Factors affecting carrier transport in ultrafast III-V compound semiconductor based photodiodes

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FACTORS AFFECTING CARRIER TRANSPORT IN ULTRA-FAST III-V COMPOUND SEMICONDUCTOR BASED PHOTODIODES

A Dissertation

Presented to

The Faculty of the Department of Applied Science

The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of

Doctor of Philosophy

by

James McAdoo

2000
APPROVAL SHEET

This dissertation is submitted in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

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Approved, May 2000

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# Table of Contents

Acknowledgements vii  
List of Tables ix  
List of Figures x  
Abstract xiv  

Chapter 1  Introduction 2  

Chapter 2  Review of MSM Photodetector Technology ..........................................................7  
2.1  Response Time of MSM Photodetectors ...............................................................7  
2.1.1  Transit-time Limited MSM Photodetectors ..................................................7  
2.1.2  Recombination Time Limited MSM Photodetectors .......................8  
2.2  Limitations of LT GaAs MSM Photodetector Technology ..................10  

Chapter 3  Challenges to Ultrafast MSM Photodetector Technology ..........12  
3.1  Nanoscale Device Sizes .........................................................................................12  
3.2  Limits on Understanding of MSM Photodetector Performance .............13  
3.3  Surface Effect Limitations on MSM Photodetector Performance ..........16  
3.3.1  Early Experience with Surface Effects in MSM Photodetectors ...16  

Chapter 4  Motivation for Surface Effect Study in MSM Photodetectors ...21  
4.1  Importance of Surface States to Advances in MSM Photodetector Technology ........................................................................................................21  

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
4.1.1 Nanoscale MSM Photodetector Technology Issues .............. 21
4.1.2 MSM Photodetectors on GaSb and Other Materials .......... 22
4.1.3 Potential Benefits of Surface Recombination in MSM

Photodetectors ................................................................. 23

4.2 Limitations of Previous Assessments of Surface Effects in MSM

Photodetectors and Rationale for this Study ......................... 24

Chapter 5 Research Goal and Plan ........................................ 26
5.1 Experimental Design ..................................................... 26
5.2 Implementation ............................................................. 27

Chapter 6 Description of Experiments .................................... 29
6.1 Device Design and Fabrication ........................................ 29
6.2 Note on History of Devices .............................................. 37
6.3 Description of Surface Treatments Used ......................... 38
6.4 Description of Device Performance Tests ....................... 44

6.4.1 Dark Current ............................................................ 44
6.4.2 Capacitance ............................................................. 45
6.4.3 Optical Response ...................................................... 46
6.4.4 Frequency Response ................................................ 48

6.5 De-embedding of Frequency Response Data ................... 52

Chapter 7 Experimental Results ........................................... 56
7.1 Dark Current ............................................................... 56

7.1.1 Stability Considerations ............................................ 56
7.1.2 Process Effects on Dark Current and Leakage ............. 59
7.2 Capacitance Measurements ................................................................. 72
7.3 Optical Response Measurements .......................................................... 79
7.4 Frequency Response Measurements ...................................................... 86
Chapter 8 Simulation and Modeling .......................................................... 98
  8.1 Simulation Software ........................................................................... 98
  8.2 Description of Simulated Structures .................................................... 100
Chapter 9 Comparison Between Simulation and Experiment ...................... 102
  9.1 Surface Effect Simulations ................................................................. 102
  9.2 Comparison with Experimental Results .............................................. 104
  9.3 Parametric Sensitivity Analysis of Results .......................................... 111
Chapter 10 Interpretation of Results and Conclusions ............................... 116
  10.1 Disagreement Between Experimental Results and Surface Effect Models
       Considered ....................................................................................... 116
  10.2 Limitations of Surface Effect Models Considered .............................. 117
  10.3 Alternate Explanations of Results ..................................................... 118
  10.4 Limitations on Computational Methods ............................................ 120
    10.4.1 Computational Methods ......................................................... 120
    10.4.2 Boundary Condition Limitations ............................................. 121
    10.4.3 Indicated Improvements .......................................................... 121
  10.5 Conclusions ..................................................................................... 122
Chapter 11 Suggestions for Future Work .................................................. 124
Appendix A DEVICE FABRICATION PROCESS FLOW ............................. 126

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List of Tables

3.1 Survey of previous simulations of MSM photodetectors.................................15
6.1 Estimated MSM Photodetector performance factors.........................................36
6.2 Designation of samples for controlled damage experiment.............................39
9.1 Comparison of optical response fitting parameters (in Volts) for different cases studied........................................................................................................114
9.2 Comparison of 3 dB frequencies (GHz) for different cases studied..................115
List of Figures

1.1 MSM photodetector geometry and principal of operation.................................3
1.2 Comparison of planar/vertical PD geometries.........................................................5
3.1 Long-duration impulse response photocurrent tail characteristic of MSM
photodetectors with surface trapping effects.................................................................17
3.2 Illustration of surface trapping process that leads to MSM impulse response tail by
altering electric field profile and thus tunneling currents near electrodes....................18
6.1 Vertical cross section of MSM device structure used in this study showing epitaxial
layer structure. Note that all layers are nominally undoped with residual n-type carrier
concentration......................................................................................................................30
6.2 Scanning electron microscope (SEM) photograph of typical MSM photodetector used
in this study showing mesa isolation and device overview............................................33
6.3 Scanning electron microscope (SEM) photograph of typical MSM photodetector used
in this study showing enlarged view of bond pad region.................................................34
6.4 Scanning electron microscope (SEM) photograph of typical MSM photodetector used
in this study showing detailed view of interdigitated electrode pattern.........................35
6.5 Ion implant geometry used in controlled damage surface study..........................41
6.6 Calculated implant profiles into detector active layer..............................................42
6.7 Calculation of implant profiles into metal electrodes.................................43
6.8 Experimental setup used for frequency response measurements...............49
7.1 Five year dark current stability data for device from sample #2 ..............57
7.2 Five year optical response stability data for device from sample #2 .......58
7.3 Dark current comparison for device prior to and after H implantation (high dose)...60
7.4 Optical response comparison for device prior to and after H implantation (high
dose).................................................................................................................61
7.5 Dark current comparison between as-fabricated and H annealed devices.....63
7.6 Dark current comparison between low dose H and He surface implanted devices...64
7.7 Dark current comparison between medium dose H and He surface implanted
devices..................................................................................................................65
7.8 Dark current comparison between high dose H and He surface implanted devices...66
7.9 Dark current comparison across dose range for H surface implanted
devices..................................................................................................................67
7.10 Dark current comparison across dose range for He surface implanted devices......68
7.11 Detailed SEM image of device with high dark current at low bias.................70
7.12 Capacitance comparison between as-fabricated and H annealed devices........73
7.13 Capacitance comparison between low dose H and He surface implanted devices„74
7.14 Capacitance comparison between medium dose H and He surface implanted
devices..................................................................................................................75
7.15 Capacitance comparison between high dose H and He surface implanted devices..76
7.16 Capacitance comparison across dose range for H surface implanted devices......77
7.17 Capacitance comparison across dose range for He surface implanted devices ..........78
7.18 Optical response comparison between as-fabricated and H annealed devices ..........80
7.19 Optical response comparison between low dose H and He surface implanted devices ......................................................................................................................................................81
7.20 Optical response comparison between medium dose H and He surface implanted devices ......................................................................................................................................................82
7.21 Optical response comparison between high dose H and He surface implanted devices ......................................................................................................................................................83
7.22 Optical response comparison across dose range for H surface implanted devices ......................................................................................................................................................84
7.23 Optical response comparison across dose range for He surface implanted devices ......................................................................................................................................................85
7.24 Smoothing function used to recover useful frequency response data from noise ....87
7.25 Frequency response comparison between as-fabricated and H annealed devices ....89
7.26 Frequency response comparison between low dose H and He surface implanted devices ......................................................................................................................................................90
7.27 Frequency response comparison between medium dose H and He surface implanted devices ......................................................................................................................................................91
Figure 7.28 Frequency response comparison between high dose H and He surface implanted devices ......................................................................................................................................................92
7.29 Frequency response comparison across dose range for H surface implanted devices ......................................................................................................................................................93
7.30 Frequency response comparison across dose range for He surface implanted devices..................................................................................................................................................94

7.31 Frequency response comparison across dose range for H surface implanted devices normalized to as-fabricated control devices..............................................................................................................96

7.32 Frequency response comparison across dose range for He surface implanted devices normalized to as-fabricated control devices..............................................................................................................97

9.1 Comparison between simulated and measured dark current for as-fabricated device..................................................................................................................................................106

9.2 Comparison between simulated and measured frequency performance of as-fabricated device..................................................................................................................................................107

9.3 Comparison between frequency response measurements and simulations performed assuming a doped surface layer...........................................................................................................................................108

9.4 Comparison between frequency response measurements and simulations performed assuming surface SRH recombination....................................................................................................................................109

9.5 Comparison between optical response measurements and simulations. Measured points are plotted with symbols only...........................................................................................................................................110

9.6 Comparison between measured responsivity for device implant with high dose of He and fitted voltage dependency...........................................................................................................................................113

10.1 Simulated optical response comparison between as-fabricated device, Device with charged surface traps, and device with doped surface layer...........................................................................................................................................119
Abstract

This dissertation describes a comparative study conducted on GaAs MSM photodetectors to assess the importance of surface effects on the optical and frequency response characteristics of MSM photodetectors. MSM photodetectors on III-V compound semiconductors are technologically important because of their applications to fiber optic communication systems. While surface effects have been previously ignored, they must be considered in assessing the ultimate performance limits of such devices, especially if nanoscale MSM photodetectors are to be used. A controlled study was carried out in which high quality devices were subjected to surface damage over a known range and the resultant effects of optical and high frequency performance were observed and correlated with the damage.
FACTORS AFFECTING CARRIER TRANSPORT IN ULTRA-FAST III-V COMPOUND SEMICONDUCTOR BASED PHOTODIODES
Chapter 1

Introduction

Metal-Semiconductor-Metal (MSM) photodetectors have been extensively studied because of their usefulness in high-speed fiber optic receiver applications. These devices are very useful in monolithic Opto-Electronic Integrated Circuit (OEIC) based designs because of their fast response times, ease of fabrication, low capacitance per unit area values compared with other ultrafast detector structures, and compatibility of processing with Metal Semiconductor Field Effect Transistors (MESFETs) [1], [2], [3]. In addition, these devices may have useful applications in the generation of THz signals needed for sub-millimeter wavelength spectroscopy [4].

The structure and operation of the MSM photodetector is shown in Figure 1.1. It consists of a set of interdigitated electrodes deposited on top of an optically active semiconductor layer, typically GaAs or InGaAs [5]. The electrodes are biased to alternating potentials, as seen in this illustration. Incident optical radiation is absorbed in the gap between the electrodes and generates electron-hole pairs, leading to an external current.
Figure 1.1: MSM photodetector geometry and principal of operation
The planar geometry is the key to obtaining lower capacitance than is possible for PIN photodiodes or other devices with a vertical architecture. While closed form analytic expressions for capacitance for each type of device have been developed [6], [7], an examination of Figure 1.2 yields simple insight into this advantage. As seen in this figure, the electric field lines from the positive to negatively biased contacts in the vertical/PIN structure are all directed through the semiconductor layer, which has a high dielectric constant, typically ~13 for GaAs [8]. On the other hand, approximately half the electric field lines in the MSM device pass through the semiconductor. The rest pass through the air (or vacuum), with its dielectric constant of 1. Thus, the capacitance of an MSM device is lower by a factor of two or more than a comparable PIN or other vertical junction device for a given spacing between electrodes. The advantage of lower capacitance is offset slightly by the two-dimensional electric field distribution inside the device, which makes it more difficult to achieve fast response times [7].
Vertical Photodiode
• All E-Field Lines Through High Dielectric Const.
• Transit Time Limited by Active Layer Thickness

Planar Photodiode
• Only HALF of E-Field Lines Through High Dielectric Const.
• Transit Time Limited by Electrode Spacing AND Absorption Region Thickness

Figure 1.2: Comparison of planar/vertical PD geometries
The advantages of this reduced capacitance become more important as faster devices are sought. In order to reduce capacitance in either geometry, the device dimensions must be reduced. This reduction, however, cannot be carried on indefinitely because light must be focused into the active area. If this active area is made too small, the spot size limitation imposed by diffraction will not allow this to be accomplished. The result will be a fast device that cannot be used in practice. A device with a smaller capacitance per unit area will help alleviate this problem by allowing a larger device to be built for a given capacitance target value. This is where the advantages of MSM devices are most clear.

The reason MSM photodetectors are compatible with MESFET or HEMT processing is that the detectors can be defined with the same metalization step used to form the FET gates. Accordingly, a separate step to define the vertical absorption layer with a junction is not needed. This makes them easier to integrate with OEICs.
Chapter 2

Review of MSM Photodetector Technology

2.1 Response Time of MSM Photodetectors

As discussed by Klingenstein et. al., the photocurrent is dominated by displacement current induced on the electrodes by the presence of carrier motion in the gaps as opposed to the particle current collected at the surfaces of the electrodes [9]. It is important to understand the entire ensemble of carriers in the active layer and their motion to comprehend the overall current. For high speed applications such as fiber-optic communications and THz signal generation, the response time of the photodetector employed should be as short as possible.

2.1.1 Transit-time Limited MSM Photodetectors

If the electrodes form Schottky (rectifying) contacts with the material, then electrons and holes are collected and removed at the electrodes and the response time is dominated by the carrier transit time [3]. Provided that the gap regions are fully depleted of majority carriers by application of an appropriate bias voltage[7], there will be no opportunity for electrons and holes to recombine with them [10], and thus because
collection at the electrodes represents the only significant mechanism for removal of photogenerated carriers. The current transient produced in response to an extremely short pulse of light will not end until all the moving photogenerated carriers have been removed from the active layer.

In such a situation, the response time can be very crudely estimated as:

\[ \tau_{\text{FWHM}} = \frac{W_g}{2v_{\text{car}}}, \]

where \( \tau_{\text{FWHM}} \) is the full-width at half-maximum (FWHM) duration of the response of the device to a pulse of light of infinitesimal duration applied at \( t=0 \). \( W_g \) is the gap width, and \( v_{\text{car}} \) is the carrier velocity. Since electrons and holes can have different velocities in many materials, the response time limiting factor will be the velocity of the slower carrier, which should be used in this equation. This equation follows Sze [11] in assuming one-dimensional transport of carriers at a fixed constant velocity. In general, the so-called transit time limited response will depend on a much more complicated set of factors discussed below.

2.1.2 Recombination Time Limited MSM Photodetectors

Under other conditions, carriers may also be removed by recombination. Equation (1.1) predicts that a time response on the order of a few picoseconds or less would require an electrode gap width of a few tenths of a micron or less. This so-called "transit-time" approach to achieving high speed response poses significant technological and practical challenges. Another way to achieve fast response is to deliberately introduce recombination centers during the fabrication process. In the case of GaAs, this
may be done by Molecular Beam Epitaxy (MBE) growth of GaAs at lower than normal temperatures (typically 150-200 C). Growth at these temperatures leads to traps in the so-called LT GaAs, which cause recombination, presumably by the Shockley-Read-Hall mechanism [9]. If the recombination time is made shorter than the transit time for the structure, to first order the transient photocurrent response of the device will follow an exponential decay with a characteristic time constant equal to the carrier lifetime [12]. Cases using GaAs grown at intermediate temperatures based on the best trade-off between lifetime and transit-time are also possible [13].

Currently, the fastest demonstrated photodetectors have been recombination time limited MSM devices on GaAs [12], [14], which give response times of 0.75-1 psec. However, as pointed out by Chou, this response is achieved at the expense of sensitivity unless the electrode spacing is made very small [15]. This is because the fast response time of such devices is achieved by trapping carriers that would be collected in a transit time limited device [9]. The photoconductive gain for LT GaAs MSM photodetectors can be approximated as $T_{\text{rec}}/T_{\text{tr}}$, where $T_{\text{rec}}$ is the recombination lifetime of the material and $T_{\text{tr}}$ is the intrinsic transit time of the device structure [11]. Thus, decreasing the lifetime of the carriers without reducing the transit time results in a faster response at a lower gain. Furthermore, the response time in this case cannot be made shorter than the lifetime of the carriers. In a transit-time limited device, the drift time to the electrodes is considered the recombination time, leading to a device with a photoconductive gain of unity in this limit.
2.2 Limitations of LT GaAs MSM Photodetector Technology

To obtain high sensitivity and fast response simultaneously requires decreasing the electrode spacing. In the past, it has been very difficult to produce gap sizes needed for sub-picosecond response times [12]. Recombination time limited LT GaAs based MSM photodetectors are therefore still attractive in that they at least offer such fast response times, albeit at substantially reduced sensitivity. Recently, however, advances in lithography have made devices with the appropriate feature sizes (<300 nm) possible. Such devices have generally been fabricated using direct-write electron beam lithography to define the electrodes, so only a small number of groups can make them.

There is another problem with this approach. LT GaAs works adequately at wavelengths shorter than 850 nm or so, but the method has not been successfully generalized to other material systems. Attempts to introduce controlled, fast recombination centers in InGaAs for operation at 1310 nm and 1550 nm, as needed for long-haul fiber optic systems, have not been successful. Although ultrafast photodetectors based on LT InGaAs have been reported, reduced sensitivity is unacceptably severe with InGaAs [14]. Thus, transit-time limited devices with a response time in the picosecond regime are still needed.

If a device structure with a transit time of a few picoseconds, or less, were produced, it would not be necessary to introduce traps into the bulk material in order to reduce the response time to the desired value. In fact, it would probably be undesirable to do so, since LT GaAs exhibits lower mobility than standard GaAs (~200 vs.
$\approx 10000 \text{ cm}^2/\text{V sec.}$ [14.16]. Reducing the carrier lifetime if the transit time of the device is already short enough will simply result in a slower device for a given electrode gap.
Chapter 3

Challenges to Ultrafast MSM Photodetector Technology

3.1 Nanoscale Device Sizes

The benefits above, however, can only be achieved if the transit time can be made shorter than the carrier lifetime. For current technology, this corresponds to transit time values of \( \sim 1 \text{ psec.} \)\textsuperscript{[15]}. It is not presently known if such response times are achievable for transit time limited devices. Our survey of current literature has uncovered only two attempts at producing transit time limited MSM devices with feature sizes of \(< 300 \text{ nm.}\) The first \textsuperscript{[12]} was conducted on devices where the expected RC time constant (1.56 psec.) exceeded the expected transit time (0.4 psec.). Thus, only an upper bound of \( \sim 1.6 \text{ psec.} \) can be inferred for the actual transit time. Another study \textsuperscript{[17]} demonstrated a FWHM response time of approximately 2 psec. (100 nm gap width). Although the study of \textsuperscript{[17]} was conducted with a device scaled to yield a suitably small RC time constant, the laser used for testing operated at 832 nm. This results in substantial generation of charge at depths in excess of 0.5 \( \mu \text{m} \) because of the long penetration of 832 nm light into GaAs.
The carrier transport time is severely degraded by the large vertical distance the carriers must traverse to reach the surface.

3.2 Limits on Understanding of MSM Photodetector Performance

In addition to a lack of experimental data on whether sub picosecond response times are possible, there is a lack of modeling data as well. Simulation of carrier transport on a sub-picosecond time scale on sub-half micron device structures requires that hot carrier effects, such as ballistic transport, velocity overshoot, and perhaps even quantum mechanical effects (i.e. tunneling) be included [18]. Furthermore, as seen in the case of LT GaAs MSM photodetectors, effects of non-ideal lattice conditions can become dominant. Our survey of the literature on modeling MSM photodetectors shows that most models contain one or more of a variety of simplifying assumptions. These include:

1. use of drift-diffusion models
2. perfect Schottky (or ohmic) contacts
3. no recombination or
4. recombination via a single trap mechanism
5. ideal band structure
6. one dimensional carrier transport
7. surface effects neglected
8. neglect of velocity overshoot effects [15], [17], [19], [12], [3], [20].

Perfect Schottky contacts are assumed to be have a spatially uniform barrier height, no series resistance, and an ideality factor of unity. The current flow through them is assumed to be determined by thermionic emission with the image force effect accounted.

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for as described by Sze [11]. All of the modeling results surveyed so far include at least one such assumption. Table 3.1 provides a survey of a sample of previous MSM photodetector simulation studies.
<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Simplifying Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sano [5]</td>
<td>single trap mechanism, perfect Schottky contacts, ideal band structure, surface effects ignored</td>
</tr>
<tr>
<td>Chou and Liu [12]</td>
<td>perfect blocking contacts, no recombination, single scattering mechanism with “fitted” rate constant, surface effects ignored, one dimensional analysis, velocity overshoot ignored</td>
</tr>
<tr>
<td>McAdoo and Joshi [17]</td>
<td>perfect Schottky contacts, recombination via. single trap mechanism, ideal band structure, surface effects ignored</td>
</tr>
<tr>
<td>Koscielniai et. al.[20]</td>
<td>perfect Schottky contacts, no recombination, ideal band structure, one dimensional analysis, surface effects ignored</td>
</tr>
<tr>
<td>Sano [19]</td>
<td>perfect Schottky contacts, recombination via. single trap mechanism, ideal band structure, surface effects ignored, drift diffusion equation, velocity overshoot ignored</td>
</tr>
<tr>
<td>Soole &amp; Schumacher[3]</td>
<td>no recombination, contacts ignored, surface effects ignored, ideal band structure, drift-diffusion equations, velocity overshoot ignored</td>
</tr>
</tbody>
</table>

Table 3.1: Survey of previous simulations of MSM photodetectors
3.3 Surface Effect Limitations on MSM Photodetector Performance

Of these effects, a case can be made that surface effects are the least understood. Of the other limitations in the studies cited above, most can easily be remedied. For example, while simplified band structure models are usually used by most workers, more complicated and realistic ones have been computed and are available if needed [21]. Two dimensional effects are now consistently incorporated as computers have become faster and more powerful [22]. Similarly, full ensemble Monte-Carlo simulations contain ballistic and velocity overshoot effects sometimes neglected on devices with larger feature sizes and can be easily upgraded to include realistic scattering mechanisms.

3.3.1 Early Experience with Surface Effects in MSM Photodetectors

Surface effects, on the other hand, are hardly mentioned in current discussions of MSM photodetectors, although they are likely to be very important. Early investigators [23], [24], [25] quickly found that MSM devices often exhibit a response time degrading tail in the impulse response. That is, when stimulated with a short pulse of light, the current transient falls off exponentially initially and then exhibits a significant response for a comparatively long time as seen in Figure 3.1 [23]. This tail was eventually ascribed to surface effects related to trapped charge [24], [25]. MSM devices can also have a tail in the impulse response caused by the slow moving holes [3], but this is a much smaller effect than the serious degradation caused by the trapping effects.

MSM photodetectors are especially sensitive to surface traps because of their geometry. As seen in Figure 3.2, electrons trapped near the surface can be in close to the
Figure 3.1: Long-duration impulse response photocurrent tail characteristic of MSM photodetectors with surface trapping effects
Figure 3.2: Illustration of surface trapping process that leads to MSM impulse response tail by altering electric field profile and thus tunneling currents near electrodes.
edges of the metal electrodes. This situation can lead [26] to modification of the electric field near the contact, which in turn lead to increased tunneling current as well as changes in the image-force effect that determines the thermionic emission current from the electrodes. The duration for which this extra current persists is determined by the lifetime of the trap and is therefore controlled by the gap width. For traps with a long lifetime, this can lead to a very long tail. Also seen in situations where this tail is present is the anomalous low frequency gain effect. Because trapped carriers modulate tunneling or thermionic current from the Schottky contact until they are de-trapped, the effect from this extra component can be large enough to result in an apparent quantum efficiency (the number of photoelectrons delivered by the device to the external circuit per incident photon). This is strictly a low frequency component, however, because while the carriers de-trap at some later time, the duration of this process is not nearly fast enough to follow an ultrafast fluctuating optical signal. Thus, the device appears to have a large gain at DC [27] that eventually “rolls-off” asymptotically at high frequencies to the normally expected quantum efficiency. Since this effect is sensitive to electric fields and band bending, it also results in a photocurrent that is a strongly increasing function of DC bias [28], providing a signature of devices which have surface problems.

Once the cause of this effect was deduced in terms of surface states, the solution applied was to keep the photo-generated carriers away from the surface and avoid trapping by the surface states. This was done in either of two ways. The first was to implant a thin (~0.1-0.2 μm) donor (Si) doped layer near the top to induce a counter field that would repel carriers from the surface [28]. The second was to adopt the practice of adding a wide bandgap “cap” layer to the top such that the conduction band discontinuity
repelled carriers from the surface [27]. Because both approaches were shown technologically to work, there was thought to be little need for further study of surface effects in MSM photodetectors.

In addition, the advent of LT GaAs MSM photodetectors made the impact of surface effects seem less important, because the performance of these devices is dominated by the deliberately introduced recombination centers. Because there are so many of these centers and the recombination cross section is so high, the chance of carrier capture by these centers is much larger than that of interaction with the surface. Thus, fast recombination dominates the surface processes, rendering the latter of less importance to device performance.
Chapter 4

Motivation for Surface Effect Study in MSM Photodetectors

4.1 Importance of Surface States to Advances in MSM Photodetector Technology

The above considerations account for the recent lack of attention to surface effects. However, the need for further advances in MSM photodetector technology supports re-examining surface effects for several reasons. These factors will become important as cases arise where past methods of negating surface effects do not work.

4.1.1 Nanoscale MSM Photodetector Technology Issues

The first reason has to do with development of nanoscale transit time limited devices. Nanoscale devices must use correspondingly thin active layers to achieve the highest possible speed. This is because, as shown by [3], the electric field set up by the bias electrodes, which must be high to cause the carriers to move at high speed, does not
penetrate deeper into the active layer relative to the finger spacing. Thus, a thin layer is needed as electrode spacing is reduced. Also, the high-speed advantages associated with nanoscale gap widths are ruined if the carriers must travel large distances in the vertical direction.

In such devices with a thin active layer, a larger percentage of the carriers will be very close to the surface. In addition, the electric fields may change more quickly over a shorter distance than in the older, larger devices. Since the current production mechanisms identified are very sensitive to electric field profiles, it is not clear that the capping and doping solutions previously used will work as well on nanoscale devices. A better understanding of such surface effects may offer insight into these issues. One can envision new planar detector structures that may not allow the photocurrent to be simply "pushed" away from the offending interface or surface.

4.1.2 MSM Photodetectors on GaSb and Other Materials

For example, GaSb has been investigated for use in MSM photodetectors and found to be quite promising [29]. Although the electrons have a smaller low-field mobility in GaSb than in GaAs (4000 vs. 8500 cm$^2$/Vsec at room temperature), the holes have a much higher mobility in GaSb (1400 vs. 420 cm$^2$/V sec at room temperature) [30]. Moreover, GaSb responds to 1550 nm light as well or better than InGaAs. On the other hand, processing of GaSb is much less mature than InGaAs or GaAs, so it is not at all clear that any of the previously applied solutions will be possible. The same considerations will hold if still other materials are used for making MSM photodetectors. This example is only one of many where new geometries, materials, and
processing call for a better understanding of the limits placed on MSM photodetectors by surface effects.

4.1.3 Potential Benefits of Surface Recombination in MSM Photodetectors

In addition, one might wish to attempt to use surface effects beneficially. Although energy-barriers have helped to solve problems caused by surface traps in GaAs MSM photodetectors, perhaps introducing a controlled amount of recombination centers at the surface only could provide another way to eliminate response from the tail. If enough fast recombination centers were added to the surface, the carriers would be much more likely to recombine with these centers than to be caught in the long lifetime surface states that cause the harmful tail effects.

The undesirable surface states have a long emission rate (as the tail lasts a long time), but an even longer capture time. Thus, as argued in [31], they have a detrimental trapping effect, which is the equivalent of a lower effective mobility. However, if surface states with a long emission time but a fast capture time could be added, then they would act as recombination sites and quench the tail by not allowing the surface states to become charged by photo-generated carriers. Shown below are the equations that describe the balance between electron and hole capture and emission rates for a single trap level [32].

\[
R_{en} = v_{th} \sigma_{n} nN_{t} (1 - F) \quad (4.1) \\
R_{en} = e_{n} N_{t} F \quad (4.2) \\
R_{ep} = v_{th} \sigma_{p} pN_{t} F \quad (4.3) \\
R_{ep} = e_{p} N_{t} (1 - F) \quad (4.4)
\]
\[ F = \frac{1}{1 + e^{\left[ (E_n - E_i)/kT \right]}} \quad (4.5) \]

\[ e_n = v_n \sigma_n N_t e^{\left[ (E_n - E_i)/kT \right]} \quad (4.6) \]

\[ e_p = v_p \sigma_p N_t e^{\left[ (E_p - E_i)/kT \right]} \quad (4.7) \]

In this set of equations, \( R_{cn}, R_{cp} \) are the capture rates for electrons and holes. \( R_{cn}, R_{cp} \) are the emission rates for electrons and holes. \( N_t \) is the density of traps in the semiconductor and \( \sigma_{n,p} \) are the cross sections of the centers with respect to electrons and holes. \( E_n \) is the trap level and \( E_i \) is the intrinsic Fermi level, while \( v_{th} \) refers to the thermal velocity. The electron and hole concentrations are given by \( n \) and \( p \).

### 4.2 Limitations of Previous Assessments of Surface Effects in MSM Photodetectors and Rationale for this Study

In an excellent study in 1987, Rogers presented an explanation for the D.C. gain and tail problems formulated in terms of electrical effects of charged traps [28]. Rogers explained the tail problem in terms of charged traps altering the electric field profile around the contacts, leading to image force and tunneling effects on MSM current. This assumes a deep trap with a long emission time and without significant recombination at the traps (i.e. the trapped electron is released after a long time). Rogers' experimental results using implanted donors to fill the traps are interpreted solely in terms of modification of the electric fields near the surface caused by the donors. No mention of possible surface states created by the implantation is made.
While this explanation seems consistent with the data presented, the question of how recombination events near the surface might affect the response remains unanswered. Also, this study was done with devices fabricated on semi-insulating GaAs, whose surface properties are not the same as those of high quality epitaxial GaAs in use today because of its higher purity.

It is expected that the mobility and other carrier transport properties will change to lower values near the surface of the material due to the complicated nature of the potential there. How large an effect this will have on device performance is another question, since no studies of this are available in the literature today. While these are not the only questions, they are among the more important ones.

Once the mechanisms have been identified, we need to assess their relative magnitude. There are only four consistent observations to guide this work. First is the observation that transit-time MSM devices in which no attempts have been made to suppress surface effects show seriously degraded behavior as evidenced by the persistent photocurrent tail in the time response and the previously mentioned DC gain [28]. Second, when surface effects are suppressed to presumed negligible levels, the devices behave as expected to the extent that present measurements have been able to detect [27], [28]. No experimental information about intermediate cases is available. There have been no previous studies in which device performance has been carefully examined as a function of controlled (small) levels of surface states that have been introduced. This thesis addressed this critical need.
Chapter 5

Research Goal and Plan

The goal of this effort was to elucidate the role surface effects in carrier transport as quantitatively as possible by conducting a controlled study of performance of GaAs MSM photodetectors as surface states are deliberately introduced.

5.1 Experimental Design

The study was initiated by first obtaining devices that were free of measurable surface related effects as determined by electrical and optical tests. Samples of such devices were subjected to a set of surface modifications with some devices receiving a larger amount of the same surface treatment than did others. This method was chosen instead of testing the devices first and subjecting the same set of devices to progressively higher implant doses with testing after each implant step. This is because it allowed new tests or repetition of previous tests as the need arose. If the same devices had been used throughout, re-examination of the effects of lower doses would be impossible once the next dose in a series was carried out. After the surface treatments were performed, the
devices were tested for optical and electronic properties along with untreated control devices to assess the effects of the induced surface states.

5.2 Implementation

This plan of experiments was carried out using GaAs MSM photodetectors using the AlGaAs cap layer method [27] to suppress surface state effects. These devices were tested and shown not to suffer from the anomalous DC gain characteristic of MSM photodetectors with large concentrations of surface states. To induce surface states in a controlled fashion, ion implantations at 3 different doses separated by 1 decade each at 5 keV were done on the devices using H and He as the implanted species. These doses do not induce states that can be described as being strictly surface states since the damage profile extends into the layer. The exact damage profile can be accurately computed, however. Such damage mimics the effect of surface states since it is confined to a region within 1000 A from the top of the device, whereas the active layer is 15,000 A thick.

The key advantage of ion implantation is that it is a dry process and very controllable, in contrast to wet processes, which permit a wide range of uncontrollable effects, such as diffusion of protons if based on acids. H implantation, also known as proton bombardment, has been fairly widely studied in GaAs because of its effectiveness in modifying GaAs to make it semi-insulating, a feature used to realize device isolation [33]. Proton bombardment is known to create trap levels in III-V materials [34], making it an ideal candidate for a controlled surface state effects experiment. However, detailed studies on proton bombardment have indicated that in addition to producing damage, hydrogen bonds covalently to the atoms in the lattice [34], so He was also used over the
same dose schedule. This was in an attempt to provide insight by separating the purely physical damage effect from ion collisions with the lattice from the combination of chemical and physical effects associated with the H implantation. In addition, samples were subjected to a hydrogen anneal in an attempt to sort out effects that might arise purely from chemical interaction of hydrogen molecules or atoms with lattice atoms (at least at low thermalized energy levels).

After scheduled implantation, samples were tested to compare electrical and optical properties. These included current-voltage characteristic measurements to determine dark current as well as the same current-voltage tests under optical stimulation to determine optical responsivity, capacitance-voltage measurements, and modulation frequency tests. From analysis of these results, conclusions about the role of surface effects in GaAs MSM photodetectors are presented.

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Chapter 6

Description of Experiments

6.1 Device Design and Fabrication

The device cross-section and epitaxial layer structure is shown in Figure 6.1. It consists of a semi-insulating GaAs substrate in the <100> orientation with a GaAs epitaxial layer of 1.5 μm thickness grown by Metal-Organic Chemical Vapor Deposition (MOCVD) followed by a cap layer of Al$_{0.25}$Ga$_{0.75}$As of 100 A. This structure, in which all the grown layers are nominally undoped but with unintentional donor (i.e. n type) densities on the order of $10^{12}$-$10^{13}$ cm$^{-3}$, was grown at the Naval Research Laboratory in Washington, DC in 1995.

The carrier densities for this particular sample were not measured directly; however, the process that was followed was known to reliably yield densities on the order mentioned. For MSM devices, the intent is that the gap between the electrodes be fully depleted at as low an operating voltage as possible [10]. This requires a low doping level. There is, however, no specific number that must be obtained. As a rule of thumb, a density in the mid $10^{14}$ cm$^{-3}$ range or less is appropriate for devices with gap
Figure 6.1: Vertical cross section of MSM device structure used in this study showing epitaxial layer structure. Note that all layers are nominally undoped with residual n-type carrier concentration.
widths on the order of a few \( \mu m \). Because there was no perceived risk at the time this sample was grown, no measurements were necessary. The MSM detectors were also fabricated in 1995 using a conventional lift-off process using optical lithography as described in detail in the run-sheet of Appendix A. These were done at the NASA/Goddard Space Flight Center in Greenbelt, Md. The devices were isolated from each other using mesas defined by a sulfuric acid based chemical etch as also described in Appendix A. The interdigitated electrode patterns for the devices used in these experiments covered an active area of approximately 50 \( \mu m \times 50 \mu m \) in size. Leads to 40 \( \mu m \times 40 \mu m \) pads were provided for probing.

The metalization used for the contacts was Ti:Au with thicknesses of 500 nm and 1000 nm, respectively. The Ti:Au system is a standard metalization system for making high quality Schottky contacts on GaAs and AlGaAs substrates [12]. The Ti was used because it readily bonds to almost any substrate and to the overlaying Au with excellent adhesion. The Ti also creates the Schottky barrier with the semiconductor surface. Schottky barriers in III-V materials differ markedly from those of other systems. In contrast to Si and some other semiconductors, the III-V As based materials exhibit a phenomenon called "Fermi-level pinning" in which the surface states cause the barrier height to be fixed at almost the exact same level for almost any metal used [35]. Thus, the choice of metal is not as critical in terms of getting a good barrier as it is in Si. However, good adhesion is critical, making Ti an excellent choice for the base layer. Au is used to reinforce the contact by providing good electrical conductivity within a reasonably small thickness and to provide a material that is easily seen for probing and easily soldered in wire bonding.
After the lift-off forming the Schottky contacts was complete, the devices were isolated from each other by etching mesas around the perimeter. The reason for this is to enhance reliability. While it would have been possible to etch the mesa and then add a second metalization step to define the probing pads, thus isolating them from the active area, this would have imposed additional risks. The metal would need to have covered the step, which was etched to a depth of 2 μm to guarantee full isolation between devices. Step coverage can be difficult to achieve and there was a desire not to risk losing the entire sample. Also, the added dark current associated with the metal from the pads was not seen as being a serious issue. The additional lift-off step itself could have failed, resulting in total loss. For these reasons, a simpler isolation scheme was used that was adequate for these devices.

Figures 6.2 through 6.4 show various scanning electron microscope (SEM) images of the resultant devices. The nominal finger width and spacing of these devices are 1.5 μm each, but the lithography process was less than perfect, resulting in important consequences for these experiments. Note that the actual electrode width is closer to 2 μm with a gap of approximately 1 μm. This is because the resist was somewhat overexposed in the optical lithography step, resulting in wider fingers and more narrow gaps than intended. This is not a problem so long as the actual geometry is used for analysis of test data. Note that the gap/finger width ratio affects the expected dark current, which scales with metalized area, optical response, which scales with gap area, capacitance, which increases as gap decreases, and transit time bandwidth, which increases with decreasing gap width. Also note the trade off here. Increasing the gap is good in that it lowers capacitance but reduces the frequency response associated with the
Figure 6.2: Scanning electron microscope (SEM) photograph of typical MSM photodetector used in this study showing mesa isolation and device overview.
Figure 6.3: Scanning electron microscope (SEM) photograph of typical MSM photodetector used in this study showing enlarged view of bond pad region
Figure 6.4: Scanning electron microscope (SEM) photograph of typical MSM photodetector used in this study showing detailed view of interdigitated electrode pattern
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated Value Based on [10] at 5.0 V Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Current</td>
<td>+500 pA (STRONGLY barrier height dependent, assume 0.72 eV here)</td>
</tr>
<tr>
<td>Capacitance</td>
<td>200 fF (includes a pad-to-pad capacitance measured at 140 fF)</td>
</tr>
<tr>
<td>810 nm Responsivity</td>
<td>0.1 A/W</td>
</tr>
<tr>
<td>3dB Bandwidth</td>
<td>33 GHz</td>
</tr>
</tbody>
</table>

Table 6.1: Estimated MSM Photodetector performance factors
carrier transit process. Based on the actual gap and electrode widths, as ascertained by SEM examination of samples, the expected performance characteristics of the devices are summarized in Table 6.1.

6.2 Note on History of Devices

Because the performance of such devices can depend on their history, we provide a brief overview here. The wafer used in this study was originally fabricated for a separate NASA sponsored technology development effort led by this author. These devices were base-lined for use in a fiber optic system to be used to demonstrate data transmission inside commercial aircraft ("fly-by-light"). After this program ended, the devices became available for other uses. The wafer contained a large number of devices, but most were made with pad-to-pad spacings incompatible with the equipment available for microwave frequency probing needed for these experiments. These devices, which had larger gap and electrode widths (2-4 µm) had excellent lithography outcomes and yield. Only those devices compatible with the probes and with acceptable lithography outcomes could be used in this study. The yield of this subset of devices was quite poor, leaving only a few dozen available for this work. The remainder of that wafer has hundreds of devices still suitable for uses in other programs.

This wafer was selected for use in these experiments because, with the exception of the lithography problems on the smallest gap and finger width devices used in these tests, the electrical and optical properties of the MSM devices were excellent. The current-voltage (I-V) and capacitance-voltage (C-V) curves showed excellent devices with results that agreed with values predicted by simple drift-diffusion calculations.
having no surface effects. Certain devices were sampled late in the execution of this work and the results compared favorably to original data from 1995. Data from this study will be presented later. These devices were also successfully used in a fiber optic receiver that was evaluated out to ~800 Mbits/sec. (limited by electronics). Thus we are very confident that the devices selected for this study were known to function as expected in a manner that could be accounted for by neglecting surface effects and appear to be extremely stable.

6.3 Description of Surface Treatments Used

Eight high quality MSM photodetector samples were selected for the controlled damage experiments. Various fragments were manually cleaved and affixed with silver paste to Al₂O₃ carriers for implantation. These samples were numbered for identification and exposed to low energy (5keV) single dose H and He implants at a 7 degree tilt angle as described in Table 6.2. No anneal was performed on the implanted samples, as might normally have been done following an implant step, because the point of these experiments is to study the effects of the implant induced damage. As also shown in this table, unimplanted sample #2 was subjected to a 30 minute anneal at 275 C in a tube furnace using a mixture of 97% N₂ and 3 % H₂ at 30 s.c.c.m. flow rate. Sample #1 was held as a control sample and received no anneal or implant. It is designated "As-
Table 6.2: Designation of Samples for Controlled Damage Experiment

<table>
<thead>
<tr>
<th>Sample I.D. #</th>
<th>Surface Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H anneal</td>
</tr>
<tr>
<td>2</td>
<td>None (control sample)</td>
</tr>
<tr>
<td>3</td>
<td>$10^{12}$ cm$^2$, He</td>
</tr>
<tr>
<td>4</td>
<td>$10^{12}$ cm$^2$, H</td>
</tr>
<tr>
<td>5</td>
<td>$10^{13}$ cm$^2$, He</td>
</tr>
<tr>
<td>6</td>
<td>$10^{13}$ cm$^2$, H</td>
</tr>
<tr>
<td>7</td>
<td>$10^{11}$ cm$^2$, H</td>
</tr>
<tr>
<td>8</td>
<td>$10^{11}$ cm$^2$, He</td>
</tr>
</tbody>
</table>
fabricated" in the following sections. The implantation was carried out at Implant Sciences, Inc. The anneal was carried out thereafter.

Note that the implants were carried out after the devices were fabricated, not before, as illustrated in Figure 6.5. This ensured that the surface and near surface states created by the implant damage were located at the top of the active layer between the electrodes, not under them. The computed (model) profile plots of Figures 6.6 and 6.7 were generated by the Profile software package [36].

A Pearson distribution was used to model these plots. The built-in calculated straggle for He into Au was in error and corrected values were supplied by TRIM™, which implements the model found in [37]. The values of straggle generated for the remaining cases were physically reasonable. Because the Profile program does not handle multiple layers well, the GaAs/AlGaAs layer was approximated by a single layer of GaAs and only the Au (not Ti) was considered in assessing penetration through the contacts. These plots are for the low dose case but can be scaled over the entire 3 decade range used in these experiments by simple multiplication because the total fluxes are relatively low.
5 keV implantation ion (H or He) flux

100 Å Al$_{0.25}$Ga$_{0.75}$As

1.5 µm GaAs

Semi-insulating GaAs substrate

Figure 6.5: Ion implant geometry used in controlled damage surface study
Figure 6.6: Calculated implant profiles into detector active layer
Figure 6.7: Calculation of implant profiles into metal electrodes
The most important information to derive from the model plots is that the ions are totally blocked by the metal electrodes and that the implants are concentrated in the uppermost 1000 Å of the active layer. After these treatments were carried out, the devices were tested as described next.

6.4 Description of Device Performance Tests

6.4.1 Dark Current

Dark current was measured on-wafer using a Hewlett-Packard, Inc. model 4142B modular source monitor unit (s.m.u.) instrument controlled by software produced by Metrics, Inc. and a probe station. The D.C. probes were positioned under a viewing microscope using holders manufactured by Micromanipulator, Inc.. These holders allow enough skate by the probe tip to enable the sample to be contacted reliably.

For these tests, the instrument was operated such that the voltage was sourced by the instrument and the current that flowed in response was measured. The instrument also measures the voltage as well to provide knowledge of its exact value rather than assuming that it is the intended value. The instrument was operated in a mode that sets the device low voltage terminal to 0 Volts rather than simply tying this terminal to the instrument ground. This reduces common mode noise.

The bias voltage across the devices was swept from 0 V to 5.2 V in steps of 0.2 V. The instrument was operated in its “line average” mode, which averages 32 actual readings from the instrument acquired synchronously across one 60 Hz AC mains power
cycle. Two such averages were further averaged again to yield a single measurement for each voltage in the sweep. Points within the sweeps were separated by 0.05 seconds.

As pointed out in [27], almost all MSM photodetectors show some settling transient between application of a DC voltage level and the final current value obtained. A variable delay was introduced to allow this settling to occur, but was found to be unnecessary for these devices. In fact, a delay time of zero was found to work equally well for devices sampled prior to surface treatments. The delay was retained nevertheless, to allow these results to be more easily compared with I-V data obtained on other samples tested in this lab that have been found to be less stable.

### 6.4.2 Capacitance

C-V characteristics were obtained on-wafer using a Hewlett Packard, Inc. 4285 A 75 kHz-30 MHz precision LCR meter with the same probe station setup used for the dark current tests. The frequency was set at 2.0 MHz by first measuring admittance vs. frequency at 5.0 V bias to ensure that the device impedances were predominantly capacitive. For an impedance behaving like a capacitance in parallel with a resistance, as expected for these devices at low MHz frequencies [10], the admittance $Y$ is given as:

$$Y = (1/Z) = (1/R_p) + j\omega C_p$$

(6.1).

where $R_p$ and $C_p$ are the parallel resistance and capacitance values, respectively, and $\omega$ is the angular frequency $2\pi f$. The current leads the voltage in this case. Thus, for such an impedance we expect a plot of the imaginary part of the electrical admittance $Y$ versus frequency to be a straight line. This was found to be the case from 500 kHz to 10.5 MHz (the entire range tested for in this work) except for a small deviation at ~7 MHz so 2.0
MHz was chosen as a comfortable value for the C-V measurements. The nature of the feature at 7 MHz is not known: it may be a signature of trapping in the device.

Once this frequency was selected, the bias was swept from 0-5.6 V in steps of 0.2 V and capacitance data obtained. The small-signal voltage amplitude used was 50 mV and two readings with a “medium” averaging time setting on the instrument were in turn averaged at each voltage. There was no delay after each voltage step before measuring capacitance except that normally produced by the instrument.

The stray impedance of the 2 meter cables from the instrument to the probe station was corrected for using a standard open-short-load method. The probe capacitance was accounted for by taking a separate data set for the probes, storing the data on disk, and averaging it to yield an offset capacitance of approximately 14-15 fF that was subtracted from the instrument readings obtained with the devices contacted. The assumption here was that the capacitance of the probes is a simple additive effect that can be subtracted from the readings obtained with the devices contacted. It is also being assumed that the slight motion of the probes needed to raise and lower the tips does not affect the probe setup capacitance in a meaningful way. A test in which the probe tips were raised and lowered by an amount approximately equal to that used in contacting and breaking contact with the device was conducted with no sample present. The variance was found to be less than the natural fluctuations in readings from the instrument (~0.9 fF r.m.s.).

6.4.3 Optical Response

In order to evaluate the optical responsivity of the devices, I-V curves under illumination were obtained with the same setup used for the dark current measurements.
except that light from an 810 nm single spatial mode laser diode was coupled into the optics of the probe station. The laser light was then focused through the probe station viewing microscope objective (10 X) onto the sample and IV curves under illumination were obtained. The incident power to the devices ranged from 1.5 $\mu$W to 2.0 $\mu$W and was measured before and after each sweep with a calibrated power meter to ensure stability of the results. Also, the background ambient light level, which never exceeded 45 nW, was checked by placing an opaque paper card into the optical beam path.

The spot size was checked by observing the fact that virtually all of the power focused onto the sample by the microscope objective was successfully coupled through a 50 $\mu$m diameter pinhole. This was done by recording the power exiting the microscope objective using a calibrated optical power meter and then repeating the measurement with the light focused through the pinhole. The alignment of the focused spot to the pinhole was done by visually observing the spot with the viewing microscope as it was focused onto the surface of the pinhole substrate and then positioning the pinhole until the light could be seen to pass through it. This procedure mimics the procedure used to align the detector under test with the spot and thus validates the assumption that the light was coupled into the active area of the detector.

If the light is too tightly focused (spot size on the order of the size of the electrode width of 1.5 $\mu$m), then the shading effect of the metal electrodes can cause large variations in photocurrent with respect to the alignment between the beam and the electrode area. This can serve as a tool in some cases for mapping out the sensitive area of the MSM device, but the goal in these experiments was to obtain the overall optical response. This was also checked by visually observing light reflecting off the electrodes.
and noticing that the reflection was observed over the entire electrode set, not just a small region in the middle. Thus it was ensured that while the light was not over-filling the detector, it was not grossly under-filling it either.

6.4.4 Frequency Response

The response of the devices to light whose intensity is modulated at some frequency $f$, corresponding to an angular frequency $\omega$, was measured over a range from 1 GHz-20 GHz using the setup shown in Figure 6.8. Note that the same setup was used for the DC optical response tests except that the s.m.u. and DC probes were used to measure the device response instead of the microwave frequency electronics shown in the figure. The spectrum analyzer was a Hewlett Packard, Inc. 85637 kHz-26.5 GHz spectrum analyzer. The preamp was a Hewlett Packard, Inc. 8949 B 1 GHz-26.5 GHz 30 dB gain preamp and the bias-tee was a Wiltron, Inc. K-250 bias-tee rated for operation from ~50 MHz-26.5 GHz. The microwave probe was a Cascade-Microtech, Inc., GSG 150 air-coplanar probe (ACP) with a 150 µm pitch between probe contacts. All cables and connectors were SMA type with the
Figure 6.8: Experimental setup used for frequency response measurements
exception of a few precision air dielectric connectors that were used at a few of the junctions. Although the precision connectors have less reflection loss, there were not enough of these to use in the entire setup. In addition, the cable leading from the ACP, which was a 50 GHz cable with a V connector at each end that was interfaced to the rest of the system with a V-SMA adapter.

The GSG notation indicates that it is in the ground-signal-ground configuration and intended for use with a device having a center conductor plus two outer ground conductors (i.e. a coplanar waveguide compatible device). Referring back to figure 6.2, note that these devices only have two pads, which happen to be spaced such that they can accommodate the center finger plus ONE of the two outer ground pads of the ACP. Thus, the use of this probe was not optimal in its coupling to the detector under test. This incurred a coupling penalty of approximately -10 dB between the device and the measurement system. Fortunately, the sensitivity of the system is such that this could be accommodated, especially since there was no other available equipment capable of making such measurements.

The delivery optics shown also merit some discussion. The laser diode output was delivered on a pigtailed 810 nm single mode polarization maintaining (PM) optical fiber. This fiber was damaged just below its output termination connector, requiring that it be cleaved to expose a fresh end. This in turn required that the diverging output be collimated by a 10 X microscope objective and coupled back into the fiber input to the electro-optic modulator, which consisted of another single mode PM fiber, by another 10 X focusing objective.
The modulator, which was a JDS Uniphase, Inc. MZ-080-180-T-1-3-C2-I2-O3 DC-18 GHz Mach-Zender component manufactured as a custom item, was polarization sensitive. Thus, the free space coupling required the use of a half-wave plate to rotate the polarization of the laser light into the plane required by the modulator. This is also why all the fiber up to the modulator input is PM. The alignment was carried out with both 10X microscope objectives mounted on precision 5 axis stages (XYZ plus 2 axis tilt). With the fibers mounted on 4 axis stages (XY plus 2 axis tilt, Z defined as axis along beam).

When possible, single mode (SM) fiber should be used to carry optical signals modulated at high frequencies. If it is not used, there will be a loss in bandwidth associated with different propagation times for different modes in the fiber [38]. Unfortunately, a single mode fiber patch cord to carry the light from the modulator to the probe station was not available at the time of the experiments, so a calculable loss was observed at frequencies > 5 GHz or so. This was checked by coupling the output fiber from the modulator (SM) into the reference detector, a New Focus, Inc. model 1434 high speed detector useful to 25 GHz. This detector, unlike the probe station, could be moved so that the output of the modulator could reach the input of the New Focus detector without a patch cord.

The response degradation relative to the signal at 1 GHz was observed over several frequencies with and without the patch cord (which was NOT SM) in place. This element was found to impose an extra ~4 dB of loss at 10 GHz, for example, thus confirming it as the main loss element in the setup. An exhaustive test of this effect was not conducted, however, because the patch cord merely acted as one loss element in a complicated signal chain and the amount of loss could easily be handled by the sensitivity of the spectrum.
analyzer. The preamp was used to compensate for the large loss in optical power through the optics of the probe station.

6.5 De-embedding of Frequency Response Data

The above discussion of the fiber optic and ACP losses introduces the next topic: de-embedding of the microwave signals. As seen from Figure 6.3, there were numerous components in the signal chain leading from the detector under test to the spectrum analyzer. The signal was passed through the probe head onto a 50 GHz cable, then through the V-SMA adapter into the bias-tee, through the bias-tee to the preamp, and from the preamp to the spectrum analyzer through a cable with connectors at each end. Each cable, connector, and component in this chain was a loss (or gain in the case of the preamp) element with a response that varied with frequency. In addition, the path from the signal source driving the modulator (which generates +18 dBm power), had loss elements as well: this was in addition to a frequency dependent efficiency of the modulator itself. The question of how to calibrate these losses had to be addressed.

The solution used in these experiments was the most straightforward. The method was to keep as much as possible of the signal chain fixed and to use a photodetector of a known frequency response in place of the detector under test to conduct a frequency response sweep which can then be used to calibrate for the effects of the entire measurement system as a whole. Using this approach, one can write:

$$P_{\text{ref}}(\omega)=P_{\text{ref}}(0)G_{\text{ref}}(\omega)G_{\text{ch}}(\omega)G_{\text{mod}}(\omega)$$  \hspace{1cm} (6.2)

$$\frac{P_{\text{ref}}(\omega)}{P_{\text{ref}}(0)}=\frac{G_{\text{ref}}(\omega)G_{\text{ch}}(\omega)G_{\text{mod}}(\omega)}{(G_{\text{ref}}(0)G_{\text{ch}}(0)G_{\text{mod}}(0))}$$  \hspace{1cm} (6.3)

$$G_{\text{ref}}(0)=G_{\text{ch}}(0)=G_{\text{mod}}(0)=1$$  \hspace{1cm} (6.4)
\[ \frac{P_{\text{ref}}(\omega)}{P_{\text{ref}}(0)} = G_{\text{ref}}(\omega)G_{\text{ch}}(\omega)G_{\text{mod}}(\omega) \quad (6.5) \]
\[ \frac{P_{\text{ref}}(\omega)}{(P_{\text{ref}}(0)G_{\text{ref}}(\omega))} = G_{\text{ch}}(\omega)G_{\text{mod}}(\omega) \quad (6.6) \]
\[ P_{\text{dut}}(\omega) = P_{\text{dut}}(0)G_{\text{dut}}(\omega)G_{\text{prof}}(\omega)G_{\text{ch}}(\omega)G_{\text{mod}}(\omega) \quad (6.7) \]
\[ G_{\text{dut}}(\omega) = \frac{P_{\text{dut}}(\omega)}{(P_{\text{dut}}(0)G_{\text{ch}}(\omega)G_{\text{mod}}(\omega)G_{\text{prof}}(\omega))} \quad (6.8) \]

In this set of equations, the subscript “\text{ref}” refers to the reference detector (the New Focus 25 GHz standard detector). The subscript “\text{ch}” refers to the microwave signal chain from the input of the bias-tee to the reading on the spectrum analyzer. The subscript “\text{mod}” refers to the action of the modulator on the signal and the subscript “\text{dut}” refers to the device under test. The variable \( P \) stands for the microwave power present in the indicated element at a given frequency and \( G \) is the transfer function (normalized to 0 dB at D.C.) for that element.

While the set of equations looks confusing, its meaning is simple. The modulated light was coupled into the reference detectors and output connector of the reference detector was fed into the signal chain at the bias-tee (the same point where the signal from the \text{dut} is inserted). A signal was then measured on the spectrum analyzer vs. frequency. As shown in equation (6.2), this signal varies with frequency because of the influence of the modulator transfer function, the transfer function of the signal chain, and the frequency response of the reference detector itself. Using data supplied by the manufacturer for this particular reference detector, the readings were normalized with respect to the low-frequency limit to yield the product of the transfer functions of the modulator and signal chain as indicated in equations (6.3)-(6.6).

Once this is accomplished, the device under test stimulated was with light modulated according to the transfer function of the modulator. Its output signal was
coupled into the same signal chain using the microwave probe and cable with its associated transfer function. The frequency response trace was then normalized with respect to its low-frequency limit as well as the product of the transfer functions for the modulator and signal chain previously obtained in equation (6.6). Finally, the transfer function of the probe and cable, obtained in a separate step, was divided out to yield the transfer function of the detector under test itself. The ACP probe data was supplied by the manufacturer and the cable was measured by itself with a Hewlett Packard, Inc. 8510 vector network analyzer. While the set of equations looks cumbersome, it was easily implemented in additive form on a spreadsheet using data expressed in dB based units.

A few notes about this de-embedding are important. Microwave de-embedding is a somewhat imprecise process. This is because the many junctions and connectors in the system all present slight impedance mismatches that can result in standing wave patterns inside the cables that in turn generate data that looks “noisy” as a function of frequency. This was found in the data collected during these experiments as well. As noted earlier, the coupling from the devices under test into the microwave ACP probe was far from optimal, which made the setup especially susceptible to impedance mismatches and multiple reflections.

To account for these artifacts, a smoothing function was used to help reveal the underlying trends. The idea is that since these reflection-induced patterns typically have a periodic nature as a result of the standing-wave nature of the underlying cause, averaging over a window around the point in question can be useful in revealing the “real” pattern. This is a standard technique in microwave measurement analysis [39] and was used for this data as well. The smoothing function in this case was a gaussian window of the form
The data were then convolved across \( w(f) \) according to

\[
w(f) = e^{-\left(\frac{f}{a}\right)^2}
\]

(6.9)

While this de-embedding scheme was far from perfect and did not remove all the "noise" from the data, it did at least allow us to account for the main effects of the measurement chain. The value of the parameter "\( a \)" was picked empirically to yield maximum smoothing of the data without losing the trend beneath the noise. It was found that 2 nsec. yielded the best result.
Chapter 7

Experimental Results

7.1 Dark Current

7.1.1 Stability Considerations

Because the performance of these devices can depend on their history, we present results of our reliability study. They show that the differences in performance are a result of the surface treatments and not variability from one device to the other in the as-fabricated condition. Figure 7.1 shows dark current curves taken on a representative device from sample #2, designated “as-fabricated” in table 6.2. It shows the data taken both in 1995, shortly after the device fabrication, and in 2000, immediately after optical and frequency response testing. Figure 7.2 shows data taken under optical illumination at 810 nm.

The dark current has not remained the same over the past five years but it has not changed dramatically. The optical response has, however, has remained very stable over the years. It also shows behavior typical of high-quality MSM photodetectors: the optical
Figure 7.1: Five year dark current stability data for device from sample #2
Figure 7.2: Five year optical response stability data for device from sample #2
response saturates at a low voltage and remains fairly constant afterwards. The internal quantum efficiency is not in excess of 100 %, indicating that a "pathological" surface trapping problem is not present. In this and other plots of optical response, 810 nm responsivity is plotted, which is defined as the photocurrent divided by the incident optical power at 810 nm.

The dark current performance of this device actually improved over the past five years. Do not, however, read too much into dark current data on these devices. As discussed in [26], dark current is highly sensitive to surface conditions, especially near the contacts. It can be affected by a number of external conditions, including the surface contamination caused by handling over the years. The optical response should be considered more strongly as an indicator of the true state of the device because it is not as sensitive to factors at the surface. This particular device looks very good in this respect.

7.1.2 Process Effects on Dark Current and Leakage

Figures 7.3 and 7.4 show a similar set of data for another device, this taken from sample 6, which received the highest proton bombardment dose. The figures show the dark current and optical response properties of this device taken in 1995, shortly after fabrication, and in 2000, shortly after ion implantation. While this device behaved quite well at the time of fabrication, its behavior has been altered dramatically by the processing step. As the devices are stable over time if left alone, we can be confident that these changes reflect the effects of the surface treatments under consideration.

Because these devices are reliable and stable, changes seen after the surface treatments can be confidently attributed to those treatments. While a complete data log
Figure 7.3: Dark current comparison for device prior to and after H implantation (high dose)
Figure 7.4: Optical response comparison for device prior to and after H implantation (high dose)
was not kept, the devices were "spot-checked" for reasonable looking I-V curves (both
dark and illuminated) immediately prior to implantation. All the devices considered were
found to be acceptable before proceeding. Figures 7.5 through 7.10 show results from
dark current measurements. Because dark current originates from the metal-
semiconductor Schottky contacts and is thus proportional to the metalized area, the dark
current results have been normalized. The dark current for each device is divided by the
actual metalized area and then multiplied by the metalized area for a device with a finger
width of exactly 2 \( \mu \text{m} \) and a gap of 1 \( \mu \text{m} \). This was done because there was enough
variability from device to device to warrant such a normalization. The actual metalized
area was determined by an SEM evaluation of each device. MSM dark current is the
property that is most variable from device to device. First, it originates as thermionic
emission from the Schottky contacts and is extremely sensitive to variations in the barrier
height from location to location across the wafer. These are inevitable as a result of
processing and material non-uniformities. Thermionic emission is governed by a
Boltzmann factor involving the barrier height [11]. As a rule of thumb, this varies by an
order of magnitude for each 6 meV change in barrier height at 300 K, which allows little
room for variability across the wafer. Barrier height is also affected by surface
conditions, so substantial variation in dark current from device to device is not
unexpected.

While the data has been normalized to attempt to correct for variations in actual
vs. nominal electrode widths, dark current across a Schottky barrier is sensitive to the
electric field profile because of the image force effect as well as tunneling [11]. Since
Figure 7.5: Dark current comparison between as-fabricated and H annealed devices
Figure 7.6: Dark current comparison between low dose H and He surface implanted devices
Figure 7.7: Dark current comparison between medium dose H and He surface implanted devices.
Figure 7.8: Dark current comparison between high dose H and He surface implanted devices
Figure 7.9: Dark current comparison across dose range for H surface implanted devices
Figure 7.10: Dark current comparison across dose range for He surface implanted devices
both are non-linear effects. Small changes in electric field distributions can lead to large changes in dark current. This makes the devices very sensitive to gap width, which affects the electric field for a given voltage. Finally, any surface residues, particularly if conductive, can offer additional current pathways. Figure 7.11 shows an SEM photograph of one device from this set which shows a fair amount of material inside one of the gaps. If these residues are conductive, one would not expect this device to have the same leakage current as one with features not containing this contamination.
Figure 7.11: Detailed SEM image of device with high dark current at low bias voltage
Because of these factors, dark current measurements presented here should not be over-interpreted. The results come from a small number of samples with widely varying levels of surface quality. Some devices had a nearly pristine region between the electrodes and some did not. There was a correlation between the cleanliness of the gap (as well as its width) and the quality of the dark current data. In some cases, the leakage currents were quite large (on the order of >10 nA). These results were atypical, and are not included in the figures.

Many of the devices with larger than typical leakage currents functioned well in other aspects. The optical response, C-V, and frequency response data all looked quite good for these devices. Dark current flows at the very top surface and is highly susceptible to surface imperfections whereas the photocurrent flows just below the GaAs/AlGaAs interface and is shielded from these effects. Because of this variability, the dark IV curves are shown individually and not averaged together by process type as much of the later data are.

A few trends are seen in these results. First, the surface treatments degraded the dark current performance. The as-fabricated sample shows a fairly well-behaved, nearly saturated I-V trace. The devices receiving the surface processes are not nearly as ideal in behavior. This is not unexpected because all of the treatments are likely to lead to surface states and band-bending near the metal-semiconductor interface. In all cases, the deviation from ideal behavior appears more serious for devices exposed to hydrogen treatments, including the anneal, vs those exposed to helium based processes. This degradation becomes abruptly worse at the high dose vs the low dose for each type of
implant, the limited number of samples and wide range of normal variability for Schottky barrier based properties notwithstanding.

7.2 Capacitance Measurement Results

Figures 7.12 through 7.17 show C-V data plotted in similar groupings according to dose and species. There is not much variability amongst this data set except for the plot for the device receiving a high dose of 5 keV of helium. This device, however, had very thin electrodes compared to all the others (1 μm vs. 2 μm). The capacitance of an MSM device is decreased as the ratio of electrode width to gap with is decreased [6], so this device naturally has a lower capacitance. All of the other devices have a 5 V capacitance of approximately 200 fF with a 0 V bias value approximately 8-10 fF higher. The capacitance “rolls-off” with voltage in a trend reminiscent of a reverse biased Schottky diode. Too strong of a parallel should not be inferred because the geometries are different and the charge is stored differently. Also, there is a fair amount of “noise” on this data, which is attributable to pickup from the probe tips in the EMI rich environment in which the tests were run. As these devices were very similar other, the data were not normalized or averaged.
Figure 7.12: Capacitance comparison between as-fabricated and H-annealed devices
Figure 7.13: Capacitance comparison between low dose H and He surface implanted devices
Figure 7.14: Capacitance comparison between medium dose H and He surface implanted devices

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Figure 7.15: Capacitance comparison between high dose H and He surface implanted devices.
Figure 7.16: Capacitance comparison across dose range for H surface implanted devices
Figure 7.17: Capacitance comparison across dose range for He surface implanted devices
7.3 Optical Response Measurements

The next data shown are the optical response results. Since optical response scales with the amount of area not covered by metal, these data were normalized with respect to the nominal gap to period ratio of 2/3 (0.67). The values plotted in this series represent the responsivity in A/W expected for devices with 1/3 (0.33) of the active area exposed to light. This ratio is not one that is normally used in practice because of the high degree of obscuration, but the ratio satisfies the purpose of this study, which is comparative in nature. The data are plotted in the same groupings as the last two sets in Figures 7.18 through 7.23.

These results show several interesting trends. First is a very noticeable trend with respect to ion implant dose. The as-fabricated samples exhibit an optical response that saturates at a fairly low voltage and remains nearly flat over the remainder of the range of the sweep. As the dose is increased, the curve becomes less flat with respect to voltage. The trend is most noticeable for the high dose implanted devices. While the devices implanted with low and medium doses eventually reach a responsivity comparable to that of the control device, the devices with the high implant doses show both a substantial slope in the illuminated I-V curve and a markedly lower responsivity.

Although the optical response becomes strongly voltage dependent, no form of DC gain characteristic of trapped charge near the electrodes appears. One can perform a calculation based on the assumptions that all photons not reflected off the electrodes or semiconductor-air interface and all photons are absorbed within the thickness of the active layer (1.5 µm) using typical GaAs absorption data [40]. This calculation yields an
Figure 7.18: Optical response comparison between as-fabricated and H annealed devices
Figure 7.19: Optical response comparison between low dose H and He surface implanted devices
Figure 7.20: Optical response comparison between medium dose H and He surface implanted devices.
Figure 7.21: Optical response comparison between high dose H and He surface implanted devices
Figure 7.22: Optical response comparison across dose range for H surface implanted devices
Figure 7.23: Optical response comparison across dose range for He surface implanted devices
expected value of 0.11 A/W for these devices at 810 nm. Thus, there is clearly no case of DC gain in any of this data for any dose. As in the case of the dark current data, it appears as though hydrogen caused more harmful effects in terms of reduced response and less flatness across bias voltage. The reduction in efficiency at the highest implant dose is especially pronounced. Also, the H anneal provides no significant benefit and even seems to make the illuminated I-V curve saturate at a larger voltage than in the as-fabricated case.

7.4 Frequency Response Measurements

In the last chapter, the de-embedding technique was discussed, but we again mention that the measurement system involved numerous microwave connectors, cables, junctions, and other impedance mis-matches. While these pieces could be characterized individually, there was no way to characterize them in concert and allow a highly accurate de-embedding. As a result, the data is characterized by fluctuations that look noisy but in fact are largely caused by standing wave patterns set up in the various elements of the system depicted in Figure 6.8.

This complication is why a smoothing function was necessary. The smoothing function selects points around the center point and constructs a sliding average around each frequency by convolving the measured data with a Gaussian window function. This is equivalent to a band-limiting filter function in the Fourier transform space of the measurement domain (i.e. the time domain). This filter function limits the effect of the standing wave patterns. Figure 7.24 shows an example of a data set before and after application of the smoothing functions. As can be seen, this function captures the trend
Figure 7.24: Smoothing function used to recover useful frequency response data from noise.
in the data while suppressing the noise. Of course, it assumes a priori that the information desired is not outside the filter bandpass.

The Bode plots of Figures 7.25 through 7.30, again presented in the same groupings as the other results, show the frequency response measurement data. These Bode plots show the magnitude of the normalized frequency response of the MSM device with all possible elements de-embedded (except for the RC time constant with the 50 ohm load of the measurement system, which yields a 3 dB point of 16 GHz. Because the issue of recovering the useful information was of the utmost importance, the data for different devices of the same type are averaged whenever possible. Of course, the average values are only over two samples in all but one case (for which 3 are averaged), there is at least some benefit from averaging in some of the data. However, several trends do emerge that should be pointed out.

First, the frequency response is degraded as the dose is increased. This degradation is most apparent for the high dose cases and, while present, is not as pronounced at medium doses. At low hydrogen dose, and perhaps for the medium helium dose, the observed fluctuations in response are not beyond the device-to-device variability of the data itself. It is also possible, however, that the differences, while slight, are real, since the medium dose hydrogen results, and all of the high dose results, show unmistakable degradation in frequency performance. The maximum range of the implantation has been controlled to limit the effect to less than 10dB. While the hydrogen annealed devices have comparable performance to the as-fabricated devices, hydrogen consistently degrades the frequency response more than helium.
Figure 7.25: Frequency response comparison between as-fabricated and H annealed devices
Figure 7.26: Frequency response comparison between low dose H and He surface implanted devices
Figure 7.27: Frequency response comparison between medium dose H and He surface implanted devices
Figure 7.28: Frequency response comparison between high dose H and He surface implanted devices
Figure 7.29: Frequency response comparison across dose range for H surface implanted devices
Figure 7.30: Frequency response comparison across dose range for He surface implanted devices
Figures 7.31 and 7.32 show the relative performance of the surface-treated devices normalized to the control device. These figures confirm the above trends. The upturn at the high-frequency end of these plots reflects the fact that the smoothing function is not able to sample to the end of the range because the data set is finite. The detailed inflections in the curves are not indicative of the intrinsic properties of the devices but rather arise from the residual errors associated with the de-embedding process.
Figure 7.31: Frequency response comparison across dose range for H surface implanted devices normalized to as-fabricated control devices.
Figure 7.32: Frequency response comparison across dose range for He surface implanted devices normalized to as-fabricated control devices.
Chapter 8

Simulation and Modeling

8.1 Simulation Software

In order to better understand these results, an attempt was made to model the device using the ATLAS software package (version 5.0.9.R) published by Silvaco [41]. This software implements a solution of the drift-diffusion equations for semiconductor devices using a finite element method. It is capable of handling arbitrary device geometries and has built in material libraries and models for the III-V compound semiconductor family, which are thought to be accurate at least in the case of the GaAs/AlGaAs system. These default libraries were used in this work.

A drift-diffusion solver was chosen in lieu of development of a dedicated, application specific Monte-Carlo program because the large feature size of these devices renders velocity overshoot and ballistic effects less important [18]. Assuming that the carriers have collided enough times to reach their ensemble average velocities at each point during the simulation, the drift diffusion equations can be written:

\[
\nabla \cdot (\epsilon \nabla \psi) = -q \left( p - n + N_D^- - N_A^- \right) - \rho_f
\]  

(8.1)
\[
\frac{\partial n}{\partial t} = \frac{1}{q} \text{div} \, \vec{J}_n - U_n \tag{8.2}
\]
\[
\frac{\partial p}{\partial t} = -\frac{1}{q} \text{div} \, \vec{J}_p - U_p \tag{8.3}
\]
\[
\vec{J}_n = -q\mu_n n \nabla \phi_n \tag{8.4}
\]
\[
\vec{J}_p = -q\mu_p p \nabla \phi_p \tag{8.5}
\]
\[
\vec{J}_n = q\mu_n \vec{E}_n n + qD_n \nabla n \tag{8.6}
\]
\[
\vec{J}_p = q\mu_p \vec{E}_p p - qD_p \nabla p \tag{8.7}
\]

along with the Einstein expression
\[
D = \frac{\mu kT}{q} \tag{8.8}
\]

The highly collisional regime permits the use of Boltzman statistics for the carrier [41]. [22]:
\[
n = n_e \exp\left(\frac{q}{kT} (\psi - \phi_e)\right) \tag{8.9}
\]
\[
p = n_e \exp\left(-\frac{q}{kT} (\psi - \phi_p)\right) \tag{8.10}
\]

In these equations, \(n\) and \(p\) are the electron and holes densities. \(N_{d^+}^\text{t}\) and \(N_{a^-}^\text{t}\) are the ionized donor and acceptor densities, \(p_c\) is the free charge density, \(\psi\) is the intrinsic Fermi potential. \(\vec{J}_{n,p}\) are the electron and hole current densities. \(U_{n,p}\) refer to the net
generation-recombination rates. $\mu_{n,p}$ are the field-dependent electron and hole mobilities. $D_{n,p}$ are the diffusivities for electrons and holes, and $\phi_{n,p}$ are the electron and hole quasi-Fermi levels. These equations are standard for semiconductor device modeling and are discussed at great length in the references above. The ATLAS software package solves this set of equations with appropriate boundary conditions in order to predict the behavior of various semiconductor devices.

8.2 Description of Simulated Structures

In our computation scheme, the basic device was modeled in the as fabricated condition. In these simulations, the epitaxial layer was assumed to be 1.6 $\mu$m thick, doped n-type at $N_d=5 \times 10^{12}$ cm$^{-3}$. The Al$_{0.25}$GaAs layer was simulated as a 100 Å thick layer doped to the same level as the remaining semiconductor, with an abrupt junction onto the GaAs. ATLAS keeps track of spatially dependent material properties in modeling heterostructures. The electrodes were assumed to be perfect Schottky contacts with a barrier height of $\phi_b=1.10$ eV. The standard image-force barrier lowering mechanism was used [18]. No material was defined beneath the GaAs layer. The contacts were assumed to be opaque, but infinitely thin, with zero series resistance and capacitance. Handbook optical absorption properties were assumed for GaAs [40].

This simulation was run to model dark I-V, C-V, optical response, and frequency response simulations over the voltage and frequency ranges for which experimental data was collected. The baseline properties predicted by these simulations were in good agreement with the experimental results. Thus, the observed device properties appear to be consistent with a drift-diffusion model. In these simulations, surface traps, surface
recombination, and tunneling were ignored. We also did not include bulk traps, except for a single deep (mid-gap) level used to provide a carrier lifetime on the order of nanoseconds using Shockley-Read-Hall (SRH) recombination. To simplify convergence of the program, a simplified velocity-field profile was used that neglects the negative differential mobility region of GaAs. As shown in [16], [18], however, this is only an issue in regions where the electric field strength is less than \( \sim 4 \) V/cm or so. Since MSM detectors are biased to much higher electric field levels for efficient operation [10], this assumption is well justified.
Chapter 9

Comparison Between Simulation and Experiment

9.1 Surface Effect Simulations

Once agreement between theory and simulation was established for the as-fabricated devices, an attempt was made to model the effects of the ion implantation steps. The implanted region was modeled as a 1000 A thick layer, consistent with the Profile Code plots of Figure 6.6 and 6.7. We assumed a uniform distribution of either recombination centers or dopants, since these are the most likely products of our ion implantation steps. Appendix B is an example of a structure file used in this study, which was run on the Silvaco software. It is widely known that proton bombardment of III-V material leads to creation of deep trap levels [33], which act as recombination centers with a lifetime of <100 psec. when present in the concentrations used here [9]. Thus, treating the top 1000 A (the implanted region) as a layer populated by deep level Shockley-Read-Hall (SRH) is reasonable. Since the implanted region is thin relative to the 15000 A thick active layer, it can reasonably be approximated as a surface recombination layer. Sze [32] has shown that the SRH recombination rule for the bulk is characterized by a lifetime given by:
\[ \tau_{SRH} = \frac{1}{(v_{th} \sigma N_t)} \]  

(9.1)

where \( \tau_{SRH} \) is the SRH carrier lifetime, \( v_{th} \) is the thermal velocity, \( \sigma \) is the recombination center cross section, and \( N_t \) is the volume trap density. The equation for surface SRH recombination is the same as for the bulk except with the inverse lifetime replaced by a surface recombination velocity given by:

\[ S_{n,p} = v_{th} \sigma_{n,p} N_{st} \]  

(9.2)

where \( N_{st} \) is a surface trap density per unit area. For a very thin layer (of thickness \( L \)) of "bulk traps", the bulk SRH recombination expression can be integrated over \( L \) to yield an equivalent SRH surface recombination expression with \( N_{st} = N_t L \). The effective carrier lifetime needed in order to approximate such a thin surface recombination layer by a bulk recombination region of thickness \( L \) is:

\[ \tau_{eq} = \frac{L}{S_{n,p}} \]  

(9.3)

Here, \( S_{n,p} \) is the surface recombination velocity one wishes to model and \( L \) is the thickness of the bulk SRH region used to model it. By sensitivity analysis of this parametric modeling, one can infer the effects of our controlled damage experiment on surface recombination.

SRH recombination in a surface layer is made easier to model by several phenomenon. The resultant carrier lifetime does not depend on the exact trap level [39] for traps within +/- 10 kT of the band center. For GaAs at room temperature, this range is +/- 250 meV, which encompasses several of the known GaAs deep level defects [18] [42]. Thus, the one possibility is to take the data from the simulation, compare it with results from experiments, and determine which value of carrier lifetime for the implanted region which most closely agrees with experiment. Once a lifetime is known, the
equivalent surface recombination velocity may be calculated from equation (9.3) to
determine the effect of the surface recombination velocity on MSM device performance.
Since the centers are created in a known amount, this lifetime may be used to extract the
cross section for centers of the type produced by our ion bombardment process. This is
only one possible result of proton bombardment: proton damage, as pointed out in [42],
can lead to a wide variety of effects that may produce a range of defects with different
behaviors in GaAs. For example, it is thought that the EL2 defect induced by ion damage
is associated with the AsGa defect. This defect, however, acts like a deep donor.
Therefore, our modeling attempted to examine which behavior, an increase in donor
density, or the creation of recombination centers near the surface, gave results in better
agreement with experimental data for proton implantation. In this context, the helium
data may serve to reduce uncertainty because helium only produces damage, whereas
hydrogen may chemically bond to lattice sites or with dangling bonds at the surface.

9.2 Comparison with Experimental Results

Simulations were run to test surface recombination effects by using lifetimes
ranging from 1 nsec.-10 fsec. Along with n-type doping at levels of $10^{16}\text{cm}^{-3}$ (low),
$10^{17}\text{cm}^{-3}$ (med.), and $10^{18}\text{cm}^{-3}$ (high). These doping values, when multiplied by the layer
thickness of $10^{5}\text{cm}$, yield the known net dose of the implants. The results of these
simulations are seen in figures 9.1 through 9.5. Figures 9.1 and 9.2 show the acceptable
agreement of the simple model in accounting for the behavior of the dark current and
frequency response of the as-fabricated control device. Note that the RC time constant
effect, which yields a rolloff with a 3 dB point of 16 GHz, is not included in this
simulation, so the simulations tend to over-estimate the absolute bandwidth slightly. This is a positive test that the important phenomenon have been properly included since, as a rule, dark current is the most difficult quantity to calculate for such simulation programs [41]. Frequency response calculations are also quite demanding. Figures 9.3 and 9.4 show that the test data for frequency response agree most closely with simulations that assume a doped surface layer. The simulations done with a surface recombination layer do not agree with the experiments. They predict no significant reduction of response with increasing frequency arising from surface recombination. The calculations for which doping is varied show reasonably good agreement with the test data, although this test data is quite noisy. This is physically reasonable since positively charged ionized donors placed in a layer below the active region can enhance bandwidth by pushing the slow holes towards the top [43]. Conversely, a layer of ionized donors near the top will repel holes, thus slowing the response. Such a response is likely because of the presence of EL2 donors known to exist in GaAs.

The comparisons between simulation and experiment are enhanced since simulations indicate that charged donors near the surface act to degrade the frequency response of the devices. Figure 9.5 shows, however, that the simple model cannot account for all our observations. The maximum roll-off with frequency which occurs for the optical response is far smaller than the drastic reduction in experimental optical responses observed for the implanted devices. This degraded optical response is not predicted at all by the model that assumes ionized donors at the surface. While the effect is seen in the simulations that model surface recombination, the size of the predicted effect is much
Figure 9.1: Comparison between simulated and measured dark current for as-fabricated device
Figure 9.2: Comparison between simulated and measured frequency performance of as-fabricated device
Figure 9.3: Comparison between frequency response measurements and simulations performed assuming a doped surface layer.
Figure 9.4: Comparison between frequency response measurements and simulations performed assuming surface SRH recombination
Figure 9.5: Comparison between optical response measurements and simulations.

Measured points are plotted with symbols only.
smaller than shown by measurements. Thus, the simulations are really only in qualitative agreement with the test results.

### 9.3 Parametric Sensitivity Analysis of Results

In order to help quantify the extent of the disagreement, the optical response data (measured and simulated) were fitted by assuming that the voltage dependence of the responsivity is of the form:

\[
Re(\text{V}) = Re_{\text{max}}(1 - \exp(-\text{V}/V_{\text{fit}}))
\]

where \( Re(\text{V}) \) is the responsivity at 810 nm at a given bias voltage, \( \text{V} \) is the bias voltage, \( Re_{\text{max}} \) is the maximum responsivity of the device over the 0-5 volt range, and \( V_{\text{fit}} \) is a fitting parameter. Figure 9.6, which is a representative plot, demonstrates that this fitting procedure is appropriate. The resulting fitting parameters are reported in Table 9.1.

Table 9.2 shows a similar comparison of the 3dB frequencies for these devices. In these tables, the density column refers to either the doping density used in the simulations, the actual implant dose for measured devices, or the trap density used in the SRH surface recombination simulations. These were based on the lifetime used and assuming traps with a degeneracy of one and a cross section of \(8.5 \times 10^{-15} \text{ cm}^2\).

These results crystallize the above discussion. The fitting parameters for the optical response from the simulations with surface recombination accounted for follow the trend in the measured data, but the values are much too small to say that the model accounts for the experimental results. Specifically, each implanted ion would have to be assumed to create \(10,000\) recombination sites or the cross section would have to be assumed to be \(8.5 \times 10^{-11} \text{ cm}^2\) or more to match the experimental data for even the lowest
implanted dose. Both of these are unreasonably large values. The results of the simulations assuming only surface donor effects do not correlate with experimental results at all. The frequency response results are exactly the opposite. The trend with respect to dose is accounted for in the modeled data when surface donors are assumed but not when surface recombination only is simulated. While the model consistently predicts faster response than seen in experiments, it does not allow for the RC time constant. The trend, however, is clearly captured in this comparison.

While the hydrogen implant series follows a regular progression with respect to dose, the helium data does not. In both comparisons the performance is more seriously degraded in the devices receiving hydrogen based treatments. This suggests that the chemical behavior of the hydrogen and its interaction with atoms in the material is an important effect. If defect levels based on covalently bonded hydrogen are involved, this raises the possibility that they might migrate, either over time or in response to an applied electric field.
Figure 9.6: Comparison between measured responsivity for device implant with high dose of He and fitted voltage dependency.
<table>
<thead>
<tr>
<th>Center Density (cm$^{-2}$)</th>
<th>Surface Donor Layer (sim.)</th>
<th>Surface Recombination Layer (sim.)</th>
<th>He implanted (meas.)</th>
<th>H implanted (meas.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{16}$</td>
<td>0.1</td>
<td></td>
<td>0.57</td>
<td>0.5</td>
</tr>
<tr>
<td>$10^{17}$</td>
<td>0.12</td>
<td>0.1</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>0.1</td>
<td>1.8</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>$10^{19}$</td>
<td></td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{20}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{21}$</td>
<td></td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 9.1: Comparison of optical response fitting parameters (in Volts) for different cases studied
### Table 9.2: Comparison of 3 dB frequencies (GHz) for different cases studied

<table>
<thead>
<tr>
<th>Center Density (cm$^{-3}$)</th>
<th>Surface Donor Layer (sim.)</th>
<th>Surface Recombination Layer (sim.)</th>
<th>He implanted (meas.)</th>
<th>H implanted (meas.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{16}$</td>
<td>18.5</td>
<td></td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>$10^{17}$</td>
<td>12</td>
<td>19</td>
<td>12.6</td>
<td>7.6</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>9</td>
<td>18.5</td>
<td>7.1</td>
<td>5.6</td>
</tr>
<tr>
<td>$10^{19}$</td>
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<td></td>
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<tr>
<td>$10^{20}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{21}$</td>
<td></td>
<td>17.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 10

Interpretation of Results and Conclusions

10.1 Disagreement Between Experimental Results and Surface Effect Models Considered

Experimentally, a definite trend has been established that connects progressively higher surface damage levels with progressively degraded MSM detector performance. Simulations based on increased doping indicate a trend towards reduced frequency response associated with an electric counter-field, directed down into the device, by the positively charged ionized donors. This field causes the holes to slow down, thus reducing the frequency response. A simple theory containing only ionized donors, however, fails to explain the degraded optical responsivity at 810 nm (in A/W). Simulations predict that surface recombination is a possible mechanism that reduces the optical response, although the calculated effect is too small to account for the large experimental degradations. Simulations predict that surface recombination has no effect, which does not account for measured results.

The prospect of charged traps altering the tunneling current from the metal contacts has been ruled out because of the lack of bias-induced gain. Although the
photocurrent becomes bias dependent after bombardment, it never results in apparent quantum efficiency values above 100%. as predicted by that mechanism [28]. Thus, the observations suggest a mechanism that probably does not operate on surface states near the electrodes. All indications are that an AlGaAs cap is capable of keeping carriers away from the traps that may exist on the outer surface of the material.

10.2 Limitations of Surface Effect Models Considered

So, the independent effects of each mechanism seem to be consistent with only one of the two observed behaviors (optical response and frequency response changes) but not the other. It is natural to seek a mechanism that includes both possibilities, which leads to an important issue regarding these simulations. The outcomes presented in Figures 9.1 through 9.5 result from a standard SRH mechanism that adds a carrier loss rate term to the continuity equations resulting from traps that are filled and emptied according to detailed balance [32]. However, the carrier lifetime is the inverse product of the carrier thermal velocity with the trap concentration and the cross section. Thus, the same carrier lifetime can be obtained by either a low concentration of traps with a large cross-section or by a high concentration of trap with a small cross-section. The two situations are not equivalent. If the concentration of charged traps is high enough, they can also modify the electric field profile inside the device. To model this process, the simulator would need to include these charged traps in Poisson’s equation. The SRH recombination model used did not, since the simulation was performed to assess the effect of SRH surface recombination alone.
10.3 Alternate Explanations of Results

The implant doses of our study ranged from $10^{16}$ cm$^{-3}$ to $10^{18}$ cm$^{-3}$. whereas the background doping is between 4 and 6 orders of magnitude less. Thus, the assumption that these traps do not change the charge density is probably unsupportable. Accordingly, 3 new simulations were run which the included the presence of charge in the trap states. Figure 10.1 shows a comparison between optical response simulations for three cases. The first is the as-fabricated devices with no traps or surface doping from the implant. This compared to the case which assumed donor type traps at mid-gap with a lifetime of 1 psec. and a density of $5 	imes 10^{15}$ cm$^{-3}$. The final case assumed no traps or surface recombination and with a surface layer donor doped to $5 	imes 10^{15}$ cm$^{-3}$. The doping and trap densities in the cases of Figure 10.1 are at trap and doping level less than the low end of the range used in the rest of this study and less than the implant dose for even the lowest dose case. Note that this simulation shows a loss in optical signal comparable to the previous simulation, which did not account for trap charging. The new simulation also predicts a potential profile on the device similar to the profiles expected for the device having surface doping, although the effect is not as large. Thus, the charged traps in this simulation will also lower the response at high frequency in a manner similar to ionized donors near the surface.

These results, taken together, suggest that the dominant mechanism by which ion bombardment alters device behavior is through the generation of deep trap levels. It is believed that the short lifetime of these traps results in a surface recombination term. This term itself will lower optical efficiency without degrading the frequency response. The traps which form can become charged, leading to electric field profile changes that
Figure 10.1: Simulated optical response comparison between as-fabricated device, Device with charged surface traps, and device with doped surface layer.
degrade the frequency response. These conclusions offer insight for future work on advanced device design and processing.

10.4 Limitations on Computational Methods

It would be interesting to continue along this line by modeling higher trap densities and a wider range of lifetime values. The result shown in Figure 50 was for a trap density too small to change the electric fields enough to degrade the frequency response: it is presented as a proof of principle. The results suggest that what is needed in the model are lifetimes of $< 1 \text{ psec.}$ and a trap densities of $10^{18} \text{ cm}^{-3}$, in order to produce both the substantial signal loss and the frequency response degradation seen in the experiments.

10.4.1 Computational Methods

This is severely problematic because the routine currently used for drift-diffusion simulations experience convergence problems when such higher trap densities are used. Even cases with $10^{16} \text{ cm}^{-3}$ trap density did not converge when run on this simulator. Such convergence problems are typical with finite element simulators when large discontinuities are encountered, such as the one produced in changing from a layer with a very high density of traps and a very short lifetime to a very low doped background layer with long carrier lifetimes [41]. Unfortunately, this is the most interesting geometry for advanced heterostructures.
10.4.2 Boundary Condition Limitations

The simulator did not account for the presence of the semi-insulating substrate. It only assumed a closed region with a thickness of 1.62 μm. For effects that are highly boundary condition dependent, this failure will matter. If the potential profile should become altered to allow the carriers to be pushed into the substrate, then the semi-insulating substrate will become another major sink for carriers, which would result in substantial signal loss. This would be voltage dependent. This situation is quite likely for cases with a high concentration of charged surface traps. For this reason, our simulation may critically underestimate the optical responsivity loss associated with charged traps.

10.4.3 Indicated Improvements

Better coding efforts and more robust computational models are needed. There are issues of a more physical nature to contend with. The lifetimes used in the thin layer used to model the surface recombination process correspond to surface recombination velocities ranging from $10^4$-$10^9$ cm./sec., which should include virtually any condition that might exist on a GaAs surface. Since this range seems to produce some of the loss in optical response seen in the measurements, it might seem natural to shorten the lifetime even more to magnify the effect in the simulator. However, this would require extremely high surface recombination velocities ($>10^9$ cc/sec.) corresponding to questionable values for carrier cross-sections.
The cases studied here involve the consideration of only one type of trap. We assumed traps within +/- 10 kT of mid-gap with lifetimes that are of equal values for both electrons and holes with a degeneracy of unity. While is like a reasonable place to start, there is no fundamental knowledge that these are the types of traps present or that there are not numerous and varied types of traps. The prospect for various impurities to exist in the process steps is high. Therefore, it would probably be more appropriate to collect more data on the physical condition of the implanted surface layer. This should be done to allow a more definitive understanding of the types of trap levels involved before an extensive modeling effort is carried out in an attempt to accurately quantify the effects seen here.

10.5 Conclusions

In conclusion, we should consider this study in terms of the general insights it offers into the importance of surface effects on MSM photodetectors and as a proof-of-principle. It has been shown by our work that, contrary to conventional understanding, MSM photodetectors can be adversely affected by surface problems other than charging of traps near the edges of the metal contacts, which was thought to be the only surface problem in transit-time limited MSM photodetectors. In addition to this problem, our work shows that the frequency performance of these devices can be degraded by any mechanism that leads to a layer of positive charge near the surface, i.e. even if the traps are located away from the metal contacts on the surface. Such an outcome is likely to attend virtually any aggressive plasma or ion-mediated step, and also appears to be important even for the otherwise apparently benign process of hydrogen-soaks at elevated
temperatures. In addition, surface traps formed by such processes can also lead to a serious recombination loss in signal strength that by itself does not affect frequency response.

Since many advanced concepts for MSM photodetectors involve interfaces as part of heterostructures, each interface is a potential problem in terms of these effects. Since the effect of surface charge on bandwidth is based on electrical effects, it can be anticipated that nanoscale devices will be even more prone to problems from these effects, since the active layers are thinner and located in closer proximity to charged surface layers.
Chapter 11

Suggestions for Future Work

This thesis has given a systematic set of experiments in which surface damage was introduced in a known and controlled manner by increasing the dose of H and He in a low energy ion bombardment. The resulting effects on performance of a surface sensitive device on GaAs (MSM photodetector) have been observed. In order to fully understand and model such processes, more experimental studies of the surface characteristics and the details of the induced damage are needed. Such studies would include carefully characterizing the trap levels and cross sections in an effort to systematically locate the most probable effect. The signature would be a feature or set of features whose abundance varies in a regular manner with dose to allow separation of the induced process from the normally present background processes. Physical characterization might include TEM, PEEM, and other sophisticated diagnostics designed to identify the specific type of damage created by the implantation.

Improved computational models that more realistically model the device structure are also needed. As we have pointed out, the effect of a semi-insulating substrate has not
been accounted for in the simulations. A semi-insulating substrate has a very short carrier lifetime and can act as a sink for optically generated carriers. Modeling the substrate as a region with a very short lifetime leads to large loss terms in the time-dependent continuity equations. The resultant system of equations then becomes very stiff and difficult for a finite element simulator to solve [41]. A better approach is to model the interface with the substrate using a boundary condition of zero excess carrier density. This will circumvent the above mentioned convergence problem and allow the underlying physics to be studied more efficiently.

The observation that the hydrogen based process steps degrade the device performance more seriously than do those involving helium bears further study. This observation points to a larger, more detailed study which would elucidate the chemical interaction between hydrogen and atoms in the active layer. This is important as many processes in III-V semiconductor technology (e.g. PECVD) degrade the frequency response. These conclusions are offer insight for future work on advanced device design and processing involve hydrogen based chemistry, a fact that has far reaching implications.
Appendix A

DEVICE FABRICATION PROCESS FLOW

1. Spin-on Shipley 818-A photo-resist 4000 at r.p.m. for 30 sec.
2. Soft bake for 30 min. at 90 C in oven
3. Align and expose electrode mask level for 4.5 sec. in UVI mask aligner
4. Develop in Shipley 312 developer solution
5. Hard bake for 30 min. at 120 C in oven
6. Oxide strip in buffer HF for 5 sec.
7. Electron-beam evaporate 500 A Ti:1000 A Au after pump-down to 10^-7 Torr
8. Lift-off in acetone for 1 hour followed by gentle ultrasound agitation
9. Rinse in methanol followed by dionized water and N_2 blow dry
10. Spin-on Shipley 1811 photo-resist at 3000 r.p.m. for 30 sec.
10 Soft bake for 30 min. at 90 C in oven
11. Align and expose mesa isolation mask level for 2 sec. in UV mask aligner
12. Hard bake for 30 min. at 120 C in oven
13. GaAs mesa etch in H_2SO_4:H_2O_2: H_2O 8:1:1 for 2 minutes (-1.5 micron/minute etch rate)

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14. Resist strip in acetone

15. Rinse in methanol followed by dionized water and N₂ blow dry
Appendix B

REPRESENTATIVE ATLAS SIMULATION INPUT FILE

go atlas

TITLE GaAs MSM Optical Response Simulation with Surf. Recombination
# Silvaco International 1994
# first establish simulation grid
# use 0.1 micron spacing throughout in x direction
# use finely spaced mesh points near GaAs/AlGaAs interface
# use less fine mesh further down into material
# all dimensions are in microns
mesh
x.m l=0 spac=0.1
x.m l=1.0 spac=0.1
x.m l=1.0 spac=0.1
x.m l=2.0 spac=0.1
x.m l=2.0 spac=0.1
x.m l=3.0 spac=0.1

y.m l=0 spac=0.002
y.m l=0.02 spac=0.002
y.m l=0.02 spac=0.02  
y.m l=0.22 spac=0.02  
y.m l=0.22 spac=0.2  
y.m l=1.62 spac=0.2

# create 5 independently specified regions
# 1st is top AlGaAs layer (0.25 Al fraction)
# 3 0.1 micron thick regions on top: 2 under contacts, on in
# gap (allows surface effects to be independently place)
# 1 base region of GaAs
region num=1 x.min=0.0 x.max=3.0 y.min=0.0 y.max=0.01  
material=AlGaAs x.composition=0.25 emiss.3  
region num=2 GaAs x.min=0.0 x.max=1.0 y.min=0.01 y.max=0.1  
region num=3 GaAs x.min=1.0 x.max=2.0 y.min=0.01 y.max=0.1  
region num=4 GaAs x.min=2.0 x.max=3.0 y.min=0.01 y.max=0.1  
region num=5 GaAs x.min=0 x.max=3.0 y.min=0.1 y.max=1.62  
# place electrodes on top (1 micron wide each)  
electrode num=1 name=Anode x.min=0.0 x.max=1.0 y.min=0  
y.max=0  
electrode num=2 name=Cathode x.min=2.0 x.max=3.0 y.min=0  
y.max=0  
# set doping for all 5 regions  
doping n.type conc=5e12 region=1 uniform  
doping n.type conc=5e12 region=2 uniform  
doping n.type conc=5e12 region=3 uniform
doping n.type conc=5e12 region=4 uniform
doping n.type conc=5e12 region=5 uniform
# set contacts as Schottky contacts
# MUST turn on surf.rec switch to work properly
# turn on image force switch

contact name=Anode workfun=4.9 surf.rec barrier
contact name=Cathode workfun=4.9 surf.rec barrier
# define geometry, placement of beam of light
# (angle=90 is normal incidence to material)
# 810 nm beam with width equal to gap width
beam number=1 x.origin=1.5 y.origin=-0.5 min.window=-0.5
max.window=0.5 angle=90 wavelength=0.810
# set non-default material parameters
# imag.index set to match optical absorption coefficient
# of GaAs at 810 nm
#define 0.1 micron strip under AlGaAs in gap to have short
#carrier lifetime (0.1 psec.)
material region =1 vsatn=1e7 vsatp=1.5e7
material region=2 imag.index=0.058 vsatn=1e7 vsatp=1.5e7
#material region=3 imag.index=0.058 vsatn=1e7 vsatp=1.5e7
material region=3 imag.index=0.058 vsatn=1e7 vsatp=1.5e7
taup0=1e-13 taun0=1e-13
material region=4 imag.index=0.058 vsatn=1e7 vsatp=1.5e7
material region=5 imag.index=0.058 vsatn=1e7 vsatp=1.5e7
# set models
# Boltzmann statistics, room temp., field dependent mobility
# concentration dependent mobility, Shockley-Read Hall
# Recombination with NO trap charging
models boltzman temperature=300 print conmob fldmob srh
evsatmod=0 hvsatmod=0 b.holes=1.75
# use gummel method for numeric solution of PDEs
# solve electrons and holes
method gummel carriers=2
# solve at thermal equilibrium
solve init
# now ramp up beam power in W/cm^2 at 0 V bias
solve v1=0 v2=0 b1=0
solve prev v1=0.05 v2=0 b1=0.25
solve prev v1=0.05 v2=0 b1=0.5
solve prev v1=0.05 v2=0 b1=1
solve prev v1=0.05 v2=0 b1=2
# specify that output files will include band edges
# in addition to standard quantities
output con.band val.band
# specify DC bias sweep solution with optical power present
# sweep range=0-5.2 V
log outfile=msm_op_surfrec.dat master
solve prev v2=0 b1=2 electrode=1 vstep=.2 nsteps=25
#save device state at 5.2 V to disk
solve v1=5.2 v2=0 b1=2 outfile=msm_fld.dat master
end
Bibliography


Vita

James Alexander McAdoo

The author was born in Keosoqua, Iowa, October 7, 1967. He graduated from McLean High School in McLean, Virginia, June 1985. B.S. in Physics, *cum laude*, from the University of Rochester in May, 1989. He began working at NASA/Langley Research Center in Hampton, Virginia, in September, 1989 as a photodetector subsystems engineer and has been responsible for support of advanced photodetector technology development in support of remote atmospheric sensing applications since that time. He received an M.S. in Electrical Engineering, University of Virginia, Charlottesville, Virginia, August, 1994 with a specialization in semiconductor devices. His thesis was entitled: Circular Electrode Geometry Metal-Semiconductor-Metal Photodetectors. He currently is listed as an inventor on two U.S. patents.

In January, 1998, the author entered the College of William and Mary as a graduate student in the Department of Applied Science.