CORRELATION STUDIES OF PITS, HALL EFFECT AND VAN DER PAUW CHARACTERIZATIONS OF GaAs SUBSTRATES

by

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Approved by:

[Signature]
Major Professor
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My gratitude also goes to the Electrical and Computer Engineering for their unfailing support during my graduate program.

I am also grateful to the people in Honeywell and Motorola who freely supplied the ion implanted GaAs samples.

The opportunity to study here at all would have been only a pipe dream without the sacrificial support of my wife, Flora and my daughters Thandeko and Dumisa who had to stay behind in Zimbabwe.
CHAPTER I
INTRODUCTION

In this work, the author stands in the shadow of a succession of efforts to determine the viability of pulsed laser annealing (PLA) on GaAs as an alternative to furnace annealing. Among its other attractions, PLA not only minimizes the out-diffusion of arsenic at high temperatures but is fast and uses compact equipment.

1.1 The Work Done up to Now

The initial effort to anneal GaAs substrates was inaugurated by Drs. Andrzej Rys and Alvin Compaan from the respective departments of Electrical and Computer Engineering, and Physics. Their trailblazing graduate students, Arkady Horak, Huade Yao and Ajit Bhat successfully put together the first PLA system using the rare halide eximer laser but still met insurmountable hardware problems. This was 1986. They were soon joined by Timothy Chin who, together with Ajit Bhat finally got the system working. As a result, several wafers implanted with, in some cases, silicon and, in others, selenium ions were annealed thus spewing the spate of probings that have culminated in the present work.

Timothy Chin's study used Hall Effect and Van der Pauw techniques to establish that carrier activation
in PLA samples tends to be high. The apparent cause of this has invariably been suspected as the silicon nitride cap on the samples. An unpleasant side-effect of additional impurities, incidentally, was a drastic lowering of electron mobility in PLA samples. Follow-up efforts by Yanan Shieh involved unsuccessful efforts to make Schottky diodes for deep level transient spectroscopy (DLTS) studies of the traps that evidently kept mobility low in spite of high activation. At this point your author had joined the team and had been tasked with optimizing the DLTS workstation while Yanan Shieh continued developing Schottky diodes. Difficulties with good junctions soon led us to set up for testing the samples as they were rather than turning them into devices. This is where the photo-induced current transient spectroscopy (PICTS or PITS) technique came in handy.

My main contribution to the development of the PITS workstation was the research into viable systems in use elsewhere (Lang, 1974; Day et al, 1979; Kremer et al, 1987; Yoshie & Kamihara, 1985; Maracas, 1982; Hurtes, 1978) and the drafting of the schematic of the system adopted here. The draft was predecessor to that shown in Figure 2.3.1 which has been modified to incorporate a supervisory controller. The control computer was added by Yanan Shieh and Akhter Ahmed, a PhD student in both...
Electrical and Chemical Engineering. Once the initial bugs had been worked out of the system, I then studied ways of extending the rate window to as long a time regime as possible. In the 10 ms range used by Yanan Shieh we were having problems resolving peaks that occurred within a few tens of degrees of each other. The problem was partially due to the signal to noise improvement ratio of the boxcar averager. Additional sidelights emanated from these studies. The main one was the determination of an optimal balance among the chopper frequency, integrator and processing time constants, the rate window as well as laser power. The rest will be treated in Section 2.3.

1.2 Current Focus

This thesis, however, zeroes in on correlations among various phenomena. First we examine the correlation between the intensity of the eximer laser used in PLA and the electrical characteristics such as electron mobility, sheet resistivity and sheet carrier concentration. Samples with the same dose were selected for this study. Then through an appropriate selection of samples we next look at the variation of the characteristics with dose for a fixed laser intensity. Finally, the thermodynamic properties, activation energy and capture cross section, are subjected to the same analysis. For the wide-ranging
data pool, the author is indebted to both Timothy Chin and Yanan Shieh. Their studies provided information on high dose, high laser intensity silicon doped samples, while the author's samples were mainly of low dose and low intensity.

The experimental set-up is the subject of Chapter II. Also covered there, wherever appropriate, is the theory behind some of the empirical decisions made. Chapter III discusses the results of the author's, Yanan Shieh's and Timothy Chin's experiments in terms of the various correlations mentioned above. Then key observations are crystallized in Chapter IV. Supportive but less critical material is relegated to the appendices. An attempt has been made to give proper credit to original sources where possible yet inevitably, some information is now so widespread that its origin may inadvertently be misconstrued.

1.3 Theoretical Basis

Suppose the temperature of a GaAs sample in a vacuum is lowered to, say, 60 K and then slowly ramped up to, say, 400 K.

It can be seen on Figure 1.1 that the light-pulse-induced current transient decays slowly at low temperatures. The rate of emission increases with
Figure 1.1 Translation of a PITS signal into a spectrum.
temperature. At point a the difference between the current at \( t_1 \) and the current at \( t_2 \) approaches zero because of the extremely slow emission rate. On the other hand, the rate is so fast at point c that by the time the transient reaches \( t_1 \) it will be almost at steady state. Consequently, the change in current within the window is small. Between these extremes lies a point of maximum change in current which appears as a peak on the spectrum shown on the right of Figure 1.1 (Lang, 1974).

Section 2.3 illustrates the mathematical derivations pertaining to the use of rate windows in thermal scans.
CHAPTER II
EXPERIMENTAL TECHNIQUES

2.1 Measuring Resistivity by the Van der Pauw Method

The Van der Pauw technique is a variation of the four point probe method and is used here because of the size of the samples relative to the probe spacings. For the samples under study, only surface resistivity will be determined since the thickness is unknown.

Fig. 2.1.1 The clover-leaf pattern on a sample of arbitrary shape

Consider a thin slice (or lamella) of semi-insulating (SI) GaAs on which an n-type layer has been implanted. A clover-leaf pattern has been pulse-laser annealed on the implant (Fig. 2.1.1). The implanted surface must look smooth and uniform under a microscope if uniformly annealed. We found that non-uniform surfaces were more difficult to make good indium contacts on. The four small contacts should be confined to the tips of the clover-leaf pattern. Their small size prevents contact resistance from appreciably distorting sample resistance.
If a constant current $I_{MN}$ is now applied between M and N in that order, the resultant potential difference, $V_{PO} = V_P - V_Q$ (Fig. 2.1.1), is measurable and from it one can define the resistance

$$R_{MNPO} = \frac{V_{PO}}{I_{MN}}.$$ 

Since uniformity cannot be guaranteed, the current and voltage take-off points are customarily rotated through a quarter turn and the measurement repeated. Then,

$$R_{MPNO} = \frac{V_{MP}}{I_{NO}}.$$ 

If $t$ is the lamella's thickness and the resistivity of GaAs, then the equation (Van der Pauw, 1958)

$$\exp[-(\pi t/\rho)R_{MNPO}] + \exp[-(\pi t/\rho)R_{MPNO}] = 1$$  \hspace{1cm} (2.1.1)

holds. Hence a graphical solution can be found for

$$R_S = \frac{\rho_s}{t} = \left(\frac{\pi}{(2\ln 2)}\right) (R_{MNPO} + R_{MPNO}) f$$  \hspace{1cm} (2.1.2)

where the correction factor

$$f = f(R_{MNPO}, R_{MPNO})$$

is plotted in Fig. 2.1.2. L. J. Van der Pauw (1958) demonstrated that the theory represented by Eqs. (2.1.1) and (2.1.2) holds for arbitrary shapes as well if the four contacts are placed along the circumference of the sample (L. J. Van der Pauw, PTR 20, 1958). In the Solid State laboratory at Kansas State University, the prepared samples were tested in the configuration shown in Fig. 2.1.3.
Fig. 2.1.2 Correction factor for computing specific resistivity. (Ghandhi, 1983).

![Correction factor graph]

Fig. 2.1.3 Block diagram for the Van der Pauw measurement apparatus

The idea here is to take an arbitrary number of readings per current setting at 1-sec. intervals and average them to obtain the Van der Pauw voltage. This process is repeated for reverse currents. All samples were tested using the current settings:

$I = \{1, 3, 10, 30, 100, 300, 1000\}$ microamperes.

All readings were remotely controlled by the program AUTO
(Shieh, 1989) which then calculated \( R_s, R_H, u_H, n_s \) after all the Van der Pauw and Hall effect measurements had been effected on a sample. It may be worth mentioning here that the Van der Pauw-type clover-leaf implant pattern along with the high resistivity of the SI GaAs substrate (\( 10^7-10^8 \) ohm-cm) confine the current streamlines to the implanted layer.

2.2 The Hall Effect Measurement of the Hall Coefficient and the Sheet Carrier Concentration

With reference to Fig. 2.1.1, the electrical connections are now switched so that voltage and current paths are perpendicular to each other. In this experiment current was injected into \( N \) and tapped off at \( P \), i.e. \( (I_{NP}) \) and voltage was measured in the \( M \) to \( O \) orientation as \( V_{MO,NP} \). The measurements were then carried out as before to determine \( R_{MO,NP} \). This time, however, we wanted to compute the change in \( R_{MO,NP} \) when the surface was placed in a magnetic field \( B \) such that the current and the field were at right angles. Let \( R_{HS} \) represent the surface Hall coefficient. Then

\[
R_{HS} = \frac{(R_{MO,NP}(0) - R_{MO,NP}(B))}{B} \tag{2.2.1}
\]

For this formula to work for arbitrary shapes, the contacts need to be small and on the border of the lamella while the lamella itself should be of uniform thickness.
and geometrically hole-free according to Van der Pauw. The magnetic field $B$ induces a Lorentz force $F = q*\mathbf{v}*B$ on the charge carriers, where $\mathbf{v}$ is the carrier velocity. This force acts perpendicular to both the current streamlines and the magnetic induction. In terms of electric field effects, $\mathbf{v}$ can be derived approximately from $F$ as

$$E_{HS} = tF/q = (tJ/nq)B = R_{HS}BJ$$ (2.2.2)

where the surface Hall coefficient is

$$R_{HS} = 1/nqt = 1/N_s q$$ (2.2.3).

From Eq. (2.2.3) we can compute, $N_s$, the surface concentration of the charge carriers as

$$N_s = 1/R_{HS}q$$

Because of the stationarity of the current streamlines under a $B$ field, the current-generated electric field now acquires a component lying transverse to the streamlines but equal and opposite to the apparent Hall electric field. If we then integrate the transverse field $E_t$ from $M$ at right angles to each streamline to an arbitrary point along the far side perimeter, $O_t$ (since the locations of $O$, $M$, $P$ and $N$ were arbitrary in the first place) we obtain the change in potential difference (L. J. Van der Pauw, 1958)

$$\Delta(V_M - V_O) = \int_{M}^{O_t} E_H ds$$
\[ R_H B \int_M^{t_0} J ds \]
\[ = R_H B \left( i_{PN} / t \right) \]  

which is another way of developing (2.2.1). Eq. (2.2.5) is based on the assumed validity of \( \text{div} \ J = 0 \) and \( \text{curl} \ J = 0 \) as argued above, so that the peripheral streamlines completely determine our boundary conditions. The voltage in (2.2.5) also leads to the Hall mobility since it can be defined as

\[ \Delta V_{MO} = \Delta (V_M - V_O) = \left( \mu_H B \rho J / t \right) \]

(2.2.6). If we solve for \( u_H \), then

\[ \mu_H = \left( t / B \right) \left( \Delta R_{MO,PN} / \rho \right) \text{ cm}^2 / \text{V-s} \]  

(2.2.7)

### 2.3 Determining Activation Energy and Capture Cross Section Using PITS

#### A. Effects of the He-Ne laser beam on the sample

We shall regard the sample as an n-type photoductor. In this extrinsic case then incident light generates electron-hole pairs through gap level impurities in contrast to the band-to-band phenomena of the intrinsic case. The dark conductivity equation
\[ \sigma = q (\mu_n n + \mu_p p) \] (2.3.1)

reduces to
\[ \sigma = q\mu_n n \quad \text{since } n \gg p \] (2.3.2).

The depth of the energy level in the gap determines the long-wave cut-off point in the response of the crystal to irradiation. In (2.3.1) the definitions are

- \( q \) = electron charge
- \( \mu_n, \mu_p \) = electron or hole mobility
- \( n \) = number of electrons per unit volume
- \( p \) = number of holes per unit volume

Under illumination, the additional definitions include

- \( n_{\text{opt}} \) = number of carriers generated in a unit volume by a given photon flux, at \( t=0 \), where \( t=0 \) represents the start of the falling edge of the light pulse at an arbitrary time

- \( n(t) \) = number of carriers in the same volume after \( t>0 \).

- \( \tau \) = carrier lifetime,
- \( \eta \) = quantum efficiency,
- \( 1/a \) = light penetration depth,
- \( a \) = absorption coefficient
- \( P_{\text{opt}} \) = incident optical power,
- \( G \) = generation rate at steady state,
- \( R \) = recombination rate.

Then, the carrier concentration \( t \) seconds after removal of the laser pulse is
\[ n = n_{\text{opt}} \exp(-t/\tau) \] (2.3.3)
and
\[ R = \frac{1}{\tau} \]  \hspace{1cm} (2.3.4)
states that carrier lifetime determines the recombination rate. Let us say area, \( A = WL \), and volume = \( WLt \). In the case of laser annealed samples, \( t \ll \frac{1}{a} \) so that the optically active volume is \( WLD \). The total number of photons striking the surface per unit time is \( P_{\text{opt}}/hv \). Consequently, the total generation rate can be expressed as a function of the photo flux, i.e.
\[ G = \frac{n}{\tau} = \eta \frac{P_{\text{opt}}}{hv}/(WLD) \]  \hspace{1cm} (2.3.5)
Instead of computing \( n_{\text{opt}} \) in (2.3.3), we can re-arrange (2.3.5) to find
\[ n = \left( \frac{\eta \tau}{WLD} \right) \frac{P_{\text{opt}}}{hv} \]  \hspace{1cm} (electrons/cm\(^3\))  \hspace{1cm} (2.3.6)
where
\[ hv = \frac{hc}{\lambda} = 1.24/\lambda_{\text{He-Ne}} \]  \hspace{1cm} (eV) in this experiment.
and
\[ \eta = \left( \frac{I_p}{q} \right) \left( \frac{hv}{P_{\text{opt}}} \right). \]
The generated photo-current is
\[ I_p = (\sigma \xi) WD \]  \hspace{1cm} , where \( \sigma = q \mu_n n \)
\[ = (q\mu_n n \xi) WD \]  \hspace{1cm} (2.3.7)
If we substitute for \( n \) from (2.3.6),
\[ I_p = q[\eta \frac{(P_{\text{opt}}/hv)}{[\mu_n \tau \xi /L]}] \]  \hspace{1cm} (2.3.8)
where the photocurrent clearly varies directly with the electron mobility, electron lifetime and the electric field, even though it is primarily generated by the
photons. To emphasize the point, one may define the primary (or unmodified) photo-current as

$$I_{ph} = q[\eta(P_{opt}/h\nu)]$$

so that

$$I_p = I_{ph}[\mu_n \tau \xi /L].$$

B. High-Intensity Illumination

From the point of view of the traps, however, it will now be demonstrated that assuming saturation always occurs, the transient current can be independent of electron flux. As a case in point, our PITS set-up will be analyzed. [Ch. Hurtes, et. al., 1978]

Returning to the beginning of the transient, with no external electrical injection, the occupancy of a trap is

$$N_T^0(0) = N_T/[1 + (e_n + \sigma_p v_p \delta_p)/(e_p + \sigma_n v_n \delta_n)](2.3.10)$$

where (Hurtes, 1978)

- $N_T$ = density of traps
- $e_n, e_p$ = sums of optical and thermal emission rates for electrons and holes respectively.
- $\sigma_n, \sigma_p$ = corresponding capture cross sections
- $v_n, v_p$ = corresponding thermal velocities
- $\delta_n, \delta_p$ = densities of photo-generated carriers, assumed much larger than dark current equivalents.

Long after $t=0$, at steady-state, the dark equilibrium occupancy is
\[ N_T^0(\infty) = N_T / (1 + e_n/e_p) \]  

(2.3.11)

where the high resistivity of the substrate is assumed to reduce the free carrier densities to insignificance (Hurtes, 1978). The trap-generated current at time \( t \) becomes

\[ i(t) = qW(LD/2)[e_n N_T^0(t) + e_p (N_T - N_T^0(t))] , \quad 0 \leq t \leq \infty \]

in which we can let

\[ M = qW(LD/2) \]

and then develop the transient current as

\[ \Delta i(t) = [i(t=0) - i(t=\infty)] \exp(-t/\tau) \]

\[ = M(e_n - e_p)[N_T^0(0) - N_T^0(\infty)] \exp(-t/\tau) \]  

(2.3.12)

based on (2.3.10), (2.3.11) and \( i(t) \). Further substitution, assuming high excitation, yields

\[ \Delta i(t) = M e_n N_T [1/(1+(\sigma_p v_p/\sigma_n v_n)) - (1/1+(e_n/e_p))] \exp(-e_n t) \]  

(2.3.13)

What (2.3.13) simply demonstrates is that under high excitation conditions, \( i(t) \) is independent of photon flux. In our case, use of 25\%T, 50\%T as well as no filter produced saturation. In the case of our n-type samples, \( \sigma_n/\sigma_p > > 1 \) and \( e_n >> e_p \), so that (2.3.13) becomes

\[ \Delta i(t) = M N_T e_n \exp(-e_n t) \]  

(2.3.14)

For the two-gate experiment with \( t_2 \gg t_1 \),

\[ \Delta i(t) = i(t_1) - i(t_2) \]

\[ = i(t=0) - i(t=\infty) \]
implying $1/\tau \sim 1/t_1$ such that

$$1/t_1 = e_n = \sigma_n v_n N_c \exp(-E_T/kT_{\text{max}})$$  \hspace{1cm} (2.3.15)

is the peak equation. For (2.3.15), one runs several scans per sample with different sampling delays $t_1$ and a constant ratio $t_1/t_2$ and records the peaks. Then an Arrhenius plot of $t_1T^2$ ($K^2$s) versus $1/T$ ($K^{-1}$) graphically yields $E_T$ and $\sigma_n$ as the slope and intercept respectively.

On linear-log paper we plot the points ($1000/T$, $t_1T^2$) while as on linear-linear paper the points are ($1000/T$, $\ln(t_1T^2)$). As demonstrated in Appendix C,

$$E_T = \text{slope} \times 1000 \times k$$

$$= 0.0862 \times \text{slope} \hspace{1cm} \text{eV}$$

and

$$\rho_n = \text{intercept} / \gamma_n$$

$$= \text{intercept} / (1.9 \times 10^{20}) \hspace{1cm} \text{cm}^2.$$ 

C. The PITS Workstation

A block-by-block description of the PITS system used in this experiment now follows. The laser system provides coherent light of appropriate intensity. The dark current level is due to the 6 V battery and the series circuit shown in Fig. 2.3.2. At the heart of it all is the measuring instrumentation together with the temperature control and vacuum systems. Next is the computer network.
MODEL 124B/255 Serial 3220/3081 HELIUM-NEON LASER

Operation:

This laser is rated at 15 mW output power at the 632.8 nm wavelength. A plasma tube contains a 90% helium, and 10% neon gas mixture at 250 to 400 N/m². The optical windows at the ends of the tube are positioned at Brewster's angle (53 32' for quartz with λ = 1.45). The tube has a tungsten anode and an aluminum cathode. Brewster's angle surfaces minimize reflection loss. The resonant cavity comprises a flat mirror and a concave mirror specifically designed to reject the 3.39 μm emission and collimate the output beam for minimum divergence (0.75 mrad). In addition, ceramic magnets along the plasma tube also suppress the gain at 3.39 μm while enhancing the 632.8 nm power.

We made measurements using a Scientific Calorimeter Model 36001 with a conversion factor of 101 mV/W and an ambient off-set of 0.6 mV at the time of measuring. Table 2.3.1 shows the readings taken at approximately 2.69 m from the exit hole. It may be worthy of note that the purchase date for this laser is 11/10/84.
<table>
<thead>
<tr>
<th>Value Read (mV)</th>
<th>Power (mW)</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>10.89</td>
<td>between points B and C, no filter.</td>
</tr>
<tr>
<td>0.9</td>
<td>8.9</td>
<td>next to shroud, no filter.</td>
</tr>
<tr>
<td>0.5</td>
<td>4.95</td>
<td>.3 density, 50%T filter, 64Hz Model 50273 Ser. # 345 Oriel.</td>
</tr>
<tr>
<td>0.23</td>
<td>2.28</td>
<td>.6 density, 25%T filter, 64Hz Model 50276 Ser. # 163 Oriel.</td>
</tr>
</tbody>
</table>

Table 2.3.1 He-Ne laser output power measurements.

The laser is already installed under the optical table. To operate, just turn the ON/OFF key to ON. If the emission indicator flicks on, then the beam should emerge within a few seconds. We used a 45 prism and 2 front surface mirrors to direct the beam to the sample in the cryogenic refrigerator. The 50%T filter was an Oriel Corp. Model #50273 serial 345 with nominal density .3, while the 25%T filter was model #50276 serial 163 with .6 density.

![Diagram](image)

Fig. 2.3.1 The laser light source system

The Stanford Research System Model SR540 Optical Chopper
converts the CW output of the He-Ne laser into a pulse train of user-selected frequency. It also serves as an external trigger for both the Boxcar averager and the oscilloscope. Chopper rates can be varied from 4 Hz to 4 kHz while synchronizing signals can be used in the following modes:

- single or dual beam
- sum and difference frequency
- and synthesized chopping to 20 kHz.

Low frequency operation below 100 Hz degrades phase jitter and background noise, while extended periods of operation above 2 kHz will greatly reduce motor lifetime. Line frequency and its harmonics along with any known noise sources need to be avoided. The bottom 10% of the frequency control dial exhibits a degraded phase jitter of the reference output and should be avoided as well.

For our single beam experiment, we used the outer row of the chopper blades. Since long enough pulses for our purposes occurred at 64 Hz for the 10 ms aperture delay, 32 Hz for the 20 ms and about 15 Hz for the 50 ms delay, we found it expedient to design and fabricate a slot blocker with 2 outer slots modeled after the 6/5 slot blade. By varying the slot aperture from 0.42" to 0.84," we could vary the frequency between 64 and 32 Hz without significantly slowing down the chopper wheel. A blocker
with only one slot enabled us to realize frequencies as low as 15 Hz without significant degradation in phase jitter.

![Sample Circuit Diagram](image)

**Fig. 2.3.2 The Sample Circuit**

For fine alignment, we placed the chopper on an adjustable height platform secured to the optical table.

The current $I_S$ is a sum of the current generated by the battery, $I_B$, and the photo-current $i_P$ by the superposition principle. Since it flows through a voltage divider, $R_S$ and $R_L$ it generates a voltage across $R_L$

$$V_L = V_B(R_L/(R_S+R_L))$$

which is tapped off and amplified prior to processing. $R_L$ is in fact used as a transfer function to linearly map $I_S$ into the voltage which the boxcar can process:

$$I_S = V_L/R_L = V_B/(R_S + R_L)$$

The mapping is best when $R_S >> R_L$ so that $R_L$ can be ignored in the computation of $I_S$:

$$I_S \approx V_B/R_S.$$ Still, the need for $R_L$ is obvious from the power relationship
\[ P_L = I_s^2 R_L = I_s V_L \]
in which \( V_L \) would be zero if \( R_L \) were zero. We tried to keep \( R_L \leq R_s/10 \) in these scans, but empirically we also had to raise the PITS signal significantly above the ever-present broadband white noise.

**MODEL 162 BOXCAR AVERAGER with TWO MODEL 166 GATED INTEGRATORS:**

The boxcar averager samples and averages the amplified PITS signal from the ITHACO 120 preamplifier. Both integrators receive the same signal but sample it at different points in time as set by %Initial A and %Initial B aperture delay settings and selected Aperture Delay Range time base. For optimal operation, the gates can be set anywhere between 5\% and 100\% according to the operating manual. In our case, due to the pulse duration of the chopper output signal (trigger) the upper limit was about 88\%, for falling edge triggering. (50 ms coincides with our selected aperture duration, AD). Depending on the sample's impedance we used sensitivity settings of 500, 250 or 100 mV, with the 10 k ohm input impedance selected. We selected exponential averaging which assures a Signal-to-Noise Improvement Ratio of \( \sqrt{2N} \) where \( N = \) number of repetitions required to reach 0.63 of steady state output. At least 5\(^N\) repetitions are necessary to assure
us of this SNIR. With an averaging time constant of 10 ms our $N_{\text{max}} = [450, 3600]$ as shown on Table 2.3.2, where $t_1/t_2$ is $(\%\text{Initial A})/(\%\text{Initial B})$. While a longer averaging time constant would be expected to force broadband white noise to zero in the long run, the SNIR analysis shows that there is a point beyond which $N$ becomes low enough to contribute to signal degradation.

The 10 k ohm input impedance setting was selected to make the boxcar a high input impedance for the preamplifier whose output is 600 ohms. On the other hand the 50 ohm selection would have required a series resistance of 550 ohms for proper impedance matching, since $R_{\text{series}} = Z_{\text{source}} - 50$ ohms. DC coupling was selected to enable us to measure at arbitrarily low frequencies. With ac coupling, the -3dB frequency response occurs at 16 Hz and would possibly attenuate PITS information.

<table>
<thead>
<tr>
<th>$t_1/t_2$</th>
<th>Repetition Rate at:</th>
<th>SNIR at:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 ms</td>
<td>20 ms</td>
</tr>
<tr>
<td>.05/.5</td>
<td>450</td>
<td>900</td>
</tr>
<tr>
<td>.06/.6</td>
<td>540</td>
<td>1080</td>
</tr>
<tr>
<td>.07/.7</td>
<td>630</td>
<td>1260</td>
</tr>
<tr>
<td>.08/.8</td>
<td>720</td>
<td>1440</td>
</tr>
<tr>
<td>.1/1.0</td>
<td>900</td>
<td>1800</td>
</tr>
</tbody>
</table>

Table 2.3.2 Repetition rates for the PITS experiment.
Re-stated, the repetition rate is the number of samples of the signal picked off by the integrator between $t_1$ and $t_2$.

Fig. 2.3.3 Front panel of a series 16X gated integrator
In summary, these are the key parameters in boxcar averager setting:

1) Aperture Delay Range (ADR)

A short ADR minimizes aperture-delay jitter, labelled in Fig. 2.3.4 as E, which can be up to 0.05% of ADR. An excessively long ADR will make the ADR ramp and its overhang (F) overlap the following trigger. In PITS both extremes are important considerations. Since we want to monitor only emission rates or capture rates but not both simultaneously, our ADR needs to be selective.

2) Aperture Duration

The aperture duration (AD) is used to optimally balance resolution, SNIR, and measurement time. Best results require a shorter AD (giving a higher resolution) even though this lengthens the time taken to complete a measurement.

3) Time Constant

Since the time constant TC, affects both the SNIR, as already shown, and the measurement time, an optimal setting can be found by using the main-frame Signal Processing TC (SPTC), to boost the SNIR while shortening the measurement time with the averaging TC.
Fig. 2.3.4 Key boxcar operational parameters
(Source: Operating and Service Manual, 1983)
4) Trigger Period ($P_{\text{max}}$)

Use Fig. 2.3.5 to determine the upper limit on this.

5) Scan Time

The best way to select an optimal scan time is to use the formula

$$T_{\text{smin}} = 5[(SPTC)^2 + (OTC)^2]^{1/2} \frac{ADR}{AD},$$

where OTC is the observed time constant:

$$OTC = \frac{TC}{duty \text{ factor}},$$

and
duty factor = $\frac{AD}{\text{trigger period}}$.

Our decisions regarding these 5 parameters are discussed in detail in appendix B.

The ITHACO 1201 Low Noise Preamplifier:

This instrument amplifies the low level PITS signal as shown in Fig. 2.3.6. We set the high pass filter to ground and the low pass filter to either 10 kHz or 3 kHz depending on the noise level. Any setting below 3 kHz affected the actual shape of the PITS signal while above 10 kHz, white noise output significantly escalated. Most samples required a gain of 200 but a few gave good signals at 100 or even at 50.
Fig. 2.3.6 Basic schematic of the ITHACO 1201 preamplifier.

The HP1742A 100 MHz Oscilloscope:

The oscilloscope was mainly used to display the amplified PITS signal, the location of the gates relative to the decaying exponential edge. The alignment between the trigger signal provided by the chopper and the sample's response (the PITS signal) is also checked with the scope. It also came in handy for quick system troubleshooting and noise-level estimation when necessary.

The HP7045B X-Y Recorder

This X-Y recorder accepts floating dc or ac inputs to a 200 V peak. It has a constant high input impedance of one mega-ohm. Our unit is calibrated to within +/- 1 mm for the x and y axes. The typical accuracy rating is +/- 0.2% of full scale. It was used in the local control mode even though it has a remote control option.
In order to plot PITS signals (y) against temperature (x) we used the x-y mode. For the majority of the scans, the x and y settings of 0.1 V/cm and 0.25 V/cm respectively provided ample magnification at various settings of boxcar sensitivity and preamplifier gain. To maintain calibration, we ensured that the zero controls always actuated a response when turned.

If precautions in the Operating and Servicing Manual are followed, the X-Y recorder is rather straightforward to operate.

The Fluke 8520A Programmable Digital Multimeter:

The DMM was used mainly by the computer to read the DC voltage of the boxcar output at different points along the temperature scan.

The Cryosystems LTS Closed Cycle Refrigerator System:

This system was used to control temperature for measurements between 30 K and 360 K without the use of external supplies of liquid nitrogen and helium. Some comments on individual components follow:

Model SC 8032224 compressor unit:

The main thing to watch for here is the gas pressure indicator which read about 260 psi before power
up. Turn on/off should always be in the sequence COMPRESSOR ON-PUMP ON then PUMP OFF-COMPRESSOR OFF. Cooling without temperature control is fairly rapid in that from room temperature we could reach 30 K in less than 30 minutes.

Model 22 Cold Head/Vacuum Shroud Assembly:

As Fig. 2.3.7 illustrates this has provision for rough pumping to evacuate ambient gases from the vacuum shroud before turning on the compressor. For best results we kept the rough pump running throughout the scan to forestall possible leakage. Leakage at low pressure would cause moisture to condense on the inside surfaces of the cold head and drastically hamper the cooling process. This is because convection heat conduction greatly adds to the heat load of the cold finger. Whenever this happened, we regenerated the vacuum in the shroud for 30 minutes or so at high temperature, i.e. above room temperature, before continuing.

Model DRC-81C Temperature Controller

The controller balances the cooling effect of the refrigerator by supplying heat through a DC resistance temperature control heater. The heating coil is wrapped around the cold finger just below the cold head, i.e. the
Fig. 2.3.7 The refrigeration system.
Fig. 2.3.8 Silicon diode sensor response curve

Platform onto which the sample is fixed. We used a Lakeshore DT-470-SD-12 silicon diode sensor. Its tolerance is specified in 3 ranges as follows:

\[
\begin{align*}
0 \text{ K} & - 100 \text{ K} & 100 \text{ K} & - 305 \text{ K} & 305 \text{ K} & - 475 \text{ K} \\
\pm/\pm 0.5 \text{ K} & & \pm/\pm 1.0 \text{ K} & & \pm/\pm 2.0 \text{ K}
\end{align*}
\]

For each range we had to modify the RAMPING program to automatically alter the GAIN, RATE and RESET values for a smooth temperature response. An example is shown in App-
endix F [SUPRAMED, 1989]. The resident PROM (MB81C.OBJ) is calibrated specifically for the DT-470-SD-12 sensor response curve (Fig. 2.3.8). The most difficult task is the manual setting of these values on the front panel, but the beauty of software control is that once set in code they remain till the sensor is changed.

The HP 86B Computer Control System

We used this for both the Hall effect/Van der Pauw measurements and PITS scans. In PITS measurements we ran scans at 1 or 2 K/min depending on the quality of the sample and the contacts. Programs in Appendix D were written in BASIC and adapted for this application by various graduate students.

SUPRAMED is a modification of the ramping program in the DRC-81C Manual. PITS scans of SIGNAL vs. TEMP were plotted using LINPLOT (Doerfler, 1984), while ARRPLOT (Dlodlo, Doerfler, 1989) gave us Arrhenius plots. LINFITMD (Dlodlo, Eckhoff, 1989) computes activation energy and capture cross section based on the Arrhenius data points.

Overall System Summary

Basically, the idea is to energize the sample enough to populate whatever traps might be in the GaAs
bandgap of the annealed layer and then monitor the traps over a temperature range as they undergo depopulation. The procedure for this is to turn on the instrumentation panel and the computer. Next, turn on the rough pump and let it create a vacuum in the shroud for a few minutes. The compressor and coldhead along with the battery circuit may be next followed by the laser.

Figure 2.3.9 illustrates how the various components already discussed separately fit together. One of the limitations of the HP-86 computer is that once scanning is underway no user interaction is possible so that data analysis comes to a halt.
Fig. 2.3.9 The PITS system block diagram.
CHAPTER III
RESULTS AND DISCUSSION

3.0 Introduction.

As already noted in chapter 1, the focus here is on the laser annealed samples so far studied in this laboratory. First, correlations between electrical characteristics and laser intensity are discussed. Then the influence of dose on the characteristics is analyzed in the same light. Finally, the thermodynamic properties are surveyed for both laser and furnace annealed samples.

3.1 Van der Pauw and Hall Effect Measurements.

With reference to Table 3.1a we note that for pulsed-laser annealed samples, mobility and sheet resistivity are each linearly correlated with laser intensity at the various orders of dose magnitude. The linear relationship is illustrated by Figures 3.1 and 3.2. Patently, an increase of mobility with laser intensity was observed, along with the corresponding decline in resistivity. The inverse relationship between mobility and resistivity that was developed in equation (2.2.7) is confirmed here. On the other hand, no linear correlation could be established between sheet carrier concentration and laser intensity (Fig. 3.3).
Table 3.1a: Dependence of electrical characteristics on laser intensity. Dose = 2.0 \times 10^{13}\text{cm}^{-2}

<table>
<thead>
<tr>
<th>Laser Intensity (J/cm$^2$)</th>
<th>Mobility (cm$^2$/V-s)</th>
<th>Sheet carrier concentration (cm$^{-2}$)</th>
<th>Sheet resistivity (ohm/sheet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.26</td>
<td>229</td>
<td>6.2\times10^{13}</td>
<td>443</td>
</tr>
<tr>
<td>0.305</td>
<td>271</td>
<td>6.2\times10^{13}</td>
<td>376</td>
</tr>
<tr>
<td>0.32</td>
<td>279</td>
<td>1.0\times10^{14}</td>
<td>214</td>
</tr>
</tbody>
</table>

Correlation coefficients: 0.9957 0.6934 -0.8697

Fig. 3.1 Mobility as a function of laser intensity.
Dose = 2.0 \times 10^{13}\text{cm}^{-2}
Fig. 3.2 Resistivity as a function of laser intensity.

Dose = $2.0 \times 10^{13}\text{cm}^{-2}$

Fig. 3.3 Sheet carrier concentration versus laser intensity. Dose = $2.0 \times 10^{13}\text{cm}^{-2}$
Tests by Tim Chin (1987) tended to suggest a quadratic or parabolic fit for both mobility and sheet carrier concentration. Comparing the results, it can be seen that fairly similar data points were obtained for the $2 \times 10^{13}$ cm$^{-2}$ samples. Up to around $0.32$ J cm$^{-2}$, mobility improves with increasing laser intensity, yet, evidently, thereafter it deteriorates. Again, it has been found previously (Rys, et al, 1987; Emerson, et al, 1980) that an optimum anneal energy may exist. Rys et al (1987) further pointed out that beyond a certain optimum temperature, arsenic out-diffuses during pulsed laser annealing, an occurrence that would alter the material's properties. More importantly, since PLA does introduce traps into the crystal, the trade-off between the capacity to restore order and the capacity to add to the disorder must reach a balance somewhere, at the optimum laser intensity.

The influence of dose is illustrated in Table 3.1b and Figure 3.4. Evidently, The sheet carrier concentration has a linear correlation (coefficient, $r = -0.76$) with dose. On the other hand, the correlation coefficient is significantly low for mobility and sheet resistivity.
Table 3.1b Dependence of electrical characteristics on dose. $I = 0.32 \, J/cm^2$

<table>
<thead>
<tr>
<th>Dose $cm^{-2}$</th>
<th>Mobility $(cm^2/V-s)$</th>
<th>Sheet carrier concentration $(cm^{-2})$</th>
<th>Sheet resistivity $(ohm/sheet)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4.0 \times 10^{12}$</td>
<td>249</td>
<td>$1.2 \times 10^{14}$</td>
<td>218</td>
</tr>
<tr>
<td>$2.0 \times 10^{13}$</td>
<td>298</td>
<td>$1.0 \times 10^{14}$</td>
<td>205</td>
</tr>
<tr>
<td>$1.0 \times 10^{14}$</td>
<td>232</td>
<td>$1.0 \times 10^{14}$</td>
<td>264</td>
</tr>
<tr>
<td>$6.0 \times 10^{14}$</td>
<td>282</td>
<td>$1.0 \times 10^{14}$</td>
<td>214</td>
</tr>
</tbody>
</table>

Correlation coefficients: 0.1523  -0.7632  0.2104

Fig. 3.4 a) Dose dependence of electron mobility.

Intensity, $I = 0.32 \, J \, cm^{-2}$.
(Data : Courtesy, Yanan Shieh, 1989)
Fig. 3.4 Dose dependence of b) sheet carrier concentration
c) sheet resistivity.

Intensity, $I = 0.32 \text{ J cm}^{-2}$.
(Data : Courtesy, Yanan Shieh, 1989)
3.2 Correlation between Trap Energy and Capture Cross Section

Table 3.2 summarizes the processed data from the PITS measurements. The peaks are grouped according to increasing temperature and then numbered in groups of 1 to 5. Each realization of a peak within a group is further identified by a small letter (a through f). The sample identification numbers on the right are arbitrary mnemonics where "L" means the sample is pulsed laser annealed, "A" or "B" refers to the parent wafer as specified in the wafer documentation and the number that follows is the dose code, e.g. "4012" means the dose is $4.0 \times 10^{12}$cm$^{-2}$. The suffixed letters "A" to "D" are the samples' locations on the respective wafers. Each line of data represents the mean of several scans of the sample using different rate windows.

For this analysis, the peaks in Table 3.2 were re-ordered according to increasing energy instead of temperature and then labelled as in Table 3.3. Initially, attempts were made to keep the temperature groups arbitrarily intact but the capture cross sections appeared to reveal finer underlying patterns within these groups. Regression analysis was performed on the groups indicated in Table 3.3. Due to the re-grouping by capture cross section, prefixes "A" to "F" have been added to the peak
Table 3.2. Thermodynamic properties of traps in Si:GaAs.

<table>
<thead>
<tr>
<th>Peak #</th>
<th>Mean $T_m$(K)</th>
<th>$E_t$(eV)</th>
<th>$\sigma_n$(cm$^2$)</th>
<th>Sample #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. a.</td>
<td>35.0 +/-0.73</td>
<td>0.019</td>
<td>1.2 e-18</td>
<td>LA4012B</td>
</tr>
<tr>
<td>b.</td>
<td>36.9 +/-2.28</td>
<td>0.016</td>
<td>3.4 e-19</td>
<td>LA2013D</td>
</tr>
<tr>
<td>c.</td>
<td>41.9 +/-1.95</td>
<td>0.014</td>
<td>7.7 e-20</td>
<td>LA4012A</td>
</tr>
<tr>
<td>d.</td>
<td>43.2 +/-0.96</td>
<td>0.008</td>
<td>1.3 e-20</td>
<td>LA2013B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. a.</td>
<td>52.9 +/-1.18</td>
<td>0.022</td>
<td>1.7 e-19</td>
<td>LB6014A</td>
</tr>
<tr>
<td>b.</td>
<td>56.2 +/-1.76</td>
<td>0.068</td>
<td>1.0 e-15</td>
<td>LA2013A</td>
</tr>
<tr>
<td>c.</td>
<td>56.6 +/-0.88</td>
<td>0.089</td>
<td>5.3 e-14</td>
<td>LA2013B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. a.</td>
<td>78.5 +/-1.66</td>
<td>0.056</td>
<td>1.6 e-18</td>
<td>LA4012B</td>
</tr>
<tr>
<td>b.</td>
<td>80.8 +/-1.63</td>
<td>0.091</td>
<td>2.1 e-16</td>
<td>LA2013B</td>
</tr>
<tr>
<td>c.</td>
<td>81.3 +/-2.35</td>
<td>0.103</td>
<td>9.7 e-16</td>
<td>LA2013A</td>
</tr>
<tr>
<td>d.</td>
<td>82.86 +/-0.96</td>
<td>0.138</td>
<td>9.8 e-14</td>
<td>LA4012A</td>
</tr>
<tr>
<td>e.</td>
<td>88.1 +/-1.32</td>
<td>0.064</td>
<td>2.3 e-18</td>
<td>LB6014A</td>
</tr>
<tr>
<td>f.</td>
<td>96.6 +/-1.68</td>
<td>0.176</td>
<td>3.3 e-13</td>
<td>LA2013D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. a.</td>
<td>152.4 +/-2.17</td>
<td>0.184</td>
<td>1.2 e-16</td>
<td>LA4012B</td>
</tr>
<tr>
<td>b.</td>
<td>153.9 +/-</td>
<td>0.56</td>
<td>1.1 e-19</td>
<td>LA2013A</td>
</tr>
<tr>
<td>c.</td>
<td>154.4 +/-1.53</td>
<td>0.52</td>
<td>1.0 e-19</td>
<td>LA2013D</td>
</tr>
<tr>
<td>d.</td>
<td>160.6 +/-2.31</td>
<td>0.144</td>
<td>2.8 e-18</td>
<td>LA4012A</td>
</tr>
<tr>
<td>e.</td>
<td>166.0 +/-1.27</td>
<td>0.23</td>
<td>1.3 e-20</td>
<td>LA2013B</td>
</tr>
<tr>
<td>f.</td>
<td>169.5 +/-2.73</td>
<td>0.129</td>
<td>9.9 e-19</td>
<td>LB6014A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. a.</td>
<td>319.8 +/-3.14</td>
<td>0.69</td>
<td>2.0 e-12</td>
<td>LA4012A</td>
</tr>
<tr>
<td>b.</td>
<td>322.8 +/-1.76</td>
<td>0.71</td>
<td>3.5 e-17</td>
<td>LA2013B</td>
</tr>
<tr>
<td>c.</td>
<td>325.8 +/-3.15</td>
<td>0.57</td>
<td>1.5 e-14</td>
<td>LA4012B</td>
</tr>
<tr>
<td>d.</td>
<td>327.4 +/-3.42</td>
<td>0.34</td>
<td>7.4 e-18</td>
<td>LB6014A</td>
</tr>
</tbody>
</table>
Table 3.3 Peak grouping by correlation.

<table>
<thead>
<tr>
<th>Peak Group Number</th>
<th>Temp. (K)</th>
<th>$E_t$ (eV)</th>
<th>$\sigma_n$ ($x 10^{-20} \text{cm}^2$)</th>
<th>Least Squares Fit</th>
<th>Correl. Coeff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1.d</td>
<td>43.2</td>
<td>0.008</td>
<td>1.3</td>
<td></td>
<td>Exponential 0.98</td>
</tr>
<tr>
<td>A1.c</td>
<td>41.9</td>
<td>0.014</td>
<td></td>
<td></td>
<td>7.7</td>
</tr>
<tr>
<td>A1.b</td>
<td>36.9</td>
<td>0.016</td>
<td>34.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1.a</td>
<td>35.0</td>
<td>0.019</td>
<td>120.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2.a</td>
<td>52.9</td>
<td>0.022</td>
<td>17.0</td>
<td></td>
<td>Exponential 1.00</td>
</tr>
<tr>
<td>B2.b</td>
<td>56.2</td>
<td>0.068</td>
<td>100,000.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2.c</td>
<td>56.6</td>
<td>0.089</td>
<td>5,300,000.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3.a</td>
<td>78.5</td>
<td>0.056</td>
<td>160.0</td>
<td></td>
<td>Insufficient data</td>
</tr>
<tr>
<td>C3.e</td>
<td>88.1</td>
<td>0.064</td>
<td>230.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D3.b</td>
<td>80.8</td>
<td>0.091</td>
<td>21,000.0</td>
<td></td>
<td>Either</td>
</tr>
<tr>
<td>D3.c</td>
<td>81.3</td>
<td>0.103</td>
<td>97,000.0</td>
<td></td>
<td>Exponential 0.96</td>
</tr>
<tr>
<td>D3.d</td>
<td>82.86</td>
<td>0.138</td>
<td>9,800,000.0</td>
<td>or</td>
<td></td>
</tr>
<tr>
<td>D3.f</td>
<td>96.6</td>
<td>0.176</td>
<td>33,000,000.0</td>
<td></td>
<td>Power 0.98</td>
</tr>
<tr>
<td>E4.f</td>
<td>169.5</td>
<td>0.129</td>
<td>99.0</td>
<td></td>
<td>Either</td>
</tr>
<tr>
<td>E4.d</td>
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</tr>
<tr>
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<td>or</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Power 1.00</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
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</tr>
</tbody>
</table>
numbers used in Table 3.2. In the new scheme, note that
groups A and B are still the original groups 1 and 2 in
Table 3.2. C and D split up group 3 peaks while E and
F subdivide group 4 into two respective subgroups based on
the thermally referenced behavior of the cross sections.
The carrier cross sections were found to change
exponentially within these subgroups and this behavior of
the capture cross section led to the use of the prefixes
to aid in the subdivision. The Table 3.2 identities of the
peak groups have been preserved through the numbers 1 to 5
following the prefixes.

The energies were treated as the independent
variable while the cross sections were made dependent. The
objective was to find out if there was any correlation
between the magnitude of a trap energy and its
corresponding cross section. In each group, a strong
correlation was observed with a correlation coefficient in
the range 0.96 <= r <= 1.0. Cross sections tend to
increase exponentially with activation energy, which
suggests a definite pattern throughout. From group D on to
the deeper traps, a power relationship emerges as a better
model than the exponential, at least in terms of the
correlation coefficient. Group G actually gives a perfect
fit to a quadratic curve.

These observations intuitively suggest that
peaks are distinguishable not only by their energies but by the group they fall into. The group encompasses peaks with identical temperature response as evidenced by the change in capture cross sections with both temperature and energy. In groups A, E, F and G cross sections and energies decrease with increasing temperature unlike groups B, C and D whose energies and cross sections increase with temperature. This manner of viewing the peaks offers a potential tool for making finer distinctions among traps that might otherwise appear identical. Different thermal behavior suggests differences in material characteristics that may not be revealed by trap energy alone.

In addition, we may be able to distinguish peaks having the same activation energy by both peak temperature range and cross section either collectively or separately. Examples include peaks G5.c and F4.b which occur in the respective temperature ranges 319.8 - 327.4 K and 152.4 - 169.5 K and yet have the same activation energy, 0.56 eV +/-1.8 %.

Also observed was an invariable increase of the cross section with trap energy within each group. The pattern of changes in cross section has some periodicity from group to group. Apparently, there is need for caution in classifying peaks using the cross sections due to this
behavior. See peaks A1.d and F4.e. Before peaks can be identified as being the same, their activation energy, capture cross section and peak temperature should match within the bounds of a system error.

It has been asserted (Blakemore and Rahimi, 1984) that the multiphonon emission (MPE) theory may explain the behavior of cross sections in a way that reveals complicated thermal dilational characteristics. According to this theory (Blakemore and Rahimi, 1984), the capture cross section is the thermal average

$$\text{MPE} = \frac{A}{(2kT^*Sh_\text{w})} \exp(-E_B/kT^*)$$

where

- $S$ is the Huang-Rhys factor for a single equivalent phonon energy, $hw$
- $T^* = [hw\coth(hw/4kT)]/4k$
- $A \approx 10^{-14} \text{ cm}^2 \text{ eV}$, a parameter.

In order to test the applicability of the MPE theory to the above intuitive observations, it was tried on previously collected data (Yanan, 1989). The data was also arranged in the manner of Table 3.3 and the result is displayed in Table 3.4. Peak identification labels P1 to P5 before the colon are in line with Yanan's identific-
Table 3.4 Peak grouping by correlation. (Source: Yanan, 1989)

<table>
<thead>
<tr>
<th>Peak Group Number</th>
<th>Temp. (K)</th>
<th>$E_t$ (eV)</th>
<th>$n \times 10^{-19} \text{cm}^2$</th>
<th>Least Squares Fit Correl. Coeff.</th>
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<tr>
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<tr>
<td>3</td>
<td>60</td>
<td>0.05</td>
<td>320.0</td>
<td>or Power 0.90</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
<td>0.06</td>
<td>1000.0</td>
<td></td>
</tr>
<tr>
<td>5</td>
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</tr>
<tr>
<td>6</td>
<td>58</td>
<td>0.07</td>
<td>27000.0</td>
<td></td>
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<td>P2:1</td>
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<td>Either</td>
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<td>2</td>
<td>83</td>
<td>0.08</td>
<td>1500.0</td>
<td>Exponential 0.90</td>
</tr>
<tr>
<td>3</td>
<td>86</td>
<td>0.09</td>
<td>2300.0</td>
<td>or Power 0.96</td>
</tr>
<tr>
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<td>83</td>
<td>0.09</td>
<td>8900.0</td>
<td></td>
</tr>
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<td>or Power 0.89</td>
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Table 3.5 Peak grouping by correlation - sample identification. (Source: Yanan, 1989)

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<th>Temp. (K)</th>
<th>$E_f$ (eV)</th>
<th>$\sigma_n$ ($\times 10^{-19}$ cm$^2$)</th>
<th>Sample Number</th>
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<td>F4012</td>
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<td>320.0</td>
<td>L2013</td>
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50
ation scheme while the subdivisions comply with the scheme developed for Table 3.3.

As already depicted by the MPE theory, there is no simple correlation between the peak temperature and the capture cross section. On the contrary, activation energy gives an exponential fit with $0.875 \leq r \leq 0.996$ or a power fit with $0.893 \leq r \leq 0.998$. The reader should note that in Table 3.3 we were dealing with PLA silicon doped samples exclusively. By contrast, Table 3.4 is a mixed group including selenium and silicon implanted PLA as well as furnace annealed (FA) samples. Table 3.5 indicates the source sample's identity number according to Shieh (1989). Comparing Tables 3.3 and 3.4, one may infer that the MPE theory holds in this case and supports the hypothesis of an approximately exponential relationship between the activation energy and the capture cross section. However, the relationship between the latter and temperature change is not as straightforward. Fig. 3.5 is a scatter diagram of the logarithm of the cross section as a function of activation energy and peak temperature. The data is from Table 3.3 and is used here to graphically illustrate the validity of the indicated least squares approximations. The curves were inserted by hand to show the sequences.
**Fig. 3.5**

**CORRELATION of $6\eta$ vs $E_t$**
Hall Effect and Van der Pauw measurements were made on PLA silicon and selenium doped GaAs samples. Comparisons were made with previous results from this laboratory. Correlation studies on the data indicate that electron mobility improves with increasing PLA light intensity only up to a point between 0.32 and 0.33 J cm$^{-2}$. Beyond that it declines significantly. It appears as though higher intensities dislodge inordinate amounts of ions from the silicon nitride cap. In turn this intensifies the influence of impurity scattering in the annealed layer. Higher intensity also triggers the possible out-diffusion of arsenic by elevating the temperature. This may make the annealed sample less conductive. Intensities lower than 0.3 J cm$^{-2}$ produce low mobilities as well but for different reasons. This time inadequate re-ordering of the implant damaged crystal is the cause.

Unlike mobility, sheet carrier concentration is more directly correlated with dose than with laser intensity. Higher dose samples produced lower concentrations than low dose ones, relative to their respective doses. In both cases, nevertheless, activation is still
high, yet, in spite of this, impurity-induced scattering and possibly elemental out-diffusion during annealing manage to keep mobility low.

Results of PITS scans carried out by Yanan Shieh were also reviewed and compared with the author's. For both sets of data, correlations between trap activation energy and capture cross section were investigated. It was found that relations between these characteristics tend to be exponential within particular temperature ranges. Inter-range behavior of the cross section is periodic while that of the activation energy monotonically increases with temperature. The periodic behavior seems to indicate an orderly crystalline response to temperature change. There is a chance that if we can isolate these patterns for various impurities in GaAs we may be able to identify the sources of certain peaks without being tied down to a specific temperature.

The importance of this is that realizations at specific temperatures are so far not always reproducible. May we note, parenthetically, that some of the peaks are due to residual crystal damage from ion implantation, rather than impurities. Notwithstanding this point, the value of taking into account the activation energy, the capture cross section as well as the temperature range of the trap is that collectively these characteristics
constitute a more precise distinction among the peaks. Consequently, unraveling a definite pattern of relationships among them becomes important.
REFERENCES


Sorab K. Ghandhi, VLSI Fabrication Principles. Si and GaAs, Wiley Interscince, 1983.


APPENDIX A

TABLES OF SCAN DATA BY SAMPLE

These are the tables of data as collected for each sample. PITS scans are listed first followed by the electrical scans, viz. Van der Pauw and Hall Effect.

Peak location numbers are included as a cross-reference to Table 3.2. PITS scan numbers are indices denoting the sequence in which the scans were taken. They cross-reference the actual readings on the X-Y charts.
SOURCE: Motorola 4264A wafer.

Si:GaAs Dose: 4.0 x10^{12} \text{ cm}^{-2}

Anneal Laser Intensity: 0.29 J cm^{-2}

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<th>Y (ln( *T^2))</th>
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**LA4012A (cont.)**

**HALL EFFECT and VAN DER PAUW READINGS**

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SOURCE: Motorola 4264A wafer.
Si:GaAs Dose: 4.0 x10^{12} \text{ cm}^{-2}
Laser Intensity: 0.29 \text{ J cm}^{-2}

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<tr>
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LA4012B (cont.)

**HALL EFFECT and VAN DER PAUW READINGS**

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<th>( V_{VDP1} ) (mV)</th>
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**SOURCE**: Motorola 4264A wafer.

**Si:GaAs**: 2.0 x10^{13} \text{ cm}^{-2}

**Anneal**: Laser Intensity: 0.32 J cm^{-2}

### PITS Scan

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### HALL EFFECT and VAN DER PAUW READINGS

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<th>V_B (mV)</th>
<th>V_{VDP1} (mV)</th>
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Si:GaAs: 2.0 \times 10^{13} \text{ cm}^{-2}
Dose: 2.0 \times 10^{13} \text{ cm}^{-2}
Anneal Laser Intensity: 0.305 J cm^{-2}

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**HALL EFFECT and VAN DER PAUW READINGS**

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SOURCE: Motorola 4264A wafer.
Si:GaAs Dose: 2.0 \times 10^{13} \text{ cm}^{-2}
Anneal Laser Intensity: 0.26 \text{ J cm}^{-2}

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HALL EFFECT and VAN DER PAUW READINGS

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A9
LA2013D
SOURCE: Motorola 4264A wafer.
Si:GaAs
Dose: $2.0 \times 10^{13}$ cm$^{-2}$
Anneal Laser Intensity: 0.26 J cm$^{-2}$

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HALL EFFECT and VAN DER PAUW READINGS

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<th>V$_{B}$ (mV)</th>
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SOURCE: Motorola 4264B wafer.
Si:GaAs: $6.0 \times 10^{14}$ cm$^{-2}$
Laser Intensity: $0.29$ J cm$^{-2}$

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<th>Y (ln($^2$T))</th>
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### HALL EFFECT and VAN DER PAUW READINGS

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<th>$V_{B}$ (mV)</th>
<th>$V_{\text{VDP1}}$ (mV)</th>
<th>$V_{\text{VDP2}}$ (mV)</th>
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All
SOURCE: Honeywell 21 and 23 LEC SI
Se:GaAs
Dose: $2.2 \times 10^{12}$ cm$^{-2}$
Anneal Laser Intensity: $0.234$ J cm$^{-2}$

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<tr>
<th>PITS (ms)</th>
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<th>Y (ln(T^2))</th>
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**HALL EFFECT and VAN DER PAUW READINGS**

<table>
<thead>
<tr>
<th>$I_{NP}$ (mA)</th>
<th>$V_{static}$ (mV)</th>
<th>$V_B$ (mV)</th>
<th>$V_{VDP1}$ (mV)</th>
<th>$V_{VDP2}$ (mV)</th>
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</thead>
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<td>10.7624</td>
<td>15.6410</td>
<td>4.0570</td>
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</table>
APPENDIX B

RATE WINDOW SELECTION

The rate window specifications set out below are results of different attempts to get as sharp a set of peaks as possible. Initially, there was a general agreement that 10 ms was low enough for the aperture duration range at 64 Hz chopper frequency. The 64 Hz frequency was later changed to 32 and then 20 Hz. A low frequency was desirable in order for the pulse to last long enough to populate the traps. Chapter II already covered the manner in which we avoided phase jitter. Virtually all the PITS scans listed in Appendix A were made in the 20 and 50 ms ADR settings in the manner detailed here.

A $t_1/t_2$ ratio of 10 was used. Anything greater than 8 would have sufficed (Itoh and Yanai, Conf. Ser.). Generally, as $t_1$ gets smaller, the low peaks become shoulders but at the upper end, $t_{2\text{max}}$ is also limited to 43 ms or 86 % of ADR in the 50 ms range. There is no similar upper limit in the 20 ms range yet for all ranges there is an absolute minimum $t_1$. This is the point at which $t_1 = t_0$, i.e. the beginning of the decaying exponent. In other words, $t_0$ separates the trap-filling and the trap-emptying phases of the PITS transient. Fig. B.1 illustrates the constraints while Table B.1 lists the selection of settings used.

B1
Table B.1 Rate window selection array.

<table>
<thead>
<tr>
<th>t₁ /t₂</th>
<th>(%A)/(%B)</th>
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<th>20 ms</th>
</tr>
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<td></td>
</tr>
<tr>
<td>9/90</td>
<td></td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>8/80</td>
<td>4.0</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>7.5/75</td>
<td></td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>7/70</td>
<td>3.5</td>
<td>1.4</td>
<td></td>
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<tr>
<td>6/60</td>
<td>3.0</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>5/50</td>
<td>2.5</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>
Fig. B.1 a) The 20 Hz chopper-controlled laser pulse train which fills the traps with electrons.

b) The PITS signal showing the exponential trap filling (rising edge) and emptying (falling edge). Note that $t_0$ marks the beginning of trap emptying.

c) Times $t_1$ and $t_2$ mark the interval over which the integrators sample the PITS signal and give the spectrum in Fig. B.2.

Waveforms of PITS measurements
Fig. B.2 The jagged waveform is the noisy spectrum before smoothing. Using a 3-point moving average produced the smoothed spectrum. Several such scans are used in developing Arrhenius plot data.
ARRHENIUS PLOT FOR SAMPLE HLSI3SxB

Fig. B.3 The Arrhenius plot for LB6014A showing excellent low temperature behavior of peaks.
C.1 Statistical solution for $E_t$ and $\sigma_n$ and the linear correlation coefficient, $r$.

Regression coefficients $a$ and $b$, which are constants, are used to estimate the intercept and the slope coefficients for each pair of peak data points $(x_i, y_i)$. The least squares line approximating the $n$ pairs of data points has the equation (Freund and Walpole, 1980)

$$y = a + bx \quad \ldots \ldots (C.1)$$

To determine the constants $a$ and $b$ the normal equations of the least squares line

$$\Sigma_i y = an + b \Sigma_i x$$
$$\Sigma xy = a \Sigma x = b \Sigma x^2 \quad \ldots \ldots (C.2)$$

must be solved. (Subscripts are assumed for $x$ and $y$). The solutions yield

$$a = \frac{(\Sigma y)(\Sigma x^2) - (\Sigma x)(\Sigma xy)}{n \Sigma x^2 - (\Sigma x)^2}$$
$$b = \frac{n \Sigma xy - (\Sigma x)(\Sigma y)}{n \Sigma x^2 - (\Sigma x)^2} \quad \ldots \ldots (C.3)$$

Here, $a$, which determines the intercept, depends on the origin while the slope coefficient $b$ is invariant under a translation of axes. In solving

$$\ln(\tau T^2) = -\ln(\gamma_n \sigma_n) + E_t / kT \quad \ldots \ldots (C.4)$$
for trap energy and cross section, let

\[ E_T = \text{slope} \times 1000 \times k \]
\[ = 0.0862 \times b \]

...(C.5)

and let

\[ \sigma_n = \left(\frac{1}{\gamma_n}\right) \times \exp(\text{abs(intercept)}) \]
\[ = (5.2632 \times 10^{-21}) \times \exp(-a) \]

...(C.6)

where

\[ \text{slope} = b \]
\[ = \left(\frac{T}{1000}\right) \left[ \ln(T^2) + \ln(\gamma_n \sigma_n) \right] \]

...(C.7)

and the relation of (C.1) to (C.4) is rather obvious. These equations, save (C.4), constitute the key algorithm of the program LINFITMD modified by the author from LINFIT (N. Dean Eckhoff, 1986).

The linear coefficient, \( r \), can be formed from the standard error of estimate \( S_{y.x} \) of \( \ln(\tau T^2) \) on \( (1000/T) \) or, in general, \( y \) on \( x \). The standard error of estimate measures the scatter of the data points \( y \) about the regression curve (Spiegel(SCHAUM), 1975):

\[ S_{y.x}^2 = \frac{\left[ (\Sigma y^2 - a \Sigma y - b \Sigma xy) / (n-2) \right]}{S^2} \]

\[ = S^2 \ (1 - r^2) \quad , \quad r^2 \leq 1 \]

...(C.8)

where

\[ r^2 = 1 - \frac{\sum(y - y_{est})^2}{\sum(y - E(y))^2} \]

...(C.9)

and
\[ \Sigma (y - E(y))^2 = \Sigma (y - \text{\(y_{\text{est}}\))}^2 + \Sigma (\text{\(y_{\text{est}}\)} - E(y))^2 \quad \ldots (C10) \]

In words equation (C.10) states that

Total variation = Unexplained variation + Explained variation

in that order. Hence combining (C.9) and (C.10)

\[ r^2 = \frac{\Sigma (\text{\(y_{\text{est}}\)} - E(y))^2}{\Sigma (y - E(y))^2} \]

= Explained variation/Total variation

= Coefficient of determination. \quad \ldots (C.11)

Under conditions of perfect linear correlation, implying also perfect linear regression, \( r^2 = 1 \) or \( r = +/ -1 \). On the other hand total variation is all unexplained if \( r = 0 \).

While (C.8) through (C.11) explain the importance of \( r \), a more practical computational approach is

\[ r = \frac{n \Sigma xy - (\Sigma x)(\Sigma y)}{\sqrt{[n \Sigma x^2 - (\Sigma x)^2][n \Sigma y^2 - (\Sigma y)^2]}} \quad \ldots (C.12) \]

which is used in LINFITMD. Table C.1 summarizes the linear correlation coefficient values for all the peaks in Table 3.2.

Another significance of \( r \) is in relation to the population correlation coefficient, \( \rho \). If the parent population is assumed to be bivariate normal, inferences
about their coefficient of determination can be made based on the 95% confidence interval (Wonnacott, 1981). These inferences are shown on Table C.1. The asterisked rows show that the number of samples balanced with the linear correlation of the data points determines the confidence level at which inference can be made regarding the linear population parameters. This only helps in evaluating the linear regression model of the population but does not affect other non-linear estimates of correlation.
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<th>Peak#</th>
<th>n</th>
<th>$E_t$(eV)</th>
<th>$r$</th>
<th>$\rho_{\text{min}}$</th>
<th>$\rho_{\text{range}}$</th>
<th>$\rho_{\text{max}}$</th>
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<td>+0.04</td>
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<td>-0.6</td>
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<td>0.81</td>
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<td>+1.0</td>
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</table>

Table C.1: Linear correlation coefficients: Sample estimates ($r$) of

A time series is defined as a set of observations generated sequentially in time. Variations in these observations occur due to both deterministic and random factors. A good mathematical model to represent a time series is therefore a stochastic process, and the series of observations may then be regarded as a sample function or realization of the process.

In this experiment, a series of signal amplitude versus temperature scans were conducted over time. Sample readings were taken at temperature increments of 2 degrees per minute. A time series representation of each scan would be the curve representing the deviation of the signal from the expected value over time.

The sensitivity setting of the boxcar had to be such as to respond to even low peak realizations. This proved difficult to achieve without admitting some noise into the signal processing filter. Using a moving average filter subroutine called SMOOTH this white noise was removed from the PITS data before plotting.

An illustration of how the moving average works is shown in Table C.2.
Table C.2a. Moving Average of a PITS signal over a Peak

<table>
<thead>
<tr>
<th>Temp(°K)</th>
<th>Unadjusted signal A</th>
<th>Three-point moving average</th>
</tr>
</thead>
<tbody>
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<td>51</td>
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<td></td>
</tr>
<tr>
<td>53</td>
<td>4.1293</td>
<td>4.1396</td>
</tr>
<tr>
<td>55</td>
<td>4.1665</td>
<td>4.1676</td>
</tr>
<tr>
<td>57</td>
<td>4.207</td>
<td>4.1991</td>
</tr>
<tr>
<td>59</td>
<td>4.2237</td>
<td>4.1939</td>
</tr>
<tr>
<td>61</td>
<td>4.1511</td>
<td>4.1522</td>
</tr>
<tr>
<td>63</td>
<td>4.0818</td>
<td></td>
</tr>
</tbody>
</table>

It is noteworthy that averaging over every \( k \) points, i.e. 
\[
(1/k)[a_1 + a_2 + \ldots + a_{k-1} + a_k] = b_k
\]
waits \((k-1)\) observations at the endpoints, such that the expectation array is that much smaller than the observation array. Generally scans performed in this laboratory allow at least 15 °K at both ends of the temperature axis, which effectively takes care of this problem for \( k < (15/\text{scan rate}) \).

A more serious problem with a moving average is that, as in Table C.2b, it may eliminate a peak from the data. This is particularly evident in low peaks close to a dominant one. A partial remedy is to keep \( k \) small, e.g. \( k=2, 3 \). In addition, as in weighted least squares fitting, different weights may be assigned according to the magnitude of the deviation. The weights would be inverses.
of the deviations which would in turn ensure that the worst deviations have the least influence over the resulting signal.

Table C.2b Moving average of a PITS signal over a peak with an oblitarating effect.

<table>
<thead>
<tr>
<th>Temp(°K)</th>
<th>unadjusted signal A</th>
<th>Three-point moving average</th>
</tr>
</thead>
<tbody>
<tr>
<td>53</td>
<td>4.234</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>4.2644</td>
<td>4.2646</td>
</tr>
<tr>
<td>57</td>
<td>4.2995</td>
<td>4.3008</td>
</tr>
<tr>
<td>59</td>
<td>4.3425</td>
<td>4.3189</td>
</tr>
<tr>
<td>61</td>
<td>4.3188</td>
<td>4.3216</td>
</tr>
<tr>
<td>63</td>
<td>4.3036</td>
<td>4.338</td>
</tr>
<tr>
<td>65</td>
<td>4.3917</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX D

PROGRAMS

LINFIT2M is an adaptation of LINFIT in which the main results are the correlation coefficient and the least squares line data points. These are used in analyzing Hall Effect, Van der Pauw and PITS data for linear correlation.

Somewhat related to LINFIT2M is LINFITMD whose special output routines are created for PITS data analysis for determining activation energy and capture cross sections (lines 2132 - 2138). The algorithm is explained in Appendix C.

The main modifications to Doug Doerfler's LINPLOT include a friendlier user interface and a smoothing option in case of noisy data. Previously, one had to quit LINPLOT load a smoothing function, use it and then go back to LINPLOT. The subroutine Smooth can be incorporated in any other plotting program, be it linear-log, log-log or log-linear.

ARRPLOT produces Arrhenius plots by simply changing the LABEL from a PLOT line to any user-selected character.
**Program Title: SUPRAMED**

**Programmer** : Mohele Dlodlo

**Date** : 12 Jan. 1989

**Version** : 2.0

**Program Description**: SUPRAMED, adapted from the DRC-81 Instruction manual, controls the Temperature Controller making it ramp upwards or downwards at the user's prerogative. It also reads the output voltages of the Temperature Controller's thermometer via the Keithley DVM and the boxcar. The thermocouple indicates temperature in degrees Celsius and the boxcar's output is the PITS spectrum. A hard copy is issued and if requested a diskette file is created with a backup copy.

**DIM K#(15), K#(50)**

**REAL TEMP(500.2), TEMPV(500,2)**

**HEATER_POWER, GAIN, RATE ARE RESET ARE SET MANUALLY BY THE USER. THE INITIAL SETPOINT TEMPERATURE IS ENTERED VIA THE KEYBOARD. THE TIME IN SECONDS AND DESIRED FINAL TEMPERATURE ARE REQUESTED. THE BIC WILL RAMP THE SET POINT TO THE FINAL TEMPERATURE LINEARLY WITH A QUANTIZED TEMPERATURE INCREMENT.**

**DIM A##(50)** ! Dimension array for reading the DRC BIC

**T_WAIT=20 ! Sampling rate in seconds**

**K_EDB=.9 ! Incremental change in control T which implies equilibrium**

**CLEAR ! Clear the display**

**REQUEST THE INITIAL SETPOINT TEMPERATURE.**

**DISP "INITIAL TEMPERATURE:"; @ INPUT K_INITIAL**

**BEGIN: DISP "SELECT A HEATER POWER,GAIN, RATE AND RESET MANUALLY"**

**DISP "ON THE DRC-BIC TO OBTAIN THE DESIRED INITIAL TEMPERATURE."**

**DISP**

**DISP "TEMPERATURE TO RAMP TO":"@ INPUT K_FINAL**

**DISP "TIME TO REACH ":K_FINAL;" IN SECONDS";@ INPUT T_FINAL**

**DISP "INCREAMENT OF TEMPERATURE TO TAKE DATA."; @ INPUT K_INC**

**ADJUST THE DRC BIC TO OBTAIN EQUILIBRIUM AT THE INITIAL SETPOINT.**

**OUTPUT 712 ;"S"; VAL# (K_INITIAL)**

**K=K_INITIAL**

**WAIT1: WAIT 1000*T_WAIT ! WAIT T_WAIT SECONDS**

**K=K**

**OUTPUT 712 ;"WC" @ ENTER 712 ; A# ! READ CONTROL TEMPERATURE.**

**K=VAL (A#(1,6))**

**IF ABS (K-KU)>K_EOB OR ABS (K-K_INITIAL)>1 THEN WAIT1**

**OUTPUT 712 ;"W1" @ ENTER 712 ; A# ! READ W1**

**DISP "W1 = ";A#**

**POSITION=VAL (A#(1))**

**DISPLAY_ID#=A#(3,5)**

**CONTROL_ID#=A#(7,9)**

**GA[N]=VAL (A#(11,12))**

**RATE=VAL (A#(14,15))**

**RESET1=VAL (A#(17,18))**

**HEATER_RANGE=VAL (A#(20))**

**P=1**

**DISP "W1 = " ;A#**

**PRINT "REMOTE SENSOR POSITION=";POSITION**

**PRINT "DISPLAY SENSOR ID=";DISPLAY_ID#**

**PRINT "CONTROL SENSOR ID=";CONTROL_ID#**

**PRINT "GAIN=";GA[N]; "RATE=";RATE;"RESET=";RESET1**

**PRINT "HEATER POWER RANGE=";HEATER_RANGE;"WATTS"**

**PRINT IS 701**

**T=0**
NORMHL GO: 80 SETPOINT, "VR7D8T1? SETPOINT=SETPOINT+K_SPINC*SGN.5
OUTPUT IF: X, DDD.DDD, 2X, "V INPUT A* IMAGE ALL PROCEED: YES TIMEOUT INPUT; :1 IS "WC* BEEP F* "THERMAL 123 SLOPE: Store_data; TIME ADD SKIP: P, TEMP(P,2)=T_INC=2*T_INC...COMPUTER
DISP! IF: 60*SLOPE: TEMPV; "SETPOINT:" TO TO 1000*T_INC

690 K_SPINC=.1 "NORMAL INCREMENT OF SETPOINT
690 SETPOINT=K_INITIAL
700 SLOPE=(K_FINAL-K_INITIAL)/T_FINAL ; COMPUTER RAMP SLOPE(K/SEC.)
710 DISP "RAMP =";60*SLOPE; "KELVIN PER MINUTE";SLOPE; "KELVIN PER SECOND"
720 T_INC=K_SPINC/ABS (SLOPE) ; TIME TO INCREMENT SETPOINT IN SECOND
730 IF T_INC<.9 THEN K_SPINC=.2 @ T_INC=2*T_INC
740 IF T_INC>1 AND K_SPINC=.2 THEN T_INC=2.5*T_INC @ K_SPINC=.5
750 CN TIMER=1.1000*T_INC GOTO GO ; TIMEOUT T_INC SECONDS - RESTART TIMER
760 PROCEED: GOTO PROCEED ; YES THIS STATEMENT IS CORRECT
770 GO: OUTPUT 712 ; "WC" @ ENTER 712 : $A! 90 MS READ TIME.
780 IF FP (ABS (SETPOINT-K_INITIAL)/K_INC)> THEN SKIP
790 DISP T; " SECONDS : "; "SETPOINT = "; "SETPOINT:" K
800 DISP "CONTROL TEMPERATURE = "; A# ALL DISP TAKE .23 SECONDS
810 IF SETPOINT=94 THEN 1460
820 IF SETPOINT=114 THEN 1490
830 IF SETPOINT=134 THEN 1520
840 IF SETPOINT=162 THEN 1550
850 IF SETPOINT=186 THEN 1580
860 IF SETPOINT=208 THEN 1610
870 IF SETPOINT=232 THEN 1640
880 IF SETPOINT=256 THEN 1670
890 IF SETPOINT=280 THEN 1700
900 IF SETPOINT=304 THEN 1730
910 IF SETPOINT=328 THEN 1760
920 PRINT "SET";SETPOINT; "CONL."; A$
920 TEMPR(P,1)=VAL (A#)
940 TEMP(P,2)=T
950 TEMPV(P,1)=SETPOINT
960 ! READS FLUKE DVM
970 OUTPUT 707 ; "VR70812" @ ENTER 707; $F
980 MANTISSA=#F1,81 @ EXPONENTF=#10,12
990 TEMPV(P,2)=VAL (MANTISSA#)*10^ (EXPONENTF)
1000 PRINT "PITS"; TEMPV(P,2)
1010 DISP USING 1020 ; P.TEMPV(P,1),TEMPV(P,2)
1020 IMAGE "READING NUMBER",2X,DDD,4X,"THERMAL COUPLE TEMP.",2X,DDD.DDD,DDD,2X,"VOLTAGE",2X,DDD.DDD.DDD
1030 N=P+1
1040 SKIP: T=T+T_INC ! ADD TIME FOR K_SPINC
1050 IF T>T_FINAL THEN COMPLETE ! IS RAMP TIME PERIOD COMPLETE?
1060 SETPOINT=SETPOINT+K_SPINC*SGN (SLOPE) ! INCREMENT THE SETPOINT
1070 OUTPUT 712 ; "$"; VAL$ (SETPOINT)
1080 GOTO PROCEED
1090 COMPLETE: DISP "RAMPING COMPLETE." @ OFF TIMER= 1
1100 K_INITIAL=K_FINAL
1110 FOR J=10 TO 160 STEP 50 @ BEEP J,500 @ NEXT J
1120 ON ERROR GOTO 1240
1130 ! Store data:
1140 DISP "ENTER THE PITS FILE NAME!" @ INPUT file_name$
1150 DISP "NUMBER OF READINGS =":P-1
1160 CREATE +file_name$+D700",400,20
1170 ASSIGN 1 TO +file_name$+D700"
1180 FOR N=1 TO P-1
1190 PRINT# 1 , TEMPV(N,1),TEMPV(N,2)
1200 NEXT N
1210 ASSIGN# 1 TO *
1220 DISP "DATA STORAGE COMPLETED"
1230 GOTO 1290
1240 OFF ERROR
1250 BEEP 50,500
1260 DISP "Disk write ERROR. Hit PAUSE. Correct problem. Hit CONT. Re-enter."
1270 WAIT 4000
1280 GOTO 1130
1290 DISP "NEED TO STORE RAMPING DATA?" @ INPUT ANS$
1300 IF ANS="Y" THEN 1790
1310 DISP "RAMPING NUMBER":P-1
1320 ON ERROR GOTO 1490

D3
1330 DISP "ENTER BACK-UP DATA FILE NAME" @ INPUT ramp_name$
1340 CREATE ramp_name$@"D700",400,20
1350 ASSIGN# 2 TO "ramp_name$@"D700"
1360 FOR M=1 TO P-1
1370 PRINT# 2 : TEMPR(M,2),TEMPR(M,1)
1380 NEXT M
1390 ASSIGN# 2 TO  
1395 GOTO 1440
1400 OFF ERROR @ BEEP 50,500
1410 DISP "FILE NAME ERROR. TRY DIFFERENT FILE NAME!"
1420 WAIT 4000
1430 GOTO 1330
1440 DISP "READING COMPLETE!"
1450 GOTO 1790
1460 OUTPUT 712 ;"P";96;"W1" @ ENTER 712 ; K$
1470 DISP KS @ PRINT KS
1480 GOTO 920
1490 OUTPUT 712 ;"P";90;"W1" @ ENTER 712 ; K$
1500 DISP KS @ PRINT KS
1510 GOTO 920
1520 OUTPUT 712 ;"P";85;"W1" @ ENTER 712 ; K$
1530 DISP KS @ PRINT KS
1540 GOTO 920
1550 OUTPUT 712 ;"P";81;"W1" @ ENTER 712 ; K$
1560 DISP KS @ PRINT KS
1570 GOTO 920
1580 OUTPUT 712 ;"P";75;"W1" @ ENTER 712 ; K$
1590 DISP KS @ PRINT KS
1600 GOTO 920
1610 OUTPUT 712 ;"P";81;"W1" @ ENTER 712 ; K$
1620 DISP KS @ PRINT KS
1630 GOTO 920
1640 OUTPUT 712 ;"P";85;"W1" @ ENTER 712 ; K$
1650 DISP KS @ PRINT KS
1660 GOTO 920
1670 OUTPUT 712 ;"P";91;"W1" @ ENTER 712 ; K$
1680 DISP KS @ PRINT KS
1690 GOTO 920
1700 OUTPUT 712 ;"P";95;"W1" @ ENTER 712 ; K$
1710 DISP KS @ PRINT KS
1720 GOTO 920
1730 OUTPUT 712 ;"P";97;"W1" @ ENTER 712 ; K$
1740 DISP KS @ PRINT KS
1750 GOTO 920
1760 OUTPUT 712 ;"P";98;"W1" @ ENTER 712 ; K$
1770 DISP KS @ PRINT KS
1780 GOTO 920
1790 END
117235

D4
LINFIT - makes a least squares fit to data with a straight line

Y = A + B * X


Written for - HP86B, in HP BASIC. User interface - M. E. Dlodlo 17/2/89

Date - 10/18/86. Kansas State University

Variables - X(I) - the independent variable
Y(I) - the dependent variable
STDEV(I) - the standard deviation of Y, if needed
NPTS - number of data points to be used in fit. must be less than or equal to the dimension for X, Y, and STDEV
MODE* - indicates type of fit, U = unweighted, D = weight with data points, or V = weight with STDEV
A - intercept coefficient
B - slope coefficient
SIGMA - std. dev. for A
SIGMB - std. dev. for B
R - linear correlation coefficient

Options - MODE* is entered from the keyboard
Data are entered from DATA statements within the program

DIM X(100), Y(100), STDEV(100)

10 DISPO"Enter mode of least squares ... U(unweighted), D(weighted w/data pts), or V(weighted w/data variances)"
20 INPUT MODE#

30 IF MODE#="U" THEN GOTO 1054
40 IF MODE#="u" THEN GOTO 1054
50 IF MODE#="D" THEN GOTO 1054
60 IF MODE#="d" THEN GOTO 1054
70 IF MODE#="V" THEN GOTO 1054
80 IF MODE#="v" THEN GOTO 1054
90 IF MODE#="y" THEN GOTO 1054
100 IF MODE#="Y" THEN GOTO 1054
110 PRINT "Enter desired data identification < = 8 CHAR"
120 PRINT ISIHLOKO#
130 PRINT INYANGA#
140 PRINT ISIHLOKO# @ PRINT INYANGA#
150 PRINT
160 CLEAR
200 GOSUB RDATA
250 GOSUB NORMEQN
300 GOSUB EST
350 GOSUB OUTPT
400 DISP "END"
500 END

1000 RDATA:
1010 DISP "Enter mode of least squares... U(unweighted), D(weighted w/data pts), or V(weighted w/data variances)"
1020 INPUT MODE#
1030 IF MODE#="U" THEN GOTO 1054
1040 IF MODE#="u" THEN GOTO 1054
1050 IF MODE#="D" THEN GOTO 1054
1060 IF MODE#="d" THEN GOTO 1054
1070 IF MODE#="V" THEN GOTO 1054
1080 IF MODE#="v" THEN GOTO 1054
1090 IF MODE#="y" THEN GOTO 1054
1100 IF MODE#="Y" THEN GOTO 1054
1110 READ NPTS@ DISP " X " @ " Y "
1120 FOR I=1 TO NPTS
1130 READ X(I), Y(I)
1140 NEXT I
1200 NEXT I
1210 IF MODE#="U" THEN GOTO 1130
1220 IF MODE#="u" THEN GOTO 1130
1230 IF MODE#="D" THEN GOTO 1130
1240 IF MODE#="d" THEN GOTO 1130
1250 GOTO 1130

D5
```plaintext
1100 FOR I=1 TO NPTS
1110 READ STDEV(I)
1120 NEXT I
1130 : Data will always be: 1st statement is NPTS (only)
1132 : 2nd statement & more (as needed) contains X,Y pairs
1134 : 3rd (if needed) contains STDEV
1140
1150 DATA 1
1155 : DATA 17.12.1.22671,17.64.1.86097,17.76.2.06739
1160 : DATA 18.69.2.43799
1165 : DATA 11.75.1.97952,12.41.2.56418,12.41.2.78748
1170 : DATA 12.71.3.20963
1175 : DATA 6.46,4.09284,6.48,3.57543,6.51,3.85545,6.55,4.53421
1180 : DATA
1190 RETURN
1200 RETURN
1210 NORMEQN: ! Form normal equations
1210 SUM=X@ SUM=Y@ SUMXX=0@ SUMXY=0@ SUMYY=0
1220 FOR I=1 TO NPTS
1230 STDEV(I)=1
1240 IF MODE$="U" THEN GOTO 1700
1250 IF MODE$="u" THEN GOTO 1700
1260 IF MODE$="V" THEN GOTO 1650
1270 IF MODE$="v" THEN GOTO 1650
1280 "Weight with data pts
1290 IF Y(I)=0 THEN GOTO 1700
1300 WT=1/Y(I)
1310 IF WT<0 THEN WT=-WT
1320 GOTO 1700
1330 "Weight with variances
1340 WT=1/(STDEV(I)*STDEV(I))
1350 SUM=SUM+WT
1360 SUMXX=SUMXX+WT*X(I)
1370 SUMXY=SUMXY+WT*Y(I)
1380 SUMYY=SUMYY+WT*Y(I)*Y(I)
1390 NEXT I
1400 RETURN
1410 EST: ! Calculate the intercept, slope, and st. dev.
1420 DET=SUMXX-SUMX*SUMX
1430 B=(SUMXY-SUMX*SUMY)/DET
1440 A=(SUMXX*SUMY-SUMX*SUMXY)/DET
1450 VARNCE=1
1460 IF MODE$="U" THEN GOTO 2000
1470 IF MODE$="u" THEN GOTO 2000
1480 IF MODE$="V" THEN GOTO 2000
1490 IF MODE$="v" THEN GOTO 2000
1500 IF MODE$="D" THEN GOTO 2000
1510 IF MODE$="d" THEN GOTO 2000
1520 C=NPTS-2
1530 :VARNCE=(SUMXX+A*A+SUMB*B#SUMXX=2*(A*SUMY+B*SUMXY-A*B*SUMXX))/C
1540 SIGMA=SDR (VARNCE/SUMXX/DET)
1550 SIGMB=SDR (VARNCE/SUM/DET)
1560 R=(SUM*SUMXX-SUMX*SUMYY) / (DET*(SUM+SUMYY-SUMXY))
1570 RETURN
1580 RETURN
1590 OUTPUT: ! Display the intercept, slope, st. dev., and correlation coeff
1600 PRINT "SIGNATURE DATA for ":
1610 PRINT "Intercept = ";A; +/- ";SIGMA @ PRINT "INTERCEPT= ";A
1620 PRINT "Slope = ";B; +/- ";SIGMB @ PRINT "SLOPE= ";B
1630 PRINT "Corr Coef = ";:R @ PRINT "Corr. Coef. = ";:R
1640 PRINT
1650 ET=8.62+10^-2 @ DISP "ET= ";:Et
1660 PRINT "Et = ";:Et
1670 CS=EXP (-A)*10^-20/1.9 @ PRINT "CROSS SECTION = ";:CS
1680 PRINT "Cross Section = ";:CS @ PRINT
1690 FOR I=1 TO NPTS
1700 Y(I)=A+B*X(I)
1710 NEXT I
1720 Y(I)=EXP (Y(I))
```

D6
2160 PRINT "X = ";X(I);"Y = ";Y(I)
2170 NEXT I
2190 RETURN
Program Title: ARRPLOT

Programmer: Mqhele E. Dlodlo
Graduate Student, Kansas State University

Date: 15 Jan 1989

Version 2.0

Program Description: ARRPLOT is a plot routine developed to provide scatter diagrams (e.g. Arrhenius plots) on linear axes.

Type 1 plots divide the horizontal axis into 10 intervals.

Type 2 plots divide the horizontal axis into 8 intervals and uses the point numbers to label the X-axis.

Parameters that are supplied to ARRPLOT:

- X(*) - X-axis data array: (real)
- Y(*) - Y-axis data array: (real)
- Npts - Number of points in X(*) and Y(*): (integer)
- Type - Type of numbering for the X-axis: (integer)
  1 - Use values in X(*) to label the X-axis: 10 intervals
  2 - Use the point number to label the X-axis: 8 intervals
- Xtitle* - Title for the X-axis
- Ytitle* - Title for the Y-axis
- Title* - Title of the plot
- Name* - Users name
- Date* - Date the plot was generated

Subroutines within ARRPLOT:

- Initialize1 - Initializes the data for a Type=1 plot
- Initialize2 - Initializes the data for a Type=2 plot
- Axes_label - Draws and labels the axes: Labels the plot
- Plot_1 - Plots data points for a Type=1 plot
- Plot_2 - Plots data points for a Type=2 plot

Data - Data needs to be stored in a file as two columns. The left column is the x-axis data and the right column is the y-axis data.

OPTION BASE 0

Option declarations

REAL X(800), Y(800)

REAL Aspect, Fract, Scale, Xmax, Xmin, Xrange, Xpower, Xinter
REAL Ymax, Ymin, Yrange, Ypower, Yinter

INTEGER Npts, Plotter, Type

DIM Xtitle*[60], Ytitle*[60], Title*[60], Name*[60], Date*[60]

DIM Dummy*[60], File_name*[60]

CLEAR

DISP & BEEP

DISP TAB (5); "THE DATA FILE IS ASSUMED TO BE IN LEFT DRIVE"

WAIT 2000

CLEAR

DISP

DISP TAB (5); "HORIZONTAL AXIS TITLE (60 CHARACTER LIMIT)"

INPUT Xtitle#

DISP TAB (5); "VERTICAL AXIS TITLE (60 CHARACTER LIMIT)"

INPUT Ytitle#

DISP TAB (5); "THE PLOT TITLE IS (60 CHARACTER LIMIT)"
D9
1300 IF Ymax>Ymin THEN 1330
1310 DISP "ERROR. Ymax must be greater than Ymin"
1320 GOTO 1260
1330 Yrange=Ymax-Ymin
1340 DISP "Would you like to change the limits of the horizontal axis (y/n)?";
1350 INPUT Dummy*
1360 IF Dummy*="N" OR Dummy*="n" THEN GOTO 1450
1370 DISP Xmax,"is the old normalized maximum."
1380 DISP "What is the new normalized maximum value";
1390 INPUT Xmax
1400 IF Xmax>Xmin THEN 1440
1410 DISP Xmax,"is the old normalized maximum."
1420 DISP "What is the new normalized minimum value";
1430 INPUT Xmin
1440 Xrange=Xmax-Xmin
1450 GOTO 990
1460 CLEAR @
1470 CLEAR @
1480 TAB(5):"Enter:"
1490 TAB(11);"1 to rerun ARRPLOT"
1500 !
1510 INPUT A
1520 IF A=1 THEN 440
1530 DISP @
1540 DISP TAB(5);"This program has ended."
1550 END
1560 !
1570 !
1580 !
1590 Scale=10 ! Divide the axis into ten intervals
1600 Xmax=-9.99999999999E+499 ! Set initial min. and max.
1610 Xmin=9.99999999999E+499
1620 Ymax=-9.99999999999E+499
1630 Ymin=9.99999999999E+499
1640 FOR I=0 TO Npts-1 ! Search data for the min and max values
1650 IF X(I)>Xmax THEN Xmax=X(I)
1660 IF Y(I)>Ymax THEN Ymax=Y(I)
1670 IF X(I)<Xmin THEN Xmin=X(I)
1680 IF Y(I)<Ymin THEN Ymin=Y(I)
1690 NEXT I
1700 Xpower=INT(LGT (Xmax-Xmin)) ! Base 10 power of the range
1710 Xmin=Xmin/10^Xpower
1720 Xmax=Xmax/10^Xpower
1730 Xrange=Xmax-Xmin
1740 Ypower=INT(LGT (Ymax-Ymin))
1750 Ymin=Ymin/10^Ypower
1760 Ymax=Ymax/10^Ypower
1770 IF Ymin<0 THEN Ymin=INT(Ymin-(Ymax-Ymin)*.1)/10
1780 Yrange=Ymax-Ymin
1790 Ypower=Ypower+1
1800 RETURN
1810 !
1820 !
1830 !
1840 !
1850 Scale=8 ! Divide the X-axis into 8 intervals
1860 FOR I=0 TO Npts-1 ! Assign values to the X-axis array X(*)
1870 X(I)=I+1
1880 NEXT I
1890 Xmax=Npts ! Declare the min and max values of the X-axis array
1900 Xmin=0
1910 Fract=Xmax/8-IP (Xmax/8) ! Determine the min and max values for the Y-axis
1920 IF Fract<0 THEN Xmax=8*IP (Xmax/8+1)
1930 Xrange=Xmax-Xmin ! Determine the range
IF

LABEL

Plot

and

<

MOVE

10,3

Determines

I

/10

Yi

Xi

"Scale:

1/10

>Ymax

Plot

Plot

Plot

2010

Ymax=yn/10"Ypower

2020

Yoower=INT

RETURN

2080

Axes_label: !

2100 !

2110 Aspect=RAT10 ! Determines relative size of the X and Y dimensions

2120 DEG

2130 LORG 7

2140 CSIZE 2.5

2150 MOVE 77*Aspect,91

2160 LABEL Name# ! Plot the users name

2170 MOVE 85*Aspect,91

2180 LABEL Da_te# ! Plot the date

2190 LORG 6

2200 CSIZE 4,6,10

2210 MOVE 55*Aspect,10

2220 LABEL Title# ! Plot the title

2230 CSIZE 3.5

2240 MOVE 55*Aspect,20

2250 LABEL Xtitle# ! Plot the X-axis title

2260 IF Type=2 THEN GOTO 2300

2270 CSIZE 2.5

2280 MOVE 55*Aspect,17

2290 LABEL USING "9A,K" ; "Scale: 1E",Xpower ! Plot the X-axis base 10 power

2300 CSIZE 3.5

2310 LDIR 90

2320 LORG 4

2330 MOVE 10*Aspect,55

2340 LABEL Ytitle# ! Plot the Y-axis title

2350 CSIZE 2.5

2360 MOVE 12*Aspect,55

2370 LABEL USING "9A,K" ; "Scale: 1E",Ypower ! Plot the Y-axis base 10 power

2380 !

2390 ! Draw the axes

2400 !

2410 LOCATE 20*Aspect,85*Aspect,25,90 ! Define the plotting area

2420 FRAME

2430 SCALE Xmin,Xmax,Ymin,Ymax ! Scale the plotting area

2440 Xinter=Xmin ! Declare the axes intercept

2450 Yinter=Ymin

2460 IF Type=1 THEN AXES Xrange/100,Yrange/100,Xinter,Yinter,10,10,3

2470 IF Type=2 THEN AXES Xrange/8,Yrange/100,Xinter,Yinter,1,10,3

2480 !

2490 ! Label the Y-axis

2500 !

2510 CSIZE 2.5

2520 LDIR 0

2530 LORG 8

2540 I=0

2550 IF Yinter+I*Yrange/10>Ymax THEN 2600

2560 MOVE Xinter-Xrange/100,Yinter+I*Yrange/10

2570 LABEL USING "3D,2D" ; Yinter+I*Yrange/10

2580 I=I+1

2590 GOTO 2550

D11
2600 !
2610 ! Label the X-axis
2620 !
2630 LORG 9
2640 I=1
2650 IF Xinter+I*Xrange/Scale>Xmax THEN 2710
2660 MOVE Xinter+I*Xrange/Scale,Yinter-Yrange/50
2670 IF Type=1 THEN LABEL USING "3D.2D" ; Xinter+I*Xrange/Scale
2680 IF Type=2 THEN LABEL USING "5D.0D" ; Xinter+I*Xrange/Scale
2690 I=I+1
2700 GOTO 2650
2710 RETURN
2720 !
2730 Plot_1:
2740 !
2750 !
2760 !
2770 PEN 1
2780 MOVE X(0)/10^Xpower,Y(0)/10^Ypower
2790 FOR I=0 TO Npts=1
2800 MOVE X(I)/10^Xpower,Y(I)/10^Ypower
2805 LABEL "x"
2810 NEXT I
2820 PEN 0
2830 !
2840 !
2850 !
2860 !
2870 !
2880 !
2890 !
2900 !
2910 RETURN
2920 !
2930 Plot_2:
2940 !
2950 MOVE X(0),Y(0)/10^Ypower
2960 FOR I=0 TO Npts=1
2970 PLOT X(I),Y(I)/10^Ypower,-1
2980 NEXT I
2990 PEN 0
3000 RETURN
31404
Revised for ease of use by Mqhele E. Dlodlo
Grad. E. E. at Kansas State University
Also added was a smoothing routine
Revision date: 18 February 1989

Program Title: LINPL0T2
Programmer: Doug Doerfler
Graduate Student, Kansas State University
Date: 06-02-84

Description: LINPL0T is a plot routine developed to provide
genral purpose plot routine for linear-linear plots. 1 plots divide the horizontal axis into 10 intervals.
2 plots divide the horizontal axis into 8 intervals and
uses the point numbers to label the X-axis. LINPL0T2 is
customized for curve plotting.

Parameters that are supplied to LINPL0T2
- X(*) - X-axis data array: (real)
- Y(*) - Y-axis data array: (real)
- Npts - Number of points in X(*) and Y(*): (integer)
- Type - Type of numbering for the X-axis: (integer)
  1 - Use values in X(*) to label the X-axis: 10 intervals
  2 - Use the point number to label the X-axis: 8 intervals
- Xtitle* - Title for the X-axis
- Ytitle* - Title for the Y-axis
- Title* - Title of the plot
- Name* - Users name
- Date* - Date the plot was generated

Subroutines within LINPL0T2
- Initialize1 - Initializes the data for a Type=1 plot
- Initialize2 - Initializes the data for a Type=2 plot
- Axes_label - Draws and labels the axes; Labels the plot
- Plot_1 - Plots data points for a Type=1 plot
- Plot_2 - Plots data points for a Type=2 plot
- Smooth - Moving average trend remover

Data - Data needs to be stored in a file as two columns. The
left column is the x-axis data and the right column is
the y-axis data.

OPTION BASE 0
Declarations

REAL X(800),Y(800)
REAL Aspect,Fract,Scale,Xmax,Xmin,Xrange,Xpower,Xinter
REAL Ymax,Ymin,Yrange,Ypower,Yinter
INTEGER Npts,Plotter,Type
DIM Xtitle*$60,Ytitle*$60,Title*$60,Name*$60,Date*$60
DIM Dummy*$60,File_name*$60
CLEAR

D13
620 DISP TAB (5); "HORIZONTAL AXIS TITLE (60 CHARACTER LIMIT)"
630 INPUT Xtitle$
640 DISP TAB (5); "VERTICAL AXIS TITLE (60 CHARACTER LIMIT)"
650 INPUT Ytitle$
660 DISP TAB (5); "THE PLOT TITLE IS (60 CHARACTER LIMIT)"
670 INPUT Titles$
680 DISP TAB (5); "USERS NAMES (60 CHARACTER LIMIT)"
690 INPUT Name$
700 DISP TAB (5); "WHAT IS THE DATE"
710 INPUT Date$
720 DISP TAB (5); "HOW MANY OBSERVED VALUES ARE BEING PLOTTED"
730 INPUT Npts
740 points=Npts+points
750 Type=l
760 X(0)=30
770 FOR K=1 TO Npts-1
780 X(K)=K+30
790 Y(K)=1.519-.0005405*(X(K)-X(K)**2/(X(K)+204)
800 NEXT K
810 Y(0)=1.519-.0005405*(X(0)-X(0)**2/(X(0)+204)
820 FOP K=Npts TO points-1
830 X(K)=X(K-Npts)
840 Y(K)=1.519-.0005405*(X(K)-X(K)**2/(X(K)+204)
850 NEXT K
860 ! Initializing the arrays refers to finding maximum and minimum values, the range of the values, and normalizing the data by dividing by the base 10 power of the range.
870 !
880 DISP "Initializing the arrays for plotting"
890 ON Type GOSUB Initialize1,Initialize2
900 BEEP
910 ! Determine what plotter the user wishes to use and make declarations accordingly.
920 DISP "Which plotter is to be used (1-CRT, 2-7470A)"
930 INPUT Plotter
940 IF Plotter=2 THEN GOTO 1080
950 PLOTTER IS 1
960 GCLEAR
970 GRAPHALL
980 GOTO 1150
990 PLOTTER IS 705
1000 OUTPUT 705; "VS8"
1010 DISP "Set up plotter and press END LINE";
1110 INPUT Dummy$
1120 !
1130 ! Output the data to the specified plotter
1140 !
1150 GOSUB Axes_label
1160 ON Type GOSUB Plot_1 ! Plot_2
1170 BEEP
1180 IF Plotter=1 THEN INPUT Dummy$
1190 ALPHA
1200 DISP "Would you like to smooth the data " @ INPUT Smooth$
1210 IF Smooth$="Y" OR Smooth$="y" THEN GOSUB Smooth
1220 DISP "Would you like to change the plotter or the axes limits (y/n)"
1230 INPUT Dummy$
1240 IF Dummy$="N" OR Dummy$="n" THEN GOTO 1460
1250 DISP "Would you like to change the limits of the vertical axis (y/n)";
INPUT Dummy*
IF Dummy*="N" OR Dummy*="n" THEN GOTO 1340
DISP Ymax:" is the new normalized maximum value"
INPUT Ymax
DISP Ymin:" is the old normalized minimum value"
INPUT Ymin
IF Ymax>Ymin THEN 1330
Yrange=Ymax-Ymin
DISP "Would you like to change the limits of the horizontal axis (y/n)"
INPUT Dummy*
IF Dummy*="N" OR Dummy*="n" THEN SOTO
DISP Xmax:" is the old normalized maximum value"
DISP "What is the new normalized maximum value"
INPUT Xmax
DISP Xmin:" is the old normalized minimum value"
DISP "What is the new normalized minimum value"
INPUT Xmin
IF Xmax>Xmin THEN 1440
Xrange=Xmax-Xmin
SOTO
CLEAR 8
DISP 8
DISP TAB(5);"Enter:
DISP TAB(11):"2 to rerun LNPLOT" to quit"
INPUT A
IF A=1 THEN CHAIN "ADC TEST"
IF A=2 THEN 440
DISP i3
DISP TAB(5);"This program has ended." GOTO 99999
uvo
**************************
Initialized!
**************************
Scale=10
Divide the axis into 10 intervals
Xmax=-9.99999999999E499 ! Set initial min. and max.
Xmin=-9.99999999999E499
Ymax=-9.99999999999E499
Ymin=-9.99999999999E499
FOR I=0 TO points-Npts-1 ! Search data for the min and max values
IF X(I)>Xmax THEN Xmax=X(I)
IF Y(I)>Ymax THEN Ymax=Y(I)
IF X(I)<Xmin THEN Xmin=X(I)
IF Y(I)<Ymin THEN Ymin=Y(I)
NEXT I
Xpower=INT(LOG((Xmax-Xmin)/10)) ! Base 10 power of the range
Xmin=Xmin/10^Xpower
Xmax=Xmax/10^Xpower
Xrange=Xmax-Xmin
Ypower=INT(LOG((Ymax-Ymin)/10))
Ymin=Ymin/10^Ypower
Ymax=Ymax/10^Ypower
IF Ymin<0 THEN Ymin=INT(Ymin-(Ymax-Ymin)*.1)/10
Ymax=INT(Ymax+(Ymax-Ymin)*.1)/10
Yrange=Ymax-Ymin
Ypower=Ypower+1
RETURN ! **************
Initialize2!
! **************
Scal_e=8 ! Divide the X-axis into 8 intervals
FOR I=0 TO Npts-1 ! Assign values to the X-axis array X(*)
   X(I)=I+1
NEXT I

FOR I=0 TO Npts ! Declare the min and max values of the X-axis array
   Xmin=X(I)
NEXT I

Frac=Xmax/B-IP(Xmax/B) ! Determine the min and max values for the Y-axis
IF Frac<> 0 THEN Xmax=B*IP(Xmax/B+1)
Xrange=Xmax-Xmin ! Determine the range
Ymax=9.99999999999E499
Ymin=-9.99999999999E499
FOR I=0 TO Npts-1 ! Assign values to the Y-axis array Y(*)
   Y(I)=1
NEXT I

Xmax=Npts ! Declare the min and max values of the X-axis array
Ymax=0
Ymin=0

Fract=Xmax/8-IP(Xmax/8) ! Determine the min and max values for the Y-axis
IF Fract<> 0 THEN Xmax=8*IP(Xmax/8+1)

Xrana=Xmax-Xmin ! Determine the range
Ymax=-9.99999999999E499
Ymin=9.99999999999E499
FOR I=0 TO Npts-1 ! Assign values to the Y-axis array Y(*)
   Y(I)=1
   Ymax=Y(I)
   Ymin=Y(I)
NEXT I

Ypower=INT(LOG((Ymax-Ymin)/10)) ! Determine the base 10 power of Yrange
Ymin=Ymin/10^Ypower
Ymax=Ymax/10^Ypower
Yrange=Ymax-Ymin

RETURN

Axes_label: ! ***************

Aspect=RATIO ! Determines relative size of the X and Y dimensions

DES

LONG 7
CSIZE 2.5
MOVE 77*Aspect,91
LABEL Name*! Plot the users name
MOVE 85*Aspect,91
LABEL Da_te*! Plot the date
LONG 6
CSIZE 4.6,10
MOVE 55*Aspect,10
LABEL Title*! Plot the title
CSIZE 3.5
MOVE 55*Aspect,20
LABEL Xtitle*! Plot the X-axis title
CSIZE 2.5
MOVE 55*Aspect,17
LABEL USING "9A,K" ; "Scale: 1E",Xpower ! Plot the X-axis base 10 power
CSIZE 3.5
MOVE 19*Aspect,10
LABEL Ytitle*! Plot the Y-axis title
CSIZE 2.5
MOVE 15*Aspect,55
LABEL USING "9A,K" ; "Scale: 1E",Ypower ! Plot the Y-axis base 10 power

FRAME

LOCATE 20*Aspect.85*Aspect.25,90 ! Define the plotting area

SCALE Xmin,Xmax,Ymin,Ymax ! Scale the plotting area

Yinter=Ymin
IF Type=1 THEN AXES Xrange/100,Yrange/100,Xinter,Yinter,10,10,3
IF Type=2 THEN AXES Xrange/8,Yrange/100,Xinter,Yinter,1,10,3

Yrange=Ymax-Ymin

CSIZE 2.5
LDIR 0
LORG 0
IF Yinter+I*Yrange/10>Ymax THEN 2600
MOVE Xinter-Xrange/100,Yinter+I*Yrange/10
LABEL USING "3D.2D"; Yinter+I*Yrange/10
I=I+1
GOTO 2550
! Label the X-axis
GOTO 2600
LORG 9
IF Xinter+I*Xrange/Scale>Xmax THEN 2710
MOVE Xinter+I*Xrange/Scale,Yinter-Yrange/50
IF Type=1 THEN LABEL USING "3D.2D"; Xinter+I*Xrange/Scale
I=I+1
GOTO 2690
GOTO 2550
RETURN
! **************
Plot_1:
! **************
PEN 1
MOVE X(0)/10^Xpower,Y(0)/10^Ypower
FOR I=1 TO Npts-1
PLOT X(I)/10^Xpower,Y(I)/10^Ypower,-1
NEXT I
PEN 0
GOTO 2910
GOTO 2910
MOVE X(Npts)/10^Xpower,Y(Npts)/10^Ypower
FOR I=Npts+1 TO Npts+points-1
PLOT X(I)/10^Xpower,Y(I)/10^Ypower,-1
NEXT I
PEN 0
GOTO 2900
NEXT L2
RETURN
! **************
Plot_2: Curve 2 on the same axes
! **************
MOVE X(0),Y(0)/10^Ypower
FOR I=1 TO Npts-1
PLOT X(I),Y(I)/10^Ypower,-1
NEXT I
PEN 0
GOTO 99999
RETURN
GOTO 3010
3010 DISP "Enter the no. of points per average " @ INPUT Navg
EST=15
FOR J=15 TO Npts-1+Navg-1
Y(J)=Y(J-1)
AVE=0
FOR K=EST TO EST+Navg-1
AVE=AVE+Y(K)
NEXT K
AVE=AVE/Navg
Y(EST)=AVE
EST=EST+1
NEXT I
FOR J=15 TO Npts-1
AVE=0
FOR K=EST TO EST+Navg-1
AVE=AVE+Y(K)
NEXT K
AVE=AVE/Navg
Y(EST)=AVE
EST=EST+1
RETURN
D17
4150 NEXT J
4160 DISP "Enter the smooth data filename " @ INPUT FAYILI#
4170 CREATE FAYILI#:"D700",409,50
4180 ASSIGN 1 TO FAYILI#:"D700"
4190 FOR I=0 TO Npts-1
4200 PRINT# 1 ; X(I),Y(I)
4210 NEXT I
4220 ASSIGN 1 TO *
4230 RETURN
99999 END
112563
5 ! Revised for ease of use by Mqhele E. Dlodlo
6 ! Grad. E. E. at Kansas State University
7 ! Also added was a smoothing routine
8 ! Revision date: 18 February 1989
9 !
10 !******************************************************************************
11 ! Program Title: LINPLOTMD
12 !
13 ! Programmer: Doug Doerfler
14 ! Graduate Student, Kansas State University
15 !
16 ! Date: 06-02-84
17 !
18 ! Version 1.0
19 !
20 ! Program Description: LINPLOT is a plot routine developed to provide
21 ! a general purpose plot routine for linear-linear plots.
22 ! Type 1 plots divide the horizontal axis into 10 intervals.
23 ! Type 2 plots divide the horizontal axis into 8 intervals and
24 ! uses the point numbers to label the X-axis.
25 !
26 ! Parameters that are supplied to LINPLOT
27 ! X(*) - X-axis data array: (real)
28 ! Y(*) - Y-axis data array: (real)
29 ! Npts - Number of points in X(*) and Y(*): (integer)
30 ! Type - Type of numbering for the X-axis: (integer)
31 ! 1 - Use values in X(*) to label the X-axis: 10 intervals
32 ! 2 - Use the point number to label the X-axis: 8 intervals
33 ! Xtitle# - Title for the X-axis
34 ! Ytitle# - Title for the Y-axis
35 ! Title# - Title of the plot
36 ! Name# - User's name
37 ! Date# - Date the plot was generated
38 !
39 ! Subroutines within LINPLOT
40 ! Initialize1 - Initializes the data for a Type=1 plot
41 ! Initialize2 - Initializes the data for a Type=2 plot
42 ! Axes_label - Draws and labels the axes; Labels the plot
43 ! Plot_1 - Plots data points for a Type=1 plot
44 ! Plot_2 - Plots data points for a Type=2 plot
45 ! Smooth - Moving average trend remover
46 !
47 ! Data - Data needs to be stored in a file as two columns. The
48 ! left column is the x-axis data and the right column is
49 ! the y-axis data.
50 !
51 !******************************************************************************
52 !
53 ! Option Base 0
54 !
55 ! Declarations
56 !
57 ! REAL X(800), Y(800)
58 ! REAL Aspect, Fract, Scale, Xmax, Xmin, Xrange, Xpower, Xinter
59 ! REAL Ymax, Ymin, Yrange, Ypower, Yinter
60 ! INTEGER Npts, Plotter, Type
61 ! DIM Xtitle#[60], Ytitle#[60], Title#[60], Name#[60], Date#[60]
62 ! DIM Dummy#[60], File_name#[60]
63 ! CLEAR
64 ! DISP
65 ! DISP
66 ! DISP TAB (5): "THE DATA FILE IS ASSUMED TO BE IN LEFT DRIVE"
67 ! DISP 3000
68 ! CLEAR
69 ! DISP
70 ! DISP
71 !
72 !******************************************************************************
D19
620 DISP TAB (5); "HORIZONTAL AXES TITLE (60 CHARACTER LIMIT)"
630 INPUT Xtitle$  
640 DISP TAB (5); "VERTICAL AXES TITLE (60 CHARACTER LIMIT)"
650 INPUT Ytitle$  
660 DISP TAB (5); "THE PLOT TITLE IS (60 CHARACTER LIMIT)"
670 INPUT Title$  
680 DISP TAB (5); "USERS NAMES (60 CHARACTER LIMIT)"
690 INPUT Name$  
700 DISP TAB (5); "WHAT IS THE DATE"
710 INPUT Date$  
720 DISP TAB (5); "HOW MANY OBSERVED VALUES ARE BEING PLOTTED"
730 INPUT Mots  
740 TVpe=1
765 DISP "INPUT FILE NAME"; @ INPUT filename$  
770 ASSIGN# 1 TO file_name$;:D700"  
780 ASSIGN# 2 TO file_name$;:D700"  
790 FOR K=0 TO Npts-1
810 READ# 1 ; X(K),Y(K>
830 NEXT K
850 ASSIGN** 1 TO *  
860 ASSIGN* 2 TO *  
870 ! Initializing the arrays refers to finding maximum and minimum values, the  
880 ! range of the values, and normalizing the data by dividing by the  
890 ! base 10 power of the range.  
900 !
920 DISP "Initializing the arrays for plotting"  
930 ON Type GOSUB Initialize1,Initialize2  
940 BEEP  
950 ! Determine what plotter the user wishes to use and make declarations  
960 ! accordingly.  
970 !
990 DISP "Which plotter is to be used (1-CRT. 2-7470A)"
1000 INPUT Plotter  
1010 IF Plotter=2 THEN GOTO 1080  
1020 DISP "END LINE will allow you to exit graphics mode after plotting."
1030 WAIT 3000  
1040 PLOTTER IS 1  
1050 GCLEAR  
1060 GRAPHALL  
1070 GOTO 1150  
1080 PLOTTER IS 705  
1090 OUTPUT 705 ;"VS8"
1100 DISP "Set up plotter and press END LINE";  
1110 INPUT Dummy$  
1120 !
1130 ! Output the data to the specified plotter  
1140 !
1150 GOSUB Axes_label  
1160 ON Type GOSUB Plot_1 ; Plot_2  
1170 BEEP  
1180 IF Plotter=1 THEN INPUT Dummy$  
1190 ALPHA  
1193 DISP "Would you like to smooth the data " ; @ INPUT Smooth$  
1195 IF Smooth$="Y" OR Smooth$="y" THEN GOSUB Smooth  
1200 DISP "Would you like to change the plotter or the axes limits (Y/N)"
1210 INPUT Dummy$  
1220 IF Dummy$="N" OR Dummy$="n" THEN GOTO 1460  
1220 DISP "Would you like to change the limits of the vertical axis (Y/N)";  
1240 INPUT Dummy$
IF Dummy$="N" OR Dummy$="n" THEN GOTO 1340
1255 DISP Ymax: "is the old normalized maximum value"
1260 DISP "What is the new normalized maximum value?"
1265 INPUT Ymax
1270 DISP Ymin: "is the old minimum value"
1275 DISP "What is the new normalized minimum value?"
1280 INPUT Ymin
1290 IF Ymax>Ymin THEN 1330
1300 DISIP "ERROR. Ymax must be greater than Ymin"
1310 GOTO 1260
1320 Yrange=Ymax-Ymin
1330 DISP "Would you like to change the limits of the horizontal axis (y/n)?": INPUT Dummy*$
1340 IF Dummy$="N" OR Dummy$="n" THEN GOTO 1450
1350 DISIP "is the old normalized maximum value"
1360 DISIP "is the new normalized maximum value";
1370 INPUT Xmax
1380 IF Xmax>Xmin THEN 1440
1390 DISIP "ERROR. Xmax must be greater than Xmin"
1400 GOTO 1370
1410 Xrange=Xmax-Xmin
1420 GOTO 1270
1430 CLEAR @ DISP @ DISP @ DISP
1440 DISP TAB (5): "Enter:"
1450 DISP TAB (11): "1 to return to ADC TEST"
1460 DISP TAB (11): "2 to rerun LINPLOT"
1470 DISP TAB (11): "3 to quit"
1480 INPUT A
1490 IF A=1 THEN CHAIN "ADC TEST"
1500 IF A=2 THEN 440
1510 DISIP @ DISP TAB (5): "This program has ended."
1520 GOTO 9999
1530 I****************
1540 Initializel: !
1550 ! ****************
1560 Scale=10 ! Divide the axis into ten intervals
1570 Xmax=-9.99999999999E499 ! Set initial min. and max.
1580 Xmin=9.99999999999E499
1590 Ymax=-9.99999999999E499
1600 Ymin=9.99999999999E499
1610 FOR I=0 TO Npts+points-1
1620 ! Assign values to the X-axis array X(*)
1630 ! Search data - for the min and max values
1640 ! Base 10 power of the range
1650 IF X(I)>Xmax THEN Xmax=X(I)
1660 IF Y(I)>Ymax THEN Ymax=Y(I)
1670 IF X(I)<Xmin THEN Xmin=X(I)
1680 IF Y(I)<Ymin THEN Ymin=Y(I)
1690 NEXT I
1700 Xpower=INT (LGT ((Xmax-Xmin)/10)) ! Base 10 power of the range
1710 Xmin=Xmin/10^Xpower
1720 Ymax=Ymax/10^Xpower
1730 Xrange=Xmax-Xmin
1740 Ypower=INT (LGT ((Ymax-Ymin)/10))
1750 Ymin=Ymin/10^Ypower
1760 Ymax=Ymax/10^Ypower
1770 IF Ymin<0 THEN Ymin=INT (Ymin-(Ymax-Ymin)*.1)/10
1780 Ymax=INT (Ymax+(Ymax-Ymin)*.1)/10
1790 Yrange=Ymax-Ymin
1800 Ypower=Ypower+1
1810 RETURN
1820 ! ****************
1830 Initialize2: !
1840 ! ****************
1850 Scale=8 ! Divide the X-axis into 8 intervals
1860 FOR I=0 TO Npts-1 ! Assign values to the X-axis array X(*)

D21
1870  X(I)=I+1
1880 NEXT I
1890 Xmax=Npts ! Declare the min and max values of the X-axis array
1900 Xmin=0
1910 Fract=Xmax/B*IP (Xmax/B) ! Determine the min and max values for the Y-axis
1920 IF Fract<>0 THEN Xmax=B*IP (Xmax/B+1)
1930 Xrange=Xmax-Xmin ! Determine the range
1940 Ymax=-9.99999999999E499
1950 Ymin=9.99999999999E499
1960 FOR I=0 TO Npts-1
1970 IF Y(I)>Ymax THEN Ymax=Y(I)
1980 IF Y(I)<Ymin THEN Ymin=Y(I)
1990 NEXT I
2000 Ypower=INT (LGT ((Ymax-Ymin)/10)) ! Determine the base 10 power of Yrange
2010 Ymin=Ymin/10^Ypower
2020 Ymax=Ymax/10^Ypower
2030 IF Ymin<0 THEN Ymin=INT (Ymin-(Ymax-Ymin) *.1)/10
2040 Ymax=INT (Ymax+(Ymax-Ymin) *.1)/10
2050 Yrange=Ymax-Ymin
2060 Ypower=Ypower+1
2070 RETURN
2080 ! ***************
2090 Axes_label:
2100 ! ******************
2110 Aspect=RATIO ! Determines relative size of the X and Y dimensions
2120 DEG
2130 10R6
2140 CSIZE 2,5
2150 MOVE 77*Aspect,91
2160 LABEL Name* ! Plot the users name
2170 MOVE 85*Aspect,91
2180 LABEL Date* ! Plot the date
2190 10R6
2200 CSIZE 4,6,10
2210 MOVE 55*Aspect,10
2220 LABEL Title* ! Plot the title
2230 CSIZE 3,5
2240 MOVE 55*Aspect,20
2250 LABEL Xtitle* ! Plot the X-axis title
2260 IF Type=2 THEN GOTO 2300
2270 CSIZE 2,5
2280 MOVE 55*Aspect,17
2290 LABEL USING "A,A.K" ; "Scale: 1E",Xpower ! Plot the X-axis base 10 power
2300 CSIZE 3,5
2310 LDIR 90
2320 10R4
2330 MOVE 10*Aspect,55
2340 LABEL Ytitle* ! Plot the Y-axis title
2350 CSIZE 2,5
2360 MOVE 12*Aspect,55
2370 LABEL USING "A,A.K" ; "Scale: 1E",Ypower ! Plot the Y-axis base 10 power
2380 !
2390 ! Draw the axes
2400 !
2410 LOCATE 20*Aspect,85*Aspect,25,90 ! Define the plotting area
2420 FRAME
2430 SCALE Xmin,Xmax,Ymin,Ymax ! Scale the plotting area
2440 Xinter=Xmin ! Declare the axes intercept
2450 Yinter=Ymin
2460 IF Type=1 THEN AXES Xrange/100,Yrange/100,Xinter,Yinter,10,10,3
2470 IF Type=2 THEN AXES Xrange/8,Yrange/100,Xinter,Yinter,1,10,3
2480 !
2490 ! Label the Y-axis
2500 !
2510 CSIZE 2,5
2520 LDIR 0

D22
2530 LORG B
2540 I=0
2550 IF Yinter+I*Yrange/Ymax THEN 2600
2560 MOVE Xinter-Xrange/100,Yinter+I*Yrange/10
2570 LABEL USING "3D.2D"; Yinter+I*Yrange/10
2580 I=I+1
2590 GOTO 2550
2600 !
2610 ! Label the X-axis
2620 !
2630 LORG 9
2640 I=1
2650 IF Xinter+I*Xrange/Xmax THEN 2710
2660 MOVE Xinter+I*Xrange/Xmax,Yinter-Yrange/50
2670 IF Type=1 THEN LABEL USING "3D.2D"; Xinter+I*Xrange/Xmax
2680 IF Type=2 THEN LABEL USING "5D.0D"; Xinter+I*Xrange/Xmax
2690 I=I+1
2700 GOTO 2650
2710 RETURN
2720 ! *************
2730 Plot_1 !
2740 ! *************
2750 FOR L2=1 TO 2
2760 IF L2=1 THEN 2770 ELSE 2840
2770 PEN 1
2780 MOVE X(0)/10^Xpower,Y(0)/10^Ypower
2790 FOR I=1 TO Npts-1
2800 PLOT X(I)/10^Xpower,Y(I)/10^Ypower,-1
2810 NEXT I
2820 PEN 0
2830 GOTO 2900
2840 PEN 2
2850 MOVE X(Npts)/10^Xpower,Y(Npts)/10^Ypower
2860 FOR I=Npts+1 TO Npts+points-1
2870 PLOT X(I)/10^Xpower,Y(I)/10^Ypower,-1
2880 NEXT I
2890 PEN 0
2900 NEXT L2
2910 RETURN
2920 ! *************
2930 Plot_2 ! Curve 2 on the same axes
2940 ! *************
2950 MOVE X(O),Y(O)/10^Ypower
2960 FOR I=1 TO Npts-1
2970 PLOT X(I),Y(I)/10^Ypower,-1
2980 NEXT I
2990 PEN 0
3000 RETURN
3010 GOTO 99999
3990 ! ********************************
4000 Smooth !
4010 ! ********************************
4020 DISP "Enter the no. of points per average " @ INPUT Navg
4030 EST=15
4040 FOR I=Npts TO Npts-1+Navg-1
4050 Y(I)=Y(Npts)
4060 NEXT I
4070 FOR J=15 TO Npts-1
4080 AVE=0
4090 FOR K=EST TO EST+Navg-1
4100 AVE=AVE+Y(K)
4110 NEXT K
4120 AVE=AVE/Navg
4130 Y(EST)=AVE
4140 EST=EST+1
4150 NEXT J

D23
4160 DISP "Enter the smooth data filename " @ INPUT FAYILI$
4170 CREATE FAYILI$:"D700",409,50
4180 ASSIGN 1 TO FAYILI$:"D700"
4190 FOR I=0 TO Npts-1
4200 PRINT 1; X(I),Y(I)
4210 NEXT I
4220 ASSGN# 1 TO *
4230 RETURN
999999 END
112635
CORRELATION STUDIES OF PITS, HALL EFFECT AND VAN DER PAUW CHARACTERIZATIONS OF GaAs SUBSTRATES

by

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ABSTRACT

In the fabrication of integrated circuits, defects often appear to affect carrier activation. Two problems arising from this are currently under study at Kansas State University. Either donors do not move into substitutional locations in the substrate after annealing or substitution and activation do take place, but the electrons are trapped at a nearby defect. If these defects can be characterized and properly identified, then eventually they can possibly be eliminated, so that radiative recombination efficiency and therefore device reliability of GaAs can be enhanced.

This thesis discusses correlation studies on the data so far gathered on the deep level crystal defects in pulsed-laser annealed samples of GaAs implanted with Si and Se to a dose ranging from $2.2 \times 10^{12}$ to $6.0 \times 10^{14}$ cm$^{-2}$. A pulsed XeCl eximer laser ($\lambda = 308$ nm) was used to anneal these samples at energy densities ranging from 0.2 to 0.32 J/cm$^2$.

Photo-induced current transient spectroscopy (PITS) was the means of investigation of the residual defects in the PLA samples. Emission coefficient behavior related to deep level trap emptying on the falling edge of
an incident light pulse was observed.

These observations revealed three dominant and two trace peaks in the PITS spectra between 40 K and 400K over the 0.5 ms and 4 ms rate window range. The corresponding activation energies fell between 0.008 eV and 0.8 eV. Hall and Van der Pauw measurements were used in the study of sheet carrier concentration and electron mobility. The correlations between laser energy density (J.cm$^{-2}$), the dose (cm$^{-2}$), and the electrical characteristics, as well as the linear correlation of Arrhenius data points used in the determination of trap energies are presented and discussed.