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THE USE OF MICROWAVES TO CHARACTERIZE OPTICALLY
STIMULATED SEMICONDUCTORS

The Ohio State University

Ph.D.

1980

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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

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To My Wife and Our Parents

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TABLE OF CONTENTS

	Page
DEDICATION	iii
ACKNOWLEDGMENTS	iv
VITA	v
LIST OF TABLES	ix
LIST OF FIGURES	x
INTRODUCTION	1
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 OF CONTENTS CONT.

	Page
III DEVICE APPLICATION	63
A. Optical Detector	63
B. Control of Microwave Transmission Through a Periodic Surface	67
IV SUMMARY	71
A. Theory	71
B. Experimental	73
C. Final Remarks	75
APPENDIXES	
A Computer Programs	76
B Sample Data	94
BIBLIOGRAPHY	98

LIST OF TABLES

TABLE		Page
1.1	Coefficients for Eqs. 1-57 through 1-67 describing the conductivity of silicon.	26
2.1	Results of Step 1.	47
2.2	Results of Step 2.	49
2.3	Results of Step 3 and a list of constants used throughout the calculations.	50
2.4	Results of Steps 4 and 5.	50

LIST OF FIGURES

FIGURE		Page
1.1	Reflection and transmission of plane waves by a semiconductor at normal incidence.	8
1.2	Exaggerated view of the electrons diffusing at a faster rate than the holes.	20
1.3	Illustration depicting a wafer (shaded area) in a waveguide with a prescribed coordinate system.	28
2.1	Block diagram illustrating the experimental apparatus.	39
2.2	Optical portion of the experimental apparatus.	41
2.3	Illustration depicting the microwave apparatus.	43
2.4	Block diagram describing the computational steps used in the numerical analysis.	48
2.5	Electron-hole pair concentration through the silicon wafer after the light pulse passed.	52
2.6	Plot of the space-time matrix which is the plot of the results of step 7.	54
2.7	Comparison of the experimental and theoretical results.	56

FIGURE		Page
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.	57
2.9	Slope of the curves illustrated in Figure 2.8 at the .5 energy mark as a function of tau.	58
2.10	Plot of normalized transmitted microwave energy versus time with infinite surface recombination velocity on both surfaces of a silicon wafer.	59
2.11	Slope of the curves illustrated in Figure 2.10 at the .5 energy mark as a function of tau.	60
2.12	Plot of normalized transmitted microwave energy versus time with zero surface recombination velocity on both surfaces of a silicon wafer.	61
2.13	Slope of the curves illustrated in Figure 2.12 at the .5 energy mark as a function of tau.	62
3.1	The response of an existent optical detector.	65
3.2	The RF response of the silicon on sapphire wafer.	66
3.3	Illustration showing the periodic array and wafer mounted in waveguide.	69
3.4	Plots illustrating the frequency response of no sample, periodic array only, and periodic array with silicon wafer.	70

FIGURE		Page
B.1	Plot of the incident intensity of the laser pulse illuminating the silicon wafer.	95
B.2	Plot of the intensity of the laser pulse exiting the silicon wafer.	96
B.3	Plot of the transmitted microwave energy in response to the incident light pulse.	97

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 recombining, 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

$$\vec{E}_i = \hat{x} \left[E_0 e^{ik_1 z - i\omega t} + E_1 e^{-ik_1 z - i\omega t} \right] \quad (1-1)$$

$$\vec{H}_i = \hat{y} \left[\frac{k_1}{\omega \mu_1} E_0 e^{ik_1 z - i\omega t} - E_1 e^{-ik_1 z - i\omega t} \right] \quad (1-2)$$

Medium 2

$$\vec{E}_s = \hat{x} \left[E_2^+ e^{ik_2 z} + E_2^- e^{-ik_2 z} \right] e^{-i\omega t} \quad (1-3)$$

$$\vec{H}_s = \hat{y} \left[\frac{k_2}{\omega \mu_2} E_2^+ e^{ik_2 z} - E_2^- e^{-ik_2 z} \right] e^{-i\omega t} \quad (1-4)$$

Medium 3

$$\vec{E}_t = \hat{x} E_3 e^{ik_3 z - i\omega t} \quad (1-5)$$

$$\vec{H}_t = -\hat{y} \frac{k_3}{\omega \mu_3} E_3 e^{ik_3 z - i\omega t} \quad (1-6)$$

The propagation factors for each of the media are:

$$k_1 = \sqrt{\omega^2 \epsilon_1 \mu_1} \quad (1-7)$$

$$k_2 = \sqrt{\omega^2 (\epsilon'_2 + i\epsilon''_2) \mu_2} \quad (1-8)$$

$$k_3 = \sqrt{\omega^2 \epsilon_3 \mu_3} \quad (1-9)$$

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_o . From Stratton's work [5], the transmission coefficient is found to be

$$T_o = \left| \frac{1}{(1+Z_{12})(1+Z_{23})} \frac{4e^{i(k_2-k_3)d}}{1+r_{12}r_{23}e^{2ik_2d}} \right|^2 \text{Re}[Z_{13}] \quad (1-10)$$

where

$$Z_{jl} = \frac{\mu_j k_l}{\mu_l k_j} \quad l, j = 1, 2, 3 \quad (1-11)$$

$$r_{jl} = \frac{1 - Z_{jl}}{1 + Z_{jl}} \quad l, j = 1, 2, 3 \quad (1-12)$$

and

$$k_l = \beta_l + i\alpha_l \quad l = 1, 2, 3 \quad (1-13)$$

Since ϵ''_2 is the only unknown parameter, it may be varied until the corresponding computed value of T_o 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

$$\vec{S}_r = \text{Re} [\frac{1}{2} \vec{E} \times \vec{H}^*] \quad (1-14)$$

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

$$\xi_T = \int_S \vec{S}_r \cdot \hat{n} da \quad (1-15)$$

Thus,

$$\xi_T = AB \frac{\beta}{2\omega\mu_2} \left[|E_2^+|^2 (e^{-2\alpha_2 d} - 1) + |E_2^-|^2 (1 - e^{-2\alpha_2 d}) \right] \quad (1-16)$$

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

$$\xi_T = -\text{Re} [S_o] [1 - R_o - T_o] AB \quad (1-17)$$

where $\text{Re}(S_o)$ is the incident intensity and the reflection coefficient is [5]

$$R_o = \left| \frac{r_{12} + r_{23} e^{2ik_2 d}}{1 + r_{12} r_{23} e^{2ik_2 d}} \right|^2 \quad (1-18)$$

Further, the energy coupled into the semiconductor per unit time is given by

$$\text{Re}[S_o] [1-R_o] AB = \frac{\beta_2}{2\omega\mu_2} \left[|E_2^+|^2 - |E_2^-|^2 \right] AB \quad (1-19)$$

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

$$|E_2^+|^2 = \text{Re}[S_o] \frac{(1-R_o)e^{2\alpha_2 d} - T_o}{\frac{\beta_2}{2\omega\mu_2} (e^{2\alpha_2 d} - e^{-2\alpha_2 d})} \quad (1-20)$$

and

$$|E_2^-|^2 = \text{Re}[S_o] \frac{(1-R_o)e^{-2\alpha_2 d} - T_o}{\frac{\beta_2}{2\omega\mu_2} (e^{2\alpha_2 d} - e^{-2\alpha_2 d})} \quad (1-21)$$

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 α_2 and β_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 $-C(z)h\omega$, thus

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

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

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

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

will be considered, where:

$\mu(z)$ is the unit step function,

C_0 is the saturation level for the concentration close to the surface ,

α_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 semi-conductor is

$$\vec{E}_s = \hat{x} (E_2^+ e^{ik_2(z-z_1)} + E_2^- e^{-ik_2(z-z_1)}) e^{-i\omega t} \quad (1-25)$$

and

$$\vec{H}_s = \hat{y} \frac{k_2}{\omega \mu_2} \left[E_2^+ e^{ik_2(z-z_1)} - E_2^- e^{-ik_2(z-z_1)} \right] e^{-i\omega t} \quad (1-26)$$

where E_2^- is assumed to be negligible since α_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

$$\text{Re} [\vec{S}_s] = \hat{z} \frac{\beta}{2\omega \mu_1} |E_2^+|^2 e^{-2\alpha_2(z-z_1)} \quad z_1 < z < d \quad (1-27)$$

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

$$\text{Re} [\nabla \cdot \vec{S}_s] = \frac{-\beta_2 \alpha_2}{\omega \mu_2} |E_2^+|^2 e^{-2\alpha_2(z-z_1)} \quad (1-28)$$

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

$$C_0 e^{-2\alpha_2(z-z_1)} h \omega = \frac{-\beta_2 \alpha_2}{\omega \mu_2} |E_2^+|^2 e^{-2\alpha_2(z-z_1)} \quad (1-29)$$

Also, relating the transmitted intensity, $\text{Re} [S_t]$, to $|E_2^+|^2$

$$\text{Re} [S_t] = \frac{\beta_2^2 + \alpha_2^2}{\beta_2 \omega \mu_2} |E_2^+|^2 e^{-2\alpha_2(d-z_1)} T_{23} \quad (1-30)$$

and combining Eqs. 1-29 and 1-30 gives a solution for C_0 in terms of z_1 ;

$$C_o = \frac{\text{Re}[S_T]}{T_{23} h \omega} \frac{\beta_2^2 \alpha_2}{\beta_2^2 + \alpha_2^2} e^{2\alpha_2(d-z_1)} \quad (1-31)$$

where T_{23} is the transmission coefficient between media two and three;

$$T_{23} = \text{Re}[Z_{23}^*] \left| \frac{2}{1 + Z_{23}} \right|^2 \quad (1-32)$$

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

$$C_T = C_o \left[z_1 + \frac{1}{2\alpha_2} [1 - e^{-2\alpha_2(d-z_1)}] \right] \quad (1-33)$$

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

$$C_T = \frac{(1 - |r_{12}|^2) \text{Re}[S_o] - \text{Re}[S_T]}{h \omega} AB \quad (1-34)$$

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,

$$\frac{\partial n}{\partial t} = -R_n + \mu_n \nabla \cdot (n \vec{E}) + D_n \nabla^2 n \quad (1-35)$$

and another for holes,

$$\frac{\partial p}{\partial t} = -R_p - \mu_p \nabla \cdot (p \vec{E}) + D_p \nabla^2 p \quad (1-36)$$

relate the total change of electrons and holes per unit volume per unit time $\frac{\partial n}{\partial t}$ and $\frac{\partial p}{\partial t}$, 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:

$$n = n' + n_0 \quad (1-37)$$

n - total electron concentration per unit volume

n' - excited electron concentration

n_0 - electron background concentration

$$p = p' + p_o \quad (1-38)$$

p - total hole concentration per unit volume

p' - excited hole concentration

p_o - hole background concentration

$$R_n = \frac{n - n_o}{\tau_n} \quad (1-39)$$

R_n - recombination rate for electrons

τ_n - lifetime for the electrons

$$R_p = \frac{p - p_o}{\tau_p} \quad (1-40)$$

R_p - recombination rate for holes

τ_p - lifetime for the holes.

D_n - diffusion coefficient for electrons

D_p - diffusion coefficient for holes

μ_n - mobility for the electrons

μ_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 imbalance 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

$$\frac{\partial p}{\partial t} \cong \frac{\partial n}{\partial t} \quad (1-41)$$

and

$$\nabla_p = \nabla_n \quad (1-42)$$

leads to

Figure 1.2 : Exaggerated view of the electrons diffusing at a faster rate than the holes.

$$\frac{\partial n}{\partial t} (\mu_p p + \mu_n n) = -R_n \mu_p p + \mu_n n R_p + \mu_p \mu_n (p-n) \vec{E} \cdot \nabla n + \mu_p p D_n \nabla^2 n + \mu_n n D_p \nabla^2 p \quad (1-43)$$

Combining Einstein's relationships for holes,

$$D_p = \frac{kT}{q} \mu_p \quad (1-44)$$

and for electrons

$$D_n = \frac{kT}{q} \mu_n \quad (1-45)$$

gives

$$D_p \mu_n = D_n \mu_p \quad (1-46)$$

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

$$\frac{\partial n}{\partial t} = \frac{-R_n \mu_p p + \mu_n n R_p}{\mu_p p + \mu_n n} + \frac{\mu_p \mu_n (p-n) \vec{E} \cdot \nabla n}{\mu_p p + \mu_n n} + \frac{\mu_p D_n (n+p)}{\mu_p p + \mu_n n} \nabla^2 n \quad (1-47)$$

Noting that $(n-p)\nabla n$ is small and that n' is approximately equal to p' gives the final result;

$$\frac{\partial n'}{\partial t} = -\frac{n'}{\tau_a} + D_a \nabla^2 n' \quad (1-48)$$

where τ_a and D_a are the ambipolar lifetime and diffusion coefficients, respectively;

$$\tau_a = \frac{n'(\mu_p + \mu_n) + (\mu_p p_o + \mu_n n_o)}{n' \left(\frac{\mu_p}{\tau_n} + \frac{\mu_n}{\tau_p} \right) + \frac{\mu_p}{\tau_n} p_o + \frac{\mu_n}{\tau_p} n_o} \quad (1-49)$$

and

$$D_a = \frac{\mu_p D_n (2n' + n_o + p_o)}{n'(\mu_p + \mu_n) + \mu_p p_o + \mu_n n_o} \quad (1-50)$$

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

$$\frac{n'_m{}^{k+1} - n'_m{}^{k-1}}{2\delta} = D_{am} \frac{n'_m{}^k - 2n'_m{}^k + n'_m{}^{k-1}}{h^2} - \frac{n'_m{}^k}{\tau_{am}} \quad (1-51)$$

where

- m is the spatial index
- k is the temporal index
- h is the incremental spatial displacement
- δ is the incremental temporal displacement

and solving for $n'_m{}^k$ gives,

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

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

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

and a new $n'_m{}^k$ is computed by

$$n'_m{}^k = n'_m{}^k + W * \text{Error} \quad (1-54)$$

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,

$$n = n' + n_o \quad (1-55)$$

and

$$p = n' + p_o \quad (1-56)$$

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

$$\sigma = q(n\mu_n + p\mu_p) \quad (1-57)$$

where q is the electric charge of an electron. Berz [6] determined the mobilities, μ_n and μ_p to be

$$\mu_n = \frac{1}{\frac{1}{F} \left[\frac{1}{\mu_{ln}} + \frac{\mu_{1n} + \mu_{hen}}{\mu_{1n} \mu_{hen}} \right]} \quad (1-58)$$

and

$$\mu_p = \frac{1}{\frac{1}{F} \left[\frac{1}{\mu_{lp}} + \frac{\mu_{1n} + \mu_{hen}}{\mu_{1n} \mu_{hen}} \right]} \quad (1-59)$$

where μ_1 , μ_{he} , and μ_l are the components related to lattice, electron-hole, and impurity scattering, respectively. The statistical factor F is

$$F = \frac{.0954 + .473 S - .383 S^2}{.0956 + .866 S - .776 S^2} \quad (1-60)$$

$$S = \frac{\mu_{lv}}{\mu_{lv} + \frac{\mu_{1v} \mu_{hev}}{\mu_{1v} + \mu_{hev}}} \quad v = n, p \quad (1-61)$$

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

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

$$\mu_{1p} = \mu_{1n} \quad (1-63)$$

$$\mu_{ln} = C_1 \left(\frac{T_l}{300} \right)^{-2.4} \quad (1-64)$$

$$\mu_{lp} = C_2 \left(\frac{T_l}{300} \right)^{-2.5} \quad (1-65)$$

$$\mu_{hen} = \frac{\sqrt{2}}{2} \frac{N}{p} \mu_{1n} \quad (1-66)$$

$$\mu_{hep} = \mu_{hen} \frac{p}{n} \quad (1-67)$$

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 .

Coefficients	Values
A	2.45×10^{21}
B	1.41×10^{20}
C_1	1350
C_2	480

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:

- $\sigma(z)$ - conductivity as a function of z in the semiconductor
- ϵ_2 - permittivity of the semiconductor
- μ_2 - permeability of the semiconductor
- ϵ_1, ϵ_3 - permittivity of space in the waveguide
- μ_1, μ_3 - permeability of space in the waveguide
- ω - 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 ω 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.

$$\nabla \times \vec{H} = [\sigma(z) + j\omega\epsilon_2] \vec{E}_s \quad (1-68)$$

and

$$\nabla \times \vec{E}_s = -j\omega\mu_2 \vec{H}_s \quad (1-69)$$

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

$$\nabla \times \nabla \times \vec{E}_s = -j\omega\mu_2 (\sigma(z) + j\omega\epsilon_2) \vec{E}_s \quad (1-70)$$

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

$$\vec{E}_t = \hat{x} E_3 \sin\left[\frac{y\pi}{b}\right] \exp\left[z\left(\frac{\pi^2}{b^2} - \omega^2\mu_3\epsilon_3\right)^{1/2}\right], \quad (1-71)$$

$$z \leq 0$$

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

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

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;

$$\frac{d^2 f(z)}{dz^2} = \left[\left(\frac{\pi}{b}\right)^2 + j\omega\mu_2 (\sigma(z) + j\omega\epsilon_2) \right] f(z), \quad (1-73)$$

$$d \leq z \leq 0$$

A recursion relation is formed by first approximating the second derivative of $f(z)$ as

$$\frac{d^2 f(z)}{dz^2} \approx \frac{f_{m+1} - 2f_m + f_{m-1}}{h^2} \quad (1-74)$$

where

h is an incremental length

m is an integer; $m = 1, 2, \dots, n$

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;

$$f_{m+1} = \left[h^2 \left(\frac{\pi}{b} \right)^2 + j\omega\mu_2 \left(\sigma(z) + j\omega\epsilon_2 \right) + 2 \right] f_m - f_{m-1} \quad (1-75)$$

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 $z = 0$;

$$\hat{x} E_3 \sin \left(\frac{y\pi}{b} \right) \exp \left[\left((0.) \left(\frac{\pi}{b} \right)^2 - \omega^2 \mu_3 \epsilon_3 \right)^{1/2} \right] = \hat{x} E_3 \sin \left(\frac{\pi y}{b} \right) f(0) \quad (1-76)$$

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

$$f_1 = f_0 + \sum_{i=1}^{\infty} \frac{h^i}{i!} \left. \frac{\partial^i f(z)}{\partial z^i} \right|_{z=0} \quad (1-78)$$

The first term has already been determined to be unity. The second term is determined first by showing that $\partial(\vec{E}_t \cdot \hat{x}) / \partial z$ 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

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

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

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

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

$$\left. \frac{\partial (\vec{E}_s \cdot \hat{x})}{\partial z} \right|_{z=0} = \frac{\mu_1}{\mu_3} \left. \frac{\partial (\vec{E}_t \cdot \hat{x})}{\partial z} \right|_{z=0} \quad (1-82)$$

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

$$\left. \frac{\partial f(z)}{\partial z} \right|_{z=0} = \frac{\mu_2}{\mu_3} \left(\left(\frac{\pi}{b} \right)^2 - \omega^2 \mu_3 \epsilon_3 \right)^{1/2} \quad (1-83)$$

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

$$\frac{\partial^k f(z)}{\partial z^k} = \left[\left(\frac{\pi}{b} \right)^2 - \omega^2 \mu_2 \epsilon_2 \right] \frac{\partial^{k-2} f(z)}{\partial z^{k-2}} + \quad (1-84)$$

$$j \omega \mu_2 \sum_{p=0}^{k-2} \frac{(k-2)!}{p!(k-2-p)!} \frac{\partial^p \sigma(z)}{\partial z^p} \frac{\partial^{k-2-p} f(z)}{\partial z^{k-2-p}}$$

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

$$T = \frac{1}{\frac{\frac{\mu_1}{\mu_2}}{2 \left(\frac{\pi}{b} \right)^2 - \omega^2 \mu_1 \epsilon_1} \left. \frac{\partial f(z)}{\partial z} \right|_{z=d} + \frac{f(d)}{2}} \quad (1-87)$$

and

$$R = \frac{f(d) \left(\left(\frac{\pi}{b} \right)^2 - \omega^2 \mu_1 \epsilon_1 \right)^{\frac{1}{2}} - \frac{\mu_1}{\mu_2} \left. \frac{\partial f(z)}{\partial z} \right|_{z=d}}{f(d) \left(\left(\frac{\pi}{b} \right)^2 - \omega^2 \mu_1 \epsilon_1 \right)^{\frac{1}{2}} + \frac{\mu_1}{\mu_2} \left. \frac{\partial f(z)}{\partial z} \right|_{z=d}} \quad (1-88)$$

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

$$T = \frac{1}{\frac{\mu_1 (f(nh) - f((n-1)h))}{2\mu_1 \left(\left(\frac{\pi}{b} \right)^2 - \omega^2 \mu_1 \epsilon_1 \right)^{\frac{1}{2}} h} + \frac{f(nh)}{2}} \quad (1-89)$$

and

$$R = \frac{f(nh) \left(\left(\frac{\pi}{b} \right)^2 - \omega^2 \mu_1 \epsilon_1 \right)^{\frac{1}{2}} - \frac{\mu_1}{\mu_2} \frac{f(nh) - f((n-1)h)}{h}}{f(nh) \left(\left(\frac{\pi}{b} \right)^2 - \omega^2 \mu_1 \epsilon_1 \right)^{\frac{1}{2}} + \frac{\mu_1}{\mu_2} \frac{f(nh) - f((n-1)h)}{h}} \quad (1-90)$$

where the $\frac{\partial f(z)}{\partial z}$ is approximated by

$$\left. \frac{\partial f(z)}{\partial z} \right|_{z=d} \approx \frac{f(nh) - f((n-1)h)}{h} \quad (1-91)$$

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 $Re(S_o)$, the incident optical intensity are needed. These quantities are usually obtained experimentally. To characterize the material, ϵ'' of Eq. 1-8 must be determined. Using Eqs. 1-7 through 1-13 ϵ'' is computed by trial and error. Throughout the rest of the calculations ϵ'' is used indirectly through Eqs. 1-8 and 1-13 leading to useful values for α_2 and β_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_o 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 wave length 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 neodymium YAG laser
- 2) one-quarter ($\frac{1}{4}$) 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 ($\frac{1}{4}$) 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

$$\text{Re}[S_o] = \frac{\xi_i}{A_s} \quad (2-1)$$

where ξ_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

Measurement Number	ξ_i (joules)	A_s (meter) ²	$\text{Re}[S_o]$ joules (meter) ² /pulse
1	7.15×10^{-3}	2.88×10^{-4}	3.99
2	3.04×10^{-3}	2.88×10^{-4}	1.06×10^1
3	1.72×10^{-2}	2.88×10^{-4}	3.89×10^1
4	4.99×10^{-2}	2.88×10^{-4}	1.73×10^2

Step 2 divides the transmitted energy ξ_t by the incident energy ξ_i to get the optical transmission coefficient T_o ;

Computation of the incident optical energy per (meter) ² per pulse	Step 1
Computation of the optical transmission coefficient T_0	Step 2
Computation of the absorption coefficient	Step 3
Computation of the optical reflection coefficient R_0	Step 4
Computation of the magnitudes of the electric fields squared	Step 5
Computation of the first quest for the space-time matrix	Step 6
Generalized computation of the space-time matrix	Step 7
Computation of the microwave transmission coefficient	Step 8

Figure 2.4: Block diagram describing the computational steps used in the numerical analysis.

$$T_o = \xi_t / \xi_i \quad (2-2)$$

The results are tabulated in Table 2.2.

Table 2.2
Results of Step 2

Measurement Number	ξ_i joules	ξ_t joules	T_o unitless
1	1.15×10^{-3}	1.24×10^{-4}	.108
2	3.04×10^{-3}	3.07×10^{-4}	.101
3	1.12×10^{-2}	1.09×10^{-3}	.097
4	4.99×10^{-2}	1.40×10^{-2}	.281

Step 3 implements Eqs. 1-7 through 1-13. By guessing values for ϵ'' until the computed and measured values for T_o agree, α_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_o 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.

Constants	Value	Units
ω	1.777×10^{15}	$(\text{sec})^{-1}$
ϵ_1, ϵ_3	8.85×10^{-12}	farad/meter
μ_1, μ_2, μ_3	1.26×10^{-6}	henry/meter
ϵ'_2	1.04×10^{-10}	farad/meter
ϵ''_2	3.70×10^{-14}	farad/meter
d	2.85×10^{-5}	meter
β_2	2.07×10^7	$(\text{meter})^{-1}$
α_2	2.97×10^2	$(\text{meter})^{-1}$
T_o	2.81×10^{-1}	unitless

Table 2.4
Results of Steps 4 and 5

Measurement Number	$ R_o $ unitless	$ E_2^+ ^2$ $(\text{volts/meter})^2$	$ E_2^- ^2$ $(\text{volts/meter})^2$
1	.364	5.69×10^2	9.73
2	.358	1.52×10^3	2.24×10^1
3	.356	5.60×10^3	7.62×10^1
4	.543	2.08×10^4	3.38×10^2

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 2.84×10^{-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 $t = 0$, Δt , 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

$$C(x,t) = \sum_{m=0}^{\infty} A_m e^{-(1/\tau + \lambda_m^2 D) t} \cos[\lambda_m z] \quad 0 \leq z \leq d \quad (2-3)$$

where

$$\lambda_m = \frac{(2m+1)\pi}{2d} \quad (2-4)$$

and

Figure 2.5 : Electron-hole pair concentration through the silicon wafer after the light pulse passed.

$$\begin{aligned}
A_m = \frac{2}{d} \frac{1}{\gamma^2 + \lambda^2} \left[\left(\eta^+ e^{-\gamma d} (-\gamma \cos[\lambda_m d] + \lambda \sin[\lambda_m d]) + \eta^- e^{\gamma d} (\gamma \cos[\lambda_m d] + \lambda \sin[\lambda_m d]) \right) \right. \\
\left. - (-\eta^+ \gamma + \eta^- \gamma) \right] \quad (2-5)
\end{aligned}$$

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 τ 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 τ as illustrated in Figure 2.9. By determining the corresponding slope from the experimental results, a lifetime of 7 μsec 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.

Figure 2.9 : Slope of the curves illustrated in Figure 2.8 at the .5 energy mark as a function of τ .

Figure 2.10 : Plot of normalized transmitted microwave energy versus time with infinite surface recombination velocity on both surfaces of a silicon wafer.

Figure 2.11 : Slope of the curves illustrated in Figure 2.10 at the .5 energy mark as a function of tau.

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 (1×2 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 band-pass 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 τ , the bulk lifetime. It was found that each of the curves fits the equation

$$S = K \left(\frac{1}{\tau_B} + \frac{1}{\tau_S} \right) \quad (4-1)$$

remarkably well, where:

S is the slope

K is some constant

τ_B is the bulk lifetime

τ_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 $1/\tau_S$ and k . From these results, τ_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 τ_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.

```

00010 DOUBLE PRECISION NERAN, NREFL, MED, MDED
00020 DOUBLE PRECISION DFLCAT, DEFC, COM(2), TFAC
00030 DOUBLE PRECISION CON(201, 201), TR, TAU, OUTT(201), OUTER(201), SCALE
00040 COMPLEX*16 DCMPLEX
00050 EQUIVALENCE(CON, G4)
00060 COMPLEX*16 ED, TRAN, REFL, EDI1, DED, SCR4, CDSQRT, CDABS
00070 COMPLEX*16 A, F(11), SI(11)
00080 COMPLEX*16 GH, SCR6
00090 DOUBLE PRECISION GS, CB, D, F4, U, U, EO, E, HH, T, F4PI, F4PIC, F4M1, H, UO
00100 DOUBLE PRECISION F4M1C, F4C, PI, SIGMA, SCR1, SDT2, CX, CS, DENFC, CB, SCR3
00110 DOUBLE PRECISION SCOMX(201)
00120 CALL ERRSET(208, 256, -1, 1)
00130 DO 750 ISCALE=1, 10
00140 SCALE=ISCALE*.5
00150 TAU=7.0-6
00160 I1=1
00170 I2=2
00180 I3=3
00190 I4=4
00200 PI=3.141592654
00210 C=2.99792508
00220 U=PI*4.0-7
00230 UO=U
00240 EO=1./(U*C*C)
00250 B=22.0-3
00260 210 CONTINUE
00270 D=2.849D-3
00280 HX=201
00290 NT=201
00300 TM=.5D-5

```

```

00310      CB=1.D16
00320      N=NX-1
00330      II=N
00340      HN=2.602D-4
00350      W=2.*PI*10.0D9
00360      E=E0*11.7D0
00370      H=4N/DFLOAT(N)
00380      I900=0
00390 C
00400 C
00410 900  CONTINUE
00420      CALL REDIS(NX,NT,TH,CON,TAU,CB,D,H,HN,I900,SCALE)
00430 C
00440 C
00450      WRITE(6,15)TH,D,TAU,H,NX,NT,HN,SCALE
00460 15  FORMAT(1X,/,/,1X,'TH,D,TAU,H,NX,NT,HN,SCALE',/,1X,7(G12.4,2X))
00470      WRITE(6,39)
00480 C
00490 C
00500      DO 700 ITI=1,NT
00510      T=TH*(ITI-1)
00520      DO 10 I=1,NX
00530      TEMP=CON(I,ITI)+CB
00540      XCB=CB
00550      SCONX(I)=TEMP*(SNOBN(TEMP,TEMP,XCB,300.)+SNOBP(TEMP,TEMP,XCB,300.)
00560      X)*1.602D-19/1.D4
00570 10  CONTINUE
00580 C
00590 C
00600      DO 605 I=1,11

```

```

00610 SI(I)=0.
00620 605 CONTINUE
00630 SI(1)=SCONX(1)
00640 SI(2)=(SCONX(2)-SCONX(1))/H
00650 F(1)=1.
00660 F(2)=CDSQRT(DCHPLX(((PI/B)**2-U*U*E0),0.00))
00670 DO 610 K=2,10
00680 F(K+1)=(0.0,0.0)
00690 KM1=K-1
00700 DO 620 IP=1,KM1
00710 IP=IP-1
00720 F(K+1)=DCPUKH(K-2,IP)*SI(IP+1)*F(K-IP-1)+F(K+1)
00730 620 CONTINUE
00740 F(K+1)=((PI/3)**2-U*U*U*E)*F(K-1)+(0.,1.)*U*U*F(K+1)
00750 610 CONTINUE
00760 GH=(0.0,0.0)
00770 DO 630 IP=1,10
00780 GH=GH+F(IP)*(H**(IP-1))/DGFAC(IP-1)
00790 630 CONTINUE
00800 C
00810 C
00820 301 CONTINUE
00830 FHP1=0.00
00840 FHPIC=0.00
00850 FHM1=1.00
00860 FHMIC=0.00
00870 FHC=0.00
00880 FM=CON(1)
00890 FLIC=CON(2)
00900 SCRI=H*H*((PI/B)**2-U**2*U*E)

```

```

00910      M=1
00920      SDT2=(DSQRT((T*D*1.0D-12)/3600.0D))*2.
00930 100   CONTINUE
00940 C
00950      SIGMA=SCONK(M+1)
00960 C
00970      FMP1=(SCR1+2)*FM-H*H*W*U*SIGMA*FMC-FMM1
00980      FMP1C=SCR1*FMC+H*H*W*U*SIGMA*FM+2*FMC-FMM1C
00990      IF(M.LT.II) GO TO 500
01000      WRITE(6,*)CX,SIGMA,FMP1,FMP1C,H
01010      500   CONTINUE
01020      IF(M+1.EQ.N)GO TO 110
01030      FMM1=FM
01040      FMM1C=FMC
01050      FM=FMP1
01060      FMC=FMP1C
01070      M=M+1
01080      GO TO 100
01090      110   CONTINUE
01100      ED=DCMPLX(FMP1,FMP1C)
01110      EDM1=DCMPLX(FM,FMC)
01120      DED=(ED-EDM1)/DCMPLX(1,0.0D)
01130      SCR3=((PI/B)**2-W**2*U*EO)
01140      SCR4=DCMPLX(SCR3,0.0D)
01150      TRAN=(2./(ED+DED/DSQRT(SCR4)))
01160      REFL=(DSQRT(SCR4)-DED/ED)/(DSQRT(SCR4)+DED/ED)
01170      MTRAN=CDABS(TRAN)
01180      MREFL=CDABS(REFL)
01190      OUTT(ITI)=MTRAN*MTRAN
01200      OUTR(ITI)=MREFL*MREFL

```

```

01210      MED=CDA3S(ED)
01220      MDED=CDA3S(DED)
01230      DBMTRA=DLOG10(MTRAN)*20.00
01240      DBMREF=DLOG10(MREFL)*20.00
01250 39    FORMAT(1X,/,/,/,/,1X,'TIME,TRAN,REFL',/)
01260      WRITE(6,40)T,DBMTRA,DBMREF
01270 40    FORMAT(1X,3(G11.4,3X))
01280 C
01290 C
01300 700    CONTINUE
01310 C
01320 C
01330      DO 750 ITI=1,NT
01340      T=TH*(ITI-1)
01350      OUTT(ITI)=OUTT(ITI)/OUTT(1)
01360      OUTR(ITI)=OUTR(ITI)/OUTR(1)
01370      WRITE(6,*)T,OUTT(ITI),OUTR(ITI)
01380 750    CONTINUE
01390      CALL EXIT
01400      END
01410 C
01420 C
01430 C
01440 C
01450 C
01460      FUNCTION DELNC (CX,CB)
01470 C IF CX+CB<0 THEN N-TYPE, ELSE P-TYPE.
01480      DOUBLE PRECISION B(6),A(6),ANSWER,PAR(5),DCX,DCB,DELNC
01490      DOUBLE PRECISION PAR1(4),T1(4),A1(4),DT,DABS
01500      DATA PAR/2 35020,6.0019,9.5013,1.007,3.5015/

```



```

01510      DATA B/1.04D-6,1.43D-12,2.0D-16,6.93D-9,6.97D-14,2.0D-16/
01520      DATA A/.456,.744,.940,.543,.837,1.0/
01530      DATA PAR1/1.50D17,2.40D18,1.50D16/
01540      DATA B1/4.00D-17,1.47D-14,3.30D-11,7.20D-17/
01550      DATA A1/.966,.832,.650,1.000/
01560      DCX=CX
01570      DCB=CB
01580      DT=DABS(DCX)+DABS(DCB)
01590      I=1
01600      IF(DCX+DCB.GT.0.0D0)GO TO 20
01610      5  CONTINUE
01620      IF(DT.GE.PAR(I))GO TO 10
01630      I=I+1
01640      IF(I.EQ.6) GO TO 10
01650      GO TO 5
01660      10  DELNC=DABS(DCX+DCB)*B(I)*((DT)**(A(I)-1))
01670      RETURN
01680      20  IF(DT.GE.PAR1(I)) GO TO 30
01690      I=I+1
01700      IF(I.EQ.4) GO TO 30
01710      GO TO 20
01720      30  DELNC=DABS(DCX+DCB)*B1(I)*((DT)**(A1(I)-1))
01730      RETURN
01740      END
01750 C
01760 C
01770 C
01780 C
01790 C
01800      FUNCTION IFAC(N)

```

```

01810      DOUBLE PRECISION IFAC,X
01820      IFAC=1.D0
01830      IF(N.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.D0
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

```

```

02110      DCPURM=IFAC(I)/IFAC(K)/IFAC(I-K)
02120      RETURN
02130      END
02140 C*****
02150 C
02160 C
02170 C
02180 C*****
02190      SUBROUTINE INT(UX,UT,TU,C,TAU,CB,D,U,SATH)
02200      DOUBLE PRECISION TH,C,TAU,CB,D,U,SATH,XNX,DISPIN,XIT,XITM1
02210      DIMENSION C(MX,NT)
02220      NTM1=NT-1
02230      NXM1=NX-1
02240      XNX=NX
02250      XNT=NT
02260      DO 20 IT=2,NTM1
02270      DO 20 IX=2,NXM1
02280      XIT=IT
02290      XMX=MX
02300      X=H*(XMX-1)
02310      T=TH*(XIT-1)
02320      C(MX,IT)=DISPIN(TAU,D,X,T,SATH,CB)
02330      CONTINUE
02340      DO 40 MX=1,NX
02350      Z=(MX-MX)*H
02360      C(MX,1)=((B2*A2)/(U*U*U2*1.054E-34))*((E2P*EXP((-2.)*A2*Z))
02370      X+(E2H*EXP(2.*A2*Z)))
02380      WRITE(5,*)MX,C(MX,1)
02390      C(MX,NT)=0.00
02400      CONTINUE
40

```

```

02410 DO 30 IT=1,NT
02420 C(MX,IT)=0.
02430 XITH1=IT-1
02440 C(1,IT)=C(1,1)*DEXP(-TH*XITH1/TAU)
02450 30 CONTINUE
02460 RETURN
02470 END
02480 C*****
02490 C
02500 C
02510 C
02520 C*****
02530 FUNCTION DISPIN(TAU,D,Y,T,SATH,CB)
02540 DOUBLE PRECISION TAU,D,Y,T,SATH,XI,TEMP,OUT,DSIN,PLUS,DARCOS
02550 DOUBLE PRECISION PI,DISPIN,XDISP
02560 XDISP(XI)=2.00*CS*2.00/(XI*PI)
02570 CS=1.022
02580 PI=2.00*DARCOS(0.00)
02590 DISPIN=0.00
02600 M=1
02610 XM=M
02620 10 CONTINUE
02630 TEMP=XM*PI/SATH
02640 OUT=DSIN(TEMP*SATH)
02650 IF((1.00/TAU+TEMP**2)*T.GT.115.00)GO TO 40
02660 PLUS=DEXP(-1.00*(1.00/TAU+TEMP**2)*T)*DSIN(TEMP*X) *XDISP(XI)
02670 GO TO 70
02680 40 PLUS=0.00
02690 70 DISPIN=DISPIN+PLUS
02700 I=I+2

```

```

02710      XM=M
02720      IF(PLUS.LE.DISPIN*1.D-4.AND.PLUS.GE.DISPIN*(-1.D-4))GO TO 60
02730      GO TO 10
02740      60      DISPIN=DISPIN
02750      RETURN
02760      END
02770      C
02780      C
02790      C
02800      C
02810      C
02820      C
02830      C
02840      C
02850      C
02860      C
02870      C
02880      C
02890      C
02900      C
02910      C
02920      C
02930      XM=XM*1.E-6
02940      XP=XP*1.E-6
02950      C=C*1.E-6
02960      A=1.
02970      B=1.
02980      C=1.
02990      D=1.
03000      XHE=((2.**.5)*2.45E21*C)/(2.*XP*ALOG(1.+1.41E20*D/(XM+XP)))

```

FUNCTION SHOBH(XN,XP,XC,T)

THIS FUNCTION CALCULATES THE ELECTRON MOBILITIES FOR SILICON.
N,P,AND C ARE IN ATOM/(CMETER**3)
T IS IN DEGREES KELVIN
N IS THE ELECTRON CONCENTRATION
P IS THE HOLE CONCENTRATION
C IS THE IMPURITY CONCENTRATION

```

03010      XINP=(2.45E21*C)/(XC*ALOG(1.+1.41E20*D/(XN+XP)))
03020      XA=(XHE*XINP)/(XHE+XINP)
03030      Z=(1350.*A)/(1350.*A+XA)
03040      F1=.0954+.473*Z-.383*(Z*Z)
03050      F2=.0956+.866*Z-.776*(Z*Z)
03060      F=F1/F2
03070      SMOBN=F*(1350.*A*XA)/(1350.*A+XA)
03080      XN=XN*1.E6
03090      XP=XP*1.E6
03100      C=C*1.E6
03110      RETURN
03120      END
03130 C
03140 C
03150 C
03160 C
03170 C
03180      FUNCTION SMOBP(XN,XP,XC,T)
03190 C
03200 C
03210 C      THIS FUNCTION CALCULATES THE HOLE MOBILITIES FOR SILICON.
03220 C      N,P,AND C ARE IN ATOM/(METER**3)
03230 C      T IS IN DEGREES KELVIN
03240 C      N IS THE ELECTRON CONCENTRATION
03250 C      P IS THE HOLE CONCENTRATION
03260 C      C IS THE IMPURITY CONCENTRATION
03270 C
03280 C
03290      XN=XN*1.E-6
03300      XP=XP*1.E-6

```

```

03310      C=C*1.E-6
03320      A=1.
03330      B=1.
03340      C=1.
03350      D=1.
03360      XH3=((2.**.5)*2.45E21*C)/(2.*X1*ALOG(1.+1.41E20*D/(XN+XP)))
03370      X11P=(2.45E21*C)/(XG*ALOG(1.+1.41E20*D/(XN+XP)))
03380      XA=(XNE*X11P)/(XNE+X11P)
03390      Z=(480.*B)/(430.*B+XA)
03400      F1=.0054+.473*Z-.383*(Z*Z)
03410      F2=.0956+.866*Z-.776*(Z*Z)
03420      F=F1/F2
03430      SMO3P=F*(430.*B*XA)/(430.*B+XA)
03440      XN=XN*1.E6
03450      XP=XP*1.E6
03460      C=C*1.E6
03470      RETURN
03480      END

03490      C
03500      C
03510      C
03520      C
03530      C
03540      C
03550      C
03560      C
03570      C
03580      C
03590      C
03600      C

SUBROUTINE REDIS(CX,CT,TH,C,TAU,CB,D,H,SATH,I900,SCALE)
DOUBLE PRECISION C,ERROR,CB,SATH,TH,H,W,TAU,D
DOUBLE PRECISION CNO,CPO,UP,UN,SCALE
DIMENSION C(201,201)
DA(CX)=(CX+CX+CPO+CPO)*UP*UN*.0259/((CX+CPO)*UP+(CX+CNO)*UN)

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```

03610      CNO=CB
03620      CPO=CB
03630      NXM1=NX-1
03640      NTM1=NT-1
03650      W=1.75
03660      XNX=NX
03670      IF(I900.EQ.1)GO TO 903
03680      CALL SINT(NX,IT,TH,C,TAU,CB,D,H,SATH,SCALE)
03690      IF(I900.EQ.0)GO TO 902
03700      CONTINUE
03710      I901=0
03720      ILOG=0
03730      DO 20 IT=2,NTM1
03740      DO 20 IX=2,NXM1
03750      TEMPN=C(MX,IT)+CNO
03760      TEMPP=C(MX,IT)+CPO
03770      XCB=CB
03780      UP=SHOBP(TEMPP,TEMPP,XCB,300.)/1.E4
03790      UN=SHOBN(TEMPP,TEMPP,XCB,300.)/1.E4
03800      ERROR=(DA(C(MX,IT))*(C(MX+1,IT)+C(MX-1,IT))/(H*H))
03810      X-(C(MX,IT+1)-C(MX,IT-1))/(2.D0*TH))
03820      X/((2.D0*DA(C(MX,IT)))/(H*H)+(1.D0/TAU))-C(MX,IT)
03830      C(MX,IT)=C(MX,IT)+J*(ERROR)
03840      IF(ERROR.GT.C(MX,IT)*1.D-3.OR.ERROR.LT.C(MX,IT)*(-1.D-3))ILOG=1
03850      CONTINUE
03860      I901=I901+1
03870      IF(I901.GT.2)GO TO 902
03880      IF(ILOG.NE.0)GO TO 5
03890      CONTINUE
03900      I900=1

```



```

03910      WRITE(6,*)TH,ILOG
03920      DO 40 I=1,NT
03930      IPRI=(NX-1)/10
03940      WRITE(6,100)(C(II,I),II=1,NX,IPRI)
03950 100    FORMAT(1X,'1',1X,11E11.4)
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(NX,NT)
04080      NXM1=NX-1
04090      NTM1=NT-1
04100      DO 10 I=1,NUM
04110      DO 20 KX=2,NXM1
04120      DO 20 KT=2,NTM1
04130      C(KX,KT)=(C(KX,NT)+C(KX,NT+1)+C(KX,NT-1)+C(KX+1,NT)+C(KX-1,
04140      XKT))/5.00
04150 20     CONTINUE
04160      WRITE(6,*)I
04170 10     CONTINUE
04180      RETURN
04190      END
04200 C

```

```

04210 C
04220 C
04230 C
04240 C
04250 SUBROUTINE SINT(NX,NT,TH,C,TAU,CB,D,H,SATH,SCALE)
04260 DOUBLE PRECISION TH,C,TAU,CB,D,H,SATH,XNX,DISPIN,XIT,XITM1
04270 DIMENSION C(NX,NT)
04280 DOUBLE PRECISION CP,SP,TH,AM(50),XMP(50),GAM,ETM,ETP,ET,SUM
04290 DOUBLE PRECISION B2,A2,W,U2,E2P,E2M,Z,PI2
04300 DOUBLE PRECISION CNO,CPO,UP,UN,DAX,CX,SCALE
04310 DA(CX)=(CX+CX+CNO+CPO)*UP*UN*.0259/((CX+CPO)*UP+(CX+CNO)*UN)
04320 CNO=CB
04330 CPO=CB
04340 XNX=NX
04350 B2=2.0275E7
04360 A2=297.19
04370 U=1.777E15
04380 U2=1.2566E-6
04390 E2P=1321.71*1.76*SCALE
04400 E2M=294.41*1.76*SCALE
04410 PI2=2.00*DARCOS(0.00)/2.00
04420 GAM=2.00*A2
04430 ET=B2*A2/U/W/U2/1.054D-34
04440 ETP=ET*E2P
04450 ETM=ET*E2M
04460 WRITE(6,*)ETP,ETM,ET,GAM
04470 NTH1=NT-1
04480 NXH1=NX-1
04490 DO 10 I=1,50
04500 T I=I-1

```

```

04510 XMP(I)=(2.D0*TI+1.D0)*PI2/SAT4
04520 CP=DCOS(XMP(I))*SATH
04530 SP=DSIN(XMP(I))*SATH
04540 AM(I)=(2.D0/SATH/(GAM*GAM+XMP(I)*XMP(I)))*
04550 X((ETP*DEXP(-GAM*SATH))*(-GAM*CP+XMP(I)*SP)+
04560 XETM*DEXP(GAM*SATH)*(GAM*CP+XMP(I)*SP))-
04570 X(-ETP*GAM+ETM*GAM)
04580 WRITE(9,*)AM(I),XMP(I),SP,CP,I
04590 10 CONTINUE
04600 DO 20 IT=1,NT
04610 IF(IT.EQ.1)GO TO 26
04620 TEMPN=C(NX,IT-1)+CNO
04630 TEMPP=C(NX,IT-1)+CP0
04640 XCB=CB
04650 UP=SHOBB(TEMPN,TEMPP,XCB,300.)/1.E4
04660 UN=SHOBB(TEMPN,TEMPP,XCB,300.)/1.E4
04670 DAX=DA(C(NX,IT-1))
04680 DO 25 I=1,50
04690 TI=TI
04700 AM(I)=AM(I)*DEXP(-(1.D0/TAU+XMP(I)*XMP(I)*DAX)*TI)
04710 25 CONTINUE
04720 26 CONTINUE
04730 DO 20 NX=1,NX
04740 XMX=HX
04750 Z=(XMX-XMX)*H
04760 C(NX,IT)=0.D0
04770 DO 35 I=1,50
04780 C(NX,IT)=C(NX,IT)+AM(I)*DCOS(XMP(I)*Z)
04790 35 CONTINUE
04800 20 CONTINUE

```

```
04810      DO 40 I=1,NX
04820      C(I,NT)=0.00
04830 40    CONTINUE
04840      RETURN
04850      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.

HOW MANY (1-64)? 1
US1 +100.E-03;
HS1 +20.E-09;

Figure B.2

Figure B.3

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