Chapter 5  Lateral Diffusion Lengths of Minority Carriers

The nBn photodetector is proposed as a tool for measuring the lateral diffusion length of minority carriers in an epitaxially grown crystal layer; the layer of interest is incorporated into the nBn photodetector as the absorption layer. The nBn photodetector architecture appears to be well suited to this task for two reasons: the device does not suffer from surface leakage current, and it is possible to define an nBn pixel without etching into the absorption layer. The magnitude of the current measured for an isolated nBn photodetector at a given temperature is proportional to an effective area over which it collects minority current carriers. This relationship is valid as a result of diffusion current dominating the dark current; surface leakage current results in the measured current being proportional to the perimeter of the photodetector. Minority carriers are able to diffuse from distant points in the sample to the mesa of the pixel as a consequence of the absorption layer being unetched and intact.

5.1 Technique for Calculating Lateral Diffusion Length

The diffusion length, $L$, of free minority charge carriers is the average distance the hole or electron travels, from the time it is generated to when it subsequently recombines. Diffusion length is defined as

$$L = \sqrt{D\tau},$$

(5.1.1)

where $D$ is the diffusion coefficient, and $\tau$ is the lifetime of the minority carrier. All three quantities are temperature-dependent. The magnitude of the diffusion length is dependent on the crystalline quality of the epitaxial layer. Diffusion length is a parameter worth investigating, as it is a fundamental material property. However, it also directly impacts the calculation of the thermal activation energy of the dark current for nBn photodetectors.

The magnitude of the current measured for an isolated nBn photodetector depends on the temperature-dependent lateral diffusion length. Carriers within a diffusion length of the mesa may be collected by the nBn photodetector; this effective area is larger than the area of the mesa when the diffusion length is non-zero. In this chapter, two forms of current density are
5.1 Calculation of Diffusion Length

examined. One is referred to as current density, \( J \), and it is calculated by dividing the measured current, \( I \), by the area of the mesa. The other is called effective current density, \( J_{\text{eff}} \), and it is calculated by dividing the measured current by the effective area. For the case of a non-zero lateral diffusion length, the effective current density is not a function of the temperature-dependent effective area. Both current and current density are, in general, functions of temperature.

Working with effective current density, rather than current or current density, permits a more accurate estimation of the thermal activation energies, \( E_A \), of individually measured nBn photodetectors. As is discussed in Chapter 1, the accurate calculation of thermal activation energy requires knowledge of the temperature dependence of the current measured for the photodetector,

\[
I(T) \approx \left[ f(T) \right] \exp \left( \frac{-E_A}{kT} \right),
\]

(5.1.2)

The exponential term that includes the thermal activation energy is one source of temperature dependence, and the temperature dependence of the other terms are collected into the function \( f(T) \). More accurately defining and dividing out \( f(T) \) results in a better estimate of \( E_A \). The temperature-dependent effective area is a multiplicative component of \( f(T) \).

The lateral diffusion length of minority carriers in the absorption layer can be estimated using current measured as a function of voltage for several differently sized nBn photodetectors, which derive from a single MBE growth. The effective area is assumed to extend beyond the physical dimensions of the mesa by a diffusion length, \( L_P \), in all directions.

Figure 5.1.1 is a sketch showing the top view of both the mesa area and the effective area associated with a single nBn photodetector. The black area represents the footprint of the mesa, and the effective area, which is the entire region over which carriers are collected, includes both the black and the gray regions. In the figure, the mesa is rectangular with side lengths \( S_1 \) and \( S_2 \), the effective area extends beyond the edges of the mesa by the width of a lateral diffusion length, \( L_P \).
5.1 Calculation of Diffusion Length

Figure 5.1.1 Mesa area and effective area of a pixel. The black center region is the physical area of the mesa, and S_1 and S_2 are the side lengths. The effective area includes the mesa area and extends a lateral diffusion length, L_P, beyond it on all sides. The region the effective area extends beyond the mesa is represented by the gray region.

For the general case of an nBn photodetector pixel, the relationship between the current and current density for an individual pixel may be expressed as:

\[ I = A_{\text{eff}} J \]  
(5.1.3)

where \( A_{\text{eff}} \) extends over both the black mesa area and the gray regions indicated in Figure 5.1.1. The expressions for \( A_{\text{eff}} \) for a rectangular and a square pixel with side length S, are

\[
A_{\text{eff}}^R = \left( S_1 S_2 + 2(S_1 + S_2)L_P + \pi L_P^2 \right)
\]  
(5.1.4a)

\[
A_{\text{eff}}^S = \left( S^2 + 4SL_P + \pi L_P^2 \right)
\]  
(5.1.4b)

respectively. A substantially similar model is used by Plis et al.\(^{109}\) to calculate the lateral diffusion lengths for absorption layers consisting of type-II InAs / GaSb strained layer superlattices, although the modeled effective area described in that paper features squared off, rather than rounded, corners.
Assuming the values of the two unknowns, $L_P$ and $J$, are common to all devices fabricated from a single growth and measured under the same conditions, the diffusion length may be extracted from current taken as a function of voltage (I-V) data of only two differently sized devices. The determination of $L_P$ relies on the measured current being a function of the effective area, and on the measured current approaching zero as the effective area goes to zero. The method used in this work to estimate $L_P$ can be thought of in graphical terms. The current data point corresponding to a single voltage bias and temperature is recorded for two or more differently sized pixels; all of these devices are products of a single sample growth. These current data are plotted as functions of trial effective areas, which are computed individually for each pixel using a single trial value of $L_P$ and the appropriate version of Equation (5.1.4). A series of these plots is generated by varying the trial value of $L_P$, and by extension the values of the computed trial effective areas. In each plot, a linear fit is applied to the data. The value of $L_P$ identified as being a good estimate of the actual lateral diffusion length is that which results in the linear fit intersecting the origin. This approach is used in the following analysis.

Extracting estimates of the lateral diffusion length from I-V data taken for p-n junction photodiodes is not as straightforward of a proposition. A significant fraction of the total current measured for cooled photodiodes is contributed by surface leakage current, whose presence adds a term proportional to the perimeter of the pixel to the right side of Equations (5.1.4). Without knowledge of the proportionality constant, which in addition to being generally unknown is not expected to be the same for any two photodiodes, estimating the diffusion length of a crystal layer using I-V data from photodiodes is a less attractive approach than using I-V data from nBn photodetectors.

The reverse voltage bias chosen to select the current values used in these calculations is one for which the devices exhibit photosensitivity, but one that does not result in the device being maximally photosensitive. For the lowest device temperatures used in this analysis, the dark currents measured over the range of reverse voltage biases for which the nBn photodetectors are most photosensitive commonly fall near or below the sensitivity limit of the HP Semiconductor Parameter Analyzer. At and below this sensitivity limit, the current data is obscured by system noise. This is a particular problem for the devices with smaller mesa areas. Dark currents corresponding to larger reverse biases are greater in magnitude and are measureable at lower temperatures.
5.1 Calculation of Diffusion Length

Preliminary efforts to determine lateral diffusion lengths are described in Section 5.2. Measurements are taken on several nBn photodetectors processed from growth G2-563, known as Benchmark, which has a history of producing devices exhibiting good performance. These photodetectors possess rectangular, rather than square, mesas, and the local environments of the individual pixels differ from one another. Variations in the data cast doubt on the accuracy of the lateral diffusion lengths calculated from these current measurements. Subsequent sections include the description of a new photolithography mask set, which is designed to both suppress the variations in the measured current and to aid in characterizing the sources of the variations. The new mask set produces square devices, which have similar local environments and are isolated from one another. A selection of crystal growth samples are processed into nBn photodetectors using this mask, and analyses of the results are presented. Included in this selection of samples are a few possessing strained absorption layers. Lateral diffusion lengths are calculated for all samples using the measured I-V data taken at different temperatures. The estimated diffusion lengths are collected in Table 5.4.1, which is found in Section 5.4.4.

5.2 Diffusion Lengths Calculated From Preliminary Experimental Data

Individual photodetectors processed from growth G2-563 (Benchmark) have a history of being strong performers and are considered benchmarks in the MBE Laboratory. This crystal growth sample possesses an unintentionally doped InAs absorbing layer and an AlAs_{0.18}Sb_{0.82} barrier layer. These photodetectors exhibit a weak dependence of the magnitude of the current on reverse bias voltages from 1 to greater than 3 V and BLIP temperatures as high as 220 K.

5.2.1 InAs / AlAsSb on InAs Substrate (G2-563: Benchmark)

Figure 5.2.1 shows curves of I-V data that are taken for a selection of differently sized devices fabricated from sample Benchmark. The physical dimensions of the devices analyzed in this section are listed in Table 5.2.1. The data are taken over a range of temperatures. All of these nBn photodetectors have similar values of thermal activation energies, which are consistent with the thermal activation energies expected of InAs-based nBn photodetectors with this barrier composition.
5.2 Preliminary Data

Figure 5.2.1 I-V curves for Benchmark, various temperatures. Current data are plotted for several devices, listed in Table 5.2.1, fabricated from the Benchmark growth, G2-563.

<table>
<thead>
<tr>
<th>Device</th>
<th>G2-563 E2_10</th>
<th>G2-563 E1_4</th>
<th>G2-563 E6_2</th>
<th>G2-563 E5_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activation Energy [eV]</td>
<td>0.428</td>
<td>0.427</td>
<td>0.430</td>
<td>0.422</td>
</tr>
<tr>
<td>Side Length 1, S1 [cm]</td>
<td>$84 \times 10^{-4}$</td>
<td>$176 \times 10^{-4}$</td>
<td>$234 \times 10^{-4}$</td>
<td>$477 \times 10^{-4}$</td>
</tr>
<tr>
<td>Side Length 2, S2 [cm]</td>
<td>$55 \times 10^{-4}$</td>
<td>$104 \times 10^{-4}$</td>
<td>$175 \times 10^{-4}$</td>
<td>$176 \times 10^{-4}$</td>
</tr>
<tr>
<td>Area of Mesa [cm$^2$]</td>
<td>$4.620 \times 10^{-3}$</td>
<td>$18.304 \times 10^{-3}$</td>
<td>$40.950 \times 10^{-3}$</td>
<td>$83.952 \times 10^{-3}$</td>
</tr>
<tr>
<td>Square pixel equivalent side length [cm]</td>
<td>$67.97 \times 10^{-4}$</td>
<td>$135.29 \times 10^{-4}$</td>
<td>$202.36 \times 10^{-4}$</td>
<td>$289.74 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 5.2.1 Parameters for nBn photodetector devices from Benchmark. These data describe the four pixels discussed in Section 5.2.
Obtaining meaningful effective current density as a function of voltage ($J_{\text{eff}}-V$) data from current as a function of voltage data requires knowledge of the effective areas over which each of the photodetectors collects minority carrier holes. It is expected that when the temperature-dependent effective current density is accurately computed, the four effective current density curves corresponding to each temperature will overlay one another.

**Figure 5.2.2** J-V curves for Benchmark, various temperatures. Current density is shown at left. At right are current data taken at -0.6 V and plotted versus mesa area. The upper-right and lower-right plots correspond to a 270 K and a 171 K device temperature, respectively. Also shown are linear fits to the data, teal crosses marking the origins, and error bars.

Simply dividing each of the current traces by the corresponding mesa area of the pixel does not produce uniformly good overlap of the curves, as seen in Figure 5.2.2. The traces are more closely grouped than they are in the I-V plots of Figure 5.2.1, however. The two plots on the right side of Figure 5.2.2 show current data (black squares) plotted as a function of the mesa area. These data are taken at a bias voltage of -0.6 V and correspond to the warmest and coolest temperatures measured. The teal cross marks the origin, and a linear fit computed for the four points is shown. The intersection of the linear fit with the zero-current line nearly coincides with the origin for the data taken at 270 K, but it is displaced to a larger
5.2 Preliminary Data

degree for the data taken at 171 K. The high degree of scatter of the data points around the linear fit is a concern.

Figure 5.2.3 $J_{\text{eff}}$-$V$ curves for Benchmark, various temperatures. Effective current density is shown at left. At right are current data taken at -0.6 V and plotted versus effective area. The upper-right and lower-right plots correspond to a 270 K and a 171 K device temperature, respectively. Also shown are linear fits, teal crosses marking the origins, and error bars.

The lateral diffusion lengths, which are computed using Equation (5.1.3) and collected in Table 5.4.1, are used to compute the temperature-dependent effective areas. The diffusion lengths for the five warmest temperatures are calculated to be 3 microns or less, while the diffusion lengths at 171 K and 146 K are estimated to be 14 and 86 microns, respectively. The data taken at 146 K are not shown in these figures. The resulting $J_{\text{eff}}$-$V$ curves for each temperature are shown in Figure 5.2.3.

The poor effect of using the estimated lateral diffusion lengths in these effective current density calculations is unexpected. The $J_{\text{eff}}$-$V$ curves in Figure 5.2.3 have a moderately tighter configuration than those in Figure 5.2.2, but they do not overlap at any temperature. The linear fits shown in the rightmost plots pass through the origin, suggesting the lateral
diffusion lengths are accurately computed given the available data, but the degree of scatter around the linear fit casts doubt on the quality of the data. It is not possible to determine from this data whether the scatter is due to one or more poorly performing devices, or whether it correlates with an intrinsic device parameter, such as the area of the mesa.

5.2.2 InAs / AlAsSb on InAs Substrate (G2-563: Benchmark) at 195 K

An investigation into the underlying cause of the scatter in the experimental data presented in Section 5.2.1 is conducted by measuring I-V curves for a greater number of photodetectors from the same Benchmark crystal growth at a single temperature, 195 K.

![I-V curves for Benchmark, 195 K. Measured current is plotted for seven nBn photodetectors fabricated from crystal growth sample Benchmark.](image_url)

**Figure 5.2.4** I-V curves for Benchmark, 195 K. Measured current is plotted for seven nBn photodetectors fabricated from crystal growth sample Benchmark.
In addition to being more numerous, these devices possess a larger variation in pixel sizes than the previous selection. This is expected to help reveal trends in the data, such as whether the scatter is related to the physical area of the pixels. The larger number of devices surveyed should also enable the easier identification of a poorly performing device that may negatively influence the linear fit. The I-V curves of these devices are shown in Figure 5.2.4.

The J-V traces resulting from dividing the current data by the respective mesa areas are plotted on the left in Figure 5.2.5. As seen in Section 5.2.1, this approximation of current density results in a tighter grouping of the curves, but not in a good overlap. The linear fit through the points taken at a -0.6 V bias misses crossing the origin by a wider margin than is seen in the previous section.

The lateral diffusion length is calculated using this data and Equation (5.2.4a). It is estimated to be 122 microns, which is substantially larger than the 3 microns computed in Section 5.2.1 for a device temperature of 195 K.
This larger lateral diffusion length is used to compute the effective areas and corresponding effective current densities for the individual pixels. The resulting curves, plotted in Figure 5.2.6, are more tightly grouped than those in Figure 5.2.5 and those shown in Section 5.2.1, but they still do not overlap well. As in Figure 5.2.3 in Section 5.2.1, the rightmost plot shows considerable scatter of the data around a linear fit that passes through the origin.

**Figure 5.2.6** $J_{\text{eff}}$–$V$ curves for Benchmark, 195 K. Effective current density is shown at left. At right are current data taken at -0.6 V and plotted versus effective area. Also shown is a linear fit, a teal cross marking the origin, and error bars.

That the two smallest devices, E3 and E2, show the greatest deviation from the grouping of curves is interesting but inconclusive; overall, the curves are not positioned according to device size. The displacement of the current density curve for device E2 from the main grouping in Figure 5.2.6 is also in seeming contrast to the current density curves shown in Figure 5.2.3. In the latter case, the curve for photodetector E2 falls within the main grouping. It is again not clear whether one or more of the devices is defective, or if the data follow a trend.
5.3 Revised Photolithography Mask Set

There is little reason, other than the puzzling $J_{\text{eff}}$-V data described in the previous section, to suspect one or more of these devices is a poor performer or conclude that an intrinsic property of the nBn photodetector is perturbing the data. An alternative to pursuing these lines of inquiry is investigating whether the dissimilar local environments surrounding each photodetector pixel significantly influences the results presented in Section 5.2.

The Benchmark crystal growth G2-563 was processed into devices using a “transistor” photolithography mask set, which produces rectangular devices separated from one another by variable widths of material. This material is some combination of exposed and oxidized AlAsSb, unetched material, and unetched material covered by gold. A pictorial representation of a block of devices processed using this mask is shown in Figure 5.3.1.

It is possible that the interface between the exposed and fully oxidized AlAsSb barrier layer and the InAs active layer is a more effective recombination and/or scattering surface for holes than the interface between the un-oxidized AlAsSb buried beneath the InAs contact layer and the InAs active layer. If this is the case, the measured current density would vary with the location of the photodetector within the block of devices and depend on the particular, and variable, fraction of free carriers lost to surface recombination. The effect would reduce the magnitude of the measured current for some devices more than others, but it would not otherwise impact the performance, assessed by metrics such as the BLIP temperature, of individual photodetectors.
Figure 5.3.1 ‘Transistor’ photolithography mask set. Illustrated is the layout of the fabricated devices.
5.3 Photolithography Mask Sets

Figure 5.3.2 Revised photolithography mask set. Illustrated is the layout of the fabricated devices.
5.3 Photolithography Mask Sets

It is difficult to draw conclusions about the effects of the local environment on the measured current using devices fabricated by the transistor photolithography mask. The transistor mask produces many examples of certain types of devices, such as E1, E3 and E9, and none have identical local environments. However, quantifying the effects of a particular local environment on the measured current would require not only defining the extent of the local environment, but also determining the effects of each of the features within the local environment on the measured current. This task is made more difficult in the presence of unrelated effects, such as material dislocations, which also affect the magnitude of the measured current.

A new photolithography mask set is designed by the author for the task of testing and comparing the results of individual nBn photodetectors. It is used in place of the transistor mask set when processing subsequent nBn photodetectors. A pictorial representation of a block of photodetectors produced by this new mask set is shown in Figure 5.3.2. As compared with the transistor photolithography mask set, the new photolithography mask set more tightly constrains the local environment of each pixel to promote the direct comparison of the current data measured for different pixels. Pixels are also made square, as opposed to rectangular, to simplify analysis of the data and because there is no compelling reason prefer a rectangular shape.

In the revised mask set, pixels with side lengths ranging from 10 to 210 microns are surrounded by identical borders consisting of etched material of uniform width. The width of etched material is varied according to which group (A, B C, ...) the pixels belong. Pixels covering three quarters of the device block belong to the A group, featuring a 20 micron etch width, and the B group, which possesses a 50 micron etch width. The remaining quarter of the device block contains pixels of selected side lengths surrounded by etch widths varying from 10 to 200 microns; these are members of groups C through G.

Multiple photodetectors that have the same side length, but which are surrounded by etched borders with a variety of widths, may be used to investigate the impact of a differing local environment on the measured current. The availability of this variety is intended to provide the means to investigate the importance of surface recombination at the interface between the oxidized AlAsSb barrier layer and the underlying InAs active layer. Unprocessed and gold-covered material at least 200 microns in extent separate one pixel from another.
5.4 Diffusion Lengths Calculated from Experimental Data

Temperature-dependent lateral diffusion lengths are calculated using I-V data taken for nBn photodetectors fabricated from four different crystal growths. All growth samples are processed using the revised photolithography mask set. Unfortunately, no unprocessed material remains from Benchmark crystal growth G2-563, which makes it impossible to directly compare the nBn photodetectors presented in Section 5.2 with devices processed using the revised photolithography mask set. As is the case in Section 5.2, current measurements are functions of both voltage and temperature. These data are obtained for pixels with three different side lengths: device 4A has a side length of 60 microns, device 5A has a side length of 90 microns, and device 8A has a side length of 180 microns. All devices belong to pixel group A, in which mesas are surrounded by a 20 micron wide etched border. This border consists of exposed and oxidized AlAsSb.

Devices processed from crystal growth G2-854, which is referred to as InAsControl(GenII), are the subject of Section 5.4.1. These nBn photodetectors possess an InAs absorption layer and an AlAs\textsubscript{0.195}Sb\textsubscript{0.805} barrier layer, and the substrate is InAs. The devices discussed in Section 5.4.2 are fabricated from crystal growth G2-869, which is called InAsSbAbsorber(GenII). These have an InAs\textsubscript{0.89}Sb\textsubscript{0.11} absorption layer and an AlAs\textsubscript{0.21}Sb\textsubscript{0.79} barrier layer, and the substrate is also InAs. Section 5.4.3 discusses data taken for devices produced from samples G4151, which is referred to as GaAsSubstrate(Riber), and G2-858, which is labeled GaAsSubstrate(GenII). Both are grown on GaAs substrates and have InAs absorption layers. The barrier layer of GaAsSubstrate(Riber) is AlAs\textsubscript{0.195}Sb\textsubscript{0.805}, and that of GaAsSubstrate(GenII) is AlAs\textsubscript{0.10}Sb\textsubscript{0.81}. The absorption layers in all samples are unintentionally doped. Crystal growths InAsSbAbsorber(GenII), GaAsSubstrate(Riber), and GaAsSubstrate(GenII) feature absorption layers with lattice constants that are different from those of the respective substrates. The mismatch between the lattice constants is 0.32% for InAsSbAbsorber(GenII) and 7.1% for GaAsSubstrate(Riber) and GaAsSubstrate(GenII).\textsuperscript{32} The absorption layers of these three lattice-mismatched samples are expected to contain dislocations, as they exceed the pseudomorphic critical thickness.\textsuperscript{72} More information about these crystal growth samples may be found in Chapter 4.
5.4 Lateral Diffusion Lengths from Data

5.4.1 InAs / AlAsSb on InAs Substrate (G2-854: InAsControl(GenII))

Figure 5.4.1 shows current data, measured as functions of both voltage and temperature, for three differently sized pixels processed from crystal growth InAsControl(GenII). The thermal activation energies of these three devices range from 0.408 to 0.413 eV.

![Figure 5.4.1 I-V curves for InAsControl(GenII) photodetectors. Current data are plotted for various temperatures for three nBn photodetectors fabricated from InAsControl(GenII).](image)

Calculating current density by dividing the current data by the respective mesa areas of the pixels results in the curves shown in Figure 5.4.2. The poor overlap of the traces at each temperature suggests that it is incorrect to assume the lateral diffusion length is negligible. The two plots at right show current data as a function of the respective mesa areas. The current data are measured with each of the three pixels under an -0.6 V applied bias. The data in the upper-right plot is taken at a device temperature of 308 K, and that in the lower-
right plot at 171 K. The data points show less scatter around the linear fits than is the case in the similar plots shown in Section 5.2. The linear fits in Figure 5.4.2 do not pass through the origin, and in all cases there is an obvious margin separating the location of the origin from the intersection of the linear fit and the zero-current line. This indicates the computed lateral diffusion lengths at all measured temperatures exceed those computed from the current data taken for the devices fabricated from Benchmark and presented in Section 5.2.1.

![Figure 5.4.2](image)

**Figure 5.4.2** J-V curves for InAsControl(GenII) photodetectors. Current density is shown at left. At right are current data taken at -0.6 V and plotted versus mesa area. The upper-right and lower-right plots correspond to a 270 K and a 171 K device temperature, respectively. Also shown are linear fits, teal crosses marking the origins, and error bars.

The left side of Figure 5.4.3 shows the temperature-dependent current density plotted as a function of voltage. The effective current density is obtained by dividing the measured current data by the appropriate value of temperature-dependent effective area. Calculations use current data measured when the device is under a -0.6 V voltage bias, and the effective areas used in these calculations are determined for each pixel size using Equation (5.1.4). For each temperature, the estimate of lateral diffusion length is varied until the linear fit passes through the origin; the two plots at the right of the figure illustrate this. The calculated
5.4 Lateral Diffusion Lengths from Data

Lateral diffusion lengths range from 34 microns at 308 K to 166 microns at 171 K, and these are recorded in Table 5.4.1. The \( J_{\text{eff}} - V \) curves show good overlap with one another for each temperature; the overlap is better than that achieved for the devices of the Benchmark case and shown in Section 5.2. The two plots at right show the experimental data points to be in good agreement with the linear fit.

![Figure 5.4.3](image.png)

**Figure 5.4.3** \( J_{\text{eff}} - V \) curves for InAsControl(GenII) photodetectors. Effective current density is shown at left. At right are current data taken at -0.6 V and plotted versus effective area. The upper-right and lower-right plots correspond to a 270 K and a 171 K device temperature, respectively. Also shown are linear fits, teal crosses marking the origins, and error bars.

The Benchmark and InAsControl(GenII) crystal growths both possess an unintentionally doped InAs absorption layer lattice matched to an InAs substrate. The diffusion lengths computed for the devices fabricated from Benchmark in Section 5.2.1 are not similar to those reported for the InAsControl(GenII) photodetectors in the present section. In Section 5.2.2, current data taken at the single temperature of 195 K for seven Benchmark photodetectors are used to calculate the lateral diffusion length. This estimated lateral diffusion length of 122 microns is nearly identical to that computed for the photodetectors processed from crystal growth InAsControl(GenII), 121 microns. This similarity is interesting and may be significant, but more measurements are required to explore this question. If rates of surface
recombination are higher for the Benchmark photodetectors, as a consequence of the individual devices being surrounded by larger expanses of exposed and oxidized AlAsSb, the minority carrier lifetimes and lateral diffusion lengths are expected to be smaller. It is possible that the scatter in the data taken for the Benchmark photodetectors results in an erroneously high estimated value of the lateral diffusion length at 195 K.

The accuracy of the lateral diffusion lengths calculated for the Benchmark photodetectors is unknown. A pseudo-random phenomenon, related to the local environments of the nBn photodetectors fabricated using the transistor mask set, is posited to affect the magnitude of the currents measured for the Benchmark photodetectors examined in Sections 5.2.1 and 5.2.2. This variation would plausibly have a greater negative impact on the calculated linear fits when a smaller sampling of devices are used, as in Section 5.2.1, than when a larger selection of photodetectors is used, as in Section 5.2.2. Averaging the data obtained for a large enough sampling of devices may allow for a reasonable estimation of an overall lateral diffusion length when the local environments of the devices vary.

When the effects of the local environments of the photodetectors are homogenized, as they are when the devices are processed using the revised photolithography mask set, it is possible that data from substantially fewer devices may be required to obtain a usefully accurate estimate of the lateral diffusion length. In the InAs / AlAsSb nBn photodetector the value of the lateral diffusion length is likely influenced by the area of oxidized AlAsSb surrounding the mesa. However, the precise width of the oxidized AlAsSb material surrounding a particular photodetector pixel is not known. The process of fabricating an nBn photodetector involves etching through the InAs contact layer; a border of exposed AlAsSb, which oxidizes when exposed to air, surrounds the mesa. If oxidation of the exposed AlAsSb layer leads to the oxidation of the adjacent AlAsSb material that is covered by unetched portions of the InAs contact layer, it may be that the border of oxidized AlAsSb material surrounding the measured InAsControl(GenII) photodetector pixels is larger than the nominal etch width. A consequence of this may be that the lateral diffusion length changes with time. This is expected if there is increased rate of surface recombination at the interface between an oxidized AlAsSb barrier layer and the underlying InAs absorption layer, and if the regions of the AlAsSb barrier layer that are covered by the unetched contact layer material become progressively more oxidized with time.
5.4 Lateral Diffusion Lengths from Data

Basing the calculation of lateral diffusion length on current measurements taken for devices fabricated using the revised photolithography mask set and on Equation (5.1.4b) is supported by data presented in this Section. The current density curves presented in Figure 5.4.3 overlap well at each temperature. The current data taken for the Benchmark photodetectors in Section 5.2, which were processed using the transistor photolithography mask set, appear to indicate a pseudo-random, pixel-to-pixel, variation in the lateral diffusion length. It may be possible to calculate an acceptable average value, if data from enough nBn photodetectors are analyzed. Comparison of the data presented in this section and in Section 5.2 suggests the pixel-to-pixel variation in the lateral diffusion length is substantially reduced when the revised photolithography mask set is used to fabricate the nBn photodetectors.

5.4.2 InAsSb / AlAsSb on InAs Substrate (G2-869: InAsSbAbsorber(GenII))

Employing absorption layers of different compositions in the nBn photodetector permits the range of detected wavelengths to be customized. One approach to tuning the cutoff wavelength in a III-V semiconductor-based nBn photodetector is incorporating a lattice-mismatched ternary, rather than the lattice-matched binary, as the absorption layer. Unfortunately, a strained epilayer thick enough to absorb a sufficient number of incident photons generally exceeds the pseudomorphic critical thickness and is expected to possess dislocations, which reduce the diffusion lengths of free carriers by scattering carriers and providing recombination sites.

A trio of nBn photodetectors processed from crystal growth InAsSbAbsorber(GenII) are used to investigate the lateral diffusion lengths of minority carrier holes in the strained InAs$_{0.89}$Sb$_{0.11}$ absorption layer. The InAs$_{0.89}$Sb$_{0.11}$ layer is one micron thick and grown on an InAs substrate. The activation energies of the surveyed devices are ~0.41 eV. Chapter 4 explores the effect of dislocations in the absorption layer on measured current magnitudes and thermal activation energies.

The temperature-dependent I-V data measured for the surveyed InAsSbAbsorber(GenII) photodetectors, which are devices of the type 4A, 5A and 8A and side lengths of 60, 90, and 180 microns respectively, are plotted in Figure 5.4.4.
Figure 5.4.4 I-V curves for InAsSbAbsorber(GenII) photodetectors. Data are plotted for various temperatures for three nBn photodetectors fabricated from InAsSbAbsorber(GenII).

Current density data, which are obtained by dividing the current data plotted in Figure 5.4.4 by the respective mesa areas, are shown in Figure 5.4.5. Using the area of the mesa to approximate the effective area appears to be more accurate for this case than for the cases discussed in the preceding sections. This supports the prediction of minority carriers possessing shorter lateral diffusion lengths in thick lattice-mismatched material than in higher-quality unstrained InAs material. The plot on the upper-right side of Figure 5.4.5 shows the current data points taken for the three devices under a -0.75 V voltage bias, and for a device temperature of 308 K, plotted as a function of mesa area. The plot on the lower-right is similar and corresponds to a temperature of 171 K. In both cases, the experimental data agree well with the linear fits. The differences between the location of the origin and the intersections of the linear fits with the zero-current axis indicate that the actual effective areas
are larger than the physical areas of the mesas at every measured temperature. The difference in the y-axis intercepts between the two rightmost plots is a consequence of the lateral diffusion length increasing with decreasing temperature.

Figure 5.4.5  J-V curves for InAsSbAbsorber(GenII) photodetectors. Current density is shown at left. At right are current data taken at -0.75 V and plotted versus mesa area. The upper-right and lower-right plots correspond to a 270 K and a 171 K device temperature, respectively. Also shown are linear fits, teal crosses marking the origins, and error bars.

Plots of the $J_{\text{eff}}$-V curves, which are obtained by dividing the temperature-dependent measured current data by the respective temperature-dependent effective areas, are shown in Figure 5.4.6. These $J_{\text{eff}}$-V curves overlap well with one another at each temperature. The two rightmost plots show the linear fits passing through the origin and the linear fits in good agreement with the measured data points.

The lateral diffusion lengths are computed for all six temperatures using the measured current data corresponding to a device bias of -0.75 V and Equation (5.4.4a). The calculated diffusion lengths are recorded in Table 5.4.1.
5.4 Lateral Diffusion Lengths from Data

Figure 5.4.6  $J_{\text{eff}}$-$V$ curves for InAsSbAbsorber(GenII) photodetectors. Effective current density is shown at left. At right are current data taken at -0.75 V and plotted versus effective area. The upper-right and lower-right plots correspond to a 270 K and a 171 K device temperature, respectively. Also shown are linear fits, teal crosses marking the origins, and error bars.

These calculated temperature-dependent lateral diffusion lengths, and the trends they follow, contrast with those of the case of the lattice-matched InAs-based nBn photodetectors fabricated from InAsControl(GenII). The magnitudes of the lateral diffusion lengths calculated in this section, for the case of the InAsSbAbsorber(GenII) photodetectors, are essentially invariant from room temperature through 195 K; they vary between 10 and 16 microns. In addition, the lateral diffusion lengths computed for this temperature range are two to three times lower than the lateral diffusion length computed for the lattice-matched InAsControl(GenII) case at room temperature. An increase in the estimated lateral diffusion length for the InAsSbAbsorber(GenII) case occurs definitively for only the lowest device temperature considered here, 171 K. However, this larger lateral diffusion length is still less than that computed for the InAsControl(GenII) case at room temperature.
The differences in the lateral diffusion lengths computed for the InAsContol(GenII) and the InAsSbAbsorber(GenII) cases are a probable result of the higher dislocation density present in the lattice-mismatched $\text{InAs}_{0.89}\text{Sb}_{0.11}$ absorption layer. Dislocations are known to function as recombination and scattering sites for free carriers.$^{100,103-105}$ The minority carrier holes present in the material of crystal growth InAsSbAbsorber(GenII) have a greater probability of recombining at a dislocation before they reach the contact. It is probable that the dislocations effectively screen free carriers located more than a lateral diffusion length distant from the mesa of the test pixel, which leads to minority carriers in InAsSbAbsorber(GenII) photodetectors having a reduced average lateral diffusion length for a given temperature when compared with those in InAsControl(GenII) photodetectors.

5.4.3 InAs / AlAsSb on GaAs Substrates

(G4151: GaAsSubstrate(Riber); G2-858: GaAsSubstrate(GenII))

Growth of epilayers on lattice-mismatched substrates is of general interest, as using lower cost and larger-diameter substrates, such as GaAs, in place of more expensive and smaller substrates, such as InAs, is attractive from cost and manufacturing perspectives.$^2$ While the incentives are undeniable, the approximately 7% mismatch in lattice constants between InAs and GaAs$^{32}$ results in InAs epilayers grown directly on GaAs having high densities of dislocations. While it is accepted that the presence of dislocations negatively affects the performance of semiconductor-based electrical devices,$^{72}$ it is interesting to explore the degree to which nBn photodetectors are affected.

Analysis of InAs-based nBn photodetectors grown on lattice-mismatched GaAs substrates and fabricated from two samples, GaAsSubstrate(GenII) and GaAsSubstrate(Riber), reveal the two to be similar despite having different histories. The growth of GaAsSubstrate(Riber) occurred nearly 3 years before that of GaAsSubstrate(GenII), and it was not stored under inert atmosphere. In addition, GaAsSubstrate(Riber) was grown on the Riber MBE machine using a thin silicon wafer as a carrier wafer, while GaAsSubstrate(GenII) was mounted on a thicker solid molybdenum block and grown using the Gen II MBE machine. Lateral diffusion lengths computed for these two cases appear to be invariant over the examined temperature range, and they are smallest of all cases presented in this chapter.
The average calculated thermal activation energies, ~0.27 eV for the GaAsSubstrate(Riber) photodetectors and ~0.33 eV for the GaAsSubstrate(GenII) photodetectors, are lower than expected for the case of diffusion current dominating the dark current. The thermal activation energies are also lower than the bandgap energy of InAs. This is not the result of measuring devices which perform more poorly than others processed from the same growth; a selection of devices from each sample were surveyed and found to behave similarly. The primary dark current in these devices arises from Shockley-Read-Hall generation current, as discussed in Chapter 4. The nBn photodetectors processed from GaAsSubstrate(Riber) and GaAsSubstrate(GenII) and examined in this section perform well enough to achieve BLIP operating conditions.
Temperature-dependent current-voltage data are measured for the nBn photodetectors processed from growths GaAsSubstrate(Riber) and GaAsSubstrate(GenII) and are plotted in Figures 5.4.7 and 5.4.8, respectively. The current traces for these two cases are more tightly grouped at each temperature than is true for both the InAsControl(GenII) case, in which a lattice-matched InAs absorption layer is grown on an InAs substrate, and the InAsSbAbsorber(GenII) case, in which a lattice-mismatched InAs$_{0.95}$Sb$_{0.05}$ absorption layer is grown on an InAs substrate. This indicates the lateral diffusion lengths of GaAsSubstrate(Riber) and GaAsSubstrate(GenII) are comparatively smaller.

![Figure 5.4.8](image)

**Figure 5.4.8** I-V curves for GaAsSubstrate(GenII) photodetectors. Current data are plotted for various temperatures for three nBn photodetectors fabricated from GaAsSubstrate(GenII).

Current density data are calculated by dividing the current data shown in Figures 5.4.7 and 5.4.8 by the respective physical mesa areas of the pixels. These approximations of current density for the GaAsSubstrate(Riber) and GaAsSubstrate(GenII) cases are plotted in Figures...
5.4.9 and 5.4.10, respectively. In both of these cases, the current density curves are closely grouped at every temperature, which is in contrast to the cases examined in previous sections; unlike the previously discussed cases, the values of current density computed for the GaAsSubstrate(Riber) and GaAsSubstrate(GenII) cases closely approximate values of effective current density. As the current traces at each temperature nearly overlap, each of the linear fits to the data shown in the rightmost plots of both figures is close to intersecting the origin.

![Figure 5.4.9](image)

**Figure 5.4.9** J-V curves for GaAsSubstrate(Riber) photodetectors. Current density is shown at left. At right are current data taken at -0.5 V and plotted versus mesa area. The upper-right and lower-right plots correspond to a 270 K and a 171 K device temperature, respectively. Also shown are linear fits, teal crosses marking the origins, and error bars.
Figure 5.4.10  J-V curves for GaAsSubstrate(GenII) photodetectors. Current density is shown at left. At right are current data taken at -0.75 V and plotted versus mesa area. The upper-right and lower-right plots correspond to a 270 K and a 171 K device temperature, respectively. Also shown are linear fits, teal crosses marking the origins, and error bars.

Estimates of the temperature-dependent lateral diffusion lengths are calculated for the GaAsSubstrate(Riber) and GaAsSubstrate(GenII) cases, and these are recorded in Table 5.4.1. The calculations are made using Equation (5.1.4b) and current data taken when the GaAsSubstrate(Riber) and GaAsSubstrate(GenII) photodetectors operate under -0.50 V and -0.75 V voltage biases, respectively.
5.4 Lateral Diffusion Lengths from Data

Figure 5.4.11 $J_{\text{eff}}$-$V$ curves for GaAsSubstrate(Riber) photodetectors. Effective current density is shown at left. At right are current data taken at -0.5 V and plotted versus effective area. The upper-right and lower-right plots correspond to a 270 K and a 171 K device temperature, respectively. Also shown are linear fits, teal crosses marking the origins, and error bars.

Plots of the $J_{\text{eff}}$-$V$ curves resulting from dividing the measured current data for each device by the respective effective areas are shown in Figures 5.4.11 and 5.4.12. In both cases, the $J_{\text{eff}}$-$V$ curves overlap well at each temperature. The rightmost plots in both figures show the linear fits passing through the origin, and the experimental data points show little scatter around the corresponding linear fit.
5.4 Lateral Diffusion Lengths from Data

Figure 5.4.12 $J_{\text{eff}}$-V curves for GaAsSubstrate(GenII) photodetectors. Effective current density is shown at left. At right are current data taken at -0.75 V and plotted versus mesa area. The upper-right and lower-right plots correspond to a 270 K and a 171 K device temperature, respectively. Also shown are linear fits, teal crosses marking the origins, and error bars.

The lateral diffusion lengths computed in both cases are approximately invariant over the entire investigated temperature range, 171 K < T < 308 K, which is not true of the other cases examined in previous sections of this chapter. The average lateral diffusion length for GaAsSubstrate(Riber) case is slightly higher than that of the GaAsSubstrate(GenII) case, which is assumed to be a consequence of the higher dislocation density in the latter, as is discussed in Chapter 4.

5.4.4 Conclusions

As expected, the magnitudes of the estimated lateral diffusion lengths generally increase with decreasing temperature, and they also decrease with increasing densities of dislocations in the absorption layer. Unexpected were the large calculated magnitudes of the lateral
diffusion lengths, especially those calculated for the case of nBn photodetectors fabricated from lattice-matched InAs / AlAsSb epilayers grown on InAs substrates. These estimated lateral diffusion lengths are larger than the effective minority carrier lifetimes reported in the literature for bulk InAs suggest is possible. The diffusion length at 77 K is predicted to be just under 40 microns when the published overall lifetime, $3.18 \times 10^{-6}$ s, and diffusion coefficient at 77 K, $4.58 \text{ cm}^2/\text{s}$, are used in Equation (5.1.1). The authors of Reference 110 finds this measured effective lifetime is limited by surface recombination. When the authors instead use the calculated Auger lifetime of $7.67 \times 10^{-4}$ s, the diffusion length is predicted to be around 590 microns. This suggests that surface recombination in the absorption layer of the nBn photodetector is suppressed, which may be a result of the influence of the overlying and intact barrier layer. Plis. et al. have reported values of lateral diffusion lengths computed using temperature-dependent current measurements taken for nBn photodetectors that use type-II InAs / GaSb strained layer superlattices as absorption layers. The lateral diffusion lengths they report for warmer temperatures, $250 \text{ K} < T < 300 \text{ K}$, are less than 20 microns, but the values increase markedly for progressively cooler temperatures; they reach 50-60 microns at 170 K and are as high as 90-100 microns at 77 K.

The data reported by Plis et al. contain two notable trends shared with the data reported in this chapter. The first is the highest temperature for which the lateral diffusion length begins to increase. The epilayers comprising the lattice-matched sample InAsControl(GenII), which is discussed in this chapter, are expected to contain low densities of dislocations and scattering sites. The devices measured by Plis et al. incorporate InAs / GaSb strained layer superlattices, which are expected to scatter carriers at the multiple material interfaces. In the case of InAsControl(GenII), the lateral diffusion length immediately increases as the temperature is lowered from 308 K. The data reported by Plis et al. show a rise in diffusion length occurring only for temperatures lower than 250 K. Referencing the results reported by Plis et al. and the InAsControl(GenII) case data, the dislocations present in growth samples InAsSbAbsorber(GenII), GaAsSubstrate(GenII), and GaAsSubstrates(Riber) appear to have a larger negative impact on free carriers than scattering from the InAs / GaSb strained layer superlattices. In the case of InAsSbAbsorber(GenII), an increase in the estimated diffusion length first occurs at the comparatively low temperature of 171 K, and no increase is seen for the data derived from samples GaAsSubstrate(GenII) and GaAsSubstrate(Riber). This is reasonable, as GaAsSubstrate(GenII) and GaAsSubstrate(Riber) are expected to have the highest dislocation densities and suffer the greatest degradation in performance.
5.4 Lateral Diffusion Lengths from Data

The second trend in the estimated lateral diffusion length data is the rate at which the lateral diffusion lengths increase with decreasing temperature. Comparing the data of Plis et al. with the data obtained for the InAsControl(GenII) case, the lateral diffusion lengths of the former increase at approximately half the rate of the latter. This difference seems reasonable in light of the projected difference in scattering center densities between the two. Overall, the values of the lateral diffusion lengths presented in this chapter, including those based on sample InAsControl(GenII), appear to be consistent with one another and the results of a similar analysis reported in the literature.

The local physical environments of the pixels and the crystalline qualities of the epilayers appear to influence the values of the lateral diffusion lengths calculated using the method described in this chapter. Differences in the physical layout of the local environment of the InAs / AlAsSb nBn photodetectors apparently result in pseudo-random variations in the magnitudes of the measured device currents. It is concluded that the quantity and physical layout of the exposed, and therefore oxidized, AlAsSb barrier layer surrounding an nBn photodetector pixel influence the magnitude of the current collected by a pixel. This may occur as the result of a compromised interface between the oxidized AlAsSb barrier layer and the underlying absorption layer providing more opportunities for recombination and scattering than exist when the barrier layer is not oxidized.

Although it is difficult to quantify and remove the effects of these variations on the necessary pixel-by-pixel basis, it may be possible to obtain a useful average value of the lateral diffusion length by calculating it using the I-V measurements from a large enough selection of pixels (Sections 5.2.1 and 5.2.2). An alternative to this approach is working with pixels possessing similar local environments. With homogenized local environments, the pixel-to-pixel variations are reduced and the I-V measurements of fewer devices are necessary to calculate acceptably accurate values of the lateral diffusion lengths (Section 5.4.1). It should also be possible to quantify the effect the local environment of the pixel has on the calculated lateral diffusion length. The approach recommended in this work is fabricating several sets of nBn photodetector pixels, in which each set has a different and well-defined local environment, from a single growth sample. The lateral diffusion length for each set should be calculated from the I-V measurements and then compared with the others.
Table 5.4.1  Lateral diffusion lengths computed from experimental data. Current measurements used in the calculations are taken for nBn photodetectors fabricated from portions of the listed sample crystal growths. The Benchmark photodetectors are processed using the transistor photolithography mask set, and all others are processed using the revised photolithography mask set.

The values of the lateral diffusion lengths calculated for the lattice-matched InAsControl(GenII) case are plotted on a semi-logarithmic scale in Figure 5.4.13 as a function of inverse temperature. It appears that these data can be described using two linear fits; the data corresponding to the warmer temperatures have a steeper slope than those taken at cooler temperatures. This suggests that the magnitude of the lateral diffusion length is subject to an as-yet undefined process characterized by high and low temperature thermal activation energies.
Figure 5.4.13  Calculated lateral diffusion lengths with linear fits. Data is calculated for the lattice-matched InAsControl(GenII) case. Two linear fits are applied to the data, and the one with the steeper slope corresponds to the warmer temperature region.