the LN2 pour filled dewar through two DB-25 connectors. They contain an analog-to-digital-converter (ADC) for digitizing the pixel data, a digital-to-analog-converter (DAC) component for ad-
justing the detector bias, a second ADC for reading the detector temperature, low-voltage-differential-signaling (LVDS) receivers and transmitters, and the various voltage regulators required to power the ROIC and circuit components. The second stage electronics consist of a field-programmable-gate-array (FPGA), LVDS receivers and transmitters, double-data-rate (DDR3) memory, phase-locked-loop (PLL) integrated-circuit (IC), universal-serial-bus (USB) 3.0 IC, and the various voltage regulators for supplying power to the second stage components. The FPGA controls all of the signal timing for the ROIC as well as data collection and forwarding to the USB 3.0 IC which then transmits packets of data to a host machine. Frames are assembled and stored on a hard drive by a custom software application running on a PC in the control room of the radiation facility. User commands from the custom software application apply various settings to the read-out electronics and are transmitted to the FPGA over the USB 3.0 interface. QE, NEDT, dark current density, and activation energy measurements are performed as automated processes. The application software, FPGA firmware, and USB 3.0 firmware, was written by the author for the purposes of this experiment. CMOS electronics are intrinsically rad-tolerant up to $1 \times 10^{14}$ neutrons/cm$^2$ and throughout the tests conducted there were no abnormalities seen in the operation of the first stage electronics in the radiation chamber. A depiction of the test electronics and the dewar where the FPA is housed can be seen in Figure 5.2.

5.3. Noise Equivalent Differential Temperature

NEDT is a measure of a detectors sensitivity, given as the minimum temperature difference for which a detectors signal to noise ratio is equal to one under uniform illumination conditions measured in milli-kelvin. The NEDT of an array of pixels is found by measuring the temporal noise of the individual pixels in the array at a specific scene temperature and then dividing by the signal transfer function (SiTF) of the pixel, Equation 5.1. This involves taking the standard deviation in each pixel over 25 sequential frames. Measurements of NEDT are independent of scene temperature and weakly dependent on operating temperature.
The SiTF of an IR photodetector is a measure of its responsivity. The measurement requires stepping a blackbody source through multiple temperatures and plotting the recorded voltage versus temperature at each step, where the slope of the plotted line is equal to the SiTF given in mV/K, Equation 5.2. Generally the average of 25 sequential frames are used at each point to reduce the temporal noise of the pixels by a factor of 5. An example of the SiTF for FPA QF6-HLW12-35 can be seen in Figure 5.3, plotting the median signal of the FPA versus the temperature of the blackbody source. A measurement of an IR detector’s SiTF also provides information pertaining to the detector’s gain, linearity, dynamic range and saturation level.

\[ SiTF = \frac{dV_{out}}{dT_s} \ [mV/K] \]  

\[ NEDT = \frac{\sigma}{SiTF} \ [mK] \]  

Figure 5.2: Test setup.
Figure 5.3: Measured signal in millivolts versus temperature the slope of which is equal to the detectors signal transfer function.

The NEDT of a IR detector is heavily dependent on the f-number ($F/\#$) of the cold shield used with the device. The cold shield is a low emissivity baffle that is kept at the same temperature as the device under test (DUT) and is responsible for keeping stray radiation out of the detector. The $F/\#$ of a cold shield is the ratio of the focal length to the diameter of the entrance pupil. It determines how much radiation will reach the FPA, with smaller $F/\#$'s producing darker images. The measured value of NEDT will increase with an increasing $F/\#$ for a constant scene temperature. A typical $F/\#$ for a LWIR sensor is between $F/2$ and $F/4$. An $F/2.3$ cold shield was used with the devices characterized in this paper.

Uniformity of the scene being imaged by the detector with time has an effect on the standard deviation of the recovered signal and is therefore crucial to the measurements success. A uniform field is achieved through the use of a calibrated blackbody source controlled using a proportional integral differential (PID) control loop set to a desired temperature. The sensor is positioned approximately 2.5 inches from the blackbody source. It is important that the window through which the detector views the field remains at a constant ambient
temperature and is not affected by the blackbody source. Blackbody sources and controllers designed for the testing of IR cameras can demonstrate a uniformity of ±0.01 °C across the aperture with a absolute temperature accuracy of ±0.005 °C between 0 °C and 50 °C [31].

When obtaining data from a pixel array there may be defective or unresponsive pixels and it is important that they are excluded from the measurement statistics. To determine which pixels should be omitted frames are recorded at two different scene temperatures, typically 20 °C and 40 °C. The frame recorded at 20 °C is subtracted from the frame at 40 °C and a histogram of the array is generated from the resulting pixel data. Pixels that fall above or below boundary conditions for minimum and maximum response are removed from the data by creating a pixel map containing ones and zeros signifying “bad pixels” and “good pixels”. A non-uniformity-correction (NUC) can also be used to eliminate unresponsive pixels from the array. NUC consists of two images with gain and offset information for each pixel that when combined with actual image data of a flat field, eliminates any non-uniformity in the image. A NUC also implies identifying any “bad pixels”, averaging the response of their surrounding pixels, and replacing the unresponsive pixel with the average.

A plot of the median value of NEDT versus bias for FPA QF6-HLW12-35 is pictured below in Figure 5.4. It was generated by taking 25 frames at scene temperatures of 20 °C, 30 °C, and 40 °C. The standard deviation of each pixel in the array minus the “bad pixels” for the 25 frames at a scene temperature of 30 °C is divided by the SiTF found in each pixel between 40 °C and 20 °C. The median value of all the pixels in the array is then taken to be the NEDT in mK at each operating bias. At the optimal bias for this particular FPA there is a measured NEDT of 25 ± 4 mK.

5.4. Quantum Efficiency

QE is a measure of a detector’s ability to convert radiant energy into electrical energy dependent on the minority carrier lifetime and diffusion length of the material. The QE of a detector can be found by dividing the number of electrons generated in the FPA per unit time by the number of photons incident on the detector per unit time, Equation 5.3.
Figure 5.4: Noise equivalent differential temperature versus bias at an operating temperature of 78 kelvin.

\[ QE = \frac{dN_{el}/dt}{dN_{ph}/dt} \cdot 100 \% \]  \hspace{1cm} (5.3)

The radiant exitance or the radiant flux per unit area emitted by a hot blackbody source is given by the Stefan-Boltzmann law which states that the power emitted by the surface is directly proportional to the fourth power of its absolute temperature, Equation 5.4.

\[ M_e = \epsilon \sigma T^4 \]  \hspace{1cm} [W/cm^2] \hspace{1cm} (5.4)

Where \( \epsilon \) is the emissivity of the blackbody surface, and \( \sigma \) is the Stefan-Boltzmann constant (5.2 \( \cdot \) 10\(^{-12}\) \( W/cm^2/K^4\)). The Stefan-Boltzmann law can be derived from Planck’s law, Equation 5.5, of blackbody radiation by integrating over all wavelengths at a given temperature. Planck’ law describes the spectral radiance given off by a blackbody at an absolute temperature, \( T \), expressed in units of watts per steradian per nanometer.
\[ P(\lambda, T_s) = \frac{2hc^2}{\lambda^5 \left[ e^{hc/\lambda kT_s} - 1 \right]} \cdot 10^{-10} \quad [W/cm^2/\mu m/Sr] \quad (5.5) \]

Figure 5.5: Photon flux versus temperature of a blackbody source (2\(\mu\)m – 12.3\(\mu\)m).

Where \(h\) is equal to Planck’s constant \((6.63 \cdot 10^{-34} \text{ J} \cdot \text{s})\), \(c\) is the speed of light, \(\lambda\) is the wavelength of light, and \(k\) is Boltzmann’s constant \((1.38 \cdot 10^{-23} \text{ J/K})\). The rate at which photons interact with the surface of a detector placed a distance \(L\) from a blackbody source with area \(A_s\) is given by Equation, 5.6.

\[ \frac{dN_{ph}(\lambda, T_s)}{dt} = \tau_{tr} \epsilon \cdot \int_{\lambda_0}^{\lambda_{co}} \frac{P(\lambda, T_s) A_s A_{pix}}{hc/\lambda} \cdot \frac{d\lambda}{L^2} \quad [\text{ph/s}] \quad (5.6) \]

Where \(\lambda_0\) is the lower limit of integration equal to 2 \(\mu\)m, \(\lambda_{co}\) is the cutoff wavelength of the detector which is approximated as 12.3 \(\mu\)m, and \(A_{pix}\) is the area of a single pixel within the FPA. The above equation for radiant flux can be solved for by numerical approximation using a method such as the trapezoid rule, \(\int_a^b f(x)dx \approx \frac{b-a}{N} \sum_{j=1}^{N} \frac{f(x_{j+1})+f(x_j)}{2}\). This result is depicted in Figure 5.5 for scene temperatures between 20 \(^\circ\)C and 100 \(^\circ\)C.
The number of electrons generated in the detector per second, or the electron flux, is given as the measured photocurrent divided by the charge of an electron \((1.602 \cdot 10^{-19} \, C)\), written as Equation 5.7. Where, \(C_{int}\) is the size of the integration capacitor, from the ROIC data sheet, equal to approximately 0.94235 \(pF\) and \(\tau_{int}\) is the integration time. Multiplying the signal accumulated in millivolts by the total capacitance results in a value for the amount of charge collected, in Coulombs, which when divided by the time it took to amass is equal to the measured current.

\[
\frac{dN_{el}}{dt} = \frac{i_{photo}}{e}
\]

In order to recover the photo-current component from the measured total current the array is sampled at two different scene temperatures with a constant integration time. Subtracting one frame from the other removes the dark current component and any fixed pattern or baseline offset introduced by the ROIC. The electron flux as a function of bias captured by the FPA used in this experiment is visible in Figure 5.6. Scene temperatures of 20 °C
and 40 °C were used at an integration time that results in an 80% full well capacity when viewing the 40 °C scene temperature.

The QE of the detector depends in large part on the minority carrier lifetime being long and the carrier mobility high, so that optically generated electron-hole pairs can be collected before they recombine. The median QE of the FPA as a function of detector bias is shown in Figure 5.7. At the optimal operating bias of FPA QF6-HLW12-38 the QE was measured to be 15.7 ± 0.7 %.

5.5. Dark Current Density

Dark current density is a measure of the amount of signal generated in the detector material in the absence of photo-generated minority carriers. It will determine the operating temperature of the detector and the BLIP performance with larger F-number optics [42].
Dark current density measurements are performed by placing a cold stop at the same temperature as the detector material in front of the FPA. By doing so photo-current is eliminated allowing for the observation of solely dark current. Ideally, the amount of charge generated per second in each pixel would exclude any fixed pattern noise and baseline offsets generated by the ROIC. This is accomplished by sampling the pixel array at two different integration times, up to several hundred micro-seconds apart, dependent on the operating temperature of the FPA. Subtracting the two frames and dividing by the difference in the integration time of the frames results in a value which represents the signal accumulated in the detector material per-second, minus fixed pattern noise and an offset supplied by the ROIC. This value can be converted to volts per second and then multiplied by the integration capacitance and divided by the pixel area to get a value for the dark current density of the pixel in A/cm², Equation 5.8. The array will have a distribution of dark current density values closely grouped together. It is common practice to take the median value of the array when plotting dark current density as a function of bias.

\[
J_{\text{dark}} = \frac{V_{\text{out}}(\tau_{2\text{int}}) - V_{\text{out}}(\tau_{1\text{int}})}{\tau_{2\text{int}} - \tau_{1\text{int}}} \cdot \frac{C_{\text{int}}}{A_{\text{pix}}} \quad [A/cm^2]
\] (5.8)
An important quality of infrared detectors is how dark current density changes with bias and temperature. This will often determine the ideal operating conditions of detector. Constant dark current density with increasing bias is a sign that the detector is diffusion limited. Increasing dark current density with bias implies a portion of the total dark current is supplied by generation-recombination associated with the SRH effect. When dark current density measurements are independent of device operating temperature the dominant mechanism affecting dark current is from TAT. By performing the above mentioned steps at multiple values of detector bias a plot such as the one in Figure 5.8 can be created which shows dark current density versus bias as a function of operating temperature.

5.6. Activation Energy

From the data recorded in Figure 5.8 an Arrhenius plot can be created from which the activation energy of detector material can be recovered. Arrhenius plots are used to display the logarithm of a kinetic constant versus the inverse of temperature. The Arrhenius equation can be written as follows, $R(T) = Ae^{E_a/(kT)}$. Where $R(T)$ is a rate constant dependent on
the absolute temperature $T$, $E_a$ is the activation energy of the reaction or the minimum energy required for a reaction to take place, and $k$ is Boltzmann’s constant. This equation can also be written as, $ln(R(T)) = -\frac{E_a}{k} \frac{1}{T} + ln(A)$. Which is equivalent to $y = mx + b$ and is easily plotted resulting in the slope of the plot equal to $E_a$. The rate constant in this case is the magnitude of dark current generated in the detector material dependent on its operating temperature. With increasing temperature in the photodiodes of the FPA there will be a rapidly increasing number of electrons hole pairs which have acquired enough energy from phonon absorption to become excited across the optical bandgap of the detector material. Fundamentally, the dark current dependence of a photodiode constructed from a T2SLS material system or from a bulk material, on temperature is the same and is a function of the photodiodes optical bandgap. The activation energy recovered from the Arrhenius plot of $\ln(J_d)$, taken at a photodiodes optimal bias condition, versus $1/kT$ represents the bandgap energy of the photodiode and by extension its cutoff wavelength.

$$E_a = -k \left[ \frac{\partial \ln(R(T))}{\partial (1/T)} \right] \text{ [eV]}$$ (5.9)

At temperatures greater than 70 K the activation energy recovered from the Arrhenius plot reflects the cutoff wavelength of the detector. At temperatures less than 70 K the activation energy decreases significantly. This implies a diffusion limited dark current above 70 K and SRH limited dark current below 70 K [48]. This effect can be confirmed through investigating the radiation hardness of the detector when exposed to heavy particles, which will induce trap sites and increase the SRH component of dark current. The Arrhenius plot of the data from Figure 5.8 for several bias points is seen in Figure 5.9. The median value of $J_d$ for the array is used when constructing the plot. The activation energy for an optimal operating bias value of 380 mV is found to be equal to, $E_a = 0.1006 \text{ eV}$. This is equivalent to a wavelength of $\lambda = 12.33 \mu \text{ m}$.

5.7. Photoluminescence
Figure 5.9: Arrhenius plot constructed from dark current density data as a function of operating temperature for several values of detector bias.

Photoluminescence is a technique used to analyze the spontaneous emission spectrum of a semiconductor device. The information gathered from photoluminescence techniques is used to produce an estimate for the minority carrier lifetime of a structure and is an accepted method for finding trap sites within T2SLS devices [53]. Generally photoluminescence involves the absorption of light in a direct bandgap material from a laser which generates EHP’s that will decay and emit photons. The spectrum and spatial resolution of emitted photons are examined to draw conclusions as to the properties of the semiconductor sample. Factors that have an effect on this type of experiment are, the laser spot size, excitation wavelength, lateral diffusion of energy, built in potential barriers within the device structure, gradient doping, and SRH trap sites.

There are two important states that determines the minority carrier lifetime of a pn-junction. The first is known as the low-injection regime and is when the excess carrier density is much smaller than the equilibrium carrier density. Here carrier lifetime is independent of the excess carrier density. The high-injection regime occurs when the excess carrier density
is much greater than the equilibrium carrier density and in this case carrier lifetime has a strong dependence on the number of excess carriers present. Photoluminescence offers a way to distinguish these two regimes and can provide useful insight into the dark current mechanisms and recombination events that limit the effectiveness of a detector.

5.7.1. Time-resolved Differential Transmission

Time-resolved differential transmission (TDT), explained in [29], works by optically exciting a T2SLS absorber with a short pulse of radiation from a pump laser. This produces a number of EHPs in the absorber dependent on the sample temperature, spot size, wavelength and intensity of the radiation. A second optical source is then used to probe the transient charge carrier population at nano-second intervals following the pulse from the pump laser. This is accomplished by measuring the difference in the transmitted signal through the absorber as a function of the time delay between the pump and probe pulses. The further away from the pump pulse that the probe pulse is generated the more time there will be for EHPs to decay and recombine meaning that when the probe pulse reaches the sample more of its energy will be absorbed and less of its energy will be transmitted. The relationship between the difference in transmitted energy due to the pump laser as a function of time is than a measure of the excess carrier density of the sample.

5.7.2. Time-resolved Microwave Reflectance

A similar pump-probe method can be implemented using a microwave Gunn diode and microwave detector instead of a quantum cascade laser and photodiode to probe the sample, known as time-resolved microwave reflectance (TMR). This method takes advantage of the fact that semiconductors become more conductive with the generation of EHPs. From the Drude model this translates to a high reflectance at long wavelengths [28]. TMR examines the percentage of energy reflected by a sample following a pulse from a pump laser instead of the fraction of energy transmitted to recover a measurement of excess carrier density.
5.7.3. Minority Carrier Lifetime From Photoluminescence

Minority carrier lifetimes ($\tau$) as a function of excess carrier density ($\Delta n$) can be recovered from TMR or TDT measurements by applying the following relationship.

$$\tau^{-1} = -\frac{1}{\Delta n} \frac{\partial \Delta n}{\partial t} = -\frac{1}{\Delta n} \frac{\partial \Delta n}{\partial S/S} \frac{\partial S/S}{\partial t}$$ \hspace{1cm} (5.10)

In the above equation $\Delta S/S$ is the recovered signal as a function of time which represents the population of optically generated EHPs [7]. Taking the derivative of the data set results in the rate of decay of the excess carriers. This can then be fit to a second order exponential, $S(t) = At^2 + Bt + C$, where $A$ is equal to the Auger coefficient ($C_n, C_p$), $B$ corresponds to the radiative recombination coefficient ($B_r$), and $C$ represents the inverse of the minority carrier lifetime [51] [50]. Fitting the measured data to an exponential so that, $S(t) = At^2 + Bt + C$, where $A$ is equal to the Auger coefficient ($C_n, C_p$), $B$ corresponds to the radiative recombination coefficient ($B_r$), then the minority carrier lifetime can be extracted as the inverse of $C$ [51] [50].

Two unique time constants can be determined from the decay of the reflected or transmitted signals signifying the difference between the low-injection and high-injection regimes. In the high injection regime it is assumed that all trap site energy levels are occupied and Auger and/or radiative recombination mechanisms are dominant [7]. Separating the Auger lifetime of a detector from the radiative recombination lifetime requires extensive knowledge of a detectors band structure. This is usually accomplished by analyzing TMR or TDT measurements as a function of dopant levels, pulse intensity and temperature [7]. In the low injection regime at low temperatures SRH recombination is observed to be the dominant mechanism [52]. At high equilibrium carrier densities Auger recombination becomes the dominant mechanism at all temperatures [52].

The total minority carrier lifetime of a device is given as a combination of the various recombination effects as,
\[
\frac{1}{\tau} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{\text{Radiative}}} + \frac{1}{\tau_{\text{Auger}}} + \frac{2S}{t},
\] (5.11)

where \( t \) is the thickness of the absorption region and \( S \) is the surface recombination rate \([33]\). Through minority carrier lifetime measurements performed as a function of doping levels and temperature two distinct time constants associated with the two injection regimes can be identified giving insight into the dominant recombination mechanisms in each regime. Significant effort has been made to reduce the effectiveness of defect energy levels in T2SLS devices in the MWIR and LWIR the biggest difference of which comes from using the InAs/InAsSb material system over InAs/GaSb. SRH generation-recombination mechanisms remain the biggest obstacle for T2SLS device to overcome in terms of limiting dark current and increasing minority carrier lifetime in the low injection regime. Long minority carrier lifetimes in T2SLS detectors are directly related to strong carrier localization \([55]\). Recall that strong localization is synonymous with thicker layers which has the effect of decreasing the wavefunction overlap and reducing the absorption coefficient.
Chapter 6

RADIATION

There are two distinct effects from harmful radiation that are a concern to the operability of semiconductor devices. They are total-ionizing-dose (TID) due to high energy photons such as x-rays, and gamma-rays, and displacement damage (DD) which is caused by heavy particles such as, neutrons, and protons. Free protons can also cause ionization as they are a charged particle interacting with atomic nuclei which has the effect of forcefully expelling electrons as their kinetic energy is reduced. Gamma-rays are produced artificially by irradiating cobalt-59 with neutrons thereby creating the radioactive isotope cobalt-60 which then decays through beta decay to nickel-60 and in the process emits two gamma-rays with energies of 1.17 MeV and 1.33 MeV. X-rays are generated by bombarding a material, typically tungsten or copper, with high energy electrons through the use of an electric field. The collision of an electron with the material at the anode of the electric field and its rapid deceleration causes it to lose some of its energy in the form of a high energy photon. The x-ray spectrum produced in this manner covers a wide range and can be controlled through the kinetic energy of the impulse electrons. Fast neutrons (1 MeV - 14 MeV) can be produced in either a particle accelerator by fusing isotopes of hydrogen together or through nuclear fission of enriched uranium-235 and other fissionable materials. Neutron generation through fusion reaction has two forms each producing neutrons with specific energy levels and requiring deuterium (\(^{2}\text{H}\)) and tritium (\(^{3}\text{H}\)). A deuterium-tritium reaction will produce \(^{4}\text{He}\) and a 14.1 MeV neutron while a deuterium-deuterium reaction will produce \(^{3}\text{He}\) and a 2.5 MeV neutron. Neutrons produced through nuclear fission in either a thermal reactor or in a fast reactor have a mean energy of 2 MeV and follow the Maxwell–Boltzmann distribution dependent on the temperature of the system. Protons are produced by stripping a hydrogen anion of its electrons. This is accomplished by accelerating the hydrogen isotope using a
positive voltage in a vacuum sealed linear accelerator, where it passes through carbon foil producing a free proton on the other side. A cyclotron is used to accelerate a free proton using a constant magnetic field and a rapidly varying electric field. The energy a proton can reach is dependent on the cyclotrons resonance frequency which is determined by its size.

\[ E = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}, \]

where \( B \) is the strength of the magnetic field, \( m \) is the mass of the particle, \( q \) the particles charge, and \( R \) the radius of the metal electrodes through which the high frequency electric field is generated to accelerate the particle. Cyclotrons are capable of producing free protons with energies of several hundred electron volts.

The effects of TID occur when a high energy photon strikes a semiconductor material releasing its energy which is then absorbed by the lattice creating multiple electron hole pairs. The ionization of a semiconductor material is particularly harmful to devices which depend on oxide layers to operate. Secondary electrons that acquire enough energy from the deceleration of the initial ionization event can surmount the semiconductor-oxide interface and become embedded in the oxide layer changing its potential energy. For a complementary-metal-oxide-semiconductor (CMOS) ROIC which depends on field-effect-transistors (FET) to move charge from the pixel wells to the ADC and to control the integration and reset periods of the imaging cycle, the presence of ionizing radiation can cause unwanted anomalies in the image. Most commonly these abnormalities manifest themselves as random telegraph noise in the individual pixel behavior. The detector material itself is predicted to show minimal degradation with TID. Previous studies performed on the susceptibility of InAs/GaSb T2SLS devices to gamma-rays reported a 5% increase in dark current density when dosed with a 20 kRad silicon equivalent and a negligible effect on responsivity [49] [43] [48].

DD occurs when a heavy particle, such as a neutron or proton, strikes the semiconductor lattice and physically alters the arrangement of atoms. This creates trap sites that promote dark currents and decrease the minority carrier lifetime of the material [42] [34] [10] [11] [5] [4] [3]. The effects of DD in a semiconductor lattice are associated with the SRH process, the only difference being that instead of material impurities creating non uniform energy states in the band structure they are created by vacancy and interstitial pairs [11] [34]. The
The energy level of the trap states determines their generation-recombination (GR) efficiency with midgap levels having a significant effect on dark current and minority carrier lifetimes. The dark current mechanism through which SRH GR takes place is independent of the trap-assisted-tunneling (TAT) mechanism although they have a similar operation. TAT is the process by which carriers are advanced through a hetero-barrier utilizing a trap state which contributes to the wavefunction overlap and facilitates transmission through the barrier. GR describes the process through which an electron is promoted from the valence band to the conduction band (generation) via a trap site with an energy level within the bandgap, and vice-versa (recombination). TAT is identified as having a near-zero activation energy, meaning it is a temperature independent mechanism. GR lifetimes are based on a power law involving temperature. When not diffusion limited increasing thermal energy will cause generation to dominate recombination. When diffusion limited increasing thermal energy will cause recombination to dominate generation. Both TAT and GR are dependent on bias with different magnitudes. As bias increases and the absorber region is depleted there will be a larger number of trap sites contributing to GR dark currents. At the same time a stronger electric field will cause an increase in TAT as carrier drift velocity becomes greater. As a semiconductor material warms up some of the smaller magnitude dislocations introduced through DD will realign themselves to their original states in a process known as annealing. Annealing requires providing enough thermal energy to the lattice structure that a dislocation will be dislodged from its current high energy state and travel back to its previous location at a lower energy state.

6.1. Radiation Testing of Infrared Focal Plane Arrays

The FPAs used in this study were designed by QmagiQ, LLC to operate with a 12 µm cutoff wavelength using the InAs/InAsSb material system grown on a GaSb substrate and bump bonded to a FLIR Systems silicon ROIC. The detector material does not contain an anti-reflection coating and the GaSb substrate was removed following the bump bonding process. Pixels are delineated in the detector material with a pitch of 30 µm in a 320x256
The ROIC was wire bonded to an 84 pin LCC and mounted inside of a pour-fill LN2 dewar. The effects from TID and DD were looked at in regards to how FPA qualification factors such as dark current density, activation energy, quantum efficiency, and noise equivalent differential temperature degraded with exposure to several radiation sources.

The gamma facility at White Sands Missile Range in NM was used to examine the response of two FPAs to TID. The gamma-ray source is a $^{60}$Co source meaning that 1.1732 MeV and 1.3325 MeV photons are produced during beta decay. The FPAs were tested at a dose rates of approximately 60 Rads/sec and 70 Rads/sec in incremental doses up to a total accumulated dose greater than 30 kRads. An x-ray source at Draper laboratory was used to qualify the experimental setup and determine the expected results prior to the devices being exposed to high energy gamma-rays. A maximum of 50 keV x-rays were used at dose rates less than 1 Rads/sec. Exposures were performed in incremental steps with video recorded at 60 fps throughout each exposure. Dark current density versus common detector bias measurements were carried out between each exposure using a blank cold aperture at the operating temperature of the FPA. The first stage of the custom read-out electronics are connected to the back of the LN2 pour filled dewar using 1 foot shielded DB-25 cables so as not to expose the PCBs to the ionizing radiation. The shielded DB-25 cables added a small amount of fixed pattern noise which was negligible when taking the median value of the array. The PCBs were completely surrounded by 4 inches of lead to knock down the incident photon energy. Throughout the tests conducted in the gamma-ray and x-ray environments there were no abnormalities seen in the operation of the custom electronics.

The fast burst neutron reactor at White Sands Missile Range in NM was used to analyze the degradation in two FPAs from increasing DD. The first FPA was tested using a blank cold aperture at the same temperature as the detector material to measure dark current density between bursts and activation energy pre-and-post irradiation. It was given neutron pulses of $1 \times 10^{11}$ neutrons/cm$^2$, and $1 \times 10^{12}$ neutrons/cm$^2$. The second FPA was tested using an F/2.3 aperture and a Ge window with QE and NEDT measurements performed between bursts. It was subjected to neutron pulses of $1 \times 10^{11}$ neutrons/cm$^2$, $5 \times 10^{11}$ neutrons/cm$^2$, $4 \times 10^{11}$ neutrons/cm$^2$, and $2 \times 10^{11}$ neutrons/cm$^2$. 
and \(1 \times 10^{12}\) neutrons/cm\(^2\). Video was recorded at 60 fps through each exposure to the reactor core. A bare ROIC that had not been previously hybridized to detector material was given a \(1 \times 10^{12}\) neutrons/cm\(^2\) pulse to rule out the ROIC as being responsible for any of the effects seen in the cooled detector material. CMOS electronics are intrinsically rad-tolerant up to \(1 \times 10^{14}\) neutrons/cm\(^2\) and throughout the tests conducted there were no abnormalities seen in the operation of the first stage electronics in the radiation chamber.

The proton beam at the Francis H. Burr Proton Therapy Center in Massachusetts General Hospital was used to determine the effects of protons on the dark current density measurement of an FPA. 200 MeV protons were used in order to limit the ionizing radiation dose the ROIC would receive. The energy deposited by a proton in silicon is given by a table from the National Institute of Standards and Technology [36]. The stopping power of a 200 MeV proton in silicon is 3.62 MeV/(g/cm\(^2\)) which when multiplied by the fluence in protons/cm\(^2\) results in MeV/g. The dimensions of energy per unit mass are the same as the SI unit of dose. A simple conversion gives Rads = \(1.6 \times 10^{-8} \times 3.62\) MeV/(g/cm\(^2\)) \(\times\) fluence. The FPA tested was given an accumulated fluence of \(2.5 \times 10^{11}\) protons/cm\(^2\) which is an equivalent of 14.5 kRads deposited in the silicon ROIC. Dark current density measurements were performed between accumulated fluencies of \(1 \times 10^{11}\) protons/cm\(^2\), \(1.5 \times 10^{11}\) protons/cm\(^2\), \(2 \times 10^{11}\) protons/cm\(^2\), and \(2.5 \times 10^{11}\) protons/cm\(^2\). Arrhenius data was taken prior to irradiation, directly following the last exposure of the FPA to the proton beam, and after a 300 K annealing period. QE and NEDT measurements of the FPA were compared pre-and-post irradiation following the 300 K annealing period.

### 6.2. Bias Dependency on the Number of Ionization Events From Low energy X-Rays

It was discovered that ionization events occurring in the FPA from a low energy x-ray source operated at a low dose rate are frequent at common detector bias below the optimal bias, but become infrequent in the operating bias region of the FPA, Figure 6.1b. When exposed to a minimal rad rate the number of ionization events per frame as well as the
average number of electrons generated per event increased with bias up to the operating range of the photodiodes in the array. The turn-on bias of the T2SLS IR FPAs used in this study was determined by the height of an unintentional hetero-barrier in the valence band edge between the absorber and an adjacent barrier layer which is meant to suppress dark current in the absorber. This barrier must be overcome with bias before minority carriers can flow across the interface. FPA QF6-HLW12-35 was used for this experiment and from Figure 6.12 it is evident that the bias at which pixels become active, and a measurable amount of photocurrent is returned, occurs at roughly 200 mV for this particular device. At bias greater than 340 mV the majority of pixels in the array are operating at their optimal performance.

(a) Example of an x-ray event when operated under dark conditions close to zero bias at a frame rate of 60 fps. (b) Correlation between the number of ionization events and the increase in the number of electrons generated with each event versus bias.

Figure 6.1: Effects of ionizing radiation with common detector bias.

The criteria for an ionization event to have occurred was determined to be an increase in the number of electrons from one frame to the next exceeding 40k electrons or approximately 7 mV. Figure 6.1a depicts one example of an x-ray event occurring at a common detector bias near of 94 mV for a frame rate of 60 fps. The initial gain of approximately 275 mV is equivalent to 493k electrons. Figure 6.1b depicts the average number of ionization events recorded per frame versus bias, counted for 100 sequential frames at each bias step. It can be seen that after the detector reaches its operating region and the diodes are fully turned
on, the number of ionization events recorded per frame drops off significantly. The average number of electrons generated per event begins increasing once the FPA reaches its operating region indicating that the magnitude of the ionization event has a bias dependence. It doesn’t appear to be coincidence that the relative extrema of Figure 6.1b occur at the critical points of Figure 6.2. A reason for why the number of ionization events occurring in the operating bias region of the FPA drops off so significantly is not apparent.

![Figure 6.2](image)

Figure 6.2: Baseline values of median QE (a) and NEDT (b) versus bias for FPA QF6-HLW12-35.

6.3. Dark Current Density as a Function of TID

Measurements of dark current density versus bias for FPA QF6-HLW12-23 showed no response to gamma-ray irradiation with increasing dose, Figure 6.4 top. After 32 kRads there was a slight drop in the arrays median value of dark current density. Between 16 kRads and 32 kRads a number of pixels showed decreases in their recovered signal signifying damage to the transistor which controls integration of charge in the direct injection circuit of the FLIR Systems ROIC. This inevitably led to the median value of dark current density for the array, following a total dose of 32 kRads, appearing lower. Shortly after a total dose of 32 kRads, the ROIC ceased integrating entirely and the output from the ROIC became centered around the 1.6 V reference voltage for all of the pixels in the array. However, features of the array such a scratch with higher intensity pixels and a closely grouped section of dead pixels
were still distinguishable and verified that pixel data was being read out and that the array was simply not integrating correctly. Figure 6.3b depicts the state of the array following a total dose of 32 kRads of gamma-rays. Pixels that had integration failures, showing sharp declines in their signal, similar to the pixel shown in Figure 6.3a, appear dark and make up 5% of the array. The first instance of a pixel experiencing this behavior occurred after 150 seconds or approximately 26 kRads for a 70 Rads/s rate. The number of pixels showing signs of failure increased up to the point the gamma-ray source was shut off.

Figure 6.3: Example of pixel experiencing failure of the FET which controls integration of charge into the holding capacitor (a). State of FPA QF6-HLW12-23 following 32 kRads TID (b).

At roughly 48 kRads the ROIC failed entirely as all of the pixels became saturated at 4.38 V. After a hard reset the ROIC was outputting pixel data again but was unresponsive to changes in the integration time and the externally applied common detector bias had become pinned at the internal bias of the direct injection circuit for the pixel array. Following a 300 K annealing period overnight the ROIC was operating but did not respond to changes in integration time and the DAC which controls the external bias of the detector could not be set to values greater than the internal bias of the ROIC. The readout electronics received a total dose of less than 1 kRad with no noticeable differences in their behavior. When disconnecting the readout electronics from the dewar assembly the DAC worked as expected. The PCBs used to test device QF6-HLW12-23 were also used to test device QF6-HLW12-37 two days
later with no discernible differences in their operation thereby ruling them out as a culprit for the effects seen in the data.

The dark current density of device QF6-HLW12-37 was looked at for both x-ray and gamma-ray irradiation. The results showed almost identical behavior for both tests as seen in Figure 6.4 middle and Figure 6.4 bottom. The slight difference between the measurements performed with x-rays (middle Fig. 6.4) and those with gamma-rays (bottom Fig. 6.4) is attributed to the detector being approximately 2 kelvin warmer when the x-ray test was done. Both tests showed a slight degradation in dark current density after a 1 kRad exposure and minimal increases after 2 kRads. The dark current density versus bias measurement performed after 30 kRads with gamma-ray exposure showed a significant decrease as a large percentage of pixels became unresponsive to changes in the integration time. The state of the array following 30 kRads TID is depicted in Figure 6.5. The first occurrence of a pixel experiencing a dramatic loss of signal appeared after 23 kRads in FPA QF6-HLW12-37. The number of pixels showing signs of deterioration increased steadily up to 30 kRads TID with 38% of the array affected. Histograms of the FPAs dark current density at its optimal bias are depicted in Figure 6.6, showing the transformation the array went through with gamma-ray irradiation. After 1 kRad and up until 30 kRads the histograms of dark current density at the detectors optimal bias experienced minimal changes. After 40 kRads of gamma-ray exposure the pixel values read out were centered around the 1.6V offset of the ROIC. The detector was annealed at 300 K overnight resulting in the ROIC recovering slightly. After 1 month and a 373.15 K anneal the FPA recovered almost back to its original form with damage existing primarily in pixels at the center of the array. Following a 373 K anneal the mean dark current density of the array resembled a value closer to that recovered after a 1 kRad gamma-ray exposure than its baseline value. However, the temperature of the array was slightly warmer than 77 K during the dark current density measurement taken after the 373 K annealing period which could explain the increase.

The fundamental difference between the two FPAs tested was the turn-on bias, determined to be the point when the median pixel value of the array was within the operating
Figure 6.4: Median dark current density versus bias. Top: QF6-HLW12-23 gamma-rays. Middle: QF6-HLW12-37 50 keV x-rays. Bottom: QF6-HLW12-37 gamma-rays.
Figure 6.5: Example of pixel experiencing failure of the FET which controls integration of charge into the holding capacitor (a). State of FPA QF6-HLW12-37 following 30 kRads TID (b).

bias region. Recall that the operating bias region of the FPAs is determined by the height of an unintentional hetero-barrier in the valence band edge between the absorber and an adjacent barrier layer. The turn-on bias of FPA QF6-HLW12-23 occurs near 0 mV as opposed to 350 mV for FPA QF6-HLW12-37. It can be seen from Figure 6.4 that the turn-on bias of QF6-HLW12-37 was significantly reduced with TID. The likely cause of the attenuated turn-on bias is an accumulation of charge in the barrier layer with ionizing radiation which contributes to a lowering of the unintentional hetero-barrier. The diminished turn-on bias means that there will be increased depletion in the absorbing layers at the same operating bias leading to greater depletion dark currents.

Figure 6.7a depicts the dark current density of each device, at its optimal operating bias, versus total dose. Again, the difference in the baseline (0 kRads) dark current density measurement for device QF6-HLW12-37 when tested using x-rays and when using gamma-rays is attributed to a deviation in the operating temperature of the FPA of approximately 1-2 K.
Figure 6.6: Dark current density of FPA QF6-HLW12-37 at 78K and 430 mV common detector bias. From left to right and top to bottom: before irradiation, after 1 kRads gamma-ray exposure, after 30 kRads, after 40 kRads, after a 24 hour 300 K anneal, after 1 month and 373 K anneal.
6.4. Imaging Defects From Ionizing Radiation

An effect from ionizing radiation that limits the imaging capability in T2SLS detectors is the appearance of bright pixels. FPAs QF6-HLW12-23 and QF6-HLW12-37 were subjected to the $^{60}$Co source at rates of 70 Rads/s and 60 Rads/s respectively with increasing duration to reach a desired TID. Figure 6.8 depicts a frame from both device QF6-HLW12-23 (6.8a) and QF6-HLW12-37 (6.8b) following a total dose of 1 kRad of gamma-rays. It can be seen that device QF6-HLW12-37 accumulated more bright pixels with greater intensities following the gamma-ray exposure than did QF6-HLW12-23. The major difference between the two FPAs is the lower operating bias of device QF6-HLW12-23 which was set at 140 mV during exposure to the radiation source. The detector bias of device QF6-HLW12-37 was set at 430 mV during exposure to the gamma-ray and was set at 400 mV during exposure to the x-ray source. The lower operating bias of QF6-HLW12-23 could be limiting the effect ionizing radiation has on the detector material and would confirm the effect seen in FPA QF6-HLW12-35 where the magnitude of ionization events was looked at versus detector bias, Figure 6.1b.

Figure 6.7b depicts the percentage of the array which experienced ionization events with each exposure. The difference in the percentage of FPA QF6-HLW12-37 affected by ionizing
radiation events from x-rays and with gamma-rays, could be a result of the 30 mV difference in bias during exposure. It could also be an effect of the higher energy photon. More samples would need to be tested in order to determine if photon energy or bias is responsible for the result.

Figure 6.8: Comparison of frames from the two FPAs exposed gamma-ray irradiation after 1 kRad TID.

Figures 6.9 and 6.10 represent the recovered signal in a few randomly selected pixels for each array versus time through the 1 kRad gamma-ray exposure. The point where pixels intensities begin increasing indicates when the source is turned on and the point where pixel intensities begin decreasing reflects when the source is shut off after 1 kRad. For a frame rate of 60 fps and at a Rad rate of approximately 70 Rads/second this is equivalent to 15 seconds. The majority of pixels in each array appear as they do in the bottom rows of Figures 6.9 and 6.10. The top rows of pixels represent the behavior of the bright pixels that become visible with exposure to gamma-rays in each array. These pixels are recognized as having voltage swings between subsequent frames three hundred times greater than the background noise of the detector prior to gamma irradiation. The appearance of such pixels with TID is not a random process as the same pixels are identified with each subsequent dose step signifying a non-uniform susceptibility to ionizing radiation throughout the array. It is not known why some pixels are more sensitive than others to TID. The effect could be caused by pixel-to-pixel variation during the growth process. Figure 6.7b depicts the number these
pixels found with each dose step. There appears to be a correlation between the number of pixels identified and total accumulated dose but a more radiation hardened ROIC is needed to be certain.

Before irradiation there is an increasing relationship between the number of bright pixels appearing in the image and detector bias. As detector bias is increased the recovered signal in select pixels reaches a point where it begins increasing exponentially with bias signifying a shift in the dominant dark current density mechanism of the pixel from diffusion to TAT. Determining the optimal operating bias of the FPA is a function of its median values for dark current density, signal to noise ratio, and the number of bright pixels appearing with bias balanced with the gain in the FPAs median value of quantum efficiency. The changing turn-on bias of FPA QF6-HLW12-37 with ionizing radiation causes a percentage of the bright pixels in the array as opposed to them being created by an ionization event. This is evident in the dark current density versus bias measurements taken for each pixel in the array pre and post irradiation. Following irradiation, as bias is increased a greater number of pixels reach a point where TAT becomes the dominant dark current density mechanism causing the pixel to appear brighter than the surrounding pixels.

6.5. Effects of Neutron Fluence on Dark Current Density

In a previous study of proton fluence on InAs/GaSb complementary barrier infrared detectors operating in the 10.2 $\mu$m wavelength, it was theorized that with the introduction of DD the GR component of dark current increases, but is only slightly affected by bias. At the same time, the tunneling component of dark current increases and has a greater effect at larger bias [5]. The results gathered here for DD in a InAs/InAsSb T2SLS FPA operating with a cutoff wavelength of 12.3 $\mu$m show good agreement with this previous study.
Figure 6.9: Comparison of a few randomly selected pixels in the array of device QF6-HLW12-23 through 1 kRad of gamma-ray exposure. Pixels on the bottom row represent the majority of pixels in the array while pixels on the top row depict those that showed unusual behavior to TID.

Figure 6.10: Comparison of a few randomly selected pixels in the array of device QF6-HLW12-37 through 1 kRad of gamma-ray exposure. Pixels on the bottom row represent the majority of pixels in the array while pixels on the top row depict those that showed unusual behavior to TID.
Figure 6.11: Dark current density versus bias with neutron fluence for a 77 K operating temperature (a). Arrhenius plot of dark current density pre and post irradiation with 1 MeV neutrons (b).

Figure 6.11b depicts the Arrhenius plot of dark current density versus operating temperature; before irradiation, directly following an accumulated fluence of $1.1 \times 10^{12}$ neutrons/cm$^2$, and after a 300 K annealing period for FPA QF6-HLW12-38. From the plot it can be seen that GR recombination is the dominant dark current mechanism below 80 K as there is a minimal temperature dependence. The fact that dark current density is lower post irradiation at higher operating temperatures suggest that the displacements introduced continue to have an effect on recombination after the detector becomes diffusion dark current limited. In a follow up study using a second FPA from the same batch, subjected to a proton beam, the decrease in dark current density at higher operating temperatures following irradiation was also present confirming this result, Figure 6.15b. In both sets of data following a 300 K annealing period the dark current density failed to recover at higher operating temperatures and even appeared to decrease further in the neutron study.

Figure 6.11a depicts the change in dark current density versus bias undergone by FPA QF6-HLW12-38 with accumulated neutron fluence. TAT had a greater effect on dark current density at higher bias as evident by the increasing slope of the plot. However, TAT did not become the dominant mechanism as plots of dark current density versus bias remained a function of detector operating temperature. This indicates that at higher bias dark current density was a function of both GR and TAT mechanisms. The second FPA exposed to high...
energy protons showed TAT became the dominant dark current mechanism at a bias 400 mV after the FPA reached its operating bias region, Figure 6.15a. It can be speculated that because the operating bias region of FPA QF6-HLW12-38 occurs after 200 mV that for bias greater than 600 mV TAT could become the dominant dark current mechanism.

6.6. Effects of Neutron Fluence on QE & NEDT

The QE and NEDT measurements of an IR detector are representative of the detectors ability to convert incident radiation to electrical signal and its sensitivity to distinguishing signal from background noise. They are therefore the best evidence of a IR detectors ability to image a scene. Figure 6.12 depicts the change in QE and NEDT versus bias with accumulated neutron fluence. Following a neutron pulse with a fluence of $1 \times 10^{12}$ neutrons/cm$^2$, there was an absolute decrease in QE of 2.3% and an increase in NEDT of 82 mK at the detectors optimal operating bias of 380 mV. At neutron fluencies of $6 \times 10^{11}$ neutrons/cm$^2$ and $1.6 \times 10^{12}$ neutrons/cm$^2$, the decreasing relationship between QE and bias is a result of the Fermi level approaching the intrinsic energy level. The depletion of trap sites in the absorber region of the photo-diode allows for increased GR due to the SRH effect thereby reducing the recombination lifetime of optically generated minority carries and increasing dark current density. The decreasing relationship between QE and bias was also seen in a second device, subjected to a high energy proton beam, when analyzing measurements taken before irradiation and after a 300 K annealing period, Figure 6.14b.
From Figure 6.12, the QE and NEDT data suggests that the pixels of the array become active at lower bias with accumulated neutron fluence. The turn-on bias of the T2SLS IR FPAs used in this study was determined by the height of an unintentional hetero-barrier in the valence band edge between the absorber and an adjacent barrier layer which was meant to suppress dark current in the absorber. This barrier must be overcome with bias before minority carriers can flow across the interface. The results indicate that neutron bombardment reduces this barrier and therefore the threshold voltage of the photodiode. Shifting the operating bias of the detector after each dose to account for this lower threshold voltage would yield the following QE and NEDT measurements, Table 6.1. These results show a decrease in NEDT as well as a reduction in standard deviation when compared to measurements taken at the FPAs optimal bias condition prior to irradiation, Table 6.2. The lower turn-on bias of the detectors with DD was also evident in the dark current density vs bias data as the point where the curve starts to roll over occurs at a lower bias than the baseline data, Figure 6.11a.
Table 6.1: QE and NEDT with shifted operating bias.

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<th>baseline operating bias: 380 mV</th>
<th>1E11 neutrons/cm² operating bias: 360 mV</th>
<th>5E11 neutrons/cm² operating bias: 320 mV</th>
<th>1E12 neutrons/cm² operating bias: 300 mV</th>
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</thead>
<tbody>
<tr>
<td>QE (%)</td>
<td>15.7 ± 0.7</td>
<td>15.4 ± 0.7</td>
<td>14.5 ± 0.7</td>
<td>13.7 ± 0.75</td>
</tr>
<tr>
<td>NEDT (mK)</td>
<td>25 ± 4</td>
<td>26 ± 7</td>
<td>29 ± 10</td>
<td>41 ± 13</td>
</tr>
</tbody>
</table>

Table 6.2: QE and NEDT with nominal operating bias.

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<thead>
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<th></th>
<th>baseline operating bias: 380 mV</th>
<th>1E11 neutrons/cm² operating bias: 380 mV</th>
<th>5E11 neutrons/cm² operating bias: 380 mV</th>
<th>1E12 neutrons/cm² operating bias: 380 mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE (%)</td>
<td>15.7 ± 0.7</td>
<td>15.6 ± 0.7</td>
<td>15.0 ± 0.9</td>
<td>13.3 ± 1.1</td>
</tr>
<tr>
<td>NEDT (mK)</td>
<td>25 ± 4</td>
<td>26 ± 11</td>
<td>46 ± 33</td>
<td>107 ± 51</td>
</tr>
</tbody>
</table>

After a sitting overnight at 300 K the detector showed a recovery in both QE and NEDT. The resulting QE and NEDT measurements taken after a one day anneal revealed a similar plot to those taken following the $5 \times 10^{11}$ neutrons/cm² shot. After a one month period at room temperature and a 373.15 K anneal, the FPA recovered slightly more than it did after the 300 K anneal.

### 6.7. NEDT Versus Time Following a Neutron Pulse

Directly following the pulse from the nuclear reactor there was a momentary increase in the amount of temporal noise detected by the FPA which quickly dissipated with an exponential decay. This effect is likely caused by ionizing radiation associated with the fast burst reactor pulse and smaller magnitude dislocations annealing out of the material. Figure 6.13 depicts the median NEDT of the array following a neutron burst. Twenty-five sequential frames were used at each point at a frame rate of 60 fps. The NEDT of the FPA is calculated by taking the standard deviation of each pixel in the array, excluding any non-responsive pixels found prior to irradiation, in increments of 25 frames. The values are then multiplied by the signal transfer function calculated for each pixel prior to irradiation. The median
value of the array is then plotted versus time. There was approximately two hours between shots and frames were not captured for the entire duration of the cool-down and calibration times of the reactor. The trend shown in Figure 6.13 is consistent for the approximately 3 minutes of video taken following the neutron pulse. The variation between device QF6-HLW12-35 and device QF6-HLW12-38 after the $1 \times 10^{12}$ neutrons/cm$^2$ shot can be attributed to the difference in scene temperature. Recall that device QF6-HLW12-35 imaged a room temperature germanium window at the front of the dewar whereas QF6-HLW12-38 imaged a 77 K blank aperture inside of the dewar.

![Figure 6.13: NEDT versus time following a neutron event device 38 (a) device 35 (b).](image)

6.8. Effects of Proton Fluence on Dark Current Density

FPA QF6-HLW12-41 was subjected to a 200 MeV proton beam. After an accumulated fluence of $2.5 \times 10^{11}$ protons/cm$^2$ there was a increase in dark current density at the detectors optimal bias condition and at a 77 K operating temperature, from $2.2 \times 10^{-4} \pm 0.24 \times 10^{-4}$ A/cm$^2$ to $2.9 \times 10^{-4} \pm 0.78 \times 10^{-4}$ A/cm$^2$. Unlike FPA QF6-HLW12-38, which had a turn-on bias around 200 mV, FPA QF6-HLW12-41 had a turn-on bias near 0 mV prior to irradiation which did not shift with accumulated proton fluence. It is not known why FPA QF6-HLW12-41 did not exhibit the same turn-on bias as QF6-HLW12-38 as both detectors came from the same batch. At roughly 400 mV detector bias, TAT becomes the dominant mechanism contributing to dark current density. This is evident by the fact that dark current
density becomes almost completely independent of temperature at this point, Figure 6.15a. At lower detector bias and up to 85 K GR, due to the SRH process, is the dominant dark current density mechanism. After 85 K and at low bias, near the turn-on bias of the FPA, diffusion dark current dominates before being overtaken by GR and eventually TAT at higher bias. As the operating temperature is increased diffusion dark current continues to dominate at higher bias before being supplanted by TAT. After a 300 K annealing period the detector recovered only slightly.

Figure 6.14: Dark current density versus bias as a function of proton fluence, 77 K operating temperature (a). QE versus bias before and after irradiation with $2.5 \times 10^{11}$ protons/cm$^2$, 77 K operating temperature (b).

Figure 6.15: Dark current density versus bias as a function of operating temperature post irradiation (a). Arrhenius plot of $J_d$ versus $q/kT$ pre and post irradiation (b).
6.9. QE and NEDT Before and After Irradiation 200 MeV protons

Measurements of QE and NEDT were performed prior to exposure to the proton beam and after a 300 K anneal. Histograms of the data at the detectors optimal bias are depicted in Figure 6.17. The median value of QE dropped by an absolute 2.9% signifying a greater effect in the SLS material from protons than that of fast neutrons. Plots of QE and NEDT versus bias for device QF6-HLW12-41 before and after irradiation with 200 MeV protons revealed similar outcomes to those seen in FPA QF6-HLW12-35 when exposed to fast neutrons, Figures 6.12a and 6.12b. Unlike dark current density the reduction in QE for both protons and fast neutrons remained relatively uniform throughout the array.
6.10. Bare ROIC

A bare ROIC not hybridized to detector material was tested using the x-ray source and with gamma-rays with no transient effects detected in either test. This result is expected for the bare ROIC but it was necessary to prove in order to rule out the ROIC as being responsible for any effects seen in the detector data. The failure point of the bare ROIC tested using gamma-rays coincided with the results from device QF6-HLW12-23 and QF6-HLW12-37.
A bare ROIC was also subjected to a neutron pulse of $1 \times 10^{12}$ neutrons/cm$^2$. The desired temperature of the core of the nuclear reactor for a $1 \times 10^{12}$ neutrons/cm$^2$ shot was 50 °C. The 400 micro-second pulse was captured in a single frame and appeared as a Gaussian distribution over approximately 10 rows of pixels. The pixel intensities of the three brightest rows of the pulse captured by device QF6-HLW12-35 and the pulse captured by the bare ROIC not hybridized to detector material were averaged. The bare ROIC registered an increase of 724 mV for a 46.8 °C shot while device QF6-HLW12-35 registered an increase of 900 mV for a 56.7 °C shot. This signifies that the major imaging defect from a neutron pulse was due to the ROIC and not the detector material. If the effects from the pulse could be eliminated in the ROIC, continuous imaging through an event would be possible with the detectors used in this study.
Chapter 7

CONCLUSION

The characterization of the effects experienced by state-of-the-art LWIR T2SLS FPAs to harmful radiation revealed the possibility of a detector capable of imaging through a radiation event. The amount of damage to the pixels of the array appears to be a function of the energy of the incident radiation and the common detector bias. The FPAs used in this study were designed by QmagiQ, LLC to operate with a 12 µm cutoff wavelength using the InAs/InAsSb material system grown on a GaSb substrate and bump bonded to a FLIR Systems silicon ROIC. The radiation sources used included; the proton beam at the Francis H. Burr Proton Therapy Center in Massachusetts General Hospital, the fast burst neutron reactor at White Sands Missile Range in NM, the gamma facility at White Sands Missile Range in NM, and a low energy x-ray generator at Draper Laboratory. Measurements of QE, NEDT, dark current density, and activation energy were conducted prior to irradiation, directly following exposure to a radiation source, and after an annealing period. Video was captured at 60 fps throughout each exposure utilizing custom hardware and software developed by the author for the purposes of this experiment. It has been demonstrated that the measurement system developed for these experiments is a robust and capable solution for collecting in-situ data in a radiation environment.

Low dose rate measurements performed using a low energy x-ray source revealed that the number of ionization events recorded per frame and the number of electron-hole pairs generated from those events was dependent on bias. The number of ionization events produced by the low energy x-ray source operating at a low rad rate was reduced significantly in the detectors operating bias region. The unintentional potential barrier located between the absorber layers and a barrier layer meant to suppress dark current, which had varying heights in the devices tested, was diminished in the presence of ionizing radiation leading to
a lower turn-on bias.

Two FPAs were subjected to gamma-rays resulting in varying degrees of damage. FPA QF6-HLW12-23 showed minimal increases in dark current density with accumulated dose while device QF6-HLW12-37 showed a small increase in dark current density following an accumulated dose of 1 kRad and minimal increments with subsequent dose steps. The major difference in the dark current density plot of device QF6-HLW12-37 before and after irradiation occurred at biases outside of the detectors operating region signifying a reduction in the turn-on bias of the pixels of the array. It is thought that the reduction in turn on bias led to increased depletion generated dark currents in FPA QF6-HLW12-37.

Ionizing radiation caused some of the pixels in the arrays to behave erratically showing large increases in intensity and voltage swings far above their baseline noise levels. Bright pixels that were affected by the ionizing radiation began to anneal once the source of radiation was turned off. The arrays appeared to have a non-uniform susceptibility to ionizing radiation that could be caused by pixel-to-pixel variances in the growth of the detector material. The turn-on bias of the two FPAs exposed to the gamma-ray source occurred at different points which led to a greater number of bright pixels with larger magnitudes appearing in FPA QF6-HLW12-37 than in QF6-HLW12-23, with exposure to ionizing radiation. The number of pixels affected appeared to be a function of total dose, however a more radiation hardened ROIC is needed to test this hypothesis further. A minimal turn-on bias is beneficial to the radiation hardness of the T2SLS FPAs used in this study.

It was discovered that the FLIR Systems ISC9705 ROIC used in this study was tolerant to TID up to 20 kRads. A reduced response to integration time in the individual pixels of the array was the first indication of failure in the ROIC. After an accumulated dose of 30 kRads roughly 5 % of FPA QF6-HLW12-23 showed signs of damage versus 38 % of FPA QF6-HLW12-37.
Two FPAs with identical baseline characteristics for QE, NEDT and dark current density were subjected to neutron pulses totaling fluencies greater than $1 \times 10^{12}$ neutrons/cm$^2$. Histograms of dark current density, QE, and NEDT following neutron bursts revealed right skewed distributions and increasing standard deviation with neutron fluence. Figure 7.1 depicts the effects of displacement damage applied to the image of a scene taken prior to irradiation with FPA QF6-HLW12-35. The amount of damage in each pixel following a neutron pulse was recovered by taking the difference in the mean of 25 frames recorded under uniform illumination before and after irradiation. The difference was then applied to a scene imaged with the same bias and integration time.

The overall degradation of the FPA array to a neutron fluence greater than $1 \times 10^{12}$ neutrons/cm$^2$ was limited to a percent increase in dark current density of $114 \pm 406 \%$, a relative decrease
in QE of 12.5 % and a percent increase in NEDT of 64 ± 225 % at a 77 K operating temperature. The most significant effect to image quality from displacement damage was due to an increase in the standard deviation of dark current density and NEDT for the array which blurs the features of an image. With the array exhibiting only a small loss in QE a NUC could be performed to smooth out the variation in dark current density between pixels returning the array to a good working condition.

An FPA tested using 200 MeV protons showed considerable degradation in dark current density with proton fluence and a large amount of pixels becoming saturated when struck by protons. The turn on bias of FPA QF6-HLW12-41 before irradiation was near 0 mV and did not shift with accumulated proton fluence. After a 300 K annealing period the FPA recovered only slightly.
Appendix A

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