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

by

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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

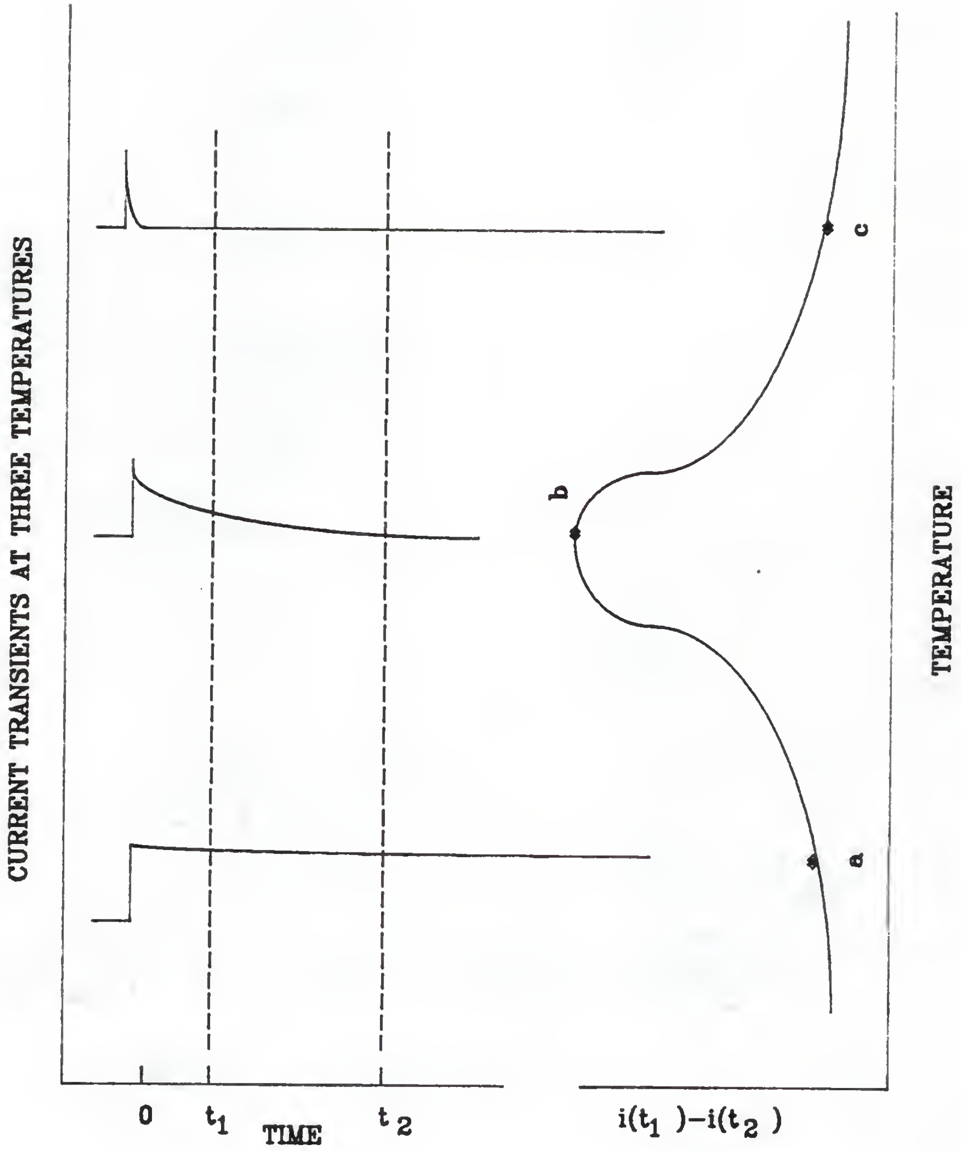


Figure 1.1 Translation of a PITS signal into a spectrum.

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.

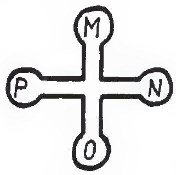


Fig. 2.1.1 The clover-leaf pattern on a sample of arbitrary shape

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, $V_{PO} = V_P - V_O$ (Fig. 2.1.1), is measurable and from it one can define the resistance

$$R_{MNPO} = (V_{PO}/I_{MN}).$$

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

$$R_{MPNO} = (V_{MP}/I_{NO}).$$

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

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

holds. Hence a graphical solution can be found for

$$R_S = \rho_S/t = (\pi/(2\ln 2))\ (R_{MNPO} + R_{MPNO})\ f \qquad (2.1.2)$$

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.

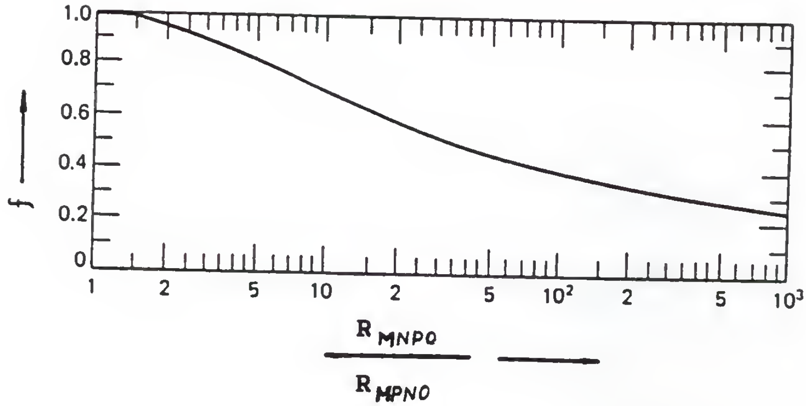


Fig. 2.1.2 Correction factor for computing specific resistivity. (Ghandhi, 1983).

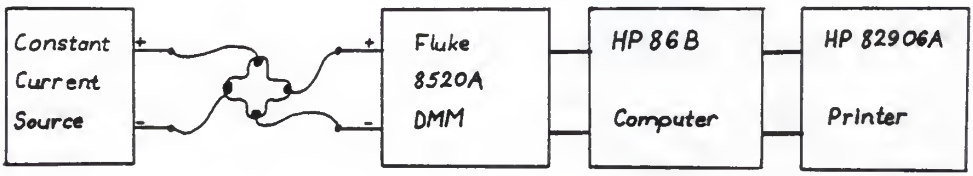


Fig. 2.1.3 Block diagram for the Van der Pauw measurement apparatus

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

$$R_{Hs} = (R_{MO,NP}(0) - R_{MO,NP}(B))/B \qquad (2.2.1)$$

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 $F = q*v*B$ on the charge carriers, where v is the carrier velocity. This force acts perpendicular to both the current streamlines and the magnetic induction. In terms of electric field effects, v can be derived approximately from F as

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

where the surface Hall coefficient is

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

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)**

$$\Delta(V_M - V_O) = \int_M^{O_t} E_H ds$$

$$= R_H B \int_M^{O_t} J ds$$

$$= R_H B(i_{PN}/t) \qquad (2.2.5)$$

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

$$\Delta V_{MO} = \Delta (V_M - V_O) = (\mu_H \ B \ J \ \rho)/t \qquad (2.2.6).$$

If we solve for u_H, then

$$\mu_H = (t/B) \ (\Delta R_{MO,PN}/\rho) \quad cm^2/V\text{-}s \qquad (2.2.7)$$

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 photoconductor. 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

$$\sigma = q\ (\mu_n n + \mu_p p) \qquad (2.3.1)$$

reduces to

$$\sigma = q\mu_n n \quad \text{since } n >> p \qquad (2.3.2).$$

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

$\mu_{n,p}$ = 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_{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.

τ = carrier lifetime,

η = quantum efficiency,

1/a = light penetration depth,

a = absorption coefficient

P_{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

$$n = n_{opt} \exp(-t/\tau) \qquad (2.3.3)$$

and

$$R = 1/\tau \tag{2.3.4}$$

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 << 1/a so that the optically active volume is WLD. The total number of photons striking the surface per unit time is P_{opt}/hv. Consequently, the total generation rate can be expressed as a function of the photo flux, i.e.

$$G = n/\tau = \eta(P_{opt}/hv)/(WLD) \tag{2.3.5}$$

Instead of computing n_{opt} in (2.3.3), we can re-arrange (2.3.5) to find

$$n = (\eta \tau /WLD)\ (P_{opt}/hv) \quad (\text{electrons/cm}^3) \tag{2.3.6}$$

where

$$hv = hc/\lambda = 1.24/\lambda_{He\text{-}Ne} \quad (\text{eV}) \text{ in this experiment.}$$

and

$$\eta = (I_p/q)\ (hv/P_{opt}).$$

The generated photo-current is

$$I_p = (\sigma\xi)WD \quad , \text{ where } \sigma = q\ \mu_n n$$

$$= (q\mu_n n\xi)WD \tag{2.3.7}$$

If we substitute for n from (2.3.6),

$$I_p = q[\eta(P_{opt}/hv)][\mu_n \tau \xi /L] \tag{2.3.8}$$

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

$$I_{ph} = q[\eta(P_{opt}/hv)] \quad (2.3.9)$$

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

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

where (Hurtes, 1978)

N_T = density of traps

e_n, e_p = sums of optical and thermal emission rates for electrons and holes respectively.

σ_n, σ_p = corresponding capture cross sections

v_n, v_p = corresponding thermal velocities

δ_n, δ_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

$$N_T^O(\infty) = N_T/(1 + e_n/e_p) \qquad (2.3.11)$$

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

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

in which we can let

$$M = qW(LD/2)$$

and then develop the transient current as

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

$$= M(e_n - e_p)[N_T^O(0) - N_T^O(\infty)]\exp(-t/\tau) \qquad (2.3.12)$$

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

$$\Delta i(t) = Me_n N_T[1/(1+(\sigma_p v_p/\sigma_n v_n))$$

$$- (1/1+(e_n/e_p))]\exp(-e_n t) \qquad (2.3.13)$$

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

$$\Delta i(t) = MN_T\, e_n \exp(-e_n t) \qquad (2.3.14)$$

For the two-gate experiment with $t_2 >> t_1$,

$$\Delta i(t) = i(t_1) - i(t_2)$$

$$= i(t=0) - i(t=\infty)$$

implying $1/\tau$ $1/t_1$ such that

$$1/t_1 = e_n$$

$$= \sigma_n v_n N_c \exp(-E_T/kT_{max}) \qquad (2.3.15)$$

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^2s) versus $1/T$ (K^{-1}) graphically yields E_t and σ_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,

$$E_t = \text{slope}*1000*k$$

$$= 0.0862*\text{slope} \quad \text{eV}$$

and

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

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

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/m^2. 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 um 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 um 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.

Value Read (mV)	Power (mW)	Constraints
1.1	10.89	between points B and C, no filter.
0.9	8.9	next to shroud, no filter.
0.5	4.95	.3 density, 50%T filter, 64Hz Model 50273 Ser. # 345 Oriel.
0.23	2.28	.6 density, 25%T filter, 64Hz Model 50276 Ser. # 163 Oriel.

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.

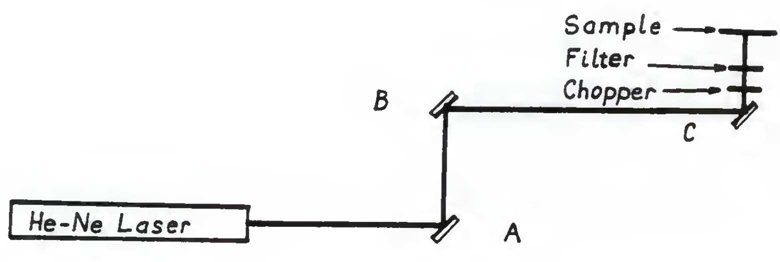


Fig. 2.3.1 The laser light source system

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

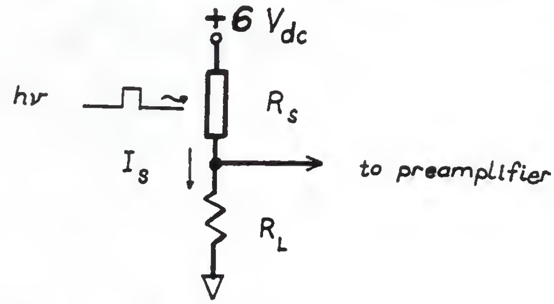


Fig. 2.3.2 The Sample Circuit

jitter. 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:

$$I_S \doteq V_B/R_S.$$

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 $R_L <= R_S/10$ 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(2 N) 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_{max} = [450, 3600] as shown on Table 2.3.2, where t_1/t_2 is (%Initial A)/(%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_{series} = Z_{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.

t1/t2	Repetition Rate at:			SNIR at:		
	10 ms	20 ms	50 ms	10 ms	20 ms	50 ms
.05/.5	450	900	2250	30	42	67
.06/.6	540	1080	2700	33	46	73
.07/.7	630	1260	3150	35	50	79
.08/.8	720	1440	3600	38	54	85
.1/1.0	900	1800	---	42	60	---

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.

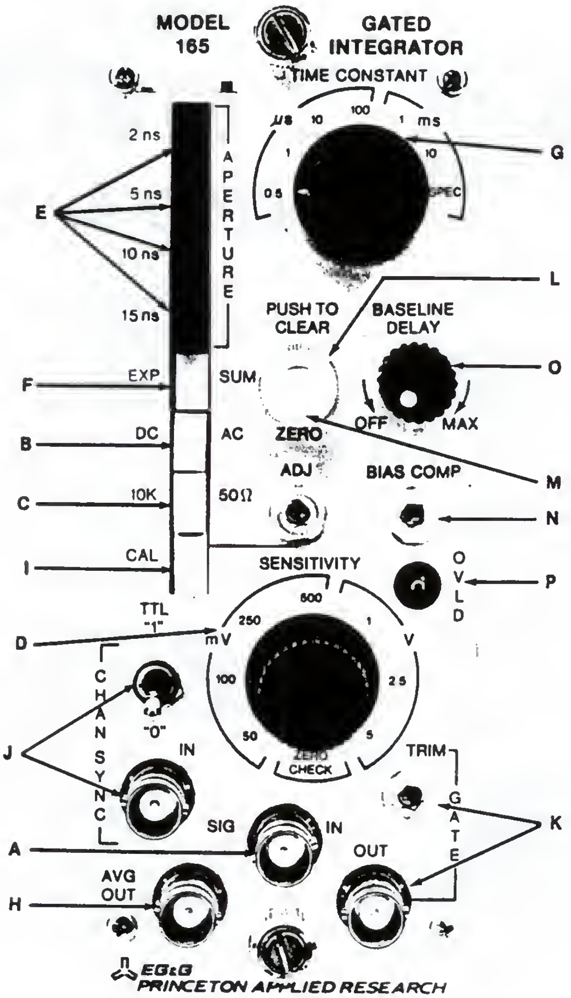


Fig. 2.3.3 Front panel of a series 16X gated integrator

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.

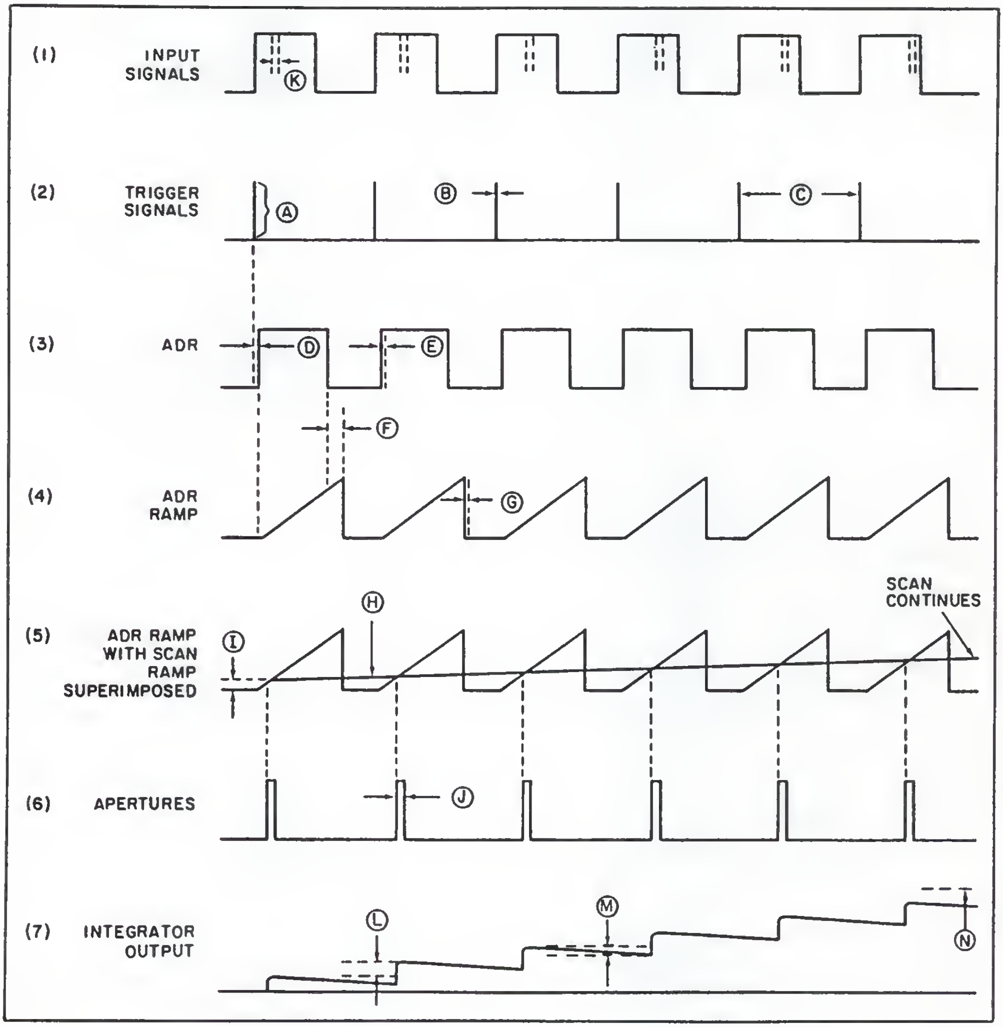


Fig. 2.3.4 Key boxcar operational parameters
(Source: Operating and Service Manual,1983)

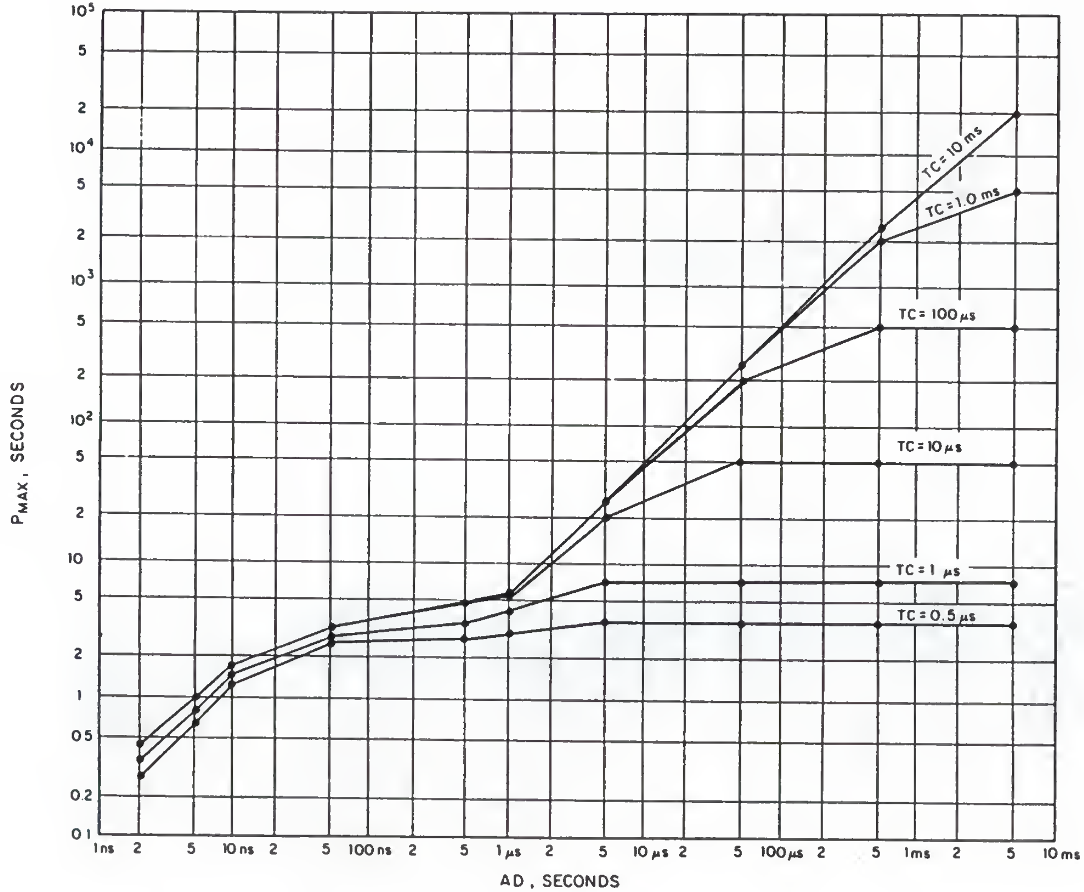


Fig. 2.3.5 Determining the trigger period.
(Source: Operating and Service Manual,1983)

4) Trigger Period (P_{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

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

where OTC is the observed time constant:

$$OTC = TC/\text{duty factor}$$

and

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

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.

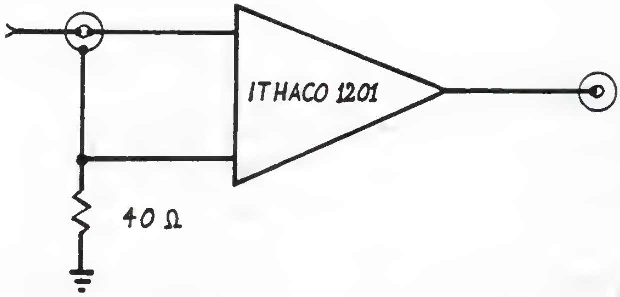


Fig. 2.3.6 Basic schematic of the ITHACO 1201 preamplifier.

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 shooting trouble 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 straight forward 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

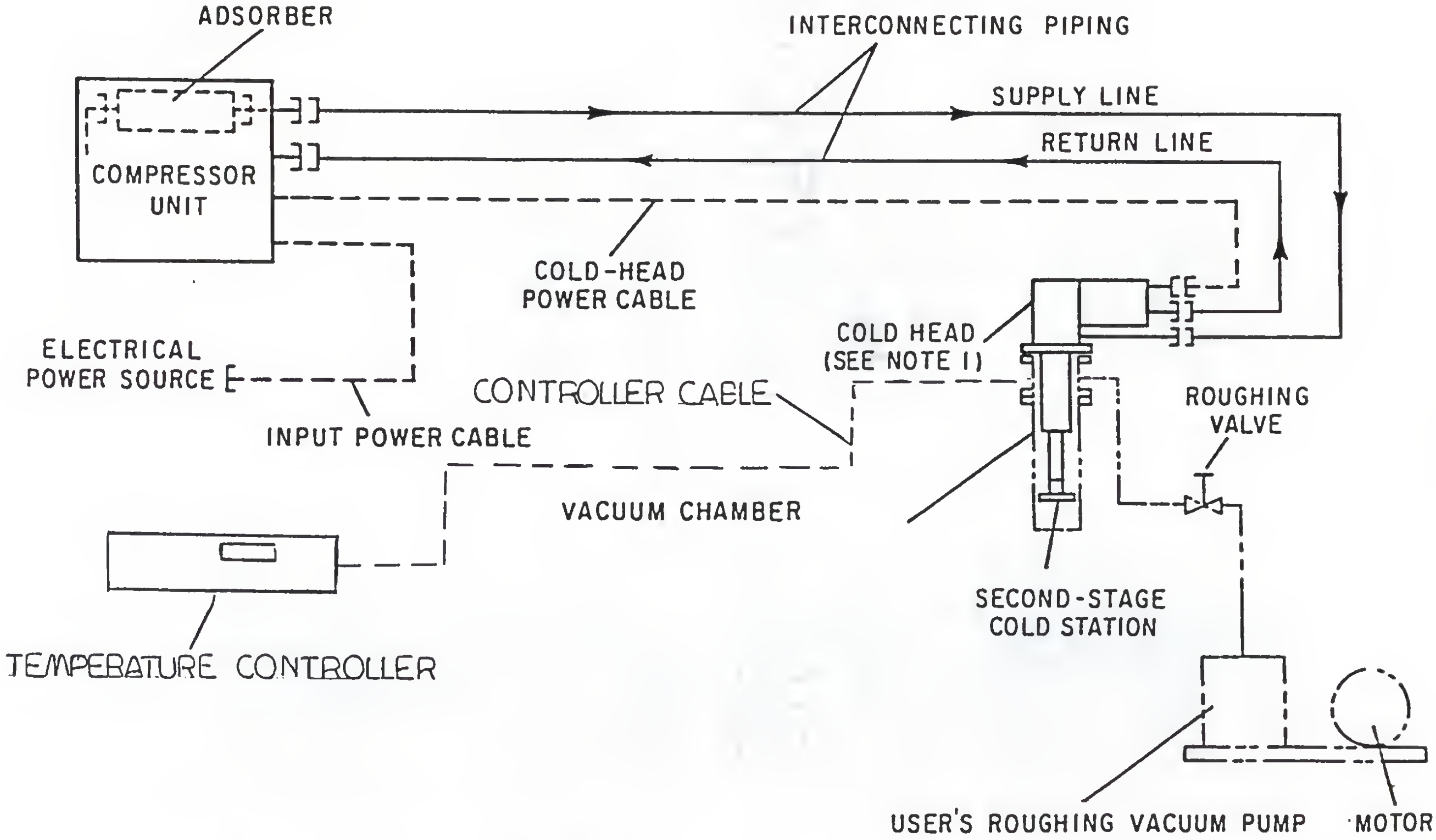
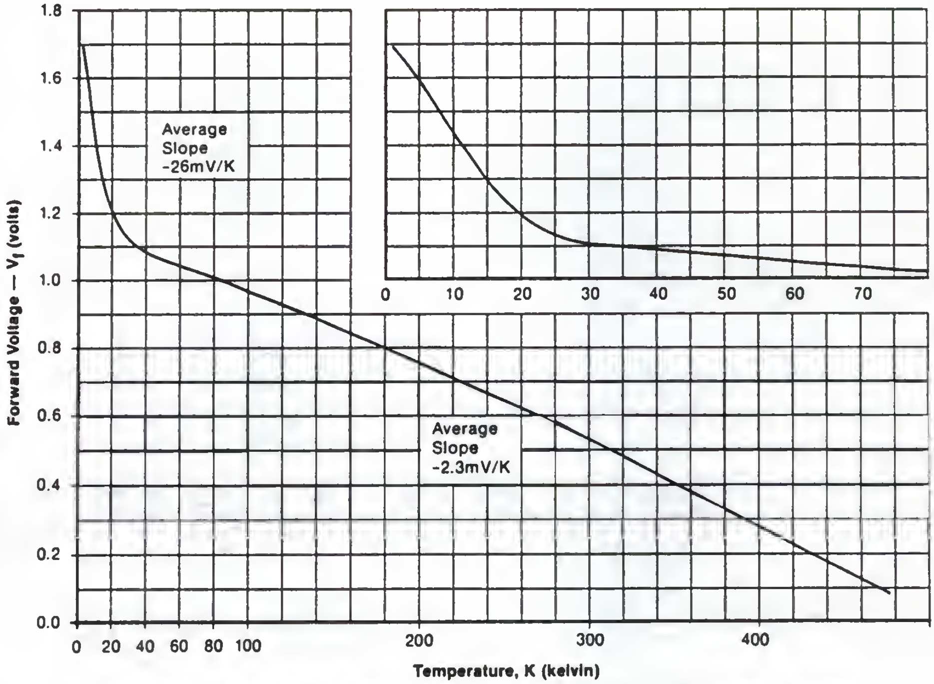


Fig. 2.3.7 The refrigeration system.



Standard temperature response (Curve 10) for DT-470 Series Sensors.
All Sensors track this Curve within specified tolerance bands.

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:

0 K - 100 K	100 K - 305 K	305 K - 475 K
+/- 0.5 K	+/- 1.0 K	+/- 2.0 K

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 Appendix 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.

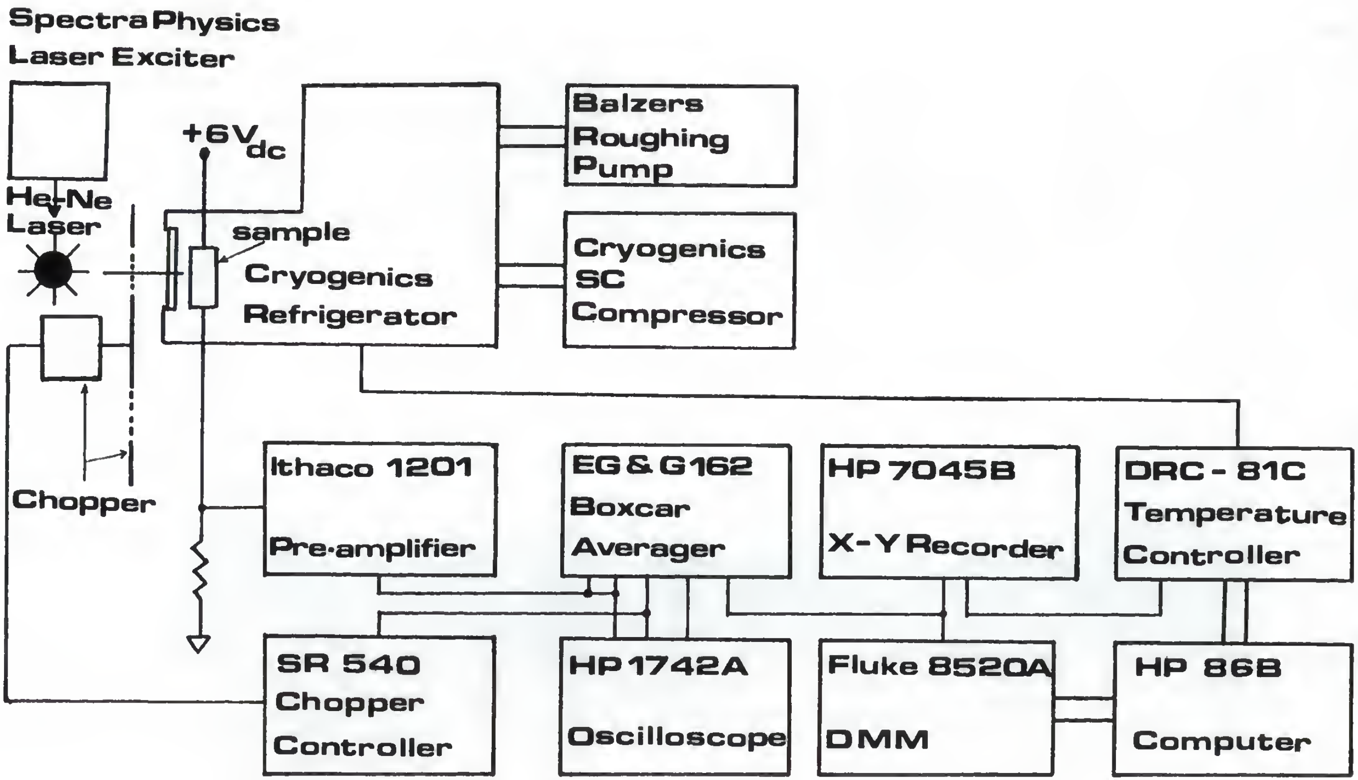


Fig. 2.3.9 The PITS system block diagram.

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 x $10^{13}cm^{-2}$

Laser Intensity (J/cm^2)	Mobility ($cm^2/V\text{-}s$)	Sheet carrier concentration (cm^{-2})	Sheet resistivity (ohm/sheet)
0.26	229	6.2×10^{13}	443
0.305	271	6.2×10^{13}	376
0.32	279	1.0×10^{14}	214
Correlation coefficients:	0.9957	0.6934	-0.8697

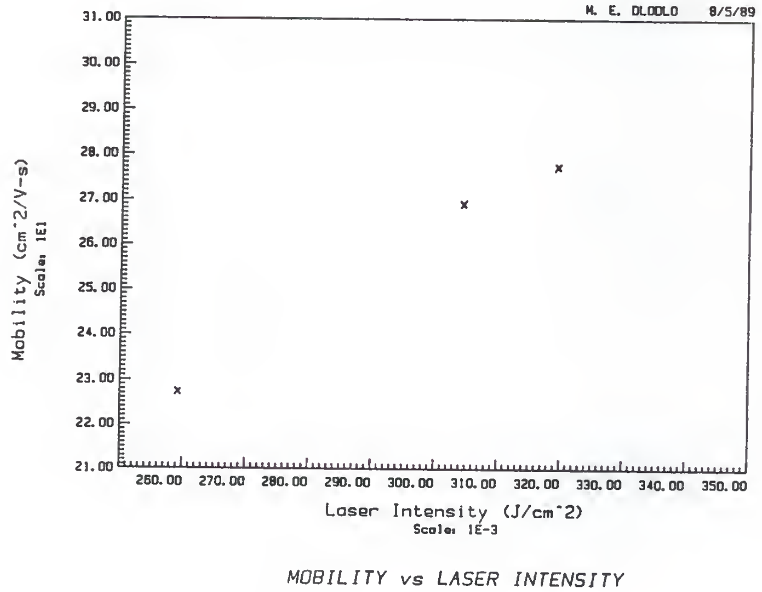
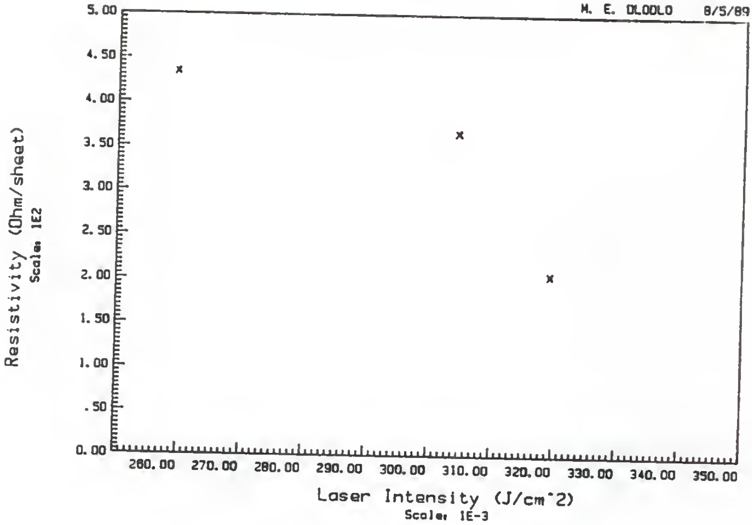


Fig. 3.1 Mobility as a function of laser intensity. Dose = 2.0 x $10^{13}cm^{-2}$



Sheet Resistivity vs Laser Intensity

Fig. 3.2 Resistivity as a function of laser intensity. Dose = 2.0 x 10^{13}cm^{-2}

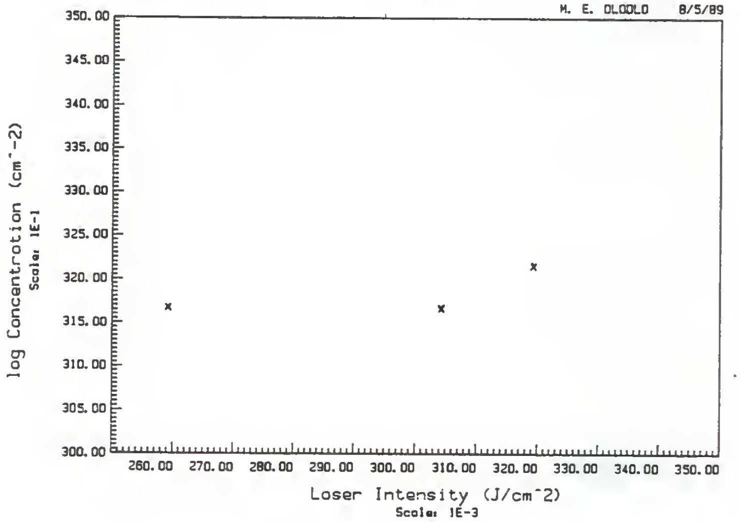


Fig. 3.3 Sheet carrier concentration versus laser intensity. Dose = 2.0 x 10^{13}cm^{-2}

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 x 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

Dose	Mobility	Sheet carrier concentration	Sheet resistivity
cm^{-2}	(cm^2/V-s)	(cm^{-2})	(ohm/sheet)
$4.0x10^{12}$	249	$1.2x10^{14}$	218
$2.0x10^{13}$	298	$1.0x10^{14}$	205
$1.0x10^{14}$	232	$1.0x10^{14}$	264
$6.0x10^{14}$	282	$1.0x10^{14}$	214
Correlation coefficients:	0.1523	-0.7632	0.2104

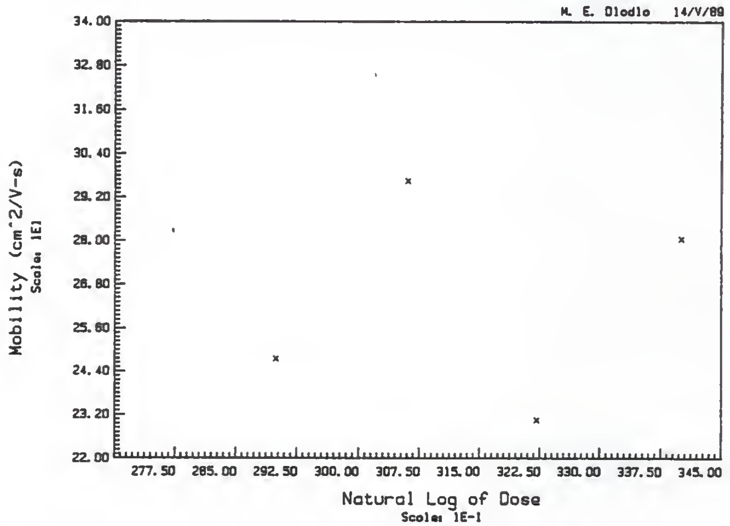
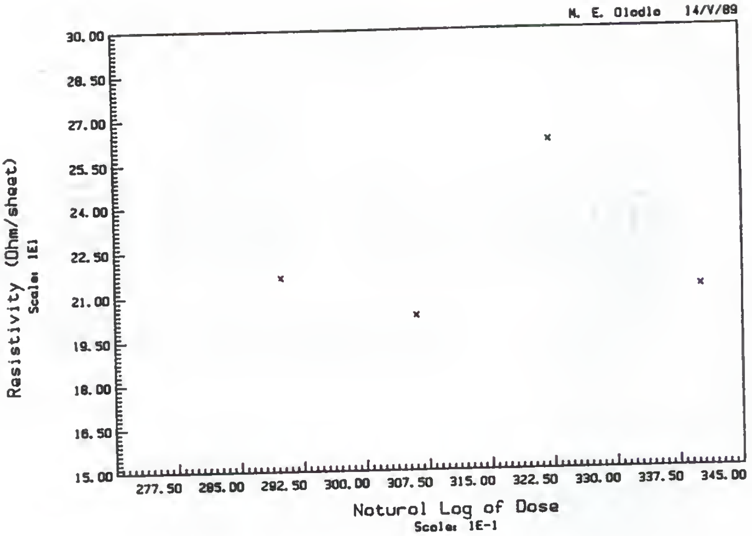
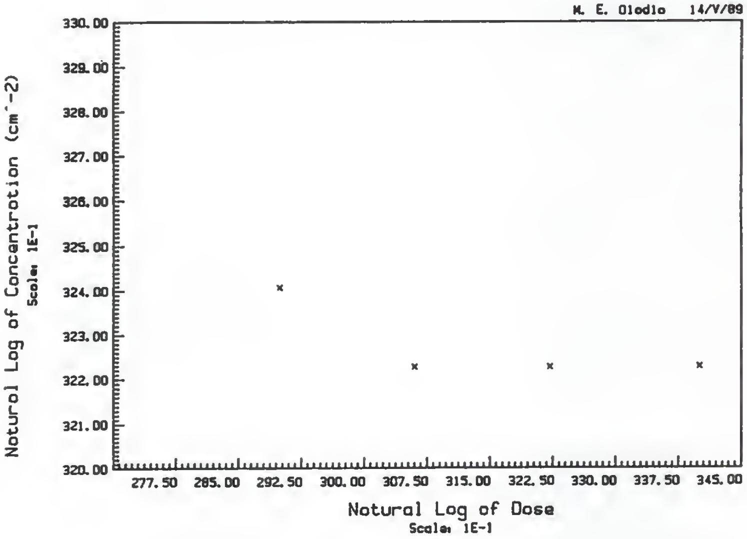


Fig. 3.4 a) Dose dependence of electron mobility.

Intensity, I = 0.32 J cm^{-2}.
(Data : Courtesy, Yanan Shieh, 1989)



b) *Resistivity vs Dose*



c) *Sheet Corrier Concentrotion vs Dose*

Fig. 3.4 Dose dependence of b) sheet carrier concentration
c) sheet resistivity.

Intensity, I = 0.32 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.

Peak #		Mean T_m(K)	E_t(eV)	σ_n(cm^2)	Sample #
1.	a.	35.0 +/-0.73	0.019	1.2 e-18	LA4012B
	b.	36.9 +/-2.28	0.016	3.4 e-19	LA2013D
	c.	41.9 +/-1.95	0.014	7.7 e-20	LA4012A
	d.	43.2 +/-0.96	0.008	1.3 e-20	LA2013B
2.	a.	52.9 +/-1.18	0.022	1.7 e-19	LB6014A
	b.	56.2 +/-1.76	0.068	1.0 e-15	LA2013A
	c.	56.6 +/-0.88	0.089	5.3 e-14	LA2013B
3.	a.	78.5 +/-1.66	0.056	1.6 e-18	LA4012B
	b.	80.8 +/-1.63	0.091	2.1 e-16	LA2013B
	c.	81.3 +/-2.35	0.103	9.7 e-16	LA2013A
	d.	82.86 +/-.96	0.138	9.8 e-14	LA4012A
	e.	88.1 +/-1.32	0.064	2.3 e-18	LB6014A
	f.	96.6 +/-1.68	0.176	3.3 e-13	LA2013D
4.	a.	152.4 +/-2.17	0.184	1.2 e-16	LA4012B
	b.	153.9 +/-	0.56	1.1 e-19	LA2013A
	c.	154.4 +/-1.53	0.52	1.0 e-19	LA2013D
	d.	160.6 +/-2.31	0.144	2.8 e-18	LA4012A
	e.	166.0 +/-1.27	0.23	1.3 e-20	LA2013B
	f.	169.5 +/-2.73	0.129	9.9 e-19	LB6014A
5.	a.	319.8 +/-3.14	0.69	2.0 e-12	LA4012A
	b.	322.8 +/-1.76	0.71	3.5 e-17	LA2013B
	c.	325.8 +/-3.15	0.57	1.5 e-14	LA4012B
	d.	327.4 +/-3.42	0.34	7.4 e-18	LB6014A

Table 3.3 Peak grouping by correlation.

Peak Group Number	Temp. (K)	E_t (eV)	σ_n (x $10^{-20}cm^2$)	Least Squares Fit	Correl. Coeff. r
A1.d	43.2	0.008	1.3	Exponential	0.98
A1.c	41.9	0.014	7.7		
A1.b	36.9	0.016	34.0		
A1.a	35.0	0.019	120.0		
B2.a	52.9	0.022	17.0	Exponential	1.00
B2.b	56.2	0.068	100,000.0		
B2.c	56.6	0.089	5,300,000.0		
C3.a	78.5	0.056	160.0	Insufficient data	
C3.e	88.1	0.064	230.0		
D3.b	80.8	0.091	21,000.0	Either	
D3.c	81.3	0.103	97,000.0	Exponential	0.96
D3.d	82.86	0.138	9,800,000.0	or	
D3.f	96.6	0.176	33,000,000.0	Power	0.98
				Either	
E4.f	169.5	0.129	99.0	Exponential	1.00
E4.d	160.6	0.144	280.0	or	
E4.a	152.4	0.184	12,000.0	Power	1.00
				Either	
F4.e	166.0	0.23	1.3	Exponential	1.00
F4.c	154.4	0.52	10.0	or	
F4.b	153.9	0.56	11.0	Power	1.00
				Either	
				Exponential	1.00
G5.d	327.4	0.34	740.0	or Power	0.99
G5.c	325.8	0.57	1,500,000.0	or	
G5.a	319.8	0.69	200,000,000.0	Quadratic	1.00
5.b	322.8	0.71	3,500.0	Insufficient data	

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

$$_{MPE} = [A/(2kT^{*}Shw)]\exp(-E_B/kT^{*})$$

where

S is the Huang-Rhys factor for a single equivalent phonon energy, hw.

$T^{*} = [hw\coth(hw/4\ kT)]/4\ k$

$$\approx \begin{cases} T, & kT > hw/2 = 34 \text{ meV for GaAs (Lang, 1980)} \\ hw/4\ k & \text{at low temperatures where zero-point lattice vibrations are independent of temperature.} \end{cases}$$

$A \approx 10^{-14}$ cm^2 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)

Peak Group Number	Temp. (K)	E_t (eV)	n (x $10^{-19}cm^2$)	Least Squares Fit	Correl. Coeff. r
P1:1	57	0.02	2.0	Either	
2	62	0.03	3.8	Exponential	0.92
3	60	0.05	320.0	or Power	0.90
4	70	0.06	1000.0		
5	48	0.06	100000.0		
6	58	0.07	27000.0		
P2:1	107	0.05	4.3	Either	
2	83	0.08	1500.0	Exponential	0.90
3	86	0.09	2300.0	or Power	0.96
4	83	0.09	8900.0		
5	86	0.10	12000.0		
6	94	0.11	15000.0		
7	108	0.15	100000.0		
P3:1	175	0.23	1.9	Either	
2	180	0.25	45000.0	Exponential	0.88
3	175	0.27	500000.0	or Power	0.89
4	180	0.32	4600000.0		
5	173	0.33	31000000.0		
P4:1	269	0.30	1400.0	Either	
2	246	0.32	9700.0	Exponential	1.00
3	273	0.56	49000000.0	or	
4	279	0.60	140000000.0	Power	1.00
P5:1	357	0.79	170000000.0	Insufficient data	
2	346	0.80	700000000.0		

Table 3.5 Peak grouping by correlation - sample identification. (Source: Yanan, 1989)

Peak Group Number	Temp. (K)	E_t (eV)	σ_n (x $10^{-19} cm^2$)	Sample Number	Dopant if NOT Si
P1:1	57	0.02	2.0	F4012	
2	62	0.03	3.8	L2212	Se
3	60	0.05	320.0	L2013	
4	70	0.06	1000.0	F2212	Se
5	48	0.06	100000.0	L6014	
6	58	0.07	27000.0	L6014	
P2:1	107	0.05	4.3	F4012	
2	83	0.08	1500.0	L1014	
3	86	0.09	2300.0	L4012	
4	83	0.09	8900.0	L2013	
5	86	0.10	12000.0	L6014	
6	94	0.11	15000.0	F6014	
7	108	0.15	100000.0	F2212	Se
P3:1	175	0.23	1.9	L6014	
2	180	0.25	45000.0	L4012	
3	175	0.27	500000.0	L1014	
4	180	0.32	4600000.0	L2013	
5	173	0.33	31000000.0	L2212	Se
P4:1	269	0.30	1400.0	F6014	
2	246	0.32	9700.0	F2212	Se
3	273	0.56	49000000.0	F4012	
4	279	0.60	140000000.0	F4012	
P3:1	357	0.79	170000000.0	F6014	
2	346	0.80	700000000.0	L1014	

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 <= r <= 0.996 or a power fit with 0.893 <= r <= 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.

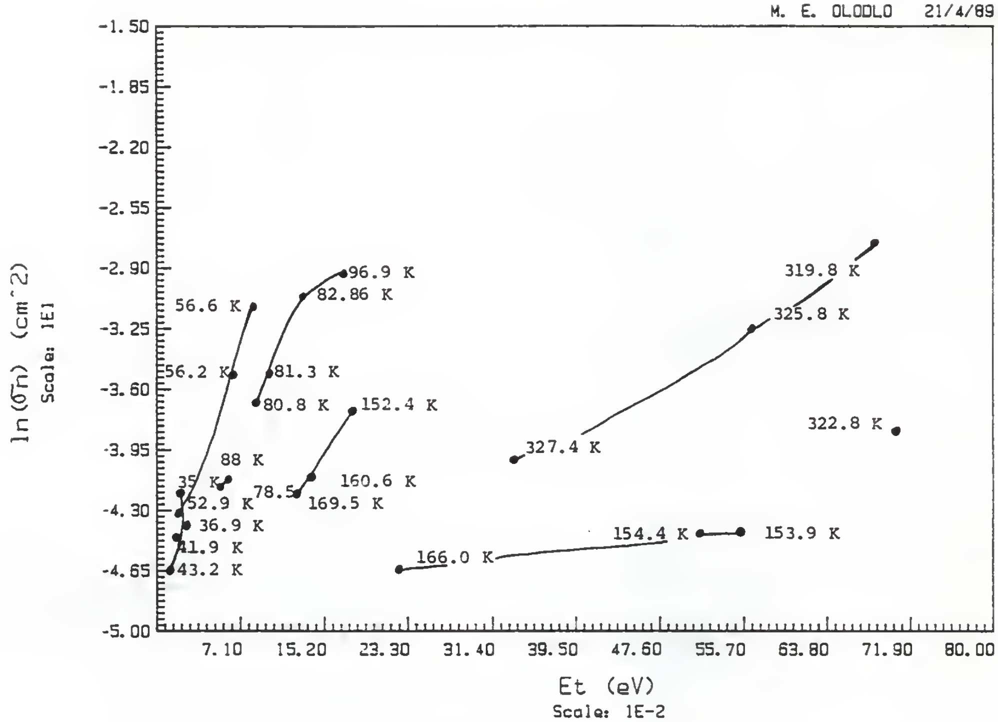


Fig. 3.5 CORRELATION of σn vs Et

CHAPTER IV

CONCLUSIONS

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.

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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.

LA4012A
SOURCE : Motorola 4264A wafer.
Si:GaAs
Dose : 4.0 x10^{12} cm^{-2}
Anneal
Laser Intensity: 0.29 J cm^{-2}

PITS Scan #	(ms)	T (^{o}K)	X (1000/T)	Y (ln(*T^2)	Peak Location #
5	3.0	39.0	25.64	1.5180	1.a
4	2.5	40.5	24.69	1.4111	1.b
1	2.0	42.3	23.64	1.2750	1.c
2	1.6	43.9	22.78	1.1261	1.d
3	1.4	44.0	22.73	0.9971	1.e
5	3.0	81.9	12.21	3.0019	2.a
4	2.5	81.5	12.27	2.8097	2.b
1	2.0	83.5	11.98	2.6351	2.c
2	1.6	83.7	11.95	2.4167	2.d
3	1.4	83.9	11.93	2.2856	2.e
5	3.0	157.6	6.35	4.3110	3.a
4	2.5	161.4	6.20	4.1763	3.b
1	2.0	164.5	6.19	3.9544	3.c
5	3.0	316.0	3.16	5.7023	4.a
1	2.0	319.7	3.13	5.3189	4.c
2	1.6	323.7	3.09	5.1219	4.d

LA4012A (cont.)

HALL EFFECT and VAN DER PAUW READINGS

I_{NP} (mA)	V_{static} (mV)	V_B (mV)	V_{VDP1} (mV)	V_{VDP2} (mV)
0.001	0.0001	0.0002	0.0002	0.0001
0.003	0.0002	0.0002	0.0005	0.0003
0.01	0.0007	0.0007	0.0016	0.0009
0.03	0.0021	0.0021	0.0047	0.0028
0.1	0.0067	0.0069	0.0159	0.0093
0.3	0.0167	0.0177	0.0476	0.0278
1.0	0.0353	0.0397	0.1573	0.1016

LA4012B
SOURCE : Motorola 4264A wafer.
Si:GaAs
Dose : 4.0 $x10^{12}$ cm^{-2}
Anneal
Laser Intensity: 0.29 J cm^{-2}

PITS Scan #	(ms)	T (^oK)	X (1000/T)	Y ($\ln(*T^2)$)	Peak Location #
1	3.0				
2	2.5	34.3	29.15	1.0788	1
3	2.0	34.7	28.82	0.8789	1
4	1.6	36.0	27.78	0.7293	1
1	3.0	75.8	13.19	2.8471	3
2	2.5	78.7	12.71	2.7393	3
3	2.0	79.4	12.59	2.5344	3
4	1.6	80.2	12.47	2.3313	3
1	3.0	149.0	6.71	4.1987	4
2	2.5	152.3	6.57	4.0602	4
3	2.0	153.6	6.51	3.8541	4
4	1.6	154.8	6.46	3.6465	4
1	3.0	322.6	3.10	5.7437	5
2	2.5	323.7	3.09	5.5682	5
3	2.0	325.9	3.07	5.3586	5
4	1.6	330.8	3.02	5.1653	5

LA4012B (cont.)

HALL EFFECT and VAN DER PAUW READINGS

I_{NP} (mA)	V_{static} (mV)	V_B (mV)	V_{VDP1} (mV)	V_{VDP2} (mV)
0.001	0.0089	0.0092	0.0001	0.0001
0.003	0.0003	0.0003	0.0004	0.0002
0.01	0.0009	0.0009	0.0014	0.0005
0.03	0.0027	0.0028	0.0043	0.0016
0.1	0.0089	0.0092	0.0143	0.0054
0.3	0.0267	0.0275	0.0430	0.0163
1.0	0.0888	0.0916	0.1432	0.0544

LA2013A
SOURCE : Motorola 4264A wafer.
Si:GaAs
Dose : 2.0 $x10^{13}$ cm^{-2}
Anneal
Laser Intensity: 0.32 J cm^{-2}

PITS Scan #	(ms)	T (^{o}K)	X (1000/T)	Y (ln($*T^2$)	Peak Location #
4	4.0	53.5	18.69	2.4380	2
3	2.5	56.3	17.76	2.0694	2
1	1.5	56.5	17.70	1.5662	2
2	2.0	56.7	17.64	1.8610	2
0	1.0	58.4	17.12	1.2267	2
4	4.0	78.7	12.71	3.2096	3
3	2.5	80.6	12.41	2.7875	3
2	2.0	80.6	12.41	2.5642	3
1	1.5	82.9	12.06	2.3330	3
0	1.0	85.1	11.75	1.9796	3
4	4.0	152.6	6.55	4.5342	4
2	2.0	153.7	6.51	3.8555	4
1	1.5	154.3	6.48	3.5754	4
3	2.5	154.8	6.46	4.0928	4

HALL EFFECT and VAN DER PAUW READINGS

I_{NP} (mA)	V_{static} (mV)	V_B (mV)	V_{VDP1} (mV)	V_{VDP2} (mV)
0.001	0.1189	0.1142	0.0849	0.0402
0.003	0.3549	0.3426	0.4690	0.1213
0.01	1.1821	1.1438	1.5630	0.4050
0.03	3.5509	3.4321	4.6944	1.2175
0.1	11.8078	11.4158	15.6410	4.0570
0.3	35.1534	34.0058	46.9547	12.1760
1.0	114.9534	111.37	156.4490	40.5349

LA2013B
SOURCE : Motorola 4264A wafer.
Si:GaAs
Dose : 2.0 x10^{13} cm^{-2}
Anneal
Laser Intensity: 0.305 J cm^{-2}

PITS Scan #	(ms)	T (^{o}K)	X (1000/T)	Y (ln(*T^2)	Peak Location #
7	2.0	41.9	23.87	1.2560	1
3	1.0	43.7	22.88	1.3401	1
4	1.5	44.1	22.68	1.0706	1
7	2.0	55.8	17.92	1.8289	2
6	1.8	56.1	17.83	1.7343	2
5	1.0	57.8	17.3	1.2062	2
2	2.5	78.9	12.67	2.7449	3
7	2.0	80.3	12.45	2.5569	3
4	1.5	80.7	12.20	2.3111	3
5	1.0	83.4	11.90	1.9395	3
2	2.5	162.9	6.14	4.1948	4
7	2.0	164.9	6.06	3.9961	4
5	1.0	166.1	6.02	3.3174	4
11	2.0	320.7	3.12	5.3264	5
10	2.0	322.6	3.10	5.3382	5
9	2.5	325.0	3.08	5.5762	5

LA2013B (cont.)

HALL EFFECT and VAN DER PAUW READINGS

I_{NP} (mA)	V_{static} (mV)	V_B (mV)	V_{VDP1} (mV)	V_{VDP2} (mV)
0.001	0.0814	0.0800	0.1253	0.0425
0.003	0.2461	0.2385	0.3759	0.1280
0.01	0.8251	0.7972	1.2573	0.4296
0.03	2.4789	2.3949	3.7768	1.2897
0.1	8.2595	7.9825	12.5838	4.2908
0.3	24.7340	23.9495	37.7807	12.8725
1.0	82.2821	79.7677	125.8708	43.0000

LA2013C
SOURCE : Motorola 4264A wafer.
Si:GaAs
Dose : 2.0 $x10^{13}$ cm^{-2}
Anneal
Laser Intensity: 0.26 J cm^{-2}

PITS Scan #	(ms)	T (^{o}K)	X (1000/T)	Y (ln(*T^2)	Peak Location #
2	2.2	76.6	13.05	2.5579	3
1	2.0	78.2	12.23	2.5039	3
3	1.2	78.5	12.74	2.0008	3
3	1.2	88.5	11.30	2.2406	3
1	2.0	88.5	11.30	2.7514	3
2	2.2	158.8	6.30	4.0160	4
3	1.2	160.7	6.22	3.4336	4

HALL EFFECT and VAN DER PAUW READINGS

I_{NP} (mA)	V_{static} (mV)	V_B (mV)	V_{VDP1} (mV)	V_{VDP2} (mV)
0.001	0.0120	0.0139	0.1100	0.1183
0.003	0.0867		0.3309	0.3536
0.01	0.0833	0.0509	1.1035	1.1778
0.03	0.2498	0.1519	3.3128	3.5360
0.1	0.8311	0.5049	11.0393	11.7838
0.3	2.4888	1.5184	33.1223	35.3616
1.0	8.2391	5.0202	110.3910	117.8200

LA2013D
SOURCE : Motorola 4264A wafer.
Si:GaAs
Dose : 2.0 $x10^{13}$ cm^{-2}
Anneal
Laser Intensity: 0.26 J cm^{-2}

PITS Scan #	(ms)	T (^oK)	X (1000/T)	Y (ln($*T^2$)	Peak Location #
4	4.0	34.1	29.33	1.5369	1
3	2.5	36.1	27.70	1.1817	1
2	2.0	37.0	27.03	1.0080	1
5	1.0	40.4	24.75	0.4886	1
4	4.0	94.6	10.57	3.5779	3
3	2.5	96.5	10.36	3.1476	3
1	1.5	98.7	10.13	2.6817	3
4	4.0	152.4	6.56	4.5315	4
3	2.5	154.7	6.46	4.0915	4
1	1.5	156.1	6.41	3.5987	4

HALL EFFECT and VAN DER PAUW READINGS

I_{NP} (mA)	V_{static} (mV)	V_B (mV)	V_{VDP1} (mV)	V_{VDP2} (mV)
0.001	0.0046	0.0228	0.1100	0.5358
0.003	0.0584	0.0702	0.3296	0.2745
0.01	0.1944	0.2332	1.1077	0.9155
0.03	0.5825	0.7010	3.3040	2.7507
0.1	1.9412	2.3350	11.0068	9.1647
0.3	5.7797	6.9576	33.0509	27.5286
1.0	18.5008	22.3809	110.1167	91.9459

LB6014A
SOURCE : Motorola 4264B wafer.
Si:GaAs
Dose : 6.0 x10^{14} cm^{-2}
Anneal
Laser Intensity: 0.29 J cm^{-2}

PITS Scan #	(ms)	T (^{o}K)	X (1000/T)	Y (ln(*T^2)	Peak Location #
4	1.6	52.1	19.19	1.4686	2
3	1.4	52.1	19.19	1.3350	2
2	1.2	52.4	19.08	1.1924	2
1	1.0	54.9	18.21	1.1033	2
4	1.6	87.0	11.49	2.4941	3
3	1.4	87.3	11.45	2.3674	3
2	1.2	87.6	11.42	2.2201	3
1	1.0	90.3	11.07	2.0985	3
4	1.6	166.0	6.02	3.7862	4
3	1.4	168.4	5.94	3.6814	4
2	1.2	170.0	5.88	3.5462	4
1	1.0	173.5	5.76	3.4046	4
4	1.6	325.25	3.075	5.1314	5
3	1.4	325.3	3.074	4.9982	5
2	1.2	325.7	3.070	4.8465	5
1	1.0	333.3	3.000	4.7103	5

HALL EFFECT and VAN DER PAUW READINGS

I_{NP} (mA)	V_{static} (mV)	V_B (mV)	V_{VDP1} (mV)	V_{VDP2} (mV)
0.001	0.0000	0.0000	0.0001	0.0001
0.003	0.0001	0.0002	0.0002	0.0002
0.01	0.0003	0.0006	0.0006	0.0005
0.03	0.0008	0.0017	0.0017	0.0016
0.1	0.0026	0.0055	0.0056	0.0053
0.3	0.0079	0.0166	0.0168	0.0160
1.0	0.0280	0.0569	0.0560	0.0534

LE2212A
SOURCE : Honeywell 21 and 23 LEC SI
Se:GaAs
Dose : 2.2 $x10^{12}$ cm^{-2}
Anneal
Laser Intensity: 0.234 J cm^{-2}

PITS Scan #	(ms)	T (^oK)	X (1000/T)	Y (ln($*T^2$)	Peak Location #
1	3.0	57.0	17.54	2.2770	2
4	2.5	57.7	17.33	2.1190	2
3	2.0	58.6	17.06	1.9269	2
2	1.6	59.1	16.92	1.7207	2
8	4.0	90.8	11.01	3.4959	3
1	3.0	92.2	10.85	3.2389	3
4	2.5	92.5	10.81	2.2789	3
9	1.6	98.1	10.19	2.7342	3
6	4.0	151.5	6.60	4.5197	4
5	3.5	151.8	6.59	4.3901	4
1	3.0	156.8	6.38	4.3008	4

HALL EFFECT and VAN DER PAUW READINGS

I_{NP} (mA)	V_{static} (mV)	V_B (mV)	V_{VDP1} (mV)	V_{VDP2} (mV)
0.001	0.1496	0.1469	0.0849	0.0402
0.003	0.7724	0.3218	0.4690	0.1213
0.01	2.5739	1.0752	1.5630	0.4050
0.03	7.7289	3.2297	4.6944	1.2175
0.1	25.7559	10.7624	15.6410	4.0570

APPENDIX B

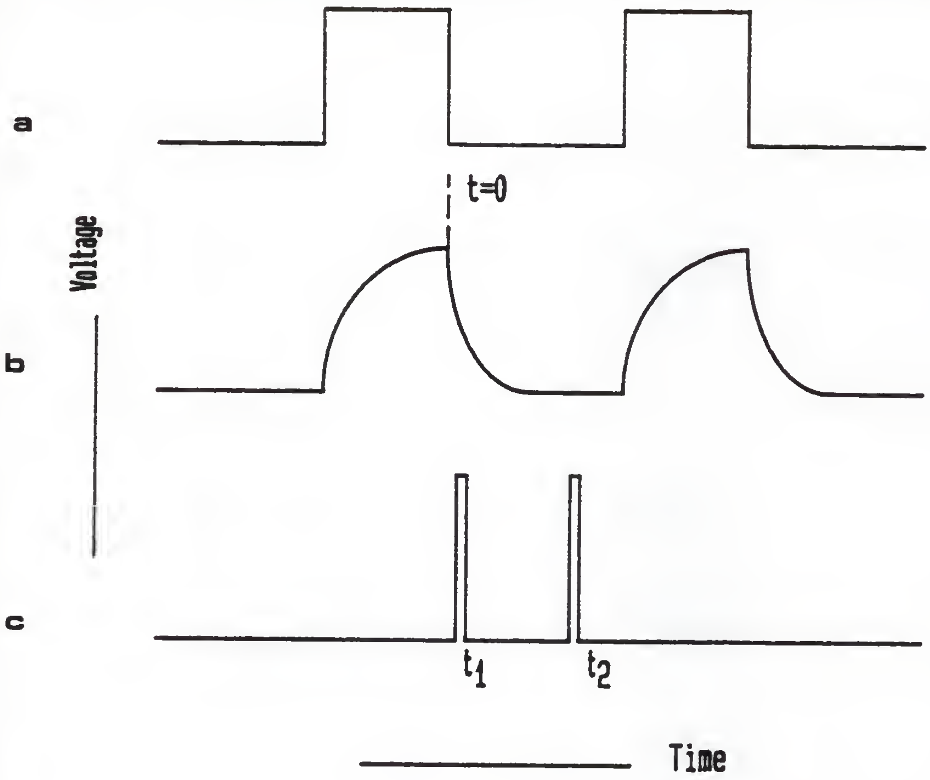
RATE WINDOW SELECTION

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 apperture 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_{2max} 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.

Table B.1 Rate window selection array.

ADR :	50 ms	20 ms
t_1 / t_2		
(%A)/(%B)	ms	ms
10/100		2.0
9/90		1.8
8/80	4.0	1.6
7.5/75		1.5
7/70	3.5	1.4
6/60	3.0	1.2
5/50	2.5	1.0

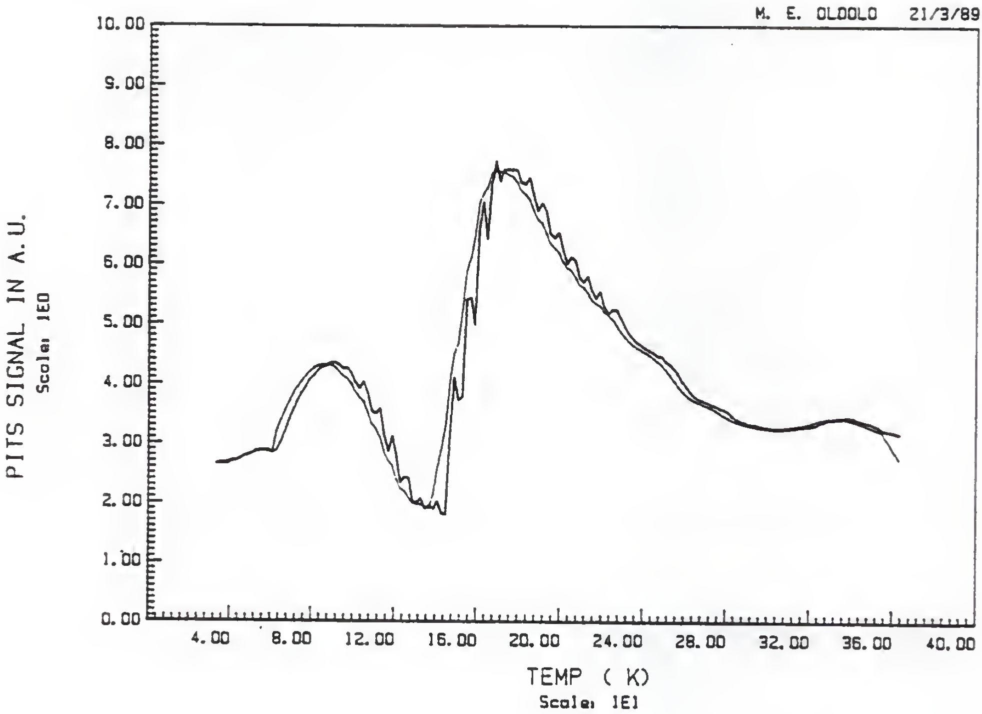


Waveforms of PITS measurements

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_o marks the beginning of trap emptyinng.

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.



PITS SCAN FOR SAMPLE HLSI3SB

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.

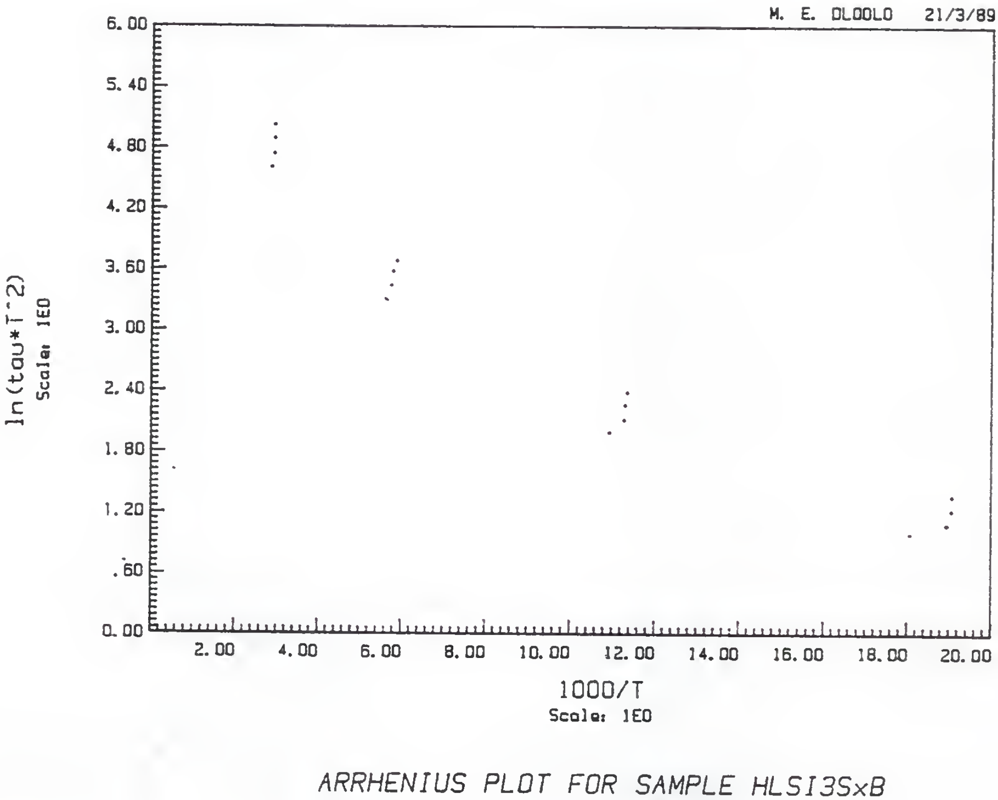


Fig. B.3 The Arrhenius plot for LB6014A showing excellent low temperature behavior of peaks.

APPENDIX C
CORRELATION AND TIME SERIES ANALYSIS

C.1 Statistical solution for E_t and σ_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)

$$y = a + bx \qquad \text{....(C.1)}$$

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

$$\Sigma_i y = an + b\,\Sigma_i\, x$$
$$\Sigma xy = a\Sigma x = b\Sigma x^2 \qquad \text{...(C.2)}$$

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

$$a = \frac{(\Sigma y)(\Sigma x^2)-(\Sigma x)(\Sigma xy)}{n\Sigma x^2 - (\Sigma x)^2}$$

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

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

$$\ln(\tau T^2) = -\ln(\gamma_n \sigma_n) + E_t/kT \qquad \text{...(C.4)}$$

for trap energy and cross section, let

$$E_t = slope * 1000 * k$$
$$= 0.0862 * b \quad ...(C.5)$$

and let

$$\sigma_n = (1/\gamma_n)* \exp(abs(intercept))$$
$$= (5.2632 e-21)*\exp(-a) \quad ...(C.6)$$

where

$$slope = b$$
$$= (T/1000)[\ln(T^2) + \ln(\gamma_n \sigma_n)] \quad ...(C.7)$$

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):

$$S^2_{y.x} = [(\sum y^2 - a\sum y - b\sum xy)/(n-2)]$$
$$= S^2 \ (1-r^2) \ , \ r^2 <=1 \quad ...(C.8)$$

where

$$r^2 = 1- \sum(y-y_{est})^2 / \sum(y-E(y))^2 \quad ....(C.9)$$

and

$$\Sigma(y-E(y))^2 = \Sigma(y-y_{est})^2 + \Sigma(y_{est}-E(y))^2 \quad ...(C10)$$

In words equation (C.10) states that

Total variation = Unexplained variation + Explained variation

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

$$r^2 = \Sigma(y_{est} - E(y))^2 / \Sigma(y-E(y))^2$$

= Explained variation/Total variation

= Coefficient of determination. ...(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 approch is

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

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, ρ. 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.

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

Sample#	Peak#	n (sample scans)	E_t(eV)	r	ρ_{min} (ρ range)	ρ_{max}
LA4012A	1.c	5	0.014	0.96	+.4	+1.0
	3.d	5	0.138	0.88	+0.04	+0.98
	4.d	3	0.144	0.82	-0.85	+1.0
	5.a	3	0.69	0.96	-0.6	+1.0
LA4012B	1.a	3	0.019	0.93	-0.5	+1.0
	3.a	4	0.056	0.88	-0.32	+1.0
	4.a	4	0.184	0.94	-0.1	+1.0
	5.c	4	0.56	0.95	0.0	+1.0
LA2013A	2.b	4	0.068	0.95	0.0	+1.0
	3.c	4	0.103	0.97	+0.1	+1.0
	4.b	4	0.56	0.61	-0.5	+0.98
LA2013B	1.d	3	0.008	0.42	-0.93	+0.97
	2.c	3	0.089	0.99998	+1.0	+1.0
	3.b	4	0.091	0.997	>+0.8	+1.0
	4.e	4	0.23	0.887	-0.06	+1.0
	5.b	3	0.71	-0.88	-1.0	+0.75
LA2013D	1.b	4	0.016	0.68	-0.64	0.98
	3.f	3	0.176	0.99999	+1.0	+1.0
	4.c	3	0.52	0.97	+1.0	+1.0
LB6014A	2.a	4	0.022	0.78	-0.53	+0.99
	3.e	4	0.064	0.85	-0.4	+1.0
	4.f	4	0.129	0.99	+1.0	+1.0
	5.d	4	0.34	0.81	-0.5	+1.0

C.2 Time Series Analysis and Trend Removal (U. Narayan Bhat, 1984)

A time series is defined as a set of observations generated sequentially in time. Variations in these observ-ations 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

Temp(^{o}K)	Unadjusted signal A	Three-point moving average
51	4.1229	
53	4.1293	4.1396
55	4.1665	4.1676
57	4.207	4.1991
59	4.2237	4.1939
61	4.1511	4.1522
63	4.0818	

It is noteworthy that averaging over every k points, i.e.

$(1/k)[a_1 + a_2 +....+ a_{k-1} + a_k) = b_k$

wastes (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 ^{o}K at both ends of the temperature axis, which effectively takes care of this problem for k<(15/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.

Temp(^{o}K)	unadjusted signal A	Three-point moving average
53	4.234	
55	4.2644	4.2646
57	4.2995	4.3008
59	4.3425	4.3189
61	4.3188	4.3216
63	4.3036	4.338
65	4.3917	

APPENDIX D

PROGRAMS

LINFIT2M is an adaptation of LINFIT in which the main results are the 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 expalined 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.

```
10 ! ***********************************************************************
20 !
30 ! Program Title: SUPRAMED
40 !
50 ! Programmer   : Mqhele Dlodlo
60 !
70 ! Date         : 12 Jan. 1989
80 !
90 ! Version      : 2.0
100 !
110 ! Program Description : SUPRAMED, adapted from the DRC-81 Instruction
120 !          manual, controls the Temperature Controller making it ramp
130 !          upwards or downwards at the user's prerogative. It also reads
140 !          the output voltages of the Temperature Controller's thermo-
150 !          couple via the Keithley DVM and the boxcar. The thermocouple
160 !          indicates Temperature in degrees Celcius and the boxcar's
170 !          output is the PITS spectrum. A hard copy is issued and if
180 !          requested a diskette file is created with a backup copy.
190 !
200 ! ***********************************************************************
210 OPTION BASE 1
220 CLEAR
230 DIM F$[16].K$[50]
240 REAL TEMPR(500.2),TEMPV(500,2)
250 !   HEATER POWER,GAIN,RATE ARE RESET ARE SET MANUALLY BY THE
260 !   USER. THE INITIAL SETPOINT TEMPERATURE IS ENTERED VIA THE
270 !   KEYBOARD. THE TIME IN SECONDS AND DESIRED FINAL TEMPERATURE
280 !   ARE REQUESTED. THE 81C WILL RAMP THE SET POINT TO THE FINAL
290 !   TEMPERATURE LINEARLY WITH A QUANTIZED TEMPERATURE INCREMENT
310 DIM A$[50] ! Dimension array for reading the DRC 81C
320 T_WAIT=20 ! Sampling rate in seconds
330 K_EQB=.9 ! Incremental change in control T which implies equilibrium
340 CLEAR ! Clear the display
350 !   REQUEST THE INITIAL SETPOINT TEMPERATURE.
360 DISP "INITIAL TEMPERATURE:";@ INPUT K_INITIAL
370 BEGIN: DISP "SELECT A HEATER POWER,GAIN,RATE AND RESET MANUALLY"
380    DISP "ON THE DRC-81C TO OBTIAN THE DESIRED INITIAL TEMPERATURE."
390    DISP
400    DISP "TEMPERATURE TO RAMP TO";@ INPUT K_FINAL
410    DISP "TIME TO REACH ";K_FINAL;" K";" IN SECONDS";@ INPUT T_FINAL
420    DISP "INCREMENT OF TEMPERATURE TO TAKE DATA." @ INPUT K_INC
430 !   ADJUST THE DRC 81C TO OBTIAN EQUILIBRIUM AT THE INITIAL SETPOINT.
440    OUTPUT 712 :"S";VAL$ (K_INITIAL)
450    K=K_INITIAL
460    WAIT1: WAIT 1000*T_WAIT ! WAIT T_WAIT SECONDS
470       KO=K
480       OUTPUT 712 :"WC" @ ENTER 712 ; A$ ! READ CONTROL TEMPERATURE.
490       K=VAL (A$[1,6])
500       IF ABS (K-KO)>K_EQB OR ABS (K-K_INITIAL)>1 THEN WAIT1
510    OUTPUT 712 :"W1" @ ENTER 712 ; A$ ! READ W1
520    DISP "W1 =";A$
530 POSITION=VAL (A$[1])
540 DISPLAY_ID$=A$[3,5]
550 CONTROL_ID$=A$[7,9]
560 GAIN=VAL (A$[11,12])
570 RATE=VAL (A$[14,15])
580 RESET1=VAL (A$[17,18])
590 HEATER_RANGE=VAL (A$[20])
600 PRINTER IS 701
610 PRINT "REMOTE SENSOR POSITION=";POSITION
620 PRINT "DISPLAY SENSOR ID=";DISPLAY_ID$
630 PRINT "CONTROL SENSOR ID=";CONTROL_ID$
640 PRINT "GAIN=";GAIN,"RATE=";RATE,"RESET=";RESET1
650 PRINT "HEATER POWER RANGE=";HEATER_RANGE;"WATTS"
660 P=1
670 T=0
```

```
680 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 ON 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$ ! 80 MS READ TIME.
780    IF FP (ABS (SETPOINT-K_INITIAL)/K_INC)>0 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=138 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$
930    TEMPR(P,1)=VAL (A$)
940    TEMPR(P,2)=T
950    TEMPV(P,1)=SETPOINT
960 ! READS FLUKE DVM
970    OUTPUT 707 ;"VR7D8T1?" @ ENTER 707 ; F$
980    MANTISSAF$=F$[1,8] @ EXPONENTF$=F$[10,12]
990    TEMPV(P,2)=VAL (MANTISSAF$)*10^VAL (EXPONENTF$)
1000    PRINT "PITS=",TEMPV(P.2)
1010    DISP USING 1020 ; P,TEMPR(P,1),TEMPV(P,2)
1020   IMAGE "READING NUMBER",2X,DDD,4X,"THERMAL COUPLE TEMP.",2X,DDDD.DDD,2X,"V
OLTAGE",2X,DDDD.DDDDD
1030 P=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 ;"S";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$="N" THEN 1790
1310 DISP "RAMPING NUMBER=":P-1
1320 ON ERROR GOTO 1400
```

```
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 K$ @ PRINT K$
1480 GOTO 920
1490 OUTPUT 712 ;"P";90;"W1" @ ENTER 712 ; K$
1500 DISP K$ @ PRINT K$
1510 GOTO 920
1520 OUTPUT 712 ;"P";85;"W1" @ ENTER 712 ; K$
1530 DISP K$ @ PRINT K$
1540 GOTO 920
1550 OUTPUT 712 ;"P";81;"W1" @ ENTER 712 ; K$
1560 DISP K$ @ PRINT K$
1570 GOTO 920
1580 OUTPUT 712 ;"P";75;"W1" @ ENTER 712 ; K$
1590 DISP K$ @ PRINT K$
1600 GOTO 920
1610 OUTPUT 712 ;"P";81;"W1" @ ENTER 712 ; K$
1620 DISP K$ @ PRINT K$
1630 GOTO 920
1640 OUTPUT 712 ;"P";85;"W1" @ ENTER 712 ; K$
1650 DISP K$ @ PRINT K$
1660 GOTO 920
1670 OUTPUT 712 ;"P";91;"W1" @ ENTER 712 ; K$
1680 DISP K$ @ PRINT K$
1690 GOTO 920
1700 OUTPUT 712 ;"P";95;"W1" @ ENTER 712 ; K$
1710 DISP K$ @ PRINT K$
1720 GOTO 920
1730 OUTPUT 712 ;"P";97;"W1" @ ENTER 712 ; K$
1740 DISP K$ @ PRINT K$
1750 GOTO 920
1760 OUTPUT 712 ;"P";98;"W1" @ ENTER 712 ; K$
1770 DISP K$ @ PRINT K$
1780 GOTO 920
1790 END
 117235
```

```
10 ! ..................................................................
12 ! 11 Feb 1989 adapted for PITS by Mqhele E. Dlodlo : LINFITMD.
14 ! LINFIT - makes a least squares fit to data with a straight line
16 !          Y = A + B * X
18 !
20 ! Written by - N. Dean Eckhoff (after Bevington. Philip R., "Data Reduction
22 !              and Error Analysis for the Physical Sciences," McGraw-Hill.
24 !              1969, pp 104-105), Department of Nuclear Engineering.
26 !
28 ! Written for - HP86B. in HP BASIC. User interface - M. E. Dlodlo 17/2/89
30 !
32 ! Date - 10/18/86. Kansas State University
34 !
36 ! Variables - X(I) - the independent variable
38 !             Y(I) - the dependent variable
40 !             STDEV(I) - the standard deviation of Y, if needed
42 !             NPTS - number of data points to be used in fit, must be less
44 !                    than or equal to the dimension for X, Y, and STDEV
46 !             MODE$ - indicates type of fit, U = unweighted, D = weight
48 !                     with data points, or V = weight with STDEV
50 !             A - intercept coefficient
52 !             B - slope coefficient
54 !             SIGMA - stnd. dev. for A
56 !             SIGMB - stnd. dev. for B
58 !             R - linear correlation coefficient
60 !
62 ! Options - MODE$ is entered from the keyboard
64 !           Data are entered from DATA statements within the program
66 !
68 ! ..................................................................
100 DIM X(100),Y(100),STDEV(100)
110  PRINTER IS 701
120  DISP "DO YOU WANT TO LABEL THE RESULTS (Y/N) " @ INPUT Y$
130  IF Y$="N" THEN GOTO 180
140  DISP "INPUT DESIRED DATA IDENTIFICATION <= 8 CHAR "
150  INPUT ISIHLOKO$
160  DISP "ENTER DATE AS DD/MM/YY " @ INPUT INYANGA$
170  PRINT ISIHLOKO$ @ PRINT INYANGA$
180  PRINT
190 CLEAR
200 GOSUB RDATA
300 GOSUB NORMEQN
400 GOSUB EST
500 GOSUB OUTPT
550 DISP "END "
600 END
1000 RDATA:
1010   DISP "Enter mode of least squares ... U(unweighted), D(weighted w/"
1020   DISP "      data pts), or V(weighted w/data variances)"
1030   INPUT MODE$
1040   IF MODE$="U" THEN GOTO 1054
1042   IF MODE$="u" THEN GOTO 1054
1044   IF MODE$="D" THEN GOTO 1054
1046   IF MODE$="d" THEN GOTO 1054
1048   IF MODE$="V" THEN GOTO 1054
1050   IF MODE$="v" THEN GOTO 1054
1052     DISP "Mode not correct. re_enter!" @ GOTO 1010
1054   READ NPTS@ DISP "  X   ","   Y  "
1056   FOR I=1 TO NPTS
1060     READ X(I),Y(I)
1070     DISP X(I),Y(I)
1080   NEXT I
1090   IF MODE$="U" THEN GOTO 1130
1092   IF MODE$="u" THEN GOTO 1130
1094   IF MODE$="D" THEN GOTO 1130
1096   IF MODE$="d" THEN GOTO 1130
```

```
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 4
1155 ! DATA 17.12,1.22671,17.64,1.86097,17.76,2.06939
1160 ! DATA 18.69,2.43799
1165 ! DATA 11.75,1.97962,12.41,2.56418,12.41,2.78748
1170 ! DATA 12.71,3.20963
1180   DATA 6.46,4.09284,6.48,3.57543,6.51,3.85545,6.55,4.53421
1190 ! DATA
1200 RETURN
1500 NORMEQN: ! Form normal equations
1510   SUM=0 @ SUMX=0 @ SUMY=0 @ SUMXX=0 @ SUMXY=0 @ SUMYY=0
1520   FOR I=1 TO NPTS
1530     WT=1
1540     IF MODE$="U" THEN GOTO 1700
1542     IF MODE$="u" THEN GOTO 1700
1550       IF MODE$="V" THEN GOTO 1650
1552       IF MODE$="v" THEN GOTO 1650
1560         ! Weight with data pts
1570         IF Y(I)=0 THEN GOTO 1700
1580           WT=1/Y(I)
1590           IF WT<0 THEN WT=-WT
1600           GOTO 1700
1650       ! Weight with variances
1660       WT=1/(STDEV(I)*STDEV(I))
1700     SUM=SUM+WT
1710     SUMX=SUMX+WT*X(I)
1720     SUMXX=SUMXX+WT*X(I)*X(I)
1730     SUMY=SUMY+WT*Y(I)
1740     SUMYY=SUMYY+WT*Y(I)*Y(I)
1750     SUMXY=SUMXY+WT*X(I)*Y(I)
1760   NEXT I
1800 RETURN
1900 EST: ! Calculate the intercept, slope, and st. dev.
1910   DET=SUM*SUMXX-SUMX*SUMX
1920   A=(SUMXX*SUMY-SUMX*SUMXY)/DET
1930   B=(SUMXY*SUM-SUMX*SUMY)/DET
1940   VARNCE=1
1950   IF MODE$="U" THEN GOTO 2000
1952   IF MODE$="u" THEN GOTO 2000
1954   IF MODE$="D" THEN GOTO 2000
1956   IF MODE$="d" THEN GOTO 2000
1960     C=NPTS-2
1970     VARNCE=(SUMYY+A*A*SUM+B*B*SUMXX-2*(A*SUMY+B*SUMXY-A*B*SUMX))/C
2000   SIGMA=SQR (VARNCE*SUMXX/DET)
2010   SIGMB=SQR (VARNCE*SUM/DET)
2020   R=(SUM*SUMXY-SUMX*SUMY)/SQR (DET*(SUM*SUMYY-SUMY*SUMY))
2030 RETURN
2100 OUTPT: ! Ouput the intercept, slope, st. dev., and correlation coeff
2105   PRINT "SIGNATURE DATA for ";
2110   DISP "Intercept = ";A;" +/- ";SIGMA @ PRINT "INTERCEPT= ";A
2120   DISP "Slope     = ";B;" +/- ";SIGMB @ PRINT "SLOPE= ";B
2130   DISP "Corr Coef = ";R @ PRINT "Corr. Coef. = ";R
2131  PRINT
2132 Et=8.62*B*10^-2 @ DISP "Et= ";Et
2134  PRINT "Et = ";Et
2136 CS=EXP (-A)*10^-20/1.9 @ PRINT "CROSS SECTION= ";CS
2138  DISP "Cross Section = ";CS @ PRINT
2140 FOR I=1 TO NPTS
2150     Y(I)=A+B*X(I)
2152     Y(I)=EXP (Y(I))
```

```
2160     PRINT "X= ";X(I);"Y= ";Y(I)
2170 NEXT I
2180 RETURN
```

```
10 ! **********************************************************************
20 !
30 ! Program Title:  ARRPLOT
40 !
50 ! Programmer:  Mqhele E. Dlodlo
60 !              Graduate Student. Kansas State University
70 !
80 ! Date:  15 Jan 1989
90 !
100 ! Version 2.0
110 !
120 ! Program Description:  ARRPLOT is a plot routine developed to provide
130 !          scatter diagrams (e. g. Arrhenius plots) on linear axes.
140 !          Type 1 plots divide the horizontal axis into 10 intervals.
150 !          Type 2 plots divide the horizontal axis into 8 intervals and
160 !          uses the point numbers to label the X-axis.
170 !
180 ! Parameters that are supplied to ARRPLOT
190 !      X(*) - X-axis data array:  (real)
200 !      Y(*) - Y-axis data array:  (real)
210 !      Npts - Number of points in X(*) and Y(*):  (integer)
220 !      Type - Type of numbering for the X-axis:  (integer)
230 !             1 - Use values in X(*) to label the X-axis: 10 intervals
240 !             2 - Use the point number to label the X-axis: 8 intervals
250 !      Xtitle$ - Title for the X-axis
260 !      Ytitle$ - Title for the Y-axis
270 !      Title$ - Title of the plot
280 !      Name$ - Users name
290 !      Date$ - Date the plot was generated
300 !
310 ! Subroutines within ARRPLOT
320 !       Initialize1 - Initializes the data for a Type=1 plot
330 !       Initialize2 - Initializes the data for a Type=2 plot
340 !       Axes_label - Draws and labels the axes: Labels the plot
350 !       Plot_1 - Plots data points for a Type=1 plot
360 !       Plot_2 - Plots data points for a Type=2 plot
370 !
380 ! Data - Data needs to be stored in a file as two columns. The
390 !        left column is the x-axis data and the right column is
400 !        the y-axis data.
410 !
420 ! **********************************************************************
430 !
440 OPTION BASE 0
450 !
460 ! Declarations
470 !
480 REAL X(800),Y(800)
490 REAL Aspect.Fract,Sca_le,Xmax,Xmin,Xrange,Xpower,Xinter
500 REAL Ymax,Ymin,Yrange,Ypower,Yinter
510 INTEGER Npts,Plotter,Type
520 DIM Xtitle$[60],Ytitle$[60],Title$[60],Name$[60],Da_te$[60]
530 DIM Dummy$[60],File_name$[60]
540 CLEAR
550 DISP
560 DISP @ BEEP
570 DISP TAB (5);"THE DATA FILE IS ASSUMED TO BE IN LEFT DRIVE"
580 WAIT 2000
590 CLEAR
600 DISP
610 DISP
620 DISP TAB (5);"HORIZONTAL AXIS TITLE (60 CHARACTER LIMIT)";
630 INPUT Xtitle$
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 Title$
680 DISP TAB (5):"USERS NAMES (60 CHARACTER LIMIT)":
690 INPUT Name$
700 DISP TAB (5):"WHAT IS THE DATE";
710 INPUT Da_te$
720 DISP TAB (5):"HOW MANY OBSERVED VALUES ARE BEING PLOTTED":
730 INPUT Nots
740 !
750 points=Npts
760 Type=1
765 DISP "INPUT FILE NAME!" @ INPUT file_name$
770 ASSIGN# 1 TO  file_name$&":D700"
780 !
790 FOR K=0 TO Npts-1
800 READ# 1 ; X(K),Y(K)
810 NEXT K
820 !
830 !
840 !
850 ASSIGN# 1 TO  *
860 !
870 !
880 ! Initializing the arrays refers to finding maximum and minimum values. the
890 !      range of the values, and normalizing the data by dividing bv the
900 !      base 10 power of the range.
910 !
920 DISP "Initializing the arrays for plotting"
930 ON Tvpe GOSUB Initialize1 ,Initialize2
940 BEEP
950 !
960 ! Determine what plotter the user wishes to use and make declarations
970 !      accordinglv.
980 !
990 DISP "Which plotter is to be used (1-CRT, 2-7470A)";
1000 INPUT Plotter
1010 IF Plotter=2 THEN GOTO 1080
1020 DISP "END LINE will allow you to exit graphics mode after plotting."
1030 WAIT 3000
1040 PLOTTER IS 1
1050 GCLEAR
1060 GRAPHALL
1070 GOTO 1150
1080 PLOTTER IS 705
1090 OUTPUT 705 ;"VS8"
1100 DISP "Set up plotter and press END LINE";
1110 INPUT Dummy$
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
1200 DISP "Would you like to change the plotter or the axes limits (v/n)":
1210 INPUT Dummv$
1220 IF Dummv$="N" OR Dummy$="n" THEN GOTO 1460
1230 DISP "Would you like to change the limits of the vertical axis (y/n)":
1240 INPUT Dummy$
1250 IF Dummv$="N" OR Dummy$="n" THEN GOTO 1340
1255 DISP Ymax."is the old normalized maximum."
1260 DISP "What is the new normilized maximum value";
1270 INPUT Ymax
1275 DISP Ymin,"is the old normalized minimum."
1280 DISP "What is the new normalized minimum value";
1290 INPUT Ymin
```

```
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
1365 DISP Xmax,"is the old normalized maximum."
1370 DISP "What is the new normalized maximum value";
1380 INPUT Xmax
1385 DISP Xmin,"is the old normalized minimum."
1390 DISP "What is the new normalized minimum value";
1400 INPUT Xmin
1410 IF Xmax>Xmin THEN 1440
1420 DISP "ERROR. Xmax must be greater than Xmin"
1430 GOTO 1370
1440 Xrange=Xmax-Xmin
1450 GOTO 990
1460 CLEAR @ DISP @ DISP
1470 DISP TAB (5):"Enter:"
1480 DISP TAB (11);"1 to rerun ARRPLOT"
1490 !
1500 DISP TAB (11):"2 to quit"
1510 INPUT A
1520 !
1530 IF A=1 THEN 440
1540 DISP @ DISP TAB (5);"This progaram has ended."
1550 END
1560 !
1570 Initialize1: !
1580 !
1590 Sca_le=10 ! Divide the axis into ten intervals
1600 Xmax=-9.99999999999E499 ! Set initial min. and max.
1610 Xmin=9.99999999999E499
1620 Ymax=-9.99999999999E499
1630 Ymin=9.99999999999E499
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)/10)) ! 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)/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 Sca_le=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
```

```
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 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
```

```
2600 !
2610 ! Label the X-axis
2620 !
2630 LORG 9
2640 I=1
2650 IF Xinter+I*Xrange/Sca_le>Xmax THEN 2710
2660      MOVE Xinter+I*Xrange/Sca_le,Yinter-Yrange/50
2670      IF Type=1 THEN LABEL USING "3D.2D" ; Xinter+I*Xrange/Sca_le
2680      IF Type=2 THEN LABEL USING "5D.0D" ; Xinter+I*Xrange/Sca_le
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
 114404
```

```
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
10 ! ********************************************************************
20 !
30 ! Program Title:  LINPLOT2
40 !
50 ! Programmer:  Doug Doerfler
60 !              Graduate Student, Kansas State University
70 !
80 ! Date:  06-02-84
90 !
100 ! Version 2.0  by Mqhele E. Dlodlo
110 !
120 ! Program Description:  LINPLOT is a plot routine developed to provide
130 !          a general purpose plot routine for linear-linear plots.
140 !          Type 1 plots divide the horizontal axis into 10 intervals.
150 !          Type 2 plots divide the horizontal axis into 8 intervals and
160 !          uses the point numbers to label the X-axis. LINPLOT2 is
170 !          customized for curve plotting.
180 ! Parameters that are supplied to LINPLOT2
190 !      X(*) - X-axis data array:  (real)
200 !      Y(*) - Y-axis data array:  (real)
210 !      Npts - Number of points in X(*) and Y(*):  (integer)
220 !      Type - Type of numbering for the X-axis:  (integer)
230 !             1 - Use values in X(*) to label the X-axis: 10 intervals
240 !             2 - Use the point number to label the X-axis: 8 intervals
250 !      Xtitle$ - Title for the X-axis
260 !      Ytitle$ - Title for the Y-axis
270 !      Title$ - Title of the plot
280 !      Name$ - Users name
290 !      Date$ - Date the plot was generated
300 !
310 ! Subroutines within LINPLOT2
320 !       Initialize1 - Initializes the data for a Type=1 plot
330 !       Initialize2 - Initializes the data for a Type=2 plot
340 !       Axes_label - Draws and labels the axes; Labels the plot
350 !       Plot_1 - Plots data points for a Type=1 plot
360 !       Plot_2 - Plots data points for a Type=2 plot
370 !       Smooth - Moving average trend remover
375 !
380 ! Data - Data needs to be stored in a file as two columns. The
390 !         left column is the x-axis data and the right column is
400 !         the y-axis data.
410 !
420 ! ********************************************************************
430 !
440 OPTION BASE 0
450 !
460 ! Declarations
470 !
480 REAL X(800),Y(800)
490 REAL Aspect,Fract,Sca_le,Xmax,Xmin,Xrange,Xpower,Xinter
500 REAL Ymax,Ymin,Yrange,Ypower,Yinter
510 INTEGER Npts,Plotter,Type
520 DIM Xtitle$[60],Ytitle$[60],Title$[60],Name$[60],Da_te$[60]
530 DIM Dummy$[60],File_name$[60]
540 CLEAR
550 !
560 !
570 !
580 !
590 CLEAR
600 DISP
610 DISP
```

```
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 Title$
680 DISP TAB (5);"USERS NAMES (60 CHARACTER LIMIT)";
690 INPUT Name$
700 DISP TAB (5);"WHAT IS THE DATE";
710 INPUT Da_te$
720 DISP TAB (5);"HOW MANY OBSERVED VALUES ARE BEING PLOTTED";
730 INPUT Npts
740 DISP TAB (5);"HOW MANY EXPECTED VALUES ARE BEING PLOTTED";
750 INPUT points
755 points=Npts+points
760 Type=1
770 X(0)=30
780 FOR K=1 TO Npts-1
790     X(K)=K+30
800     Y(K)=1.519-.0005405*(X(K)*X(K))/(X(K)+204)
810 NEXT K
820     Y(0)=1.519-.0005405*(X(0)*X(0))/(X(0)+204)
830 FOR K=Npts TO points-1
840     X(K)=X(K-Npts)
850     Y(K)=1.519-.0005405*(X(K)*X(K))/(X(K)+204)
860 NEXT K
870 !
880 ! Initializing the arrays refers to finding maximum and minimum values. the
890 !     range of the values, and normalizing the data by dividing by the
900 !     base 10 power of the range.
910 !
920 DISP "Initializing the arrays for plotting"
930 ON Type GOSUB Initialize1 ,Initialize2
940 BEEP
950 !
960 ! Determine what plotter the user wishes to use and make declarations
970 !     accordingly.
980 !
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
1230 DISP "Would you like to change the limits of the vertical axis (y/n)";
```

```
1240 INPUT Dummy$
1250 IF Dummy$="N" OR Dummy$="n" THEN GOTO 1340
1255 DISP Ymax;" is the old normalized maximum value"
1260 DISP "What is the new normilized maximum value";
1270 INPUT Ymax
1275 DISP Ymin;" is the old minimum value"
1280 DISP "What is the new normalized minimum value";
1290 INPUT Ymin
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
1365 DISP Xmax;" is the old normalized maximum value"
1370 DISP "What is the new normalized maximum value";
1380 INPUT Xmax
1385 DISP Xmin;" is the old minimum value"
1390 DISP "What is the new normalized minimum value";
1400 INPUT Xmin
1410 IF Xmax>Xmin THEN 1440
1420 DISP "ERROR, Xmax must be greater than Xmin"
1430 GOTO 1370
1440 Xrange=Xmax-Xmin
1450 GOTO 990
1460 CLEAR @ DISP @ DISP
1470 DISP TAB (5);"Enter:"
1480 DISP TAB (11);"1 to return to ADC TEST"
1490 DISP TAB (11);"2 to rerun LINPLOT"
1500 DISP TAB (11);"3 to quit"
1510 INPUT A
1520 IF A=1 THEN CHAIN "ADC TEST"
1530 IF A=2 THEN 440
1540 DISP @ DISP TAB (5);"This progaram has ended."
1550 GOTO 99999
1560 ! ****************
1570 Initialize1: !
1580 ! ****************
1590 Sca_1e=10 ! Divide the axis into ten intervals
1600 Xmax=-9.99999999999E499 ! Set initial min. and max.
1610 Xmin=9.99999999999E499
1620 Ymax=-9.99999999999E499
1630 Ymin=9.99999999999E499
1640 FOR I=0 TO points-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)/10)) ! 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)/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 Sca_1e=8 ! Divide the X-axis into 8 intervals
```

```
1860 FOR I=0 TO Nots-1 ! Assign values to the X-axis arrav X(*)
1870      X(I)=I+1
1880 NEXT I
1890 Xmax=Npts ! Declare the min and max values of the X-axis arrav
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
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 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
2600 !
2610 ! Label the X-axis
2620 !
2630 LORG 9
2640 I=1
2650 IF Xinter+I*Xrange/Sca_le>Xmax THEN 2710
2660     MOVE Xinter+I*Xrange/Sca_le,Yinter-Yrange/50
2670     IF Type=1 THEN LABEL USING "3D.2D" ; Xinter+I*Xrange/Sca_le
2680     IF Type=2 THEN LABEL USING "5D.0D" ; Xinter+I*Xrange/Sca_le
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 2910
2840 GOTO 2910
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(0),Y(0)/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
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
10 ! ***********************************************************************
20 !
30 ! Program Title:  LINPLOTMD
40 !
50 ! Programmer:  Doug Doerfler
60 !              Graduate Student, Kansas State University
70 !
80 ! Date:  06-02-84
90 !
100 ! Version 1.0
110 !
120 ! Program Description:  LINPLOT is a plot routine developed to provide
130 !          a general purpose plot routine for linear-linear plots.
140 !          Type 1 plots divide the horizontal axis into 10 intervals.
150 !          Type 2 plots divide the horizontal axis into 8 intervals and
160 !          uses the point numbers to label the X-axis.
170 !
180 ! Parameters that are supplied to LINPLOT
190 !      X(*) - X-axis data array:  (real)
200 !      Y(*) - Y-axis data array:  (real)
210 !      Npts - Number of points in X(*) and Y(*):  (integer)
220 !      Type - Type of numbering for the X-axis:  (integer)
230 !             1 - Use values in X(*) to label the X-axis: 10 intervals
240 !             2 - Use the point number to label the X-axis: 8 intervals
250 !      Xtitle$ - Title for the X-axis
260 !      Ytitle$ - Title for the Y-axis
270 !      Title$ - Title of the plot
280 !      Name$ - Users name
290 !      Date$ - Date the plot was generated
300 !
310 ! Subroutines within LINPLOT
320 !        Initialize1 - Initializes the data for a Type=1 plot
330 !        Initialize2 - Initializes the data for a Type=2 plot
340 !        Axes_label - Draws and labels the axes; Labels the plot
350 !        Plot_1 - Plots data points for a Type=1 plot
360 !        Plot_2 - Plots data points for a Type=2 plot
370 !        Smooth - Moving average trend remover
375 !
380 ! Data - Data needs to be stored in a file as two columns. The
390 !          left column is the x-axis data and the right column is
400 !          the y-axis data.
410 !
420 ! ***********************************************************************
430 !
440 OPTION BASE 0
450 !
460 ! Declarations
470 !
480 REAL X(800).Y(800)
490 REAL Aspect.Fract.Sca_le,Xmax,Xmin.Xrange,Xpower,Xinter
500 REAL Ymax.Ymin,Yrange,Ypower,Yinter
510 INTEGER Npts,Plotter,Type
520 DIM Xtitle$[60],Ytitle$[60],Title$[60],Name$[60],Da_te$[60]
530 DIM Dummy$[60],File_name$[60]
540 CLEAR
550 DISP
560 DISP
570 DISP TAB (5);"THE DATA FILE IS ASSUMED TO BE IN LEFT DRIVE"
580 WAIT 3000
590 CLEAR
600 DISP
610 DISP
```

```
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 Title$
680 DISP TAB (5);"USERS NAMES (60 CHARACTER LIMIT)";
690 INPUT Name$
700 DISP TAB (5):"WHAT IS THE DATE";
710 INPUT Da_te$
720 DISP TAB (5);"HOW MANY OBSERVED VALUES ARE BEING PLOTTED":
730 INPUT Npts
740 DISP TAB (5):"HOW MANY EXPECTED VALUES ARE BEING PLOTTED";
750 INPUT points
760 Type=1
765 DISP "INPUT FILE NAME!" @ INPUT file_name$
770 ASSIGN# 1 TO  file_name$&":D700"
780 ASSIGN# 2 TO  file_name$&":D700"
790 FOR K=0 TO Npts-1
800 READ# 1 ; X(K),Y(K)
810 NEXT K
820 FOR I=0 TO points-1
830 READ# 2 ; X(I+Npts),Y(I+Npts)
840 NEXT I
850 ASSIGN# 1 TO  *
860 ASSIGN# 2 TO  *
870 !
880 ! Initializing the arrays refers to finding maximum and minimum values. the
890 !     range of the values, and normalizing the data by dividing by the
900 !     base 10 power of the range.
910 !
920 DISP "Initializing the arrays for plotting"
930 ON Type GOSUB Initialize1 ,Initialize2
940 BEEP
950 !
960 ! Determine what plotter the user wishes to use and make declarations
970 !     accordingly.
980 !
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
1230 DISP "Would you like to change the limits of the vertical axis (y/n)";
1240 INPUT Dummy$
```

```
1250 IF Dummy$="N" OR Dummy$="n" THEN GOTO 1340
1255 DISP Ymax;" is the old normalized maximum value"
1260 DISP "What is the new normilized maximum value";
1270 INPUT Ymax
1275 DISP Ymin;" is the old minimum value"
1280 DISP "What is the new normalized minimum value";
1290 INPUT Ymin
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
1365 DISP Xmax;" is the old normalized maximum value"
1370 DISP "What is the new normalized maximum value";
1380 INPUT Xmax
1385 DISP Xmin;" is the old minimum value"
1390 DISP "What is the new normalized minimum value";
1400 INPUT Xmin
1410 IF Xmax>Xmin THEN 1440
1420 DISP "ERROR, Xmax must be greater than Xmin"
1430 GOTO 1370
1440 Xrange=Xmax-Xmin
1450 GOTO 990
1460 CLEAR @ DISP @ DISP
1470 DISP TAB (5);"Enter:"
1480 DISP TAB (11);"1 to return to ADC TEST"
1490 DISP TAB (11);"2 to rerun LINPLOT"
1500 DISP TAB (11);"3 to quit"
1510 INPUT A
1520 IF A=1 THEN CHAIN "ADC TEST"
1530 IF A=2 THEN 440
1540 DISP @ DISP TAB (5);"This progaram has ended."
1550 GOTO 99999
1560 ! ****************
1570 Initialize1: !
1580 ! ****************
1590 Sca_le=10 ! Divide the axis into ten intervals
1600 Xmax=-9.99999999999E499 ! Set initial min. and max.
1610 Xmin=9.99999999999E499
1620 Ymax=-9.99999999999E499
1630 Ymin=9.99999999999E499
1640 FOR I=0 TO Npts+points-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)/10)) ! 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)/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 Sca_le=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
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 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
2600 !
2610 ! Label the X-axis
2620 !
2630 LORG 9
2640 I=1
2650 IF Xinter+I*Xrange/Sca_le>Xmax THEN 2710
2660     MOVE Xinter+I*Xrange/Sca_le,Yinter-Yrange/50
2670     IF Type=1 THEN LABEL USING "3D.2D" ; Xinter+I*Xrange/Sca_le
2680     IF Type=2 THEN LABEL USING "5D.0D" ; Xinter+I*Xrange/Sca_le
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 Nots+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(0),Y(0)/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
```

```
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 Nots-1
4200      PRINT# 1 ; X(I),Y(I)
4210 NEXT I
4220 ASSIGN# 1 TO  *
4230 RETURN
99999 END
 112635
```

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

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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 2.2×10^{12} to 6.0×10^{14} cm^{-2}. A pulsed XeCl eximer laser (= 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.