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THE USE OF MICROWAVES TO CHARACTERIZE
OPTICALLY STIMULATED SEMICONDUCTORS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy in the Graduate School of
The Ohio State University

by

Harold Kent Brown, B.S., M.S.

The Ohio State University
1980

Reading Committee:  
Dr. Robert J. Garbacz
Dr. Robert G. Kouyoumjian
Dr. Marlin O. Thurston

Approved By
Dr. Marlin O. Thurston
Department of Electrical Engineering
To My Wife and Our Parents
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VITA

June 12, 1955 .... Born, Winston-Salem, North Carolina

1975 ............ B.S.E.E., Florida Institute of Technology, Melbourne, Florida

1976-1977 ........ Teaching Associate, Department of Electrical Engineering, The Ohio State University, Columbus, Ohio

1977............. M.Sc., The Ohio State University, Columbus, Ohio

1977-1980 ....... Research Assistant, Solid State Laboratory, The Ohio State University

PUBLICATIONS

"Propagation of Electromagnetic Waves Through Silicon with an Arbitrary Concentration Distribution".

FIELDS OF STUDY

Major Field: Electrical Engineering


Dr. M.O. Thurston and Dr. J.M. Swartz
FIELDS OF STUDY CONT.

Studies in Electromagnetism. Dr. R.G. Kouyoumjian and Dr. R.J. Garbcz.

Studies in Digital and Computer Architecture. Dr. K.J. Breeding.

Studies in Quantum Mechanics. Dr. P.E. Wigen.

# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>VITA</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
</tbody>
</table>

**Chapter**

I  **THEORETICAL INVESTIGATION**  4

A. Introductory Remarks  4

B. Optical Absorption  7

C. Carrier Redistribution  17

D. Microwave Transmission and Reflection Coefficients  26

E. Review  35

II  **EXPERIMENTAL RESULTS**  38

A. Description of Apparatus  38

B. Apparatus Calibration and Data Collection  44

C. Presentation of Collected Data and Correlation to Theoretical Results  46
<table>
<thead>
<tr>
<th>III</th>
<th>DEVICE APPLICATION</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Optical Detector</td>
<td>63</td>
</tr>
<tr>
<td>B.</td>
<td>Control of Microwave Transmission Through a Periodic Surface</td>
<td>67</td>
</tr>
<tr>
<td>IV</td>
<td>SUMMARY</td>
<td>71</td>
</tr>
<tr>
<td>A.</td>
<td>Theory</td>
<td>71</td>
</tr>
<tr>
<td>B.</td>
<td>Experimental</td>
<td>73</td>
</tr>
<tr>
<td>C.</td>
<td>Final Remarks</td>
<td>75</td>
</tr>
</tbody>
</table>

| APPENDIXES | |
| A | Computer Programs | 76 |
| B | Sample Data | 94 |

| BIBLIOGRAPHY | |
|             | 98 |
## LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Coefficients for Eqs. 1-57 through 1-67 describing the conductivity of silicon.</td>
<td>26</td>
</tr>
<tr>
<td>2.1</td>
<td>Results of Step 1.</td>
<td>47</td>
</tr>
<tr>
<td>2.2</td>
<td>Results of Step 2.</td>
<td>49</td>
</tr>
<tr>
<td>2.3</td>
<td>Results of Step 3 and a list of constants used throughout the calculations.</td>
<td>50</td>
</tr>
<tr>
<td>2.4</td>
<td>Results of Steps 4 and 5.</td>
<td>50</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Reflection and transmission of plane waves by a semiconductor at normal incidence.</td>
<td>8</td>
</tr>
<tr>
<td>1.2</td>
<td>Exaggerated view of the electrons diffusing at a faster rate than the holes.</td>
<td>20</td>
</tr>
<tr>
<td>1.3</td>
<td>Illustration depicting a wafer (shaded area) in a waveguide with a prescribed coordinate system.</td>
<td>28</td>
</tr>
<tr>
<td>2.1</td>
<td>Block diagram illustrating the experimental apparatus.</td>
<td>39</td>
</tr>
<tr>
<td>2.2</td>
<td>Optical portion of the experimental apparatus.</td>
<td>41</td>
</tr>
<tr>
<td>2.3</td>
<td>Illustration depicting the microwave apparatus.</td>
<td>43</td>
</tr>
<tr>
<td>2.4</td>
<td>Block diagram describing the computational steps used in the numerical analysis.</td>
<td>48</td>
</tr>
<tr>
<td>2.5</td>
<td>Electron-hole pair concentration through the silicon wafer after the light pulse passed.</td>
<td>52</td>
</tr>
<tr>
<td>2.6</td>
<td>Plot of the space-time matrix which is the plot of the results of step 7.</td>
<td>54</td>
</tr>
<tr>
<td>2.7</td>
<td>Comparison of the experimental and theoretical results.</td>
<td>56</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>2.8</td>
<td>Plot of normalized transmitted microwave energy versus time with infinite surface recombination velocity on one side of a silicon wafer and zero surface recombination velocity on the other.</td>
<td>57</td>
</tr>
<tr>
<td>2.9</td>
<td>Slope of the curves illustrated in Figure 2.8 at the .5 energy mark as a function of tau.</td>
<td>58</td>
</tr>
<tr>
<td>2.10</td>
<td>Plot of normalized transmitted microwave energy versus time with infinite surface recombination velocity on both surfaces of a silicon wafer.</td>
<td>59</td>
</tr>
<tr>
<td>2.11</td>
<td>Slope of the curves illustrated in Figure 2.10 at the .5 energy mark as a function of tau.</td>
<td>60</td>
</tr>
<tr>
<td>2.12</td>
<td>Plot of normalized transmitted microwave energy versus time with zero surface recombination velocity on both surfaces of a silicon wafer.</td>
<td>61</td>
</tr>
<tr>
<td>2.13</td>
<td>Slope of the curves illustrated in Figure 2.12 at the .5 energy mark as a function of tau.</td>
<td>62</td>
</tr>
<tr>
<td>3.1</td>
<td>The response of an existent optical detector.</td>
<td>65</td>
</tr>
<tr>
<td>3.2</td>
<td>The RF response of the silicon on sapphire wafer.</td>
<td>66</td>
</tr>
<tr>
<td>3.3</td>
<td>Illustration showing the periodic array and wafer mounted in waveguide.</td>
<td>69</td>
</tr>
<tr>
<td>3.4</td>
<td>Plots illustrating the frequency response of no sample, periodic array only, and periodic array with silicon wafer.</td>
<td>70</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>B.1</td>
<td>Plot of the incident intensity of the laser pulse illuminating the silicon wafer.</td>
<td>95</td>
</tr>
<tr>
<td>B.2</td>
<td>Plot of the intensity of the laser pulse exiting the silicon wafer.</td>
<td>96</td>
</tr>
<tr>
<td>B.3</td>
<td>Plot of the transmitted microwave energy in response to the incident light pulse.</td>
<td>97</td>
</tr>
</tbody>
</table>
INTRODUCTION

Attempts have been made in the past to characterize semiconductor properties using microwave radiation. Early investigators [1] suspended a block of semiconductor material in free space, measured the scattered radiation, and calculated the effective mobility and lifetime of the sample from the measurements. Problems arose with this approach because the scattered radiation was sensitive to the angle of incident radiation. Other experimenters [2] fabricated diodes and placed them into a waveguide with the leads parallel to the electric field; however, reasonable correlation between experimental and theoretical results was not shown. More recently [3], thin devices, primarily solar cells, have been placed inside a waveguide in such a way that the entire guide cross section was covered. In this latter work, lifetime of the material was claimed to have been measured accurately, but no conclusive results were shown.

It is the intent of this work to correlate the dynamic response of the microwave reflection and transmission coefficients
of a semiconductor wafer with an incident light pulse as a stimulus. The semiconductor is mounted in a waveguide, clamped between two flanges, covering the entire cross-sectional area. A pulse of light from a laser is coupled into the waveguide illuminating the semiconductor wafer. As the light creates electron-hole pairs in the semiconductor, the dynamic response of the microwave transmission and reflection coefficients is characterized. Both theoretical and experimental analyses are presented.

The solution is divided into three sequential modules, optical absorption, carrier redistribution and microwave characterization. In each of the modules, the fundamental equations are used, such as Maxwell's equations for the optical absorption and microwave characterization modules and the continuity equations for the carrier redistribution module. The fundamental equations are reduced to a discrete form and are solved on a digital computer. The solutions are then correlated with experimental results.

In addition to the theoretical calculations and experimental verification, two possible applications are presented using semiconductors in waveguide. One device illustrates the feasibility of using silicon in close proximity to a periodic array to allow switching action even in the band pass. The other device is a
large-area optical detector which is resistant to damage from excessive optical energies. Experimental characteristics of both of these devices are presented.

This work is presented in four chapters. In Chapter I, the theoretical analysis is developed leading to the equations that are to be solved on a digital computer. Described in Chapter II are the experimental apparatus and the method of data collection. Also presented is a comparison between the theoretical and the experimental results with sample calculations. In Chapter III, two device applications and the corresponding experimental results are discussed. The conclusions in Chapter IV highlight important aspects of the work and propose areas for further study.
CHAPTER I
THEORETICAL INVESTIGATION

A. Introductory Remarks

Electromagnetic waves may be used to interrogate certain internal processes in semiconductors. By stimulating a semiconductor sample with an incident light pulse, electron-hole pairs are generated provided that the associated photon energy of the light pulse is larger than the band-gap of the material. The presence of an increased number of electrons and holes increases the conductivity of the semiconductor and reduces the transmission of microwaves. As the electrons and holes return to equilibrium by recombing, the microwave reflection and transmission coefficients relax to their respective steady-state values. The purpose of this chapter is to develop theory which relates the intensity of the incident light pulse to the microwave reflection and transmission coefficients via the electron-hole pair recombination mechanism within the semiconductor.

In Section B, the electron and hole concentrations are computed after the light pulse has passed through the sample.
Two methods are presented, of which one is used if the band-gap is approximately equal to or larger than the incident photon energy, and the other is used if the band-gap is much smaller than the incident photon energy.

For the case when the band-gap is larger than the incident photon energy, the optical absorption coefficient and the Poynting vector inside the semiconductor are related to the incident and transmitted energies of the light pulse. The carrier concentration can be computed by assuming that for every photon or equivalent energy absorbed, one electron-hole pair is generated, and that the divergence of the Poynting vector gives the photon energy absorbed per unit volume per second in the semiconductor.

When the band gap is much less than the incident photon energy, a more complicated model is needed. It is assumed that the excess carrier concentration in the sample is saturated at a concentration \(C_0\) extending a distance \(z_1\) into the incident surface, and that beyond \(z_1\) there is an exponential decay of carriers. Knowing the optical absorption coefficient for the semiconductor, the incident and transmitted energies of the light pulse are related to \(C_0\) and \(z_1\), thereby giving the concentration distribution.
Using either of the carrier distributions of the electron-hole pairs computed in Section B as an initial condition, derivations in Section C describe the time decay process of the excited electron-hole pairs. Proceeding with the continuity equations for electrons and holes while assuming that the excited electron and hole concentrations and their respective first and second derivatives are approximately equal, a simple diffusion equation is developed with associated ambipolar lifetime and diffusion coefficients. The final equation is then formulated so that it may be solved numerically using a digital computer. Also, the equations relating the conductivity to the concentration are presented in Section C.

As the excited electrons and holes decay, the transmission and reflection coefficients of the medium at microwave frequencies will vary. In Section D, a review of the computation of these microwave reflection and transmission coefficients is presented. A complete treatment was developed previously [4]. Presented here is a derivation which starts with Maxwell's equations and assumes an arbitrarily varying conductivity in the z direction. Since the conductivity appears in numerical form, the final equations are transformed so that they may be solved by a digital computer.
In Section E, a review of the equations needed for the numerical analysis is presented. The computer programs solving these equations are listed in Appendix A, while the solutions are correlated with experimental data in Chapter II, Section C.

B. Optical Absorption

As a short pulse of light propagates through a semiconductor, the intensity of the light pulse decays while electrons are excited to a higher energy level, thereby creating electron-hole pairs. The number of electron-hole pairs produced can be computed by determining the intensity of the light pulse and relating it to the number of photons absorbed.

Case I

If the band-gap of a semiconductor material is approximately equal to or larger than the incident photon energy, there is little absorption by direct interband transitions, and the absorption coefficient due to other processes can be assumed to be small and constant throughout the material. Three homogeneous media, characterized by the propagation factors $k_1$, $k_2$, and $k_3$, and separated by plane boundaries, are considered as shown in Fig. 1.1 [5]. The electromagnetic fields in media one through three are:
Figure 1.1: Reflection and transmission of plane waves by a semiconductor at normal incidence.
Medium 1

\[ \mathbf{E}_i = \hat{x}\left[ E_0 e^{ik_1 z - i\omega t} + E_1 e^{-ik_1 z - i\omega t} \right] \]  
\[ \mathbf{H}_i = \hat{y}\left[ \frac{k_1}{\omega \mu_1} \left( E_0 e^{ik_1 z - i\omega t} - E_1 e^{-ik_1 z - i\omega t} \right) \right] \]  

Medium 2

\[ \mathbf{E}_s = \hat{x}\left[ E_2 e^{ik_2 z} + E_2 e^{-ik_2 z} \right] e^{-i\omega t} \]  
\[ \mathbf{H}_s = \hat{y}\left[ \frac{k_2}{\omega \mu_2} \left( E_2 e^{ik_2 z} - E_2 e^{-ik_2 z} \right) \right] e^{-i\omega t} \]  

Medium 3

\[ \mathbf{E}_t = \hat{x}\left[ E_3 e^{ik_3 z - i\omega t} \right] \]  
\[ \mathbf{H}_t = \hat{y}\left[ \frac{k_3}{\omega \mu_3} E_3 e^{ik_3 z - i\omega t} \right] \]  

The propagation factors for each of the media are:

\[ k_1 = \sqrt{\omega^2 \varepsilon_1 \mu_1} \]
In Eqs. 1-3 and 1-4, $E_2^+$, $E_2^-$, and $k_2$ must be determined before the field description is complete. The propagation factor $k_2$ can be computed by using experimental data for the magnitude of the optical transmission coefficient $T_0$. From Stratton's work [5], the transmission coefficient is found to be

$$T_0 = \left| \frac{1}{(1 + Z_{12})(1 + Z_{23})} \frac{4e^{i(k_2 - k_3)d}}{1 + r_{12}r_{23}e^{2ik_2d}} \right|^2 \text{Re}[Z_{13}]$$

(1-10)

where

$$Z_{jl} = \frac{\mu_j k_l}{\mu_k k_j} \quad l, j = 1, 2, 3$$

(1-11)

$$r_{jl} = \frac{1 - Z_{jl}}{1 + Z_{jl}} \quad l, j = 1, 2, 3$$

(1-12)

and

$$k_l = \beta_l + i\alpha_l \quad l = 1, 2, 3$$

(1-13)

Since $\varepsilon''_2$ is the only unknown parameter, it may be varied until the corresponding computed value of $T_0$ agrees with the experi-
mental value. To determine $E_2^+$ and $E_2^-$, the experimentally measured incident and transmitted light intensities will be used.

The mean intensity of the light pulse is described by the real part of the complex Poynting vector

$$\mathbf{S}_r = \text{Re} \left[ \frac{1}{2} \mathbf{E} \times \mathbf{H}^* \right]$$

By integrating over the entire surface of the semiconductor, the total energy absorbed per unit time is

$$\xi_T = \int_S \mathbf{S}_r \cdot \hat{n} \, da$$

Thus,

$$\xi_T = AB \frac{\beta}{2\omega \mu_2} \left[ |E_2^+|^2 \left( e^{-2\alpha d} - 1 \right) + |E_2^-|^2 \left( 1-e^{-2\alpha d} \right) \right]$$

where $AB$ is the illuminated area of the wafer shown in Figure 1.1. $\xi_T$ can also be stated in terms of the incident intensity and the optical reflection and transmission coefficients, $R_o$ and $T_o$, respectively;

$$\xi_T = -\text{Re} \left[ S_o \right] \left[ 1-R_o-T_o \right] AB$$

where $\text{Re}(S_o)$ is the incident intensity and the reflection coefficient is $[5]$. 
Further, the energy coupled into the semiconductor per unit time is given by

\[
R_o = \left| \frac{r_{12} + r_{23} e^{2ik_2d}}{1 + r_{12} r_{23} e^{2ik_2d}} \right|^2 \quad (1-18)
\]

By combining Eqs. 1-16, 1-17, and 1-19, \(|E_2^+|^2 \) and \(|E_2^-|^2 \) can be computed, leading to

\[
|E_2^+|^2 = \text{Re}[S_0] \left\{ \frac{\beta_2 (1-R_0)e^{2\alpha_2d} - T_0}{2\omega\mu_2 \left( e^{2\alpha_2d} - e^{-2\alpha_2d} \right)} \right\} \quad (1-20)
\]

and

\[
|E_2^-|^2 = \text{Re}[S_0] \left\{ \frac{(1-R_0)e^{-2\alpha_2d} - T_0}{2\omega\mu_2 \left( e^{-2\alpha_2d} - e^{2\alpha_2d} \right)} \right\} \quad (1-21)
\]

Knowing \(|E_2^+|^2 \) and \(|E_2^-|^2 \) does not lead to a solution of \(E_2^+ \) and \(E_2^- \) since phase relationships are not known. However, taking the real part of the divergence of the Poynting vector in the semiconductor gives the energy absorbed per unit volume per unit time as a function of \(z\);
\[ \xi_A = \frac{-\beta_2 \alpha_2}{\omega \mu_2} \left[ |E_2^+|^2 e^{-2\alpha_2 z} + |E_2^-|^2 e^{2\alpha_2 z} \right] \quad (1-22) \]

Therefore, knowing only \( |E_2^+|^2 \) and \( |E_2^-|^2 \) and the computed values of \( \alpha_2 \) and \( \beta_2 \) is sufficient for the desired solution.

Since the energy is absorbed in quantum increments and for every photon absorbed one electron-hole pair is generated Eq. 1-22 can be set equal to \(-C(z)\hbar\omega\), thus

\[ C(z) = \frac{\beta_2 \alpha_2}{\omega \mu_2 \hbar} \left[ |E_2^+|^2 e^{-2\alpha_2 z} + |E_2^-|^2 e^{2\alpha_2 z} \right] \quad (1-23) \]

where \( C(z) \) is the number of electron-hole pairs generated per unit volume per laser pulse, and \( \hbar \) is Planck's constant divided by \( 2\pi \).

**Case II**

If the incident photon energy is substantially higher than the band-gap energy, the incident light will be very effective in generating electron-hole pairs and the absorption coefficient will be high. In addition, if the incident light pulse is of sufficient intensity to excite most of the available electrons to a higher energy level, the absorption coefficient is not constant throughout the semiconductor. Under such conditions, the absorbing medium is divided into two regions. In the first region, close
to the incident surface, it is assumed that most of the available electrons are excited, giving a concentration $C_0$ penetrating to a depth $z_1$ into the incident surface. By the time the light pulse has penetrated into the second region, its intensity will have decreased such that the absorption coefficient can be assumed to be constant. In this region, the concentration distribution will be of the exponential form. Thus, the concentration distribution

$$C(z) = C_0 \left[ \mu(z) - \mu(z-z_1) + \mu(z-z_1) e^{-2\alpha_2(z-z_1)} \right]$$  \hspace{1cm} (1-24)

will be considered, where:

- $\mu(z)$ is the unit step function,
- $C_0$ is the saturation level for the concentration close to the surface,
- $\alpha_2$ is the absorption coefficient in the region between $z_1$ and $d$,
- $z_1$ is the depth of saturation.

In the region of $z_1 < z < d$, the EM wave inside the semiconductor is

$$E_s = i \Phi (E^+_2 e^{ik_2(z-z_1)} + E^-_2 e^{-ik_2(z-z_1)} ) e^{-i\omega t}$$  \hspace{1cm} (1-25)

and
where $E^{-}_2$ is assumed to be negligible since $\alpha_2$ and $d$ are assumed to be large enough to eliminate any internal reflections. The mean intensity of the light pulse in this region is

$$\text{Re} \left[ \mathbf{S}_s \right] = \frac{\beta}{2 \omega \mu_1} \frac{\alpha_2}{|E^+_2|^2} e^{-2\alpha_2(z-z_1)} \quad z_1 < z < d$$

(1-27)

where $\mathbf{S}_s$ is the Poynting vector. Computing the energy absorbed in the region $z_1 < z < d$,

$$\text{Re} \left[ \nabla \cdot \mathbf{S}_s \right] = \frac{-\beta_2 \alpha_2}{\omega \mu_2} \frac{\alpha_2}{|E^+_2|^2} e^{-2\alpha_2(z-z_1)}$$

(1-28)

and relating $\text{Re} (\nabla \cdot \mathbf{S}_s)$ to quantum absorption leads to

$$C_0 e^{-\frac{-\alpha_2(z-z_1)}{h \omega}} \frac{\beta_2 \alpha_2}{\omega \mu_2} \frac{\alpha_2}{|E^+_2|^2} e^{-2\alpha_2(z-z_1)}$$

(1-29)

Also, relating the transmitted intensity, $\text{Re} \left[ S_t \right]$, to $|E^+_2|^2$

$$\text{Re} \left[ S_t \right] = \frac{\beta_2^2 + \alpha_2^2}{\beta_2 \omega \mu_2} \frac{\alpha_2}{|E^+_2|^2} e^{-2\alpha_2(d-z_1)} \quad T_{23}$$

(1-30)

and combining Eqs. 1-29 and 1-30 gives a solution for $C_0$ in terms of $z_1$;
where $T_{23}$ is the transmission coefficient between media two and three;

$$T_{23} = \text{Re}[Z_{23}^*] \left| \frac{2}{1 + Z_{23}} \right|^2$$

(1-32)

So far, only one of the needed equations relating $C_o$ and $z_1$ to each other has been determined. To complete the solution, Eq. 1-24 is integrated from $z = 0$ to $z = d$ to give the total number of electron-hole pairs generated in the semiconductor per light pulse; giving the second needed equation

$$C_T = C_o \left[ z_1 + \frac{1}{2\alpha_2} \left[ 1 - e^{-2\alpha_2(d-z_1)} \right] \right]$$

(1-33)

where $C_T$ is related to the experimentally measured incident and transmitted intensities by

$$C_T = \frac{(1 - \left| r_{12} \right|^2) \text{Re}[S_o] - \text{Re}[S_T]}{\text{AB}}$$

(1-34)

Combining Eqs. 1-33 and 1-31 gives a transcendental equation for $z_1$ which must be solved by successive approximation. Once $z_1$ is known $C_o$ may be found using Eq. 1-31 thus giving the needed coefficients for Eq. 1-24.
C. Carrier Redistribution

In the previous section, the concentration distribution $C(z)$ of the electron-hole pairs generated by an incident light pulse was determined. After the light pulse passes, the electrons and holes tend to diffuse to less populated areas of the semiconductor. Also, a recombination process takes place that allows the electrons and holes to annihilate each other so the total number of pairs decreases. The continuity equations that describe this process, one for electrons,

$$\frac{\delta n}{\delta t} = -R_n + \mu_n \nabla \cdot (nE) + D_n \nabla^2 n$$

(1-35)

and another for holes,

$$\frac{\delta p}{\delta t} = -R_p - \mu_p \nabla \cdot (pE) + D_p \nabla^2 p$$

(1-36)

relate the total change of electrons and holes per unit volume per unit time $\frac{\delta n}{\delta t}$ and $\frac{\delta p}{\delta t}$, respectively, with their respective recombination, drift, and diffusion rates per unit volume per unit time. The variables used in Eqs. 1-35 and 1-36 are defined as:

$$n = n' + n_0$$

(1-37)

$n$ - total electron concentration per unit volume

$n'$ - excited electron concentration

$n_0$ - electron background concentration
\[ p = p' + p_o \]  
(1-38)

\[ p \] - total hole concentration per unit volume
\[ p' \] - excited hole concentration
\[ p_o \] - hole background concentration

\[ R_n = \frac{n - n_o}{\tau_n} \]  
(1-39)

\[ R_n \] - recombination rate for electrons
\[ \tau_n \] - lifetime for the electrons

\[ R_p = \frac{p - p_o}{\tau_p} \]  
(1-40)

\[ R_p \] - recombination rate for holes
\[ \tau_p \] - lifetime for the holes.

\[ D_n \] - diffusion coefficient for electrons
\[ D_p \] - diffusion coefficient for holes
\[ \mu_n \] - mobility for the electrons
\[ \mu_p \] - mobility for the holes

The assumption will be made throughout the following derivation that the partial derivatives with respect to time for \( n \) and \( p \) are approximately equal. A similar assumption will be made for space derivatives. In reality, however, as the electrons
and holes redistribute, the electrons tend to diffuse faster than the holes, assuming that the electrons have a larger diffusion coefficient than do the holes, as illustrated in Figure 1.2. While the inbalance of electrons and holes develops, an electric field is formed between the electrons and holes. As a result, the diffusion of the holes is aided by the field. The basic assumption states that although the electron and hole diffusion coefficients are different, the electric field from charge unbalance prevents the excited electron and hole concentrations and their respective derivatives from differing significantly from each other throughout the semiconductor. This, in turn, allows the use of a simple diffusion equation provided that effective or "ambipolar" mobility, lifetime, and diffusion coefficients are used.

Multiplying Eq. 1-35 by \( \mu_p p \) and Eq. 1-36 by \( \mu_n n \), adding the two, and letting

\[
\frac{\partial p}{\partial t} \approx \frac{\partial n}{\partial t} \tag{1-41}
\]

and

\[
\nabla p = \nabla n \tag{1-42}
\]

leads to
Figure 1.2: Exaggerated view of the electrons diffusing at a faster rate than the holes.
\[
\frac{\delta n}{\delta t} (\mu_p p + \mu_n n) = - R_n \mu_p p + \mu_n n R_p + \mu_p \mu_n (p-n) \vec{E} \cdot \nabla n + \\
\mu_p p D_n \nabla^2 n + \mu_n n D_p \nabla^2 p
\]  \hspace{1cm} (1-43)

Combining Einstein's relationships for holes,

\[
D_p = \frac{kT}{q} \mu_p
\]  \hspace{1cm} (1-44)

and for electrons

\[
D_n = \frac{kT}{q} \mu_n
\]  \hspace{1cm} (1-45)

gives

\[
D_p \mu_n = D_n \mu_p
\]  \hspace{1cm} (1-46)

Assuming \(\nabla^2 n\) equals \(\nabla^2 p\) and combining Eqs. 1-43 and 1-46 gives

\[
\frac{\delta n}{\delta t} = \frac{-R_n \mu_p p + \mu_n n R_p}{\mu_p p + \mu_n n} + \frac{\mu_p \mu_n (p-n) \vec{E} \cdot \nabla n}{\mu_p p + \mu_n n} + \\
\frac{\mu_p D_n (n+p)}{\mu_p p + \mu_n n} \nabla^2 n
\]  \hspace{1cm} (1-47)

Noting that \((n-p)\nabla n\) is small and that \(n'\) is approximately equal to \(p'\) gives the final result;
\[
\frac{\partial n'}{\partial t} = -\frac{n'}{\tau_a} + D_a \nabla^2 n'
\]  \hspace{1cm} (1-48)

where \( \tau_a \) and \( D_a \) are the ambipolar lifetime and diffusion coefficients, respectively;

\[
\tau_a = \frac{n'(\mu_p + \mu_n) + (\mu_p p_o + \mu_p n_o)}{n'(\frac{\mu_p}{\tau_p} + \frac{\mu_n}{\tau_n}) + \frac{\mu_p}{\tau_p} + \frac{\mu_n}{\tau_n}} \hspace{1cm} (1-49)
\]

and

\[
D_a = \frac{\mu_p D_n(2n' + n_o + p_o)}{n'(\mu_p + \mu_n) + \mu_p p_o + \mu_n n_o} \hspace{1cm} (1-50)
\]

Using the results of Section B as the initial condition (letting \( n(z,t) \) at time equals zero be \( C(z) \)) and Eq. 1-48, the electron-hole pair concentration can be computed throughout the semiconductor as a function of time by using numerical methods.

Approximating Eq. 1-48 by the difference equation

\[
\begin{align*}
\frac{n'_{m+1} - n'_{m}}{2 \delta} &= D_{am} \frac{n'_{m+1} - 2n'_{m} + n'_{m-1}}{h^2} - \frac{n'_{m}}{\tau_{am}} \\
&= D_{am} \frac{k}{h^2} - \frac{n'_{m}}{\tau_{am}}
\end{align*}
\]  \hspace{1cm} (1-51)

where

- \( m \) is the spatial index
- \( k \) is the temporal index
- \( h \) is the incremental spatial displacement
- \( \delta \) is the incremental temporal displacement
and solving for \( n'_{m}^{k} \) gives,

\[
n'_{m}^{k} = \frac{D_{am} \left[ \frac{n'_{m}^{k+1} + n'_{m-1}^{k}}{2} \right] - \frac{n'_{m}^{k+1} - n'_{m}^{k-1}}{2\delta}}{1 \frac{1}{\tau_{am}} + 2D_{am} \frac{2}{h^2}}
\]  \hspace{1cm} (1-52)

Applying the successive over relaxation method (SOR), an error factor is developed,

\[
\text{Error} = \frac{D_{am} \left[ \frac{n'_{m+1}^{k} + n'_{m-1}^{k}}{2} \right] - \frac{n'_{m}^{k+1} - n'_{m}^{k-1}}{2\delta}}{1 \frac{1}{\tau_{am}} + 2D_{am} \frac{2}{h^2}} - n'_{m}^{k}
\]  \hspace{1cm} (1-53)

and a new \( n'_{m}^{k} \) is computed by

\[
n'_{m}^{k} = n'_{m}^{k} + W \times \text{Error}
\]  \hspace{1cm} (1-54)

where \( W \) is the relaxation factor. The desired solution is obtained by repeatedly using Eqs. 1-53 and 1-54 over all ranges of \( m \) and \( k \) until the error is reduced to tolerable limits.* Once \( n' \) is

* The values of \( n \) over the ranges of \( m \) and \( k \) are referred to as the space-time matrix.
known, the electron and hole concentrations become known respectively as,

\[ n = n' + n_0 \] \hspace{1cm} (1-55)

and

\[ p = n' + p_0 \] \hspace{1cm} (1-56)

The conductivity of the semiconductor is related to \( n \) and \( p \) by

\[ \sigma = q(n\mu_n + p\mu_p) \] \hspace{1cm} (1-57)

where \( q \) is the electric charge of an electron. Berz [6] determined the mobilities, \( \mu_n \) and \( \mu_p \) to be

\[ \mu_n = \frac{1}{\frac{1}{F} \left[ \frac{1}{\mu_{ln}} + \frac{\mu_{1n} + \mu_{he}}{\mu_{1n} \mu_{he}} \right]} \] \hspace{1cm} (1-58)

and

\[ \mu_p = \frac{1}{\frac{1}{F} \left[ \frac{1}{\mu_{lp}} + \frac{\mu_{1n} + \mu_{he}}{\mu_{1n} \mu_{he}} \right]} \] \hspace{1cm} (1-59)

where \( \mu_1, \mu_{he}, \) and \( \mu_l \) are the components related to lattice, electron-hole, and impurity scattering, respectively. The statistical factor \( F \) is

\[ F = \frac{.0954 + .473 S - .383 S^2}{.0956 + .866 S - .776 S^2} \] \hspace{1cm} (1-60)
\[ S = \frac{\mu_{\nu}}{\mu_{\nu} + \frac{\mu_{1\nu}}{\mu_{1\nu} + \mu_{\text{hev}}}} \quad \nu = n, p \] (1-61)

The individual mobility components are related to \( n, p \), the temperature (\( T \)) and total impurity concentration (\( N \)) by,

\[ \mu_{1n} = A \left( \frac{T}{300} \right)^{1.5} \left[ 1 + \frac{B}{(n+p)} \left( \frac{T}{300} \right)^2 \right] \] (1-62)

\[ \mu_{1p} = \mu_{1n} \] (1-63)

\[ \mu_{\nu n} = C_1 \left( \frac{T}{300} \right)^{-2.4} \] (1-64)

\[ \mu_{\nu p} = C_2 \left( \frac{T}{300} \right)^{-2.5} \] (1-65)

\[ \mu_{\text{hen}} = \sqrt{\frac{2}{n}} \frac{N}{p} \mu_{1n} \] (1-66)

\[ \mu_{\text{hep}} = \mu_{\text{hen}} \frac{p}{n} \] (1-67)
The coefficients $A$, $B$, $C_1$, and $C_2$ are listed in Table 1.1 for silicon.

**Table 1.1**

Coefficients for Eqs. 1-57 through 1-67 describing the conductivity of silicon.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$2.45 \times 10^{21}$</td>
</tr>
<tr>
<td>$B$</td>
<td>$1.41 \times 10^{20}$</td>
</tr>
<tr>
<td>$C_1$</td>
<td>1350</td>
</tr>
<tr>
<td>$C_2$</td>
<td>480</td>
</tr>
</tbody>
</table>

D. Microwave Transmission and Reflection Properties

In this section, a theoretical expression describing the propagation of an electromagnetic wave through bulk semiconductor material in a waveguide is derived. Transmission and reflection coefficients of the materials are then computed. The results of Section C are used to generate the conductivity profile in the direction of propagation ($z$-direction). The variables used throughout the derivation are defined as follows:
27

\( \sigma(z) \) - conductivity as a function of \( z \) in the semiconductor

\( \epsilon_2 \) - permittivity of the semiconductor

\( \mu_2 \) - permeability of the semiconductor

\( \epsilon_1, \epsilon_3 \) - permittivity of space in the waveguide

\( \mu_1, \mu_3 \) - permeability of space in the waveguide

\( \omega \) - angular frequency in radians per second

\( \hat{x} \) - unit vector in the \( \hat{x} \) direction

\( \hat{y} \) - unit vector in the \( \hat{y} \) direction

\( \hat{z} \) - unit vector in the \( \hat{z} \) direction

\( b \) - width of the waveguide along the \( y \) direction

Note that the coordinate system to be used here is rotated and shifted from that chosen in Sections B and C. It is depicted in Figure 1.3. This change in the coordinate system simplifies the numerical solution. The wave is assumed to propagate in the minus \( \hat{z} \) direction and \( \epsilon_1, \epsilon_2, \epsilon_3, \mu_1, \mu_2, \mu_3 \) and \( \omega \) are assumed to be real constants. Also an \( e^{j\omega t} \) time dependence is assumed throughout and suppressed for convenience.

To achieve the desired solution, a recursion relation describing the electric field throughout the semiconductor is developed. Starting with Maxwell's equations in the semiconductor,
Figure 1.3: Illustration depicting a wafer (shaded area) in a waveguide with a prescribed coordinate system.
\[ \nabla \times \mathbf{H} = \left[ \sigma(z) + j \omega \epsilon_2 \right] \mathbf{E}_s \]  
(1-68)

and

\[ \nabla \times \mathbf{E}_s = -j \omega \mu_2 \mathbf{H}_s \]  
(1-69)

and taking the curl of Eq. 1-69, and combining it with Eq. 1-68 gives the wave equation,

\[ \nabla \times \nabla \times \mathbf{E}_s = -j \omega \mu_2 (\sigma(z) + j \omega \epsilon_2) \mathbf{E}_s \]  
(1-70)

Since the time-independent representation of the TE_{10} transmitted wave in the waveguide is [7] of the form

\[ \mathbf{E}_t = \hat{x} E_3 \sin \left[ \frac{y \pi}{b} \right] \exp \left[ z \left( \frac{\pi^2}{b^2} - \omega^2 \epsilon_3 \right)^{1/2} \right], \]  
(1-71)

\[ z \leq 0 \]

the electric field in the semiconductor is proposed to be of a similar form

\[ \mathbf{E}_s = \hat{x} E_3 \sin \left[ \frac{\pi y}{b} \right] f(z), \quad d \leq z \leq 0 \]  
(1-72)

where \( f(z) \) is a function to be determined. Substituting Eq. 1-72 into Eq. 1-70 gives the final form of the wave equation which is to be solved;

\[ \frac{d^2 f(z)}{dz^2} = \left[ \left( \frac{\pi}{b} \right)^2 + j \omega \mu_2 (\sigma(z) + j \omega \epsilon_2) \right] f(z), \]  
\[ d \leq z \leq 0 \]  
(1-73)
A recursion relation is formed by first approximating the second derivative of \( f(z) \) as

\[
\frac{d^2 f(z)}{dz^2} \approx \frac{f_{m+1} - 2f_m + f_{m-1}}{h^2}
\]

(1-74)

where

- \( h \) is an incremental length
- \( m \) is an integer; \( m = 1, 2, \ldots, n \)
- \( z \) is equal to \( mh \)
- \( nh \) is the semiconductor wafer thickness

Next, combining Eqs. 1-73 and 1-74 and solving for \( f_{m+1} \) gives the intended recursion relationship;

\[
f_{m+1} = \left[ h^2 \left( \frac{\pi}{b} \right)^2 + j\omega \mu_2 \left( \sigma(z) + j\omega \epsilon_2 \right) + 2 \right] f_m - f_{m-1}
\]

(1-75)

To start the recursion, \( f_0 \) and \( f_1 \) must be determined.

Knowing that the tangential component of the electric field is continuous across an interface, \( f_0 \) is computed by setting Eqs. 1-71 and 1-72 equal at \( z = 0 \);

\[
\hat{x} E_3 \sin \left( \frac{\pi}{b} \right) \exp \left[ \left( 0. \right) \left( \frac{\pi}{b} \right)^2 - \omega^2 \mu_3 \epsilon_3 \right] = \hat{x} E_3 \sin \left( \frac{\pi y}{b} \right) f(0)
\]

(1-76)
which reduces to

\[ f_0 = 1 \quad (1-77) \]

To solve for \( f_1 \), \( f(z) \) is expanded around \( z = 0 \) by using the MacLaurin series and then evaluating it for \( z = h \) so that

\[ f_1 = f_0 + \sum_{i=1}^{\infty} \frac{h^i}{i!} \frac{\partial^i f(z)}{\partial z^i} \bigg|_{z=0} \quad (1-78) \]

The first term has already been determined to be unity. The second term is determined first by showing that \( \frac{\partial (E_t \cdot \hat{x})}{\partial z} \) is continuous across the boundary at \( z = 0 \), and then by applying Eqs. 1-71 and 1-72.

Applying one of Maxwell's equations,

\[ \nabla \times \vec{E}_t = -j\omega \mu_3 \vec{H}_t \quad (1-79) \]

to Eq. 1-71, the tangential component at \( \vec{H}_t \) becomes

\[ \hat{y} j \frac{1}{\omega \mu_3} \frac{\partial (E_t \cdot \hat{x})}{\partial z} = \hat{y} (\vec{H}_t \cdot \hat{y}) \quad (1-80) \]

Also, in a similar fashion, the tangential component of \( \vec{H} \) for the semiconductor is

\[ \hat{y} j \frac{1}{\omega \mu_2} \frac{\partial (E_s \cdot \hat{x})}{\partial z} = \hat{y} (\vec{H}_s \cdot \hat{y}) \quad (1-81) \]

Since the tangential component of \( \vec{H} \) is continuous across the
interface at \( z = 0 \) (assuming no free surface current densities),

Eq. 1-80 and 1-81 can be set equal if evaluated at \( z = 0 \), giving

\[
\frac{\delta (E_s \cdot \hat{x})}{\delta z} \bigg|_{z = 0} = \frac{\mu_1}{\mu_3} \frac{\delta (E_t \cdot \hat{x})}{\delta z} \bigg|_{z = 0}
\]  

(1-82)

Substituting Eqs. 1-71 and 1-72 into Eq 1-82 leads to

\[
\frac{\delta f(z)}{\delta z} \bigg|_{z = 0} = \frac{\mu_2}{\mu_3} \left( \left( \frac{\pi}{b} \right)^2 - \omega^2 \mu_2 \epsilon_2 \right) \frac{k^2 - \omega^2 \mu_3 \epsilon_3}{2}
\]  

(1-83)

which is the second term of Eq. 1-78.

The remaining terms of Eq. 1-78 are determined by taking the \( k \)-th derivative of Eq. 1-73, giving a general form

\[
\frac{\delta^k f(z)}{\delta z^k} = \left[ \left( \frac{\pi}{b} \right)^2 - \omega^2 \mu_2 \epsilon_2 \right] \frac{\delta^{k-2} f(z)}{\delta z^{k-2}} + \]

\[
\frac{j \omega \mu_2}{p! (k-2-p)!} \frac{(k-2)!}{\delta z^{k-2-p}} \frac{\delta^p \sigma(z)}{\delta z^p} \frac{\delta^{k-2-p} f(z)}{\delta z^{k-2-p}}
\]

(1-84)

Now that \( f_0 \) and \( f_1 \) have been calculated, the electric field throughout the semiconductor is defined by Eqs. 1-72 and 1-75. To
compute the transmission and reflection coefficients, the field across the interface at \( z = d \) must be matched.

The reflection and transmission coefficients \( R \) and \( T \), respectively, are defined by

\[
R \equiv \frac{E_{sd} - E_{id}}{E_{id}} \quad (1-85)
\]

and

\[
T \equiv \frac{E_{to}}{E_{id}} \quad (1-86)
\]

where

\( E_{id} \) is the incident electric field at \( z = d \) with the wafer absent

\( E_{sd} \) is the total electric field inside the semiconductor at \( z = d \)

\( E_{to} \) is the transmitted electric field in the waveguide at \( z = 0 \).

It should be noted that in this derivation all the electric fields are assumed to remain parallel to \( \hat{x} \). Matching the \( H \) fields at \( z = d \) and using Maxwell's equations, Eqs. 1-72, 1-85, 1-86, the transmission and reflection coefficients can be computed to be
Since \( f(z) \) as expressed in Eq. 1-75 is not in closed form, Eqs. 1-87 and 1-88 must be approximated, such that

\[
T = \frac{1}{\mu_1 \left[ \frac{f(nh) - f((n-1)h)}{f(nh)} \right] + \frac{\mu_1}{\mu_2} \left( \frac{\partial f(z)}{\partial z} \right) \bigg|_{z = d} + \frac{f(d)}{2}}
\]

(1-89)

and

\[
R = \frac{f(d) \left( \left( \frac{\pi}{b} \right)^2 - \omega^2 \mu_1 \epsilon_1 \right)^{\frac{3}{2}}}{\mu_2} \left( \frac{\partial f(z)}{\partial z} \right) \bigg|_{z = d} + \frac{\mu_1}{\mu_2} \left( \frac{\partial f(z)}{\partial z} \right) \bigg|_{z = d}
\]

(1-90)
where the \( \frac{\delta f(z)}{\delta z} \) is approximated by

\[
\left. \frac{\delta f(z)}{\delta z} \right|_{z = d} \approx \frac{f(nh) - f((n-1)h)}{h}
\]  \hspace{1cm} (1-91)

E. Review

Presented in this section is a review (through reference) of the major equations used throughout this chapter. For complete details please refer to the appropriate section, for this is intended only as a summary.

To begin the calculations, \( T_O \), the optical transmission coefficient and \( \text{Re}(S_O) \), the incident optical intensity are needed. These quantities are usually obtained experimentally. To characterize the material, \( \epsilon'' \) of Eq. 1-8 must be determined. Using Eqs. 1-7 through 1-13 \( \epsilon'' \) is computed by trial and error. Throughout the rest of the calculations \( \epsilon'' \) is used indirectly through Eqs. 1-8 and 1-13 leading to useful values for \( \alpha_2 \) and \( \beta_2 \).

The electron-hole pair concentration throughout the semiconductor, after the light pulse, is given by Eq. 1-23. The needed coefficients, \( |E_2^+|^2 \), \( |E_2^-|^2 \), and \( R_0 \) are given by Eqs. 1-20, 1-21, and 1-18, respectively.

Computing the carrier concentration as a function of space and time is performed in two steps. First, an initial guess of
a space-time matrix is needed. There is no best method of making a guess. Usually a simple theoretical model is sufficient; however, a poor guess may substantially increase computation time. The initial guess used in this work is described in the calculations presented in Chapter 2–C. The second step involves the implementation of Eqs. 1-54, 1-53, 1-49, and 1-50. These equations are used to iterate through the space-time matrix until a solution is obtained for the electron-hole pair concentration with a tolerable error.

Next, the conductivity of the semiconductor is computed as a function of space and time. Utilizing Eqs. 1-57 through 1-67 each element of the space-time matrix is converted from carrier concentration to conductivity. Conductivity is the dominant variable in the computation of the microwave transmission and reflection coefficients.

Computation of the microwave reflection and transmission coefficients is achieved with the implementation of Eqs. 1-75, 1-77, 1-78, 1-84, and 1-89 through 1-91. Equation 1-75 is the equation that describes the normalized electric field in the semiconductor. To start the iteration process Eqs. 1-77, 1-78, and 1-84 are used in a combined fashion where the partial derivative in Eq. 1-84 is computed numerically from the space-time
matrix. After Eq. 1-75 is iterated through the sample, Eqs. 1-89 through 1-91 are used to match the boundary conditions and compute the microwave transmission and reflection coefficients.

Sample calculation of the above equations are illustrated in Chapter 2, Section C. Also, comparison of experimental and theoretical results is presented.
CHAPTER II

EXPERIMENTAL RESULTS

A. Description of Apparatus

The apparatus can be divided into three sections; optical, microwave, and detection. The initial stimulus is a light pulse with a wavelength of 1.06 micrometers, generated by a Q-switched neodimium YAG laser. An optical system is used to couple the light into a microwave waveguide, thus illuminating the semiconductor sample as illustrated in Fig. 2.1. A run of x-band waveguide is used to support propagation of a 10 gigahertz continuous wave (CW) microwave which is generated by a klystron oscillator, and guided to the semiconductor sample. Finally, two types of detectors are used, one for light pulses and one for the transmitted microwave. Note that only one of the detectors can be in operation at any given time. The output of each detector is coupled into a digitizer and then fed into a graphics display and copier. Presented next, is a detailed description of the apparatus and some of the methods used for alignment and tuning.
Figure 2.1: Block diagram illustrating the experimental apparatus.
The optical system consisted of

1) Q-switched neodium YAG laser
2) one-quarter (¼) to two (2) inch beam expander
3) optically flat mirror
4) convex lens
5) optical benches, mounts, filters, and other hardware.

The optical portion of the apparatus is shown in Figure 2.2.

The laser was pulsed once every second, producing a one-quarter (¼) inch beam of light for a duration of 20 nanoseconds, having approximately 30 millijoules of energy at a wavelength of 1.06 micrometers. Filters were placed in the beam's path to reduce its total energy content. To distribute the beam's energy so that it would not harm certain pieces of the optics, the beam was expanded to two inches in diameter with a beam expander. A mirror was used for convenience in the table set-up to reflect the laser beam through a one thirty-second inch hole at a 90 degree bend in the waveguide, thus illuminating the semiconductor sample. The focal length of the lens was chosen to illuminate the entire semiconductor sample.
Figure 2.2: Optical portion of the experimental apparatus.
The microwave apparatus, used to measure the reflection and transmission coefficients, is shown in Figure 2.3. An x-band (8-11 Gigahertz) signal was generated by a klystron oscillator and coupled into the waveguide and then guided through a cavity-type frequency meter, an attenuator and a unifeed line to enter a cavity formed by EH tuner No. 1 and the sample. The unifeed line was used to prevent any energy from coupling out the cavity into the waveguide approaching the klystron. Since unifeed lines are not an ideal impedance match to waveguides, EH tuner No. 1 was tuned to eliminate any standing waves in the cavity. The directional coupler directs reflected energy from the sample to the RF detector at point B where EH tuner No. 2 is used to maximize the coupling.

Two types of detectors were placed at point A. An optical detector was positioned to capture all of the light that passed through the waveguide system so the total incident and transmitted light energies could be measured. Once the light energies were determined, the optical detector was replaced by a broad-band microwave detector to measure the transient response of the transmitted microwave energy when the light pulse from the laser illuminated the semiconductor sample. The outputs of the detectors were fed into a digitizer which allowed
Figure 2.3: Illustration depicting the microwave apparatus.
the results to be presented in a graphics display and reproduced on a copier system.

B. Apparatus Calibration and Data Collection

Before any experiments could be performed, the optical system had to be aligned with the microwave waveguide so that the semiconductor sample would be properly illuminated. The first step taken was to align the laser cavity, the center of the sample and the microwave waveguide so that they were on the same plane. Then, while the laser was being pulsed, a phosphorescent card was used to determine the direction of the beam. The phosphorescent card glowed yellow when exposed to the laser beam. Using the mirror, the beam was directed to the convex lens and focussed through a hole in the waveguide. Fine tuning was accomplished by slightly moving the lens. The card was also used to make sure that the cross-section of the waveguide at the sample-mount was illuminated. Once alignment was achieved visually, a pin diode was moved across the cross-sectional area of the sample mount to check for uniform illumination.

To prepare the microwave apparatus for the measurement of the reflection and transmission coefficients, the following procedure was followed:
1) Set the klystron oscillator at 10 Giga Hz.

2) Place a sliding short circuit at point A as shown in Figure 2.3.

3) Adjust EH tuner No. 2 until a peak reading is achieved at point B.

4) Move the sliding short circuit at point A and record the maximum and minimum values at point B. Adjust EH tuner No. 1 to reduce the difference between the maximum and minimum.

5) Repeat steps 3 and 4 until the maximum and minimum readings are within .3 db of each other.

Once the apparatus was calibrated, the incident and transmitted optical energies along with the corresponding microwave transmission and reflection coefficients could be measured. The incident optical energy was measured by placing an optical detector at point A, shown in Figure 2.3, while the laser was pulsing at a rate of one pulse per second. The output of the detector was coupled into a digitizer where the signal was converted to a digital form which could then be processed by a graphics system. The graphics system integrated the pulse to
give the corresponding energy of the pulse. The transmitted energy measurement was performed much the same way, except that the sample was placed between the optical detector and the waveguide as illustrated in Figure 2.3.

Although the apparatus was set to measure the microwave transmission and reflection coefficients, considerable trouble was encountered measuring the latter. Since the directional coupler attenuated the signal 10 dB, and the broad-band detector was not very sensitive, the measured signal was well into the range of the background noise. Due to these types of problems, most of the efforts were concentrated on measuring the transmission coefficient. Also, it was found to be more feasible to measure the change in transmitted field strength instead of the transmission coefficient. Either measured quantity can be correlated to the theoretical calculation.

C. Presentation of Collected Data and Correlation with Theoretical Results

A single silicon wafer was used as a sample to evaluate the validity of the theoretical derivation discussed in Chapter I. The sample had a thickness of 285 micrometers and was polished on one surface while being lapped on the other. Also, the sample was intrinsic at room temperature. Experimentally, four curves
were generated illustrating the microwave transmission characteristics as a function of time at different incident light energies.

Eight computational steps describe the numerical calculations as shown in Figure 2.4. Step 1 calculates the incident light energy per meter squared per pulse which is given by

$$\text{Re} [S_0] = \frac{\xi_i}{A_s}$$  \hspace{1cm} (2-1)

where $\xi_i$ is the incident energy and $A_s$ is the area of the illuminated surface. Table 2.1 lists the results of Eq. 2-1.

**Table 2.1**

Results of Step 1

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$\xi_i$ (joules)</th>
<th>$A_s$ (meter$^2$)</th>
<th>Re[$S_0$] (joules (meter)$^2$/pulse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$7.15 \times 10^{-3}$</td>
<td>$2.88 \times 10^{-4}$</td>
<td>3.99</td>
</tr>
<tr>
<td>2</td>
<td>$3.04 \times 10^{-3}$</td>
<td>$2.88 \times 10^{-4}$</td>
<td>$1.06 \times 10^1$</td>
</tr>
<tr>
<td>3</td>
<td>$1.72 \times 10^{-2}$</td>
<td>$2.88 \times 10^{-4}$</td>
<td>$3.89 \times 10^1$</td>
</tr>
<tr>
<td>4</td>
<td>$4.99 \times 10^{-2}$</td>
<td>$2.88 \times 10^{-4}$</td>
<td>$1.73 \times 10^2$</td>
</tr>
</tbody>
</table>

Step 2 divides the transmitted energy $\xi_t$ by the incident energy $\xi_i$ to get the optical transmission coefficient $T_o$;
Figure 2.4: Block diagram describing the computational steps used in the numerical analysis.
\[ T_0 = \frac{\xi_t}{\xi_i} \]  

(2-2) 

The results are tabulated in Table 2.2.

### Table 2.2

Results of Step 2

<table>
<thead>
<tr>
<th>Measurement Number</th>
<th>( \xi_i ) (joules)</th>
<th>( \xi_t ) (joules)</th>
<th>( T_0 ) (unitless)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 1.15 \times 10^{-3} )</td>
<td>( 1.24 \times 10^{-4} )</td>
<td>.108</td>
</tr>
<tr>
<td>2</td>
<td>( 3.04 \times 10^{-3} )</td>
<td>( 3.07 \times 10^{-4} )</td>
<td>.101</td>
</tr>
<tr>
<td>3</td>
<td>( 1.12 \times 10^{-2} )</td>
<td>( 1.09 \times 10^{-3} )</td>
<td>.097</td>
</tr>
<tr>
<td>4</td>
<td>( 4.99 \times 10^{-2} )</td>
<td>( 1.40 \times 10^{-2} )</td>
<td>.281</td>
</tr>
</tbody>
</table>

Step 3 implements Eqs. 1-7 through 1-13. By guessing values for \( \varepsilon'' \) until the computed and measured values for \( T_0 \) agree, \( \alpha_2 \) can be determined, which gives the absorption characteristics for the silicon-wafer. Table 2.3 gives the values of the constants used and the results.

Steps 4 and 5 compute the optical reflection coefficient \( R_0 \) and the magnitudes of the electric field squared \( |E_2^+|^2 \) and \( |E_2^-|^2 \), respectively. Table 2.3 lists the constants used in these equations while Table 2.4 gives the results.
Table 2.3
Results of Step 3 and a List of Constants Used Throughout the Calculations.

<table>
<thead>
<tr>
<th>Constants</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega$</td>
<td>$1.777 \times 10^{15}$</td>
<td>(sec)$^{-1}$</td>
</tr>
<tr>
<td>$\epsilon_1, \epsilon_3$</td>
<td>$8.85 \times 10^{-12}$</td>
<td>farad/meter</td>
</tr>
<tr>
<td>$\mu_1, \mu_2, \mu_3$</td>
<td>$1.26 \times 10^{-6}$</td>
<td>henry/meter</td>
</tr>
<tr>
<td>$\epsilon_2'$</td>
<td>$1.04 \times 10^{-10}$</td>
<td>farad/meter</td>
</tr>
<tr>
<td>$\epsilon_2''$</td>
<td>$3.70 \times 10^{-14}$</td>
<td>farad/meter</td>
</tr>
<tr>
<td>$d$</td>
<td>$2.85 \times 10^{-5}$</td>
<td>meter</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>$2.07 \times 10^7$</td>
<td>(meter)$^{-1}$</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>$2.97 \times 10^2$</td>
<td>(meter)$^{-1}$</td>
</tr>
<tr>
<td>$T_0$</td>
<td>$2.81 \times 10^{-1}$</td>
<td>unitless</td>
</tr>
</tbody>
</table>

Table 2.4
Results of Steps 4 and 5

| Measurement Number | $|R_0|$ unitless | $|E_2^+|^2$ (volts/meter)$^2$ | $|E_2^-|^2$ (volts/meter)$^2$ |
|--------------------|----------------|--------------------------------|-------------------------------|
| 1                  | 0.364          | $5.69 \times 10^2$            | 9.73                          |
| 2                  | 0.358          | $1.52 \times 10^3$            | $2.24 \times 10^1$            |
| 3                  | 0.356          | $5.60 \times 10^3$            | $7.62 \times 10^1$            |
| 4                  | 0.543          | $2.08 \times 10^4$            | $3.38 \times 10^2$            |
Step 6 is performed in two parts. The first part computes the carrier concentration at \( t = 0 \), or immediately after the light pulse has passed. Equation 1-23 describes the electron-hole pairs concentration which is plotted for an incident energy of \( 2.84 \times 10^{-2} \) joules (measurement number 1) as illustrated in Figure 2.5.

Part 2 computes an estimate of the entire space-time matrix. The equation used is a closed form solution of Eq. 1-48 which assumes \( D_a \) is a constant which, in general, is not the case.

However, if one computes the concentration at some small increment of time after \( t = 0 \), \( \Delta t \), and then recomputes a new initial boundary condition, and uses an updated value \( D_a \), a very good estimate of the space-time matrix can be achieved. The form of the solution used is

\[
C(x,t) = \sum_{m=0}^{\infty} A_m e^{-\left(\frac{1}{\tau} + \lambda_m^2 D\right)t} \cos(\lambda_m z) \quad 0 \leq z \leq d
\]

where

\[
\lambda_m = \frac{(2m+1)\pi}{2d}
\]

and
Figure 2.5: Electron-hole pair concentration through the silicon wafer after the light pulse passed.
\[
A_m = \frac{2}{d} \frac{1}{\gamma^2 + \lambda^2} \left[ \eta e^{-\gamma d} \left( -\gamma \cos[\lambda \cdot d] + \lambda \sin[\lambda \cdot d] \right) + \eta^d \left( \gamma \cos[\lambda \cdot d] + \lambda \sin[\lambda \cdot d] \right) - (-\eta^+ \gamma + \eta^- \gamma) \right]
\]

while

\[
\gamma = 2\alpha_2 , \quad (2-6)
\]

\[
\eta^+ = \frac{\beta_2 \alpha_2}{\omega^2 \mu_2 h} |E_2^+|^2 , \quad (2-7)
\]

and

\[
\eta^- = \frac{\beta_2 \alpha_2}{\omega^2 \mu_2 h} |E_2^-|^2 \quad (2-8)
\]

Step 7 implements Eqs. 1-51 through 1-67 which, when iterated a sufficient number of times, converges to a self consistent solution giving a general solution for the space-time matrix. A plot describing the decay process is given in Figure 2.6 for measurement No. 1.

Step 8 utilizes Eqs 1-75, 1-77, 1-78, 1-84, 1-89, and 1-90 which compute the microwave transmission coefficient and
Figure 2.6: Plot of the space-time matrix which is the plot of the results of step 7.
the normalized transmitted energy. Figure 2.7 concludes the results for measurements 1 through 4 and compares them to the experimental results. To obtain such a close match between theory and experiments, the life-time of the material had to be determined. First, a series of curves were generated which illustrated the transmission characteristics as a function of time for a range of different \( T \) as displayed in Figure 2.8.

Next, the slope was computed for each curve at the .5 transmission level and plotted as a function of \( T \) as illustrated in Figure 2.9. By determining the corresponding slope from the experimental results, a lifetime of 7 \( \mu \text{sec} \) was computed from Figure 2.9 and used throughout the calculations.

Two other boundary conditions were considered during the theoretical calculation. The first boundary condition assumed infinite surface recombination velocity at both surfaces which is approximately the situation in a semiconductor with both surfaces lapped. Figures 2.10 and 2.11 illustrate the results. The other limiting boundary condition was zero surface recombination velocity at the surfaces. This condition is difficult to achieve in practice but can be approached with careful polishing and chemical treatment of the surface. The results of these computations are illustrated in Figures 2.12 and 2.13.
Figure 2.7: Comparison of the experimental and theoretical results.
Figure 2.8: Plot of normalized transmitted microwave energy versus time with infinite surface recombination velocity on one side of a silicon wafer and zero surface recombination velocity on the other.
Energy mark as a function of tau.

Figure 2.9: Slope of the curves illustrated in Figure 2.8 at the 0.5

1 (microseconds)

Slope of Normalized Transmitted Energy at Half Power
Figure 2.10: Plot of normalized transmitted microwave energy versus time with infinite surface recombination velocity on both surfaces of a silicon wafer.
Energy mark as a function of tau.

Figure 2.11: Slope of the curves illustrated in Figure 2.10 at the 0.5 t (microseconds)

Slope of Normalized Transmitted Energy at Half Power
Figure 2.12: Plot of normalized transmitted microwave energy versus time with zero surface recombination velocity on both surfaces of a silicon wafer.
Figure 2.13 : Slope of the curves illustrated in Figure 2.12 at the .5 energy mark as a function of tau.
CHAPTER III

DEVICE APPLICATIONS

Two possible applications become apparent during the experimental phase of this dissertation. One device could be used as a high-power optical detector, measuring the total energy and the shape of an incident light pulse. The other application deals with an existing periodic array which is transparent to a narrow range of microwave frequencies. By incorporating a semiconductor device with this type of array, even the frequencies which normally pass through the device can be shut off for a short period of time. Section A of this chapter will deal with the optical detector leaving the periodic array structure to section B.

A. Optical Detector

Many optical detectors are plagued with the inability to handle large amounts of power without incurring permanent damage. By placing a semiconductor slab in a waveguide and using microwaves to determine the number of free carriers
which, in turn, is related to the incident optical energy, optical detection can be achieved. Response time and sensitivity are the two parameters that must be considered. If the wafer thickness and the device bulk lifetime are large, the sensitivity will be high. There will also be a fast rise time. However, since the dominant decay process for the free carriers is surface recombination, the carriers could take tens of milliseconds to return to their initial states. By reducing the wafer thickness, the number of free carriers per square centimeter decreases, thus decreasing the sensitivity. With the reduction in wafer thickness, the speed of the device increases.

Using these ideas, a large area detector (1 x 2 cm) was fabricated using a silicon on sapphire wafer. This type of wafer was used to achieve a very thin active layer. The silicon thickness, in this case, was approximately one micrometer; and the sapphire was used only as a carrier. By illuminating the wafer with a 20 nanosecond pulse of light, as shown in Figure 3.1, a response comparable to that of a known detector was obtained as shown in Figure 3.2. It was also found that creating a plasma by focussing excessive optical power on the wafer did not change the results.
Figure 3.1: The response of an existent optical detector.
Figure 3.2: The RF response of the silicon on sapphire wafer.
If the energy of an incoming optical pulse is the only parameter to be measured, an intrinsic wafer on the order of 250 micrometers thick would give good sensitivity with a built-in storage mechanism. Although the optical pulse might be in the nanosecond range in duration, the electron-hole pairs that are generated from the incident photons occur instantaneously. Once the electron-hole pairs are generated, the pulse will require tens of microseconds to decay. Therefore, slow and inexpensive electronics can be used to make the ultimate measurement. Figure 3.2 illustrates the relationship of the incident optical power and an easily measured parameter of the transmitted microwave energy. To implement the optical measurements discussed so far in a practical fashion, a different microwave configuration would have to be developed. The configuration would have to expose much of the silicon directly to the incident optical energy instead of directing light through a pin hole. These developments are left to future studies.

B. Control of Microwave Transmission Through a Periodic Surface

Periodic structures have been used to transmit a narrow band of microwave frequencies and to reflect all others. If intrinsic silicon is placed over the periodic structure as shown in
Figure 3-3, light pulses can be used to generate electron-hole pairs, thus preventing microwaves from passing through the structure for a short period of time, even at the bandpass. Experiments were performed to determine whether the silicon would affect the properties of the periodic structure. First, a periodic structure was mounted in waveguide and then the transmitted microwave energy was recorded while varying the incident microwave frequency. Next, a low doped silicon wafer was placed next to the periodic structure while the experiments were repeated. As illustrated in Figure 3.4, the attenuation factor was not altered. However, there was a shift in the bandpass frequencies, which was expected because of the permittivity of the silicon.

Although optical excitation is not practical, two important points have been brought forth. The first is that intrinsic silicon will not affect the bandpass properties of the periodic structure, except for a slight shift in spectrum which can be compensated by changing the physical dimensions of the structure. Secondly, enough electron-hole pairs can be generated to cut off the microwave transmission. By developing an electronic means of generating the electron-hole pairs, a practical switch could be developed. Such a device may merit further study.
Figure 3.3: Illustration showing the periodic array and wafer mounted in waveguide.
Figure 3.4: Plots illustrating the frequency response of no sample, periodic array only, and periodic array with silicon wafer.
CHAPTER IV

SUMMARY

In this dissertation, a theoretical model is developed describing the microwave transmission and reflection properties of semiconductor wafers after they have been illuminated with a short pulse of light from a laser. The purpose of this work is to develop a workable model with a minimum of unknown variables while obtaining reasonable correlation with an associated experiment. The model has three fundamental parts. The first part describes the absorption mechanism of the incident light pulse throughout the semiconductor, giving the electron-hole pair concentration as a function of position. In the second part the electron-hole pair concentration during the decay process is described. Part three describes the microwave properties of the semiconductor as the electron-hole pairs return to their equilibrium state.

An experiment was developed to test the theoretical model. A laser generating a 20 nano-second light pulse illuminated a
silicon wafer clamped between two flanges in a waveguide. The light pulse was directed and focused through a pinhole at a bend in the waveguide so as to minimize microwave leakage. The microwave energy transmitted through the silicon wafer was measured with respect to time and correlated with the results from the theoretical model.

A. Theory

Several plots were produced illustrating the results of the theoretical investigation. Figures 2.8, 2.10, and 2.12 describe the microwave response of a silicon wafer for three different boundary conditions after it was illuminated with a short pulse of light. Each curve on the respective plots corresponds to a device with a different lifetime. As expected, it was found that as the surface recombination velocity was increased, the time needed for the silicon to return to steady state decreased. Also, as the bulk life-time increased, the surface conditions became dominant in the decay process. Figures 2.9, 2.11, and 2.13 corresponding to Figures 2.8, 2.10, and 2.12, respectively, illustrate the slope of the transmitted microwave intensity at the 50 percent level as a function of tau, the bulk lifetime. It was found that each of the curves fits the equation
remarkably well, where:

- $S$ is the slope
- $K$ is some constant
- $\tau_B$ is the bulk lifetime
- $\tau_S$ is the effective surface lifetime

This result allows measurement of the bulk and effective surface lifetimes without altering the wafer or making any physical contact with it. By keeping the surface conditions the same for several wafers with different bulk lifetimes, the slope of the transmitted intensity could be fitted to Eq. 4-1, giving $1/\tau_B$ and $K$. From these results, $\tau_B$ may be determined for each device. Similar procedures could be used on a single wafer by varying the surface conditions, determining first $1/\tau_B$ and $K$ and then $\tau_S$.

B. **Experimental**

Figure 2.7 illustrates the comparison between the theoretical and experimental results. In this figure, the normalized transmitted microwave energy is plotted with respect to time. The discrepancy or slight shift between the theoretical
and experimental results is attributed to an uncertainty in the amount of optical energy absorbed and coupled to the electron hole pair generation. There are several possible explanations for such an uncertainty. The most obvious would be an error in the measurement of the incident optical energy. Also, it is undoubtedly true that the quantum efficiency of the process of creation of electron-hole pairs is less than unity. A quantum efficiency less than unity could result, for example, from other photon absorption processes such as intra-band transitions. Such transitions are relatively unlikely in materials that have low concentrations of holes and electrons. However, as the concentration of conduction electrons increases there is an increasing probability of transitions from the bottom of the conduction band to higher levels in the same band. The decay of such excitation is predominantly nonradiative and thus will not result indirectly in electron-hole pair generation. A similar process in the valence band is also known to occur. Whatever the cause, a correction of the effective incident optical energy would result in excellent agreement between the theoretical and experimental curves shown in Figure 2.7.
C. Final Remarks

Several directions for further research were opened during the course of this investigation. One particularly interesting area would be refinement of the measurement technique for bulk lifetime and effective surface lifetime. When measuring the time rate of change (slope) of the transmitted microwave energy, the measurement is taken at the 50 percent level, which corresponds to a particular level of carrier concentration. If the slopes are studied experimentally for different samples with transmitted microwave energies other than the 50 percent level, accurate measurements of lifetime at different concentrations could be obtained. Such measurement of the bulk and effective surface lifetimes would be particularly advantageous since they could be made without having to subject the sample to undue processing, such as creating a pn-junction, or growing an oxide, which in turn, could alter the coefficients which were initially to be measured. Most all techniques at present for measuring lifetimes of materials, process the materials to some extent. Thus, the dynamic response of lifetime with respect to carrier concentration could be studied in detail. Additional work in the area of optical detection and microwave switching as discussed in Chapter III appears to be promising.
APPENDIX A

Below is a sample listing of one of the eleven computer programs used in the theoretical computations. Care should be used when trying to implement this program on any machine other than an IBM 370 or equivalent since special functions are needed in order to resolve overflow and underflow problems.


```fortran
00310  CB=1.D6
00320  N=3Y-1
00330  IT=N
00340  HN=2.692D-4
00350  U=2.*PI*13.099
00360  E=EO*11.700
00370  H=I3/DFLOAT(I)
00380  I900=0
00390  C
00400  C
00410  CONTINUE
00420  CALL REDIS(NX,NT,TH,CON,TAU,CB,O,Y,NN,N900,SCALE)
00430  C
00440  C
00450  WRITE(6,15)T1,O,TAU,1,MM,NT,NN,SCALE
00460  15 FORMAT(1X,/,'TH','/D TAII,'/1X,'MN,NT,NN,SCALE','/1X,7(12.4,2X))
00470  WRITE(6,39)
00480  C
00490  C
00500  DO 700 ITI=1,NT
00510  T=TH*(ITI-1)
00520  DO 10 I=1,NN
00530  TEMP=CON(I,ITD)+C3
00540  XC3=C3
00550  SCONX(I)=TEMP*(S1058(TEMP,TEMP,XC3,300.)+S1088(TEMP,TEMP,XC3,300.))
00560  X)*1.602D-19/1.04
00570  10 CONTINUE
00580  C
00590  C
00600  DO 605 I=1,11
```
M = 1
S = SQRT((T*D1*1.00-12)/3600.00) * 2.
CONTINUE
SIGMA = SCNX(M+1)
C
F*P1 = (SCR1+2)*F1-H*I*U*U*SIGMA*FMC-F*M1
F*PIC = SCR1*F*IC+H*I*U*U*SIGMA*F1+2*FMC-F*MIC
IF(M.LT.II) GO TO 500
WRITE(6,*) CX, SIGMA, F*P1, F*PIC, M
CONTINUE
GO TO 110
F*M1 = F1
F*MIC = FMC
F1 = F*P1
F*IC = F*PIC
M = M+1
GO TO 100
01090  110  CONTINUE
01100  ED = DCMPLX(F*P1, F*PIC)
01110  EDM1 = DCMPLX(F1, F*IC)
01120  DED = (ED-EDM1)/DCMPLX('1, 0.00)
01130  SCR3 = ((PI/B)**2-U**2*U*EO)
01140  SCR4 = DCMPLX(SCR3, 0.00)
01150  TRAN = (2./DE+DED)/DCMPLX(SCR4)
01160  REFL = (DCMPLX(SCR4)-DED/ED)/(DCMPLX(SCR4)+DED/ED)
01170  MTRAN = CDABS(TRAN)
01180  MREFL = CDABS(REFL)
01190  OUTT(1TI) = MTRAN*TRAN
01200  OUTR(1TI) = MREFL*REFL
HEC=CODAE(EO)
HED=CODAE(EO)
DBTRA=DCG10(*TRAN)*20.0
DBREF=DCG10(*REFL)*20.0
FORMAT(1X,*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/*/* /*
DATA B/1.04D-6, 1.43D-12, 2.9D-16, 6.93D-9, 6.97D-14, 2.0D-16/
DATA A/450, 744, 940, 543, 837, 1.0/
DATA PAR1/1.50D10, 2.40D13, 1.50D16/
DATA B1/4.00D-17, 1.47D-14, 3.30D-11, 7.20D-17/
DATA A1/.966, .832, .650, 1.000/
DCX=CX
DCB=C3
DT=ABS(CX)+ABS(C3)
I=1
IF(DCX+DC3.GT.0.000)GO TO 20
5 CONTINUE
IF(DT.GE.PAR(I))GO TO 10
I=I+1
IF(I.EQ.6)GO TO 19
GO TO 5
10 DELNC=ABS(CX+DC3)*B(I)**((DT)**(A(I)-1))
RETURN
20 IF(DT.GE.PAR1(I))GO TO 30
I=I+1
IF(I.EQ.4)GO TO 30
GO TO 29
30 DELNC=ABS(CX+DC3)*B1(I)**((DT)**(A1(I)-1))
RETURN
END
FUNCTION IFAC(I)

01510
01520
01530
01540
01550
01560
01570
01580
01590
01600
01610
01620
01630
01640
01650
01660
01670
01680
01690
01700
01710
01720
01730
01740
01750
01760
01770
01780
01790
01800
01810  DOUBLE PRECISION IFAC, X
01820  IFAC=1.00
01830  IF(Y.EQ.0)GO TO 20
01840  DO 10 I=1,N
01850     X=I
01860  IFAC=IFAC*X
01870  10   CONTINUE
01880  RETURN
01890  20   IFAC=1.00
01900  RETURN
01910  END
01920  C
01930  C
01940  C
01950  C
01960  C
01970  FUNCTION DCFAC(I)
01980  DOUBLE PRECISION IFAC
01990  COMPLEX*16 DCFAC
02000  DCFAC=IFAC(I)
02010  RETURN
02020  END
02030  C
02040  C
02050  C
02060  C
02070  C
02080  FUNCTION DCPURM(I,K)
02090  DOUBLE PRECISION IFAC
02100  COMPLEX*16 DCPURM
CONTINUE
C(AX,XT)=C(AX,1)
WRITE(5,'(2*AV2X2)')
C=Z2*AV2X2(2*AV2X2)/(2*AV2X2)
C=F112*AV2X2*0.546-3.4*AV2X2(2*AV2X2)
CONTINUE
C(AX,IT)=DISPXY(2,XY,IT,SAIT,CM)
L=IT*IT-1)
X=XY-1
XY=XY
IT=IT
DO Z=1,2
DO I=1,2
NXT=XY
XY=XY+1
NXY=XY
XY=XY
END
DIMENSION C(AX,XT)
DOUBLE PRECISION T1,X,TAU2,TAU1,CUT3,DY,LY
SUBROUTINE IFLAC(1,IFLAC(1),IFLAC(1))
C
END
RETURN
C
INCPT=IFLAC(1)/IFLAC(K)/IFLAC(1-1)
02410 DO 30 IT=1, IT
02420 C(MX, IT)=0.
02430 XITM1=IT-1
02440 C(1, IT)=C(1, 1) * EXP(-TH*XITM1/TAU)
02450 30 CONTINUE
02460 RETURN
02470 END

02480 C***********************************************************************
02490 C
02500 C
02510 C

02520 C***********************************************************************
02530 FUNCTION DISPIN(TAU, D, X, T, SATY, CB)
02540 DOUBLE PRECISION TAU, D, X, T, SATY, XM, TEMP, OUT, OSIN, PLUS, DARCOS
02550 DOUBLE PRECISION PI, DISPIN, XDISP
02560 XDISP(XM)=2.00*CS*2.00/(XM*PI)
02570 CS=1.022
02580 PI=2.00*DARCOS(3.00)
02590 DISPIN=0.00
02600 M=1
02610 XM=1
02620 10 CONTINUE
02630 TEMP=XM*PI/SATY
02640 OUT=OSIN(TEMP*SATY)
02650 IF((1.00/TAU+TEMP**2.00)*T.GT.115.00) GO TO 40
02660 PLUS=0*EXP(-1.00*(1.00/TAU+TEMP**2.00)*T)*OSIN(TEMP*2)*XDISP(XM)
02670 GO TO 70
02680 40 PLUS=0.00
02690 70 DISPIN=DISPIN+PLUS
02700 I=I+2
02710 XM=!
02720 IF(PLUS.LE.DISP1N*1.0-4.AND.PLUS.GE.DISP1N*(-1.0-4))GO TO 60
02730 GO TO 10
02740 60 DISP1N=DISP1N
02750 RETURN
02760 END
02770 C
02780 C
02790 C
02800 C
02810 C
02820 FUNCTION SM0NR(XN,XP,XC,T)
02330 C
02840 C
02350 C THIS FUNCTION CALCULATES THE ELECTRON MOBILITIES FOR SILICON.
02860 C N,P,AND CARE IN ATOM/(METER**3)
02870 C T IS IN DEGREES KELVIN
02380 C N IS THE ELECTRON CONCENTRATION
02390 C P IS THE HOLE CONCENTRATION
02900 C C IS THE IMPURITY CONCENTRATION
02910 C
02920 C
02920 XN=XN*1.0E-6
02940 XP=XP*1.0E-6
02950 C=C*1.0E-6
02960 A=1.
02970 B=1.
02980 C=1.
02990 D=1.
03000 XNR=(2.**5)*2.45E21*C/(2.*XP*ALOC(1.4142060/(XN+XP)))
RETURN
END

FUNCTION SMOB(XN, XP, XC, T)

THIS FUNCTION CALCULATES THE HOLE MOBILITIES FOR SILICON.

N, P, AND CARE IN ATOM/(METER * 3)

T IS IN DEGREES KELVIN

N IS THE ELECTRON CONCENTRATION

P IS THE HOLE CONCENTRATION

C IS THE IMPURITY CONCENTRATION

XI=XI*1.E-6

XP=XP*1.E-6
| I=900 | 0.03490 |
| I=1000 | 0.05605 |
| I=1100 | 0.07710 |
| I=1200 | 0.09815 |
| I=1300 | 0.11920 |
| I=1400 | 0.13925 |

CONTINUE

I(1000) = 0.03490
I(1100) = 0.05605
I(1200) = 0.07710
I(1300) = 0.09815
I(1400) = 0.11920

CONTINUE
03910 WRITE(6,*),TH,ILOG
03920 DO 40 I=1,MT
03930 IPRI=(IX-1)/10
03940 WRITE(6,100)(C(II,I),II=1,NX,IPRI)
03950 100 FORMAT(1X,'1',1X,1E11.4)
03960 40 CONTINUE
03970 RETURN
03980 END
03990 C
04000 C
04010 C
04020 C
04030 C
04040 SUBROUTINE AVE(C,NX,NT,NUM)
04050 C
04060 C
04070 DOUBLE PRECISION C(IX,NT)
04080 IX1=IX-1
04090 XT1=NT-1
04100 DO 10 I=1,NUM
04110 DO 20 XX=2,NX1
04120 DO 20 KT=2,XT1
04130 C(XX,KT)=(C(XX,NT)+C(XX,NT+1)+C(XX,NT-1)+C(XX+1,NT)+C(XX-1,
04140 XKT))/5.00
04150 20 CONTINUE
04160 CONTINUE
04170 10 CONTINUE
04180 RETURN
04190 END
04200 C
SUBROUTINE SINT(NX, NT, TH, C, TAU, CB, D, I, SATH, SCALE)

DOUBLE PRECISION TH, C, TAU, CB, D, I, SATH, XNX, DISPLN, XIT, XITM1

DIMENSION C(IK, NT)

DOUBLE PRECISION CP, SP, TH, AH(50), XMP(50), GAM, ETM, ETP, ET, SUM


DOUBLE PRECISION CN0, CP0, U1, U3, DAX, CX, SCALE

DA(CX) = (CX + CX + CN0 + CP0) * UP * UN * 0.0259 / ((CX + CP0) * UP + (CX + CN0) * UN)

CN0 = CB
CP0 = CB
XNX = NX
B2 = 2.0275E7

A2 = 297.19

U = 1.777E15

U2 = 1.2566E-6

E2P = 1321.71*1.76*SCALE

E2M = 294.41*1.76*SCALE

PI2 = 2.0*DO*DARCOS(0.0) / 2.0

GAM = 2.0*DO*A2


ETP = ET * E2P

ETM = ET * E2M

WRITE(3, *) ETP, ETM, ET, GAM

NTM1 = NT - 1

NXM1 = IX - 1

DO 10 I = 1, 50

T I = I - 1
04510 XMP(I) = (2.0*D1+1.0)*PI2/SAT4
04520 CP = DCOS(XMP(I)*SAT16)
04530 SP = DSIN(XMP(I)*SAT16)
04540 AM(I) = (2.00/SATH/(GA1+GA1+XMP(I)*XMP(I)))*
04550 X((-ETP*DEXP(-GA1*SAT16)*(-GA1*CP+XMP(I)*SP)+
04560 XETM*DEXP(GA1*SAT16)*(GA1*CP+XMP(I)*SP))-
04570 X((-ETP*GA1+ETM*GA1))
04580 WRITE(*,*)AM(I),XMP(I),SP,CP,I
04590 10 CONTINUE
04600 DO 20 IT=1,N
04610 IF(IT.EQ.1)GO TO 26
04620 TEMP=C(INX,IT-1)+CM
04630 TEMPP=C(INX,IT-1)+CP
04640 XCB=CB
04650 UMP=SHOBP(TEMP,TEMPP,XCB,300.)/1.E4
04660 U1=SHOBP(TEMP,TEMPP,XCB,300.)/1.E4
04670 DAX=DA(C(INX,IT-1))
04680 DO 25 I=1,50
04690 T=T+1
04700 AII(I)=AII(I)*DEXP(- (1.00/TAU+XMP(I)*XMP(I))*DAX)*T
04710 25 CONTINUE
04720 26 CONTINUE
04730 DO 20 INX=1,NX
04740 XMX=MX
04750 Z=(INX-XMX)*1
04760 C(INX,IT)=0.00
04770 DO 35 I=1,50
04780 C(INX,IT)=C(INX,IT)+AII(I)*DCOS(XMP(I)*Z)
04790 35 CONTINUE
04800 20 CONTINUE
04310      DO 40 I=1,NX
04320      C(I,MT)=C.DO
04330      CONTINUE
04340      RETURN
04350      END
APPENDIX B

Illustrated below are three graphs depicting the raw data produced by a Techtronix digitizer, computer, and copier system. In the text, the raw data is replotted in a more convenient form.

Figure B.1: Plot of the incident intensity of the laser pulse illuminating the silicon wafer.

Figure B.2: Plot of the intensity of the laser pulse exiting the silicon wafer.

Figure B.3: Plot of the transmitted microwave energy in response to the incident light pulse.
$U_{max} \ 1.718 \ volts$
$T_r \ 13.28 \ nsec$
$P_w \ 24.21 \ nsec$
$Power \ 5.772 \ watts$
$P \times P_w \ 139.74 \ microjoules$
$Energy \ 172.98 \ microjoules$

Figure B.1
HOW MANY (1-64)? 1
VS1 +100.E-03;
HS1 +20.E-09;

Umax 0.178 volts
Tr 14.06 nsec
Pw 25 nsec
Power 0.598 Watts
P*Pw 14.94 microjoules
Energy 17.45 microjoules

Figure B.2
Figure B.3

- U_{max} = 0.058 volts
- T_r = 0 nsec
- P_w = 20507.81 nsec
- Power = 0.194 Kwatts
- P*P_w = 3978.51 microjoules
- Energy = 4297.61 microjoules
BIBLIOGRAPHY


