METAL-SEMICONDUCTOR SCHOTTKY BARRIER

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Master of Science in ~~Statistics~~ physics

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ABSTRACT

In this thesis theoretical and experimental investigation of metal-semiconductor junciton consisting of Aluminium deposited on monocyrstalline silicon are discribed.

The films of Alluminium have been deposited on P-type silicon, in the <100> and <111> orientation and resistivities of 7-13 and 100 ohm-cm, by vacuum depositon. The silicon wafters have been treated chemically. The experiemtnal procedures followed in the work are; the I-V vharacteristics, forward biase and C-V characteristics for different frequencies of superimposed signal 10kHz, 20 kHz, 40 kZ, 100 kZ and 100 kHz. Measurement have been made using hp Model 4275A multifrequency meter and 4041B pA meter/Dc voltage source for C-V and I-V characteristics respectively. Low frequency C-V measurement (Quasistatic capacitance-voltage) have been tried using hp 4041B pA meter, but inconsistency of the result (maybe lack of appropriate test fixture) We have developed all the software programmes used for the present work.

the barrier height obtained by various techniques were as follows. the hole barrier was obtained as $_{Bh}$ = 0.57 eV for chemically cleaned and oxdize for 1½ hr. from I-V characteristics and $_{Bh}$ = 0.53eV from C-V characterstics. The active doping ocncentration obtained form $1/C^2$-V slope shows to decrease as frequency increases. Also the barrier height obtained from this measurement shows frequency dependence. The range of the barrier height obtained is (0.49 eV - 0.65 eV).

The above result suggest that we can make good diodes from vacuum deposition of aluminium on P-type silicon and possible application to hybrid circuit.

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I INTRODUCTION

1. HISTORICAL DEVELOPMENT OF METAL-SEMICONDUCTOR(M-S) CONTACT

The earliest systematic investigation of metal-semiconductor contact rectifiing systems is generally attributed to Braun [1], who in 1874 noted the dependenc of the toal resistance on the polarity of the applied voltage and detailed surface condition. The point contact rectifire in various forms found practical application beginning in 1904 [2]. In 1931, Wison [3] formulated the transport theory of semiconductors based on the band theory of solids. This theory was then applied to M-S contacts. In 1938, Schottky [4] suggested that the potential barrier could arise from stable space charges alone without the presence of chemical layer. The Model arising from this consideration is known as Schottky barrier.

The general accepted view of the nature and theory of idealized rectifing contacts between a metal and semiconductor is due to in large part to Schottky [4] and to early contribution by Wagner [5], Spenke [6], Mott [7] and Davydov [8]. While Schottky basic Model has remained intact its detail have undergond considerable refinement and extension, and in few cases important and far reaching modification. Among the pretinient refinment and extension made were the general improvement of the theory by Spenke [9], the introduction of IMAGE FORCE effect by Landsberg [10], the inclusion of field dependence of MOBILITY AND DIFFUSION by Landsberg [11] and Stratton [12] and inclusiong of QUANTUM MECHANICAL TUNNELING effects by Padovani and Stratton [13]. The more important modification on the other hand resulted from Bardeen [14], Introduction of the effects of ELECTRICAL SURFACE DOUBL LAYER due to surface states and inclusion of effect of minority carrier injection by Bardeen and Brattains [15].

Technologically, the first important contribution to the fabrication of Schottky barrier were made in 1940's with the development of microwave radar when point contact first used and applied extensively, primarily as Microwave detector and mixer. An excellent treatment of this early work on technology and application of point contact diode was made by Torrey and Whitmer [16].

However, the discovery in 1948 of Minority carrier injection and transistor action in semiconductor cause an important and basic diversion in the effort, and almost terminated the activity on point contact rectifiers. While the study of (M-S) contact continued for many years there after, the emphasis was now predominantly on the study of injection transport and collection of minority carriers. The role of M-S contact except in point contact diode was suddenly reduced to that of providing ohmic contact to semiconductors. After several years considerable effort was again devoted to the study of M-S schottky barriers. The revival of this interest is in large part due tot he following circumstances [17].

i) With the extensive fundamental knowledge of semiconductor accumulated and the availability of ahighly advanced semiconductor technology (silicon) a new approach to the basic problem of M-S barrier appeared.

ii) Minority carrier Transit and Charge Storage effects set un upper limit to the high frequency operation of all minority carrier devices. This serious limitation appeared avoidable in utilizing Non-Injecting or Majority carrier Schottky barrier.

iii) The newly proposed high frequency metal-base transistor [18,19] based on Schottky barrier emitter and collector junction provide added motiva-ion for further study of Schottky barrier.

The resulting new effort probably recieved an additional impulse from resulting of a detailed study on M-S barriers produced vacuum cleavage of silcon crystal in stream of evaporating metals atoms [20]. This technique, to be subsequently applied quite extensively to other system as well, made possible the fabrication of structurally ideal Schottky diodes, with the usual uncertainities of interfacial films and impurities which were involved in most previous experimental work [21]. It becomes possible to fabricate barriers with high reproducible characterstic by various investigator [22,23,2 The result provided a sound basis for critical quantitative evaluation of existing barriers theories and shedding considerable light on many of basic underlying mechanism.

2. TECHNOLOGICAL ASPECT

At present Schottky barriers are always made by the deposition of the metal film on a clean semiconductor surface. The other possibility namely the deposition of semiconductor film on a clean metal surface has also been tried in connection with the development of metal base transistor results obtained using this method have been found disappointing [25], no Schottky barriers with good rectification property have ever been bade this way and reported in literature.

The following are the fabriction methods often used for metal deposition to form M-S contacts.

i) Vacuum depositon through resistive or electron beam heating,

ii) Sputtering in a high frequency or dc system,

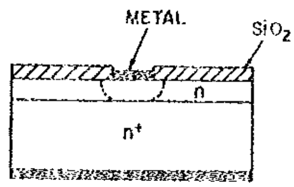
iii) plasma gun,

iv) Electolytic depositon

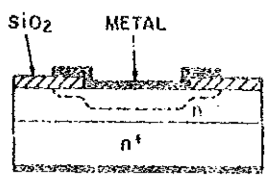
v) fabrication of silicide contact, through heating of suitable metal-silicide contact,

vi) therm compressing bonding,

Different types of M-S contact devices structures for various application given below [26]



(a) SMALL AREA CONTACT



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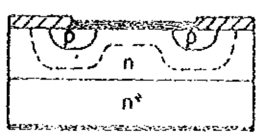
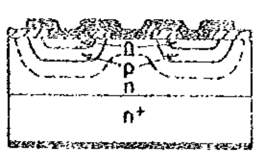


(c) DIFFUSED GUARD RING



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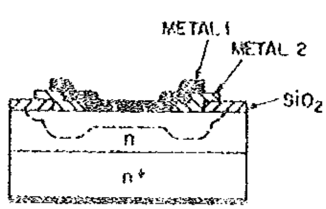
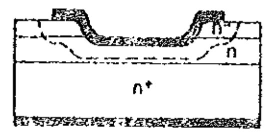
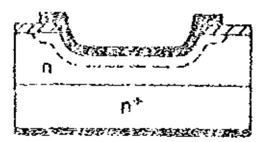


(e) METAL GUARD RING



(f) HIGH RESISTIVITY GUARD LAYER



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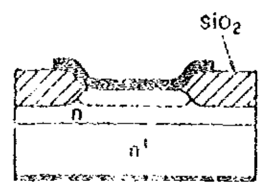
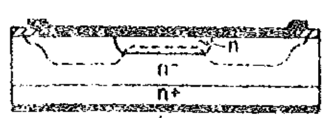
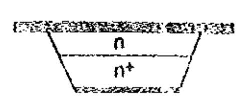


(h) OXIDE ISOLATED



(i) METAL-OVERLAP LATERALLY-DIFFUSED



(j) TRUNCATED CONE

The method of preparation of M-S contact for the present work using method (i) with its detail procedure is given in Chapter III. After fabrication of M-S contact different method of investigation is used such as electrical, optical and Rutherford back scattering of ions etc., are used. Among the above the electrical method would be discussed in short (present method of the work), detail is given in ChapterIII.

2.1 Electrical Method

This involves obtaining(I-V) curves at different termperatures photoelectric method involves obtaining I-V curves under light radiation with different wave length for analysis of topography of depletion layer one spacial case is determination of barrier height by fowler plot. Other measurement involves C-V measurement and transient measurement etc. Transient measurement involves as DEEP LEVEL TRANSIENT SPECTROSCOPY (DLTS), ADMITANCE SPECTROSCOPY (AS), DIELECTRIC SPECTROSCOPY OF SEMI-CONDUCTORS (DSS) and THERMAL STIMULATED CURRENT (TSC) etc. which are geared for mesuring position, concentration profile, activation energy, electron and hole capture cross section of Deep traps and Deep level DEFECTS [27].

In the present work I-V curves, QUASI STATIC C-V curves for differnt ramp rate at low frequencies and C-V curves at relatively high frequency is used. The detailed method is discussed in Chapter III.

Present application and uses for contacts for semi-conductor (particularly Silicon) include among others; Integrated circuit, Discrete components e.g. transistor, power componenents, varactors, mixers, microwave generators, photo detectors, particle detector, gamma and x-ray detector and solar cells.

3. INVESTIGATION OF M-S CONTACT

In recent periods, several theories were presented to exaplain the behaviour of M-S contacts. To give some, the effect of shallow and deep donors level was discussed by Robert and Crowell in 1973 [28], Thermo-electronic emission over the barrier of majority carriers under forward bias Rhoderick in 1972 [29], effect of minority carriers Rhoderick in 1978 [30] in ac properties of M-S contacts, effects of charge trapped in states localised at the interface by Simeonov in 1984 [31], effect of interface trapped charge on conductance by Barret and Muret in 1983 [32], and on capacitance by Werner et.al. in 1986 [33], and recently effect of deep traps on cacitance by Shahid and Jonscher in 1987 [34].

In the work presented, we describe the effect of shallow and deep acceptor level in Metal-p semi conductor using the lines followed by Robert and Crowell [28] and for deep hole traps using the lines followed by Shahid and JohnSchor [34].

In order to verify the theory one needs accurate experimental methods for the investigation of the contact. The main aim of the thesis was to develop the experimental methods using the facilities available in the department. Various methods have been developed using the multifrequency LCR meter and PA meter. The methods are based on the use of the the hp 9000/300 computer which controls the instruments. A set of software programms has been prepared for the measurement. They are described in chapter II and attached in the appendix.

Samples of M-S contacts were prepared by the author in co-operation with Physics Department of the Dar-es-Salaam University. The samples were prepared by vaccum deposition technique. Aluminium was used as the metal and silicon as the semiconductor. Detailed description of the technology is given in Chapter III. Experimental results are given in Chapter IV with discussion. Finally, it would be found interesting to compare the measured barrier heights to the reported in literature for purpose of conclusion.

CHAPTER II

THEORY OF M-S (Metal-Semiconductor) JUNCTION

In the first part of this chapter, M-S junction is presented and describes the band diagram of ideal M-S junctions and offers a thorough characterization of junction barrier height.

In the second part the current transport is discussed. Three different theories are presented. The Thermionic-theory by Bethe [1], describes adequately the current transport in high-mobility semiconductory (silicon, Germanium), Diffusion-Theory by Schottky [2], applicable to low-mobility semiconductor (Gallium phosphide and most of II-VI compounds Zinc oxide, zinc sufide cadmium sulfide), and Thermionic emission - Diffusion theory proposed by Crowell and Sze [3], which is the synthesis of the above two theories limiting cases are discussed in this part.

in the third part the relation between charge distribution and the electrostatic potential funciton is treated interms of junciton capacitance. Three different cases are discussed. Ideal M-S junciton Capacitance, effect of deep impurity level at low and intermediate frequency and effect of deep traps.

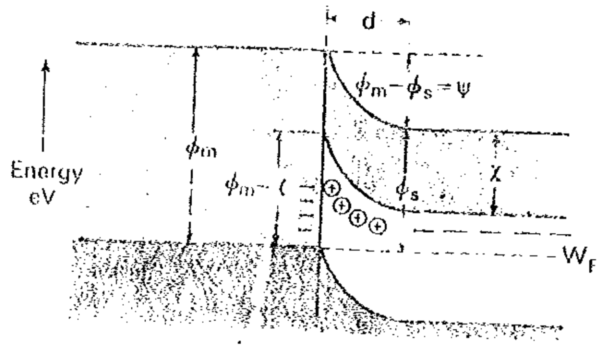
At the end of the chapter a relation for M-p Semiconductor is presented, as authours modification of Crowell and Roberts model and Sahid and Jonscher [17].

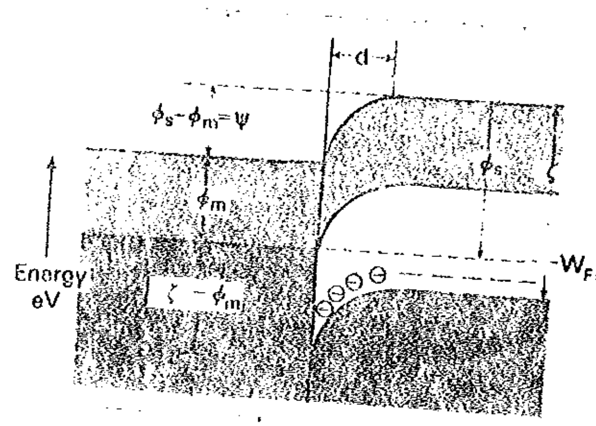
1. ENERGY BAND RELATION AT A M-S CONTACT

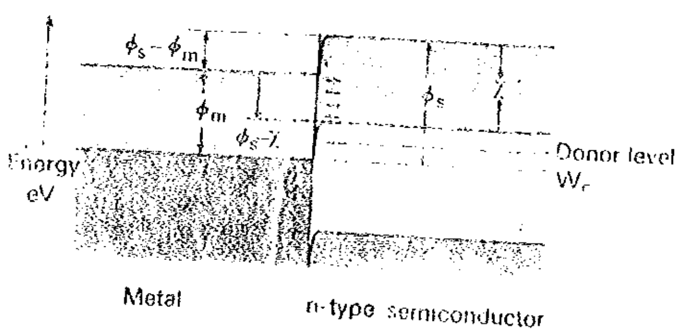
In this section an energy band diagram for metal-semiconductor is presented. A contact between the metal and semiconductor can be classified into two, when the work function of metal (ϕ_m) is greater or less than the work function of the semiconductor (ϕ_s). For the case of n-semiconductor the contact is a rectifire when $\phi_m > \phi_s$ and ohmic when $\phi_m < \phi_s$.

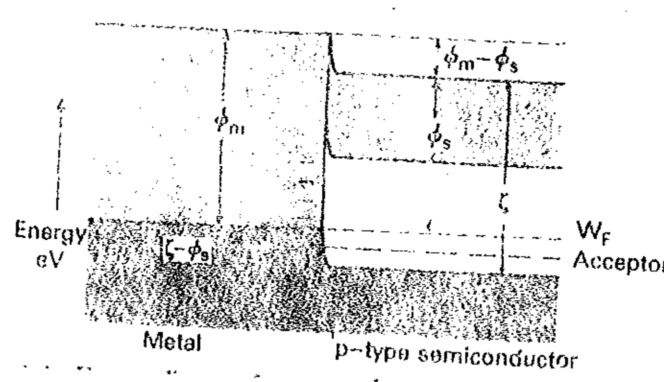
For the case of p-semiconductor the contact is a rectifire when $\phi_m < \phi_s$ and ohmic when $\phi_m > \phi_s$.

In both cases the semiconductors are non-degenerate. The energy bond diagra for above are given below [4].





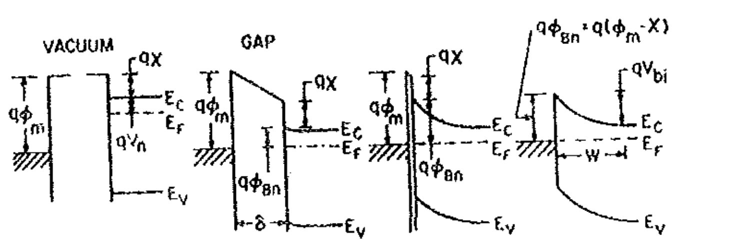




1.1 Ideal Condition and Surface States

When a metal is making contact with a semiconductor, a barrier will be formed at a metal-semiconductor interface. Since our aim is in rectifying contact, where a semiconductor is moderately doped ($< 10^{17} cm^{-3}$), the cases are when a work function of the metal is less than that of semiconductor for p-type and work function of the metal is greater than that n-type semiconductor [5].

a) An ideal contact between a metal and n-type semiconductor



(a)

where $q\phi_m$ = metal work function

$q(X+V_n)$ - Semiconductor work funciton

$q(X)$ - electron affinity for the semiconductor

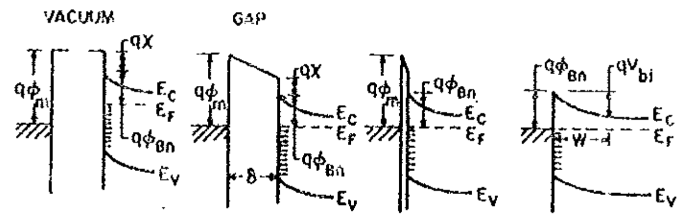
qV_n - difference between E_c and E_F

δ - Separation, ϕ_B - barrier height

When a metal is making contact with a semiconductor the fermi levels in the two materials must be coincident at thermal equilibrium. Relative to the fermi level in the metal fermilevel in the semiconductor is lowered by an amount equal to the difference between the two work funcitons $q[\phi_m-(X+V_n)]$ known as contact potential difference. As δ becomes small enough to comparable to the interatomic distance, the gap becomes transparent to electrons, and limiting value of the barrier height would be

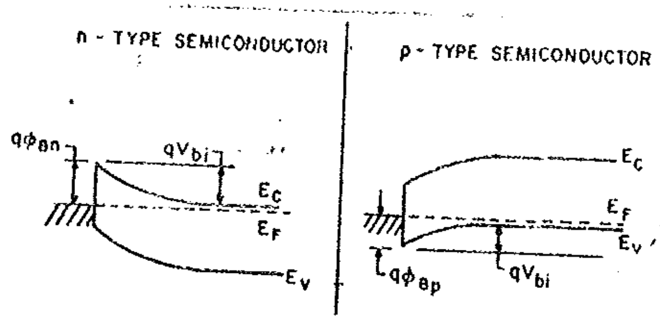
$$\phi_{Bn} = q(\phi_m - \chi) \qquad (1)$$

b) when large surface states is present on the semicon ductor surface



The surface is occupied to a level E_F. If the density of the surface state is sufficiently large to accomodate only additional surface charges resulting from diminishing δ without altering appreciably the occupation level E_F, the space charge in the semiconductor will remain unaffected. As a result the barrier hight ϕ_{Bn} is determined by the property of the semiconductor surface independent of metal work funciton. Its dependence will be shown later.

c) Energy band diagram of metal- n type and p-type semiconductor under different biasing condition.



i) thermal Equlbilibrium

The Schottky barrier lowering (also referred as image force lowering) $\Delta\phi$ and location of lowering X_m is shown and given as

$$X_m = \frac{q}{16\pi\epsilon_o E} \quad \text{cm} \quad (1)$$

$$= \frac{q}{4\pi\epsilon_o} E \quad \text{V}$$

The above result can be applied to a metal-semiconductor contact where ϵ_o of the vacuum permittivity is replaced by the appropriate dielectric primittivity of the semiconductor medium [6], and E by the maximum field at the interface.

Thus, at high fields the Schottky barrier is considerably lowered, and the effective metal work funciton for thermionic emission ($q\phi_B$) is reduced. Although the barrier lowering is small in metal-semiconductor contact as compared to the metal vacuum system, it does have a profound effect on current transport processes in metal-semiconductor contact, which will dicuss later.

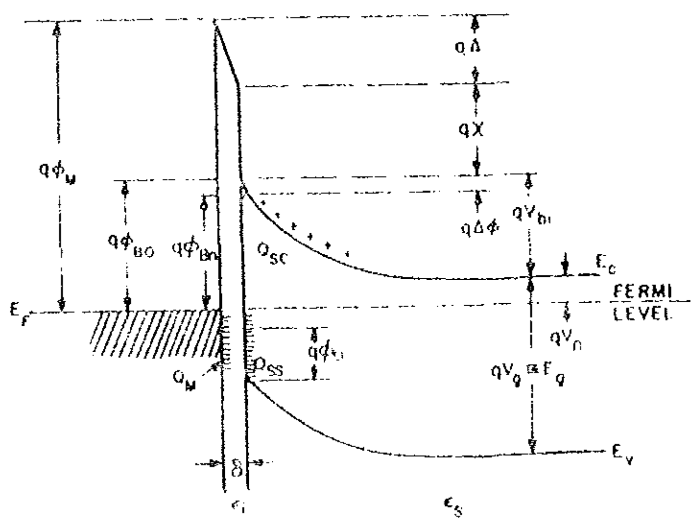
1.2 General Expression of Barrier Heights

The barrier heights of metal-semiconductor systems are, in general, determined by both the metal work function and surface states. A general expression can be obtained on the basis of the following assumption [7].

i) With intimate contact between the metal and the semiconductor and with an interfacial layer of atomic dimension this layer will be transparent to electrons and can withstand potential across it.

ii) the surface states per unit area per electron volt at the interface are a property of the semiconductor surface and are independent of the metal.

A more detailed energy band diagram of metal – n-type semiconductor contact is shown below, with an interfacial layer of the order of atomic distan incorporating Schottky effect .



where ϕ_m = work funciton of metal

ϕ_{Bn} = barrier height of metal-semiconductor barrier

ϕ_{Bo} = asymptotic value of $_{Bn}$ at zero electric field

ϕ_o = energy level at the surface

$\Delta\phi$ = image force barrier lowering

Δ = potential across interfacial layer

χ = electron affinity of semiconductor

V_{bi} = built in potential

ϵ_s = permittivity of semiconductor

ϵ_i = permittivity of interfacial layer

δ = thickness of interfacial layer

Q_{sc} = space charge density in semiconductor

Q_{ss} = surface state density on semiconductor

Q_M = surface charge density on metal

The first quantity of interst is energy level of ϕ_o at the surface. It coincide with the termilevel before contact is made. It specified the level [8] below which all surface state must be filled for charge neutrality at the surface. Since δ is of order of atomic distance it will be essentially transparent to electrons. If D_s is surface states density in state /cm²/eV, and assumed to be constant over the range from $q\phi_o$ to E_F, then

$$Q_{ss} = -q\ D_s[E_g - q\phi_o - q\phi_{Bn} - q\Delta\phi]\ \frac{C}{cm^2} \tag{1}$$

and the space charge density that forms in the depletion layer of semiconductor at thermal equilibrium is

$$Q_{sc} = [2q\varepsilon_s N_D(\phi_{Bn} - V_n \pm \Delta\phi - \frac{kT}{q}))]^{\frac{1}{2}}\ \frac{C}{cm^2} \tag{2}$$

For thin interfacial layer assumed the total surface charge density on the semiconductor is equal to Q_M develope on the metal surface

$$Q_M = -(Q_{ss} + Q_{sc}) \tag{3}$$

From Gaus's law the potential across the interfacial layer can be obtained

$$\Delta = \frac{-\delta\ Q_M}{i} \tag{4}$$

from the band diagram in the above figure for thermal equilibrium

$$\Delta = \phi_m - (X + \phi_{Bn} + \Delta\phi) \tag{5}$$

If Δ is eliminated from (4) and (5) and used to substitute Q_M in (3) and using (1), (2) and (3), we can write an expression for barrier height ϕ_{Bn} as

$$\phi_{Bn} = [C_2(\phi_m - X) + (1-C_2)(E_s/q - \phi_o) - \Delta\phi] + \{\frac{C_2^2 C_1}{2} - C_2^{3/2}[C_1(\phi_m - X) + (1-C_2)(E_s/q - \phi_o)\frac{C_1}{C_2} - \frac{C_1}{C_2}(V_n + \frac{kT}{q}) + \frac{C_2 C_1^2}{4}]\}^{\frac{1}{2}} \tag{6}$$

where $C_1 = \frac{2q\varepsilon_s N_D \delta^2}{\varepsilon_i^2}$, $C_2 = \frac{\varepsilon_i}{\varepsilon_i + q^2 \delta D_s}$ (7)

for vacuum cleaved or well cleaned semiconductor ε_i can be approximated by ε_o (free-space) value since δ is order of 4 or 5 Å and this leads to an over estimation of C_2. For moderately doped semiconductor ($N_D < 10^{18}$ cm^{-3}) , $\varepsilon_s \approx 10\varepsilon_o$, $\varepsilon_i = \varepsilon_o$ then C_1 is of order of .01 V and the term { } in (6) is less than 0.4V. Neglecting the { } term equ. (6) reduces to

$$\phi_{Bn} = C_2(\phi_m - X) + (1-C_2)\left(E_s/q - \phi_o\right) - \Delta\phi \equiv C_2\phi_m + C_3 \qquad (8)$$

If C_2 and C_3 can be determined experimentally and If X is known, then

$$\phi_o = E_g/q - \frac{C_2 X + C_3 + \Delta\phi}{1-C_2} \qquad (9)$$

from (7)

$$D_s = \frac{(1-C_2)\varepsilon_i}{C_2 \delta q^2} \qquad (10)$$

The two limiting cases can be obtained directly from equation 8

i) When $D_s \longrightarrow \infty$ then $C_2 \longrightarrow 0$ and

$$q\phi_{Bn} = (E_g - q\phi_o) - q\Delta\phi \qquad (11)$$

barrier height is independent of Metal work function and is determined entricely by doping and surface properties of semiconductor.

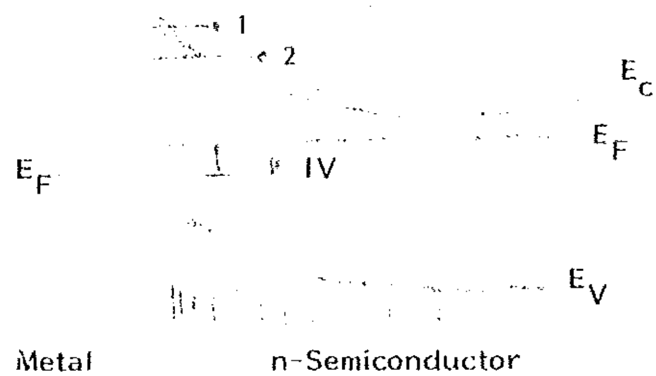
2) When $D_s \longrightarrow 0$, then $C_2 \longrightarrow 1$ and

$$q\phi_{Bn} = q(\phi_m - X) - q\Delta\phi \qquad (12)$$

This is barrier height for an ideal Schottky barrier where surface state effect are neglected. Identical to eq. (1) of 1.1 except Schottky lowering term.

2. CURRENT TRANSPORT PROCESS

The current transport in metal-semiconductor contact is mainly due to majority carriers, in contrast to p-n Junctions, where minority carrier are responsible for the transport. There are two basic transport processes under forward biase (the inverse processes occur under reverse biase). For metal n-semiconductor they are shown below [9].



First transport of electrons from semiconductor over the potential barrier into the metal: Dominant process for Schottky diods with moerately doped semiconductor (eg. S_i $N_D < 10^{17}$ cm^{-3}) operated at moderate temperatures.

Second Quantum mechanical tunneling of electrons through the barrier:- important for heavily doped (eg. S_i ND $\gg 10^{18}$ cm^{-3}) and for most ohmic contacts.

2.1 Thermionic Emission Theory

Thermionic-emission theory was derived on the assumption:

i) $q\phi_{Bn} \gg kT$

ii) thermal equilibrium is established at the plane that determines emission

iii) the existence of net current flow does not affect this equilibrium.

Because of the above assumption, the shape of barrier height is immaterial, and current flows solely depend on barrier height. The current density from semiconductor to metal is given by the concentration of electron with energies sufficient to overcome the potential barrier and traverse in x-direction.

$$J_{s\to m} = \int_{E_{min}}^{\infty} q V_x \, dn = \int_{E_{min}}^{\infty} q V_x N(E)F(E)dE \qquad (1)$$

where V_x is carrier velocity in direction of transport, E_{min} .
The minimum energy required for thermionic emission, dn concentration of electrons per unit volume in the energy interval E and E+dE, N(E) and F(E) are density of states and Fermi distribution funciton respectively.

$$dn = 4\pi\left(\frac{2m^*}{h^3}\right)^{3/2} (E-E_c) \, e^{\frac{-(E-E_c+qV_n)}{kT}} \, dE$$

$$J_{s\to m} = \left(\frac{4\pi q m^* k^2}{h^3}\right) T^2 \exp\left[\frac{-q(V_n + V_{bi})}{kT}\right] \exp\left[\frac{qV}{kT}\right]$$

$$J_{s\to m} = A^* T^2 \exp\left[\frac{-q\phi_B}{kT}\right] \exp\left[\frac{qV}{kT}\right] \qquad (2)$$

where $A^* = \frac{4\pi q m^* k^2}{h^3}$ effective Rechardson constant neglecting effect of quantum mechanical reflection and optical phonon scattering.

where $\phi_B \longrightarrow \phi_B - \Delta\phi$ when image-force effect are considered.

For multiple valley semiconductor for a single energy minimum

$$\frac{A^*}{A} = \frac{1}{m_o}[l_1{}^2 m_y{}^* m_z{}^* + l_2{}^2 m_x{}^* m_y{}^*]^{\frac{1}{2}} \qquad (3)$$

where l_1, l_2, l_3 = are direction cosines of normal to the principle axis of the elllipsoid.

$m_x{}^*, m_y{}^* m_z{}^*$ = component of effective mass tensor

for holes for a maxima at the center as in Ge, Si, GaAs, the two maxima at k = 0 gives rise to isotropic current flow from both light hole and heavy hole.

$$\frac{A^*}{A} = \frac{m^*_{eh} + m^*_{hh}}{m_o} \qquad (4)$$

Since barrier height remains the same for electrons moving from metal to semiconductor, the current flowing into the semiconductor is thus unaffecte by the applied voltage, therefore it must be equal to the current flowing from S→ M when thermal equilibrium prevails i.e at V = 0.

$$J_{m \to s} = +A^* T^2 \exp[\frac{-q\phi_B}{kT}] \qquad (5)$$

The total current density is then given by

$$J = J_{s \to m} - J_{m \to s}$$

$$J = J_{ST}[\exp(\frac{qV}{kT}) - 1] \qquad (6)$$

where $J_{ST} = A^* T^2 \exp[\frac{-q\phi_B}{kT}]$

2.2 Diffusion Theory

The Diffusion theory was derived on the assumption

i) $\phi_{Bn} \gg kT$

ii) effect of electron collision with in the depeltion region

iii) carrier concentration at $x = 0$ (interface) and $X = W$ (depletion end) are unaffected by current flow.

iv) the impurity concentration of semiconductor is nondegenerate.

Since current densities in depletion region depends on local field and concentration gradient, for one dimension in X direction.

$$J_x = J_n = q(N_n \; E + D_n \frac{\partial n}{\partial x})$$

$$= qD_n(\frac{-qn}{kT} \frac{\partial V(x)}{\partial x} + \frac{\partial n}{\partial x}) \qquad (1)$$

Where N_n mobility of electron, D_n Diffusion constant, $V(x)$ electrostatic potential.

Assuming steady state condition, and condition (ii) as

$$n(O) = N_c \exp[\frac{-E_{c(O)} - E_F)}{kT}] \qquad (2)$$

$$n(W) = n = N_c \exp[-qV_n/kT]$$

$$qV(x) = \frac{q^2 N_D}{\epsilon_s} [Wx - \frac{x^2}{2}] - q\,\phi_{Bn}$$

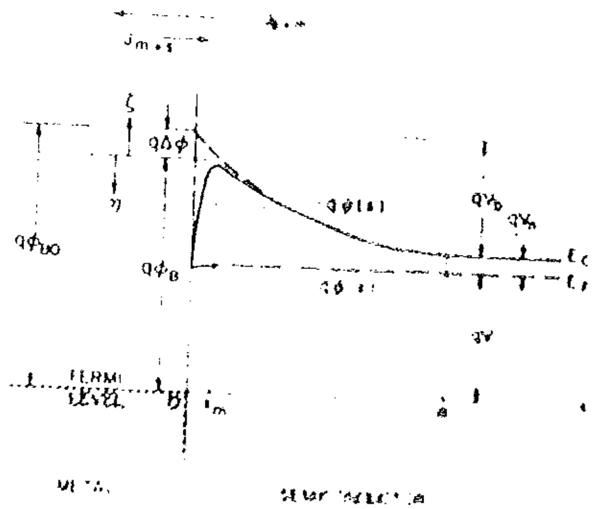
Integrating (1) from the interface $x = 0$ to end of depletion region total current density is given as

$$J_n = J_{SD}\,[\exp(qV/kT)-1] \qquad (3)$$

where $J_{SD} = \frac{q^2 D_n N_c}{kT} [\frac{q(V_{bi}-V)\; 2N_D}{\epsilon_s}]^{\frac{1}{2}}$

2.3 Thermionic Emission Diffusion Theory [3]

It is a synthesis of Thermionic Emission and Diffusion approaches, derived from boundary condition of Thermionic Recombination Velocity V_r near a metal-semiconductor interface. The model for metal-n semiconductor contact is given below incorporating Schottky effect.



Where $q\psi(x)$ electron potential energy and $q\phi(x)$ the quasii-fermi level Since carrier diffusion depends upon potential configuration we consider the electron potential energy $q\psi(x)$, and $q\phi_{Bn} >> kT$ so that charge density is that of ionized donors. On the region X_m to W the current density assoc ated with the im ref is given by

$$J_n = qN_n \frac{d\phi_n}{dx} \tag{1}$$

and for non degenerate condion

$$\begin{aligned} n &= N_c \exp[-\frac{(E_c(x) - E_F)}{kT}] \\ &= N_c \exp[\frac{-q(\phi_n - \psi)}{kT}] \end{aligned} \tag{2}$$

and if the portion of the barrier from X_m to interface acts as Sink for electr we can have the current density in terms of an effective recombination velocity V_R at X_m.

$$J_n = q(n_m - n_o)V_R \tag{3}$$

Where $n_m = N_c \exp\left[\frac{-q(\psi(X_m) - \phi_{Bn})}{kT}\right]$ concentration at X_m

$n_o = N_c \exp[-q\phi_{Bn}/kT]$ - quasi-equilibrium concentration at X_m

$\phi(W) = -V$ -(3)

Integrating (1) from X_m to W and using (2) with condition in (3) the total current density would be:

$$J = \frac{qN_cV_R}{1 + V_R/V_D} \exp\left(\frac{-q\phi_{Bn}}{kT}\right)\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \tag{4}$$

where $V_D = \left[\int_{x_m}^{W} \frac{q}{n_m kT} \exp[\phi_{Bn}+\psi]_{dx}\right]^{-1}$ (5)

= effective diffusion velocity associated to transport of electron in region W ---> X_m.

$$V_R = \frac{\int_0^{\infty} V_x \exp[-m^*V_x^2/2kT]_{dV_x}}{\int_{-\infty}^{\infty} \exp[-m^*V_x^2/2kT]_{dV_x}} = \frac{A^*T^2}{qN_c} \tag{6}$$

= effective thermal velocity

If we consider two limiting condition for (4)

1) $V_D >> V_R$ then preexponential term is dominated by V_R and thermion emmisson most nearly applies eq. (2) of 2.1

2) $V_D << V_R$ diffusion theory most nearly applies, eq. (3) of 2.2

Including the image force effect for $\psi(x)$, for the calculation of VD in (5) from band diagram above fig(1)

$$\psi(x) = \phi_{Bn} + \Delta\phi - Ex \frac{-q}{16\pi\varepsilon_s x} \quad (6)$$

and n_m to be independent of field E then result of (5)

$$V_D \propto E\mu \quad (7)$$

The complete expression of the J-V characteristic considering the electron-opti phonon scattering [11], crossing the potential energy maximum and in addition quantum mechanical reflection and tunneling by Schottky barrier [12] would modify the Richardson const. A* in thermionic emission theory [1], and look as follow.

$$J = A^{**}T^2 \exp(\frac{-q\phi_{Bn}}{kT}) \quad [\exp(\frac{qV}{kT}) - 1] \quad (8)$$

The current density (8) was derived from assumption [3] given in (2) and (3) by using the current density equation or "ohm's law" relating current to the gradient of Quasi -fermi level $q\phi_n$. When transport occurs the approximation is made that the mobile carrier density still given by equilibrium fermi-distribution, but E_F replaced by $q\phi_n$ (quasi fermi level). The quasi fermi level varies with time and position, adjusting the carrier density at each time and position to accomodate the current that is flowing including both drift and diffusion [13]. In principle the current density can be determined using the Boltzmann transport equation taking into account all scattering mechanism that limit the transport.

The Boltzmann equaton has been solved [14], within the semiconductor of Schottky diodes, thus providing general transport equation suitable to describe the transport process in the vicinity of the metal. The current-voltage characteristic has then been derived in two limiting condition

i) $\lambda >> L_D^2/W$ — L_D = Debye extrinsic length of semiconducotr, W = depleton width

ii) $\lambda << L_D^2/W$ — λ = carrier mean free path

where in the first condition it resemble to J-V derived [1] and in the second condition resemble to J-V derived [2] and intermidiate case to J-V characteristic of [3], but recombination velocity found to be twice as that of [14].

2.4 Tunneling Current

For heavily doped semiconductors ($N_D > 10^{18}cm^{-3}$) for operation at low temperature the tunneling current become more dominant. The expression in sect. 2.1 eq. (1) would be modified to include both thermionic and tunneling [15] components given below

$$J_{s \to m} = \frac{A^*T}{k} \int_0^\infty T(\xi) \exp \frac{[-q(V_b+V_n+\xi - \Delta\phi]}{kT} d\xi \qquad (1)$$

$$+ \frac{A^*T}{k} \int_0^{q(V_b-\Delta\phi)} F_s T(\eta)(1-F_m) d\eta$$

and from metal to semiconductor

$$J_{m \to s} = -\frac{A^*T}{k} \exp\left(\frac{-q\phi_{Bn}}{kT}\right) \int_0 T(\xi) \exp(-\xi/kT) d\xi$$

$$- \frac{A^*T}{k} \int_0^{q(V_b-\Delta\phi)} F_m T(\eta) (1-F_s) d\eta \qquad (2)$$

- where ξ, η are height measured above and below potential maxima repsectively in fig ( ) of set 2.3
- F_m, F_s fermi distribution function of metal and semiconductor respectively
- $T(\xi)$ and $T(\eta)$ transmission co-efficient above and below the potential maximum.

Then total current is the sum of (1) and (2).

If tunneling mponent dominates the current flow for high doping and low temperatures, transmission coefficient has the form given by[16].

$$T(\eta) \sim \exp[-q\phi_{Bn}/E_{oo}] \tag{3}$$

and thetunneling current J_t has similar expression

$$J_t \sim \exp[-q\phi_{Bn}/E_{oo}] \tag{4}$$

where $E_{oo} = \frac{qh}{2}\left(\frac{N_D}{\epsilon_s m^*}\right)^{\frac{1}{2}}$

The theoretical result for J-V characteristic of Schottky diode can be generalized taking II efect as

$$J = J_s[\exp(qV/_{nkT}) - 1] \tag{5}$$

$$n = \frac{q}{kT}\ \frac{dV}{d(\ln J)} \text{ - ideality factor} \tag{6}$$

3. CAPACITANCE - VOLTAGE CHARACTERISTIC OF SCHOTTKY BARRIERS

3.1 Capacitance-Voltage Relationship for Shallow Level

When the capacitance voltage (C-V) relationship of metal semiconductor diod is considered, the ionized doping concentration in the semiconductor depletion region is customarily assumed to be constant or to vary smoothly withdistance into the semiconductor (on a scale comparable to debye extrinsic length).

If we consider for the previous contact given under the abrupt approximation, that is

$$\rho(x) = qN_D \qquad x < W$$
$$\rho = 0 \qquad x > 0 \tag{1}$$
$$\frac{dV}{dx} = E = 0 \qquad x > 0$$

where N_D ionized donor concentration, charge density, W depletion layer width. The result of depletion layer width is similar to one-sided abrupt P^+-n junction [17], given as

$$W = \frac{2\varepsilon_s}{qN_D}(V_{bi} - V - \frac{kT}{q}) \tag{2}$$

where V - bias, ε_x - seminconductor permittivity.

The space charge per unit area Q_{sc} and depletion layer capacitance per unit are of the barrier are given

$$Q_{sc} = qN_D W = [2q\varepsilon_s N_D(V_{bi} - V - \frac{kT}{q})]^{\frac{1}{2}} \frac{C}{cm^2} \tag{3}$$

$$C = \frac{|Q_{sc}|}{dV} = \frac{\varepsilon_x}{W} = \frac{q\varepsilon_s N_D}{2(V_{bi} - V - \frac{kT}{q})}^{\frac{1}{2}} \tag{4}$$

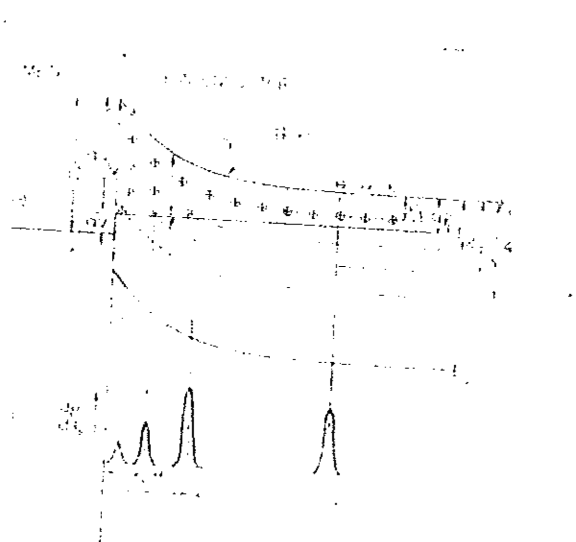
3.2.1 Low and Intermediate Frequency Capacitance-Voltage Relation of Schottky Barriers in Presence of Deep Levels

The existence of deep impurity levls throughout the semiconductor may affect the C-V relationship [17]. These levels can lie below the fermi level in the semiconductor bulk and therefore electrically inactive. Near a metal contact to the semiconductor, however, since the energy bands are bent, these levels may emerge above the fermi level in n semiconductor and below the fermilevel in p-type semiconductor over the portion of depletion layer charge in both n and p semiconductor. Such levels have clearly evider effects on the shape of potential barrier and C-V relationship.

The case of Metal-p type semiconductor contact in the presence of deep acceptor impurities level has ben considered in line to reference [17]. The case for metal-n semiconductor would be discussed next.

3.2.1 Low Frequency Response

In this section we will see an expression for low frequency Shottky barrier (C-V) relationship for a distribution of spatially uniform imparities level. The mode of [17] is metal-n semiconductor Schottky potential energy barrier is given below



where $q\phi$ - barrier energy

$q\psi$ - energy of conduction band relative to the fermi level in the seminconductor

$q\psi_f$, $q\psi_s$ - values of q deep in the bulk and at surface of the semiconductor respectively

E_1, E_2, E_3, E_4 - absolute energies of deep impurities level measured from conduction band.

The quantity $\frac{d\rho(x)}{d\psi_s}$ resulting from an incremental change of DC bias will be appreciable near the edge of depletion layer due to the change in electron concentration, and near points within the depletion region where each of the impurity level passes beneath the fermi level. The integral of $\frac{d\rho(x)}{d\psi_s}$ is the low frequency capacitance per unit area of Schottky barrier, as shown in fig (2).

From poisson equation

$$\frac{d^2\psi(x)}{dx^2} = \frac{1}{2}\left(\frac{d\psi}{dx}\right)^{-1}\left(\frac{d}{dx}\right)\left[\left(\frac{d\psi}{dx}\right)^2\right] = -\frac{\rho(x)}{\varepsilon_s} \qquad (1)$$

Integrating (1) from deep in the bulk $\psi = \psi_f$ to the interface $\psi = \psi_s$ we obtain the electric field strength at surface of semiconductor

$$\frac{d\psi}{d}\Big|_{x=0} = -E_s \qquad (2)$$

and using the result with Gauß's law the net charge per unit area stored in depletion region, σ_s is

$$\sigma_s = E_s = -\varepsilon\left(\frac{d\psi}{dx}\right)\Big|_{x=0}) = \left[2\varepsilon_s\int_{\psi_f}^{\psi_s}\rho(\psi)\,d\psi\right]^{\frac{1}{2}} \qquad (3)$$

The capacitance per unit area of Schottky barrier, C at band bendin $(\psi_s - \psi_f)$, and at a frequency at which all the impurity level may respond in semiconductor is then obtained

$$C = \frac{d\sigma_s}{d\psi_s} = \frac{\varepsilon\rho(\psi_s)}{\sigma_s} \qquad (4)$$

The validity of (4) requires [17], σ_s contain no appreciable contribi ion from minority carriers, only effects of ionized impurities and majority carriers charge.

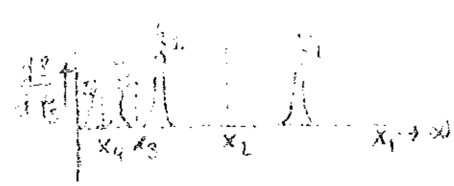
The flat band capacitance per unit area c_f when we apply a voltage which makes $\psi_s \longrightarrow \psi_f$, i.e., $\rho(\psi_s) \longrightarrow \rho(\psi_f) = 0$ can be obtained by expan ing $\rho(\psi)$ in tailor series, and using (2) and substituting in (3), flat-band capacitance per unit area

$$C_f = \lim_{\psi_s \to \psi_s} \frac{d\sigma_s}{d\psi_s} = \left[\left(\frac{d\rho}{d\psi}\right) \psi_f \right]^{\frac{1}{2}} \qquad (5)$$

In a range of band bending, where $\rho(\psi_s)$ may show appreciable varia ion, over small changes in ψ_s due to submergence of impurity level at the semiconductor surface as ψ_s decreases, $\rho(\psi_s)$ will be dominant in determini C in (4). Infact, it is this variation in $\rho(\psi_s)$ which should prmit the use of C-V relationship for Impurity Level Spectroscopy [18].

3.2.2 Intermediate Frequency response

Let us now consider the c-V relationship for frequnecies of applied ac votage at which one or more of the impurities level cannot respond. Consider figure belop plotted again for four level system [17]



As seen $\frac{d\rho}{d\psi_s}$ become appreciable within any particular portion of depletion regin mainly because charge change in a single impurity level, or for the case of a level lying above fermi level in the bulk because of change in free electfon near the edge of depletion layer. Accordingly a portion of the total law frequency incremental capacitance may be associated with area under each of peak of the impurity level lying below the fermi level and with the electron at the edge of the depletion layer.

The capacitance associated with 4^{th}, 3^{rd}, 2^{nd} energy levels our four level system for a single value of DC bias,

$$C_4 = \int_0^{x_4} \frac{d}{d \ \ s} dx \qquad C_3 = \int_{x_4}^{x_3} \frac{d}{d \ \ s} dx \qquad C_2 = \int_{x_3}^{x_2} \frac{d}{d \ \ s} dx$$, and

that associated with free-elction change.

$$C_1 = \int_{x_2}^{\infty} \frac{d\rho}{d\psi_s} dx \tag{5}$$

x_i = (i=1,2,3,4) are naturally chosen point of minimum $\frac{d\rho}{d\psi_s}$

The response time associated with each of the peaks τ (1=1,2,3,4) to an instantaneous incremental change in bias is given by

$$\tau_i = \frac{1}{C_{n_i} n_i} \tag{7}$$

where C_{n_i} electron capture coefficient

n_i electron concentration when E_i and E_F coincide.

Therefore from the above (7) condition

$$\tau_1 << \tau_2 << \tau_3 << \tau_4 \qquad (8)$$

If the ac frequency of the sum preimposed signal is w_i (for convenience) satisfies the condition (17).

$$\frac{2\Pi}{\tau_i} << w_i << \frac{2\Pi}{\tau_{i-1}} \qquad (9)$$

is applied then both i^{th} level and deeplying level cannot respond to the ac voltage. Thus no change of charge will take place in response to the ac signal of that frequency near points where these level crosses the fermi-level. Then $x = x_i$ determine a plane parallel to the interface beyond which (i.e., $x > x_i$ charge respond to the ac signal and for $x < x_i$ the i^{th} and deep lying level does not respond to the ac signal).

If we apply an ac modulation voltage $\delta\psi_s$, at a frequency w_i, charge change $\delta\sigma_i$, occurs beyond X_i, In addition there is a change in ψ, $\delta\sigma$ at X_i change in charge is given by

$$\delta\sigma_i = \left(\frac{d\sigma}{d\psi}\right)\Big|_{\psi_i} \cdot \delta\psi = \varepsilon\delta E_i \qquad (9)$$

from Gaus's law

$$\delta\psi_s = \delta\psi + x_i\rho E_i$$

$$= \delta\psi + \frac{x_i}{\varepsilon}\delta\sigma_i$$

$$\text{here} \quad x_i = \int_{\psi_s}^{\psi_i} \frac{d}{E} = \varepsilon \int_{\psi_s}^{\psi_i} \frac{d}{\sigma(\psi)} \qquad (10)$$

Then the capacitance per unit area at a freqncy w_i

$$C_{w_i}^{-1} = \frac{\delta\psi_s}{\delta\sigma_i} = \frac{d\psi}{d\sigma}\Big|_{\psi_i} + \frac{x_i}{\varepsilon} \tag{11}$$

It capacitance C_{w_i} may be characterized as being two series capacitor when band bending greater than ψ_i occurs.

3.2.3 Specific Impurity Concentration

In this section we will see how the general relationship derived so far for the model would look like when all use specific impurities.

If we neglect the contribution of holes to the total space charge and assume charge neutrality exist deep in the bulk of semiconductor and maxwel Boltzmann stastics apply to electrons in conduction band and fermidirac statics apply to the impurity atoms.

$$\rho(x) = \rho(\psi) = q\Big(\sum_d N_j f_i(\psi) - \sum_a N_i[1-f_i(\psi)]$$

$$- \Big\{\sum_d N_i f_i(\psi_f) - \sum_a N_i[1-f_i(\psi_f)]\Big\}\exp\Big[\frac{-q(\psi-\psi_f)}{kT}\Big] \tag{12}$$

where $\sum_d N_i$ and $\sum_a N_i$ sum overall impurities species which are donor and acceptor species respectively.

$$f_i(\psi) = \frac{1}{1+g_i\exp[-(q\psi-E_i)/kT]}$$

probability of ionization of donor impurity species.

In the above case acceptor impurites are included for some possible existence above midgap and of course to make the distribution generalize [17]. Using (12) for the total charge density for the model the total charge stored in the depletion region is from (3)

$$\upsilon_s = (2\varepsilon kT)^{\frac{1}{2}} \{u_s \sum_d N_i + \sum_{d+a} N_i \ln [f_i(\psi_f)/f_i(\psi_s)] +$$

$$[\sum_d N_i f_i(\psi_f) - \sum_a N_i[1-f_i(\psi_f)] \quad \exp(-u_s) - 1)\}^{\frac{1}{2}} \tag{13}$$

where $u_s = \frac{q(\psi_s - \psi_f)}{kT}$ band bending in unitys of $\frac{kT}{q}$.

The flat band capacitance c_f from (5)

$$C_f = (\frac{q^2\varepsilon}{kT})^{\frac{1}{2}}(\sum_d N_i f_i(\psi_f)[2-f_i(\psi_f)] \quad \sum_a \{N_i[1-f_i(\psi_f)]^2\})^{\frac{1}{2}} \tag{14}$$

If it assumed that all donors are ionized in bulk i.e $f_i(\psi_f) \longrightarrow 1$ or no acceptor or none of the acceptor ionized then C_f can be represen as C_D (as parallel plate capacitor of distance L_D). It is a convenient p meter for normalization.

$$C_D = \frac{A\varepsilon}{[\frac{kT}{q^2 \sum_d N_i}]^{\frac{1}{2}}} = \frac{A\varepsilon}{L_D} \tag{15}$$

Then for the given charge distribution (12) the C-V relation for the ca: of a number of levels and for a frequency at which all levels may respo so called low frequency capacitance using(13) in (3).

$$C = \frac{\varepsilon q(\sum_d N_i f_i(\psi_s) - \sum_a N_i[1-f_i(\psi_s)] - \sum_d N_i f_i(\psi_f) - \sum_a N_i[1-f_i(\psi_f)] \quad e^{\frac{-q(\psi_s-\psi_f)}{kT}}}{(2\varepsilon kT)^{\frac{1}{2}}(u_s \sum_d N_i + \sum_{d+a} N_i \ln[f_i(\psi_f)/f_i(\psi_s) + [e^{\frac{-q(\psi_s-\psi_f)}{kT}} - 1] X \quad \text{cont}}$$

$$\text{cont.} \quad \sum_d N_i f_i(\psi_f) - \sum_a N_i[1-f_i(\psi_f)] \quad [\exp[\frac{-q(\psi_s-\psi_f)}{kT}] - 1])^{\frac{1}{2}} \tag{16}$$

and also $1/c^2$ - V relation from (16)

$$\left[\frac{C_D}{C}\right]^2 = \frac{2\left\{\sum_d N_i\left(u_s \sum_d N_i + \sum_{d+a} N_i \ln[f_i(\psi_f)/f_i(\psi_s)]\right] + [\exp(-u_s)-1]\left\{\sum_d N_i f_i(\psi_f) - \sum_a N_i[1-f_i(\psi_f)]\right\}\right\}}{\left(\sum_d N_i f_i(\psi_s) - \sum_a N_i[1-f_i(\psi_s)]\right) - \left\{\sum_d N_i f_i(\psi_f) - \sum_a N_i[1-f_i(\psi_f)]\right\} e^{-u_s}} \quad (17)$$

for large values of u_s i.e. $u_s >> 1$ (corresponding to large values of reverse biase voltage) and ψ_s is large enough that $f_i(\psi_s) \longrightarrow 1$, for all impurities level (17) reduces to

$$\frac{1}{2}\left[\frac{C_D}{C}\right]^2 \doteq u_s - u_{int} \quad (18)$$

$$\text{where } u_{int} = \frac{\left\{-\sum_{d+a} N_i \ln f_i(\psi_f) + \sum_d N_i f_i(\psi_f) - \sum_a N_i[1-f_i(\psi_f)]\right\}}{\sum_d N_i}$$

In a similar manner the intermediate-frequency capacitance-voltage relationship can be obtained, for the given charge distribution (12) and using (10) and (11), would be given as follows:

$$\frac{C_D}{C_{w_i}} = \frac{C_D}{C(\psi_i)} + \frac{1}{\sqrt{2}} \int_{u_i}^{u_s} \frac{du}{[u-u_{int}+u_{\ell}(\psi)]^{\frac{1}{2}}} \quad (19)$$

$$\text{where } u_c(\psi) = \frac{\exp(-u)\left[\sum_d N_i f_i(\psi_f) - \sum_d N_i(1-f_i(\psi_f)]\right] - \sum_{d+a} N_i \ln f_i(\psi)}{\sum_d N_i}$$

and

$$u_{\ell} = \frac{q(\psi-\psi_f)}{kT}$$

$C(\psi_i) = \left(\frac{d\sigma}{d\psi}\Big|_{\psi_i}\right)$ is the low frequency capacitance per unit area at a total band bending $(\psi_i-\psi_f)$.

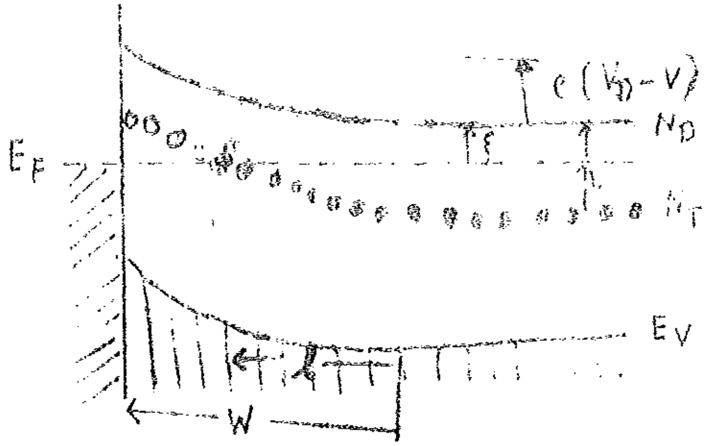
4. DEEP TRAPS AND C-V RELATIONSHIP

Silicon always has some bulk traps levels located in band gap near mid gap. Thus, bulk traps originate from residual impurities such as nickel, iron, manganese, zinc, copper and gold that in device grade silicon, usually have densities order of magnitude smaller than the densities of dominant ionized donors or acceptors impurities in n and p type semiconductor [19]. A bulk trap must change occupancy by only one unit of chare, i.e in changir occupancy the charge state of donor-type trap can go from neutral to one unit of positive charge and vice versa or for an acceptor type trap from neutral to one unit of negative charge and vice versa.

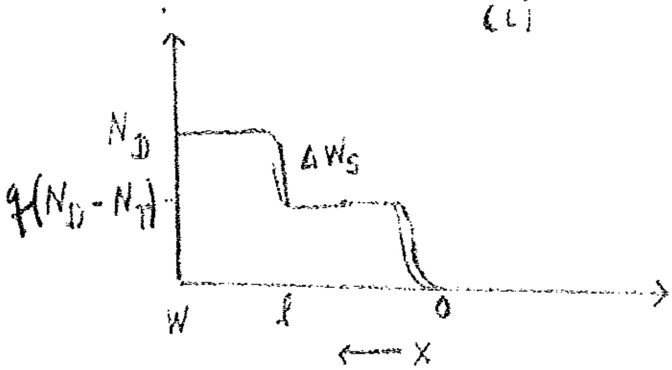
Not only deep dopant levels affect the C-V relationship of Schottky diodes as discussed previously but also deep traps in the bulk would affect the relation.

In this section we will consider, how charging of deep electron traps would bring a change in observed cpacitance from static point of view within the depletion region of Schottky diode.

The model of [20] of Schottky barrier diode for this purpose is given below where (i) depits the band diagram of metal n-semiconductor with the trap energy level and (ii) shows the distribution of trapped charges and space charge is depletion region.



(i)



(ii)

where N_D, N_t - shallow donor level and trapping level density

E_F, E_t - fermi-level and trap level energy

V_D, V - diffusion potential and applied bias

ξ - position of fermilevel deep in the bulk below conduction band

η - position of E_T below conduction band edges

W,l - depletion width and place where fermilevel cut trapp levels.

The application of small voltage causes some of traps levels to move with respect to the fermilevel at position $x = \ell$ where trap levels crosses the fermilevel, this owuld change the occupancy of the deep trap levels which result in modification of depletion layer charge distribution which affects C-V charactersitic [21].

If we observe the static processes, using poison equation

$$\frac{d^2\psi}{dx^2} = -\frac{e}{\varepsilon}(N_D N_T) \quad 0 < x < \ell \tag{1}$$

$$\frac{d^2\psi}{dx^2} = -\frac{e}{\varepsilon} N_D \quad \ell < x < W$$

Using boundary condition $E = 0$, $\psi = 0$ at $x = 0$ end depletion layer

$$\psi = -\frac{e}{\varepsilon}(N_D - N_T)x^2 \quad 0 < x < \ell \tag{2}$$

$$\psi = \frac{-e}{\varepsilon}\left(N_D\frac{x^2}{2} - N_T \ell x + N_T\frac{\ell^2}{2}\right) \quad \ell < x < W$$

And using condition $\psi = V_D - V$ at $x = W$

$$\psi = \frac{\xi - \eta}{-e} \quad x = \ell \tag{3}$$

$$\ell = \left[\frac{2\varepsilon(\xi - \eta)}{e^2(N_D - N_T)}\right]^{\frac{1}{2}}$$

As voltage changes by ΔV, the corresponding capacitance for incremental charge ΔQ, given as low frequency capacitance

$$C_{ef} = \frac{\Delta Q}{\Delta V} = \frac{\varepsilon}{W}\frac{1}{1-s/m} = C\frac{1}{1-s/m} \tag{4}$$

where $C_\infty = \varepsilon/W$ high frequency capacitance

$s = N_T/N_D$ compensation ration

$m = W/\ell$

The incremental capacitance $\Delta C = C_{ef} - C_{hf}$ is given as

$$C = C_{ef} - C_{hf} = \frac{C_\infty}{1 - s/m} - C = \frac{C_\infty}{m/s - 1} \qquad 5$$

The dependence of m on applied biase can be found from equ. (2) of 2nd part and subtitued in (5) gives us the dependence of incremental capacit per unit area as

$$\frac{\Delta C}{C_\infty} = \frac{S}{/S^2 - S + \mu(1-S)}$$

where $\mu = \frac{q(Vd-V)}{\eta - \xi}$ dimensionless energy parameter

Modification of Crowell-Robert Model for P seminconductor

We derive C-V relationship for metal-P semiconductor using Crowell-Robert model [17] for metal-n. Semiconductor contact. We assumed the effect of minority carrier are negligible for the contribution of space cha charge neutrality exist deep in the bulk, that fermidirac statistic holes apply to impurity atoms, and Boltzman stastics apply to in the valence band.

The charge distribution is given by

$$\rho(x) = q\{ \sum_d N_i(1-f_i(\psi)) - \sum_a N_i f_i(\psi)$$

$$-(\sum_d N_i(1-f_i(\psi_f)) - {}_a N_i(f_i(\psi)) e^{\frac{-q(\psi_f - \psi)}{kT}}$$

$\sum_d N_i$, $\sum_a N_i$ are sum over donor and acceptor impurity species

$$f_i(\psi) = 1/a + \frac{1}{f_i} \exp\left(\frac{q\psi - E_i}{kT}\right)$$

= probability of ionization of acceptor impurity.

from equ to σ_s the total charge stored in depletion region is

$$\sigma_s = (\varepsilon kT)^{\frac{1}{2}} \left(u_s \sum_d N_i + \sum_{d+a} N_i \ln\left(\frac{1-f_i(\psi_s)}{1-f_i(\psi_f)}\right) \right.$$

$$\left. + \left(\sum_d N_i(1-f_i(\psi_f) - \sum_d N_i f_i(\psi_f)\right) \left(e^{u_s}-1\right) \right)$$

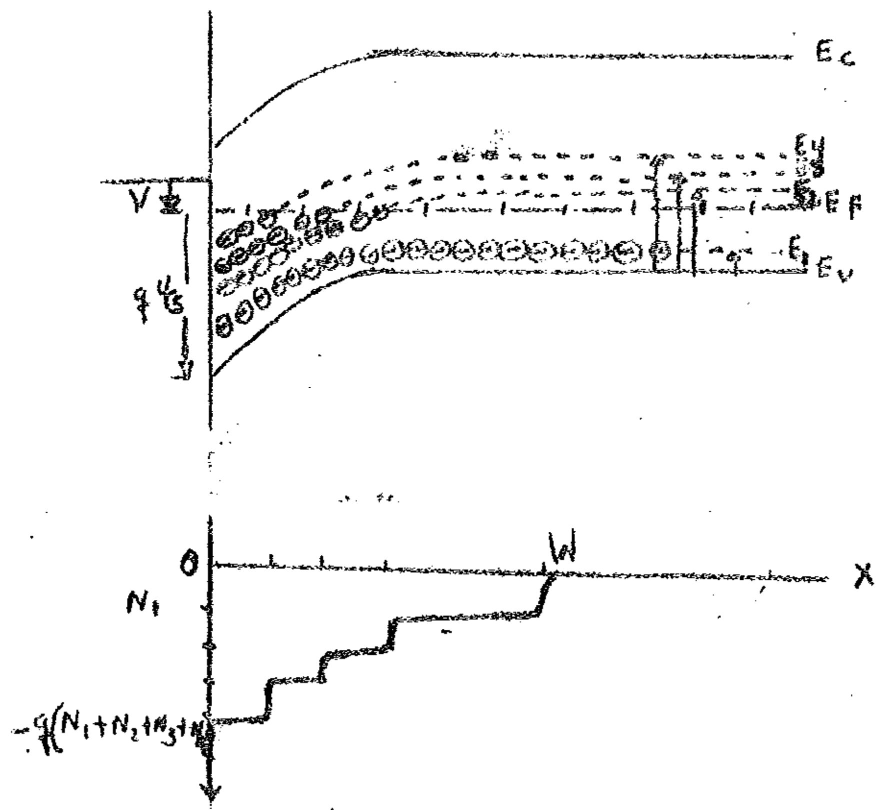
and the reciprocal of nomalized capacitance squared is given from equ

as

$$\left[\frac{C_D}{C}\right]^2 = \frac{2 \sum_a N_i(+u_s \sum_d N_i + \sum_{d+a} N_i \ln \frac{f_i(\psi_s)}{f_i(\psi_f)}] + (\sum_d N_i(1-f_i(\psi_f) - \sum_a N_i f_i(\psi_f))(e^{-u_s}}{\left(\sum_d N_i(1-f_i(\psi_s) - \sum_a N_i f_i(\psi_s) - (\sum_d N_i(1-f_i(\Sigma_f) - \sum_a N_i f_i(\psi_f))(e^{u_s})\right)^2}$$

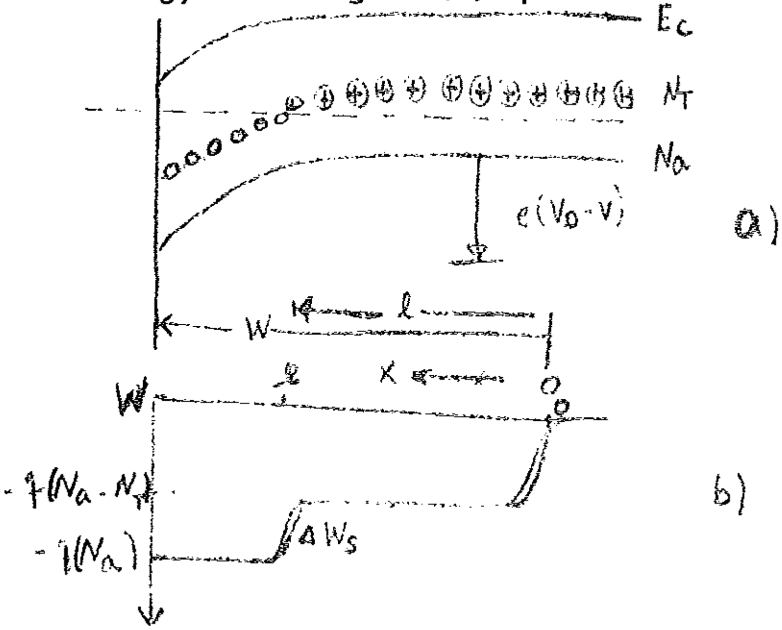
The result is identical except trivial substitution d —> a, a —> d change in $f_i(\psi)$ and in sign of u_s here down in p type but up in n-type.

The model we used is given in the figure below. where ψ = hole potential energy. ψ_f depth of E_v from fermilevel, ψ_s band bending at surfaces.



Modification of Zaidi-Jonshcer (1987) [20] Result for P Semiconductor

The model of a Schottky diode metal-p semiconductor adopted for the present analysis is given below in line with [20]. Where N_T is the densi of traps (hole), N_a is unfiorm density of shallow acceptor, E_F fermi energy, V and V_d are applied and diffussion potential, η and ξ position of hole trap and fermi level above Valence band and ΔW_s small-signal displacement of transition region. ℓ is position where trap level cut fermi level. Fig(a) energy band diagram (b) space chare distribuiton



We use static analysis as done by [20] to show the incremental capacitance due to chargine of traps.

From poinon equation

$$\frac{d^2\psi}{dx^2} = \frac{-\rho(x)}{\varepsilon_s}$$

$$\frac{d^2\psi}{dx^2} = -q/\varepsilon_s \, [N_T - N_a] \qquad 0 < x < \ell \qquad 1$$

$$\frac{d^2\psi}{dx^2} = +q/\varepsilon_s N_a \qquad \ell < x < W \qquad 2$$

Using the boundary conditions $\frac{d\psi}{dx} = 0$, $\psi = 0$ at $x = 0$

$$\psi = q/\varepsilon_s \left(N_a x^2/2 - N_T \ell x + \frac{N_T \ell^2}{2}\right) \quad \ell < x < W \qquad 3$$

$$\psi = -q/\varepsilon_s (N_T - N_a)\ x^2/2 \qquad \ell < x < 0 \qquad 4$$

and at $x = W$ $\psi = V_D - V$ and at $x =$ $\psi = \frac{\eta - \xi}{q}$

$$\Longrightarrow V_D - V = q/\varepsilon_s \frac{N_a W^2}{2} - q/\varepsilon_s N_T W - q/_s \frac{NT}{2} \ell^2 \qquad 5$$

$$\frac{\eta - \xi}{q} = -q/\varepsilon_s (N_T - N_a)\ \ell^2/2 \qquad 6$$

from equ. (6) $\ell = \left[\frac{\alpha\varepsilon_s}{q^2} \frac{(\eta - \xi)}{(N_a - N_T)}\right]^{\frac{1}{2}}$

from equ. (5) $-dV = q/\varepsilon_s (N_a 2W - N_T \ell)W$ gives us the increment in width for slowly changing applied biase, and corresponding increment in charge.

$$\Delta Q = qN_a \Delta W$$

and resulting capacitance under this bias is low frequency capacitance C_{L_f} gives as

$$C = \frac{\Delta Q}{\Delta V} = \frac{\varepsilon_s/W}{1 - \frac{N_T \ell}{N_a W}}$$

and the high frequency capacitance $C_{h_f} = \varepsilon_s/_W$ for fast changing applied biase is the same as in the absence of traps (holes). We may write for the incremental capacitance ΔC as $C_{L_f} - C_{h_f}$

$$C_{L_f} - C_{h_f} = \frac{\varepsilon_s/W}{1 - s/m} - 1 = \frac{\varepsilon_s/W}{m/s - 1} \qquad 7$$

where $m = \frac{W}{\ell} > 1$, $\quad s = \frac{N_T}{N_a} < 1$

We can solve the dependence of m on applied biase V through W from eq.(5) and substituting in (7) we obtain incremental capacitance per unit area due to charging of traps.

$$\frac{\Delta C}{C_\infty} = \frac{S}{S^2 - S + \mu(1-S)}$$

$$\text{where} \quad \mu = \frac{q(V_d - V)}{\eta - \xi}$$

The result is same as obtained by [20] for n-type case.

CHAPTER III

EXPERIMENTAL EMTHOD

In the first part of this chapter, fabrication of the sample (metal-semiconductor contact) using Edwards 306A Vacuum chaber coating system anc the nature of samples are given. Oxidation and cleaning processes are included as subparts.

In the second part the features of the measuring instruments such as LCR multifrequency meter, PA meter and DMM (Digital multimeter) are discussed. The chart of the measuring instruments interfaced with the computer is given in App(I) and HP-IB (Hewlett Packard - Interface Bus) commands pertaining to each measuring instrument are given in consecutive appendixes.

in the third part main description of software programms which we have lost considerable time of the work are given in brief, also included are technique of measurement set up and collecting data.

.1. FABRICATION OF M-S CONTACT

Samples were prepared from commercially fabricated hyperfine silicon wafers made by Wacker-Chemitronic GMBH Company (West Germany), labeled as: Wa-No/Pos 048313/001, Prod. No. 55.60-1. Data supplied with the wafers were as follows:

Polished	One side	"
Growth	Fz	"
Diameter (mm)	50.8	"
Orientation	<111>	<100>
Off-Or(deg)	2.5±0.5	"

Thickness (μm)	280±20	"
Resistivity (ohm-cm)	7-3	100
Type	P/B	P/B

The contact metal used is aluminium. Silicon wafers were placed in 306A Edwards vacuum chamber and aluminum (Aℓ) deposition were made on the wafer by evaporating Aℓ at a pressure of 6×10^{-6} mbar. The thickne of the aluminium deposited was measured by using film thickness monitor.

Variation of our sample is in resistivity, orientation shape and area of top contact, thermal oxidation time for growing sio_2 layer.

Specification of sample prepared according to the above condition

Sample No.	Shape of upper contact	Orientation	resistivity ohm-cm	oxidation time(hr)
1	Grid	$\langle 111 \rangle$	7-13	—
2	Grid	$\langle 100 \rangle$	16-24	—
3	Grid	$\langle 100 \rangle$	100	[illegible]
4	Circular mask	$\langle 111 \rangle$	7-13	—
5	Circular mash	$\langle 111 \rangle$	7-13	$1\frac{1}{2}$
6	Circular	$\langle 110 \rangle$	100	—

1.1 Predepositon Cleaning Process

Since the wafers have been kept for a longer time in the laboratory various contaminations are possible during handling. Since there were no set of cleaning materials, we used the available and simpler chemical method.

Some of the wafers were etched using 40% concentrated HF (for removing inorganic contaminants on the surface) followed by washing with distilled water for removing the remaining HF and the we use Acetone for drying the wafer. All cleaning process were done under fume-chmber (due to high poisoness nature of HF) in plastic container (Since HF attack glass).

1.2 Oxidation Process (Sio_2 Formatin)

For investigating of small thickness of Interfacial layer of Sio_2, some of the wafters right after cleaning were taken to the furnace for growing sio_2 layer on the wafer at different temperature. The wafers are kept on a ceramic plate, which can resist heat in the working temperatures. The source for oxide formation was used atmospheric air which enters to the furnace in the back air inlet opening. Since there was no available facility for measuring the grown oxide (sio_2) as

i) weight gain method

ii) ellipsometry

iii) multiple beam interferometry, etc

we have used the chart prepared by [21], for the approximation of the thickness.

1.3 Evaporation System

Thin or thick film fabrication by evaporation is most conveniently introduced by looking at a proto type evaporation system such as one given below which resemble ours. A vaccum chamber evacuated to 10^{-5} torr or better, contains a vapour source for example a resistive wire and substrate (wafer). The material to be evaporated for the contact (evaporant) is in thermal equilibrium with the wire. When the vapour source is heated,f or example by an electric current the vapor pressure of the evaporant becomes substantial and liberated atoms are sent out into the vacuum chamber and stick to the substrate where a thin film is subsequently formed [22].

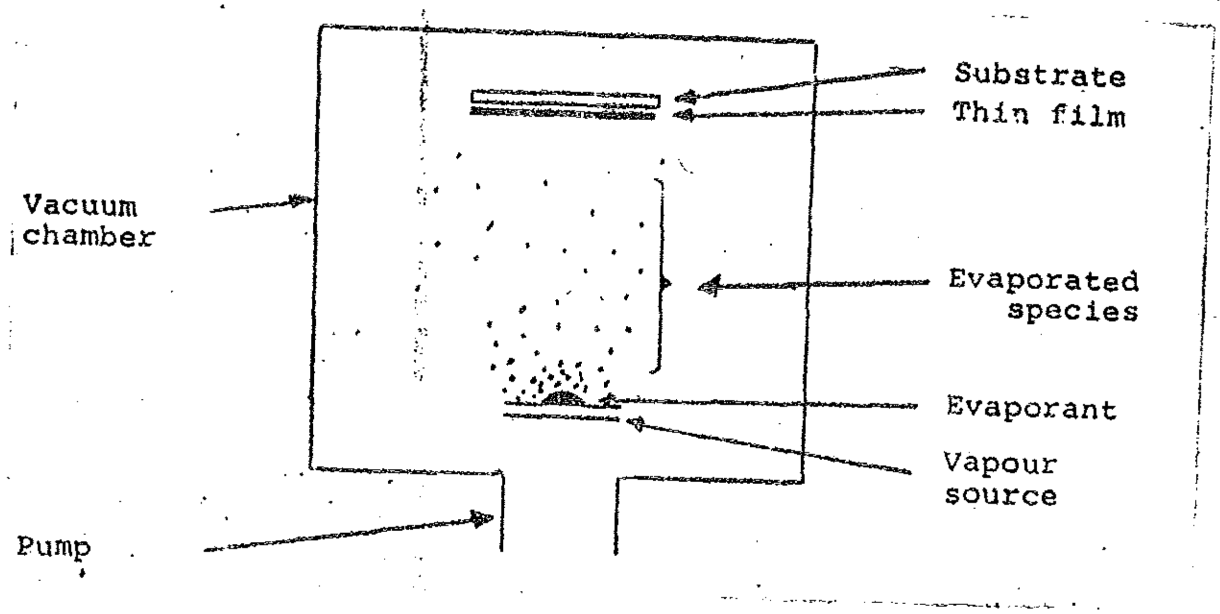


Fig (1) Principle design of an evapouration system

This thin filmdeposition can be regarded as consisting of three different steps.

i) the first involves transition from a condensed phase to vapor phase of evaporant. Theoretically, this can be described by Thermodynamics of phase transition.

ii) The second step is the vapour transport from the source to the substrate which can be accounted for interms of kinetics theory of gases.

iii) The third step is the condensation of vapor on the substraté and ensuing film growth.

2. EXPERIMENTAL TECHNIQUES

2.1 Feature of Measuring Instruments

The set up of our measuring instruments interfaced with the computer system is given in App(I). Where LCR multifrequency meter, pA meter and DMM (Digital multimeter) are used to take C-V and I-V measurements of our Schottky diodes controlled by hp 9000/310 computer having memory of 2MB.

Measurement can be done at high and low frequency ranges. For high frequency ranges, C-V measurement hp 4275A LCR multi frequency meter and for I-V measurement hp 4140B pA meter/DC voltage source are used. Low frequency C-V measurement can be done with hp 4140B pA meter with certain modificatio of the instrument test fixture, due to some problems this had been done during the period of the work so we have omitted this part of measurement.

2.1.1 LCR Multifrequency Meter

The hp Model 4275A Multifrequency meter is an instrument designed to measure impendance, capacitance, inductance, resistance, dispation factor, quality factor, conductance, suceptance, reactance and phase angle of circuit elements in 10 frequencie; 10,20,40,100,200 and 400 kH_z, 1,2,4, and

10 MH_z. In our measurement we used its capacity to measure capacitance. The range of capacitance is from .01 f farad to 1999.9 micro farad. The instrument has built in programmable Bipolar DC power supply funcitoning in biase range ±35V. The ten test signal frequencies have a frequency accuracy of 0.01%. The test signal is a sinsodial signal and can be set at desired amplitude in the range of 1mV_{rms} to 1 V_{rms} by the oscillation level control and multiplier button. The LCR multifrequency meter can be remote controlled via HP-IB remote commands from a key board and can operate as Listner and Talker. Its HP-IB adress was set to be 717. The essential HP remote command codes for the LCR meter are summarized in App(II).

2.1.2 pA Meter/DC Voltage Source

The hp Model 4140B pA Meter/DC voltage source comprises a high stabl pA (pico Amp meter) with 10^{-15} A resolution (Max) coupled with two progra DC Voltage Source (V_A and V_B). The pA meter has a basic accuracy of 0.5 over wide measurement ranges. One of the two programmable DC voltage source (V_A) can operate not only a programmable DC voltage source but as aunique stair case and accurate ramp generator. The DC votage source has an output range of ±100V in 100 mV steps or ±10V in 10 mV steps and their amprate can be set from 0.001 V/sec to 1V/sec at .001 V/S resolution Each of the DC voltage source has a current limiter to avoid damaging of the material being tested. The model can be set to measure current (I) as a universal pA meter. The measured current and capacitance displayed in Display A and applied bias in Display B.

The hp Model 4140B pA meter/DC voltage source interfaced to hp model 9000/310 computer as shown in App(I). Its HP-IB adress is 727 and can be remotelly controlled via HP-IB command from a key board and can operate as a Listner and Talker. The essential HP-IB remote commands codes for hp Model 4140B pA meter are summarized in App (III).

2.1.3 Digital Multimeter (DMMM)

The hp model 3478 A Digital Mullimeter (DMM) is able to measure voltage and current both AC and DC, and resistance. It has a display section where the measured value with the unit is displayed. It is able to make DC volt measurement five ranges 30 mV. 300 mV, 3V, 30V and 300V.

In our work DMM is used as a DC bias monitor of the sample kept in the test fixture of LCR meter. The DMM is interfaced with the hp Model 9000/310 computer as shown in App (11). Its HP-IB adress is 723. It can be remotely controlled Via HP-IB command from the key board and can operat as talker and Listner . The few esential HP-IB Remote command codes for hp-model 3478A DMM are summarized in App(IV).

3. MEASUREMENT TECHNIQUES

3.1 Software Programs

We have developed a variety of software programms for pA meter/DC voltage source for I-V and Quasi static C-V measurements using HP-IB remo command codes of App(III). And obo for LCR multifrequency meter for C-V measurement using the HP-IB command of App(II). In both cases a main software programms were developed consisting of different subprogra Each subprogramme has unique purposes such as

i) to take I-V and C-V measurements. Each respective devices unde remote control would be set for the required measurement under HP-IB commands, this time they are set as Listner. When they are triggered to start measurement from remote they act as talkers (give measured values Then measured values would be kept in the memory of the computer as one-dimensional array e.g (I(*),V(*) and C(*)).

e.g. 30 SUB Measure(N_mC(*),V(*),Low,upp,Fr,SI)

ii) To plot experimental result. The measured value stored in the computer memory would be plotted as required by the statements in the plotting subroutine.

e.g 40 SUB plot array (N,I(*),V(*),Low,upp.S$,k,Fr)

iii) To pring the data and graph. The measured values and the resulted graphs can be printed by the interfaced printer Hp model, HP-IB address 701.

e.g 50 SUB Pring (N,I(*),V(*),Low, upp,s$,k,Fr)

Although the above is the structure of the main programme for taking measurement, commands which check the accuracy of the data of hp Model 4140B pA Meter such as "serial spooling" and zero offset command for insuring zero stray capacitance are included depending on the situation. Ofcourse, subprogramms for least square fit and others are aslo incorporated. The least of the programms we developed are found in App(5).

3.2 Measurement Procedure

In this section we would try to discuss the method of collection of the data for I-V and quasistatic C-V measurement using pA meter/DC voltage source and C-V measurement with LCR multifrequency meter.

3.2.1 pA Meter/DC Voltage Source (I-V and Quasistatic C-V)

I-V and Quasistatic C-V measurement using pA meter is taken in dark. This is supplied by using hp Model 16055A Test fixture made specially for pA meter. Since there was no manufactured sample (wafer like) holder which could easily hold the wafer, we have fabricated our own holder. It is comprised of a flat copper plate for an ohmic contact on the substrate part of the wafer and short sharp conducting point of copper wire to contact to the upper part of the wafer. But no facility to control the contact pressure was included, it was done by simple touching.

i) I-V measurement

The bias supplied by single stair case generator (V_A) of pA meter to the sample is displayed on Display B and the measured current on Display A. These measured values would be stored as one dimensional array in the computer memory and further development can be done by using the software programme.

3.2.2 LCR Multifrequency Meter

We used the LCR multifrequency meter hp Model 4041A for relatively high frequency measurement, starting from 10KH$_z$. The sample placed on our fabricated sample holder is connected to hp Mode 4266 test fixture disigned specially for LCR multifrequency meter. The programmable built in Bipolar DC Voltage source is used to biase the sample. The desired test signal frequency, amplitude and biase is set from the key board via HP-IB remote commands of App(III). The measured capacitance and voltage across the sample are displayed on Display A and Display of LCR multifrequ meter and DMM respectively. The measured values are stored in the comput memory as one dimensional array of cacitance (C(*) and votage (V(*)), which can be developed for plotting and printing using the softwarec progra developed using HP-IB remote commands of LCR multifrequency meter of App(II).

CHAPTER IV

EXPERIMENTAL RESULTS AND DISCUSSION

On this chapter we present the experimental result for different samples. The I-V curves with associated LOG(I)-V curves for forward current for the measurement of barrier height is presented, while only for two samples the C-V and $1/c^2$-V curve is presented, because out hp model 4275A LCR multifrequency meter shows COF (capacitance over flows) signe in the rest samples.

In the second part discussion in reference to the result with comparis between sampies in resistively, area of top ohmic contact, and obtained resı are discussed.

1. EXPERIMENTAL RESULT FOR I-V MEASUREMENT

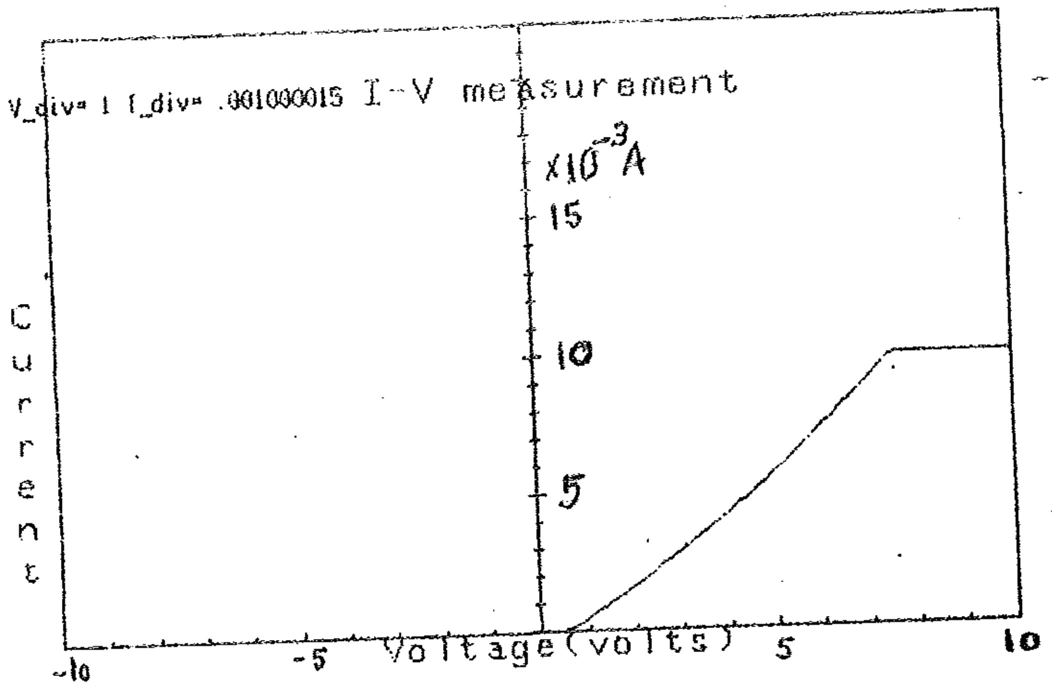
The measurement represented are description of samples I-V plot fror -10V to 10V and Log(I)-V plot of forward current from .05 to 10V. The intercepts on log(I) axis were from least square fit method for the evaluation of saturation current and barrier height. At the end of this seciton the I-V data and least square for selected region are attached.

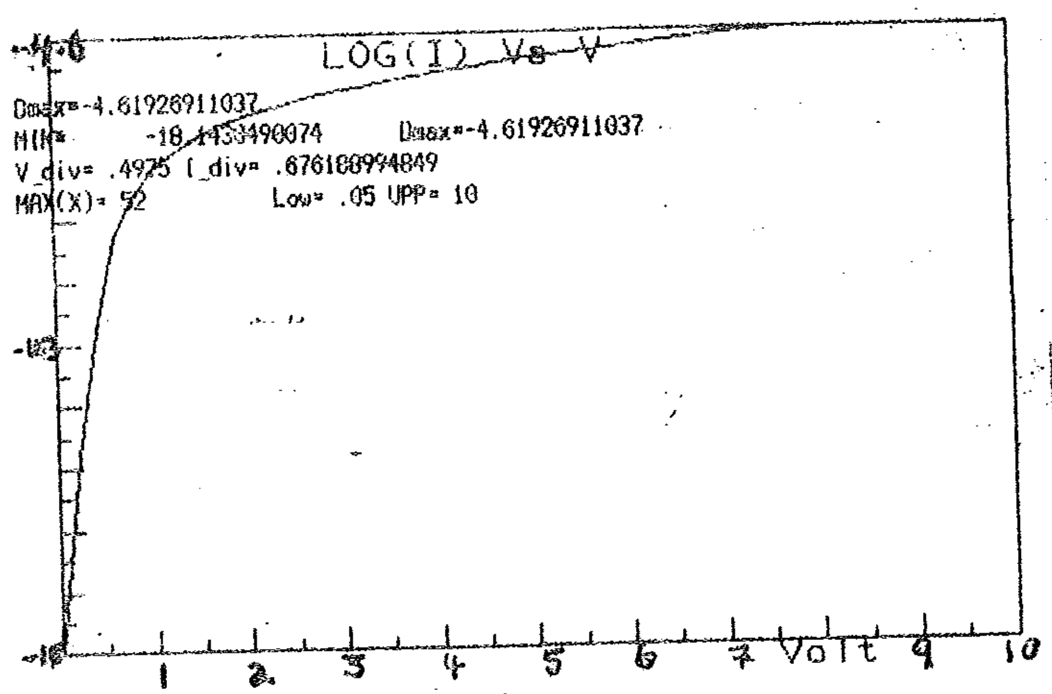
SAMPLE No. 1

I-V Characteristic

Top View  Contact pt = G - 2 Orientation = <111>

Resistivity = 7-13 ohm-im Type = Al-pSi





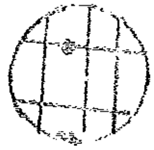
Log(I)-intercept = -6.21

ϕ_{hB}(holbarrier ht) = 0.49 eV

SAMPLE No. 2

I-V characteristic

Top View

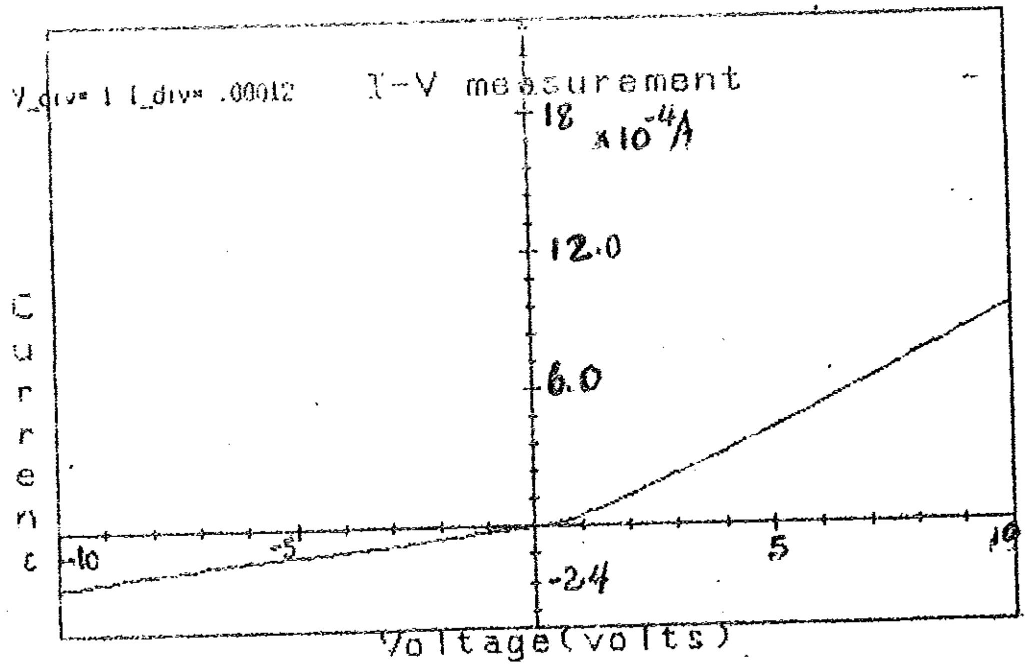


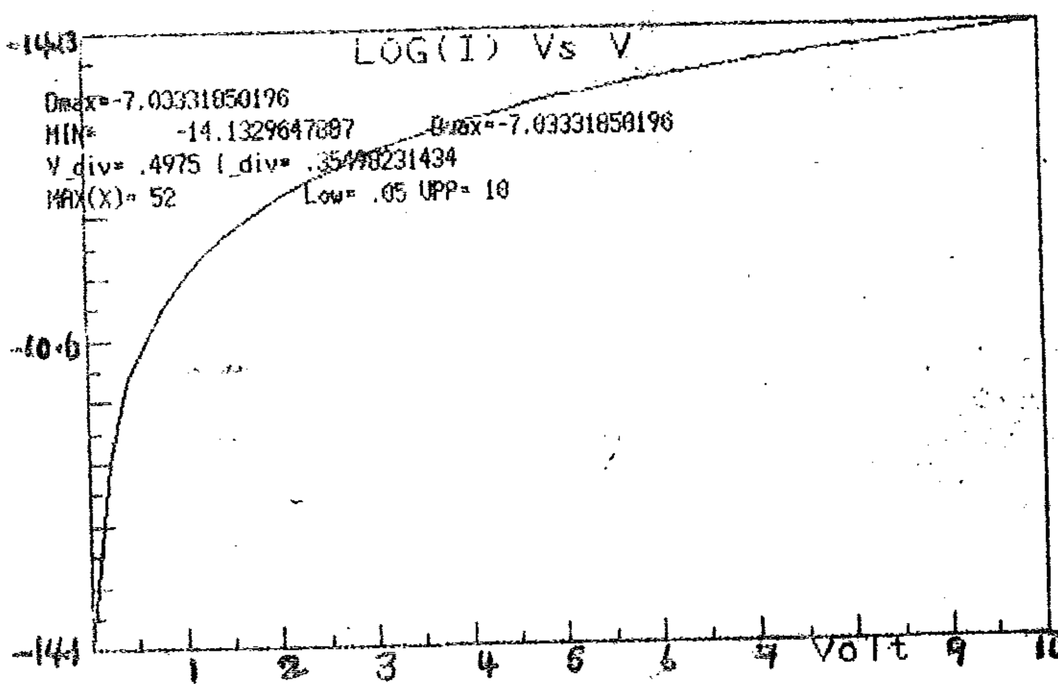
Contact pt = G-2

Resistivity = 16-24 ohm cm

Orientation = <100>

Type = Al-pSi

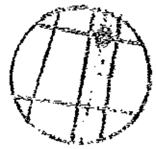




Log(I)-Intercept = -9.17

ϕ_{hB} (holebarrier ht) = 0.5beV

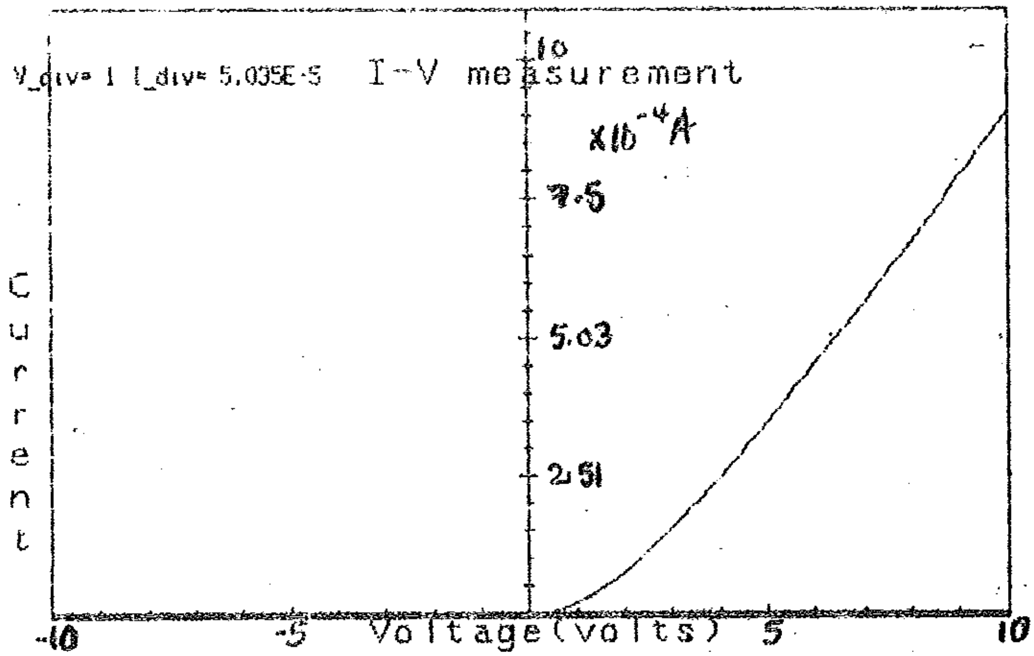
SAMPLE No. 3

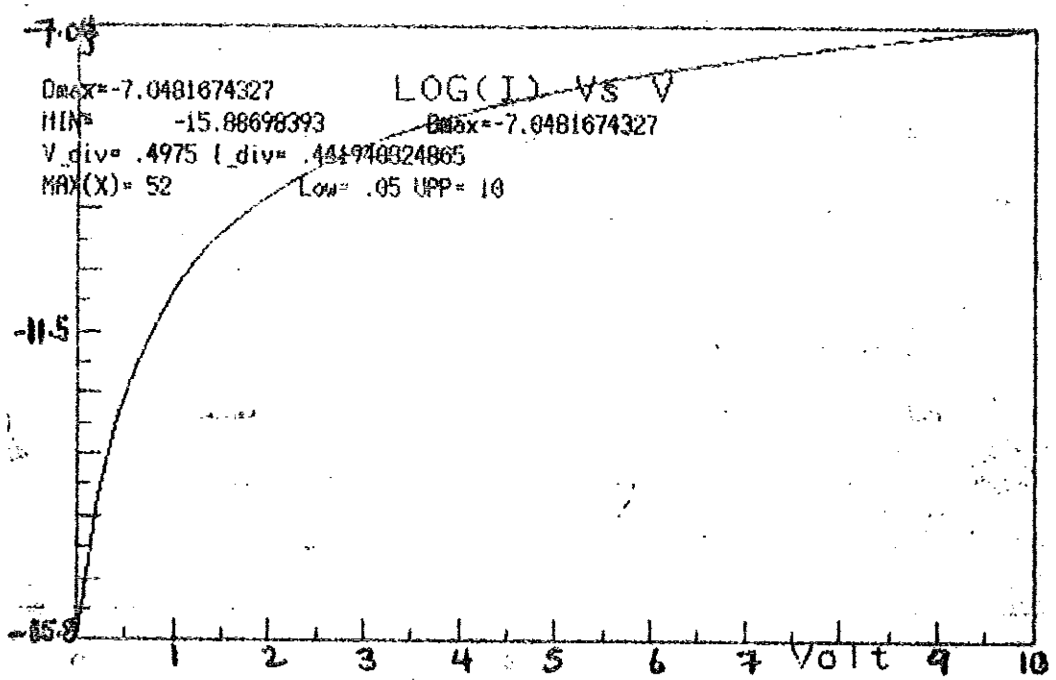
Top View  Contact pt = G-2

Resistivity = 100 ohm cm

Orientation = <100>

Type = Al-PSi





Log(I) Intercept = -9.13

ϕ_{hB}(hole barrier ht) = 0.56eV

SAMPLE No. 4

I-V Characteristic

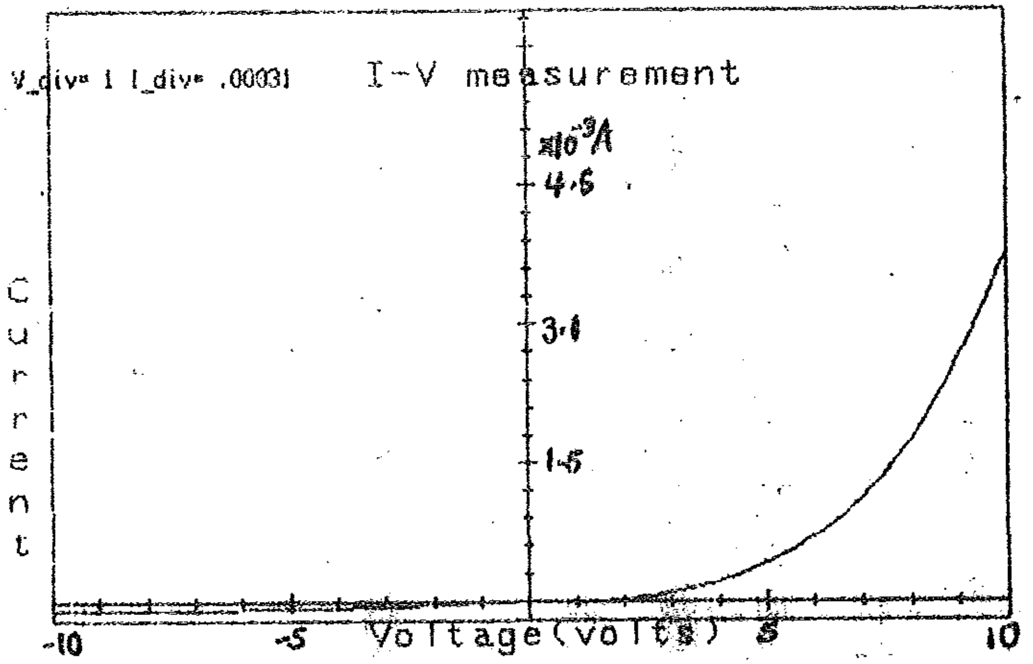
Top View 

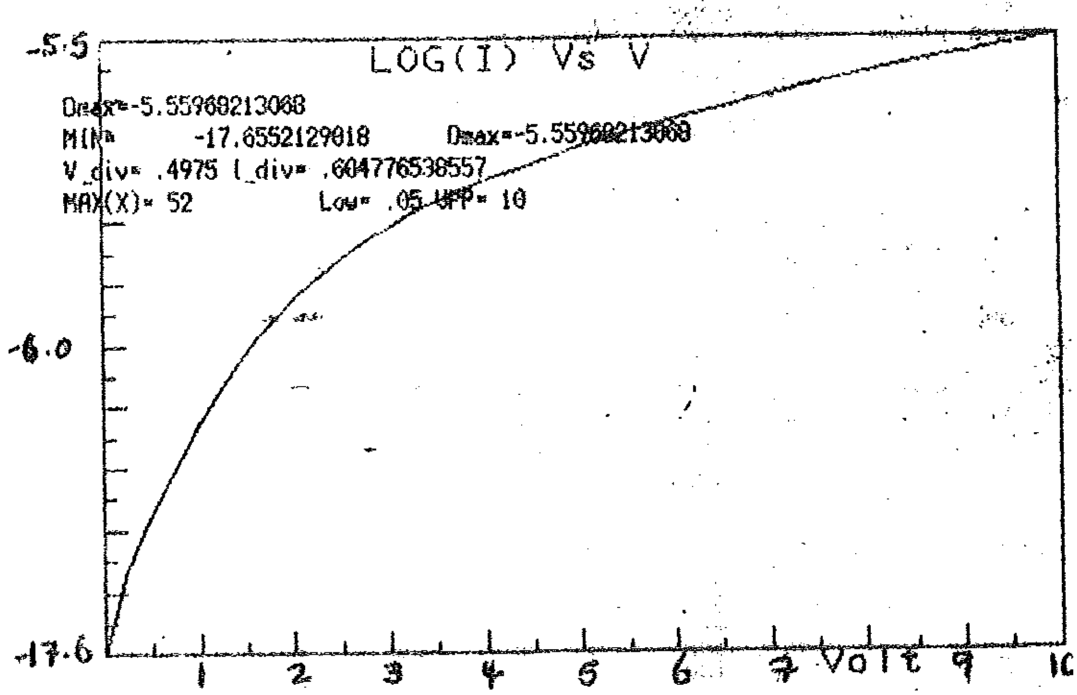
Contact pt = 2C

Orierntation = <111

Resistivity = 7-13 ohm-cm

Type = Al-pSi





Log(I)-intercept = -10.40

ϕ_{hB}(hole barrier ht) = 0.59 e'

SAMPLE No. 5

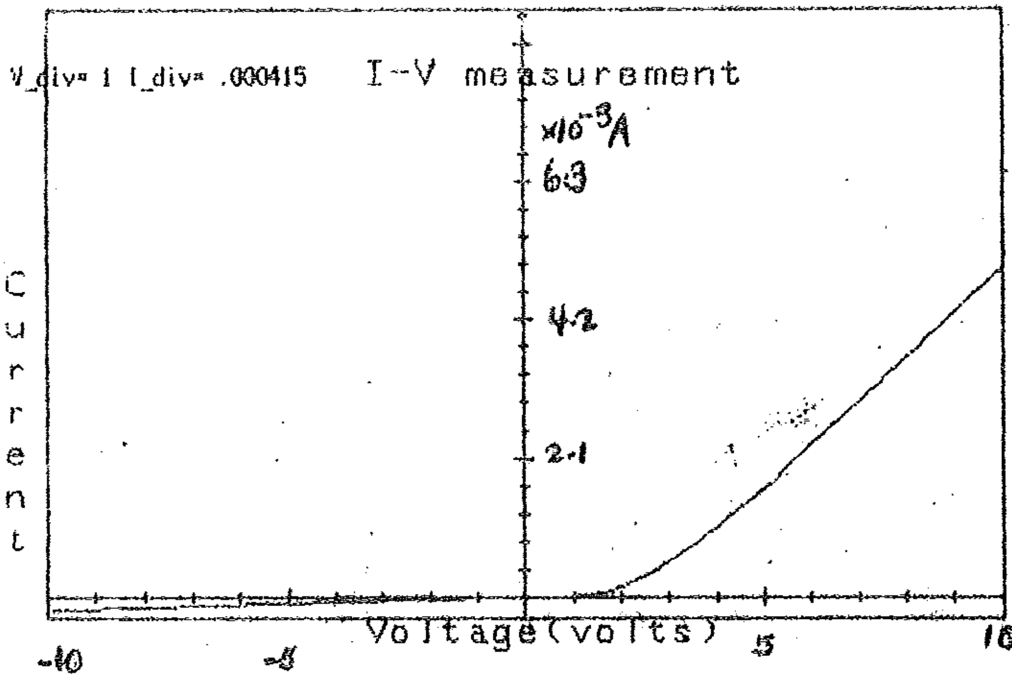
I-V Characteristic

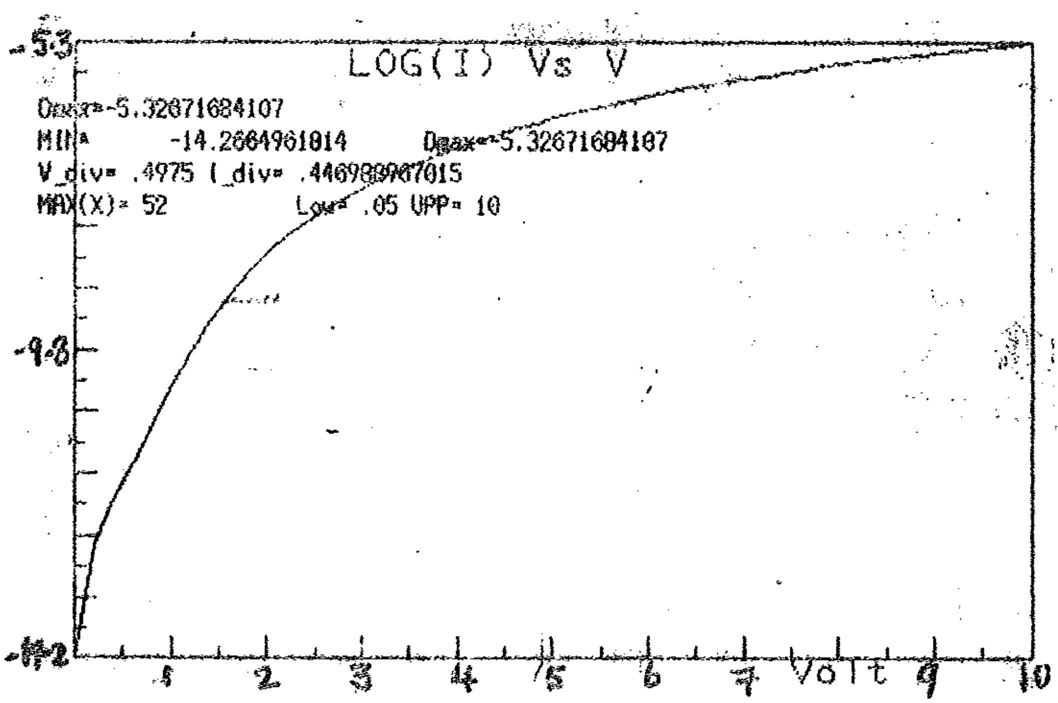
Top View  Contact pt = 1A

Orientation = <111>

Resistivity = 7-13 ohm-cm

Type = Al-pSi





Log(I)-Intercept = -7.67

ϕ_{hB}(hole barrier) = 0.52eV

SAMPLE No. 6

I-V Characteristic

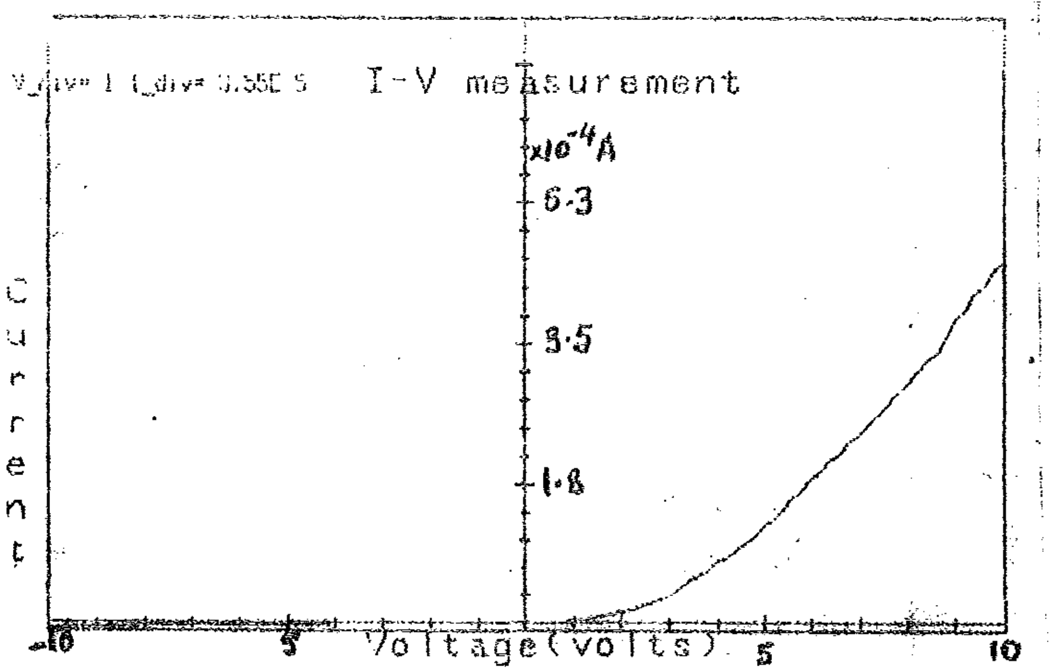
Top View 

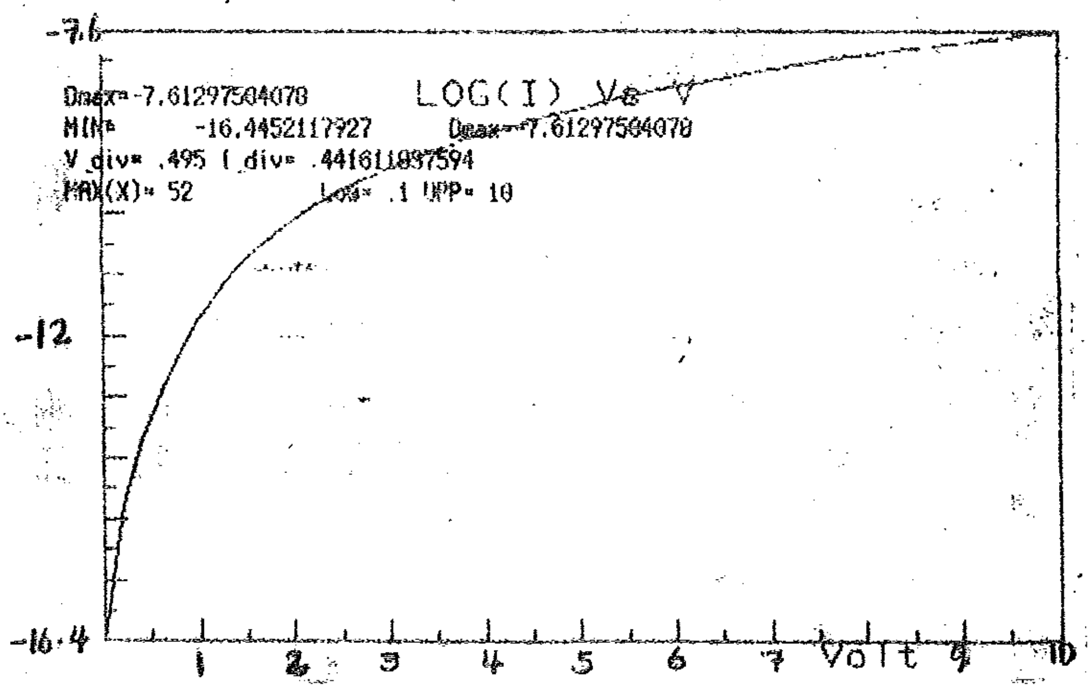
Contact pt = 1A

Resistivity = 100 ohm-cm

Orientation = <100>

Type = Al-pSi





Log(I)-Intercept = -9.73

ϕ_{hB}(hole barrier) = 0.57eV

1.0

Sample 1 Lou Upp-10 10 Volts 2 Jun 1989 12:27:28 Phys Dept AAU

VOLTAGE/Volt CURRENT/Amps

-10	-2.E-7	-9.8	-1.94E-7	-9.6	-1.89E-7	-9.4	-1.84E-7	-9.2	-1.79E-7	-9	-1.74E-7	-8.8	-1.7E-7	-8.6	-1.65E-7
-8.4	-1.6E-7	-8.2	-1.56E-7	-8	-1.51E-7	-7.8	-1.47E-7	-7.6	-1.43E-7	-7.4	-1.39E-7	-7.2	-1.34E-7	-7	-1.3E-7
-6.8	-1.26E-7	-6.6	-1.22E-7	-6.4	-1.18E-7	-6.2	-1.14E-7	-6	-1.1E-7	-5.8	-1.06E-7	-5.6	-1.02E-7	-5.4	-9.8[illegible]E-8
-5.2	-9.47E-8	-5	-9.98E-8	-4.8	-8.72E-8	-4.6	-8.38E-8	-4.4	-7.98E-8	-4.2	-7.64E-8	-4	-7.29E-8	-3.8	-6.[illegible]E-8
-3.6	-6.62E-8	-3.4	-6.28E-8	-3.2	-5.92E-8	-3	-5.6E-8	-2.8	-5.25E-8	-2.6	-4.93E-8	-2.4	-4.61E-8	-2.2	-4.26E-8
-2	-3.92E-8	-1.8	-3.62E-8	-1.6	-3.3E-8	-1.4	-2.99E-8	-1.2	-2.68E-8	-1	-2.38E-8	-.8	-2.07E-8	-.6	-1.76E-8
-.4	-1.43E-8	-.2	-1.04E-8	0	7.14E-11	.2	4.36E-7	.4	8.73E-6	.6	8.61E-5	.8	.000248	1	.00[illegible]
1.2	.000582	1.4	.000913	1.6	.00115	1.8	.00138	2	.00162	2.2	.00186	2.4	.00211	2.6	.00[illegible]36
2.8	.00261	3	.00287	3.2	.00313	3.4	.0034	3.6	.00367	3.8	.00394	4	.00422	4.2	.00[illegible]51
4.4	.0048	4.6	.00509	4.8	.00539	5	.00569	5.2	.00601	5.4	.00632	5.6	.00664	5.8	.00696
6	.00729	6.2	.00761	6.4	.00795	6.6	.00828	6.8	.00862	7	.009[illegible]	7.2	.00931	7.4	.0[illegible]966
7.6	.00986	7.8	.00986	8	.00986	8.2	.00986	8.4	.00986	8.6	.00986	8.8	.00986	9	.00[illegible]86
9.2	.00986	9.4	.00986	9.6	.00986	9.8	.00986	10	.00986	0	0				

SAMPLE No 1

2 (2)

'ample 3 Low,Upp-10 10 Volts ^ Jun 1989 99:35:52 Phys Dept AAU

OLTAGE/Volt CURRENT/Amps

-10	-.000245	-9.8	-.000238	-9.6	-.000231	-9.4	-.000225	-9.2	-.000219	-9	-.000213	-8.8	-.000209	-8.6	-.000203
-8.4	-.000198	-8.2	-.000192	-8	-.000186	-7.8	-.000181	-7.6	-.000177	-7.4	-.000171	-7.2	-.000167	-7	-.000 51
-6.8	-.000157	-6.6	-.000152	-6.4	-.000147	-6.2	-.000143	-6	-.000138	-5.8	-.000134	-5.6	-.000129	-5.4	-.000125
-5.2	-.00012	-5	-.000116	-4.8	-.000112	-4.6	-.000108	-4.4	-.000104	-4.2	-9.92E-5	-4	-9.46E-5	-3.8	-9.02E-5
-3.6	-8.58E-5	-3.4	-8.12E-5	-3.2	-7.66E-5	-3	-7.1E-5	-2.8	-6.64E-5	-2.6	-6.18E-5	-2.4	-5.7E-5	-2.2	-5.22E-5
-2	-4.72E-5	-1.8	-4.26E-5	-1.6	-3.77E-5	-1.4	-3.28E-5	-1.2	-2.76E-5	-1	-2.25E-5	-.8	-1.74E-5	-.6	-1.25E-5
-.4	-7.8E-6	-.2	-3.47E-6	0	3.83E-8	2	4.6E-6	.4	1.36E-5	.6	2.33E-5	.8	3.53E-5	1	4.9E-5
1.2	6.4E-5	1.4	8.E-5	1.6	9.66E-5	1.8	.000114	2	.000132	2.2	.00015	2.4	.000168	2.6	.000186
2.8	.000204	3	.000223	3.2	.000242	3.4	.000262	3.6	.000281	3.8	.0003	4	.00032	4.2	.000[illegible]4
4.4	.00036	4.6	.000381	4.8	.0004	5	.000421	5.2	.000441	5.4	.000461	5.6	.000482	5.8	.000[illegible]03
6	.000524	6.2	.000545	6.4	.000567	6.6	.000588	6.8	.000608	7	.000629	7.2	.00065	7.4	.000[illegible]7
7.6	.00069	7.8	.000713	8	.000735	8.2	.000755	8.4	.000777	8.6	.000797	8.8	.000818	9	.000[illegible]38
9.2	.000855	9.4	.000881	9.6	.000901	9.8	.000921	10	.000942	0	0				

SAMPLE No 2

3

mple 1 Leu Ugg-10 10 Volts

2 Jun 1999 08:56:29 Phys Dept AAU

LTAGE/Volt	CURRENT/Amps						
-10	-4.65E-6	-9.8	-4.61E-6	-9.6	-4 57E-6	-9.4	-4.54E-6
-8.4	-4.41E-6	-8.2	-4.38E-6	-8	-4.35E-6	-7.8	-4.33E-6
-6.8	-4.18E-6	-6.6	-4.15E-6	-6.4	-4.11E-6	-6.2	-4.08E-6
-5.2	-3.9E-6	-5	-3.85E-6	-4.8	-3.82E-6	-4.6	-3 77E-6
-3.6	-3.52E-6	-3.4	-3.46E-6	-3.2	-3.4E-6	-3	-3.33E-6
-2	-2 9E-6	-1.8	-2 63E-6	-1.6	-2 43E-6	-1.4	-2.2E-6
-.4	-7 43E-7	-.2	-4.02E-7	0	1.24E-9	2	7.97E-7
1.2	2.8E-5	1.4	3.84E-5	1.6	4.97E-5	1.8	6 21E-5
2.8	.000139	3	.000156	3.2	.000174	3.4	.000192
4.4	.000288	4.6	.000309	4.8	.000329	5	.000349
6	.000455	6.2	000477	6.4	.000499	6.6	.000521
7.6	.000632	7.8	.000654	8	.000677	8 2	.000701
9.2	.000816	9.4	.00084	9.6	.000863	9.8	.000888

-9.2	-4.51E-6	-9	-4.49E-6	-8.8	-4.46E-6	-8.6	-4.43[illegible]-6
-7.6	-4.3E-6	-7.4	-4.27E-6	-7.2	-4 24E-6	-7	-4 21[illegible]-6
-6	-4.04E-6	-5.8	-4.01E-6	-5.6	-3.97E-6	-5.4	-3.9[illegible]-6
-4.4	-3.72E-6	-4.2	-3.68E-6	-4	-3.62E-6	-3.8	-3.5[illegible]-6
-2.8	-3.25E-6	-2.6	-3.16E-6	-2.4	-3.06E-6	-2.2	-2.9[illegible]-6
-1.2	-1.94E-6	-1	-1.66E-6	-.8	-1.37E-6	-.6	-1.06[illegible]-6
.4	2.8E-6	.6	6.33E-6	.8	1.10E-5	1	1.9[illegible]-5
2	7.55E-5	2.2	8.98E-5	2.4	.000105	2.6	.000[illegible]21
3.6	.00021	3.8	.000229	4	.000248	4.2	.000[illegible]68
5.2	.00037	5 4	.000391	5.6	.000412	5.8	.00043[illegible]
6.8	.000542	7	.000564	7.2	.000587	7.4	.000[illegible]09
8 4	.000724	8.6	.000746	8.8	.000771	9	.000[illegible]94
10	.000911	0	0				

SAMPLE No 3

Sample:1 Low,Upp-10 10 Volts 2 Jun 1989 12:07:15 Phys Dept AAU

VOLTAGE/Volt CURRENT/Amps

-10	-.000193	-9.8	-.00019	-9.6	-.000188	-9.4	-.000185	-9.2	-.000183	-9	-.00018	-8.8	-.00017[illegible]	-8.6	-.[illegible]017[illegible]
-8.4	-.000169	-8.2	-.000165	-8	-.000162	-7.8	-.000157	-7.6	-.000155	-7.4	-.00015	-7.2	-.000[illegible]	-7	-.[illegible]014[illegible]
-6.8	-.000136	-6.6	-.000132	-6.4	-.000128	-6.2	-.000123	-6	-.000117	-5.8	-.000113	-5.6	-.000[illegible]	-5.4	-.[illegible]010[illegible]
-5.2	-9.85E-5	-5	-9.36E-5	-4.8	-8.86E-5	-4.6	-8.42E-5	-4.4	-7.97E-5	-4.2	-7.54E-5	-4	-7.11E-5	-3.8	-6.[illegible]7E-[illegible]
-3.6	-6.23E-5	-3.4	-5.83E-5	-3.2	-5.42E-5	-3	-5.01E-5	-2.8	-4.61E-5	-2.6	-4.22E-5	-2.4	-3.84E-5	-2.2	-3.[illegible]9E-[illegible]
-2	-3.13E-5	-1.8	-2.77E-5	-1.6	-2.43E-5	-1.4	-2.09E-5	-1.2	-1.75E-5	-1	-1.42E-5	-.8	-1.08E-5	-.6	-7.[illegible]8E-[illegible]
-.4	-4.34E-6	-.2	-1.71E-6	0	2.32E-9	.2	1.21E-6	.4	2.8E-6	.6	4.62E-6	.8	[illegible]03E-6	1	1.4E-[illegible]
1.2	1.97E-5	1.4	3.62E-5	1.6	6.28E-5	1.8	.0001	2	.000151	2.2	.000219	2.4	.000287	2.6	.[illegible]035[illegible]
2.8	.000443	3	.000532	3.2	.000627	3.4	.000727	3.6	.000831	3.8	.000936	4	.00105	4.2	.[illegible]117[illegible]
4.4	.00129	4.6	.0014	4.8	.00152	5	.00163	5.2	.00176	5.4	.00189	5.6	.00202	5.8	.[illegible]215[illegible]
6	.00228	6.2	.00241	6.4	.00253	6.6	.00266	6.8	.00279	7	.00292	7.2	.00306	7.4	.[illegible]319[illegible]
7.6	.00333	7.8	.00347	8	.0036	8.2	.00373	8.4	.00386	8.6	.00401	8.8	.00413	9	.[illegible]426[illegible]
9.2	.0044	9.4	.00453	9.6	.00467	9.8	.00481	10	.00493	0	0				

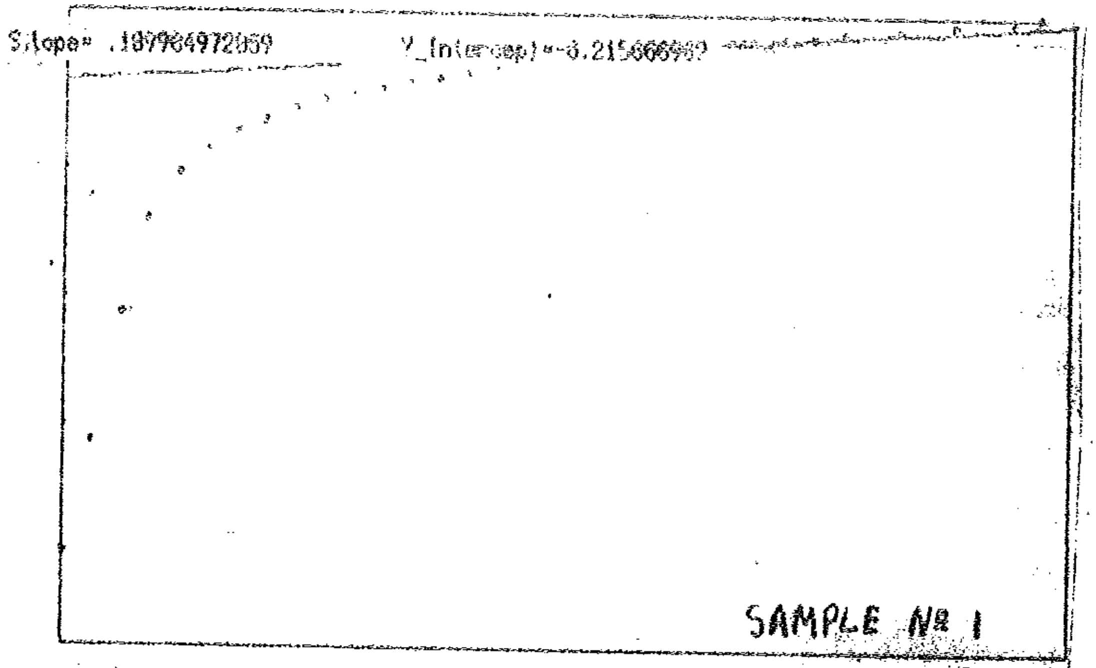
SAMPLE № 4

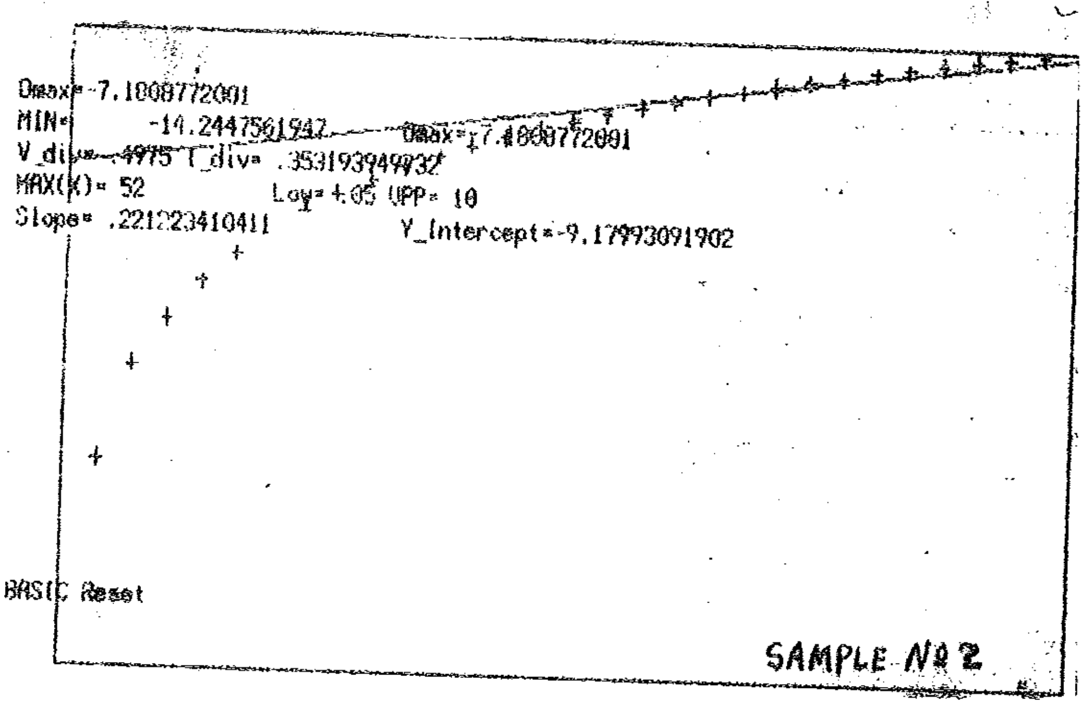
Sample:1 Low Vpp-10 10 Volts 2 Jun 1989 11:51:40 Phys Dept ARU

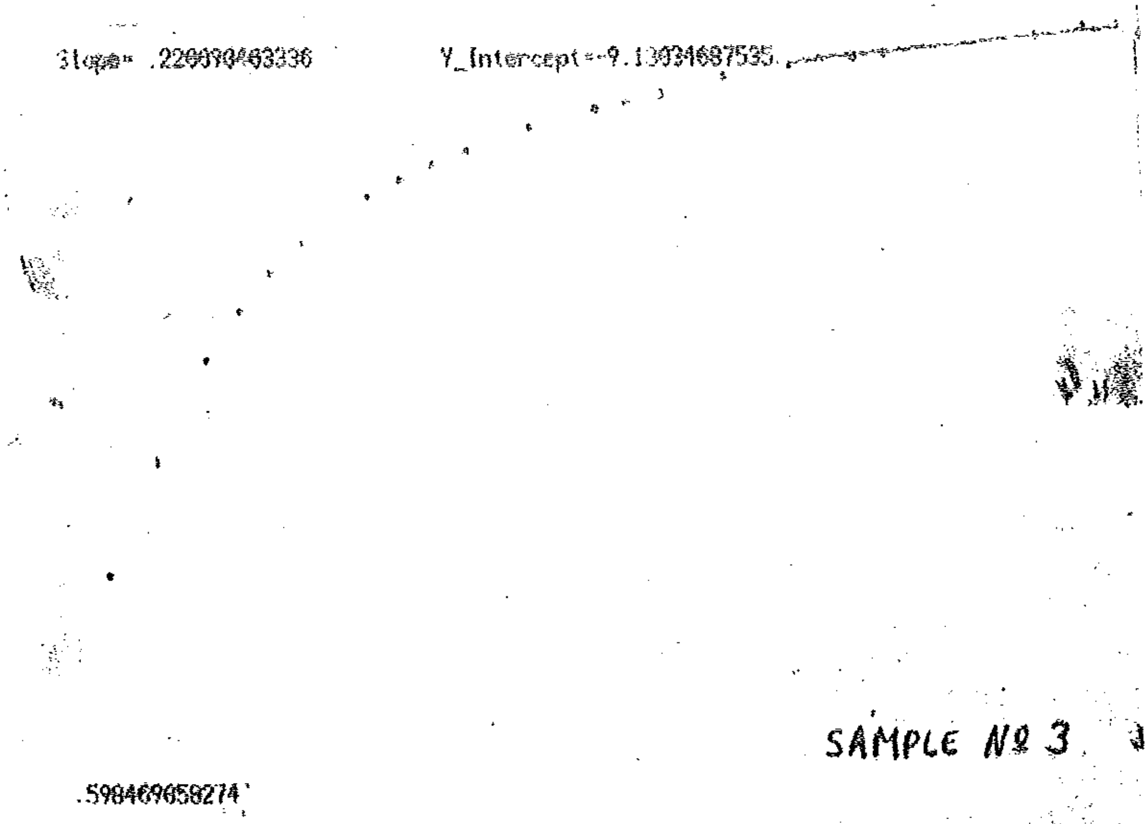
VOLTAGE/Volt CURRENT/Amps

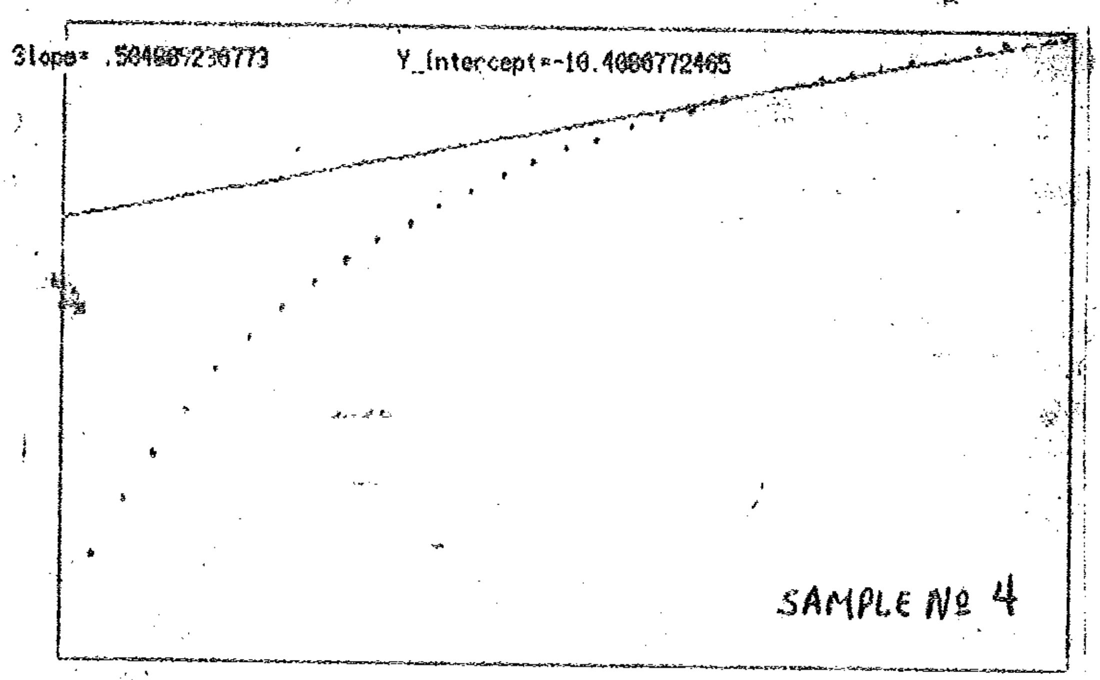
-10	-.000106	-9.8	-.000106	-9.6	-.000105	-9.4	-.000105	-9.2	-.000104	-9	-.000103	-8.8	-.000102	-8.6	-.000[illegible]
-8.4	-9.97E-5	-8.2	-9.88E-5	-8	-9.74E-5	-7.8	-9.58E-5	-7.6	-9.48E-5	-7.4	-9.32E-5	-7.2	-9.16E-5	-7	-9.01[illegible]-5
-6.8	-8.85E-5	-6.6	-8.69E-5	-6.4	-8.53E-5	-6.2	-8.36E-5	-6	-8.19E-5	-5.8	-8.E-5	-5.6	-7.82E-5	-5.4	-7.64[illegible]-5
-5.2	-7.45E-5	-5	-7.27E-5	-4.8	-7.06E-5	-4.6	-6.85E-5	-4.4	-6.64E-5	-4.2	-6.42E-5	-4	-6.2E-5	-3.8	-5.95[illegible]-5
-3.6	-5.7E-5	-3.4	-5.44E-5	-3.2	-5.17E-5	-3	-4.88E-5	-2.8	-4.58E-5	-2.6	-4.24E-5	-2.4	-3.89E-5	-2.2	-3.5E-[illegible]
-2	-3.08E-5	-1.8	-2.63E-5	-1.6	-2.15E-5	-1.4	-1.65E-5	-1.2	-1.15E-5	-1	-7.33E-6	-.8	-4.29E-6	-.6	-2.22[illegible]-6
-.4	-8.33E-7	-.2	-1.82E-7	0	1.02E-10	.2	4.E-8	.4	1.14E-7	.6	2.75E-7	.8	6.37E-7	1	1.31[illegible]-6
1.2	2.57E-6	1.4	4.55E-6	1.6	7.99E-6	1.8	1.3E-5	2	1.95E-5	2.2	2.75E-5	2.4	3.62E-5	2.6	5.1[illegible]-5
2.8	6.7E-5	3	8.54E-5	3.2	.000108	3.4	.000132	3.6	.000159	3.8	.000189	4	.000222	4.2	.000[illegible]50
4.4	.000296	4.6	.000334	4.8	.000377	5	.000423	5.2	.00047	5.4	.000523	5.6	.00058	5.8	.000[illegible]55
6	.000715	6.2	.000773	6.4	.000854	6.6	.000943	6.8	.00104	7	.00114	7.2	.00126	7.4	.00139
7.6	.00152	7.8	.00168	8	.00179	8.2	.00196	8.4	.00215	8.6	.00234	8.8	.00252	9	.002[illegible]5
9.2	.00295	9.4	.00318	9.6	.00341	9.8	.00365	10	.00392	0	0				

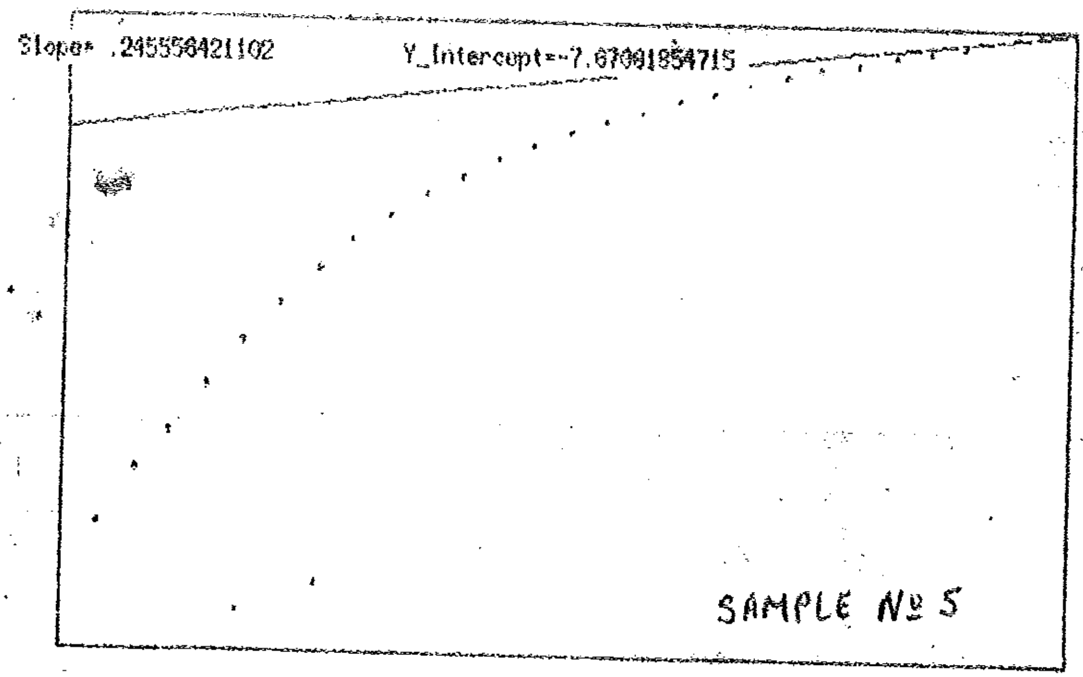
SAMPLE 5

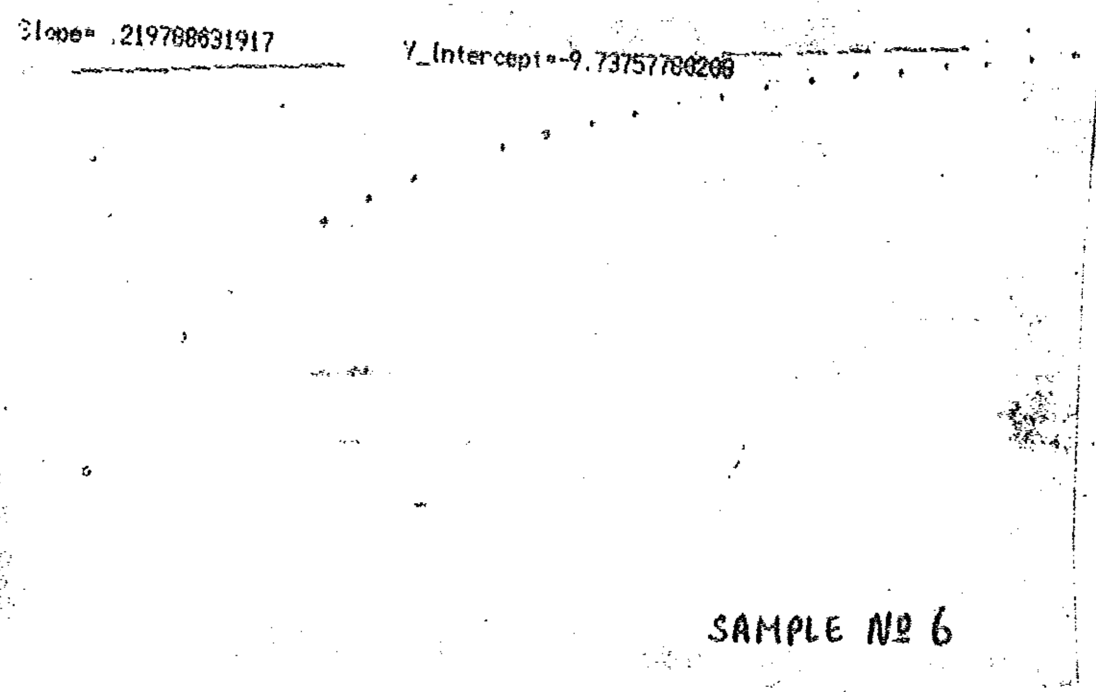

Slope= .187984972059
SAMPLE № 1


Omax= -7.1008772001
MIN= -14.2447561942
Omax= 7.4008772091
MAX(K)= 52
UPP= 10
Slope= .221223410411
Y_Intercept= -9.17993091902
BASIC Reset
SAMPLE № 2


Slope= .220090463336
Y_Intercept=-9.13034687535
SAMPLE No 3
.598469058274


Slope= .584887230773
Y_Intercept=-10.4086772465
SAMPLE No 4


Slope= .245556421102
Y_Intercept=-7.67091854715
SAMPLE № 5


Slope= .219788631917
Y_Intercept=-9.73757780208
SAMPLE № 6

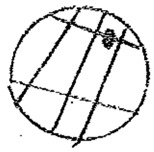
2. EXPERIMENTAL RESULT OF C-V MEASUREMENT

Experimental result of C-V measurement are presented only for Sample No. 1 and No. 3, because the capacitance of our samples as mentioned earlier were beyond the capacity of our hp model 4572A LCR multi frequency meter. In this section we presented the experimentla result of C-V and $1/C^2$-V curves of the above samples for different frequencies of super-imposed signal in the biase range -10 to 10V. Also a single $\frac{1}{C^2}$ -V curve is presented for different frequencies in the biase range -1.5 to .5 for the evaluation of barrier height and active doping concentration. A least square fit method was used for the evaluation of ϕ_{hB}(hole barrier ht) and N_B 8active doping concentration). With the experimental result (curves) specification of the sample as previously done, voltage axis intercept and slope of $1/C^2$-V are given.

SAMPLE No. 3

C- V Characteristic

Top View

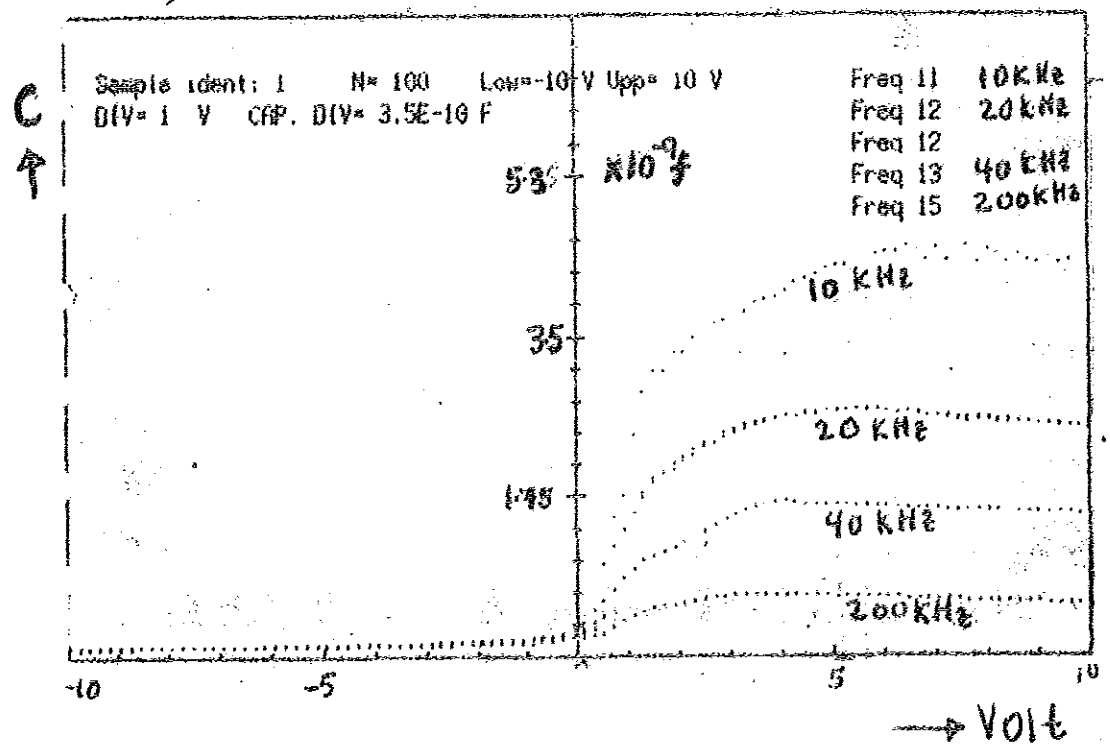


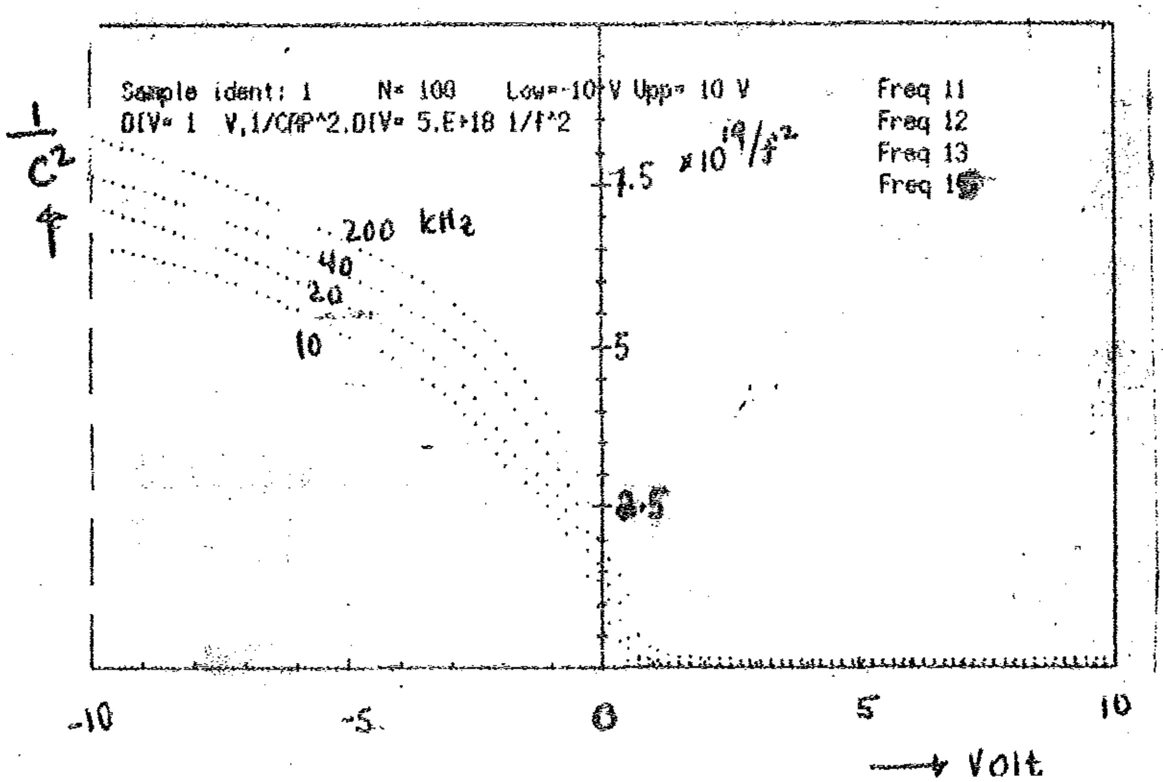
Contact pt = G-2

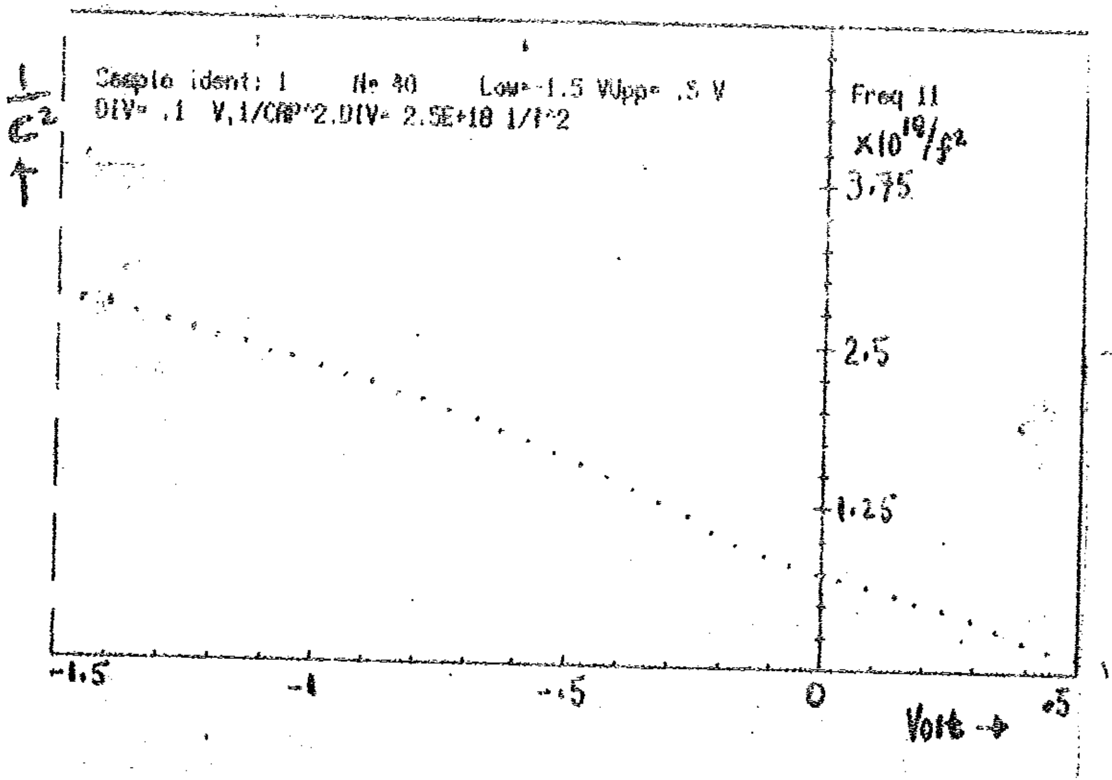
Orientation = <100>

Resistivity = 100 ohm-cm

Type = Al-pSi





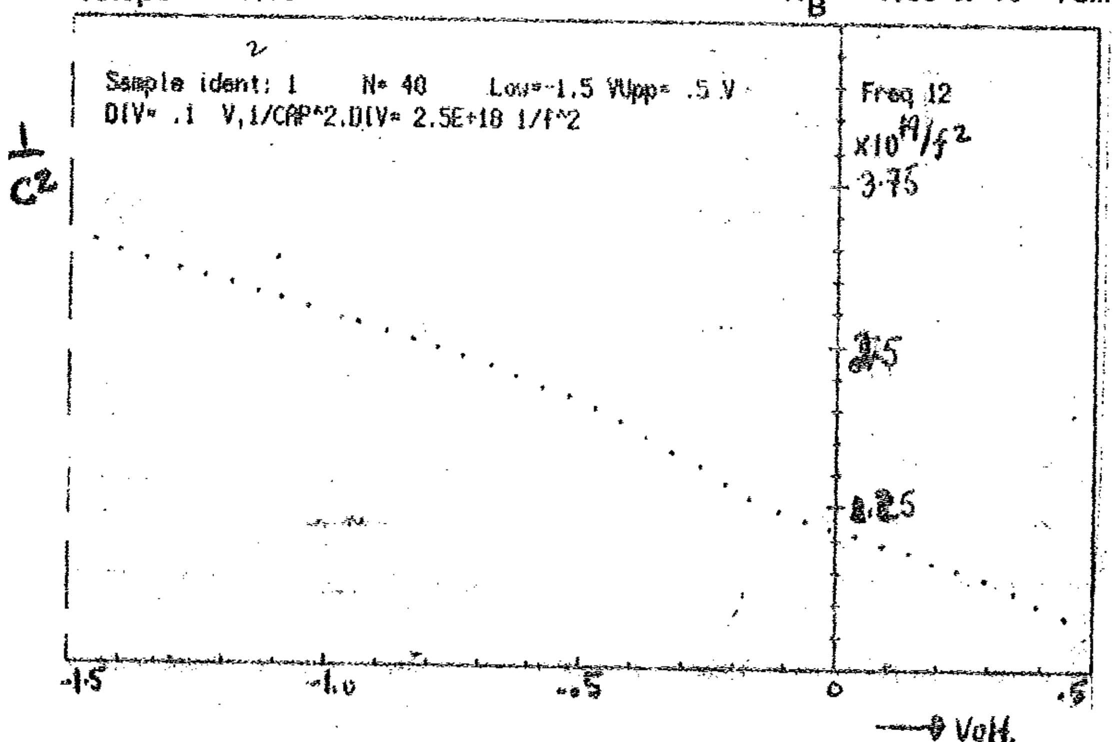


V_{int} = 0.35V

ϕ_{Bh} = 0.65 eV

.slope = -1.89

N_B = 1.55 x 10^{13}/cm³

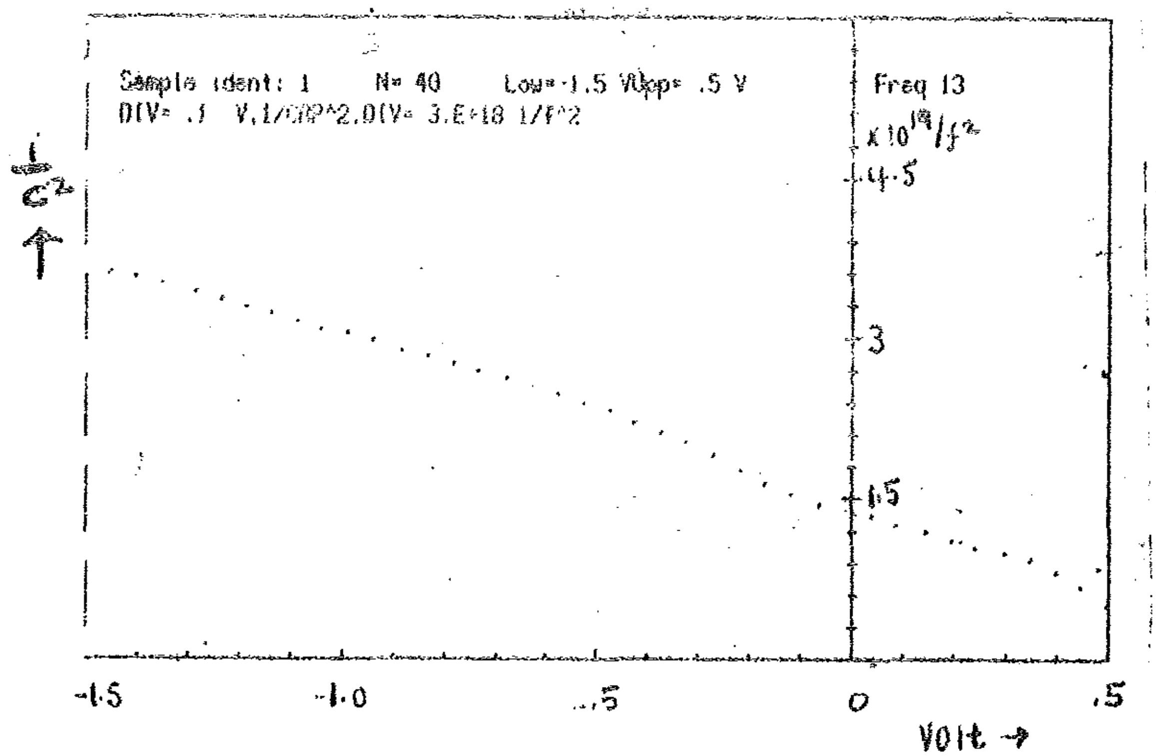


V_{int} = .32

ϕ_{Bh} = .62 eV

slope = -2.13

N_B = 4.13 x 10^{12}/cm³



V_{int} = .29

Slope = -6.16

ϕ_{Bh} = 0.60 eV

N_B = 4.77 $\times 10^{12}$/cm³

SAMPLE No. 6

C-V Characteristic

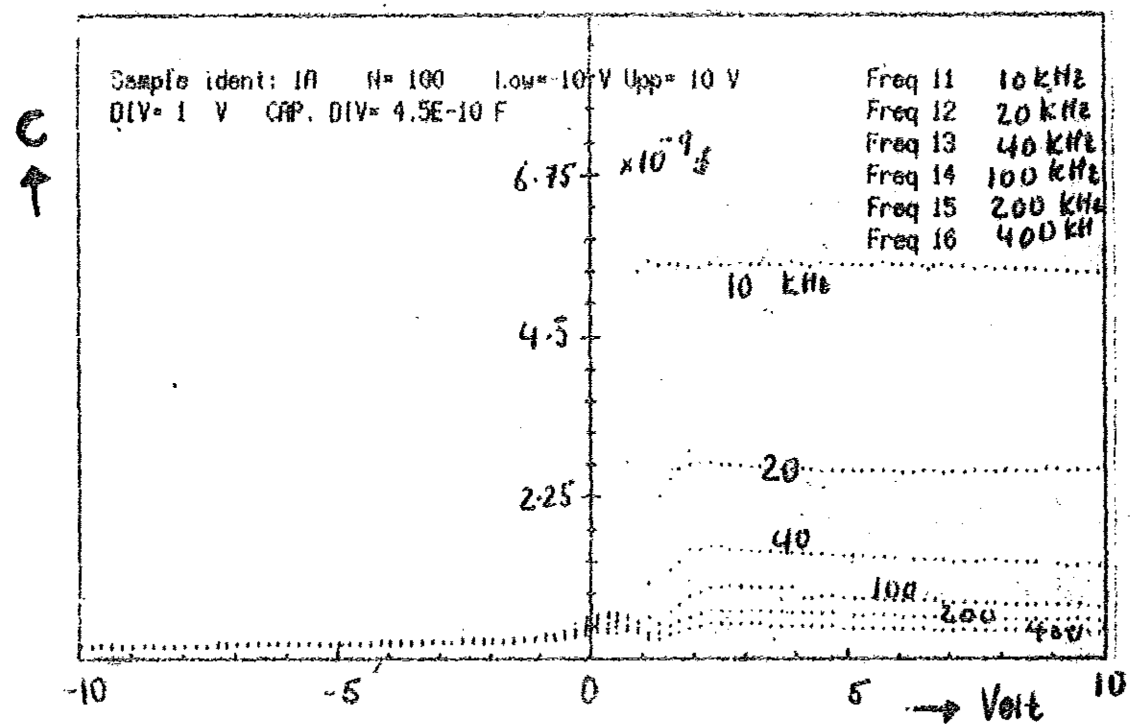
Top View

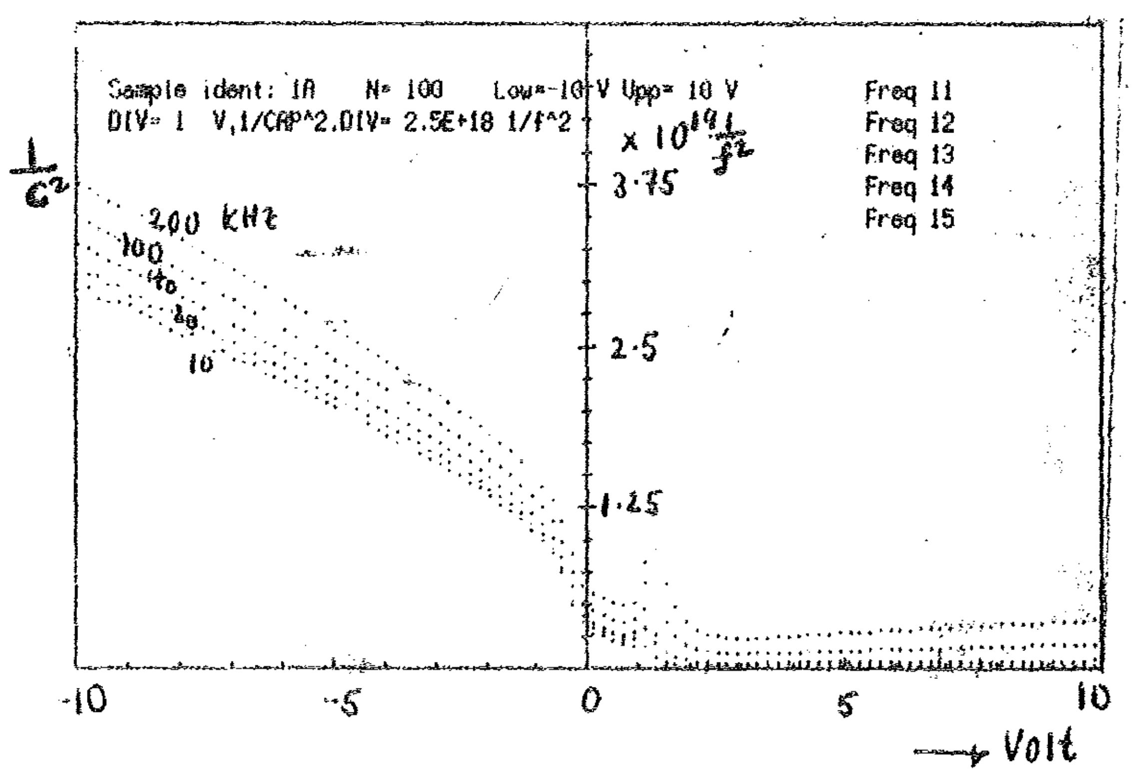
Contact pt = 1A

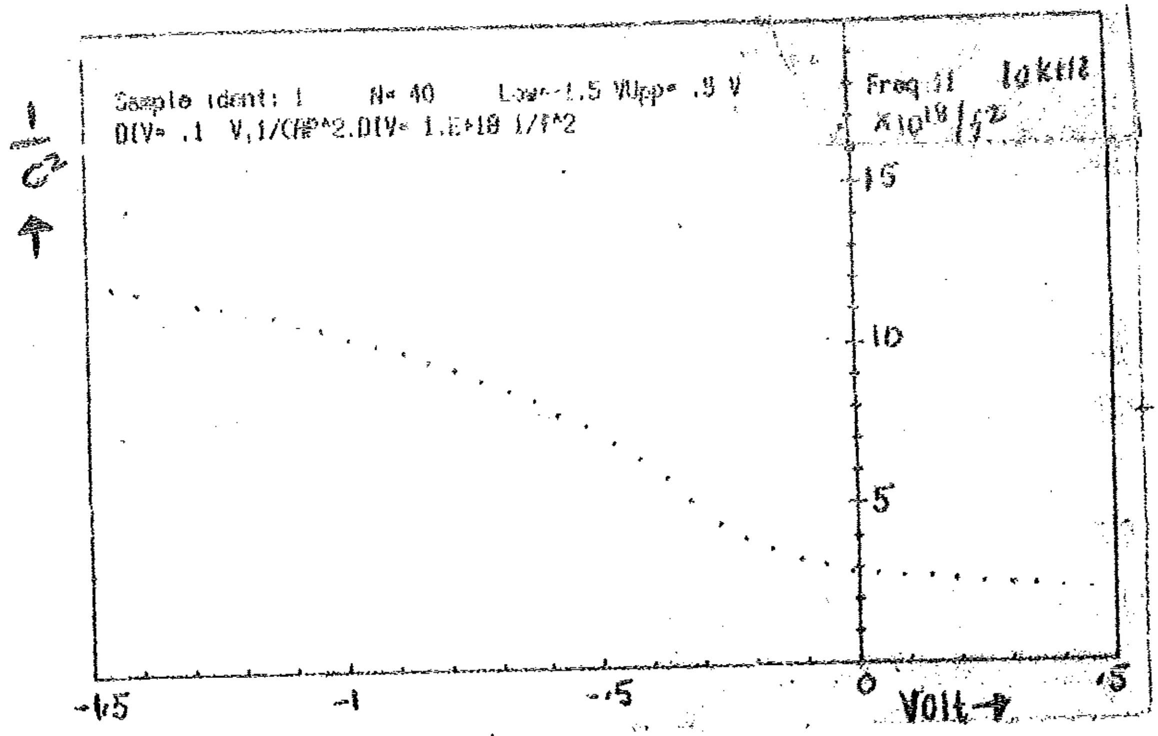
Orientation = <100>

Resistivity = 100 ohm-cm

Type = Al-pSi





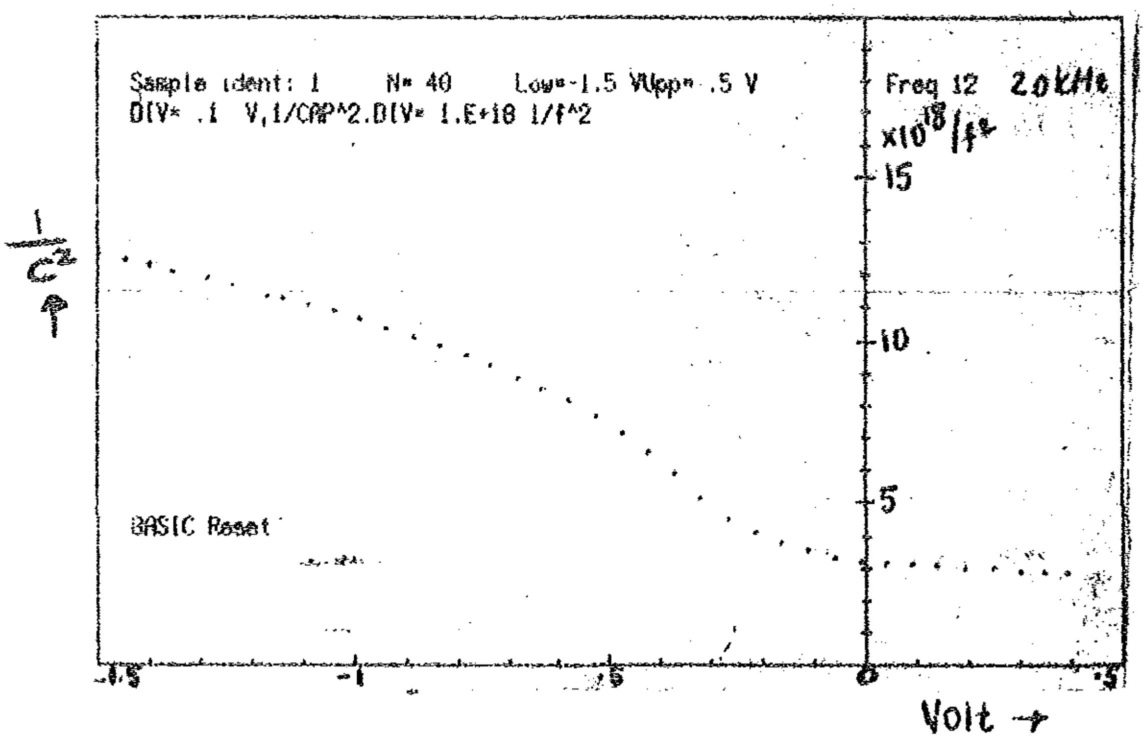


V_{int} = .25

Slppe = -9.24

ϕ_{Bh} = 0.56 eV

N_B = 3.18 x 10^{13}

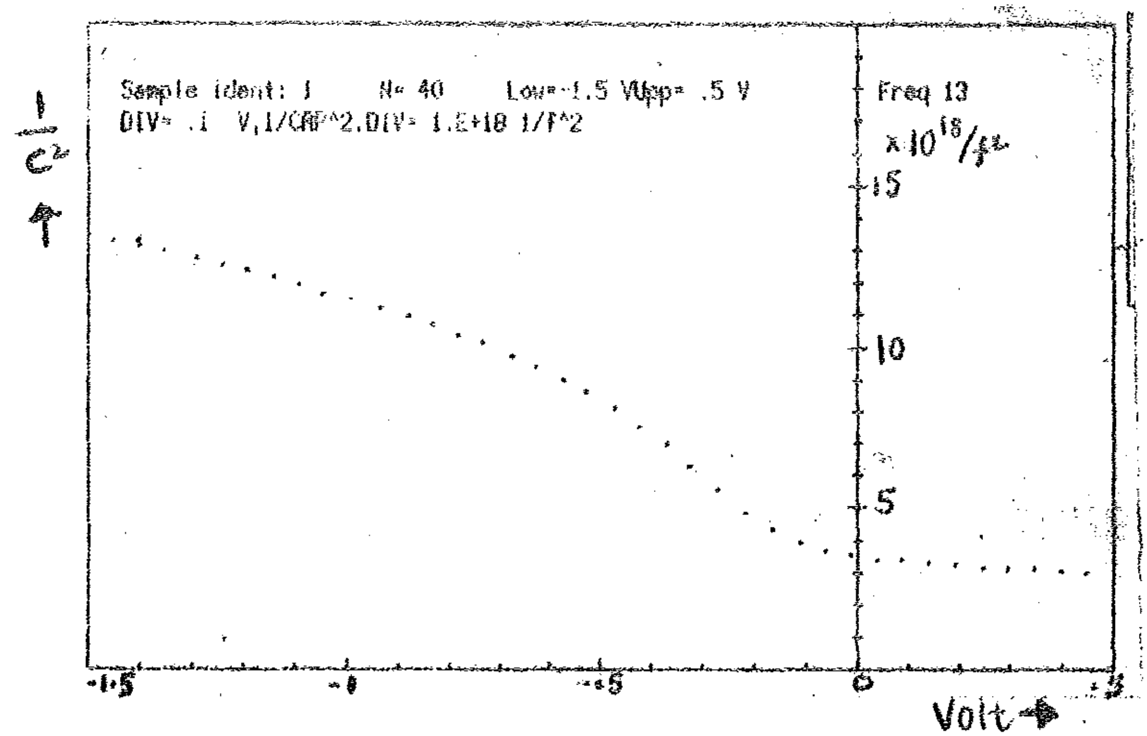


V_{int} = .21

Slope = -1.0

ϕ_{Bh} = 0.52

N_B = 2.94 x 10^{13}



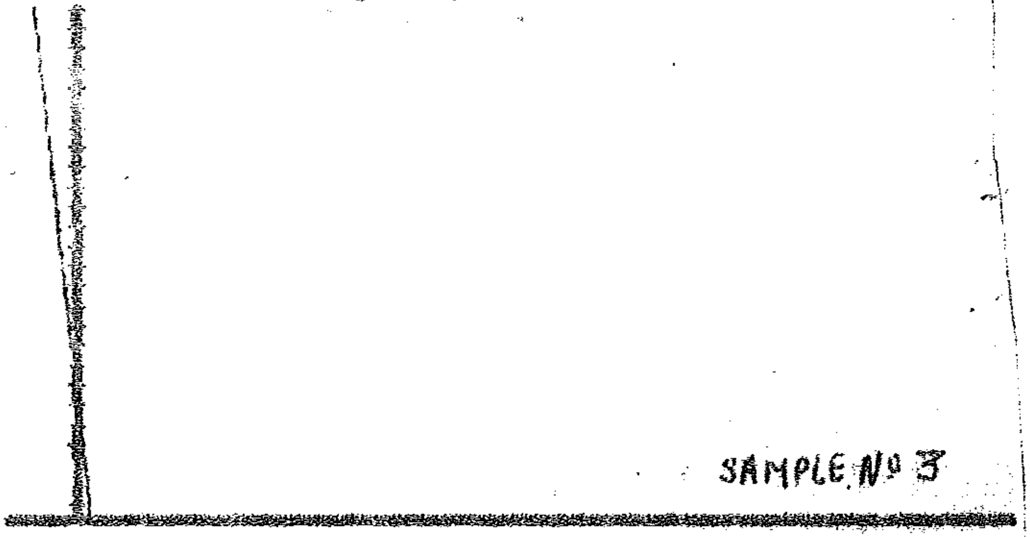
V_{int} = .19

Slope = -1.18

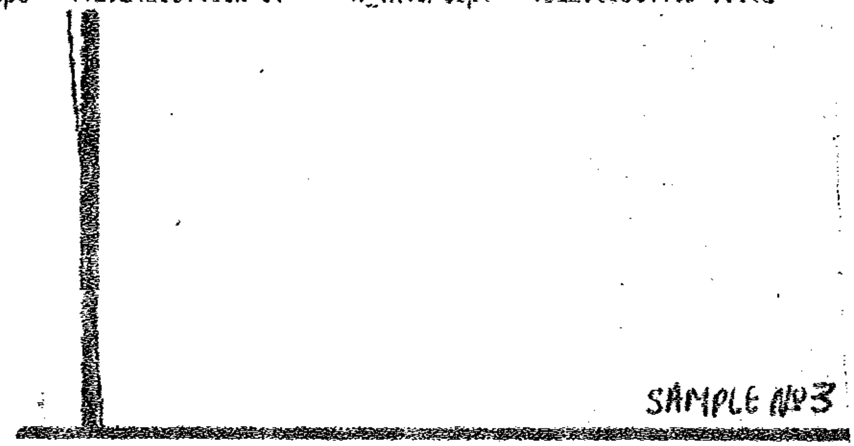
ϕ_{Bh} = 0.5 eV

N_B = 2.49 $\times 10^{13}/cm^3$

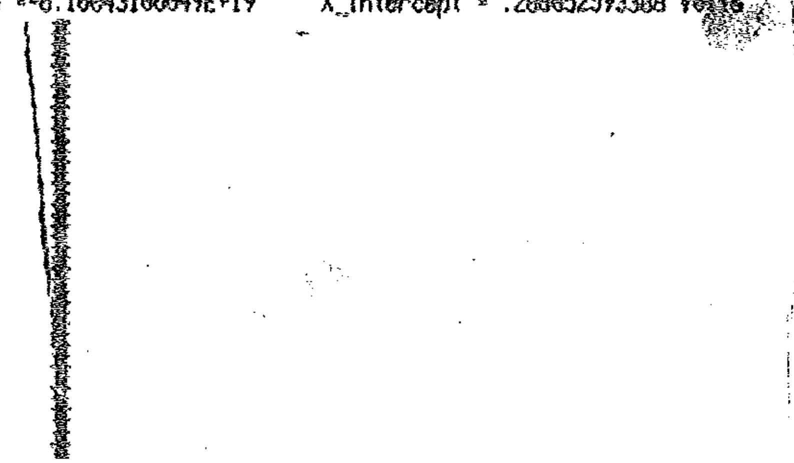
Xi=-1.497 Xf= 20
Y(1) = 2.[illegible]14127959E+19 Y(NI)= 2.35420358332E+19
Slope =-1.09855355833E+19 X_intercept = .349689398366 Volts



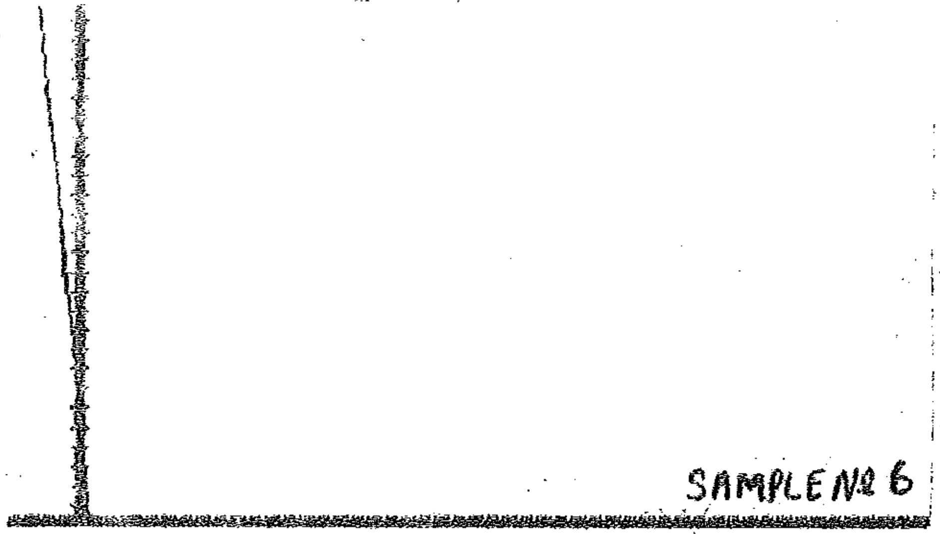
Sample count: 1 N= 40 Low=-1.5 VUpp= .5 V
DIV= .1 1/CAP^2.DIV= 5.E+18 1/f^2
Xi=-1.498 Xf= 20
Y(1) = [illegible]0036685267E+19 Y(NI)= 7.98191304869E+19
Slope =-7.21242137033E+19 X_intercept = .322065864405 Volts



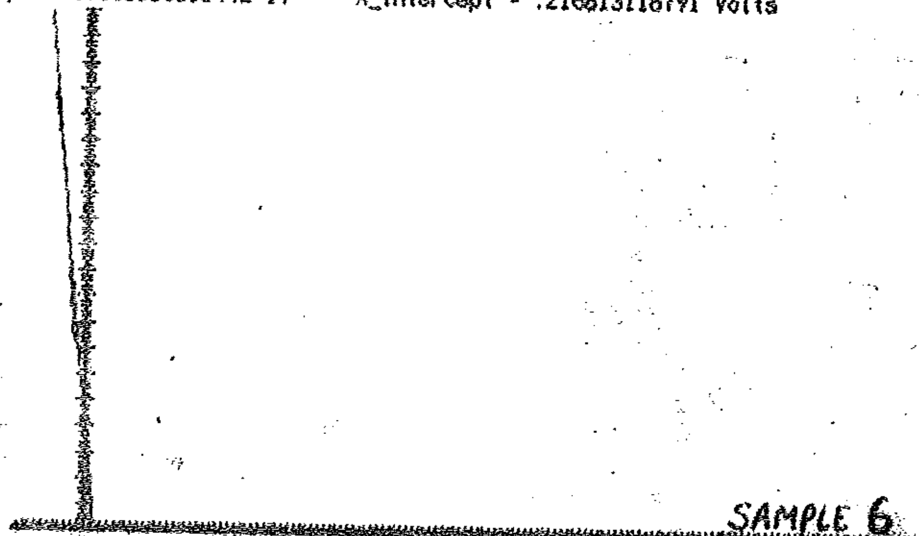
Xi=-1.498 Xf= 20
Y(1) = 7.[illegible]3935632BE+19 Y(NI)= 6.80424260[illegible]E+19
Slope =-6.16043106049E+19 X_intercept = .288652593308 Volts



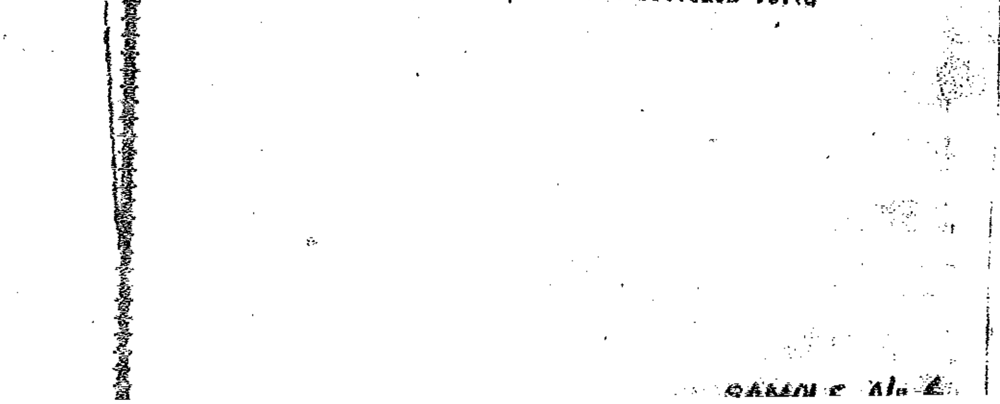
Xi=-1.4972 Xf= 20
Y(1) = 1.?1029019063E+19 Y(NI)= 1.05482550496E+19 10 kHz
Slope =-9.24767015087E+18 X_intercept = .250440044708 Volts



Xi=-1.4972 Xf= 20
Y(1) = 1.?655470077BE+19 Y(NI)= 1.03857161507E+19 20kHz
Slope =-1.00165631844E+19 X_intercept = .210813118791 Volts



Sample ident: 1 N= 40 Low=-1.5 VUpp= .5 V Freq 13 40KHz
DIV= .0 ?1/CAP^2.DIV= 1.E+18 1/f^2
Xi=-1.4972 Xf= 20
Y(1) = 1.?4471337367E+19 Y(NI)= 1.18980110927E+19
Slope =-1.18861395784E+19 X_intercept = .194458673212 Volts



3. DETERMINATION OF BARRIER ht FROM I-V CHARACTERISTICS

In this section the result of I-V curves given earlier for different samples are presented. Here Al-pSi junciton was forward biased by putting a negatavie voltage to the metal. Log(I)-V was plotted for biase 0.05 to 10V. A least squaref it method is used to find the saturatin current. From the known area of (A) o.2 cm^2 and assuming the Richardson constant (A^{**}) for holes [23] $\frac{30\ A}{cm^2 k^2}$ we then derive the barrier hts for holes (ϕ_{Bh})

$$q\phi_{Bh} = \frac{kT}{q}[\ln(AA^{**}T^2) - \ln I_s] \quad ev$$

The result of the ϕ_{Bh} for thesamples were

Sample No. 1 = 0.5 eV	Sample No. 4 = 0.59 eV
Sample No. 2 = 0.56 eV	Sample No. 5 = 0.52 eV
Sample No. 3 = 0.56 eV	Sample No. 6 = 0.57 eV

In all cases as we observed from I-V characteristics the diode shows good rectifing nature. Comparison of our results to theoretical I-V curves reported in literature has not been done, since observed ideality factor has no agreement with results reported in literature.

4. DETERMINATION OF BARRIER HEIGHTS FROM C-V CHARACTERISTICS

C-V and $1/C^2$-V curves is measuref for different frequencies of the signal. For $1/C^2$-V curve which were plotted for single frequency, least square fit has been made and voltage axis intercept gives (diffusion potential V_D). From the distance between the fermilevel and valence band (V_p) expected for our samples and correcting factor kT/q gives the result for the barrier hts of holes as

$$\phi_{Bh} = V_D + V_p + kT/q$$

Sample No.	ϕ_{Bh} (eV)	Frequency (kHz)
3	0.66	10
	0.62	20
	0.6	40
4	0.56	10
	0.52	20
	0.50	40

From the slopes we found by least square fit for $\frac{1}{C^2}$ - V curves we find active doping concentration (N_B) of the semiconductor as $N_B = \frac{2}{q\varepsilon_s \text{slope}}$. For different frequencies the value of N_B is listed below.

Sample No.	$N_B (10^{12}/cm^3)$	Frequency (kHz)
3	15.5	10
	4.13	20
	4.77	40
6	3.18	10
	2.94	20
	2.94	40

The least square fit result is attached with C-V measurements.

5. DISCUSSION

From the result of I-V characteristic of Sample No. 4, 5 and 1, from point view of the top contract area. The series resistance effect is much pronounced in No.4, and decreases in No. 5 and less in sample No. 1 as discussed by SZe[24]. This has resulted in the different barrier hts for the samples, due to the shape of top contact areas, despite the fact that they have the same nature as given in their specificalton.

From the result of I-V characteristics of samples No. 3 and No. 2, the measured barrier hts are the same which shows the independency of the barrier hts on doping concentration for non-degenerate semiconductors as reported by Archer and Yep[25].

For sample No. 1 and 2 which differs in orientation as specifled in their specification shows two typical I-V characteristics for sample No. 1 the I-V curve shows saturation for biase greater than +7V, this may be due to space charge limitation effects as discussed by sze [26]. Sample No. 2 I-V curves shows nonsaturation nature of reverse current for $V_R > 0.3V$ is due to generation current in the depletion region, since image force lowering assumption gives nonphysical image force dielectric constant at room remperature as reported by Yu and Snow [27].

The last part remain to discuss results of C-V characteristics of Sample No. 6 and No. 3. In both cases the C-V dependence on frequency is identical, i.e for the forward biase the capacitance decreases as frequency increased and reverse happen for $1/C^2$-V curve in the reverse bias region. Both indicates the fact that charge carriers, deep impurity levels (acceptor), traps would follow the low signal frequency and reach to equilibrium ionization state which could contribute to the depletion layer charge, this has been also discussed by Nicollian and Brews [28]. Observed linear nature of $1/C^2$-V curve in the reverse biase region is also discussed and reported by Crowell and Robert [29].

Barrier hts from C-V measurement on the average for Sample No.6 and No. 3 are 0.52 eV and 0.62 eV respectively.

Barrier hts from I-V measurement on Sample No. 6. and No. 3 are are 0.49 eV and 0.56 eV respectively.

From peices of information givens by sze [30] where evaporated Al on deposited on Vacuum-cleaved Si give ϕ_{Bh} for hole as 0.58 eV.

CONCLUSION

Our modification of Robert and Crowel [19] and Zahid and Jonscher [20] model of deep impurity level and deep traps of metal-n semiconductor respectively for the purpose of the present work on metal-p esemiconductor Schottky diodes observed to be in agreement with experiemental result.

It has been established that the barrier height of vacuum deposited Aluminium on p Silicon is relatively high[4] (0.49-0.65 eV). It has also been confirmed that the barrier obtained uder these condition dpends on frequency, and the barrier height measured using both I-V and C-V methods shows a maximum difference on the average ±.06 eV. It has also been confirmed that active doping concentration decreases as frequency of signal increases.

The fabrication of Aluminium junciton to nonocrystalline silicon was successfully carried through and technological application should be studied.

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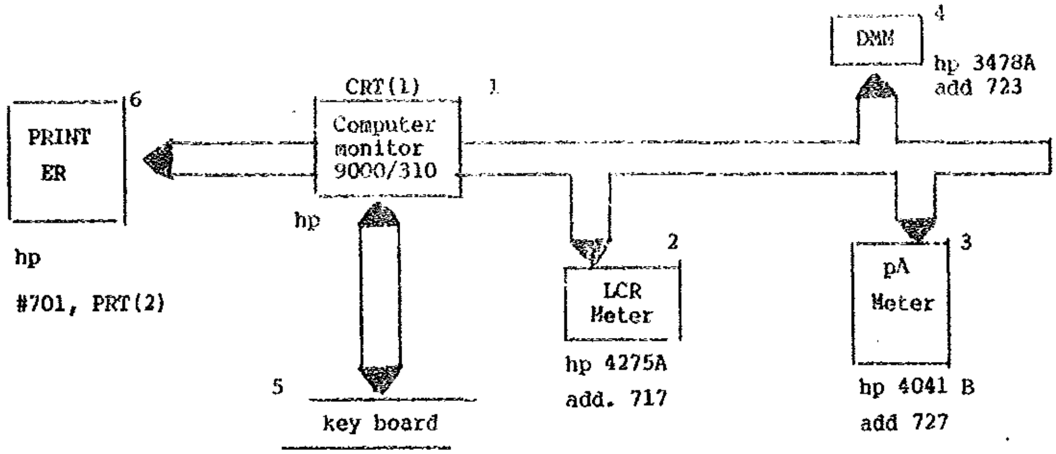
APPENDIX I

SET UP OF MEASURING INSTRUMENTS INTERFACED WITH THE COMPUTER

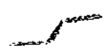
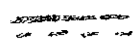


1. Main hp 9000/310 Computer, color monitor, CRT 1
2. hp 4275A, LCR MULTIFREQUENCY METER, Add. 717
3. hp 4041B, pA METER / DC VOLTAGE SOURCE, Add. 727
4. hp 3478A, DIGITAL MULTIFREQUENCY METER, Add. 723
5. KEY BOARD, hp
6. PRINTER, hp , Add PRT 2 or # 701

APPENDIX III

REMOTE PROGRAM COMMAND CODES

hp 4041B pA Meter/DC VOLTAGE SOURCE [34]

	CONTROL	PROGRAM CODE
FUNCTION	I	F1
	I-V	F2
	C-V	F3
LIMIT	10^{-2}A 10^{-12}A	H02 H12
AUTO RAGE		
Intgration	SHORT, MEDIUM	I1, I2
time	LONG	I3*
I TRIG	I NT, EXT / MAN	T1*, T2
SWEEP	AUTO START	W1
CONTROL	MANUAL	W2
	PAUSE	W3
	ABORT	W7
V_A MODE		A1
		A2
		A3
		A4
V_B MODE		B1
V_AI Limit	100μA, 1mA, 10mA	L1*, L2, L3
V_BI Limit	" " "	M1*, M2, M3
Zero set		Z
SRQ	OFF, ON(1), ON(2)	DO*, D1, D2, D4
Mask	ON(3)	
TRIGGER		E
KEY STATUS		K

APPENDIX IV

RMOTE PROGRAM COMMAND CODES

hp 3478A DIGITAL MULTIMETER (DMM)

TYPE	DESCRIPTION	PROGRAM CODES
Function	DC Volts	F1
	AC Volts	F2
	DC Currents	F5
	AC Currents	F6
Digit display	$3\frac{1}{2}$ digits	N3
d	$4\frac{1}{2}$ digits	N4
	$5\frac{1}{2}$ digits	N5
Range	Auto range	RA
	30 mV	R-2
	300 mV	R-1

```
10    ! SAMPLE PROGRAMMED
20    !CAPACITANCE  VOLTAGE MEASUREMENT AT different frequencies
30    ! 10 HZ - ... C-V MEASUREMENT 4275A HP LCR METER
40    DIM C(200),U(200),Cr(200)
50    K=0
60    K=K+1
70    CALL Meas_c(Nm,U(*),C(*),Cr(*),L,Upp,S$,K,Fr)   !Nm in main prog.,N in SUB
80    CALL Plotarr(U(*),C(*),Ue,Nm,L,Upp,S$,K,Fr)
90    INPUT "NEW FREQUENCY? Y/N",S$
100   IF S$="Y" THEN 60
110   DISP "Phys Dept GAU",DATE$(TIMEDATE),TIME$(TIMEDATE),"CV LCR Meas."
120   END
130   SUB Meas_c(N,U(*),C(*),Cr(*),Low,Upp,S$,K,Fr)
140   IF S$="Y" THEN Freq
150     INPUT "SAMPLE IDENT: ",Id$
160     REMOTE 717
170     OUTPUT 717;"A2B1C1D0M2"
180     OUTPUT 717;"E"
190     REMOTE 722
200     OUTPUT 722;"F1RAN4"
210     INPUT "N?",N
220     INPUT "Low,Upp?",Low,Upp
230     PRINT "SELECT FREQUENCY BY FIGURES IN THE BRACKETTES:"
240     PRINT
250     PRINT "10kHz (11)  20kHz (12)  40kHz (13)  100kHz (14)  200kHz (15)"
260     PRINT "400kHz(16)  1MHz  (17)  2MHz  (18)  4MHz   (19)  10MHz  (20)"
270     PRINT
280     PRINT "TO CONTINUE PRESS 'Continue' KEY"
290     PAUSE
300     PRINT CHR$(12)
310     PRINT "Sample ident: ";Id$,"N=";N,"Low=";Low;"V","Upp=";Upp;"V"
320 Freq: INPUT "FREQUENCY?",Fr
330     IF Fr>20 THEN
340       DISP "FREQ";Fr;"NOT AVAILABLE. TRY AGAIN!"
350       WAIT 3
360       GOTO Freq
370     END IF
380     PRINT TABXY(60,K+1);"Freq";Fr
390     Fr$="F"&VAL$(Fr)
400     OUTPUT 717;Fr$
410     FOR I=1 TO N
420       J=Low+(I-1)/(N-1)*(Upp-Low)
430       U=DROUND(J,3)
440       U$=VAL$(10*U)
450       Bias$="BI "&U$&"E-1V"
460       OUTPUT 717;Bias$
470       OUTPUT 717;"E"
480       ENTER 717;A,B
490       IF A<1 OR A>10 THEN
500         I=I-1
510         BEEP
520         GOTO 580
530       END IF
540       C(I)=A
550       ENTER 722;D$
560       U(I)=VAL(D$)
570       DISP "Measur. approx";INT(.25*N);"sec.      #";I,"U=";U(I),"  C=";C(I)
580     NEXT I
590     DISP
600     OUTPUT 717;"BI 0E00V"
610     WAIT 5
620   SUBEND
630   SUB Plotarr(U(*),C(*),Ue,N,L,Upp,S$,K,Fr)
```

```
...(*),Ve),Nm,Low,Upp,S$,K,Pr)
640     IF S$="Y" THEN Pen
650     Ve=MAX(C(*))
660     Ve=DROUND(1.6*Ve,1)
670     GINIT
680     VIEWPORT 0,120,24,100
690     WINDOW Low,Upp,0,Ve
700     AXES (Upp-Low)/20,Ve/20,0,0,5,5
710     PRINT "DIV=";(Upp-Low)/20;" V   CAP. DIV=";Ve/20;"F"
720 Pen:!
730     PEN K
740     FOR T=1 TO Nm
750       WAIT .1
760       PLOT V(T),C(T)
770       MOVE V(T),0
780     NEXT T
790     PEN 1
800     FRAME
810   SUBEND
```

```
10    !SAMPLE PROGRAM
20    !1/(Capacitance)^2  Vs  VOLTAGE Measurement
30    !With LEAST SQUARE FIT :For Slope & Intercept
40    ! 'C_VG',"1/C^2-V" MEASUREMENT,7245A HP LCR METER
50    DIM C(1:250),V(1:250)
60    K=0
70    K=K+1
80 !  LOADSUB Lsft FROM "Slope"
90    CALL Meas_c(Nm,V(*),C(*),Low,Upp,S$,K,Fr)
100   CALL Plotarr(Nm,V(*),C(*),Ve,Low,Upp,S$,K,Fr)
110   PAUSE
120   GCLEAR
130   INPUT "The initial index number at the linear
      segment of the curve Ni = ",Ni
140   INPUT "The final index number at the
       linear segment of the curve Nf=",Nf
150   GCLEAR
160   CALL Lsft(V(*),C(*),Ni,Nf,M,Int,Xm,Ym,V(1),+20)
170   X_intercept=-Int/M
180   PRINT "Slope =";M,"X_intercept =";X_intercept;"Volts"
190   PAUSE
200   GOTO 130
210   INPUT " NEW FREQUENCY? Y/N",S$
220   IF S$="Y" THEN 70
230   DISP "Phys Dept AAU";DATE$(TIMEDATE);TIME$(TIMEDATE),"1/C^2 Vs.V,LCRMeas"
240   END
250   SUB Meas_c(N,V(*),C(*),Low,Upp,S$,K,Fr)
260     IF S$="Y" THEN Freq
270     INPUT "SAMPLE IDENT: ",Id$
280     REMOTE 717
290     OUTPUT 717;"A2B1C1D0M2"
300     OUTPUT 717;"E"
310     REMOTE 723
320     OUTPUT 723;"F1RAN4"
330     INPUT "N?",N
340     INPUT "Low,Upp?",Low,Upp
350     PRINT "SELECT FREQUENCY BY FIGURES IN THE BRACKETTES:"
360     PRINT
370     PRINT "10kHz (11)  20kHz (12)  40kHz (13)  100kHz (14)  200kHz (15)"
380     PRINT "400kHz(16)  1MHz  (17)  2MHz  (18)  4MHz   (19)  10MHz  (20)"
390     PRINT
400     PRINT "TO CONTINUE PRESS 'Continue' KEY"
410     PAUSE
420     PRINT CHR$(12)
430     PRINT "Sample ident: ";Id$,"N=";N,"Low=";Low;"V","Upp=";Upp;"V"
440 Freq:INPUT "FREQUENCY?",Fr
450     IF Fr>20 THEN
460       DISP "FREQ";Fr;"NOT AVAILABLE, TRY AGAIN!"
470       WAIT 3
480       GOTO Freq
490     END IF
500     PRINT TABXY(60,K+1),"Freq"+Fr
510     Fr$="F"&VAL$(Fr)
520     OUTPUT 717;Fr$
530     FOR I=1 TO N
540       J=Low+(I-1)/(N-1)*(Upp-Low)
550       U=DROUND(J,3)
560       U$=VAL$(10*U)
570       Bias$="BI "&U$&"E-10"
580       OUTPUT 717;Bias$
590       OUTPUT 717;"E"
600       ENTER 717;A,B
610       IF A>1.E+10 THEN
```

```
630          BEEP
640          GOTO 710
650        END IF
660        C(I)=A
670        C(I)=1/C(I)^2
680        ENTER 723;D$
690        V(I)=VAL(D$)
700        DISP "Measur approx";INT(.25*N);"sec.
            &";I,"Ve=";V(I),"1/C^2=";C(I)
710      NEXT I
720      DISP
730      OUTPUT 717;"BI 0E00V"
740      WAIT .6
750    SUBEND
760    SUB Plotarr(Nm,V(*),C(*),Ve,Low,Upp,S$,K,Fr)
770      IF S$="Y" THEN Pen
780      Ve=MAX(C(*))
790      Ve=DROUND(1.6*Ve,1)
800      GINIT
810      VIEWPORT 0,120,24,100
820      WINDOW Low,Upp,0,Ve
830      AXES (Upp-Low)/20,Ve/20,0,0,5,5
840      PRINT "DIV=";(Upp-Low)/20;" V,1/CAP^2 DIV=";Ve/20;"1/f^2"
850 Pen: !
860      PEN K
870      FOR T=1 TO Nm
880        WAIT .1
890        PLOT V(T),C(T)
900        MOVE V(T),0
910      NEXT T
920      PEN 1
930      FRAME
940    SUBEND
950    !
960    SUB Lsft(X(*),Y(*),Ni,Nf,Slope,Intercept,Xm,Ym,Xi,Xf)
970    Sxy=0
980    Sx=0
990    Sx2=0
1000   Sy=0
1010   FOR I=Ni TO Nf
1020   Sx=Sx+X(I)
1030   Sx2=Sx2+X(I)^2
1040   Sy=Sy+Y(I)
1050   Sxy=Sxy+X(I)*Y(I)
1060   NEXT I
1070   N=Nf-Ni+1
1080   Slope=(N*Sxy-Sx*Sy)/(N*Sx2-Sx^2)
1090   Intercept=(Sx2*Sy-Sx*Sxy)/(N*Sx2-Sx^2)
1100   Xm=Sx/N
1110   Ym=Slope*Xm+Intercept
1120   VIEWPORT 10,128,25,100
1130   WINDOW Xi*1.1,Xf*1.1,0,Y(1)*1.1
1140   PRINT "Xi=";Xi,"Xf=";Xf
1150   PRINT "Y(1) =";Y(1),"Y(N1)=";Y(N)
1160   AXES ABS(X(N)-X(1))/25,ABS(Y(1)-Y(N))/25,0,0.,5,5,2
1170   PEN 2
1180   FOR I=Ni TO Nf        ! Graph of the experimental data
1190   PLOT X(I),Y(I)
1200   NEXT I
1210   PENUP
1220   PEN 4
```

```
10 ! "QUASISTATIC ~~~C-V~~~MEASUREMENT USING 4140 pA METER/DC VOLTAGE SOURCE"
20    DIM A$[50],C(150),V(150)
30    DIM C1(150),V1(150)
40    CLEAR 727
50    OUTPUT 727;"F3RA1I3A1B1L2M3"
60    INPUT "Sample:",Id$
70    INPUT "Low?",Low
80    Low$="PS"&VAL$(Low)
90    INPUT "Upp?",Upp
100   Upp$="PT"&VAL$(Upp)
110   INPUT "Step?",Step
120   Step$="PE"&VAL$(Step)
130   Hold$="PH"&VAL$(2)
140   INPUT "dv/dt?",Rate
150   Rate$="PV"&VAL$(Rate)
160   OUTPUT 727;Low$,Upp$
170   OUTPUT 727;Step$,Hold$
180   OUTPUT 727;Rate$
190   OUTPUT 727;"W1"
200   OUTPUT 727;"Z"
210   I=0
220   I=I+1
230   ENTER 727;A$
240   C(I)=VAL(A$[4,13])
250   V(I)=VAL(A$[16,21])
260   C1(I)=DROUND(C(I),3)
270   V1(I)=DROUND(V(I),3)
280   DISP C1(I),V1(I),A$
290   PRINT I,C1(I),V1(I)
300   IF A$[2,2]<>"L" THEN 220
310   PRINT "TO CONTINUE «press«`continue`KEY"
320   PAUSE
330   PRINT CHR$(12)
340   DISP
350   INPUT "DO YOU NEED GRAPH?Y/N",G$
360   IF G$="N" THEN
370     GOTO 680
380   END IF
390   !PLOTTING
400   Ve=MAX(C1(*))
410   Ve=DROUND(1.6*Ve,1)
420   GINIT
430   PLOTTER IS CRT,"INTERNAL"
440   GRAPHICS ON
450   PEN 5
460   MOVE 45,90
```

```
470   LABEL "C-V measurement"
480   MOVE 2,85
490   Label$="CAPACITANCE"
500   FOR Z=1 TO 11
510     LABEL Label$[Z,Z]
520   NEXT Z
530   MOVE 45,23
540   LABEL "VOLTAGE(volts)"
550   PEN 3
560   VIEWPORT 7,120,28,100
570   WINDOW Low,Upp,-Ve/20,Ve
580   AXES (Upp-Low)/20,Ve/20,0,0,5,5
590   PRINT "C_div=";Ve/20;"V_div=";(Upp-Low)/20
600   PEN 4
610   FOR I=1 TO MAX(I)
620     WAIT .1
630     PLOT V1(I),C1(I)
640     MOVE V1(I),0
650   NEXT I
660   PEN 2
670   FRAME
680   PRINT
690   INPUT "DO YOU NEED PRINTING?Y/n",S$
700   IF S$="N" THEN 800
710   !PRINTING
720   PRINTER IS PRT;WIDTH 160
730   PRINT "Sample:";Id$,TAB(37);"Low,Upp";Low;Upp;"volts",TAB(80);DATE$(TIMEDATE);TAB(
740   PRINT "Capacitance/P.farad";"Voltage/volts"
750   PRINT
760   FOR I=1 TO MAX(I)
770     PRINT TAB(20*I-15);V1(I),TAB(20*I-9);C1(I),
780   NEXT I
790   PRINT
800   PRINT
810   PRINTER IS CRT
820   INPUT "DO YOU NEED GRAPH TO BE PRINTED?Y/N",R$
830   IF R$="N" THEN
840     GCLEAR
850     PRINT CHR$(12)
860     PRINT "MEASUREMENT STOPS HERE"
870     PRINT "THANK YOU"
880     GOTO Done
890   END IF
900   DUMP GRAPHICS #701
910 Done:END
```

```
10   ! SAMPLE PROGRAM
20 !FOR LOG(I) Vs  V  MEASUREMENT,WITH LEAST SQUARE FIT
30     !'LOG(I)-V' MEASUREMENT 4140B pA METER/DC
40     OPTION BASE 1
50     DIM A$[50],I1(150),V1(150)
60     DIM I(150),V(150),D(150),V2(150)
```

```
70   CLEAR 727
80   OUTPUT 727;"F2I1L3"
90   INPUT "Sample:",Id$
100  INPUT "LOW?",Low
110  Low$="PS"&VAL$(Low)
120  INPUT "UPP?",Upp
130  Upp$="PT"&VAL$(Upp)
140  INPUT "STEP?",Step
150  Step$="PE"&VAL$(Step)
160  Hold$="PH"&VAL$(.1)
170  Delay$="PD"&VAL$(.2)
180  OUTPUT 727;Low$,Upp$,Step$
190  OUTPUT 727;Hold$,Delay$
200  OUTPUT 727;"W1"
210  X=0
220  X=X+1
230  ENTER 727;A$
240  I(X)=VAL(A$[4,13])
250  V(X)=VAL(A$[16,21])
260  I1(X)=-DROUND(I(X),3)
270  V1(X)=DROUND(V(X),3)
280  IF I1(X)=0 THEN
290    I1(X)=E-15                              !RESOLUTION
300    GOTO 320
310  END IF
320  D(X)=LOG(ABS(I1(X)))
330  V1(X)=ABS(V1(X))
340  DISP I1(X),V1(X),A$
350  PRINT X,I1(X),V1(X),D(X)
360  IF A$[2,2]<>"L" THEN 220
370  PRINT "TO CONTINUE PRESS`continue`KEY"
380  PAUSE
390  PRINT CHR$(12)
400  DISP
410  INPUT "DO YOU NEED GRAPH?Y/N",G$
420  IF G$="N" THEN
430    GOTO 1000
440  END IF
450 !Plotting
460  !Ve=MAX(I1(*))
470 ! Ve=DROUND(1.6*Ve,1)
480 ! Mi=MIN(I1(*))
490 ! Mi=DROUND(1.6*Mi,1)
500  GINIT
510  PLOTTER IS CRT,"INTERNAL"
520  GRAPHICS ON
530  PEN 5
540  MOVE 40,95
550  LABEL "LOG(I) Vs V "
560 ! MOVE 3,65
570 ! Label$="Current"
580 ! FOR Z=1 TO 7
590 !   LABEL Label$[Z,Z]
600  !NEXT Z
610  MOVE 92,24
620  LABEL "Volt"
630  PEN 3
640  INPUT "SWITCH =  ( positive number corresponds to  V>0)",Sw
650  IF Sw<=0 THEN L=ABS(Upp)
660  IF Sw<=0 THEN U=ABS(Low)
670  IF Sw>0 THEN L=Low
680  IF Sw>0 THEN U=Upp
```

```
700   Dmax=D(1)
710   FOR X=1 TO MAX(X)
720     IF D(X)>Dmax AND D(X)<>0 THEN Dmax=D(X)
730   NEXT X
740   PRINT "Dmax=";Dmax
750   VIEWPORT 3,120,28,100
760   WINDOW L,U,MIN(D(*)),Dmax
770   PRINT "MIN=",MIN(D(*)),"Dmax=";Dmax
780   AXES (U-L)/20,(Dmax-MIN(D(*)))/20,L,MIN(D(*)),2,2,5
790   PRINT "U_div=";(U-L)/20;"I_div=";(Dmax-MIN(D(*)))/20
800   PEN 4
810   PRINT "MAX(X)=";MAX(X),"Low=";Low;"UPP=";Upp
820   LINE TYPE 1
830   FOR X=1 TO MAX(X)
840     WAIT .1
850     PLOT U1(X),D(X)
860 !   MOVE U1(X),0
870   NEXT X
880   PEN 2
890   FRAME
900 ! LOADSUB Lsft FROM "Slope"
910   PAUSE
920   GCLEAR
930   INPUT "The initial and final index numbers Ni,Nf=?",Ni,Nf
940   GCLEAR
950   CALL Lsft(U(*),D(*),Ni,Nf,M,Int,Xm,Ym)
960   Y_intercept=Int
970   PRINT "Slope=";M,"Y_Intercept=";Int
980   PAUSE
990   GOTO 930
1000  PRINT
1010  INPUT "DO YOU NEED PRINTING?Y/N",S$
1020  IF S$="N" THEN Done
1030  !PRINTING
1040  PRINTER IS PRT;WIDTH 160
1050  PRINT "Sample:";Id$,TAB(37);"Low,Upp";Low;Upp;"Volts",TAB(80),DATE$(TIMEDATE),TAB(
1060  PRINT "VOLTAGE/Volt","CURRENT/Amps"
1070  PRINT
1080  FOR X=1 TO MAX(X)
1090    PRINT TAB(20*X-15),U1(X);TAB(20*X-9),I1(X),
1100  NEXT X
1110  PRINT
1120  PRINTER IS CRT
1130  INPUT "DO YOU NEED GRAPH TO BE PRINTED?Y/N",R$
1140  IF R$="N" THEN
1150    GCLEAR
1160    PRINT CHR$(12)
1170    PRINT "Measurement stop here"
1180    PRINT "THANK YOU"
1190    GOTO Done
1200  END IF
1210  DUMP GRAPHICS #701
1220 Done:END
1230  SUB Lsft(X(*),Y(*),Ni,Nf,Slope,Intercept,Xm,Ym)
1240  Sxy=0
1250  Sx=0
1260  Sx2=0
1270  Sy=0
1280  FOR I=Ni TO Nf
1290  Sx=Sx+X(I)
1300  Sx2=Sx2+X(I)^2
```

```
1320  Sxy=Sxy+X(I)*Y(I)
1330  NEXT I
1340  N=Nf-Ni+1
1350  Slope=(N*Sxy-Sx*Sy)/(N*Sx2-Sx^2)
1360  Intercept=(Sx2*Sy-Sx*Sxy)/(N*Sx2-Sx^2)
1370  Xm=Sx/N
1380  Ym=Slope*Xm+Intercept
1390  VIEWPORT 10,120,25,100
1400  WINDOW X(1),X(N),Y(1),Y(N)
1410  AXES (X(N)-X(1))/25,(Y(1)-Y(N))/25,0,0,5,5,2
1420  PEN 7
1430  FOR I=1 TO N
1440  PLOT X(I),Y(I)
1450  MOVE X(I),0
1460  NEXT I
1470  PENUP
1480  PEN 3
1490  FOR I=1 TO N
1500  PLOT X(I),Slope*(X(I)-Xm)+Ym
1510  NEXT I
1520  SUBEND
```

```
10    !SAMPLE PROGRAM
20    !FOR OBSERVATION OF  ROBERTS &  CROWELL  1/C^2 Vs: Vs("band bendig")
30    ! A program to plot graphs for fourimpurity donor level semiconductor
40    !     using subprogram Cdc
50    ! N21,N31,N41                !ratio of the impurities of E2 TO E1 or deep
60                                    !  to shallow impurity levels
70  ! E1=                          ! Energy of the shallow level in kT numbers
80  ! E2=                          ! Energy of the deep level in kT numbers
90  ! E3=,E4=                      !Energy of  deeper levels in their order.
100 ! Psif=                        ! The potential of Fermi level in kT numbers:
110   INPUT "N21=,N31=,N41=,E1=,E2=,E3=,E4=,Psif=?",N21,N31,N41,E1,E2,E3,E4,Psif
120   GINIT
130   PEN 5
140   CSIZE 3
150   MOVE 60,80
160   LABEL "E1 =";E1
170   MOVE 60,77
180   LABEL "E2 =;E3=;E4=";E2;E3;E4
190   MOVE 60,74
200   LABEL "N2/N1 =;N3/N1=;N4/N1=";N21;N31;N41
210   MOVE 60,71
220   LABEL "Psif =";Psif
230   VIEWPORT 1,125,25,98
240   WINDOW -2,50,-2,45
250   AXES 1,2,0,0,5,5,2
260   PEN -1
270   VIEWPORT 1,5,25,28
280   AXES .1,3,0,0,1,1,10
```

```
290  VIEWPORT 6,0,25,2
300  AXES 2,.1,0,0,1,1,10
310  VIEWPORT 1,125,25,98
320  PEN 5
330  CSIZE 3
340  CLIP OFF
350  LORG 6
360  FOR X=0 TO 40 STEP 5
370    MOVE X,-1
380    LABEL X
390  NEXT X
400  LORG 8
410  FOR Y=0 TO 100 STEP 20
420    MOVE -.5,Y
430    LABEL Y
440  NEXT Y
450  CLIP ON
460 ! LOADSUB Cdc FROM "Cdc"
470  PEN 2
480  K=0
490  K=K+1
500  PEN K
510  MOVE 0,0
520  FOR Us=1.E-6 TO 40 STEP .5
530    CALL Cdc(N21,N31,N41,Us,E1,E2,E3,E4,Psif,Cdc2)
540    PLOT Us,Cdc2/2
550  NEXT Us
560  INPUT "DO YOU NEED GRAPH FOR NEW PARAMETER? Y/N ",R$
570  IF R$="Y" THEN
580    INPUT "N12,N13,N14,E1,E2,E3,E3,Psif?",N12,N13,N14,E1,E2,E3,E4,Psif
590    GOTO 490
600  END IF
610  END
620  !SUBPROGRAM
630  SUB Cdc(N21,N31,N41,Us,E1,E2,E3,E4,Psif,Cdc2)
640  ! Subprogram for four donor impurity  level semiconductor
650    Q=1.6*1.E-19                                    ! Charge of an electron
660  !Psif=Q*Psif/KT                         ! Psif is in KT
670  !Psis=Q*Psis/KT
680    Psis=(Us+Psif)                                  ! Psis is in kT numbers
690    F1s=1/(1+2*EXP(-(Psis-E1)))
700    F2s=1/(1+2*EXP(-(Psis-E2)))
710    F3s=1/(1+2*EXP(-(Psis-E3)))
720    F4s=1/(1+2*EXP(-(Psis-E4)))
730    F1f=1/(1+2*EXP(-(Psif-E1)))
740    F2f=1/(1+2*EXP(-(Psif-E2)))
750    F3f=1/(1+2*EXP(-(Psif-E3)))
760    F4f=1/(1+2*EXP(-(Psif-E4)))
770    Num=2*(1+N21+N31+N41)*(Us*(1+N21+N31+N41)+LOG(F1f/F1s)+N21*LOG(F2f/F2s)+N31*LOG(F
780    Denom=((F1s+N21*F2s+N31*F3s+N41*F4s)-(F1f+N21*F2f+N31*F3f+N41*F4f)*EXP(-Us))^2
790    Cdc2=Num/Denom
800  SUBEND
```

```
390   NEXT X
400   LORG 8
410   FOR Y=0 TO 100 STEP 20
420     MOVE -.5,Y
430     LABEL Y
440   NEXT Y
450   CLIP ON
460 ! LOADSUB Cdc FROM "Cdc"
470   PEN 2
480   K=0
490   K=K+1
500   PEN K
510   MOVE 0,0
520   FOR Us=1.E-6 TO 40 STEP .5
530     CALL Cdc(N21,N31,N41,Us,E1,E2,E3,E4,Psif,Cdc2)
540     PLOT Us,Cdc2/2
550   NEXT Us
560   INPUT "DO YOU NEED GRAPH FOR NEW PARAMETER? Y/N ",R$
570   IF R$="Y" THEN
580     INPUT "N12,N13,N14,E1,E2,E3,E3,Psif?",N12,N13,N14,E1,E2,E3,E4,Psif
590     GOTO 490
600   END IF
610   END
620   !SUBPROGRAM
630   SUB Cdc(N21,N31,N41,Us,E1,E2,E3,E4,Psif,Cdc2)
640   ! Subprogram for four donor impurity  level semiconductor
650     Q=1.6*1.E-19                                    ! Charge of an electron
660   !Psif=Q*Psif/KT                        ! Psif is in KT
670   !Psis=Q*Psis/KT
680     Psis=(Us+Psif)                                ! Psis is in kT numbers
690     F1s=1/(1+2*EXP(-(Psis-E1)))
700     F2s=1/(1+2*EXP(-(Psis-E2)))
710     F3s=1/(1+2*EXP(-(Psis-E3)))
720     F4s=1/(1+2*EXP(-(Psis-E4)))
730     F1f=1/(1+2*EXP(-(Psif-E1)))
740     F2f=1/(1+2*EXP(-(Psif-E2)))
750     F3f=1/(1+2*EXP(-(Psif-E3)))
760     F4f=1/(1+2*EXP(-(Psif-E4)))
770     Num=2*(1+N21+N31+N41)*(Us*(1+N21+N31+N41)+LOG(F1f/F1s)+N21*LOG(F2f/F2s)+N31*L(
780     Denom=((F1s+N21*F2s+N31*F3s+N41*F4s)-(F1f+N21*F2f+N31*F3f+N41*F4f)*EXP(-Us))^:
790     Cdc2=Num/Denom
800   SUBEND
```