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Study of Direct Semiconductor Materials for an Optically Controlled Switch

Sung Taek Ko  
Old Dominion University

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STUDY OF DIRECT SEMICONDUCTOR MATERIALS FOR
AN OPTICALLY CONTROLLED SWITCH

by

Sung Taek Ko
M.S. January 1984, Hampton University

A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
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DOCTOR OF PHILOSOPHY

ELECTRICAL ENGINEERING

OLD DOMINION UNIVERSITY
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Approved by:

Vishnu K. Lakdawala (Director)
ABSTRACT

STUDY OF DIRECT SEMICONDUCTOR MATERIALS FOR AN OPTICALLY CONTROLLED SWITCH

Sung Taek Ko
Old Dominion University, 1989
Director: Dr. Vishnu K. Lakdawala

A model for a bulk GaAs photoconductive switch has been developed and solved to determine the performance of the device in closing and opening switch applications. The GaAs material has been characterized by deep level transient spectroscopy (DLTS). Two electron traps (EL2 and EL5) and one hole trap (Cu_B) have been detected and were included in the model. Simulation studies are performed on several GaAs switch systems composed of different combinations and density of deep levels to investigate the influence of deep traps in a photoconductive switch system. The electron occupancy of each deep trap is traced in the simulation to investigate the roles of each trap during the turn-on and turn-off phase of the photoconductive switch. The computed results show that small concentration of recombination centers in the switch material drastically affects the turn-off performance of the switch.
ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr. Vishnu Lakdawala and Dr. Karl Schoenbach for their guidance and support on this project. I would also like to thank Dr. Sacharia Albin and Dr. Wynford Harries for their comments on this manuscript and for serving on my committee. My special thanks go to Michael Mazzola, Gordhan Barevadia and Steven Ainsworth for their hours of help. My utmost gratitude and appreciation are expressed for the graciousness of my parents. I save my deepest thanks to my wife Kyung for longstanding encouragement and unwavering support during the course of this program.
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A  area
B  magnetic field
C  capacitance
\( c_{n,p} \)  electron, hole capture rate coefficient
d  thickness
d_0  film thickness at a center
e  (1) magnitude of electronic charge; (2) emission rate
E  (1) electric field; (2) energy
\( E_{c,v} \)  energy level of conduction, valance band
\( E_F \)  Fermi level
\( E_T \)  energy level of a trap
f  (1) frequency, (2) function \( f(R_a/R_b) \)
F(r)  envelope function
g  degeneracy
\( G_0 \)  Green function
\( G_{n,p} \)  electron, hole generation rate
h  (1) Planck constant; (2) height
\( \hbar \)  \( h / 2\pi \)
H  crystal Hamiltonian
I  current
\( J_{n,p} \)  electron, hole current density
LIST OF SYMBOLS – Continued

k  Boltzmann constant
$K_a$  Auger recombination coefficient
$K_d$  direct band to band recombination
$m^*$  effective mass
$M_{e}$  mass of material evaporated from an area $S_e$
$M_{r}$  mass of deposit received by an area $S_r$
$n$  free electron density
$n_T$  trap density occupied by electrons
$N_{c,v}$  density of state of conduction, valence band
$N_{D,A}$  donor, acceptor density
$N_I$  ionized impurity density
$N_T$  trap density
$p$  (1) free hole density; (2) distance from a center
$q$  electronic charge
$R_c$  specific resistance
$R_H$  Hall coefficient
$S(T)$  DLTS signal
$S_e$  surface area from which evaporation take place
$S_r$  surface area receiving deposit
$t$  time
$t_0$  location of peak in time of the Gaussian pulse shape
$T$  absolute temperature
$U$  effective impurity potential
$U_{n,p}$  electron, hole recombination rate
$v$  velocity
$V$  voltage

xi
LIST OF SYMBOLS - Concluded

\( V_D \)  
built-in potential

\( V_H \)  
Hall voltage

\( V_R \)  
reverse bias voltage

\( \langle v_{n,p} \rangle \)  
electron, hole thermal velocity

\( \alpha_I \)  
intrinsic absorption coefficient

\( \beta \)  
two photon absorption coefficient

\( \sigma \)  
conductivity

\( \sigma_v \)  
standard deviation of Gaussian shape pulse

\( \rho \)  
resistivity

\( \varepsilon \)  
permittivity

\( \phi_B \)  
potential barrier

\( \phi \)  
photon flux

\( \mu_{n,p} \)  
electron, hole mobility

\( \Psi \)  
wave function

\( h\nu \)  
photon energy

\( \psi \)  
Bloch function of the host crystal
CHAPTER 1
INTRODUCTION

Bulk photoconductive semiconductor switches have recently attracted attention for a number of reasons. They are inherently simple, scalable to higher power applications and optically controllable [1]. Other advantages of the switch are its capability for ultra-fast switching (pico-second range) [2] and high repetition rate (GHz range) [3].

Recently Schoenbach et al. reported a novel bulk optically controlled semiconductor switch (BOSS) which can be turned on or turned off by command [4]. The concept of BOSS is based on photo-excitation of carriers from a deep acceptor level (turn-on) and optical quenching of the carriers (turn-off). The BOSS uses a deep acceptor level (a CuB level in a GaAs:Si:Cu system) as an intermediate energy storage level. The feasibility of the switch concept has been demonstrated and results are promising [5, 6]. The BOSS has several attractive features in addition to all the advantages of the bulk photoconductive semiconductor switch. It is bistable, which means that it requires control power only for turn-on and turn-off, but not to sustain the on state. It does not have a depletion region and hence the excitation and quenching of the photoconductivity occur uniformly in the entire bulk
of the semiconductor. It has a large absorption depth because its absorption is mainly due to impurity absorption not intrinsic absorption. The large absorption depth increases the current handling capability of the switch by increasing the active region of the switch medium. These aspects make the BOSS a strong candidate for the next generation high power switch.

The performance of the BOSS system depends critically on deep levels in the material. Thus, it is necessary to characterize deep levels in the switch material before any switch experiment or any modeling. Deep levels in a semiconductor material are introduced by defects or chemical impurities in the material and are capable of capturing free carriers [7]. Deep level impurities in a semiconductor material are used to increase the resistivity of the material [8] or to reduce the carrier lifetime [9].

The deep levels have been simply classified as electron trap, hole trap or recombination center according to their capability of capturing (or trapping) free carriers [10]. The electron trap has a greater electron capture cross section than hole capture cross section, whereas the hole trap has a greater hole capture cross section than electron capture cross section. The recombination center has similar electron and hole capture cross sections. The photoconductivity of the semiconductor switch depends critically on the types, concentrations, and cross sections of the deep levels found in the switch material [11]. Therefore, a proper
understanding of the deep traps is necessary to understand the photoconductivity in semiconductor switches as well as provide a basic guideline for better photoconductive switch design.

Numerous experimental techniques have been developed to investigate the deep levels in semiconductors in the past decade and are discussed in several review articles [12-14]. Among those techniques, deep level transient spectroscopy (DLTS) is the most widely used technique because of its simplicity [14]. The DLTS technique was introduced by Lang in 1974 [15]. The technique is capable of displaying the spectrum of traps in a crystal as positive and negative peaks as a function of temperature. The sign of the peak indicates whether the trap is near the conduction or valence band, the height of the peak provides information about the trap density. Chantre et al. [16] were able to measure optical cross-sections for the deep levels by replacing the electrical pulse which is used to fill the traps in the DLTS technique with an optical pulse. Hurtes et al. [17] were able to apply the DLTS technique to high resistivity material by creating the carriers in the bulk region of the material optically. By measuring the photo-induced ac resistance of the specimen, Seabaugh [18] were able to measure the DLTS spectrum in any junction (ohmic or schottky).

The dynamic behavior of free carriers in semiconductors has been analyzed by using the Shockley-Reed-Hall (SRH) recombination model [19, 20]. In the SRH model, the generation and decay of the excess carriers are described by
two coupled nonlinear equations. Some transient solutions of the nonlinear equations have been reported for certain restricted cases [21-23] because the general analytic solutions for the equations are not known. Sah [24, 25] was able to analyze the lifetime of free carriers by relating the physical properties of the material into the circuit elements based on the SRH model. Demokan [26] demonstrated theoretically the transient photo-conductivity of intrinsic silicon by solving the continuity equation. Hwang et al. [27] developed a method to calculate the turn-off transient of photo-conductive circuit elements (InP:Fe). They used two characteristic time constants, the main recombination time and the readjustment time constant rather than a single characteristic time constant. Physical significance of the readjustment time is the time needed for readjustment of charges on recombination centers to a condition enabling equal capture rates of electrons and holes. They obtained the time constants by solving the SRH equations numerically. Recently, Iverson and Smith [28] developed a photoconductor device model that is based on time-dependent convective/diffusive continuity and transport equations. They used a numerical technique based on a finite-difference technique and solved the equations for an InP:Fe photoconductive device.

In this work, the BOSS is modeled by the kinetic theory of photoconductivity and is simulated numerically for the optically controlled switch application. The material properties of the BOSS are measured using the DLTS technique.
and are included in the simulation. Chapter 2 of this dissertation describes the basic processes and principles utilized in the preparation of samples, which were used in the characterization and switching experiments. In Chapter 3, techniques to characterize the samples are discussed in detail. Chapter 4 covers modeling and numerical simulation of BOSS systems and provides the results from the simulation. A summary of this research and the conclusions drawn from it are given in Chapter 5.
CHAPTER 2
SAMPLE PREPARATION

This chapter describes briefly the processes required to make test samples. These processes include vacuum evaporation to deposit a thin metal film on a GaAs wafer, thermal diffusion to introduce impurities into the wafer and contacts for ohmic and schottky junctions.

2-1 Vacuum Evaporation

Vacuum evaporation is a popular method for depositing metal onto semiconductor materials. This technique offers superior film composition and thickness control [29]. The evaporation of materials requires external energy. There are several methods to provide the energy needed to evaporate materials such as hot filaments and electron-beam (e-beam) bombardment. The filament technique is the simplest method and is used in our experiment. An electrical current is passed through a resistive material and evaporants are evaporated by the joule heating of the resistive material. Resistance heated wires and metal boats are the simplest evaporation sources. The materials used for the evaporation sources have high melting points and low vapor pressures. Tungsten, molybdenum and tantalum are the most commonly used
evaporation sources. The rate of film deposition depends on the evaporant, the chamber pressure and the temperature of the evaporation source. Chamber pressure of $10^{-5}$ Torr or less is commonly used in vacuum evaporation. A vapor pressure of $10^{-2}$ Torr is required to produce a useful film deposition rate. The evaporation temperature required to establish a vapor pressure of $10^{-2}$ Torr is called source operating temperature [30].

The location of the evaporation sample is also an important factor to deposit an uniform thin film on the sample. As shown in Appendix 1, the film deposits on a sample is function of the distance from the center $p$ and the height $h$. In our experiment, the location of samples for the thin film deposition are restricted to the distance from the center $p$ less than 20% of height $h$ to keep the thickness deviation of less than 10%. The thickness of the deposited mass was monitored by a simple crystal oscillator. The crystal oscillator was built in our laboratory and the circuit diagram is shown in Fig. 2-1. A 6 MHZ crystal was chosen for high sensitivity and high mass loading capacity [30]. A 5 mm diameter hole was made on the metal cap of the crystal so that an evaporated material be deposited onto the electrode of the crystal. When evaporated material is deposited on to the electrode of the crystal, the crystal's resonance frequency changes due to the mass change of the electrode. Therefore, the resonance frequency change, $\Delta f$, is a function of the film
Fig. 2-1 A crystal oscillator circuit used in the film thickness monitoring device.
thickness deposited on to the electrode of the oscillator and on to the sample located near the oscillator.

Initially, several AuGe evaporations with different $\Delta f$ were performed on plane glass and then the deposited film thickness was measured by a stylus type thickness measuring device at Allied Bendix Electronics. From the above measurement, a correlation graph for $\Delta f$ versus actual thickness of the film was made as shown in Fig. 2-2. This graph is used to find the actual deposited film thickness from the frequency change during the evaporation process.

2-2 Thermal Diffusion

Diffusion is a popular method to introduce a dopant into a semiconductor. Diffusion is a phenomenon associated with the movement of a substance through a medium from a region of high concentration to a region of low concentration. Diffusion occurs as a result of the random motion of particles. The random motion of particles is due to the thermal energy and hence diffusion is a strong function of temperature. A brief review on the atomic diffusion mechanism is provided in Appendix 2.

Cu diffusion in Si doped GaAs [31] has been performed in our laboratory to make an optically controlled semiconductor switch. A thin Cu film, with a thickness of about 400 nm, was deposited onto a GaAs wafer [31] by the vacuum evaporation technique. The Cu diffusion was carried by annealing the sample in a diffusion oven at 600 °C for 2 Hours. The
Fig. 2-2 A correlation chart between the film thickness and the frequency change Δf for AuGe evaporation.
conductivity change of 5 orders of magnitude [from $60 \, (\Omega \text{cm})^{-1}$ to $2 \times 10^{-4} \, (\Omega \text{cm})^{-1}$] was observed after the Cu diffusion. This indicates that the shallow donor (Si) has been compensated by the deep acceptor Cu. Conductivity as a function of density of diffused Cu in Si doped GaAs has been calculated by the charge neutrality condition [32] and the results are drawn in Fig. 2-3. It is shown in the figure that a dark conductivity as low as $10^{-9} \, (\Omega \text{cm})^{-1}$ can be obtained by Cu compensation. It is also noticed that over compensation of Cu does not result in a sharp increase of the dark conductivity. In fact the dark conductivity remains less than $10^{-4} \, (\Omega \text{cm})^{-1}$ for a Cu density ranging up to four times the shallow donor density.

Copper is an omnipresent impurity with a high diffusion coefficient and high solubility in GaAs [33]. The diffusion mechanism of Cu in GaAs is believed to be substitutional - interstitial. Interstitial copper results in a shallow donor carrying a single positive charge while substitutional copper is a double acceptor in GaAs [33]. Since the substitutional copper requires a vacancy, the effective diffusion rate is determined by the relative abundance of the two species, copper and vacancies. If there is no vacancy available, the Cu impurity should remain in interstitial sites. Therefore, vacancy in a GaAs material is an important factor in controlling Cu diffusion in the material.
Fig. 2-3 Conductivity as a function of density of diffused Cu in Si-doped GaAs.
2-3 Contacts

Metal - Semiconductor contacts can be divided into two groups, Schottky contacts and ohmic contacts. When metal comes into contact with a semiconductor, a charge transfer occurs until the Fermi levels of both materials align. This initial charge transfer builds up space charges at the junction and as a result a potential barrier is formed. The schottky contact is mainly due to the potential barrier at the metal - semiconductor junction and it behaves as a rectifying contact. On the other hand, the ohmic contact should not, in principle, have a potential barrier at the interface and should have a linear current-voltage characteristic independent of polarity. In practice, a contact is considered ohmic if the voltage drop across the junction is much smaller than that across the device [34].

Ohmic contacts have been realized in situations where the potential barrier exists. To be an ohmic contact, the potential barrier should be low enough so that the voltage drop across the junction is negligible or thin enough so that carriers can pass through the junction by tunneling. The ohmic behavior of Au contacts on p type Si is due to a very low potential barrier while Au contacts on n type Si is due to tunneling through the barrier [35].

The conduction properties of metal - semiconductor interfaces are determined by the emission mechanism of carriers at the interface, such as thermionic emission (TE), field emission (FE) and thermionic field emission (TFE). Fig.
2-4 shows the three emission mechanisms for metal on n-type semiconductor contacts under forward bias. In TE, the carriers are emitted over the top of a barrier, which gives rise to current rectification. TE [Fig. 2-4 (a)] is the dominant emission mechanism in a Schottky contact. In FE [Fig. 2-4 (b)], the carriers are emitted through tunneling, which is the preferred mode of current transport in ohmic contacts. TFE [Fig. 2-4(c)] is transition between TE and FE. In TFE, the carriers can not tunnel through the barrier the ground level of the conduction band, but can tunnel through the barrier somewhere above the band edge.

The electrical properties of interfaces are characterized by their specific resistance $R_c$.

\[
R_c = \left. \frac{d V}{d J} \right|_{v = 0}
\]  

(2-5)

The specific resistance $R_c$ has been calculated for the three emission mechanisms and the functional dependence of the contact resistance on semiconductor doping level has been calculated by Yu [35] as follows.

\[
R_c \propto \exp \left[ \frac{\phi B}{kT} \right] \text{ for TE}
\]

(2-6)

\[
R_c \propto \exp \left[ \frac{\phi B}{E_{00}} \right] \text{ for FE}
\]

(2-7)
Fig. 2-4 Carrier emission mechanisms at a metal semiconductor junction
(a) for thermal emission,
(b) for field emission and
(c) for thermionic field emission.

$\phi_B$ is the barrier height, $E_F$ the Fermi level,
$E_C$ the conduction band edge.
\[ R_c \propto \exp \left[ \frac{\phi_B}{E_{00} \coth \left( \frac{E_{00}}{kT} \right)} \right] \text{ for TFE } \quad (2-8) \]

where \( E_{00} = \frac{q\hbar^2}{2m^*} \left( \frac{N_D}{m^*} \right)^{1/2} \). It is evident from the equations that the TE is temperature dependent but independent of doping density. On the contrary, FE is independent of temperature but dependent on doping density. The expected functional dependency of \( R_c \) as a function of \( (N_D)^{-1/2} \) is shown in Fig. 2-5. The figure indicates that FE becomes dominant when the doping density is large while TE becomes dominant when the doping density is small.

In this research, Al has been used to make a Schottky contact on Si doped GaAs material [31]. It has been observed that the greater the shallow donor or acceptor doping density, the more difficult it is to form a Schottky contact. However, large doping densities make it easier to form an ohmic contact. This is a clear indication of the fact that ohmic behavior in a highly doped material is mainly due to the field emission of carriers at the interface because high doping density does not change the barrier height \( \phi_B \) [35]. An I-V characteristic curve measured on a curve tracer for the Schottky contact formed on a Si doped GaAs wafer [31] is shown in Fig. 2-6. The figure indicates that the forward voltage of the contact is about 0.7 V which is close to the Schottky barrier height 0.8 V [59] and the reverse breakdown voltage...
Fig. 2-5  Theoretical dependence of the specific contact resistance on the doping concentration after [35].
Fig. 2-6  I-V characteristics for the schottky contact formed on Si-doped GaAs [31].
about 12 V. This sample was used for a deep level transient spectroscopy (DLTS) measurements.

It has been reported that AuGe contacts on n-type GaAs [31] give good ohmic contacts [36]. AuGe alloy (Au: 88 %, Ge: 12 %) was used as a contact material on the n-type GaAs [31] and provided satisfactory ohmic contacts. The I-V characteristic curves for the ohmic contacts formed on a Si doped GaAs sample [31] are shown in Fig. 2-7(a) and (b). The contact annealing was done in an oven at 450 °C for 3 minutes. It is well known that the thermal annealing of contact improves the I-V characteristics of contacts. Annealing temperature between 420 °C - 550 °C for times ranging from 15 s to 5 minute is commonly used [34]. It is believed that during heating one or several contact components are molten and some of the semiconductor is dissolved in the melt. On cooling the dopant segregates from the melt together with the solidifying semiconductor. In reality, the alloying process is much more complex and the metallurgical interactions at the metal-semiconductor interface during alloying are not well understood to date [34].

It can be seen from the figures that the I-V characteristics before annealing and after annealing are quite different. Thus, the contact annealing is an important step in the process for making a good ohmic contacts.
Fig. 2-7  I-V characteristics for the ohmic contact formed on Si-doped GaAs [31].
CHAPTER 3
SAMPLE CHARACTERIZATION

Characterization of a test sample is a necessary step before any experiment or modeling. The van der Pauw technique is employed to measure the resistivity, mobility and carrier density of the sample while the DLTS technique is used to measure parameters associated with the deep levels in the material. In this chapter, the theory behind these techniques are described and the results obtained from measurements done on a GaAs sample are presented.

3-1 Van der Pauw Technique

The characteristic parameters of a medium between the current density vector \( \mathbf{J} \) and the electric field \( \mathbf{E}_1 \) are the electrical conductivity \( \sigma \) or resistivity \( \rho \), and mobility \( \mu \) :

\[
\mathbf{J} = \sigma \mathbf{E}_1 = \frac{1}{\rho} \mathbf{E}_1 = q n \mu \mathbf{E}_1
\]

If a magnetic field is applied at right angles to the direction of current flow in the medium, an electric field will build up in a direction perpendicular to both the
direction of the current and the magnetic field. The phenomenon is called the Hall effect and has been widely used for semiconductor characterization. The Hall field is due to the deflection of electrons by the Lorentz force: $q (\mathbf{v} \times \mathbf{B})$. The electric force required to balance the Lorentz force is

$$q \mathbf{E}_2 = - q (\mathbf{v} \times \mathbf{B})$$

or

$$\mathbf{E}_2 = - \mathbf{v} \times \mathbf{B} \quad .$$

(3-2)

If we assume that the electrons are moving in the $x$ direction and the magnetic field is applied in the $z$ direction, the Hall field $E_y$ is obtained

$$E_y = v_x B_z$$

or

$$1 \quad \frac{E_y}{q n} = \frac{j_x B_z}{R_H j_x B_z}$$

(3-3)

where the current $j = q n v_x$. The proportionality constant $R_H$ is called the Hall coefficient. A measurement of the Hall field for a known current density and magnetic field yields a value for the carrier concentration $n$.

$$n = \frac{1}{q R_H} = \frac{j_x B_z}{q E_y}$$

(3-4)
The mobility is simply the ratio of the Hall coefficient and the resistivity:

\[
\mu = \left| \frac{\sigma}{qn} \right| = \left| \frac{R_H}{\rho} \right| . \tag{3-5}
\]

Therefore, the Hall effect and resistivity measurement can be used to give accurate values for carrier concentration and mobility.

The standard configuration [37] and the van der Pauw configuration [38, 39] are the commonly used geometries for resistivity and Hall measurements of semiconductor materials. The standard configuration has a parallelepiped geometry thus the electrodes are parallel to each other. As a result, the field lines are uniform, which reduces the analysis of the results to simple calculations. However, the standard method is difficult to apply where the sample is thin or has an arbitrary shape.

Van der Pauw developed a novel method which can solve the problems encountered in the standard configuration [38]. The van der Pauw method is independent of the current distribution in the sample and hence the method is applicable to samples of arbitrary shape with the arbitrary placement of four point contacts on the edge of the sample. In this research, the van der Pauw method has been employed because our sample is thin.

The following discussion contains a brief review of the work done by van der Pauw [38, 40] on resistivity and Hall
effect measurements. Consider a flat sample of arbitrary shape with contacts 1, 2, 3 and 4 fixed at arbitrary places along the circumference as shown in Fig. 3-1. It is assumed that these contacts are sufficiently small to be regarded as point contacts. When a current $I_{12}$ passes through electrodes 1 and 2, a voltage $V_{43}$ appears across electrodes 4 and 3. The transfer resistance $R_a$ is defined as the ratio of the values of the voltage $V_{43}$ and that of the current $I_{12}$. Similarly, a transfer resistance $R_b$ is defined as the ratio of the values of the voltage $V_{14}$ and that of the current $I_{23}$. The resistivity of the sample derived by Van der Pauw [38] is

$$\rho = \frac{\pi d}{\ln 2} \left( \frac{R_a + R_b}{2} \right) f$$

(3-6)

where $d$ is the thickness of the sample. The function $f(R_a/R_b)$ depends on $R_a/R_b$ only and satisfied the relation [38, 40].

$$\cosh \left( \frac{R_a - R_b}{R_a + R_b} \frac{1}{\ln 2} f \right) = \frac{1}{2} \exp \left( \frac{\ln 2}{f} \right)$$

(3-7)

The function $f(R_a/R_b)$ as a function of $R_a/R_b$ has been calculated numerically and is plotted in Fig. 3-2.

When a magnetic field is applied perpendicular to the sample and current $I_{13}$ passes through the electrodes 1 and 3, a voltage $V_{24}$ appears across the electrodes 2 and 4. This voltage is the Hall voltage, $V_H$. The Hall coefficient is obtained from the equation 3-3.
Fig. 3-1 A flat and thin sample of an arbitrary shape with four small contacts at arbitrary places along the circumference.
Fig. 3-2  The function $f$ vs $R_a / R_b$.  

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The Hall mobility is obtained using equation 3-5.

\[ \mu_H = \frac{R_H}{\rho} = \frac{d}{B_z \rho} \frac{V_H}{I_{13}} \]  

(3-9)

A Hall measurement system similar to that described by Hemenger [39] was built and used for the Van der Pauw Hall measurement. Van der Pauw configuration used to measure resistivity and Hall measurement is shown in Fig. 3-3. The size of the sample is 1 cm x 1 cm and four triangular shape ohmic contacts are located at the corners of the sample. A problem associated with the Van dep Pauw Hall measurement is the size of contact. The Van der Pauw method assumes the contact is point contact. In reality, it is not possible to make a point contact onto a sample. Hence corrections are necessary for the finite size of the contact. Chwang et al. [41] reported correction factor on the Van der Pauw's resistivity and Hall coefficient measurement due to finite size contacts with square and triangular shapes on a square sample. Typical results from the van der Pauw measurements done on a n-type GaAs sample are \( R_a = 0.39 \, \Omega \), \( R_b = 0.31 \, \Omega \), \( V_H = 33.9 \, \text{mV} \) and \( I_{13} = 107 \, \text{mA} \). The values above are corrected values according to the correction factor given by Chwang et al. [41]. The function \( f(R_a/R_b) \) obtained from Fig. 3-2 for
Fig. 3-3  Van der Pauw configuration.
(a) and (b): for the resistivity measurement.
(c) and (d): for the Hall measurement.
this case is about 0.98. From the above basic values, resistivity, mobility and carrier density of the sample were calculated. For this sample, the resistivity is 0.055 Ω cm, the mobility is 4570 cm²/Vs and the free carrier density is 2.5 x 10¹⁶ cm⁻³. The measured mobility value agrees reasonably with the Hall mobility value about 5000 cm²/Vs by Vilms and Garrett [42]. Measurement technique was used extensively to determine the degree of Cu compensation of Si-doped GaAs material after the Cu diffusion.

3-2 DLTS Measurement
3-2-1 Electronic States in Semiconductors

In a perfect crystal, the wave functions of all states extend over the whole crystal and hence the same probability amplitude in every unit cell. When an impurity or other defect is introduced in the crystal, the wave functions decay with distance outside a finite set of unit cell [43]. Hence the periodicity is broken and localized states are allowed. In most cases localized states appear in the forbidden gap and affect the electronic properties of semiconductors.

For many substitutional impurities such as Si and Zn in GaAs, the defect levels are located close to the conduction or valence band with binding energy less than 50 meV. Such levels are called shallow level [44]. Other impurities such as O and Cr in GaAs produces defect levels with binding energy much greater than 50 meV. These levels are called deep levels. The binding energy is the minimum energy required to
literate a bound carrier from its impurity ion. However the definitions for the term "shallow" and "deep" given above are rather traditionally defined. Theoretically, an impurity is defined as being a deep trap if its central-cell potential alone, without any long-range Coulombic or elastic potential, is sufficiently strong to bind a state within the band gap of the host [45].

The important role of the shallow impurities is to control conductivity of the crystal. Almost all of the carriers in the shallow levels are ionized by the thermal energy $kT$ at room temperature and contribute to the conductivity. Since the solubility of the shallow impurities can be up to about $10^{20}$ cm$^{-3}$, the range of the conductivities that can be attained at room temperature is, therefore, about twelve orders of magnitude, from about $10^{-9}$ (Ω cm)$^{-1}$ to about $10^{3}$ (Ω cm)$^{-1}$ [43].

Deep level impurities, however, play an entirely different role. Since the thermal energy $kT$ is much less than the binding energy of the deep impurities at room temperature, carriers at the deep levels can not contribute to electrical conduction unless the carriers are ionized by some external energy source. Their contribution to the conductivity is negligible but they can act as a trap or a recombination center of carriers. Hence, the important role of the deep level impurities is to control the lifetime of the carriers.

Full knowledge of a defect, in principle, requires the information about a wave function in the crystal. The wave
function is obtained by solving the Schrödinger equation of the form [45-48].

\[ H \psi = E \psi \]  
(3-10)

where

\[ H = H_0 + U. \]  
(3-11)

\( H_0 \) represents the perfect crystal Hamiltonian and \( U \) is effective impurity potential which is usually centered at the site of the defect.

If the effect of the atomic, short range part of the potential \( U \) is insignificant, then the Schrödinger equation (3-10) can be reduced to a hydrogen like so-called effective mass equation [47].

\[ \left( \frac{\hbar^2}{-2m^*} \nabla^2 - \frac{e^2}{\varepsilon r} \right) F(\mathbf{r}) = E F(\mathbf{r}) \]  
(3-12)

where the \( F(\mathbf{r}) \) is a slowly varying envelope function. The energy spectrum of the equation of the equation (3-12) is

\[ E = E_n = \frac{1}{n^2} \left( \frac{e^2}{\varepsilon} \right)^2 \frac{m^*}{2\hbar^2} \quad n = 1, 2, \ldots \]  
(3-13)

The total wave function of the impurity electron is obtained from the envelope function \( F(\mathbf{r}) \) as

\[ \psi(\mathbf{r}) = \sum_{j=1}^{n} F_j(\mathbf{r}) \psi_j(\mathbf{k}, \mathbf{r}) \]  
(3-14)
where $\psi_j(\mathbf{k}, \mathbf{r})$ is Bloch function of the host crystal at the $j$th extremum of the band under consideration. This model so-called hydrogenic model has been successful in providing a good overall picture of the effects associated with shallow impurities where the potential $U$ is dominated by its long range (Coulomb) term.

For deep impurities, the atomic, short range potential is dominant and the hydrogenic model is not adequate to solve the problem. Most of the recent calculations of deep impurities are based on the scattering theoretic Green's function approach [45].

The Schrödinger equation (3-10) can be formally rearranged as

$$\Psi = (E - H_0)^{-1} U \Psi = G_0(E) U \Psi \quad \text{or} \quad [1 - G_0(E) U] \Psi = 0 \quad (3-15)$$

where $G_0 = (E - H_0)^{-1}$ is the Green function for the perfect crystal. The bound states in the gap of the host crystal are then obtained from the zeros of the determinational equation [46].

$$\det [1 - G_0(E) U] = 0 \quad (3-16)$$

There are two types of approach to solve the equations (3-15) and (3-16). The one type is the self consistent pseudopotential approach [46] and the other type is semiempirical methods such as tight binding method [43]. These
methods are still far from complete to predict the energy levels of any deep impurity with accuracy [45].

3-2-2 Deep Levels in GaAs

Gallium arsenide (GaAs) specimen has been grown by various techniques such as Bridgeman, liquid encapsulation Czochralski (LEC), vapor phase epitaxy (VPE), liquid phase epitaxy (LPE), molecular beam epitaxy (MBE), and metalorganic vapor phase epitaxy (MOVPE) [49]. The GaAs grown by different technique may have different properties due to deference in defects. For example LPE GaAs may be expected to be low in gallium vacancy defects and possibly high in arsenic vacancies. Since GaAs is a binary semiconductor, the number of possible native defects is large as shown in Table 3-1. It is also expected that the native defect may form a complex defect with impurity atoms as shown in Table 3-2. However none of these defects has been identified with any confidence [49]. Typical electron traps and hole traps in the GaAs materials are listed in Table 3-3 and 3-4 respectively.

Although there has been much work on detecting deep levels in the GaAs material, the clear picture of the deep levels are not known to date and there exists significant deviations between the deep level data reported from different laboratories [13]. For example, the energy level of the EL2 trap which is the dominant electron trap in GaAs material varies from 0.75 eV to 0.83 eV [13] and the origin of the energy level is still in doubt [14].
TABLE 3-1
POSSIBLE DEFECTS IN GALLIUM ARSENIDE\textsuperscript{a} [after 49]

<table>
<thead>
<tr>
<th>Gallium vacancies involved</th>
<th>Arsenic vacancies involved</th>
<th>Antisite defects</th>
<th>Interstitial defects involved</th>
<th>Three-component defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>V\textsubscript{Ga}</td>
<td>V\textsubscript{As}</td>
<td>Ga\textsubscript{As}</td>
<td>Ga\textsubscript{i}</td>
<td></td>
</tr>
<tr>
<td>V\textsubscript{Ga}V\textsubscript{Ga}</td>
<td>V\textsubscript{As}V\textsubscript{As}</td>
<td>As\textsubscript{Ga}</td>
<td>As\textsubscript{i}</td>
<td></td>
</tr>
<tr>
<td>V\textsubscript{Ga}V\textsubscript{As}</td>
<td>V\textsubscript{Ga}V\textsubscript{As}</td>
<td>Ga\textsubscript{As}V\textsubscript{Ga}</td>
<td>Ga\textsubscript{i}As\textsubscript{i}</td>
<td>Ga\textsubscript{i}V\textsubscript{Ga}</td>
</tr>
<tr>
<td>G\textsubscript{ai}V\textsubscript{Ga}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A\textsubscript{si}V\textsubscript{As}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G\textsubscript{As}V\textsubscript{Ga}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G\textsubscript{As}V\textsubscript{As}</td>
<td>G\textsubscript{As}V\textsubscript{As}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A\textsubscript{si}G\textsubscript{a}V\textsubscript{Ga}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A\textsubscript{si}G\textsubscript{a}V\textsubscript{As}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G\textsubscript{ai}V\textsubscript{As}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A\textsubscript{si}G\textsubscript{a}V\textsubscript{Ga}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a} Subscript indicates lattice sites and i stands for interstitial
\textsuperscript{b} Many others are possible besides the three listed as example
TABLE 3-2  
SOME HYPOTHETICAL COMPLEXES OF NATIVE DEFECTS AND ELEMENTAL IMPURITIES FOR GALLIUM ARSENIDE$^a$ [after 49]

<table>
<thead>
<tr>
<th>Group II impurities$^b$</th>
<th>Group IV impurities$^c$</th>
<th>Group VI impurities$^d$</th>
<th>Transition impurities$^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGa</td>
<td>MGa</td>
<td>DGa</td>
<td>TGa</td>
</tr>
<tr>
<td>AAs</td>
<td>MAs</td>
<td>DAs</td>
<td>TAS</td>
</tr>
<tr>
<td>AGaVAs</td>
<td>MGaVAs</td>
<td>DGaVAs</td>
<td>TGaVAs</td>
</tr>
<tr>
<td>AGaVGa</td>
<td>MGaVGa</td>
<td>DGaVGa</td>
<td>TGaVGa</td>
</tr>
<tr>
<td>AGaGaAs</td>
<td>MGaGaAs</td>
<td>DGaGaAs</td>
<td>TGaGaAs</td>
</tr>
<tr>
<td>AGaAsGa</td>
<td>MGaAsGa</td>
<td>DGaAsGa</td>
<td>TGaAsGa</td>
</tr>
<tr>
<td>AAsVAs</td>
<td>MAsVAs</td>
<td>DAsVAs</td>
<td>TASVAs</td>
</tr>
<tr>
<td>AAsVGa</td>
<td>MAsVGa</td>
<td>DAsVGa</td>
<td>TASVGa</td>
</tr>
<tr>
<td>AAsGaAs</td>
<td>MAsGaAs</td>
<td>DAsGaAs</td>
<td>TASGaAs</td>
</tr>
<tr>
<td>AAsAsGa</td>
<td>MAsAsGa</td>
<td>DAsAsGa</td>
<td>TASAsGa</td>
</tr>
</tbody>
</table>

$^a$ No defects involving interstitials have been listed or defects involving three components.

$^b$ A = Be, Mg, Zn, Cd.

$^c$ M = C, Si, Ge, Sn.

$^d$ D = O, S, Se, Te.

$^e$ T = Ti, V, Cr, Mn, Fe, Co, Ni, Cu

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### TABLE 3-3

**ELECTRON TRAPS IN GALLIUM ARSENIDE [after 50]**

<table>
<thead>
<tr>
<th>Label</th>
<th>Activation energy (eV)</th>
<th>Emission section $x 10^{-15}$ cm$^2$</th>
<th>Type of sample*</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET1</td>
<td>0.85</td>
<td>650</td>
<td>BM</td>
</tr>
<tr>
<td>ET2</td>
<td>0.3</td>
<td>2.5</td>
<td>BM</td>
</tr>
<tr>
<td>ES1</td>
<td>0.83</td>
<td>100</td>
<td>BM</td>
</tr>
<tr>
<td>EF1</td>
<td>0.72</td>
<td>7.7</td>
<td>Cr doped BM</td>
</tr>
<tr>
<td>EI1</td>
<td>0.43</td>
<td>0.73</td>
<td>VPEM</td>
</tr>
<tr>
<td>EI2</td>
<td>0.19</td>
<td>11</td>
<td>VPEM</td>
</tr>
<tr>
<td>EI3</td>
<td>0.18</td>
<td>22</td>
<td>VPEM</td>
</tr>
<tr>
<td>EB1</td>
<td>0.86</td>
<td>35</td>
<td>Cr doped LPEM</td>
</tr>
<tr>
<td>EB2</td>
<td>0.83</td>
<td>220</td>
<td>As grown MBEM</td>
</tr>
<tr>
<td>EB3</td>
<td>0.9</td>
<td>30000</td>
<td>EIM</td>
</tr>
<tr>
<td>EB4</td>
<td>0.71</td>
<td>830</td>
<td>EIM</td>
</tr>
<tr>
<td>EB5</td>
<td>0.48</td>
<td>260</td>
<td>As grown MBEM</td>
</tr>
<tr>
<td>EB6</td>
<td>0.41</td>
<td>260</td>
<td>EIM</td>
</tr>
<tr>
<td>EB7</td>
<td>0.3</td>
<td>17</td>
<td>As grown MBEM</td>
</tr>
<tr>
<td>EB8</td>
<td>0.19</td>
<td>15</td>
<td>As grown MBEM</td>
</tr>
<tr>
<td>EB9</td>
<td>0.18</td>
<td>Imprecise</td>
<td>EIM</td>
</tr>
<tr>
<td>EB10</td>
<td>0.12</td>
<td>Imprecise</td>
<td>EIM</td>
</tr>
<tr>
<td>EL1</td>
<td>0.78</td>
<td>10</td>
<td>Cr doped BM</td>
</tr>
<tr>
<td>EL2</td>
<td>0.825</td>
<td>80-170</td>
<td>VPEM</td>
</tr>
<tr>
<td>EL3</td>
<td>0.575</td>
<td>80-170</td>
<td>VPEM</td>
</tr>
<tr>
<td>EL4</td>
<td>0.51</td>
<td>1000</td>
<td>VPEM</td>
</tr>
<tr>
<td>EL5</td>
<td>0.42</td>
<td>50-200</td>
<td>VPEM</td>
</tr>
<tr>
<td>EL6</td>
<td>0.35</td>
<td>1.5</td>
<td>BM</td>
</tr>
<tr>
<td>EL7</td>
<td>0.3</td>
<td>7.2</td>
<td>As grown MBEM</td>
</tr>
<tr>
<td>EL8</td>
<td>0.275</td>
<td>7.7</td>
<td>VPEM</td>
</tr>
<tr>
<td>EL9</td>
<td>0.225</td>
<td>6.8</td>
<td>VPEM</td>
</tr>
<tr>
<td>EL10</td>
<td>0.17</td>
<td>1.8</td>
<td>As grown MBEM</td>
</tr>
<tr>
<td>EL11</td>
<td>0.17</td>
<td>0.3</td>
<td>VPEM</td>
</tr>
<tr>
<td>EL12</td>
<td>0.78</td>
<td>4900</td>
<td>VPEM</td>
</tr>
<tr>
<td>EL14</td>
<td>0.215</td>
<td>0.52</td>
<td>BM</td>
</tr>
<tr>
<td>EL15</td>
<td>0.15</td>
<td>570</td>
<td>EIM</td>
</tr>
<tr>
<td>EL16</td>
<td>0.37</td>
<td>0.004</td>
<td>VPEM</td>
</tr>
</tbody>
</table>

* BM, bulk material; VPEM, VPE material; LPEM, LPE material; MBEM, MBE material; EIM, electron irradiated material.

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## TABLE 3-4

HOLE TRAPS IN GALLIUM ARSENIDE [after 51]

<table>
<thead>
<tr>
<th>Label</th>
<th>Activation energy (eV)</th>
<th>Emission section $x 10^{-15} \text{ cm}^2$</th>
<th>Type of sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT1</td>
<td>0.44</td>
<td>12</td>
<td>VPE</td>
</tr>
<tr>
<td>HS1</td>
<td>0.58</td>
<td>0.0002</td>
<td>LPE</td>
</tr>
<tr>
<td>HS2</td>
<td>0.64</td>
<td>0.41</td>
<td>LPE</td>
</tr>
<tr>
<td>HS3</td>
<td>0.64</td>
<td>0.048</td>
<td>LPE</td>
</tr>
<tr>
<td>HB1</td>
<td>0.78</td>
<td>0.52</td>
<td>Cr doped LPE</td>
</tr>
<tr>
<td>HB2</td>
<td>0.71</td>
<td>12</td>
<td>As grown LPE</td>
</tr>
<tr>
<td>HB3</td>
<td>0.52</td>
<td>0.34</td>
<td>Fe doped LPE</td>
</tr>
<tr>
<td>HB4</td>
<td>0.44</td>
<td>34</td>
<td>Cu doped LPE</td>
</tr>
<tr>
<td>HB5</td>
<td>0.4</td>
<td>220</td>
<td>As grown LPE</td>
</tr>
<tr>
<td>HB6</td>
<td>0.29</td>
<td>20</td>
<td>Electron irradiated LPE</td>
</tr>
<tr>
<td>HL1</td>
<td>0.94</td>
<td>37</td>
<td>Cr doped VPE</td>
</tr>
<tr>
<td>HL2</td>
<td>0.73</td>
<td>19</td>
<td>As grown LPE</td>
</tr>
<tr>
<td>HL3</td>
<td>0.59</td>
<td>3</td>
<td>Fe diffused VPE</td>
</tr>
<tr>
<td>HL4</td>
<td>0.42</td>
<td>3</td>
<td>Cu diffused VPE</td>
</tr>
<tr>
<td>HL5</td>
<td>0.41</td>
<td>90</td>
<td>As grown LPE</td>
</tr>
<tr>
<td>HL6</td>
<td>0.32</td>
<td>56</td>
<td>VPE with $p^+$ layer</td>
</tr>
<tr>
<td>HL7</td>
<td>0.35</td>
<td>6.4</td>
<td>As grown MBE</td>
</tr>
<tr>
<td>HL8</td>
<td>0.52</td>
<td>0.35</td>
<td>As grown MBE</td>
</tr>
<tr>
<td>HL9</td>
<td>0.69</td>
<td>110</td>
<td>As grown VPE</td>
</tr>
<tr>
<td>HL10</td>
<td>0.83</td>
<td>170</td>
<td>As grown VPE</td>
</tr>
<tr>
<td>HL11</td>
<td>0.35</td>
<td>1.4</td>
<td>Melt grown</td>
</tr>
<tr>
<td>HL12</td>
<td>0.27</td>
<td>13</td>
<td>Zn contaminated LPE</td>
</tr>
</tbody>
</table>

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3-2-3 Deep Level Transient Spectroscopy

DLTS is performed by measuring the junction capacitance of a p-n or a Schottky junction while varying the temperature of the junction. The junction is normally reverse biased and then momentarily zero biased (zero injection pulse) or forward biased (forward injection pulse) to introduce free carriers in the depletion region. Since the carrier densities in the depletion region are very small, the free carrier capture rate at deep traps is negligible compared with the free carrier emission rate. Hence, the process is dominated by free carrier emission and the traps are empty when the junction is reverse biased.

When the junction is zero or forward biased momentarily, the depletion width shrinks and free carriers from the bulk region will be introduced into the region. The free carriers introduced by the zero or forward injection pulse will be captured at the deep traps. Thus the traps are filled and the process is dominated by free carrier capture. The carrier capture and emission at traps cause a change in the capacitance of the junction. The capacitance change is recorded while the temperature of the junction is varied from low temperature to high temperature. This provides a spectrum of the deep levels which one can use to obtain information about the activation energy, density and capture cross section of the deep levels.

For simplicity, assume for the moment that there is only one deep trap. The capture and emission processes of carriers
at the trap has been plotted in Fig. 3-4. A rate equation for the density of electron occupation $n_T$ can be written as [13]

$$\frac{d n_T}{dt} = (c_n n + e_p) N_T - (c_n n + c_p p + e_n + e_p) n_T$$

(3-17)

where $N_T = n_T + p_T$, $c_n = c_{n^0} + c_{n^t}$, $c_p = c_{p^0} + c_{p^t}$, $e_n = e_{n^0} + e_{n^t}$ and $e_p = e_{p^0} + e_{p^t}$. If we assume that the free carrier density, $n$ and $p$, are constant (which is valid within a certain time interval and $n, p \gg n_T$), the equation 3-17 is linear and has a closed form solution given by

$$n_T(t) = (n_{T0} - \frac{\beta}{\alpha} N_T) \exp(-\alpha t) + \frac{\beta}{\alpha} N_T$$

(3-18)

Where $n_{T0}$ is initial electron density at the trap,

$$\alpha = c_n n + c_p p + e_n + e_p,$$

(3-19)

and $\beta = c_n n + e_p$.

(3-20)

The steady state value for $n_T$ is obtained by substituting $t = \infty$ into equation 3-18.

$$n_T(t = \infty) = (\beta/\alpha) N_T$$

(3-21)

If we consider a reverse biased junction, the capture rates in the depletion region are neglected. Hence the coefficient $\alpha$ and $\beta$ are simplified as

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Fig. 3-4  Emission and capture processes at a deep energy level $E_T$.
(a) : for thermal processes.
(b) : for optical processes.
\[ \alpha = e_n + e_p \quad (3-22) \]
\[ \beta = e_p \quad (3-23) \]

Hence the steady state \( n_T \) for a reverse biased junction is simply

\[ n_T = \frac{e_p}{e_n + e_p} \quad N_T \quad (3-24) \]

The change of trap occupancy is observed through the junction capacitance transient. The junction capacitance for an abrupt junction is given by [44]

\[ C = A \left( \frac{e \varepsilon N_I}{2 (V_D + V_R)} \right)^{1/2} \quad (3-25) \]

For a \( p^+n \) junction, the ionized impurity density \( N_I \) is written as

\[ N_I = N_D + (N_T - n_T) \quad \text{for donor type traps} \quad (3-26) \]
\[ N_I = N_D - n_T \quad \text{for acceptor type traps} \quad (3-27) \]

Here it has been assumed that all the shallow donors are ionized, i.e., \( N_D^+ = N_D \). When a trap is of the donor type, the junction capacitance is obtained by substituting equation 3-26 into 3-25.
The above equation indicates that the capacitance is a function of \(n_T(t)\) and \(V_R(t)\).

We first consider the capacitance transient during a filling pulse \((t_1 < t < t_2)\). Since the capture rates during the filling pulse are much greater than the emission rate, coefficients \(\alpha\) and \(\beta\) can be simplified to

\[
\alpha = c_n n + c_p p \\
\beta = c_n n. \tag{3-29}
\]

Here, the hole capture rate \(c_p p\) is neglected because the zero injection pulse can not introduce minority carriers into the depletion region. The \(n_T(t)\) for the zero injection pulse is written as

\[
n_T(t) = \left( \frac{e_p}{e_n + e_p} - 1 \right) N_T \exp(-c_n n t) + N_T \tag{3-31}
\]

For electron traps, equation 3-31 is further simplified since \(e_n \gg e_p\).

\[
n_T(t) = \left[ 1 - \exp(-c_n n t) \right] N_T \tag{3-32}
\]
The above equation clearly indicates that \( n_T(t) \) is an exponential function with time constant \( \tau = 1/(c_n n) \).

By inserting equation 3-32 into equation 3-28, the capacitance transient during the injection pulse is obtained.

\[
C(t) = A \left\{ \frac{e \varepsilon [N_D + N_T \exp(-c_n n t)]}{2 V_D} \right\}^{1/2}
\]

(3-33)

Here it is assumed that the injection pulse is a square pulse defined as follows (See Fig. 3-5)

\[
\begin{align*}
V_R(t_1) &= V_{R0} \\
V_R(t_2) &= V_{R0} \\
V_R(t_1 < t < t_2) &= 0
\end{align*}
\]

(3-34) (3-35) (3-36)

After the injection pulse the reverse bias is restored and the electrons captured during the injection pulse are emitted from the traps to the conduction band. The trapped electron density for this phase is emission dominated mode and expressed as

\[
n_T(t) = \left( n_{T0} - \frac{e_p}{e_n + e_p} N_T \right) \exp(-\alpha t) + \frac{e_p}{e_n + e_p} N_T .
\]

(3-37)
Here the initial density $n_{T0}$ depends on the pulse width of the injection pulse. Hence the injection pulse width is an important parameter in DLTS measurements. If the trap is an electron trap and initially the trap is fully filled, then equation 3-37 is further simplified to become

$$n_T(t) \propto N_T \exp(-e_n t)$$  \hspace{1cm} (3-38)

The capacitance transient for this case is

$$C(t) = A \left\{ \frac{e \varepsilon \left(N_D + N_T \left[1 - \exp(-e_n t)\right]\right)}{2 \left(V_D + V_{RO}\right)} \right\}^{1/2}$$  \hspace{1cm} (3-39)

The capacitance transients based on equations 3-33 and 3-39 are plotted in Fig. 3-5. The total capacitance transient in Fig. 3-5(d) is decomposed into two parts as shown in Fig. 3-5(b) and (c) to distinguish the role of $n_T(t)$ from that of $V_R(t)$. It is indicated in the figure that the capacitance change caused by the change in bias $V_R(t)$ is much greater than that caused by the change in $n_T(t)$. This is true in general and hence all capacitance transient measurements are made during the time between the two injection pulses ($t_2 < t < t_5$). The capacitance change between the time $t_3$ and $t_4$ is...
Fig. 3-5 Temporal variation of
(a) bias on the junction,
(b) capacitance due to $n_T(t)$,
(c) capacitance due to $V_R(t)$, and
(d) total capacitance.
\[ \Delta C = C \left[ n_T(t_3) - n_T(t_4) \right] \]
\[
= A \left[ \frac{e \varepsilon}{2(V_D + V_{R0})} \frac{N_D}{N_D} \right] \left[ 1 + \frac{N_T - n_T(t_3)}{N_D} \right]^{1/2} \]
\[
- \left[ 1 + \frac{N_T - n_T(t_3)}{N_D} \right] \right] . \quad (3-40)
\]

For \( N_D \gg N_T \), the above equation is simplified as
\[
\Delta C = \frac{A}{2} \left[ \frac{e \varepsilon}{2(V_D + V_{R0})} \right] \left[ n_T(t_4) - n_T(t_3) \right] . \quad (3-41)
\]

It is apparent from the above equation that the change in capacitance is directly proportional to the change in electron occupation of a trap. Let \( \Delta C_0 \) be the magnitude of the capacitance change during the transition from a fully filled state to a fully empty state. Then \( \Delta C_0 \) is given by
\[
\Delta C_0 = A \left[ \frac{e \varepsilon}{2(V_D + V_{R0})} \right] \left[ n_T(t_4) - n_T(t_3) \right] . \quad (3-42)
\]

Let \( C_0 \) be the steady state capacitance associated with a reverse bias voltage \( V_{R0} \). By substituting \( t = \infty \) into equation 3-39, \( C_0 \) is obtained. That is,
\[
C_0 = A \left[ \frac{e \varepsilon}{2(V_D + V_{R0})} \right] \left( N_D + N_T \right) . \quad (3-43)
\]
The trap density for \( N_D \gg N_T \) is obtained by normalizing \( \Delta C_0 \) with \( C_0 \). The desired expression is

\[
N_T = 2 N_D \frac{\Delta C_0}{C_0}. \tag{3-44}
\]

The DLTS signal, \( S(T) \), defined by Lang is [15]

\[
S(T) = \frac{C(t_3) - C(t_4)}{C_0}. \tag{3-45}
\]

The DLTS signal \( S(T) \) for electron traps are obtained by inserting equation 3-38 into 3-41 and normalizing by equation 3-43.

\[
S(T) = \left[ \exp(-e_n t_4) \right] - \left[ \exp(-e_n t_3) \right] \tag{3-46}
\]

The \( e_{\text{max}} \) is obtained by differentiating \( S(T) \) with respect to \( e_n \) and setting the result equal to zero.

\[
e_{\text{max}} = \frac{\ln(t_3/t_4)}{(t_3 - t_4)} \tag{3-47}
\]

Therefore, the peak of the DLTS spectrum for a given gate window \( (t_3 \text{ and } t_4) \) is a well defined quantity. The electron emission rate \( e_n \) is temperature dependent and is obtained through the use of the principle of detailed balance [13].

\[
e_n = \sigma_n \langle v \rangle N_c / g \exp(-\Delta E_T / kT) \tag{3-48}
\]
\[ e_n = k_C \sigma_n T^2 \exp(-\Delta E_T/kT) \quad (3-49) \]

where \[ k_C = \frac{54.6 m_e^* k^2}{g \ h^2} \quad (3-50) \]

It is clear from equations 3-46 and 3-49 that the DLTS signal \( S(T) \) is a function of temperature.

In this research, a MDC deep level spectrometer system [52] as shown in Fig. 3-6 used to measure the DLTS signal. The system is a turnkey instrument designed for the deep level measurement and profiling of deep level impurities in a p-n junction or Schottky junction. The system consists of an oscilloscope, a capacitance compensator, a variable temperature cryostat and a DLS-81 unit. The variable temperature cryostat includes a sample holder for a TO-18 header, a dc power supply to heat the sample, and a thermocouple to measure the temperature of the sample. The DLS-81 unit consists of a RF bridge capacitance meter, a lock-in amplifier and two pulse generators.

A 12 bit A/D converter AD500 [53] was used to digitize the DLTS signal \( S(T) \) from the DLS-81 unit and the temperature signal from the thermocouple. The A/D converter can handle up to 8 input channels and contains programmable gain amplifiers in front end of the device. The A/D converter is installed directly into the expansion slots inside of the IBM PC-XT. A program has been written to control the A/D converter and to manipulate the digitized signals. Using the program, one can control the A/D converter and display the

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Fig. 3-6  A block diagram of the DLTS measurement system.
DLTS spectrum on a monitor. The program was written in IBM Advanced Basic and is listed in Appendix 3.

A general purpose signal analyzer which is similar to the one reported by Jansson [54] has been built to analyze the capacitance transient signal as shown in Fig. 3-7. The signal analyzer can be used in any DLTS system including an optical DLTS system. In principle, the analyzer can produce a DLTS signal $S(T)$ from a capacitance transient signal. The sample-and-hold circuits SH1, SH2 and SH3 are used to sample a signal at given times. For example, let's consider that the capacitance transient signal in Fig 3-6(d) is applied to input of the analyzer. The sampling time $t_3$, $t_4$ and $t_5$ are generated from the demultiplexer and applied to the sample-and-hold circuits SH2, SH3 and SH1 respectively. The output of SH1 is $C_0$ and is applied to the differential amplifier D1. Hence the dc component of the capacitance signal is eliminated in the output of D1. The output of D1 is applied to both SH2 and SH3. SH2 and SH3 hold capacitance values at $t_3$ and $t_4$ respectively. Therefore, the output of the differential amplifier is $C(t_3) - C(t_4)$, which is the DLTS signal $S(T)$. The rate window ($t_3$ and $t_4$) can be easily changed by varying the division ratio in the $1/N$ circuit. The outputs from the delay generator, control 1 and control 2, are designed to control a capacitance meter and a pulse bias circuit.

The capacitance transient signal has been analyzed by the signal analyzer and also by the lock-in amplifier built into the DLS-81 system. The difference between the DLTS
Fig. 3-7 A block diagram of a signal analyzer. SH1, SH2, and SH3 are sample holders. D1 and D2 are differential amplifiers.
signal from the analyzer and that from the lock-in amplifier is the expression for $e_{\text{max}}$. The $e_{\text{max}}$ for the signal analyzer is the same as the expression in the equation in 3-39, but the $e_{\text{max}}$ for the lock-in amplifier used in the DLS-81 unit is a function of the repetition frequency $f$ as [52]

$$e_{\text{max}} = 2.26 \times f \quad . \quad (3-51)$$

The results from the signal analyzer and the lock-in amplifier have been compared and the results agree well.

One difficult task is to make a good sample for the DLTS measurement. First, a schottky junction was used in the DLTS measurement. The contacts are made from the vacuum evaporation of Al on a n-type GaAs wafer as described in Chapter 2. The wafer is broken into small pieces which are rectangular in shape and around 1 mm x 1 mm in size. The small pieces are called dies and mounted to the TO-18 headers. Silver epoxy is used to attach the dies to the headers, which is cured in an oven at 150 °C for around 10 minutes. After the curing, each sample is tested with a curve tracer to see the I-V characteristics of the diode. If the I-V curve indicates a good Schottky contact as shown in Fig. 2-13, the samples are ready for the DLTS measurement.

A typical DLTS spectrum measured with an n-type GaAs sample [31] is shown in Fig. 3-8. A reverse bias of 3 V and 20 μs zero injection pulse was applied to the junction. The DLTS scan started from a low temperature near 160 K and
Fig. 3-8 A typical experimental DLTS spectrum measured on a n-type GaAs sample.
stopped at around 430 K. As shown in the figure, each peak represents a particular trap and the height of the peak is directly proportional to the density of a trap $N_T$. Here positive peaks indicate majority carrier traps, which are electron traps in n-type GaAs. The activation energy of each trap is determined from the shift of the DLTS peak with temperature measured at different rate windows with the signal analyzer (or different repetition frequencies with the lock-in amplifier). Each DLTS peak constructs one point in an Arrhenius plot [$\ln(e_n/T^2)$ versus $1000/T$]. In order to get accurate results, the measurement needs to be performed over a wide range of rate windows. The DLTS spectra with temperature at four different rate windows are shown in Fig. 3-9 and the Arrhenius plot obtained from the DLTS peaks in Fig. 3-9 are shown in Fig. 3-10. The activation energies calculated from the slopes of the Arrhenius plots are $0.81 \pm 0.02$ eV and $0.41 \pm 0.02$ eV from the conduction band. These two levels located at 0.81 eV and 0.41 eV from the conduction band are identified as an EL2 and an EL5 center respectively.

Since minority carriers (holes in n-type GaAs) are not available to introduce in the depletion region in a Schottky junction: therefore, DLTS measurement with Schottky junction can not measure parameters associated with minority carrier traps. Therefore, a second series of DLTS measurements were performed on a $p^+n$ junction in GaAs to measure the parameters for both the majority and the minority carrier traps. In a
Fig. 3-9 Typical experimental DLTS spectra. Four different spectra are shown corresponding to the four rate windows.
Fig. 3-10 Arrhenius plots for the DLTS spectra in Fig. 3-9.
p+n junction, a zero injection pulse is applied to measure the parameters for majority carriers and a forward injection pulse is applied to measure the parameters for both majority and minority carriers. The p+n GaAs junction was formed on a n-type GaAs wafer by a Zn diffusion [55]. For this p+n diode sample, ohmic contacts were made on both sides of the wafer by depositing AuGe. Otherwise, the same procedure was followed to make the DLTS measurement as in the Schottky diode described above.

Firstly, a zero injection pulse (0 V, 50 μs) with 5 V reverse bias was applied to the junction to investigate the majority carrier traps. Several DLTS scans were performed from a low temperature near 100 K to a high temperature of approximately 430 K. The time required for the DLTS scan was about one hour. A typical DLTS spectrum measured on the sample is shown in Fig. 3-11. The figure shows that there exists three main electron traps labeled as PK1, PK2 and PK3. The activation energies of the deep levels calculated from the slopes of the Arrehnius plots in Fig. 3-12 are $0.5 \pm 0.02$ eV, $0.68 \pm 0.02$ eV, and $0.83 \pm 0.02$ eV for PK1, PK2 and PK3 respectively. The level marked as PK3 has been identified as an EL2 center. The two levels marked as PK1 and PK2 are believed to be deep levels related to Cr or Ni [13].

Secondly, several DLTS scans were again performed on the p+n diode with a forward injection pulse (1.5 V, 20 μs). As shown in Fig. 3-13, there exists one positive peak marked as PK3 and one negative peak marked as PK4. The peak PK3 is
Fig. 3-11  A DLTS spectrum measured on the $p^+n$ GaAs diode (zero injection pulse).
Fig. 3-12 Arrhenius plots for electron traps in a p+n GaAs diode.
Fig. 3-13  A DLTS spectrum measured on the $p^+n$ GaAs diode (forward injection pulse).
identical to the peak PK3 in Fig. 3-11 and hence the analysis for PK3 is omitted here. The peaks PK1 and PK2 can not be seen in Fig. 3-11 because they are buried on the large peak PK4. The positive peak indicates a majority carrier trap (an electron trap in this case) and the negative peak indicates a minority carrier trap (a hole trap).

An Arrhenius plot for peak PK4 is shown in Fig. 3-14. The activation energy for the level is $0.44 \pm 0.02$ eV from the valence band. This level is identified as a Cu$_B$ level [56-58] and Cu related complexes are regarded as the origin of the level [58]. The trap densities for the deep levels are obtained by using equation 3-36. The values of the DLTS peak denoted as PK3 (EL2) is about 0.04 (from Fig. 3-11) which corresponds to a trap density of $4 \times 10^{15}$ cm$^{-3}$. Here, a shallow donor density $N_D$ of $5 \times 10^{15}$ cm$^{-3}$ was used. Similarly, the trap densities for PK1, PK2 and PK4 (Cu$_B$) calculated from equation 3-36 are about $2 \times 10^{14}$ cm$^{-3}$, $1.5 \times 10^{14}$ cm$^{-3}$ and $7.5 \times 10^{15}$ cm$^{-3}$ respectively. When these results are compared with the results measured with the Schottky contact, the EL5 level observed in the Schottky diode has totally disappeared in p$^+$n GaAs diode [55]. The trap density for the EL2 level has changed from around $7 \times 10^{15}$ cm$^{-3}$ to $4 \times 10^{15}$ cm$^{-3}$ and two new traps (PK1 and PK2) with densities of around $10^{14}$ cm$^{-3}$ have appeared in the p$^+$n diode. The change in trap densities between the Schottky and p$^+$n diode is believed to be due to the annealing during Zn diffusion [55].
Fig. 3-14 An Arrhenius plot for a hole trap in a p⁺n GaAs diode.
CHAPTER 4
MODELING

This chapter is devoted to the modeling of a photoconductive device for a closing and opening switch application. Section 4-1 describes the kinetics of the photoconductivity process in a semiconductor material to provide a theoretical bases for the model used in simulation work presented in later sections. Section 4-2 describes several switch systems used in a switch simulation to find the best candidate for the BOSS. Section 4-3 describes the numerical method employed to simulate the systems and presents the results from the numerical computations.

4-1 Kinetics of Photoconductivity

The transition of carriers from a bound state to a free state can be obtained by thermal or optical excitation. Once the carriers are excited to the free state, they will remain free and contribute to the conductivity of the material until they are captured or recombine. The static and dynamic behavior of free carriers in a photoconductive material can be described by the continuity equations for electrons and holes, rate equations for trapping kinetics, drift/diffusion current equations, and Poisson's equation: [28, 59]
\[
\frac{\partial n}{\partial t} = G_n - U_n + \frac{1}{q} \nabla \cdot \mathbf{j}_n \quad (4-1)
\]
\[
\frac{\partial p}{\partial t} = G_p - U_p - \frac{1}{q} \nabla \cdot \mathbf{j}_p \quad (4-2)
\]
\[
\frac{\partial n_i}{\partial t} = (c_{ni} n + e_p) N_{Ti} - (c_{ni} n + c_{pi} p + e_n + e_p) n_{Ti} \quad (4-3)
\]
\[
\mathbf{j}_n = q \mu_n \mathbf{E} - q D_n \nabla n \quad (4-4)
\]
\[
\mathbf{j}_p = q \mu_p \mathbf{E} - q D_p \nabla p \quad (4-5)
\]
\[
\nabla \cdot \mathbf{E} = \frac{q}{\varepsilon} \left( p - n + N_i^+ - N_i^- \right). \quad (4-6)
\]

Here the subscript \( i \) has been used to denote the \( i \)th trap. Equation 4-3 is particularly important when the change in the electron occupancy of the deep traps is significant. The generation rate, \( G_n \) in equation 4-1 includes an intrinsic ionization process (electron and hole pair generation) [60], two photon ionization [61, 62] and electron emission from all the traps:

\[
G_n = \alpha_I + \frac{\beta \hbar \nu \Phi^2}{2} + \sum e_{ni} n_{Ti} \quad (4-7)
\]
The recombination rate, $U_n$, consists of direct band to band recombination [63], Auger recombination [64, 65] and electron capture at all the traps:

$$U_n = K_d \ n_p + \Sigma c_{n_i} \ n \ (N_{T_i} - n_{T_i}) + K_a \ n^2 \ p \ . \quad (4-8)$$

Similarly the generation rate, $G_p$, and recombination rate, $U_p$, for holes will be:

$$G_p = \alpha_i + \frac{\beta \ h \ \gamma \ \phi^2}{2} + \Sigma e_{p_i} (N_{T_i} - n_{T_i}) \quad (4-9)$$

$$U_p = K_d \ n_p + \Sigma c_{p_i} \ P \ n_{T_i} + K_a \ n^2 \ p \ . \quad (4-10)$$

The capture parameters are functions of the thermal velocity of free carriers: [57]

$$c_n = \sigma_n \ <v_n> \quad (4-11)$$

$$c_p = \sigma_p \ <v_p> \ . \quad (4-12)$$

where $\sigma_n$ and $\sigma_p$ are capture cross sections of electrons and holes respectively. The optical emission at the traps is related to the external photon flux : [60]

$$e_n^o = \sigma_n^o \quad (4-13)$$

$$e_p^o = \sigma_p^o \ . \quad (4-14)$$

where $\sigma_n^o$ and $\sigma_p^o$ are optical ionization cross sections for electrons and holes respectively.
The thermal capture and emission can be correlated by the principle of detailed balance at thermal equilibrium [13].

\[
e_n^t = (c_n^t N_C/g) \exp(-\Delta E_T/kT) \tag{4-15}
\]

\[
e_p^t = (c_p^t N_V/g) \exp(-\Delta E_T/kT) \tag{4-26}
\]

where \( \Delta E_T = E_C - E_T \) for electrons and \( \Delta E_T = E_T - E_V \) for holes. The equations (4-1) through (4-6) describe the system adequately but they are nonlinearly coupled and are difficult to solve. However, they can be reduced into a manageable form by assuming spatial uniformity and charge neutrality. With these assumptions, Poisson's equation (6) and the current-density divergence terms in (1) and (2) can be eliminated. The remaining equations are simple rate equations which can be solved readily. The above assumptions are appropriate for the majority of the bulk region except that portion near the electrodes where the electric field can change drastically [28].

4-2 Switch Materials Considered in the Switch Simulation

The material used in our study is GaAs doped with Si and counter doped with Cu. The Cu introduces two deep acceptors in the GaAs material, Cu_A and Cu_B [56]. The counter doping by the deep acceptor (Cu) compensate the shallow donor (Si) and hence a high resistivity is obtained in the switch material. The thermally ionized electrons from the shallow donor level (Si) are trapped in the deep acceptors (Cu_A and
Cub). The electron occupancies of the deep acceptors depend on the density of the shallow donor.

Four different GaAs systems have been constructed and simulated to study the influence of the deep levels in the switch material. The first consideration is compensation. In system 1 the deep acceptor (Cu) is half compensated by the shallow donor (Si). In system 2 the deep acceptor is fully compensated. Therefore, half of the CuB level is occupied by electrons in system 1 and all of the CuB level is occupied by electrons in system 2.

The second consideration is to investigate the influence of recombination centers in the switch material. An effective recombination center which represents all the recombination centers in the material is included in systems 3 and 4. The effective recombination center is assumed to be located at the center of the band gap and has a density of $10^{16}$ cm$^{-3}$. Detailed information for all four systems are shown in Table 4-1. The native defects in the GaAs material, EL2 and EL5, are included in all the systems. The densities of the EL2 and EL5 levels used in the simulation are $10^{16}$ cm$^{-3}$ and $3 \times 10^{15}$ cm$^{-3}$ respectively. The energy level diagram of the GaAs material used in the switch simulation is shown in Fig. 4-1.

4-3 Numerical Computation

The simulation of the GaAs switch systems is based on the numerical integration of the differential equations in
### TABLE 4-1

DEEP LEVEL PARAMETERS ASSIGNED TO THE SYSTEMS

<table>
<thead>
<tr>
<th>parameters</th>
<th>system 1</th>
<th>system 2</th>
<th>system 3</th>
<th>system 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_T(\text{Si})$</td>
<td>$5 \times 10^{16}$</td>
<td>$1 \times 10^{17}$</td>
<td>$5 \times 10^{16}$</td>
<td>$1 \times 10^{17}$</td>
</tr>
<tr>
<td>$N_T(\text{Cu}_A)^b$</td>
<td>$2 \times 10^{16}$</td>
<td>$2 \times 10^{16}$</td>
<td>$2 \times 10^{16}$</td>
<td>$2 \times 10^{16}$</td>
</tr>
<tr>
<td>$N_T(\text{Cu}_B)^b$</td>
<td>$1 \times 10^{17}$</td>
<td>$1 \times 10^{17}$</td>
<td>$1 \times 10^{17}$</td>
<td>$1 \times 10^{17}$</td>
</tr>
<tr>
<td>$N_T(\text{EL2})$</td>
<td>$1 \times 10^{16}$</td>
<td>$1 \times 10^{16}$</td>
<td>$1 \times 10^{16}$</td>
<td>$1 \times 10^{16}$</td>
</tr>
<tr>
<td>$N_T(\text{EL5})$</td>
<td>$3 \times 10^{15}$</td>
<td>$3 \times 10^{15}$</td>
<td>$3 \times 10^{15}$</td>
<td>$3 \times 10^{15}$</td>
</tr>
<tr>
<td>$N_T(\text{RC})^c$</td>
<td>0</td>
<td>0</td>
<td>$1 \times 10^{16}$</td>
<td>$1 \times 10^{16}$</td>
</tr>
</tbody>
</table>

a. The unit of the values is $[\text{cm}]^{-3}$.
b. The ratio between $\text{Cu}_A$ and $\text{Cu}_B$ was estimated from a paper by Lang and Logan [49].
c. RC indicates a recombination center.
Fig. 4-1  Energy level diagram of GaAs:Si:Cu at 300 K.
section 4-1. Several assumptions have been made in order to perform the simulation. They are as follows:

1) Each deep level state can have either one electron or one hole in it,

2) The transitions between deep levels can be neglected, and

3) Spatial uniformity and charge neutrality is maintained.

A program was developed for the simulation in which a fifth order Runge-Kutta technique with adaptive grid control [66] is used to solve the differential equation. The program is written in FORTRAN and is listed in Appendix 4. A block diagram for the numerical computation by the technique is shown in Fig. 4-2. As shown in the figure, the integration step size is not fixed but is controlled by the local error during the numerical integration of the differential equations. If a calculated local error is greater than an error limit specified by the user, the integration step size is reduced. Conversely, when the local error is much less than the error limit the step size is increased. Thus, the integration step size is automatically controlled by the local error.

The parameters used in the simulation are listed in Table 4-2. Two laser pulses at different wavelengths are used for the optical excitation source. One laser pulse with photon energy of 1.1 eV is used to increase the conductivity (turn-on the switch) and the second laser with photon energy
Fig. 4-2  Block diagram of the numerical simulation.
### TABLE 4-2

**TYPICAL VALUES USED IN THE COMPUTATION**

<table>
<thead>
<tr>
<th>parameters</th>
<th>value</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_n$ (CuB)</td>
<td>$8 \times 10^{-21}$ cm$^2$</td>
<td>[57]</td>
</tr>
<tr>
<td>$\sigma_p$ (CuB)</td>
<td>$3 \times 10^{-14}$ cm$^2$</td>
<td>[57]</td>
</tr>
<tr>
<td>$\sigma_n$ (CuB)</td>
<td>$10^{-17}$ cm$^2$</td>
<td>[56]</td>
</tr>
<tr>
<td>$\sigma_p$ (CuB)</td>
<td>$10^{-16}$ cm$^2$</td>
<td>[56]</td>
</tr>
<tr>
<td>$\sigma_n$ (EL2)</td>
<td>$4 \times 10^{-16}$ cm$^2$</td>
<td>[69]</td>
</tr>
<tr>
<td>$\sigma_p$ (EL2)</td>
<td>$2 \times 10^{-18}$ cm$^2$</td>
<td>[69]</td>
</tr>
<tr>
<td>$\sigma_n$ (EL2)</td>
<td>$8 \times 10^{-17}$ cm$^2$</td>
<td>[70, 71, 72]</td>
</tr>
<tr>
<td>$\sigma_p$ (EL2)</td>
<td>$3 \times 10^{-17}$ cm$^2$</td>
<td>[70, 71, 72]</td>
</tr>
<tr>
<td>$\sigma_n$ (EL5)</td>
<td>$5 \times 10^{-15}$ cm$^2$</td>
<td>[69]</td>
</tr>
<tr>
<td>$\sigma_p$ (EL5)</td>
<td>$2 \times 10^{-18}$ cm$^2$</td>
<td>[*]</td>
</tr>
<tr>
<td>$\sigma_n$ (EL5)</td>
<td>$10^{-17}$ cm$^2$</td>
<td>[*]</td>
</tr>
<tr>
<td>$\sigma_p$ (EL5)</td>
<td>$10^{-17}$ cm$^2$</td>
<td>[*]</td>
</tr>
<tr>
<td>$\sigma_n$ (CuA)</td>
<td>$8 \times 10^{-21}$ cm$^2$</td>
<td>[*]</td>
</tr>
<tr>
<td>$\sigma_p$ (CuA)</td>
<td>$3 \times 10^{-14}$ cm$^2$</td>
<td>[*]</td>
</tr>
<tr>
<td>$\sigma_n$ (CuA)</td>
<td>$10^{-17}$ cm$^2$</td>
<td>[*]</td>
</tr>
<tr>
<td>$\sigma_p$ (CuA)</td>
<td>$10^{-16}$ cm$^2$</td>
<td>[*]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>26 cm/GW</td>
<td>[61]</td>
</tr>
<tr>
<td>$K_a$</td>
<td>$10^{-33}$ cm$^{-6}$ s$^{-1}$</td>
<td>[64, 65]</td>
</tr>
<tr>
<td>$K_d$</td>
<td>$7 \times 10^{-10}$ cm$^3$ s$^{-1}$</td>
<td>[63]</td>
</tr>
</tbody>
</table>

* The values are not known and have been assumed as reasonable values. Since the density of EL5 and CuA is small, the effect of these levels on the switch performance is minor.
of 0.5 eV is used to decrease the conductivity (turn-off the switch). The temporal shape of the laser pulse is assumed to be Gaussian [65].

\[ \Phi(z, t) = \Phi_o \exp\left[-(t-t_o)^2/\sigma_v^2\right] \quad (4-21) \]

where \( \sigma_v \) is standard deviation of the Gaussian shape pulse. The conductivity of the photoconducting medium is calculated from the mobilities of the free carriers.

\[ \sigma = e(\mu_n n + \mu_p p) \quad (4-22) \]

The mobility of electrons and holes are calculated by piecewise linearization method [65] because the mobilities of the free carriers are a function of free carriers. The experimental mobility data with respect to the carrier density are taken from a paper by Vilms and Garrett [42].

The temporal variations of the conductivity with photon flux are shown in Fig. 4-3(a), (b), (c) and (d) for system 1, 2, 3 and 4 respectively. A 10 ns FWHM laser pulse was used to increase the conductivity of the switch and the peak of the pulse is located at 30 ns in the figure. The "On-state" is defined as the state occurring after the turn-on transient. Here, the response before 150 ns is assumed to be the turn-on transient, while that portion of the response after 150 ns is assumed to be the on state. The conductivity at 150 ns was used as the on-state value of conductivity. Saturation of

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the photoconductivity is observed in Fig. 4-3(a), (b), (c) and (d). As the photon flux is increased, the on-state conductivity initially increases, but then reaches a saturation value at a photon flux of about $3 \times 10^{25} \text{ cm}^{-2} \text{s}^{-1}$ (5.6 MW/cm$^2$ with 1.06 μm laser). Increasing the intensity beyond this value results in a faster rise time and a higher initial (peak) conductivity, but does not increase the on-state conductivity. The on-state saturates at around $3 \times 10^{25} \text{ cm}^{-2} \text{s}^{-1}$ (5.6 MW/cm$^2$ with 1.06 μm laser) for all four systems even though the peak values for the systems are continuously increasing according to the increase of the photon flux.

The turn on characteristic of system 1 is summarized in Fig. 4-4. Here, "peak w/ pulse" (PWP) means the peak conductivity value of the system when a 10 ns FWHM laser pulse is applied as an external photoexcitation source and "peak w/ CW" (PWC) refers to the peak conductivity value (i.e., the steady state value) of the system when a CW laser is applied as an external photoexcitation source. The saturation effect of the on-state value is clearly shown in this figure. The PWP photoconductivity approaches the PWC value when the photon flux is increased. The PWC, PWP and on-state values for the systems are compared in Fig. 4-5(a), (b) and (c) respectively. It is seen from Fig. 4-5(a) and (b) that PWC and PWP became independent of the system when the photon flux is greater than $5 \times 10^{26} \text{ cm}^{-2} \text{s}^{-1}$ (93 MW/cm$^2$ with 1.06 μm laser). This indicates that the two-photon ionization process is the dominant photoionization source when the photon flux is high.
Fig. 4-3(a) Computed temporal variation of the conductivity with incident photon flux as the parameter during turn on for system 1.
Fig. 4–3(b) Computed temporal variation of the conductivity with incident photon flux as the parameter during turn on for system 2.
Fig. 4-3(c)  Computed temporal variation of the conductivity with incident photon flux as the parameter during turn on for system 3.
Fig. 4-3(d) Computed temporal variation of the conductivity with incident photon flux as the parameter during turn on for system 4.
Fig 4-4 Comparison of PWC, PWP and on-state conductivity for system 1 as a function of photon flux.
Fig. 4-5(a) Variation of PWC conductivity as a function of photon flux.
Fig. 4-5(b) Variation of PWP conductivity as a function of photon flux.
Fig. 4-5(c) Variation of on-state conductivity as a function of photon flux.
because the two-photon ionization rate is proportional to the square of the photon flux.

However, the on-state values differ between systems even at high photon fluxes. This is due to the on-state saturation effect. Here, one should note that the systems with fully occupied CuB centers (system 2 and system 4) provide better on-state photoconductivity than the systems with the half occupied CuB centers (system 1 and system 3). Fig. 4-6 shows the rise time for the systems as a function of photon flux. The laser pulse used in the rise time measurement is a rectangular shape instead of a Gaussian shape. Here the rise time is defined as the time interval between 10% to 90% of the peak. It can be seen from the figure that a rise time of 10 ns can be achieved with a photon flux of $5 \times 10^{25} \text{cm}^{-2}\text{s}^{-1}$ (9.3 MW/cm$^2$ with 1.06 µm laser) and a rise time of a nano-second is obtained with a photon flux of $10^{27} \text{cm}^{-2}\text{s}^{-1}$ (187 MW/cm$^2$ with 1.06 µm laser).

Fig. 4-7 shows a typical turn-off transient of system 3 with photon flux as a parameter. The initial photoconductivity used in the simulation is the on-state value generated by a photon flux of $5 \times 10^{25} \text{cm}^{-2}\text{s}^{-1}$ (9.3 MW/cm$^2$ with 1.06 µm laser). A 0.5 eV, 10 ns FWHM laser pulse was used to turn-off the switch. The turn-off laser optically quenches the conductivity as shown in the figure. A photon flux of $10^{26} \text{cm}^{-2}\text{s}^{-1}$ (8 MW/cm$^2$ with 2.48 µm laser) is sufficient to quench the on-state conductivity in this system. Turn off transients for all four systems are summarized in
Fig. 4-6 Variation of rise time (during turn on) as a function of photon flux.
Fig. 4-7 Computed temporal variation of the conductivity for system 3 during turn-off phase (parameter is photon flux).
Fig. 4-8. It is demonstrated in the figure that a photon flux of $10^{26}$ cm$^{-2}$s$^{-1}$ (8 MW/cm$^2$ with 2.48 μm laser) will quench the on-state conductivity to about $10^{-4}$ (Ω cm)$^{-1}$ with system 3.

Temporal variations of carriers and bound electrons at the Cu$_B$ level are shown in Fig. 4-9(a), (b), (c) and (d) for system 1, 2, 3 and 4 respectively. Here, a photon flux of $3 \times 10^{25}$ cm$^{-2}$s$^{-1}$ (the photon flux at the on-state saturation point) is used to turn on (10 ns FWHM, peak located at 30 ns) the switch and a photon flux of $5 \times 10^{26}$ cm$^{-2}$s$^{-1}$ (10 ns FWHM, peak located at 170 ns) is used to turn off the switch. As shown in the figures [Fig. 4-9 (a), (b), (c) and (d)], the turn-on laser can excite electrons and holes but the turn-off laser pulse can excite only holes. The initial fast decay in systems 1 and 2 is mainly due to direct band-to-band carrier recombination but the decay in system 3 and system 4 is mainly due to the recombination through the recombination center. Since recombination through the recombination center is much faster than the direct band-to-band recombination, the decay during the turn-off phase are faster in system 3 and system 4 than in systems 1 and 2. It is seen in Fig. 9(c) that the electron occupations at the Cu$_B$ level at $t=0$ and $t=200$ ns are different even though the free carriers are depleted. That is because some carriers (electrons) were captured in the electron traps (EL2 and EL5).

The overall performance of each system is shown in Fig. 4-10. The turn-on and turn-off parameters are the same as those used in Fig. 4-9. The turn-on phase conductivity
Fig. 4-8 Variation of the turn-off conductivity (at 200 ns) as a function of photon flux.

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Fig. 4-9(a) Computed temporal variation of the free carriers and the bound carriers at the CuB level (system 1).
Fig. 4-9(b)  Computed temporal variation of the free carriers and the bound carriers at the CuB level (system 2).
Fig. 4-9(c) Computed temporal variation of the free carriers and the bound carriers at the Cu_B level (system 3).
Fig. 4-9(d) Computed temporal variation of the free carriers and the bound carriers at the Cu$_B$ level (system 4).

[Diagram showing the computed temporal variation of the free carriers and the bound carriers at the Cu$_B$ level (system 4).]
Fig. 4-10 Temporal variation of the conductivity.
of all four systems varies over six orders of magnitude \([10^{-5} \text{ (} \Omega \text{ cm})^{-1} \text{ to } 10^{1} \text{ (} \Omega \text{ cm})^{-1}]\). The on-state conductivities of the systems remain virtually constant over the short period of time (100 ns). The turn-off phase conductivity of system 3 varies over five orders of magnitude \([10^{1} \text{ (} \Omega \text{ cm})^{-1} \text{ to } 10^{-4} \text{ (} \Omega \text{ cm})^{-1}]\) but that of systems 1, 2 and 4 changes relatively little.
CHAPTER 5
SUMMARY AND CONCLUSIONS

5-1 Summary

In this work, the GaAs material as a possible candidate for bulk optically controlled semiconductor switches (BOSS) has been studied. The study includes the preparation of test samples, the characterization of the samples and the modeling of the switch systems. The samples for the characterization and switching experiments were prepared by vacuum evaporation to deposit metal, thermal diffusion to introduce impurities and thermal annealing to make a good ohmic contacts or to diffuse impurities into the sample. The AuGe alloy provided good ohmic contacts on the Si doped GaAs material and the Al formed a Schottky contact on the material. The deep acceptor impurity (Cu) which is required in the BOSS system was introduced in the GaAs material by thermal diffusion. The thermal diffusion of Cu was performed by annealing the sample in an oven at 600 °C for 2 hours. Very low conductivity [1.9 \times 10^{-4} (\Omega \text{cm})^{-1}] was obtained after the diffusion, which is in agreement with results reported by Blanc et al. [67].

Characterization of the samples was performed using the van der Pauw technique and the DLTS technique. The van der Pauw measurements provided parameters such as resistivity,
carrier density, and mobility of the samples. The DLTS measurement provided the deep level parameters of the samples. The two electron traps, EL2 and EL5 have been detected in the samples (the Schottky junction on the Si doped GaAs). The density of the EL2 trap was about \(7 \times 10^{15} \text{ cm}^{-3}\) and the location of the trap was 0.83 eV below the conduction band. The EL2 trap is believed a dominant native defect in GaAs material and a complex involving \(\text{As}_3\) is recognized as the origin of the trap [14]. The EL5 trap was not detected in the \(p^+n\) GaAs diode where the junction was formed by Zn diffusion. This indicates that the density of the EL5 level is decreased during the thermal annealing and the level is sensitive to the temperature. The similar phenomenon was also noticed by Martin [50]. A hole trap identified as the \(\text{Cu}_B\) level was detected in the material even though Cu had not been initially doped. The deep level parameters measured in the DLTS measurements are particularly important in the BOSS system where the deep levels are used for the intermediate energy storage levels. The parameters measured in the DLTS measurement were included in the modeling of the BOSS systems.

The modeling of the various GaAs systems described in Chapter 4 gives good insight into the potential for such a material to be used as a switch. The turn on transients in Fig. 4-3(a), (b), (c) and (d) clearly indicate that there exists two time constants. One time constant which is fast, is related to direct band-to-band recombination of free carriers and the recombination of such carriers through deep
centers. The other time constant which is very slow, is related to the capture of electrons at the CuB level. The turn-on transient simulation also indicate the existence of another important effect: the saturation of the on-state conductivity. The on-state value can not increase similar to the peak value because the on-state conductivity is related to the density of the CuB level. At a given density of CuB level, there exist a maximum value of electron contribution from the CuB level and hence there exists maximum on-state conductivity. The saturation occurs at a photon flux of about $3 \times 10^{25} \text{ cm}^{-2} \text{ s}^{-1}$. This implies that a photon flux greater than $3 \times 10^{25} \text{ cm}^{-2} \text{ s}^{-1}$ will provide a faster rise time and higher peak conductivity but will not give a higher on-state conductivity. It is also shown in the turn-on transient simulation that the PWC, PWP and rise time are independent of the system configuration when the photon flux is greater than $5 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$. This indicates that two-photon ionization becomes important when the photon flux is greater than $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$.

The initial electron occupation at the CuB level is a very important parameter in the switch performance. The greater the electron occupation at the CuB level the better the on-state conductivity. However, this leads to degradation in the off-state conductivity. The best turn on conductivity was obtained with system 2 when the CuB level was fully occupied by electrons. On the other hand, the best turn-off was obtained with system 3 when half of the CuB level
is occupied by electrons and an effective recombination center is considered. It is seen from the turn-off transient simulation that a fast turn off of the switch requires a recombination center and also a partially filled Cu_B level.

The native defects (EL2 and EL5) affect the on-state conductivity by capturing free carriers (electrons) during the on-state. The trapped electrons affect the switch performance by altering the charge distribution in the Cu_B level. This effect can be seen in Fig. 4-9(c) where the electron occupation at the Cu_B level is different in the final state (after the turn-off pulse) and in the initial state (before the turn-on pulse). Hence, the density of CuB level needs to be much greater than density of deep electron traps for better on-state conductivity by reducing electron capture at the deep electron traps.

The role of the recombination center in the photoconducting material is clearly demonstrated by the computed results. The recombination center controls the free carrier decay rate even though it does not affect the turn-on transient much. The concentration of shallow donors (Si) controls both the turn-on phase transient and the turn-off phase transient. The closer the shallow donors compensate the deep acceptors (Cu) the better the on-state conductivity and the higher the dark resistivity. However, closer compensation makes the system more difficult to turn off.
5-2 Conclusions

The Cu compensation of the Si doped GaAs material by thermal diffusion gives a high resistivity material suitable for high power switching. DLTS measurements provided useful parameters for the deep traps in the GaAs material. Native defects EL2 and EL5 were detected in the material and a Cu related defect, CuB, was also detected in the material. However, the CuA was not measured because the level is too shallow to be measured in our DLS-81 system. A computer modeling of the GaAs:Si:Cu system provided useful information concerning potential switching applications, such as rise time, on-state conductivity and turn-off characteristics of the switch. In addition, the modeling provided other important parameters, such as the temporal variation of the electron occupation at the deep levels, which would be difficult to measure.

5-3 Suggestions for Further Work

The DLTS measurement could be done at lower temperature up to liquid helium temperature (2 K). This will provide deep level parameters of activation energy less than 0.2 eV. A fast DLTS system with a 100 ps injection pulse may be considered in future DLTS measurement to measure deep trap parameters with large capture cross sections. A photo-induced transient spectroscopy (PITS) [68] could be carried to measure deep level parameters in semi-insulating materials.
Several factors can be included in future modeling. One of these factors is the spatial variation of a photon flux and that of carrier densities. Velocity saturation and negative differential mobility needed to be considered for high electric field. The electrical contact characteristics may also needed to be considered in the modeling because the contacts are not ideal ohmic contacts in general.
LIST OF REFERENCES


[31] GaAs crystal purchased from Morgan Semiconductor, 2623 National Circle, Galand Texas 75047-2376 Specification:

- Crystallinity: single
- Type: N
- Growth: LEC
- Dopant: Si
- Orientation: [100]
- Thickness: 15 mil
- Surface: One side polished
- Size: 2"
- Carrier Concentration:
  - Seed: $1.3 \times 10^{13} \text{ cm}^{-3}$
  - Tail: $1.29 \times 10^{17} \text{ cm}^{-3}$


[34] A. Piotrowska, A. Guivarch and G. Pelous, "Ohmic contacts to III-V compound semiconductors: A review of


[53] Purchased from Real Time Devices. Inc., 1930 Park Forest Ave., P.O. Box 906, State College, Pennsylvania 16804.


[55] Made by Dr. Erkaya at Arizona State University. The Zn diffusion was done at 600 K for 45 minute. Junction depth : about 1.5 m

N$_{Zn}$ : about $10^{19}$ cm$^{-3}$


[70] G. M. Martin, "Key electrical parameters in semi-insulating materials; the methods to determine them in GaAs," in Proceedings of the Semi-insulating III-V


APPENDIX 1

The Thickness Distribution of Evaporated Films

The amount of material deposited on to an opposing surface depends on the position of the receiving surface with regard to the emission source. The emission pattern from a small evaporating area is not uniform in all directions. Maximum emission occurs at the normal to the emitting surface according to the cosine law of emission. An evaporation from a small area source $dS_e$ to a surface element $dS_r$ is shown in Fig. A-1. The mass deposited per unit area is expressed by [30].

$$\frac{d M_r(\phi, \theta)}{d S_r} = \frac{M_e}{\pi r^2} \cos(\phi) \cos(\theta) \quad (A-1)$$

The above equation indicates that the mass deposited per unit area is increased by reducing the angles, $\phi$ and $\theta$, and distance from the evaporation source. Therefore, it is desirable to locate samples where the angles $\phi$ and $\theta$ are minimum. It is also desirable to place samples at such a distance where the nonuniformity due to the distance is negligible. If a sample is located as shown in Fig. A-2, the deposited film thickness is calculated from the equation A-1. Since the mass deposited per unit area is equal to the density
Fig. A-1  Evaporation from a small area source \(dS_e\) on to a surface element \(dS_r\).
Fig. A-2  Evaporation on to a plane parallel surface element $dS_r$. 

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of the deposited material times the thickness $d$, equation A-1 becomes

$$d = \frac{1}{\rho} \frac{d M_r}{d S_r} = \frac{M_e}{\pi r^2 \rho} \cos(\phi) \cos(\theta) \quad (A-2)$$

Since the angle $\phi = \theta$, $\cos(\phi) = \cos(\theta) = h/r$ and $r^2 = h^2 + p^2$, the equation A-2 is rewritten as

$$d = \frac{M_e}{\rho \pi h^2 [1 + (p/h)^2]^2} \quad (A-3)$$

If we define $d_0$ as a deposited film thickness at a center ($p = 0$), then equation A-3 is simplified as

$$\frac{d}{d_0} = [1 + (p/h)^2]^{-2} \quad (A-4)$$

The thickness distribution as a function of $p/h$ are drawn in Fig. A-3. A 10% thickness difference is expected between the thickness at $p = 0$ (center) and the thickness at $p = 0.2h$. 

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Fig. A-3  Film thickness distribution.
APPENDIX 2

Atomic Diffusion Mechanism

The following is a brief review of atomic diffusion mechanisms described by Tuck [73]. Some important atomic diffusion mechanisms are the vacancy mechanism, the interstitial mechanism, the interstitialcy mechanism and the substitutional-interstitial mechanism.

The diffusion by vacancy mechanism can be explained by using the diagram shown in Fig. A-4. The vacancy in the figure is an unoccupied lattice site. The random motion due to thermal energy can cause the tracer atom in position 1 to move to the vacant lattice site at position 4. The tracer atom must overcome an energy barrier to move from position 1 to position 4 due to atoms 2 and 3. The energy barrier $E$ is called an activation energy. The tracer atom may make a further move to the right if position 5 is vacant. If position 5 is not vacant, the atom has to wait until position 5 becomes vacant or may move back to position 1. Therefore, the diffusion by vacancy mechanism is slow process. If the tracer atom is an impurity atom, the vacancy diffusion mechanism is called a substitutional diffusion mechanism.

A diagram which describes an interstitial diffusion mechanism is shown in Fig. A-5. The interstitial atom at position 1 can move to the position 2 if it overcomes the
Fig. A-4  Diffusion by vacancy mechanism.
Fig. A-5  Diffusion by interstitial mechanism.

○: host atom
○: interstitial atom
energy barrier $\Delta E$. Here the activation energy $\Delta E$ is defined same as in the vacancy mechanism. If the interstitial atom is small compare to the size of the host lattice, the activation energy $\Delta E$ will be small. Since the number of interstitial sites is generally much greater than the number of vacancies, diffusion by the interstitial mechanism is much faster than diffusion by the vacancy mechanism.

When the interstitial atom is large compared to the size of the host lattice, the activation energy will be large and diffusion by this mechanism will be difficult. In this situation, diffusion could occur through an interstitialcy mechanism. The interstitialcy mechanism is illustrated in Fig. A-6. Atom 1 pushes atom 2 to position 3 and occupies position 2. The atom 2 is now in an interstitial site. Atom 2 can displace other host atom and the second host atom would become an interstitial atom.

The substitutional-interstitial mechanism is a combination of the first two diffusion mechanisms, substitutional and interstitial. When an impurity enters a host lattice, some of the impurity atoms occupy lattice sites, while others occupy interstitial sites as shown in Fig. A-7. The atom at position 1 can diffuse into position 3 by, for example, an interstitial – interstitial – interstitial – substitutional process. The atom at position 2 can diffuse substitutional – interstitial – interstitial. Therefore, the diffusion process can occur in an arbitrary sequence of substitution and interstitial operation.
Fig. A-6  Diffusion by interstitialcy mechanism.
Fig. A-7  Diffusion by substitutional - interstitial mechanism.

{o : impurity atom  □ : vacancy
  □ : host atom}
APPENDIX 3

LIST OF A DLTS DATA MANIPULATION PROGRAM
DATA ANALYSIS FROM A DLTS SYSTEM

THIS PROGRAM IS WRITTEN BY SUNG TAEK KO ON 1/16/88

THIS PROGRAM REQUIRES A/D CONVERTER (AD500) TO TAKE DATA
FROM A DLTS SYSTEM AND DISPLAYS DLTS SPECTRA ON A SCREEN.

-------------------------------------------------------
CLS
KEY OFF: SCREEN 2
DIM SOFTKEY$(10), X(1000), Y(1000), AA(500)
DATA "START ","STOP ","MIN ","MAX ","GAIN"
DATA "MULTI ","OFFSET ","MODE ","ALAM ","END 
B1$ = " #######.## #######.##"
B2$ = "  " "  " "  
B3$ = "  " "  " "  
B4$ = "##.###aaaa ##.###aaaa"
FOR I = 1 TO 10
READ SOFTKEY$(I)
KEY I, SOFTKEY$(I)
KEY(I) ON
NEXT I
KEY ON
GOSUB 940: GOSUB 940: GOSUB 1760: GOSUB 2530
ON KEY(1) GOSUB 510
ON KEY(2) GOSUB 1870
ON KEY(3) GOSUB 2080
ON KEY(4) GOSUB 2130
ON KEY(5) GOSUB 2180
ON KEY(6) GOSUB 2270
ON KEY(7) GOSUB 2310
ON KEY(8) GOSUB 2220
ON KEY(9) GOSUB 2350
ON KEY(10) GOSUB 2400
GOTO 460
LOCATE 22, 5
PRINT " "
LOCATE 22, 5
RETURN

------------------------------------------------START
STP = 0
Nil = 0: FLG9 = 0: GOSUB 1120: GOSUB 1120: GOSUB 1170
Nil = Nil + 1
XT = 0: YT = 0
GOSUB 1170 '-------------------------------- GET DATA FROM A/D
IF FLG9 = 1 THEN 530
LOCATE 3, 10: PRINT USING B1$; X1, Y1
IF Nil > 1 THEN 670
LOCATE 18, 12: PRINT TIMES$: LOCATE 18, 23

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605 PRINT " \\
610 X(1) = X1 * MT1 + OS1: Y(1) = Y1 * MT2 + OS2 \\
620 AXT = X1: AYT = Y1: X2 = X1 \\
630 GOSUB 1640: PI = X1: P2 = Y1 \\
640 LINE (P1, P2)-(P1, P2) \\
650 NI1 = 2 \\
660 GOTO 550 \\
670 NI2 = NI2 + 1: XT = XT + X1: YT = YT + Y1 \\
680 IF NI2 < 5 THEN 560 \\
690 AXT = XT / NI2: AYT = YT / NI2 \\
700 DAXT = AXT - X2: ADAXT = ABS(DAXT) \\
710 IF ADAXT < XSTEP THEN 550 \\
720 IF ((MO = 1) AND (DAXT > 0)) THEN 740 \\
722 IF ((MO = 2) AND (DAXT < 0)) THEN 740 \\
730 GOTO 550 \\
740 X(NI1) = AXT * MT1 + OS1: Y(NI1) = AYT * MT2 + OS2: X2 = AXT \\
750 P3 = AXT: P4 = AYT: LINE (P1, P2)-(P3, P4) \\
760 P1 = P3: P2 = P4 \\
770 GOSUB 1640 \\
780 IF X1 < XALM THEN 540 \\
790 LOCATE 18, 23: PRINT TIME$ \\
800 GOSUB 470 \\
810 PRINT "TURN OFF HP 6284 POWER SUPPLY THEN PRESS Y "; \\
820 IF DYA = 0 THEN 930 \\
830 PORTB = INP(BOARD + 1) \\
840 PORTB = PORTB AND &H7 \\
850 CCF = PORTB OR &H40 \\
860 W$ = INKEY$ \\
870 OUT BOARD + 1, CCF \\
880 FOR I = 1 TO DYA: NEXT I \\
890 OUT BOARD + 1, PORTB \\
900 FOR I = 1 TO DYA: NEXT I \\
910 IF W$ = "" THEN 830 \\
920 GOSUB 2860: GOSUB 1880 \\
930 RETURN \\
940 '----------------------------------SUBROUTINE TO INITIALIZE A/D BOARD \\
950 BOARD = &H200 \\
960 BA = 200 \\
970 OUT BOARD + 3, &HB8 \\
980 OUT BOARD + 3, 5 \\
990 A = INP(BOARD) \\
1000 A = INP(BOARD + 2) \\
1010 A = A AND &H20 \\
1020 IF A <> 0 GOTO 1070 \\
1030 A = INP(BOARD + 2) \\
1040 A = A AND &H20 \\
1050 IF A = 0 GOTO 1030 \\
1060 GOTO 990 \\
1070 OUT BOARD + 3, 4 \\
1080 FOR A = 1 TO 70 \\
1090 NEXT A \\
1100 A = INP(BOARD)
'--------------------------GET DATA FROM A/D BOARD

1100 OUT BOARD + 3, 5
1110 A = INP(BOARD + 2)
1120 A = A AND &H20
1130 IF A = 0 THEN 1110
1140 RETURN

1150 '--------------------------GET DATA FROM A/D BOARD
1160 CH = 1
1170 A = INP(BOARD + 1)
1180 A = A AND &HF8
1190 NXTCH = A OR 2
1200 OUT BOARD + 1, NXTCH: GOSUB 1510
1210 FOR DELAY = 1 TO DY
1220 NEXT DELAY
1230 MSB = INP(BOARD) 'read a/d msb data.
1240 A = INP(BOARD + 2) 'check status word IBF.
1250 A = A AND &H20 'to see if the...
1260 IF A = 0 THEN 1230 'bit is set.
1270 LSB = INP(BOARD) 'read a/d lsb data.
1280 GOSUB 1570: XI = CONV

1290 CH = 3
1300 A = INP(BOARD + 1)
1310 A = A AND &HF8
1320 NXTCH = A OR 8
1330 OUT BOARD + 1, NXTCH: GOSUB 1510
1340 FOR DELAY = 1 TO DY
1350 NEXT DELAY
1360 MSB = INP(BOARD) 'read a/d msb data.
1370 A = INP(BOARD + 2) 'check status word IBF.
1380 A = A AND &H20 'to see if the...
1390 IF A = 0 THEN 1360 'bit is set.
1400 LSB = INP(BOARD) 'read a/d lsb data.
1410 GOSUB 1570: Y1 = CONV
1420 IF STP = 0 THEN 1500
1430 STP = 0: GOTO 1880
1440 RETURN

1450 '--------------------------SET GAIN IN A/D BOARD
1460 IF CH = 1 THEN GA = GA4 ELSE GA = GA3
1470 OUT BOARD + 3, 0
1480 OUT BOARD + 3, 2
1490 OUT BOARD + 3, GA
1500 RETURN

1510 '--------------------------CHANGE DIGITAL DATA INTO ANALOG
1520 POL = MSB AND &H80: RAN = MSB AND &H40
1530 CONV = (MSB AND &HF) * 256 + LSB
1540 CONV = ((CONV * 5000) / (4096))
1550 IF RAN = 64 THEN CONV = 6000!
1560 IF POL <> 128 THEN CONV = -1 * CONV

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1620 IF CH = 1 THEN CONV = CONV / GA1 ELSE CONV = CONV / GA2
1630 RETURN
1640 '-----------------------------------------PRINT DATA
1650 LOCATE 3, 10: PRINT USING B1$; XI, Y1
1660 LOCATE 4, 10: PRINT USING B1$; AXT, AYT
1670 LOCATE 5, 10: PRINT USING B4$; X(N11), Y(N11)
1680 LOCATE 16, 10: PRINT USING B3$; Nil, ADAXT
1690 ST2 = ADAXT / (TIMER - ST1)
1692 ST1 = TIMER: ST4 = ST2 * ST3 + YMIN
1700 IF SXT > ST9 THEN 1720
1710 SXT = SXT + ADAXT: GOTO 1750
1720 SXT = 0
1730 IF ST4 > ST8 THEN ST4 = ST8
1740 LINE (XI, YMIN)-(X1, ST4)
1750 RETURN
1760 '------------------------------------------INITIALIZE PARAMETERS
1770 XMIN = -170: XMAX = 170: XALM = 150: FLG9 = 0
1780 YMIN = -5000: YMAX = 5000
1790 XSTEP = .5: DY = 90: ST1 = TIMER
1800 NA = 5: DYA = 50: MT1 = 1: MT2 = 1
1810 GA1 = 10: GA3 = 2
1820 GA2 = 1: GA4 = 2
1830 MO = 1: TMR = 0
1840 GOSUB 2920
1850 OS1 = 273: OS2 = 0: SXT = 0
1860 RETURN
1870 STP = 1: RETURN
1880 '------------------------------------------STOP ROUTINE
1890 LOCATE 18, 23: PRINT TIME$
1900 FLG1 = 0: ST6 = 0
1910 GOSUB 470: INPUT "SAVE DATA (Y/N) "; Y$
1920 IF Y$ = "N" OR Y$ = "n" THEN 2000
1930 INPUT "OUTPUT DATA FILE NAME "; OU$
1940 OPEN OU$ FOR OUTPUT AS #2
1950 PRINT #2, "TIME:" + TIME$ + " DATE:" + DATE$
1960 FOR I = 1 TO Nil
1970 PRINT #2, X(I), Y(I)
1980 NEXT I
1990 NEXT I
2000 'GOSUB 370 :INPUT "RESET THE A/D CONVERTER ";Y$
2010 'IF Y$="N" OR Y$="n" THEN 1820
2020 'GOSUB 1010
2030 ST5 = YMIN: FLG9 = 1
2040 GOSUB 470: INPUT "CLEAR SCREEN (Y/N) "; Y$
2050 IF Y$ = "n" OR Y$ = "N" THEN 2070
2060 CLS
2070 GOSUB 2860: BEEP: RETURN
2080 '------------------------------------------INPUT MIN
2090 GOSUB 470
2092 INPUT "MINIMUM OF CH1, CH3 IN mV "; XMIN, YMIN
2100 LOCATE 8, 10: PRINT USING B1$; XMIN, YMIN
2110 GOSUB 2920
RETURN

'----------------------------------------INPUT MAX
GOSUB 470: INPUT "MAXIMUM OF CH1, CH3 IN mV "; XMAX, YMAX
LOCATE 9, 10: PRINT USING B1$; XMAX, YMAX
GOSUB 2920
RETURN

'----------------------------------------INPUT GAIN
GOSUB 470: INPUT "GAIN OF CH1, CH3 (1,10,100) GA1, GA2"
LOCATE 7, 10: PRINT USING B2$; GA1, GA2
GOSUB 2970: GOSUB 1170: RETURN

'----------------------------------------INPUT MODE
GOSUB 470: INPUT "MODE (1:INCREASE X, 2:DECREASE X)"; MO
GOSUB 470: INPUT "X VALUE STEP TO BE MONITORED "; XSTEP
LOCATE 14, 10: PRINT USING B3$; MO, XSTEP
GOSUB 2920: RETURN

'------------------------MULTIPLICATION
GOSUB 470: INPUT "MULTIPLICATION OF CH1, CH3 "; MT1, MT2
LOCATE 11, 10: PRINT USING B4$; MT1, MT2
RETURN

'--------------------------------------------- OFFSET
GOSUB 470: INPUT "OFFSET OF CH1, CH3 "; OS1, OS2
LOCATE 12, 10: PRINT USING B2$; OS1, OS2
RETURN

'-----------------------------------SET ALAM /TIMER
GOSUB 470: INPUT "ALAM DELAY (0:OFF) "; DYA
GOSUB 470: INPUT "ALAM XVALUE AT "; XALM
LOCATE 15, 10: PRINT USING B3$; DYA, XALM
RETURN

'------------------------------------------------END
LOCATE 18, 23: PRINT TIME$
GOSUB 470: INPUT "SAVE DATA (Y/N) Y"; Y$
IF Y$ = "N" OR Y$ = "n" THEN 2510
INPUT "OUTPUT DATA FILE NAME OU";
OPEN OU$ FOR OUTPUT AS #2
PRINT #2, "TIME:" + TIME$ + ' •
FOR I = 1 TO Nil
PRINT #2, X(I), Y(I)
NEXT I
CLOSE #2
LOCATE 20, 30
END

'--------------------------------------------- INITIALIZE SCREEN
VIEW (250, 1)-(630, 150), 0, 1
WINDOW (XMIN, YMIN)-(XMAX, YMAX)
INITIALIZE SCREEN
LOCATE 1, 1: PRINT " CH1   CH3"
LOCATE 2, 1: PRINT "-------------------"
LOCATE 3, 1: PRINT "CURRENT:
LOCATE 4, 1: PRINT "AVERAGED:
LOCATE 5, 1: PRINT "SCALED :"
LOCATE 6, 1: PRINT "GAIN :
LOCATE 7, 1: PRINT "MIN :
LOCATE 8, 1: PRINT "MIN :
DATE:" + DATE$
2640 LOCATE 9, 1: PRINT "MAX :"
2650 LOCATE 11, 1: PRINT "MULTIP :"
2660 LOCATE 12, 1: PRINT "OFFSET :"
2670 LOCATE 14, 1: PRINT "MODE :"
2680 LOCATE 15, 1: PRINT "ALAM :
2690 LOCATE 16, 1: PRINT "NO/STEP:
2700 LOCATE 17, 1: PRINT "-----------------------------"
2710 LOCATE 18, 1: PRINT "TIME :
2720 LOCATE 19, 1: PRINT "-----------------------------"
2730 LOCATE 3, 10: PRINT USING B1$; X1, Y1
2740 LOCATE 4, 10: PRINT USING B1$; AXT, AYT
2750 LOCATE 5, 10: PRINT USING B4$; X1, Y1
2760 LOCATE 7, 10: PRINT USING B2$; GA1, GA2
2770 LOCATE 8, 10: PRINT USING B1$; XMIN, YMIN
2780 LOCATE 9, 10: PRINT USING B1$; XMAX, YMAX
2790 LOCATE 11, 10: PRINT USING B4$; MT1, MT2
2800 LOCATE 12, 10: PRINT USING B1$; OS1, OS2
2810 LOCATE 14, 10: PRINT USING B3$; MO, XSTEP
2820 LOCATE 15, 10
2822 PRINT USING "##########.##"; DYA, XALM
2830 LOCATE 16, 10: PRINT USING B3$; NI1, ADAXT
2840 LOCATE 21, 64: PRINT DATE$ + "STKO"
2850 RETURN
2860 '--------------------- CLEAR dT/dt PORTION OF SCREEN
2870 FOR I = XMIN TO XMAX - 10 STEP 10
2880 GET (I, YMIN)-(I + 10, ST8), AA
2890 PUT (I, YMIN), AA
2900 NEXT I
2910 RETURN
2920 '------------------- SUBROUTINE TO SET INITIAL PARAMETER
2930 FLG1 = 0: ST6 = 0
2940 ST3 = XSTEP * (YMAX - YMIN) / 3
2942 ST5 = YMIN: ST8 = YMIN + (YMAX - YMIN) / 6
2950 ST9 = (XMAX - XMIN) / 400
2960 WINDOW (XMIN, YMIN)-(XMAX, YMAX)
2970 IF GA1 = 1 THEN GA3 = 2
2980 IF GA1 = 10 THEN GA3 = 3
2990 IF GA1 = 100 THEN GA3 = 1
3000 IF GA2 = 1 THEN GA4 = 2
3010 IF GA2 = 10 THEN GA4 = 3
3020 IF GA2 = 100 THEN GA4 = 1
3030 RETURN
APPENDIX 4

LIST OF A PHOTOCONDUCTIVE SWITCH SIMULATION PROGRAM WITH A DATA FILE

125
* THIS PROGRAM SIMULATE TURN ON AND TURN OFF TRANSIENT OF A
* SEMICONDUCTOR SWITCH.
* ALL PARAMETERS (CAPTURE, EMISSION, DENSITY, AND ACTIVATION
* ENERGY) FOR TRAPS AND INFORMATION FOR PHOTON FLUX TO TURN
* ON/ OFF SHOULD BE GIVEN IN DATA FILE.
* DATA FILE IS NAMED AS 'INPDATA' AND RESULTS FILE IS NAMED
* AS 'OUTDATA'.

* THIS SIMULATION CAN SIMULATE UP TO 20 IMPURITY LEVELS.

* IFLG1 = 0 : THE INITIAL ELECTRON DENSITY IN THE INPUT
* DATA IS USED

* IFLG1 = 1 : THE INITIAL ELECTRON DENSITY AT THE TRAPS AND
* FREE ELECTRON DENSITY AND FREE HOLE DENSITY IS USED FROM
* THE STEADY STATE VALUE(WHICH IS CALCULATED FROM THE RATE
* EQUATION W/O THE EXTERNAL EXCITATION).

* IFLG1 = 2 : THE INITIAL ELECTRON DENSITIES ARE CALCULATED
* FROM THE FERMILEVEL.

* IFLG2 SPECIFIES THE SHAPE OF THE TURN ON/OFF PULSE AS
* FOLLOWS

<table>
<thead>
<tr>
<th>IFLG2</th>
<th>TURN ON PULSE</th>
<th>TURN OFF PULSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>TRAPEZOID</td>
<td>TRAPEZOID</td>
</tr>
<tr>
<td>1</td>
<td>TRAPEZOID</td>
<td>GAUSSIAN</td>
</tr>
<tr>
<td>2</td>
<td>GAUSSIAN</td>
<td>TRAPEZOID</td>
</tr>
<tr>
<td>3</td>
<td>GAUSSIAN</td>
<td>GAUSSIAN</td>
</tr>
</tbody>
</table>

* THE GAUSSIAN SHAPE LASER PULSE USED IN THIS SIMULATION HAS
  FOLLOWING SHAPE.
  TFW1: FULL WIDTH HALF MAXIMUM VALUE FOR THE TURN ON LASER
  PULSE.
  TFW2: FULL WIDTH HALF MAXIMUM VALUE FOR THE TURN OFF LASER
  PULSE.
  THE STANDARD DEVIATION OF TURN ON /OFF PULSE =
  (TFW1,TFW2) /2.354.

* TWO PHOTON PROCESS HAS BEEN ADDED (4/25/88)

* RUNGE KUTTA 5TH ORDER METHOD WITH ADAPTIVE GRID CONTROL
* (MODIFIED FROM LASER1.FOR PROGRAM 5/10/88)

* 2/8/88 --------------------- PROGRAMMED BY SUNG TAEK KO
* EXPLANATIONS FOR VARIABLES

AFN1,2,3,4,5: DUMMY VARIABLE FOR ELECTRON DENSITY CALCULATION
AFNN, AFNT: DUMMY VARIABLE FOR ELECTRON DENSITY AT CONDUCTION BAND AND TRAPS
ANN, ANP: ELECTRON/HOLE DENSITY AFTER TIME STEP DELTA T
BETA: TWO PHOTON ABSORPTION COEFFICIENT
BK: BOLTZMAN CONSTANT
BNN, BNP: ELECTRON/HOLE DENSITY BEFORE TIME STEP DELTA T
CN(I), CP(I): CAPTURE PARAMETER FOR ELECTRONS AND HOLES
COEFN, COEFP: COEFFICIENT TO CALCULATE THERMAL ELECTRON/ HOLE EMISSION RATE
CRD: CURRENT DENSITY
DAG, DDG: DIGENERACY OF ENERGY STATE FOR CONDUCTION/VALENCE BAND EDGE
DKU: DIRECT PHOTO IONIZATION CROSS SECTION
DKD: RECOMBINATION COEFFICIENT
DNT1,2,3,4: DUMMY VARIABLE FOR TRAP DENSITY
DNN1,2,3,4: ELECTRON DENSITY
DNO(I), DPO(I): ELECTRON/HOLE OPTICAL IONIZATION CROSS SECTION
DTN(I), DTP(I): ELECTRON/HOLE THERMAL CAPTURE CROSS-SECTIONS
EEV: ELECTRON CHARGE
EF: FERMI ENERGY LEVEL MEASURED FROM CONDUCTION BAND
EG: ENERGY GAP
ELE: E FIELD APPLIED TO THE SWITCH
ELC: CRITICAL E FIELD
EME: ELECTRON EFFECTIVE MASS
EMH: HOLE EFFECTIVE MASS
ENE(I): ENERGY LEVEL FOR TRAPS
HOLE TRAPS - MEASURED FROM VALENCE BAND
ELECTRON TRAPS - MEASURED FROM CONDUCTION BAND
** FOR ELECTRON TRAPS, THE ENERGY LEVEL IS CONVERTED TO THE VALUE MEASURED FROM VALENCE BAND AFTER THE INITIAL DENSITY CALCULATIONS SO THAT THE ENERGY LEVELS ARE USED IN ELECTRON IONIZATION/ DEIONIZATION IN SUBROUTINES.
ENT(I): TRAP DENSITY
ERM: ELECTRON REST MASS/ELECTRON CHARGE
EPS: MAXIMUM ALLOWED ERROR
GER: GLOBAL ERROR
HN(J), HP(J): ELECTRON AND HOLE DENSITY
II: COUNTER
IFLG1: SET MODE FOR INITIAL VALUES OF TRAP DENSITY
IFLG6: TINY = 10 ^ IFLG6
TINY: LIMITING FACTOR FOR ERROR
MUE1,2: MOBILITY FOR ELECTRON
MUH1,2: MOBILITY FOR HOLE
NER1: ERROR CONTROL PARAMETER
NHT, NET, NWT: NO. OF HOLE, ELECTRON AND TOTAL TRAPS
C NO. OF DATA FOR THE SIMULATION
C DUMMY VARIABLE FOR IDENTIFYING THE TRAP NUMBER
C MAXIMUM ITERATION NUMBER IN RUNGE KUTTA CALCULATION
EX) A VALUE BETWEEN 10000 TO 100000 WILL BE GOOD CHOICE
C PHII, PHI2 : PHOTON FLUX FOR HOLE AND ELECTRON IONIZATION
C PFO, PFOF : PHOTON FLUX FOR TURN ON AND OFF
C PRE-EXPOENTIAL FACTOR FOR IONIZATION
C CROSSECTION
C MINIMUM ERROR CONTROL PARAMETER FOR DENSITY
C ELECTRON DENSITY AT TRAP
C ELECTRON DENSITY AT CONDUCTION BAND
C HOLE DENSITY AT VALENCE BAND
C DUMMY VARIABLES FOR PHOTON FLUX
C TURN ON LASER PULSE POSITION
C TURN OFF LASER PULSE POSITION
C ENERGY
C DUMMY ARRAY FOR PNT(I)
C ELECTRON AND HOLE THERMAL EMISSION RATE
C AUGER RECOMBINATION RATE
C RECOMBINATION RATE THROUGH TRAPS
C DIRECT RECOMBINATION RATE (FREE ELECTRON -FREE HOLE)
C DIRECT IONIZATION RATE COEFFICIENT
C TOTAL SHALLOW DONOR AND ACCEPTOR DENSITY
C ENERGY LEVEL
C DUMMY SIMULATION TIME
C SIMULATION TIME
C TIME TO BE MONITORED FOR RESULTS
C RISE TIME FOR TRAPEZOID PULSE
C DUMMY TIME STEP
C MONITORING THE RESULT
C SIMULATION TIME
C PEAK POSITION OF THE TURN ON PULSE
C TURN OFF PULSE
C DUMMY VARIABLE FOR TIME
C HOLE AND ELECTRON THERMAL VELOCITY
C PHOTON WAVE ENERGY FOR TURN ON AND OFF
C

PROGRAM LASER1

DOUBLE PRECISION BNN, BNP, PNT, SAD, SDD, BNT, ENT, ANN, & ERP, EMAX1, EMAX2, EMAX3, T, T1, T2, TINS, PT1, PT2, & TXF1, TXF2, TXF3, TXF4, TRS, HNEXT, TT, HMIN, ANP REAL ENE, EF, CN, CP, RNT, DNO, DPT, ELF, ELG, ELE, ELC, 1 RPT, PFO, PFOF, WPFON, WPFOF, PWE1, PWE2, BETA, 2 BK, TVH, TVE, EG, DNC, DNV, HN, HP, DNN, CRD, 3 RKU, RKD, RKA, RKT, EPS

REAL TSTS, TS, TSM, TPFON, TPFOF, CNT, TB, COEFN, 2 DAG, DØG, EME, EMIH, SAE, SDE, RT, DTN, DTP, PBETA, 3 MUE, MUH, MUE1, MUE2, MUH1, MUH2, GN1, GN2, GH1, 4 GGE, GGH, GDE, GDH, GH2, COEFP

DIMENSION ENE(20), ENT(20), CN(20), CP(20), RNT(20),
1  DNO(20), DPO(20), PNT(22), HN(500), HP(500),
2  BNT(22), DTN(20), DTP(20), NNX(500), PFE(50),
3  EGG(20), RPT(20), CNT(500), PFH(50)
   INTEGER NHT, NET, NWT, II, I, IFLG1, IFLG2, NN, NHT1,
&  NER1, NPT, IFLG3
   COMMON /BLKA/CN, CP, RNT, RPT, DNO, DPO, RKD, RKU,
&      PWE1, PWE2, PBETA, RKA
   COMMON /BLKB/ENT, ENE, NWT, EG, EG2, EGG
   COMMON /BLKC/SDD, SAD, NHT, NHT1, NWN, NWP, PMIN
   COMMON /BLKD/IFLG2, IFLG3, PT1, PT2, TFX1, TFX2, DV1,
&      DV2, PFON, PFOF, TRS, TFX3, TFX4
   COMMON /BLKE/NMAX, EPS, HMIN, TINY
C
C GPEN(7, FILE = 'INPDATA', STATUS = 'OLD',
&    FORM = 'FORMATTED')
OPEN(8, FILE = 'OUTDATA', STATUS = 'OLD',
&    FORM = 'FORMATTED')
C
C INPUT DATA FROM A FILE   --------------------------
C
READ(7,'(//5I14)') NHT, NET, NN, IFLG1, IFLG2
READ(7,'(//5I14)') NMAX, NPT, IFLG4, IFLG5, IFLG6
NWT = NHT + NET
NHT1 = NHT + 1
NWN = NWT + 1
NWP = NWN + 1
1 FORMAT(//5E14.5)
READ(7,1) HXT, EPS, TRS, PT1, PT2
READ(7,1) EF, PFON, PFOF, PWE1, PWE2
READ(7,1) TSTS, TMP, TFW1, TFW2, BETA
READ(7,1) ELE, ELC, EME, EMH, EG
READ(7,1) SAD, SAE, SDD, SDE, TINS
READ(7,1) RKD, RKU, RKA, DNC, DNV
READ(7,1) COEFN, COEFP, DAG, DDC, PNT(NWN)
READ(7,1) MUE1, MUE2, MUH1, MUH2, PNT(NWP)
READ(7,1) GN1, GN2, GH1, GH2, HMIN
C
2 FORMAT(///5E14.5)
READ(7,2) (PNT(I), I=1, NHT)
READ(7,2) (PNT(I), I=NHT1, NWT)
READ(7,2) (ENE(I), I=1, NHT)
READ(7,2) (ENE(I), I=NHT1, NWT)
READ(7,2) (ENT(I), I=1, NHT)
READ(7,2) (ENT(I), I=NHT1, NWT)
READ(7,2) (DTN(I), I=1, NHT)
READ(7,2) (DTN(I), I=NHT1, NWT)
READ(7,2) (DTP(I), I=1, NHT)
READ(7,2) (DTP(I), I=NHT1, NWT)
READ(7,2) (PFE(I), I=1, NHT)
READ(7,2) (PFE(I), I=NHT1, NWT)
READ(7,2) (PFH(I), I=1, NHT)
READ(7,2) (PFH(I), I=NHT1, NWT)
READ(7,2) (DNO(I), I=1, NHT)
READ(7,2) (DNO(I), I=NHT1, NWT)
READ(7,2) (DPO(I), I=1, NHT)
READ(7,2) (DPO(I), I=NHT1, NWT)

INITIAL PARAMETER SET UP

\[
\begin{align*}
\text{PMIN} &= 1.0 \times 10^{-5} \\
\text{TINY} &= 10.0 \times 10^\text{IFLG6} \\
\text{HNEXT} &= \text{HXT} \\
\text{EG2} &= \frac{\text{EG}}{2.0} \\
\text{EEV} &= 1.602 \times 10^{-19} \\
\text{BK} &= 8.6174 \times 10^{-5} \\
\text{RT} &= \text{BK} \times \text{TMP} \\
\text{ERM} &= 9.109 \times 10^{-31} \times \text{EEV} \\
\text{PBETA} &= \text{BETA} \times \text{EEV} / 2.0 \\
\text{TSM} &= \text{TSTS}/\text{NN} \\
\text{DV1} &= (\text{TFW1}/2.354) \times 2.0 \\
\text{DV2} &= (\text{TFW2}/2.354) \times 2.0 \\
\text{TFX1} &= (\text{TFW1} - \text{TRS}) / 2.0 \\
\text{TFX2} &= (\text{TFW2} - \text{TRS}) / 2.0 \\
\text{TFX3} &= (\text{TFW1} + \text{TRS}) / 2.0 \\
\text{TFX4} &= (\text{TFW2} + \text{TRS}) / 2.0 \\
\text{SAD} &= \text{SAD} / (1.0 + \text{DAG} \times \text{EXP}((\text{EF} - \text{EG} + \text{SAE}) / \text{RT})) \\
\text{SDD} &= \text{SDD} / (1.0 + \text{EXP}((\text{SDE} - \text{EF}) / \text{RT}) / \text{DDG}) \\
\text{TVE} &= \sqrt{3.0 \times \text{RT} / (\text{ERM} \times \text{EME})} \times 100.0 \\
\text{TVH} &= \sqrt{3.0 \times \text{RT} / (\text{ERM} \times \text{EMH})} \times 100.0 \\
\text{TMP} &= \text{TMP} \times \text{TMP}
\end{align*}
\]

CAPTURE AND EMISSION PARAMETER CALCULATION

\[
\begin{align*}
\text{DO 7 I} &= 1, \text{NHT} \\
\text{CN(I)} &= \text{DTN(I)} \times \text{TVE} \\
\text{CP(I)} &= \text{DTP(I)} \times \text{TVH} \\
\text{RNT(I)} &= \text{DTN(I)} \times \text{TMPS} \times \text{PFE(I)} \times \text{COEFN} \\
&\quad \times \text{EXP}(-\text{EG} - \text{ENE(I)}) / \text{RT} \\
\text{RPT(I)} &= \text{DTP(I)} \times \text{TMPS} \times \text{PFH(I)} \times \text{COEFP} \\
&\quad \times \text{EXP}(-\text{ENE(I)}/\text{RT}) \\
\text{BNT(I)} &= \text{ENT(I)} / (1.0 + \text{EXP}((\text{EF} - \text{EG} + \text{ENE(I)}) / \text{RT})) \\
&\quad \times (1.0 - 1.0 / (1.0 + \text{EXP}((\text{ENE(I)} - \text{EF}) / \text{RT}))) \\
\text{ENE(I)} &= \text{EG} - \text{ENE(I)}
\end{align*}
\]
CONTINUE
DO 10 I = 1, NWT
  EGG(I) = EG - ENE(I)
10 CONTINUE

C START SIMULATION

CNT(1) = PNT(1)
HN(1) = PNT(NWN)
HP(1) = PNT(NWP)
IF (IFLG1 .EQ. 0 ) GO TO 100
DO 50 I = 1, NWT
  PNT(I) = BNT(I)
50 CONTINUE
PNT(NWN) = DNC * EXP(-EF/RT)
PNT(NWP) = DNV * EXP((EF -EG)/RT)
HN(1) = PNT(NWN)
HP(1) = PNT(NWP)
IF (IFLG1 .EQ. 2) GO TO 100

C USE INITIAL VALUES FROM STEADY STATE VALUE

IFLG3 = 1
T1 = 0.0
  CALL RUNGED (PNT, T1, TINS, HNEXT, GER, IMAX, NER1)
  IF (NER1 .EQ. 1) GO TO 225
HN(1) = PNT(NWN)
HP(1) = PNT(NWP)
CNT(1) = PNT(1)
  IF (NPT .GT. 10) THEN
    WRITE(*, 55) TINS, HN(II), HP(II), GER, HNEXT
55 FORMAT(' STEADY STATE ',5E12.5)
  END IF
HNEXT = HXT

-------------------------------------------------------

100 IFLG3 = 0
II = 1
T1 = 0.0
110 T2 = T1 + TSM
IF ((T1 .LT. PT1) .AND. (T2 .GT. PT1)) THEN
  CALL RUNGED (PNT, T1, PT1, HNEXT, GER, IMAX, NER1)
  IF (NER1 .EQ. 1) GO TO 225
  CALL RUNGED (PNT, PT1, T2, HNEXT, GER, IMAX, NER1)
  IF (NER1 .EQ. 1) GO TO 225
ELSE IF ((T1 .LT. PT2) .AND. (T2 .GT. PT2)) THEN
  CALL RUNGED (PNT, T1, PT2, HNEXT, GER, IMAX, NER1)
  IF (NER1 .EQ. 1) GO TO 225
  CALL RUNGED (PNT, PT2, T2, HNEXT, GER, IMAX, NER1)
  IF (NER1 .EQ. 1) GO TO 225
ELSE

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CALL RUNGED (PNT, T1, T2, HNEXT, GER, IMAX, NER1)
    IF (NER1 .EQ. 1) GO TO 225
END IF
    HN(II) = PNT(NWN)
    HP(II) = PNT(NWP)
    CNT(II) = PNT(I)
    NNX(II) = IMAX
    T1 = T2
    IF (NPT .GT. 10) THEN
        WRITE(*, 115) II, IMAX, T1, HN(II), HP(II), GER, HNEXT
    END IF
    IF (T2 .LT. TSTS) GO TO 110
    IF (NER1 .EQ. 2) THEN
        WRITE(8,145)
    END IF
C
C PRINT RESULTS
    3 FORMAT(5E14.5)
225 WRITE(8, 230)
    230 FORMAT( '------------ INPUT DATA ----------',
        '----------------------------------',
        WRITE(8,'(5114)') NHT, NET, NN, IFLG1, IFLG2
        WRITE(8,'(5114)') NMAX, NPT, IFLG4, IFLG5, IFLG6
        WRITE(8,3) HXT, EPS, TRS, PT1, PT2
        WRITE(8,3) EF, PFON, PPOP, PWE1, PWE2
        WRITE(8,3) TSTS, TMP, TFW1, TFW2, BETA
        WRITE(8,3) ELE, ELC, EME, EMH, EC
        WRITE(8,3) SAD, SAE, SDD, SDE, TINS
        WRITE(8,3) RKD, RKU, RKA, DNC, DNV
        WRITE(8,3) COE, COEF, DAG, DDG, PNT(NWN)
        WRITE(8,3) MUE1, MUE2, MUH1, MUH2, PNT(NWP)
        WRITE(8,3) GN1, GN2, GH1, GH2, HMIN
        WRITE(8,3) (PNT(I), I=1, NWT)
        WRITE(8,3) (ENE(I), I=1, NWT)
        WRITE(8,3) (ENT(I), I=1, NWT)
        WRITE(8,3) (DNP(I), I=1, NWT)
        WRITE(8,3) (DPO(I), I=1, NWT)
    232 FORMAT(//, '------------CALCULATED DATA---------',
        '----------------------------------',
        WRITE(8,3) SDD, SAD, TVH, TVE, DV1
        WRITE(8,3) (CN(I), I=1, NWT)
        WRITE(8,3) (CP(I), I=1, NWT)
        WRITE(8,3) (RNT(I), I=1, NWT)
WRITE(8,3) (RPT(I), I=1, NWT)
WRITE(8,235)
235 FORMAT(/, '----------------RESULT-----------------',
& '----------------RESULT-----------------')
TGER = GER /NN * EPS * 1.0E+16
WRITE(8,237) NN, TGER
237 FORMAT(/,'#DATA TOTAL ERROR ',/,3X,I12, E15.5)
WRITE(8, 240)
240 FORMAT(/,' TIME PP(t) N(t) ',
& ' P(t) NT(t) C(t)')
GDE = (MUE2 - MUE1)/(GN2 - GN1)
GDH = (MUH2 - MUH1)/(GH2 - GH1)
GGE = (1.0 + (ELE*ELE)/(ELC*ELC))**1.5
GGH = (1.0 + (ELE/ELC))**2.0
DO 300 II=1, NN
TT = (II - 1) * TSM
IF (HN(II) .GT. GN2) THEN
  MUE = MUE1
ELSEIF (HN(II) .LT. GN1) THEN
  MUE = MUE2
ELSE
  MUE = MUE2 - GDE * (HN(II) - GN1)
ENDIF
IF (HP(II) .GT. GH2) THEN
  MUH = MUH1
ELSEIF (HP(II) .LT. GH1) THEN
  MUH = MUH2
ELSE
  MUH = MUH2 - GDH * (HP(II) - GH1)
ENDIF
ELF = MUE/GGE
ELG = MUH/GGH
CALL FLUX(TT, PHI, PHJ)
PHI = PHI + PHJ
COND = (HN(II)*ELF+HP(II)*ELG)*EEV
CRD = COND * ELE
WRITE(8,'(6E12.4)') TT, PHI, HN(II), HP(II),CNT(II), COND
300 CONTINUE
STOP
END

C
C
SUBROUTINE FOR ELECTRON DENSITY AT TRAPS
C THIS SUBROUTINE CALCULATES ELECTRON DENSITY GRADIENT AT TRAPS
C
SUBROUTINE RUNGEA (BNN, BNP, AFNT, DNT, NW, PHI, PHJ)
C DOUBLE PRECISION AFNT1, AFNT2, AFNT, DNT, BNN, BNP,
1

ENT, PNT(22)

COMMON /BLKA/CN(20), CP(20), RNT(20), RPT(20), DNO(20),
& DPO(20), RKD, RKU, PWE1, PWE2, PBETA, RKA
COMMON /BLKB/ENT(20), ENE(20), NWT, EG, EG2, EGG(20)

C

IF (PWE1 .GT. ENE(NW)) THEN
   PHI1 = PHI
   ELSE
      PHI1 = 0.0
   END IF

IF (PWE1 .GT. EGG(NW)) THEN
   PHI2 = PHI
   ELSE
      PHI2 = 0.0
   END IF

C

IF (PWE2 .GT. ENE(NW)) THEN
   PHJ1 = PHJ
   ELSE
      PHJ1 = 0.0
   END IF

IF (PWE2 .GT. EGG(NW)) THEN
   PHJ2 = PHJ
   ELSE
      PHJ2 = 0.0
   END IF

AFNT1 = (CN(NW)*BNN + RPT(NW) + DPO(NW)*(PHI1+PHJ1))
& *ENT(NW)
AFNT2 = (CN(NW)*BNN + CP(NW)*BNP + DNO(NW)*(PHI2+PHJ2)
& +RNT(NW) + DPO(NW)*(PHI1+PHJ1) + RPT(NW)) * DNT
AFNT = AFNT1 - AFNT2
RETURN
END

SUBROUTINE FOR ELECTRON DENSITY AT CONDUCTION BAND
THIS SUBROUTINE CALCULATES ELECTRON DENSITY GRADIENT
WITH RESPECT TO TIME.

SUBROUTINE RUNGEB(DNN, BNP, PNT, AFNN, PHI, PHJ)

DOUBLE PRECISION AFN1, AFN2, AFNN, DNN, BNP, PNT(22),
& ENT, AFN4, AFN3
INTEGER I, NWT
COMMON /BLKA/CN(20), CP(20), RNT(20), RPT(20), DNO(20),
& DPO(20), RKD, RKU, PWE1, PWE2, PBETA, RKA
COMMON /BLKB/ENT(20), ENE(20), NWT, EG, EG2, EGG(20)

AFNN = 0.0
DO 10 I=1, NWT

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IF ((PWE1 .GT. EGG(I)) .AND. (PWE2 .GT. EGG(I))) THEN
  AFN1 = (RNT(I) + DNO(I) * (PHI + PHJ)) * PNT(I)
  & - CN(I) * DNN * (ENT(I) - PNT(I))
ELSE IF (PWE1 .GT. EGG(I)) THEN
  AFN1 = (RNT(I) + DNO(I) * PHI) * PNT(I)
  & - CN(I) * DNN * (ENT(I) - PNT(I))
ELSE IF (PWE2 .GT. EGG(I)) THEN
  AFN1 = (RNT(I) + DNO(I) * PHJ) * PNT(I)
  & - CN(I) * DNN * (ENT(I) - PNT(I))
ELSE
  AFN1 = RNT(I) * PNT(I) - CN(I) * DNN * (ENT(I) - PNT(I))
END IF
AFNN = AFNN + AFN1
10 CONTINUE
AFN2 = (RKD + RKA * DNN) * DNN * BNP
IF ((PWE1 .GE. EG) .AND. (PWE2 .GE. EG)) THEN
  AFN3 = (PHI + PHJ) * RKU
ELSE IF (PWE1 .GE. EG) THEN
  AFN3 = PHI * RKU
ELSE IF (PWE2 .GE. EG) THEN
  AFN3 = PHJ * RKU
ELSE
  AFN3 = 0.0
END IF
IF ((PWE1 .GE. EG2) .AND. (PWE2 .GE. EG2)) THEN
  AFN4 = (PHI * PHI * PWE1 + PHJ * PHJ * PWE2) * PBETA
ELSE IF (PWE1 .GE. EG2) THEN
  AFN4 = (PHI * PHI * PWE1) * PBETA
ELSE IF (PWE2 .GE. EG2) THEN
  AFN4 = (PHJ * PHJ * PWE2) * PBETA
ELSE
  AFN4 = 0.0
END IF
AFNN = AFNN - AFN2 + AFN3 + AFN4
RETURN
END

SUBROUTINE FOR RUNGE KUTTA METHOD
THIS SUBROUTINE CALCULATES ELECTRON AND HOLE DENSITY
AFTER TIME STEP DELTA T.

SUBROUTINE RUNGEC(PNT, QNT, T, TSI)
COMMON /BLKC/SDD, SAD, NHT, NHT1, NWN, NWP, PMIN

ELECTRON DENSITY AT TRAPS

BNN = PNT(NWN)
BNP = PNT(NWP)
TSJ = TSI/ 2.0
CALL FLUX(T, PHI1, PHJ1)
TT = T + TSJ
CALL FLUX(TT, PHI2, PHJ2)
TT = T + TSI
CALL FLUX(TT, PHI3, PHJ3)
DO 10 I = 1, NWT
   NWW = I
   DNT = PNT(NWW)
   CALL RUNGEA(BNN, BNP, AFNT, DNT, NWW, PHI1, PHJ1)
   DNT1 = AFNT
   DNT = PNT(NWW) + TSJ*DNT1
   CALL RUNGEA(BNN, BNP, AFNT, DNT, NWW, PHI2, PHJ2)
   DNT2 = AFNT
   DNT = PNT(NWW) + TSJ*DNT2
   CALL RUNGEA(BNN, BNP, AFNT, DNT, NWW, PHI2, PHJ2)
   DNT3 = AFNT
   DNT = PNT(NWW) + TSI*DNT3
   CALL RUNGEA(BNN, BNP, AFNT, DNT, NWW, PHI3, PHJ3)
   QNT(NWW) = PNT(NWW) + TSI * ((AFNT + DNT1)/6.0 
      & + (DNT2 + DNT3)/3.0)
   IF (QNT(NWW) .LT. PMIN) QNT(NWW) = 0.0
   IF (QNT(NWW) .GT. ENT(NWW)) QNT(NWW) = ENT(NWW)
10 CONTINUE

ELECTRON DENSITY CALCULATION

CALL RUNGEB(BNN, BNP, PNT, AFNN, PHI1, PHJ1)
   DNN1 = AFNN
   DNN = BNN +DNN1*TSJ
CALL RUNGEB(DNN, BNP, PNT, AFNN, PHI2, PHJ2)
   DNN2 = AFNN
   DNN = BNN +DNN2*TSJ
CALL RUNGEB(DNN, BNP, PNT, AFNN, PHI2, PHJ2)
   DNN3 = AFNN
   DNN = BNN +DNN3*TSI
CALL RUNGEB(DNN, BNP, PNT, AFNN, PHI3, PHJ3)
   QNT(NWN)= BNN +TSI*((DNNl+AFNN)/6.0 + (DNN2+DNN3)/ 3.0)
   IF (QNT(NWN) .LT. PMIN) QNT(NWN) = 0.0

HOLE DENSITY CALCULATION FROM CHARGE NEUTRALITY

TNA = SAD
DO 20 I=1, NHT
   TNA = TNA + QNT(I)
20 CONTINUE
TND = SDD
DO 30 I=NHT1, NWT
   TND = TND + ENT(I) - QNT(I)
30 CONTINUE
QNT(NWP) = QNT(NWN) + TNA - TND
IF (QNT(NWP) .LT. 1.0E-20) QNT(NWP) = 0.0
RETURN
END

C
C ________________________________________________________
C
C SUBROUTINE FOR 5TH ORDER RUNGE KUTTA METHOD WITH ADAPTIVE
C GRID CONTROL
C THIS SUBROUTINE ADJUSTS THE INTEGRATION TIME STEP ACCORDING
C TO THE ALLOWED ERROR MAXIMUM.
C ---------------------------------------------------------
C
SUBROUTINE RUNGED(PNT, T1, T2, HNEXT, GER, IMAX, NER1)
C
PARAMETER (PGR = -0.2, PSH=-0.25, FCOR = 1./15.,
&                     ONE = 1.0, SAFETY = 0.9, ERRCON = 6.E-4)
C
DOUBLE PRECISION QNT(22), SNT(22), PNT(22), YNT(22),
&                     SAD, T1, T2, TT, T, HNEXT, HMIN, H, TSAV, HH, SDD
COMMON /BLKC/SDD, SAD, NHT, NHT1, NWN, NWP, PMIN
COMMON /BLKE/NMAX, EPS, HMIN, TINY
TT = T1
IMAX = 0
IST = 0
ISU = 0
ISV = 0
5 DO 10 I = 1, NWP
   SNT(I) = PNT(I)
10 CONTINUE
TSAV = TT
IF ((TT + HNEXT) .GT. T2) THEN
   H = T2 - TT
   ISV = 1
ELSE
   H = HNEXT
END IF
CALL RUNGEE(PNT, YNT, TSAV)
DO 12 1=1, NWP
   YNT(I) = ABS(PNT(I)) + ABS(H * YNT(I)) + TINY
12 CONTINUE
15 HH = 0.5 * H
CALL RUNGEC(SNT, QNT, TSAV, HH)
T = TSAV + HH
CALL RUNGEC(QNT, PNT, T, HH)
T = TSAV + H
IF (T .EQ. TSAV) THEN
   IF (ISV .EQ. 1) GO TO 100
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NER1 = 1
WRITE(8,18) T, H, EMX, IST, ISU
18 FORMAT(/2X,'ERROR : STEP SIZE NOT SIGNIFICANT',/,
& 'TIME=',E12.5,' STEP=',E12.5,' ERROR=',E12.5,
& /2X,'IST=',I10,' ISU=',I10)
GO TO 100
END IF
CALL RUNGEC(SNT, QNT, T, H)
EMX = 0.0
DO 20 I = 1, NWP
  QNT(I) = PNT(I) - QNT(I)
  EMX = MAX(EMX, ABS(QNT(I)/YNT(I)))
20 CONTINUE
EMX = EMX/EPS
IF (EMX .GT. ONE) THEN
  IF (IST .EQ. 0) THEN
    H = SAFETY * H * (EMX ** PSH)
    IF (H .LT. HMIN) THEN
      NER1 = 2
      H = HMIN
      HNEXT = HMIN
      IST = 1
    END IF
    GO TO 15
  ELSE
    ISU = ISU +1
    TT = T
    GO TO 77
  END IF
ELSE
  IST = 0
  TT = T
  IF (EMX .GT. ERRCON) THEN
    HNEXT = SAFETY * H * (EMX ** PGR)
  ELSE
    HNEXT = 4.0 * H
  END IF
END IF
GER = GER + EMX
DO 30 I = 1 , NWP
  PNT(I) = PNT(I) + QNT(I) * FCOR
  IF (PNT(I) .LT. PMIN) PNT(I) = 0.0
30 CONTINUE
77 IMAX = IMAX + 1
IF (IMAX .GT. NMAX) THEN
  NER1 = 1
  WRITE(8, 80)
80  FORMAT(/2X,'TOO MANY STEPS',//)
GO TO 100
END IF
IF (TT .LT. T2) GO TO 5
100 RETURN
SUBROUTINE FOR DERIVATIVE OF THE EQUATIONS

SUBROUTINE RUNGEE(PNT, YNT, T)

DOUBLE PRECISION AFNN, BNN, BNP, DNT, AFNT, YNT(22),
& PNT(22), TNA, TND, SDD, SAD, ENT, T, DNN
INTEGER I, NWN, NHT, NHT1, NWP, NWT
COMMON /BLKB/ENT(20), ENE(20), NWT, EG1, EG2, EGG(20)
COMMON /BLKC/SDD, SAD, NHT, NHT1, NWN, NWP, PMIN

BNN = PNT(NWN)
BNP = PNT(NWP)
CALL FLUX(T, PHI1, PHJ1)
DO 10 I = 1, NWT
     DNT = PNT(I)
     CALL RUNGEA(BNN, BNP, AFNT, DNT, I, PHI1, PHJ1)
     YNT(I) = AFNT
10 CONTINUE
CALL RUNGEB(BNN, BNP, PNT, AFNN, PHI1, PHJ1)
     YNT(NWN) = AFNN

TNA = YNT(NWN)
DO 20 I=1, NHT
     TNA = TNA + YNT(I)
20 CONTINUE
TND = 0.0
DO 30 I= NHT1, NWT
     TND = TND + YNT(I)
30 CONTINUE
YNT(NWP) = TNA - TND
RETURN
END

SUBROUTINE FOR PHOTON FLUX CALCULATION

SUBROUTINE FLUX(T, PHI, PHJ)

DOUBLE PRECISION T, PT1, PT2, TFX1, TFX2, TFX3, TFX4,
& TRS
COMMON /BLKD/IFLG2, IFLG3, PT1, PT2, TFX1, TFX2, DV1,
& DV2, PFON, PFOF, TRS, TFX3, TFX4
IF (IFLG3 .EQ. 1) THEN
  PHI = 0.0
  PHJ = 0.0
  GO TO 5
END IF
IF (IFLG2 .LT. 2) THEN
  TT01 = ABS(T - PT1)
  IF (TT01 .GT. TFX3) THEN
    PHI = 0.0
  ELSEIF (TT01 .LE. TFX1) THEN
    PHI = PFON
  ELSE
    PHI = PFON * (TFX3 - TT01)/TRS
  END IF
ELSE
  TT01 = (T - PT1) * (T - PT1) /DV1
  IF (TT01 .GT. 30.) THEN
    PHI = 0.0
  ELSE
    PHI = PFON * EXP(-TT01)
  END IF
ENDIF
IF ((IFLG2 .EQ. 0) .OR. (IFLG2 .EQ. 2)) THEN
  TT02 = ABS(T - PT2)
  IF (TT02 .GT. TFX4) THEN
    PHJ = 0.0
  ELSEIF (TT02 .LE. TFX2) THEN
    PHJ = PFOF
  ELSE
    PHJ = PFOF * (TFX4 - TT02)/TRS
  END IF
ELSE
  TT02 = (T - PT2) * (T - PT2) /DV2
  IF (TT02 .GT. 30.) THEN
    PHJ = 0.0
  ELSE
    PHJ = PFOF * EXP(-TT02)
  END IF
ENDIF
5 CONTINUE
RETURN
END
DATA FOR LASER2.FOR PROGRAM

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PNT(I) : HOLE TRAP (INITIAL ELECTRON DENSITY)

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PNT(I) : ELECTRON TRAP (INITIAL ELECTRON DENSITY)

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ENE(I) : HOLE TRAP (ACTIVATION ENERGY)

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ENE(I) : ELECTRON TRAP (ACTIVATION ENERGY)

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ENT(I) : HOLE TRAP (DENSITY)
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**ENT(I)**: ELECTRON TRAP (DENSITY)

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**DTN(I)**: HOLE TRAP (THERMAL ELECTRON CAPTURE CROSS-SECTION)

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**DTN(I)**: ELECTRON TRAP (THERMAL ELECTRON CAPTURE CROSS-SECTION)

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**DTP(I)**: HOLE TRAP (THERMAL HOLE CAPTURE CROSS-SECTION)

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**DTP(I)**: ELECTRON TRAP (THERMAL HOLE CAPTURE CROSS-SECTION)

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**PFE(I)**: HOLE TRAP (PRE-EXPONENTIAL FACTOR FOR ELECTRON IONIZATION)

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**PFE(I)**: ELECTRON TRAP (P. E. F. FOR ELECTRON IONIZATION)

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**DNO(I)**: ELECTRON TRAP (OPTICAL ELECTRON IONIZATION CROSS-SECTION)

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LIST OF PUBLICATIONS


BIOGRAPHICAL SKETCH

Sung Taek Ko was born in Cheju-Do, Korea, on January 12, 1955. He received B.E. degree in Electronics from Inha University, Korea in 1980 and M. S. degree in Physics from Hampton University, Hampton, VA in 1984.

From 1976 to 1979 he joined Korean Army and worked as a radio equipment repair man. From 1980 to 1982 he worked Texas Instrument Korea branch developing optoelectronic devices and sensors. From 1983 to 1984 he worked at NASA Langley research center studying for the surface flashover in vacuum. He is a member of Eta Kappa Nu and the Institute of Electrical and Electronics Engineers.