Chapter 6  Review of Research and Future Work

6.1  Review of Research

Chapter 2 investigates the use of AlAs<sub>x</sub>Sb<sub>1-x</sub> as the barrier layer material in the InAs-based nBn photodetector. The AlAs<sub>x</sub>Sb<sub>1-x</sub> ternary is immediately identified as a possible barrier layer in the InAs-based nBn photodetector: all compositions of AlAs<sub>x</sub>Sb<sub>1-x</sub> have large conduction band discontinuities with InAs (>> kT), the composition AlAs<sub>0.16</sub>Sb<sub>0.84</sub> lattice matches InAs, and experimental data indicate a composition in the range 0.14 < x < 0.17 produces a zero valence band energy offset between AlAs<sub>x</sub>Sb<sub>1-x</sub> and InAs.

Several parameters of the AlAs<sub>x</sub>Sb<sub>1-x</sub> epilayers are mathematically modeled, and the results are reported and compared with results obtained from experimental data. Mathematical predictions of the maximum pseudomorphic critical thicknesses of AlAs<sub>x</sub>Sb<sub>1-x</sub> layers are seen to be conservative; experimental data show barrier layers at least as thick as 750 Angstroms for AlAs<sub>x</sub>Sb<sub>1-x</sub> compositions 0.14 < x < 0.26 are pseudomorphically strained.

The effects of strain on the positions of the heavy hole, light hole and split-off valence band edge energies in AlAs<sub>x</sub>Sb<sub>1-x</sub> grown on InAs substrates are modeled and compared with calculations made using experimental data. Three different models are used to estimate the valence band energies of bulk AlAs<sub>x</sub>Sb<sub>1-x</sub>, and the results of each of the three approaches are individually combined with Model Solid Theory to estimate the energies of the valence band edges in the strained ternary. One of the three models shows reasonable agreement with the experimental data, and it predicts a composition close to AlAs<sub>0.16</sub>Sb<sub>0.84</sub>, which is the composition lattice matched to InAs, has a zero valence band energy offset with InAs.

These modeled results are used to estimate the thermal activation energies of a series of InAs / AlAs<sub>x</sub>Sb<sub>1-x</sub> nBn photodetectors with barrier compositions 0.14 < x < 0.26. The trends in the experimental data and the modeled results agree, however the thermal activation energies, E<sub>A</sub>, calculated using the experimental, and temperature-dependent, I-V data and

\[ I \propto T^3 \exp \left( -\frac{1.08 E_A + (E_c - E_f)}{kT} \right) \]  

(6.1.1)
are tens of milli-electron volts less than both the bandgap energy of InAs and the predictions from the model. This discrepancy is concluded to result from Equation (6.1.1) not accounting for the effects of a temperature-dependent lateral diffusion length in the InAs absorption layer. The temperature-dependent lateral diffusion length produces a temperature-dependent effective device area, $A_{\text{eff}}(T)$ such that

$$I \propto T^3 \exp \left( \frac{-1.08 E_A + (E_c - E_f)}{kT} \right) A_{\text{eff}}(T).$$

This is explored in Chapter 5. Using Equation (6.1.2) and results presented in Chapter 5, the thermal activation energy of an InAs / AlAs$_{0.195}$Sb$_{0.805}$ nBn photodetector is calculated and plotted against the modeled results. There is good agreement between the two, which indicates the effects of the temperature-dependent effective area cannot be reasonably neglected in the calculation of the thermal activation energy.

An unexpectedly serendipitous relation between the temperature-dependent terms indicates that, for the $200 \text{ K} < T < 300 \text{ K}$ temperature range in lattice-matched InAs / AlAs$_x$Sb$_{1-x}$ nBn photodetectors grown on InAs substrates, Equation (6.1.2) may be simplified. Under these conditions,

$$I \propto \exp \left( \frac{-E_A}{kT} \right)$$

appears to produce a reasonable estimate of $E_A$.

The magnitude of the dark current arising from majority carrier electrons tunneling through the barrier in InAs / AlAs$_x$Sb$_{1-x}$ nBn photodetectors is modeled for a range of barrier compositions and thicknesses. The tunneling current density for an ideal barrier are predicted to be negligibly low: less than $10^{-100}$ A/cm$^2$ for 750 Angstrom thick barriers of various compositions.

Chapter 3 compares an InAs / AlAs$_{0.18}$Sb$_{0.82}$ nBn photodetector grown on an InAs substrate with two InAs-based photodiodes. Surface leakage current dominates the dark current measured for both cooled photodiodes, while the primary component of dark current
exhibited by the nBn photodetector at all measured temperatures is diffusion current. One photodiode is obtained from a commercial vendor. The other is fabricated from sample MBELabPN(Riber), which is grown and fabricated by the author. The design of the MBELabPN(Riber) photodiode results in it possessing reduced levels of surface leakage current as compared with the commercial photodiode.

Surface leakage current, which is approximately temperature invariant, limits the performance of the photodiodes. The nBn photodetector benefits from bulk diffusion current, which decreases as the temperature is reduced, being the primary source of dark current. Surface leakage current limits the \( R_\alpha A \) computed for the commercial and MBELabPN(Riber) photodiodes. The former is limited to \( < 40 \, \Omega \, \text{cm}^2 \) and the latter to approximately \( 1000 \, \Omega \, \text{cm}^2 \) for temperatures measured down to 140 K. Measurements show that the nBn photodetector has a dark current magnitude as much as 6 orders of magnitude lower than that of the commercially available photodiode and 4 orders of magnitude lower than that of the MBELabPN(Riber) photodiode at 140 K. Neither the commercial photodiode nor the MBELabPN(Riber) photodiode achieves background limited photodetection (BLIP) operating conditions at any temperature, due to the dominance of surface leakage current. The InAs-based nBn photodetector operates in the BLIP regime for device temperatures as high as 200 K. These measurements are taken with a 0.6 V reverse bias on the nBn photodetector, a 0.05 V reverse bias on the commercial photodiode, and a 0.04 V reverse bias on the MBELabPN(Riber) photodiode.

As the dark current of the InAs-based nBn photodetector is dominated by bulk diffusion current, the \( D^* \) of the nBn photodetector will remain constant with decreasing pixel dimensions, and the \( D^* \) will improve if the field of view (FOV) is reduced while the nBn is operating under BLIP conditions. The absence of surface leakage current allows the nBn photodetector to achieve BLIP conditions. The \( D^* \) of the cooled photodiodes, in the temperature regime over which surface leakage current is the primary contributor to the dark current, will worsen as the dimensions of the pixel are decreased. As the cooled photodiodes are unable to achieve BLIP operating conditions, changes in the FOV will not improve the \( D^* \) at any temperature.

Chapter 4 explores the effects on the performance of InAs-based nBn photodetectors of thick absorption layers containing elevated densities of dislocations. Increasing densities of dislocations occur when the absorption layers possess lattice constants increasingly different
6.1 Review of Research

from that of the substrate. Dislocations form in the lattice-mismatched epilayer to relax strain. Dislocations are, in general, detrimental to the performance of electrical devices.

The nBn photodetectors fabricated from the InAsControl(GenII) sample have lattice-matched InAs / AlAs\textsubscript{0.195}Sb\textsubscript{0.805} epilayers to an InAs substrate. These devices are compared with InAs-based nBn photodetectors fabricated from lattice-mismatched growth samples. These lattice-mismatched samples have epilayers similar to those of InAsControl(GenII), but the lattice constants of the absorption layers and the respective substrates differ. Photodetectors fabricated from GaAsSubstrate(Riber) and GaAsSubstrate(GenII) are InAs / AlAs\textsubscript{0.195}Sb\textsubscript{0.805} and InAs / AlAs\textsubscript{0.190}Sb\textsubscript{0.810} nBn photodetectors, respectively, grown on GaAs substrates. Growth sample InAsSbAbsorber(GenII) produces InAs\textsubscript{0.95}Sb\textsubscript{0.05} / AlAsSb nBn photodetectors on an InAs substrate. Dark current and photocurrent are measured as functions of temperature and bias voltage, and thermal activation energies and BLIP temperatures are computed for all samples. The thermal activation energy of InAsControl(GenII) is 0.41 eV, and the BLIP temperature is 220 K. The BLIP temperatures of the InAs-based nBn photodetectors grown on GaAs substrates are 150 K for GaAsSubstrate(GenII) and 160 K for GaAsSubstrate(Riber), and the thermal activation energies are 0.33 and 0.27 eV, respectively. The BLIP temperature of InAsSbAbsorber(GenII) is 185 K, and the thermal activation energy is 0.41 eV.

The measured dark currents are the highest for the InAs-based nBn photodetectors grown on GaAs substrates, and they are lowest for those fabricated from the lattice-matched control sample, InAsControl(GenII). Considering the elevated dislocation density in the lattice-mismatched absorption layers, Shockley-Read-Hall (SRH) generation current is investigated as a likely source of the elevated dark current in the lattice-mismatched samples. A mathematical equation describing the SRH generation rate, \(G_{SRH}\), is derived for the case of the InAs-based nBn photodetector possessing a nondegenerate absorption layer,

\[
G_{SRH} \propto N_D T^{3/2} \exp \left( - \frac{E_f - E_v}{kT} \right).
\]  

(6.1.4)

This equation is dependent on the Fermi level, \(E_f\), the valence band edge energy, \(E_v\), and the dislocation density, \(N_D\). It differs from the approximation \(G_{SRH} \sim \exp(-E_g/2kT)\), which is commonly used to estimate SRH current arising in the depletion region of photodiodes, in which \(G_{SRH}\) is determined by the value of half of the bandgap energy.
All three lattice-mismatched, InAs-based nBn photodetector samples are found to be limited by SRH current, rather than by diffusion current, which dominates the dark current of the control sample. Of the two cases corresponding to samples grown on GaAs substrates, the GaAsSubstrate(GenII) photodetectors are found to have a higher Fermi level in the absorbing layer. This is expected, as GaAsSubstrate(GenII) has the larger density of threading dislocations.

The nBn architecture does not suppress SRH current from arising due to dislocations in the absorption layer. However, even the most poorly performing of the three nBn photodetectors, in which SRH generation current is the primary contributor to dark current, is able to achieve BLIP with $T \geq 150$ K. This recommends the nBn photodetector architecture as an attractive option when it is necessary for the photodetector to incorporate a lattice-mismatched absorbing layer.

The nBn photodetector is well suited for the measurement of lateral diffusion length, as it exhibits no surface leakage current, and devices may be fabricated without etching into the absorption layer. In Chapter 5, lateral diffusion lengths are calculated for the absorption layers in the four nBn photodetector samples examined in Chapter 4. Calculations are made using measurements of current as a function of voltage, which are taken over a range of temperatures. Data taken for several square devices with different pixel side lengths, $S$, are used in the calculations. The data for the differently sized pixels of each sample, for a specific temperature, are related through

$$I \propto \left[ S^2 + 4SL_p + \pi L_p^2 \right],$$

where the term in brackets is a temperature-dependent effective area extending beyond the etched edges of the mesa defining the pixel. This relation allows the temperature-dependent lateral diffusion length to be estimated using current measurements taken for two or more differently sized pixels.

Lattice-matched sample InAsControl(GenII), has the longest estimated lateral diffusion lengths, which range from 34 microns at room temperature to 166 microns at 171 K. The estimated lateral diffusion lengths of InAsSbAbsorber(GenII) are 10 to 30 microns over the same temperature range. GaAsSubstrate(GenII) and GaAsSubstrate(Riber) have lateral diffusion lengths of less than 10 microns over this temperature range, and the lateral diffusion
6.1 Review of Research

lengths for these samples appear to be temperature invariant.

The range of the magnitudes of the lateral diffusion lengths computed for these samples is attributed to the different dislocation densities in the respective absorbing layers. The greater the density, as in the InAs / AlAsSb nBn photodetectors grown on GaAs substrates, the smaller the lateral diffusion lengths. As the lateral diffusion lengths are dependent on the crystalline quality of the absorbing layer, all nBn photodetectors cannot be assumed to possess the same temperature-dependent effective areas.

6.2 Future Work

This research investigates several aspects of the InAs-based nBn photodetector, however more work is required to fully characterize this device. Researching and developing mathematical models with the guidance of experimental data will increase understanding of the nBn photodetector. This is anticipated to result in the optimization of the performance of InAs-based photodetectors, as well as to accelerate the process of realizing the nBn architecture in other material systems. Future work is also encouraged to explore using the nBn structure in applications other than imaging; this work suggests it may become a preferred tool in the measurement of the lateral diffusion length of minority carriers in the absorption layer.

Chapter 3 examines the relation between the thermal activation energy and the barrier composition in the InAs / AlAs_{x}Sb_{1-x} nBn photodetector. Thermal activation energies are modeled for InAs / AlAs_{x}Sb_{1-x} nBn photodetectors using Model Solid Theory. The predictions are based on modeling the band edge energies in the absorption and barrier layers; a minimum thermal activation energy corresponds to a zero valence band energy offset. The projected composition for which there is a zero valence band energy offset between the AlAs_{x}Sb_{1-x} and the InAs layers is approximately x = 0.16, which overlaps with the 0.14 < x < 0.17 range determined from experimental data. However, this is still a comparatively large range, and additional experimental data are required to narrow it and better assess the suitability of the model.

Conducting a series of crystal growths of InAs / AlAs_{x}Sb_{1-x} nBn photodetectors covering the compositional range 0.14 < x < 0.26, with a substantial number falling in the 0.14 < x < 0.17
range, is recommended. As the lateral diffusion lengths of the minority carriers in the InAs absorption layers are seen to be temperature-dependent, which significantly impacts the extent of the effective area, it is important to determine the lateral diffusion lengths of the devices when performing this study. This may be done in a straightforward manner when the samples are processed using the revised photolithography mask set described in Chapter 4. However, any photolithography mask set producing square pixels of different side lengths and with homogenous local environments should be suitable.

It would also be interesting to experimentally determine the maximum and minimum practical AlAs_xSb_{1-x} barrier thicknesses for a range of compositions. The maximum useful thickness is anticipated to be less than or equal to the maximum pseudomorphic critical thickness, which is not well known; modeling gives conservative results, and there are not enough experimental data to establish upper boundaries. Referencing the predictions of the majority carrier current resulting from tunneling through the barrier, which presented in Chapter 3, the minimum useful barrier thickness is likely to be less than 100 Angstroms. It would be useful to investigate these limits and to confirm, as suggested by data acquired to date, the performance of the InAs / AlAs_xSb_{1-x} nBn photodetector is not in any other way dependent on the thickness of the AlAs_xSb_{1-x} barrier. The homogeneity of the barrier may depend on growth conditions, including the choice of mounting block. A comparison between samples grown using a solid molybdenum block and those grown mounted on a silicon carrier wafer may prove informative.

The research presented in Chapter 5 suggests the magnitude of the lateral diffusion length measured for an InAs / AlAs_xSb_{1-x} photodetector is affected by the local environment of the pixel. Altering the local environment in these InAs / AlAs_xSb_{1-x} devices, especially by selectively etching away the contact layer to define a pixel, likely affects the quality of the interface between the InAs absorbing layer and AlAs_xSb_{1-x} barrier layer; as AlAs_xSb_{1-x} oxidizes when exposed to air, the interface between the oxidized AlAs_xSb_{1-x} and InAs layers is expected to be inferior to that between the unoxidized AlAs_xSb_{1-x} and InAs layers. An exploration of whether this is the case, and a step towards quantifying the effect if it is, may be performed using nBn photodetectors processed using the revised photolithography mask set, or another designed using similar guidelines. The revised photolithography mask set produces several sets of pixels, with each set containing pixels with a range side lengths. The etched width surrounding the pixels is different for each set of pixels, and the etched width is constant throughout each set. The lateral diffusion lengths measured for each of the
different sets of pixels are expected to differ, and the variation is expected to relate directly to 
the expanse of etched and oxidized material surrounding the pixels in each set. It may be 
that measurements of the lateral diffusion length are also sensitive to the conditions under 
which the nBn photodetectors are tested. It would be interesting to explore whether the 
lateral diffusion length changes when more than one pixel in a focal plane array is 
simultaneously measured, and, if so, whether it also depends on the proximity and number of 
the simultaneously polled pixels.

As seen in the data presented in Chapter 5, the crystalline quality of the absorption layer has 
a significant impact on the magnitude of the lateral diffusion length. The differences in the 
crystalline quality among the samples examined in this chapter are obvious upon cursory 
examination. It would be interesting to measure and compare the lateral diffusion lengths of 
different, but nominally equivalent, samples, as well as samples with only marginal 
differences in crystalline quality. This would be both a useful test of the sensitivity of the 
measurement and an interesting examination into the impact of small differences in 
dislocation densities on the lateral diffusion length. An independent measurement of the 
dislocation density in the layers and a measurement of the minority carrier lifetimes in the 
samples would provide helpful supporting data.

The lateral diffusion lengths measured for the InAs / AlAs\textsubscript{0.195}Sb\textsubscript{0.805} nBn photodetector grown 
on an InAs substrate are long, over 30 microns at room temperature, and this has the 
possibility of contributing to cross talk in focal plane arrays (FPAs) consisting of nBn 
photodetectors. It may also be the case that the lateral diffusion length is reduced when 
adjacent pixels are simultaneously polled; carriers may be exclusively captured by the 
nearest pixel rather than travel to and be collected at a more distant one. An investigation of 
this possibility is recommended before these devices are used in FPA-based imaging 
systems. One approach is to calculate the lateral diffusion length from the I-V data taken for 
a selection of pixels, which should be measured while those adjacent to them are 
simultaneously polled.

Chapter 4 investigates InAs-based nBn photodetectors with absorption layers that have 
lattice constants different from those of the substrates and that exceed the maximum 
pseudomorphic critical thickness. Rather than diffusion current, Shockley-Read-Hall (SRH) 
generation current, which arises due to the high dislocation in these absorption layers, 
dominates the dark current. There is a threshold density of dislocations in the epilayers of
these devices beyond which diffusion current ceases to dominate the dark current and SRH current becomes the primary component. Conducting measurements on a series of nBn photodetectors with absorption layers possessing a range of dislocation densities will better define the dislocation density for which SRH current becomes dominant.

It may also be possible to modify the magnitude of SRH current in lattice-mismatched InAs-based nBn photodetectors by growing doped n-type absorption layers. Heavily doping the absorption layers is projected to increase the magnitude of diffusion current, which may be less desirable than the increased levels of SRH current in undoped material. However, there may exist a doping level that represents an acceptable compromise.

It may also be possible to reduce the levels of SRH current by growing thick buffer layers on the lattice-mismatched substrate, or by optimizing growth techniques. The majority of dislocations would ideally terminate in the buffer layer, resulting in an absorption layer with better crystalline quality. This investigation would likely benefit by simultaneously conducting studies of the photoluminescence of the misfit absorbing layers as a primary diagnostic tool. Comparison of the photoluminescence taken for the lattice-mismatched layers with that taken for absorption layers with good crystalline quality is a faster method of evaluating crystalline quality than fabricating and testing nBn photodetectors. The possibility of fabricating high-performance nBn photodetectors possessing lattice-mismatched absorption layers is a possibility worth investigating. Such devices could facilitate the optimization of nBn photodetectors with custom cutoff wavelengths, which could positively impact mass production of nBn photodetector arrays.