**HYDROGENATED AMORPHOUS SILICON RADIATION DETECTORS:
MATERIAL PARAMETERS; RADIATION HARDNESS; CHARGE
COLLECTION**

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For nearly two decades now hydrogenated amorphous silicon has generated considerable interest for its potential use in various device applications namely, solar cells, electrolithography, large-area electronics etc. The development of efficient and economic solar cells has been on the forefront of this research. This interest in hydrogenated amorphous silicon has been motivated by the fact that amorphous silicon can be deposited over a large area at relatively low cost compared to crystalline silicon. Hydrogenated amorphous silicon, frequently abbreviated as a-Si:H, used in solar-cell applications is a micron or less thick. The basic device structure is a p-i-n diode where the i layer is the active layer for radiation to interact. This is so because intrinsic a-Si:H has superior electrical properties in comparison to doped a-Si:H which serves the purpose of forming a potential barrier on either end of the i layer.

The research presented in this dissertation was undertaken to study the properties of a-Si:H for radiation detection applications in physics and medicine. Various factors that demand immediate attention while considering hydrogenated amorphous silicon as a candidate for radiation detection are :

1.1 Active detector thickness

For radiation detection applications, unlike solar cells, thi-

cker diodes are required for sufficient energy deposition in the material and better signal to noise ratio. One main obstacle in achieving this objective has been the production of thick a-Si:H diodes with low defect density that can be fully depleted at reasonable bias voltages. It should be emphasized that the presence of a sizeable electric field is essential for charge collection in a-Si:H devices as carrier diffusion plays little role in charge collection. One fundamental difficulty encountered in obtaining fully depleted thick diodes lies in the nature of amorphous silicon. Hydrogenated amorphous silicon has a high density of states in its band gap. These states are differentiated as being either shallow or deep states. These states control the electrical properties of the material. The shallow states have dominant influence on carrier mobility as carriers are trapped and detrapped in the shallow states during their transit [Tiedje et al., 1980]. The deep states are crucial in determining the carrier lifetime. These states are also responsible for creating space charge in the material which then shapes the electric field. The thickness to which the electric field penetrates in a thick a-Si:H p-i-n diode is crucial to its usefulness as a radiation detector. The fact that a large density of charged centers exist in the i layer when the diode is under DC bias, the electric field would no longer be uniform, unlike a crystalline p-i-n diode where the electric field in the intrinsic layer is uniform [Knoll, 1979]. This problem is further discussed at the beginning of Chapter 5. Presently made a-Si:H diodes with i layer thickness between 30 to 40 microns deplete at reasonable bias voltages

without breakdown or excess noise. Evidently the density of defect states or the dangling bond density is an important parameter for reasons stated above. Presently material with defect density $\sim 1\text{-}2 \times 10^{15} \text{ cm}^{-3}$ is produced without great difficulty and enormous research is being done by various research groups to improve the quality of the material further. Chapter 2 discusses some of the material aspects relevant to my research work. In writing this chapter I have drawn heavily on the published works of various authors who specialize in this field and these works are referenced.

1.2 Device speed

The carrier mobility in hydrogenated amorphous silicon is small compared to crystalline silicon. The electron mobility is $\sim 1 \text{ cm}^2/\text{V-s}$, a factor of ~ 1000 smaller compared to crystalline silicon and the hole mobility is even smaller ($\leq 0.01 \text{ cm}^2/\text{V-s}$). Consequently, one expects an amorphous silicon device to be slow. In a $30 \text{ }\mu\text{m}$ thick detector at 300 V bias the transit time t_T ($t_T = d^2/\mu V$) for electrons is $> 30 \text{ ns}$ and for holes is $> 3 \text{ }\mu\text{s}$ limiting the device speed to several microseconds for full charge collection.

However, if one were to rely on the signal from electrons alone the device speed could be much higher. This has been demonstrated in section 5.2.4 where significant beta signal is collected at shaping times as low as 20 ns . Measurements with 860 Mev alpha particles at short shaping times also illustrate this. As thicker and improved a-Si:H diodes are realised, more energy is deposited by a

particle going through the diode. The electron collection alone would produce large enough signal making a faster a-Si:H device more realistic.

1.3 Device leakage current and noise

The leakage current of an a-Si:H p-i-n diode under reverse bias is important from noise and power dissipation considerations. In chapter 3 leakage current and noise behaviour of a well behaved a-Si:H p-i-n diode has been studied. It is found that leakage current at operating bias shows "Poole-Frenkel effect" [Hill, 1971] type of dependence on voltage and leakage current makes dominant contribution to noise in the form of "shot noise" for CR-(RC)⁴ (pseudo-Gaussian) shaping at 3 μ s shaping time.

1.4 Device degradation

Hydrogenated amorphous silicon is known to degrade on prolonged exposure to light due to Staebler-Wronski effect (i.e. the defect density of the material increases on exposure to light) [Staebler et al., 1977]. As a radiation detector little degradation has been observed in a-Si:H diodes on exposure to high radiation fluences. As discussed in Chapter 4, 1 Mev neutron fluences exceeding 10^{14} cm⁻² produced little degradation in leakage current and noise, and the effects were annealable. 1.4 Mev proton irradiation showed more damage in terms of degradation in leakage curr-

ent and noise and it became significant at 10^{13} cm⁻² fluence. This proton fluence corresponds to ~ 22 Mrad ionizing dose. The effects were partially annealable.

2.1 Structure of amorphous silicon

Fig. 2.1. Two-dimensional sketch of a random network of amorphous silicon incorporating several dangling bonds. Also shown are hydrogen atoms passivating some of the dangling bonds when amorphous silicon is hydrogenated.

X-ray and electron diffraction experiments show that the nearest neighbor environment in a-Si is approximately the same as that found in its crystalline counterpart. Although the long-range periodicity is absent in a-Si based materials, a high degree of short-range order is retained because of the chemical bonding resulting in nearly equal bond lengths and bond angles as in crystalline Si.

Generally, a continuous random network (CRN) in which all bonds are satisfied but in which there is no long-range order is used as a model for a-Si. It is widely believed that in the bulk of a-Si a Si atom on the average is surrounded by four other atoms at the same distance as in crystalline Si, forming a regular tetrahedron. Further, each of these atoms in turn has three more neighbors forming a well-defined second shell of 12 atoms none of which is a neighbor to any other. The resemblance of a-Si to crystalline Si ceases beyond the second shell [Madan , 1988]. In a CRN although the number of atoms associated with the nearest neighbors is the same, there is a variation in the interbond angles that rapidly leads to loss of order.

Polk [1971] first demonstrated the possibility of building a CRN for tetrahedrally bonded a-Si with coordination number of 4 by allowing $\pm 10^\circ$ spread in the tetrahedral bond angle of 109.5° .

Fig. 2.1 shows two-dimensional sketch of a random network for amorphous silicon. Also shown are several dangling bonds. In amorphous silicon the density of these dangling bonds is $\sim 10^{19} \text{ cm}^{-3}$. Hydrogen incorporation lowers these dangling bonds to $\sim 10^{15} \text{ cm}^{-3}$.

2.2 Effect of disorder

Because of the absence of long-range order the conduction and valence bands in a-Si differ from those in crystalline Si in having a tail of states localized in the sense of Anderson [1958]. According to

Fig. 2.2. Schematic showing states in the band gap of amorphous silicon. The shallow states are due to long-range disorder and the deep states are due to structural defects such as dangling bonds.

Anderson's state is localized if, for an electron placed in the state at $t=0$, there exists a finite probability of finding the electron in the state at $t=\infty$ or more simply the electron has not diffused. The localized band tail states in Fig. 2.2, that is the states between E_c and E_b , and E_v and E_b are supposed to be due to lack of long-range order and the deeper lying gap states denoted by E_x and E_y are ascribed to structural defects such as dangling bonds.

2.2.1 The mobility edge

Anderson [1958] predicted that for a carrier moving in a potential well of Fig. 2.3 all states would be localized if V_0/B exceeded a critical value. Here V_0 is the extent of the random potential as shown in Fig. 2.3(b) and B is the bandwidth when V_0 vanishes. Mott [1967] showed that if V_0/B was less than the critical value the states in the gap would be localized, a sharp energy, E_c , called the mobility edge, as illustrated in Fig. 2.4, would separate the localized from the extended states. The position of the mobility edge is an intrinsic property of the CRN and not a consequence of defects. In a-Si:H the position of the mobility edge is independent of

Fig. 2.3. The potential energy of an electron in the Anderson model. (a) Without random potential. (b) With random potential. B is the bandwidth when V_0 vanishes. The density of states is also shown.

Fig. 2.4. Density of states near mobility edge, E_c . The states below the edge are localized and above it are extended and thus have distinctly higher mobility.

hydrogen content [Jones et al., 1980]. The fact that hydrogen (10% or so) widens the band gap is believed to be due to a shift of the valence band downwards. One strong evidence of the existence of mobility edge is the change in the behaviour of conductivity from extended state conductivity in the conduction band to hopping conductivity in the shallow states as temperature is lowered. This is discussed in section 2.4.4.

2.3 Density of states

The states in the gap of an amorphous semiconductor not only

control the position of the Fermi energy, E_f , but also the transport properties of the material. In addition, they act as traps and recombination centers that determine the kinetics for the restoration of equilibrium after any perturbation away from thermal equilibrium. Further, in intrinsic a-Si:H the defect centers release charge which is swept out by the electric field thus producing space charge in the material which then shapes the electric field inside the sample.

The energy associated with repulsion between two electrons with opposite spins that are present in the same spatial state is called the correlation energy, U . When an electron of either spin is present on the defect center the energy of the corresponding state for the electron with opposite spin is increased by U and this configuration forms a D^- defect center as shown in Fig. 2.5(d). For localized states U is of the order of a few tenths of an eV.

The key to understanding the electronic structure of a-Si and its related alloys, for example a-Si:H, is the fact that it forms an overconstrained network in which the average coordination is 4 in comparison to ≤ 2.4 dictated by optimal bond lengths and bond angles for covalent bonding [Adler et al., 1985] leading to local strains. For an overconstrained material one expects that most of the strain is relieved by non-optimal bond angles. This is the reason why a-Si exhibits a $\pm 10^\circ$ spread from the optimal tetrahedral bond angle of 109.5° . However, during the preparation of a-Si some concentration of stretched bonds and uncoordinated atoms are likely to be introduced because of the extent of the overconstrained nature of

the network. Alloying with any element from other columns in the periodic table, e.g. hydrogen, lowers the average coordination z and this tends to reduce the overall strain. The simplest defect that uncoordination produces is a three-fold coordinated Si atom usually called a dangling bond. The conventional notation used to denote coordination and charge state of a defect is D_z^q where z is the coordination number and q is the charge state of the defect. Thus a neutral dangling bond would be denoted by D_3^0 . Tight-binding calculations of Adler [1978] indicate that D_3^0 defects yield two states in the gap, a lower filled state D^0 and an upper empty state D^- separated by U . An electron removed from a D^0 center converts it to D^+ center. The D^+ and D^- centers are spin paired and exhibit no ESR signal unlike the D^0 center which is paramagnetic and can be observed by its characteristic ESR signal ($g=2.0055$). The ground state and several of the defect centers in a-Si are shown in Fig. 2.5.

Hydrogenated amorphous silicon, $a\text{-Si}_{1-x}\text{H}_x$, has an average coordination number $z \approx 4-3x$, so that a typical concentration of 20% hydrogen decreases z from 4 to 3.4 thus inducing a considerable reduction in overall strain [Adler et al., 1985]. This reduction manifests itself by sharp decrease in local bond distortion and defects. In addition, the Si-H bond strength is approximately 3.4 eV which is about 40% greater than Si-Si bond strength of 2.4 eV. Since H is more electronegative than Si, Si-H bonding states are deep in the a-Si:H valence band while Si-H antibonding orbitals are not too far from the conduction band mobility edge.

If unoccupied defect center D^+ is taken at zero energy and the

Fig. 2.5. Schematic of local bonding configurations of ground state and several defect centers in a-Si (a) ground state, D_4^0 (b) neutral dangling bond D_3^0 (c) positively charged defect center, D_3^+ (d) negatively charged defect center, D_3^- . The bond angles shown are $\alpha = 109.5^\circ$, $\beta = 120^\circ$, $\gamma = 95^\circ$; sp and p are the spectral notations of orbitals [Adler, 1984].

energy of neutral defect center is denoted by E_d it will take energy $E_c - E_d$ to excite an electron from a neutral defect center to the con-

duction band. A negative defect center D^- has both electrons present and the two electrons repel each other, the second electron is at energy E_d+U . Only an energy of E_c-E_d-U is needed to excite it to the conduction band. The three states D^+ , D^0 and D^- all possess a minimum energy configuration which is necessarily distinct.

Fig. 2.6. Schematic of the density of states of intrinsic a-Si for $U_{eff} > 0$.

The correlation energy, U , can be defined as the energy required for the reaction

without any local atomic relaxation. However, in reality the local environment around D^+ and D^- states will relax, lowering the energy of both states and therefore the value of U . The minimum energy needed to create an oppositely charged D^+-D^- defect pair from two D^0 centers is the effective correlation energy, U_{eff} . The evidence that U_{eff} is positive in a-Si:H is provided by the ESR data [Dersch et al., 1981]. However, the possibility of negative U_{eff} in a-Si:H has been argued by some authors [Adler, 1983]. The density of states (DOS) diagram for amorphous silicon with $U_{\text{eff}} > 0$ is shown in Fig. 2.6.

2.3.1 Growth conditions and density of states

Good quality hydrogenated amorphous silicon is deposited by a glow discharge method (also called plasma enhanced chemical

Fig. 2.7. Schematic diagram of glow discharge deposition system. The deposition is commonly done at 13.56 MHz.

vapour deposition). Fig. 2.7 shows a schematic diagram of the deposition system. Intrinsic a-Si:H is deposited using silane gas (SiH_4). Phosphine (PH_3) or Diborane (B_2H_6) gases are introduced for n or p type doping.

Fig. 2.8. Localized state density, $g(E)$, for glow discharge a-Si:H. T_s is the substrate temperature. Full lines are obtained from the field effect data and the arrows indicate the Fermi level position of the samples. [Madan, 1973; Spear, 1973; Madan et al., 1976].

The density of states (DOS) in the gap of glow-discharge deposited hydrogenated amorphous silicon is critically controlled by the deposition temperature, T_s , of the substrate [Spear et al., 1972]. The DOS decreases by orders of magnitude when T_s is increased from 300° k to 570° k as shown in Fig. 2.8 [Madan, 1988]. The vast change in the DOS with change in T_s is attributed to basic structural changes occurring in the material. The films produced at low T_s generally have more H concentration, in excess of 30%, leading to formation of polymeric type structures with a greater number of Si-H₂ and Si-H₃ groups as shown in Fig. 2.9 [Lucovsky et al., 1979]. It is

Fig. 2.9. Local bonding geometries. (a) isolated groups, (b) monohydride configurations in which SiH groups are attached to second or nearest neighbor, and (c) polymeric structures based on SiH₂ units [Lucovsky et al., 1979].

the fundamental change from polymeric type structure for films deposited at low T_s to monohydride type at higher T_s that has a major effect on the reduction of the DOS. The best quality a-Si:H has an H concentration of $\sim 10\%$. Hydrogenation decreases the defect density from $\sim 10^{19} \text{ cm}^{-3}$ in pure amorphous silicon (a-Si) to $\sim 10^{15} \text{ cm}^{-3}$ in hydrogenated amorphous silicon.

Fig. 2.10. Schematic of the model proposed to explain the hydrogen elimination process from the a-Si:H film during growth [Kampas and Griffith, 1981].

The quality of the film is influenced by the pressure of the gas during deposition since high gas pressure enhances gas phase polymerisation with consequent increase in Si-H₂ and Si-H₃ groupings within the film [Kampas, 1982]. In general the hydrogen content,

C_H , of a-Si based alloy is approximately in the range of 10-30 at% which is much smaller than H/Si ratio (≈ 4) for a pure SiH_4 plasma. Kampas and Griffith [1981] suggested a model for the growth kinetics of a-Si:H film explaining the hydrogen elimination process from the film and the polyhydride formation. According to the model the SiH_2 free radicals react with the Si-H bond on the growing surface and produce an activated complex that can eliminate H_2 molecules. The amount of hydrogen remaining in the film is determined by a competition between H_2 elimination and deactivation of the complex. Further, the authors concluded that changes in the deposition parameters that control the deposition rate also increase the atomic hydrogen flux on the growing surface, which results in a higher hydrogen content in the film. Fig. 2.10 shows a schematic of the SiH_2 addition, H_2 elimination and cross-linking sequence proposed by the authors.

2.4 Electrical transport in amorphous silicon

It is vitally important to understand the processes behind the electrical transport in a-Si:H. As mentioned earlier the transport is strongly influenced by the states in the band gap which can be divided into two parts (a) tail states which result from disorder (b) mid-gap states due to point defects. The role of these states in the conductivity of the material is discussed below.

2.4.1 Conductivity in extended states

Transport in the extended states is a result of carriers excited beyond the mobility edge into states at or around E_c . The conductivity, σ , for a semiconductor can be expressed as

$$\sigma = e \int g(E) \mu(E) f(E) dE \quad (2.1)$$

where $g(E)$ is the density of states, $\mu(E)$ is the mobility and $f(E)$ is the Fermi function.

The extended state mobility in amorphous silicon has been a subject of controversy. It is generally agreed that the directly measurable quantity, the drift mobility, μ_D , is relatively small of the order of $1 \text{ cm}^2/\text{V-s}$ for electrons at room temperature. But the drift mobility is only a fraction of the band mobility, μ_0 , since it is limited by the trapping of carriers. The two are related by [Tiedje et al., 1980]

$$\mu_D = \mu_0 \frac{n_0}{n_0 + n_t} \quad (2.2)$$

where n_0 and n_t are the concentrations of free and trapped carriers respectively. The value of μ_0 extracted from μ_D is $\sim 10 \text{ cm}^2/\text{V-s}$ [Tiedje et al., 1981] or $\sim 500 \text{ cm}^2/\text{V-s}$ [Silver et al., 1982] depending upon the inferred density of states $g(E)$. One view is that conduction beyond the mobility edge proceeds with a scattering event every second or third neighbor. The other view is that the band mobility is of the same order as that of crystalline silicon (c-Si) but large den-

sities of traps greatly reduce the drift mobility. The complete absence of geminate recombination; geminate recombination is the name given to the process whereby two thermalized oppositely-charged particles attempt to escape from each other in the presence of their mutual Coulomb attraction [Adler et al., 1985]; indicating extremely rapid separation of photo-generated carriers, and recent work on multilayer structures [Abeles and Tiedje, 1983] suggesting delocalized wave functions with coherence lengths in excess of 30 Å are strong evidence in support of higher values of band mobilities. However, commonly accepted value of μ_0 , derived from transient photoconductivity experiments, is of the order of 10.

If it is assumed that conduction is due to carriers within kT of the mobility edge E_c then from eq. (2.1)

$$\sigma = e \int_{E_c}^{E_c+kT} g(E_c) \mu_0 \exp[-(E_c - E_f)/kT] dE \quad (2.3)$$

$$\begin{aligned} &\approx eg(E_c) \mu_0 \exp[-(E_c - E_f)/kT] \int_{E_c}^{E_c+kT} dE \\ &\approx eg(E_c) \mu_0 kT \exp[-(E_c - E_f)_T/kT] \end{aligned} \quad (2.4)$$

The temperature dependence of $E_c - E_f$ can be expressed as

$$(E_c - E_f)_T = (E_c - E_f)_0 - \delta_F T$$

and using eq. (2.4) we have

$$\sigma = eg(E_c) \mu_0 kT e^{\delta_F/k} \exp[-(E_c - E_f)_0/kT] \quad (2.5)$$

The pre-exponential factor in eq. (2.6) has been a subject of controversy.

$$\sigma = \sigma_0 \exp[-(E_c - E_t)/kT] \quad (2.6)$$

Fig. 2.11(a). Temperature dependence of the electron drift mobility for an electric field of 10^4 V/cm (closed circles) and 2×10^4 V/cm (open circles). The solid (broken) line is a fit to the low- (high-) field data with $T_c = 312^\circ$ K, $\mu_0 = 13$ cm²/V-s and $\nu = 4.6 \times 10^{11}$ s⁻¹. The insets are representative photocurrent decays at 300° and 190° K plotted as Log I vs Log t; the time scale is microseconds [Tiedje et al., 1981].

Fig. 2.11 (b). Temperature dependence of the hole drift mobility for an electric field of 5.8×10^4 V/cm. The solid line is a fit to the data based on eq. (2.8a) with $T = 500^\circ$ K, $\mu_0 = 0.67$ cm²/V-s and $\nu = 1.6 \times 10^{12}$ s⁻¹. The insets are representative photocurrent decays at 359° and 270° K plotted as Log I vs Log t; the time scale is in microseconds [Tiedje et al. , 1981].

Mott [1985] argues that σ_0 in a non-crystalline semiconductor system should be given by

$$\sigma_0 = 0.03 e^2 / \hbar L_i \quad (2.7)$$

where L_i is the inelastic diffusion length, consequence of electron-

phonon interaction. Using the experimental values of the time between collisions Mott concludes that the pre-exponential factor $\sigma_0 = 16 \Omega^{-1} \text{ cm}^{-1}$ and the extended state mobility $\mu_0 = 8 \text{ cm}^2/\text{V-s}$ which are consistent with most experimental values.

The value of μ_D is obtained from time of flight (TOF) experiments where carrier mobility is measured as a function of temperature [Tiedje et al., 1981]. Fig. 2.11(a,b) shows plot of electron and hole mobility as a function of $1/T$ respectively and fit to the data based on eq. (2.8).

$$t_r \equiv v^{-1} \left(\frac{v}{1-\alpha} \right)^{\frac{1}{\alpha}} \left(\frac{L^2}{\mu_0 V} \right)^{\frac{1}{\alpha}} \quad T < T_c \quad (2.8)$$

where $\alpha = T/T_c$ and the drift mobility is $\mu_0 (1-T_c/T)$ for $T > T_c$. Here, kT_c is an energy which characterizes the width of the exponential band tail. From the fit to the data it is estimated that μ_0 for electrons is $\sim 13 \text{ cm}^2/\text{V-s}$ and for holes is $\sim 0.67 \text{ cm}^2/\text{V-s}$. It is also seen that at low temperatures the electron photocurrent transient exhibits the power law decay characteristics of dispersive transport (lower inset in Fig. 2.11 (a)). However, the hole transport is dispersive over the entire temperature range and the activation energy is $\sim 0.35 \text{ eV}$.

2.4.2 Conductivity in tail states

The tail states in amorphous semiconductors are the conse-

quence of disorder and lie in the energy range $E_a < E < E_c$ and $E_v < E < E_b$ for the conduction and valence bands respectively as shown in Fig. 2.12.

The conductivity at an arbitrary energy $E = E_x$ for the conduc-

Fig. 2.12. Schematic of the density of states of a-Si:H [Street].

tion band tail can be written as

$$\begin{aligned}\sigma &= e \int \mu(E) g(E) f(E) dE \\ &= e \mu_{\text{hop}} \int_{E_a}^{\infty} g(E_x) \exp[-(E_x - E_f)/kT] dE\end{aligned}\quad (2.9)$$

where μ_{hop} is the hopping mobility, consequence of transport of carriers in the localized states by tunnelling from an occupied to an

unoccupied state [Adler et al., 1985].

Cohen [1970] showed that hopping mobility, μ_{hop} , is given by

$$\mu_{\text{hop}} = \frac{1}{6} v_{\text{ph}} \left(\frac{eR^2}{kT} \right) \exp[-W_1/kT] \quad (2.10)$$

where R is the hopping distance and W_1 is the energy difference between the initial and final states [see appendix 1].

2.4.3 Variable range hopping conductivity

Fig. 2.13. (a) Hopping of a carrier from state A below the Fermi energy to state B above it. (b) At low T , long range less energetic hops are favoured.

Thermally activated hopping conduction of carriers between localized states situated in the mid-gap region $E_b < E < E_a$ occurs at

low T , or at high T in materials with high defect density. Fig. 2.13 shows this kind of transport where a carrier hops from state A below the Fermi energy to state B above it. The hopping conductivity at E_f is given by [appendix 1]

$$\sigma_{\text{hop}} = \sigma_0 \exp\left(-\frac{A}{T^{\frac{1}{4}}}\right) \quad (2.11)$$

Eq. (2.11) is known as Mott's $T^{\frac{1}{4}}$ law [Mott, 1968].

2.4.4 Electrical transport in a-Si:H

Fig. 2.14. Plot of $\ln \sigma_D$ vs $1/T$ for typical glow discharge (GD) a-Si:H [Madan, 1988].

Glow discharge a-Si:H has a low defect density, several orders of magnitude lower than a-Si. As seen in Fig. 2.14 the Arrhenius

Fig. 2.15. Temperature dependence of (a) Electron drift mobility μ_D . (b) Conductivity σ_D in a glow discharge a-Si:H deposited at $T_s = 500^\circ \text{K}$. T_C is the temperature at which change in transport behaviour is seen [LeComber and Spear, 1970].

plot (dark conductivity σ_D vs $1/T$) exhibits a straight line behaviour and a well defined activation energy $E_D = E_c - E_f$ is obtained. The conductivity, σ , can be expressed by eq. (2.6) with activation energy $E_D \sim 0.8$ eV for intrinsic a-Si:H. Intrinsic a-Si:H is slightly n-type and activated behaviour is due to extended state conduction above E_c . This is in contrast to a-Si where unique activation energy is hard to define and conductivity is dominated by thermally activated hopping within the defect states. The change in transport mechanism in a-Si:H from extended states conduction to thermally activated hopping in the tail states was first reported by LeComber et al. [1974] showing that the drift mobility on a $\ln \mu_D$ vs $1/T$ plot had a kink at $T \sim 250^\circ$ K as shown in Fig. 2.15(a). The same kink was observed in a $\ln \sigma_D$ vs $1/T$ plot as shown in Fig. 2.15(b). The data was interpreted in terms of the existence of two regions. In the region (1) the conductivity showed activated behaviour with the activation energy $E_D = E_c - E_f$ given by eq. (2.6) and the region (2) where conductivity changed to thermally activated hopping behaviour with the activation energy given by $E_D = E_x - E_f + W$. The $\ln \mu_D$ vs $1/T$ plot was also interpreted in terms of the change in conduction from the extended states behaviour with activation energy $E_c - E_a$ (~ 0.2 eV) for region (1) to a thermally activated hopping mode within localized states with the activation energy ~ 0.1 eV for region (2). The photoconductivity measurements of Spear et al. [1974] also showed such a kink.

The evidence of $\ln \sigma_D$ vs $T^{-1/4}$ behaviour predicted by eq. (2.11) is not seen in glow discharge a-Si:H although this behavior is found

in highly defective material such as elemental evaporated Si.

2.5 Material parameters of a-Si:H for device applications

The quantities of interest in using a-Si:H for device applications are carrier mobility, carrier lifetime usually expressed as mobility-lifetime product and the dangling bond density [Qureshi et al., 1988]. While carrier mobility determines device speed and, together with carrier lifetime, determines the charge collection behaviour of a device, the defect density is crucial in shaping the electric field in the device under the influence of which carrier drifts. Therefore, the role of these parameters in a device fabricated from a-Si:H cannot be over emphasized. These parameters bear direct relationship to material quality, and their measurement is crucial in judging the quality of a-Si:H.

2.5.1 Drift mobility by transient photoconductivity method

The drift mobility is measured by time of flight (TOF) where carriers are injected at one point in the sample and their transit under the influence of electric field across the sample is studied by measuring the transit time t_T . An expression for carrier mobility under uniform electric field F is obtained as below.

The carrier velocity, v , is given by

$$v = \mu_D F$$

where μ_D is the drift mobility and F is the electric field. Also

$$v = \frac{d}{t_T}$$

Thus, for uniform electric field $F = V/d$, we have

$$\mu_D = \frac{d^2}{V t_T} \quad (2.12)$$

Some important considerations in drift mobility measurements are :

(a) The mean free path X_0 of light must be short compared to sample thickness, d , so that carriers are generated on one end of the sample and the signal is primarily due to transit of only one type of carrier. This condition is satisfied by using appropriate wave length light. We use 510 nm laser light ($X_0 \sim 0.2 \mu\text{m}$ in a-Si:H) to study diodes 12 μm or more thick.

(b) The photo-injected charge must be small so that the electric field in the sample is not perturbed by it [Street, 1983]. This can be ensured by reducing the light intensity. A rule of thumb used to avoid these space charge effects is that the injected charge be approximately an order of magnitude smaller than charge (CV) across the sample.

(c) The relaxation time, $\tau_{rel} = \epsilon_0 \epsilon_r / \sigma$, where ϵ_0 is the permittivity of vacuum, ϵ_r is the dielectric constant of amorphous silicon and σ is the conductivity, must be much larger than the transit time t_T of carriers. This condition is easily satisfied in intrinsic a-Si:H and the

mobility of both types of carriers can be measured by injecting light from the n or p side of a p-i-n diode. The relaxation time for intrinsic a-Si:H is of the order of a millisecond or longer, estimated from eq. (2.13) [Tiedje et al., 1980]

$$t \approx 10^{-12} \exp [E/kT] , \quad (2.13)$$

where t is the thermal release time and E is the energy (measured from the conduction band) of a state in the gap occupied by an electron. The relaxation time for a-Si:H can also be estimated from

Fig. 2.16. Schematic illustrating the principle behind drift mobility measurement. (a) Drift of electrons across the sample. (b) Time delay between pulsed bias and laser light.

resistivity and the dielectric constant ($\sigma \sim 10^{-10} \Omega^{-1} \text{ cm}^{-1}$, $\epsilon_0 \epsilon_s \sim 10^{-12} \text{ F/cm}$). Once relaxation occurs under applied bias, space charge is created in the sample, resulting in the shaping of the electric field. However, in a T.O.F experiment the condition of a uniform electric field is satisfied by pulsing the bias and then injecting the charge several microseconds after the applied bias, as illustrated in Fig 2.16(b). The sample is allowed to reach thermal equilibrium which usually takes several seconds, before the sequence is repeated. Typical electron transient at room temperature is shown in Fig. 2.16(a).

2.5.2 Gaussian transport

Transport of electrons at room temperature is non-dispersive and is described by Gaussian statistics [Scher et al., 1975]. The time development of the injected carriers can be described in terms of mean displacement l from the illuminated surface as shown in Fig. 2.17. The parameter β characterizes the spread of charge sheet about the mean. The charge density as a function of position and time during the transit can be described by [Leal Ferreira , 1977]

$$\rho(x, t) = A \frac{1}{t^{1/2}} \exp[-(x-x_0)^2 / B t] \quad (2.14)$$

where x_0 refers to the location where the charge sheet is created. For Gaussian transport, spread of the charge sheet by diffusion about

Fig. 2.17. Schematic representation of carrier propagation under Gaussian conditions, Top: Position of representative carriers in the sample bulk at $t = 0$ (○), $t < \tau_T$ (●) and $t \sim \tau_T$ (◐). Middle: Charge distribution in sample bulk at $t=0$, $t < \tau_T$ and $t \sim \tau_T$. Bottom: Current pulse in external circuit induced by charge displacement. Units normalized to τ_T and $i_T = i(t)$. Dashed line represents transient current for lower applied bias field, i.e. longer transit time. (1) shows charge sheet just after injection, (2) indicates charge is traversing through the bulk but not reached the farther contact and (3) shows that a fraction of injected charge has already reached the farther contact [Pfister and Scher, 1978].

the mean can be written as

$$\frac{\beta}{l} \approx \frac{t^{1/2}}{t} = t^{-1/2} \quad (2.15)$$

Thus at transit time we have

$$\frac{\beta}{l} = t_T^{-1/2} \propto \left(\frac{F}{d}\right)^{1/2} \quad (2.16)$$

For non-dispersive transport transit time is defined as the time at which current drops by 50%. This is the time for the center of the gaussian charge sheet to traverse distance d .

2.5.3 Dispersive (non-Gaussian) transport

In this mode of transport the shape of the current transient is independent of transit time t_T , a property usually referred to as universality [Scher et al. , 1975]. The charge sheet does not grow symmetrically about its mean position. Some of the injected carriers drift rapidly into the sample. A significant fraction of carriers suffer scattering and get immobilized for times of the order of transit time t_T . The charge packet grows asymmetrically where the leading edge penetrates deep into the sample and the maximum point of charge density moves slowly away from the generation point. The spread and the mean position of charge have the same time dependence giving $\beta/l = \text{constant}$ [Scher et al., 1975].

Fig. 2.18. Schematic representation of carrier propagation under ideal non-Gaussian conditions. Top: Position of representative carriers in the sample bulk at $t=0$ (•), $t < \tau_T$ (•) and $t \sim \tau_T$ (*). Middle: Charge distribution in sample bulk at $t=0$, $t < \tau_T$ and $t \sim \tau_T$. Bottom: Current pulse in external circuit induced by charge displacement in linear units (left) and logarithmic units (right). Dashed line represents transient current for lower applied bias field, i.e. longer transit time. (1) shows charge sheet just after injection, (2) indicates charge is traversing through the bulk but not reached the farther contact and (3) shows that a fraction of injected charge has already reached the farther contact [Pfister and Scher, 1978].

The current transient in the case of dispersive transport has two slopes $(1-\alpha)$ and $(1+\alpha)$ when plotted as a $\log i(t)$ vs $\log t$ plot, as shown in Fig. 2.18. Here α is the dispersion parameter. This behaviour has been modelled by Scher et al. [1975]. The transit time in this case is defined by the point of intersection of two slopes.

2.5.4 Mobility-lifetime product

The mobility-lifetime product $\mu\tau$ is a useful parameter as it determines the mean drift length, $\mu\tau F$, of carriers before capture. It is a directly measurable quantity and is obtained by measuring charge collection as a function of electric field, F . Under uniform electric field the charge collection is given by the Hecht equation [Street, 1983]

$$\int J dt = Q = Q_0 \mu \tau \frac{F}{d} [1 - \exp(-\frac{d}{\mu \tau F})] \quad (2.17)$$

where Q_0 is the injected charge due to one type of carrier and d is the sample thickness. The experiment for $\mu\tau$ measurement is done under pulsed bias conditions and the charge collection data is fitted to the Hecht equation. The $\mu\tau$ product is obtained from the fit.

2.5.5 DC bias transient

The defect centers in a-Si:H release charge causing the electric field in the sample to become nonuniform in a time of the

Fig. 2.19. Examples of the internal-electric field profile for Cr and Pt contacts to the same sample. The times marked correspond to those of the transient response. The values of W are obtained from the charge-collection measurements. $N(E)$ is derived from the exponential region of the field profile [Street, 1983].

order of a second after DC bias is applied [Street, 1983]. The photo-excited carriers move under the influence of nonuniform electric field which is caused by the presence of space charge. The field follows the drop off given by the Poisson equation ($dF/dx = -\rho/\epsilon_0\epsilon_r$)

where p is the charge density in the sample. The transient photocurrent produced by motion of photo-excited carriers in this nonuniform field is, therefore, a direct measure of the electric field

Fig. 2.20. Measurements of the field and potential profiles for two samples with higher defect density and Pd electrodes. The values of N_s are obtained from ESR measurement [Street, 1983].

inside the sample. The transient response under DC bias decreases monotonically as electrons move across the sample.

The shape of the photocurrent transient relates to the shape of the electric field inside the sample and, therefore, to the ionized defect density. This has been demonstrated in the work of Street [1983]. Fig. 2.19 shows the depletion field as a function of depth into sample. The defect density is derived from the exponential region of the field profile. The measurements were done on a-Si:H samples with n+ bottom contact and chromium contact on top of the i layer. Similar measurements made on samples with Pd contacts are shown in Fig. 2.20.

DC photoconductivity measurements on thick p-i-n diodes intended for radiation detection application purposes are of interest to measure the ionized dangling bond density which shapes the electric field in the diode. The electric field, F , is the agent for drifting the charge across the sample and the drift length is given by the product $\mu\tau F$. Since in an a-Si:H detector the electric field is nonuniform, carriers will move across the field region until they reach the low field region. In the low field region motion of charges is determined by diffusion rather than drift and carriers are eventually trapped or they recombine. Therefore, it is safe to assume that the carriers stop at the end of the depletion layer and are not collected. So in an a-Si:H diode the extent of the electric field in the bulk plays a crucial role in its usefulness as a detector.

2.6 Measurement of material parameters

A time of flight experimental setup was built to measure the

material parameters discussed in section 2.5. Fig. 2.21 is a schematic diagram of the setup. My interest was to study the material parameters of thick p-i-n diodes intended for radiation detection applications. Further, these parameters can be measured to better degree of accuracy in thick samples.

The setup consists of a Nitrogen-Dye laser combination. The laser is triggered externally by a trigger pulse from a high voltage pulser. For pulsed bias measurements the trigger pulse is delayed so that laser fires 50-100 μs after bias is applied across the amorphous silicon diode under study. For DC bias measurements

Fig. 2.21. Time of flight experimental setup with Nitrogen-Dye laser unit used to measure material parameters. The laser is 3 ns (FWHM) producing 510 nm light (MFP $\sim 0.2 \mu\text{m}$ in a-Si:H).

diode bias is derived from a regular power supply. The oscilloscope trigger pulse is generated from the light pulse that excites the dye laser by using a photodiode. The signal from the amorphous silicon diode is amplified by a wide-band amplifier before it is fed to oscilloscope for storage and analysis.

2.6.1 Drift mobility measurement

Fig. 2.22 Transient photocurrent electron signal at different pulsed bias voltages using 510 nm light. Non-dispersive transit of electrons across 27 μm p-i-n diode is seen clearly.

Carrier drift mobility is measured by pulsing the bias voltage applied to the diode under study for a duration of ~ 10 ms. The

laser aimed at either the p or n side of the diode is pulsed 50 - 100 microseconds after bias is applied. Pulsing of the bias shortly before the laser pulse is essential to establish a uniform electric field in the diode as explained in section 2.5.1. The transit time for non-dispersive transport where a charge packet spreads by diffusion (electrons at room temperature) is measured from the photocurrent transient as the time when the current falls to 50% value. In this case light is incident on the p side of the sample so that the holes are collected at the same end and the electrons traverse the sample. Fig. 2.22 shows a typical current transient plotted on a log-log plot at different bias voltages.

Fig. 2.23. Transient photocurrent hole signal from 27 μm p-i-n diode at different pulsed bias voltages. Hole mobility is dispersive with dispersion parameter $\alpha \sim 0.6$ at 300 V.

Hole transport is dispersive as discussed in section 2.5.3. The transient behaviour in case of dispersive transport is given by eq. (2.18a,b) [Scher et al., 1975]. The transit time is measured by plotting the photocurrent transient on a log-log plot and transit time is taken as the time where the two slopes intersect. Fig 2.23 shows the hole transient at different pulsed bias voltages. A hole dispersion parameter $\alpha \sim 0.6$ was estimated for the sample.

$$I(t) \approx t^{-(1-\alpha)}, \quad t < t_T \quad (2.18 \text{ a})$$

$$I(t) \approx t^{-(1+\alpha)}, \quad t > t_T \quad (2.18 \text{ b})$$

where the dispersion parameter α is $0 < \alpha < 1$.

2.6.2. Measurement of mobility-lifetime product ($\mu\tau$)

As discussed in section 2.5.4 the $\mu\tau$ product is measured from a charge collection experiment and fitting collected charge vs bias voltage data to eq. (2.17). Fig. 2.24 shows such a fit to the data. A value of $\mu_e\tau_e = 1.5 \times 10^{-7} \text{ cm}^2/\text{V}$ was obtained.

Similarly, the $\mu\tau$ product of holes is obtained by making a fit to eq. (2.17). A value of $\mu_h\tau_h = 4 \times 10^{-8} \text{ cm}^2/\text{V}$ was obtained for the sample of Fig. 2.24.

Fig. 2.24. Measurement of electron $\mu\tau$ product through a fit to the Hecht equation.

2.6.3. Defect density measurement

Fig. 2.25 shows a typical DC bias photocurrent transient from which the dangling bond density was calculated using eq. (2.19) [see appendix 2]. For a p-i-n diode values of the ionized defect density were found to be in the range of $6\text{-}8 \times 10^{14} \text{ cm}^{-3}$, approximately 1/3 of the defect density measured by ESR.

$$N_d = \frac{\epsilon_0 \epsilon_f}{q\mu} \frac{\ln [i_{dc}(t_1) / i_{dc}(t_2)]}{t_2 - t_1} \quad (2.19)$$

where N_d^* is the ionized dangling bond density. $i_{dc}(t_1)$ and $i_{dc}(t_2)$ are the values of the decaying photocurrent transient at times t_1 and t_2 , μ is the mobility, ϵ_r is the relative permittivity of silicon and q is the electronic charge.

Fig. 2.25. Transient photocurrent electron signal at different DC bias voltages from a 27 μm p-i-n diode using 510 nm light.

Table 2.1 summarizes typical values of material parameters measured on thick a-Si:H p-i-n diodes in a T.O.F experiment. Electron spin density is also listed.

Thickness (μm)	28	27	31.2
Type	Cr-n-i-p	SnO-p-i-n	SnO-p-i-n
μ_e (cm^2/Vs)	1.4	1.2	1.2
$\mu_e \tau_e$ (cm^2/V)	1.1×10^{-7}	1.2×10^{-7}	1.5×10^{-7}
μ_h (cm^2/Vs)	0.003	0.004	0.004
$\mu_h \tau_h$ (cm^2/V)	2.7×10^{-8}	1.2×10^{-8}	4×10^{-8}
N_d^+ (cm^{-3}) (TOF)	6×10^{14}	7×10^{14}	-
N_d (cm^{-3}) (ESR)	2×10^{15}	-	-

Table 2.1. Typical measured parameters of thick a-Si:H p-i-n diodes from a number of diodes studied using setup of Fig. 2.21. Defect density measurement on 31.2 μm diode could not be done due to large diode capacitance. Carrier mobility and mobility-lifetime product values are in agreement with values reported in literature on thin a-Si:H diodes. ESR measurements were done at Xerox PARC. Cr and SnO represent Chromium and Tin Oxide contacts.

The value of the ionized defect density, N_d^+ , obtained for a-Si:H p-i-n diodes by this method is $\sim 1/3$ of the defect density value, N_d , measured by ESR which measures the density of neutral defects in the sample. The same result was obtained by increasing the defect density of a sample by a factor of ~ 2 by heating and then measuring N_d^+ and N_d . A comparison of N_d^+ and N_d values on subsequent annealing further corroborated the result that only a fraction of the defects ($\sim 1/3$) is ionized when diode is biased into deep depletion.

This result can be explained on the basis of the energy of the defects and on the shift of the Fermi energy which results from the depletion bias. On depletion the Fermi energy must move down towards the center of the band gap of the i layer as it is slightly n type. The observed ionized fraction would correspond to a shift of the Fermi energy of ~ 0.1 eV [Qureshi et al., 1989].

However, the work of Matsuura [1988] who used c-Si-i-n structure for defect density measurement by heterojunction-monitored capacitance (HMC) method shows that the measured defect density is in agreement with the ESR measurement though the work of Street et al. [1990] is in support of the observation that only a fraction of the defects are ionized. This underscores the caution required in interpreting the defect density and field profile measurements by DC photoconductivity method for a-Si:H p-i-n structure. Whether the effect can be the result of the sample structure (e.g. high resistivity of the p layer effecting how rapidly the DC bias transient falls) might be worth further investigation.

A quantity of interest, the $\mu\tau N_d$ product, follows from the basic expression relating the capture processes with the trap-limited transport in amorphous semiconductor. Street [1982, 1984] has shown that this product is given by [appendix 3]

$$\mu\tau N_d \equiv \frac{1}{6} \frac{e}{kT} \frac{a}{\sigma} \quad (2.20)$$

where a is the carrier scattering length (in a-Si:H ~ 10 Å for

electrons and $\sim 5 \text{ \AA}$ for holes), σ is the capture cross section and T is the temperature. The product $\mu\tau N_d = 2.2 \times 10^8 \text{ cm}^{-1}\text{V}^{-1}$ is calculated for electrons from column 2 of Table 2.1.

3 Leakage current and noise of a-Si:H p-i-n diode

The current-voltage (I-V) characteristics of a reversed biased a-Si:H diode is of considerable interest for two reasons.

1. The leakage current is important for noise considerations when the diode is used as a radiation detector.
2. Power dissipation in a diode array especially when used as small high density pixels must be kept to a minimum.

Fig. 3.1(a). Typical I-V curve of an a-Si:H diode under reverse bias. The area around the metallic dot on its face was etched to prevent any surface leakage.

The I-V characteristics of a large number of a-Si:H p-i-n diodes fabricated by glow discharge deposition have been studied. Typical I-V characteristics under reverse bias are shown in Fig. 3.1(a,b). Fig. 3.1(b) is a plot of I vs V on a log-log plot. The plot has

Fig. 3.1(b). I-V curve of diode 1 on log-log plot. Eq. (3.1) fits the data with fitting parameters $k_1 = 5.028 \times 10^{-12}$ and $k_2 = 0.437$.

two distinct regions labelled as (1) and (2). The region (1) is low bias region extending from 0.3 to 50 V. Region (2) extends from 50 to 550 V where current increases monotonically over the voltage range. The measured data is fitted to eq. (3.1).

$$I = k_1 \exp (k_2 \sqrt{V}) \quad (3.1)$$

where V is the bias voltage. k_1 and k_2 are fitting parameters. As is seen in Fig. 3.1(b) the above equation fits the data remarkably well particularly at high bias voltage.

Table 3.1 shows measured and calculated noise (FWHM) of the diode. The leakage current and noise listed in the table were measured on the setup shown in Fig. 3.2. An LBL dual shaping amplifier with CR-(RC)⁴ (pseudo-Gaussian) shaping [Goulding, 1972] at 3 μ s shaping time was used. The charge sensitive preamplifier used was a Tennelec TC 171 with no shaping.

The noise in column 3 of Table 3.1 was calculated from the shot noise equation [Goulding et al., 1982].

Fig. 3.2. Schematic of experimental set up used for measurement of leakage current and noise listed in Table 3.1.

bias (v)	current (A)	N _{cal} (e ⁻)	N _m (e ⁻)
0	0	-	4000
100	7x10 ⁻¹⁰	4007	4200
200	6x10 ⁻⁹	4068	4170
300	2.3x10 ⁻⁸	4253	4320
400	6.2x10 ⁻⁸	4652	4650
500	1.5x10 ⁻⁷	5445	5450
550	2.35x10 ⁻⁷	6110	5950

Table 3.1. Measured and calculated noise (FWHM) for 29 μm diode of Fig. 3.1. The noise is calculated from the shot noise equation for the LBL dual shaping amplifier with CR-(RC)⁴ (pseudo-Gaussian) shaping at 3 μs shaping time as discussed in the text. A remarkable agreement is seen between the measured and calculated noise.

$$\langle N_s^2 \rangle = 0.9 \frac{I\tau}{q} \quad (3.2)$$

where τ is the shaping time, I is the leakage current and q is the electronic charge, and the noise component at 0 V bias added in quadrature. It is seen that the measured noise agrees remarkably well with the calculated noise. This shows that for a well behaved a-Si:H p-i-n diode, noise is completely accounted for by the shot noise and the noise component at 0 V bias for CR-(RC)⁴ (pseudo-Gaussian) shaping at 3 μs shaping time. A sample calculation of the

noise at 400 V bias is given below.

Sample calculation of noise at 400 V bias:

The shot noise equation for CR-RC shaping is given by

$$\langle N_s^2 \rangle = \frac{\varepsilon^2}{4q} I \tau$$

where I is the leakage current, τ is the shaping time, q is the electronic charge and $\varepsilon = 2.718$. The above equation can be written as

$$\langle N_s^2 \rangle = 1.153 \times 10^{13} \tau (\mu s) (A) \quad (rms)^2 \quad (3.3)$$

At 400 V bias $I = 6.2 \times 10^{-8}$ A and $\tau = 3 \mu s$.

Therefore, $\langle N_s^2 \rangle = 3.459 \times 10^{13} \times 6.2 \times 10^{-8} = 2.14 \times 10^6$

For CR-(RC)⁴ shaping we have [Goulding, 1972]

$$\frac{\langle N_s^2 \rangle_{CR-RC^4}}{\langle N_s^2 \rangle_{CR-RC}} = \frac{0.9}{1.87} = 0.48$$

Therefore,

$$\langle N_s^2 \rangle_{CR-RC^4} = 0.9 \frac{I \tau}{q} = 0.48 \times 2.14 \times 10^6$$

$$\langle N_s \rangle = 0.69 \times 1.463 \times 10^3 \quad (rms)$$

$$= 1009.3 \quad (rms)$$

$$= 1009.3 \times 2.35 = 2372 \quad e^- \quad (FWHM)$$

Therefore,

$$N_{cal} = \sqrt{[4000^2 + 2372^2]} = 4650 \quad e^- \quad (FWHM)$$

Fig. 3.3. Measured and calculated noise (FWHM) on another 29 μm diode from the same production run as diode 1 for 3 μs shaping time and CR-(RC)⁴ shaping. Here noise at 0 V bias is lower by a factor of 2.

Fig. 3.3. shows the calculated and measured noise of a 29 μm p-i-n diode having smaller noise component at 0 V. It is seen that the calculated noise closely follows the measured noise over the operating voltage range of the diode. The noise data is listed in Table 3.2.

bias (v)	current (nA)	N_{cal} (e ⁻)	N_m (e ⁻)	bias (v)	current (nA)	N_{cal} (e ⁻)	N_m (e ⁻)
0	0	-	2005	160	3.6	2085	2284
10	-	-	2157	220	9.5	2209	2482
20	-	-	2190	260	15.7	2334	2517
30	0.1	2007	2205	300	24.6	2501	2799
40	0.1	2007	2172	360	45.3	2853	3158
50	0.2	2010	2341	400	67	3180	3443
60	0.3	2011	2325	460	117	3839	4046
90	0.7	2020	2224	500	167	3897	4382
120	1.6	2041	2288				

Table 3.2. Calculated and measured noise at 3 μ s shaping time for a 29 μ m a-Si:H p-i-n diode using an LBL dual shaping amplifier with CR-(RC)⁴ shaping.

The I-V curve of the diode is shown in Fig. 3.4. The eq. (3.1) is fitted to the data as shown in the figure. The increase in leakage current with bias described by eq. (3.1) has the same dependence on voltage as one would expect if this increase were due to the Poole-Frenkel effect [Hill, 1971] involving excitation of carriers from neutral defects. In the Poole-Frenkel effect the ionization energy of a defect center is decreased by the applied field F , in the direction of the field by $\beta F^{1/2}$. Electron emission can take place over

Fig. 3.4. I-V curve of a 29 μm diode under reverse bias. The noise data is listed in table 3.2. The data is fitted to eq. (3.1). The fitting parameters are $k_1 = 1.745 \times 10^{-11}$ and $k_2 = 0.41$.

Fig. 3.5. The Poole-Frenkel effect. The ionization energy, E_i , of a defect center is decreased by the applied field F , in the direction of the field. The coefficient β is the Poole-Frenkel constant [Hill, 1971].

the top of the reduced barrier as in (a), or by tunnelling as in (b) of Fig. 3.5.

These measurements clearly suggest that in real devices the detector leakage current for a well behaved diode at the operating bias is the dominant contributor to noise in the form of shot noise for CR-(RC)⁴ shaping.

The noise at 0 V bias is contributed by two factors. One is the result of loading of the diode capacitance on the charge sensitive amplifier commonly known as the delta noise, given by [Goulding et al., 1982].

$$\langle N_{\Delta}^2 \rangle = \frac{kT C^2 \epsilon^2}{2q^2 \tau g_m} \quad (3.4)$$

where C is the equivalent capacitance of the diode and the amplifier input stage, τ is the shaping time, g_m is the transconductance, k is the Boltzman constant and q is the electronic charge. The second noise component is due to thermal noise. This noise component needs to be probed further.

Further, as diode area is reduced, say by a factor of 10, one expects from equations (3.3) and (3.4) a reduction in the step (shot) and delta noise approximately by factors of 3.16 and 10 respectively making the contribution of step noise component more dominant.

Radiation hardness is an important consideration when a device is to be used in a high radiation environment. Crystalline Si radiation detectors are known to degrade in their performance on prolonged exposure to radiation. One important consequence of irradiation is the introduction of energy levels in the band gap which then act as traps for the carriers causing a reduction in the carrier lifetime and change in the electrical resistivity of the device. The reverse leakage current increases and so does the noise of the device. These effects are seen in crystalline silicon detectors at particle (neutron) fluences $\sim 10^{12} \text{ cm}^{-2}$. This degradation of the device in a high radiation environment is undesirable from performance and economic considerations. It is of particular concern in high energy accelerator applications.

Hydrogenated amorphous silicon diodes have been shown to be significantly less susceptible to radiation damage owing to their inherent disorder. Most of the early studies were done on thin diodes ($\sim 1 \mu\text{m}$) for solar cell applications.

4.1 Radiation damage by electrons and alpha particles

Street [1979] has shown that the damage caused by 1 Mev electrons and 100 Kev alpha particles is predominantly in the creation of singly occupied D^0 dangling bonds and the broadening of the tail

state distribution. Both of these effects can be annealed out. The radiation induced effects were studied by electron spin resonance and luminescence. It was found that the electron or ion bombardment introduced defects which were predominantly singly occupied dangling bonds (D^0) which acted as recombination centers and quenched the photoluminescence in a-Si:H. The trend was seen to reverse on annealing.

The damage due to energetic electrons and ions is primarily the displacement of nuclei. The maximum fractional energy transfer is given by $4mM/(m+M)^2$. Since a-Si:H has two types of atoms (hydrogen ~ 10%) collision with both types of atoms results although energy transfer in electron-hydrogen collision is more than in electron-silicon collision. The removal of hydrogen results in a single dangling bond and because of small size of hydrogen atom reconstruction of Si bonds is less likely to occur. Due to the strength of the Si-H bond hydrogen will bond to the Si network. On the other hand a displaced Si atom is likely to leave behind a divacancy and a weak bond which results in localized energy states in the gap [Street ,1979].

4.2 Radiation damage by gamma rays

Recently gamma ray irradiation effects on undoped a-Si:H from 10^{16} - 10^{17} photons cm^{-2} using a Co^{60} source have been reported by Imagawa et al. [1989]. This study showed a significant increase of D^+ defect centers on irradiation which could partly be annealed out.

Fig. 4.1. Dark conductivity (closed circles) and photo conductivity (open circles) as a function of gamma ray total dose. Solid line : after irradiation; broken line : after annealing at 180° C for 2 hours [Imagawa et al., 1989].

The photo and dark conductivities increased by two orders of magnitude after irradiation as shown in Fig. 4.1. The activation energy (see section 2.4.4) decreased from 0.7 eV to 0.4-0.5 eV by gamma ray irradiation as shown in Fig. 4.2 and the samples were found p type which meant that the Fermi energy moved down towards the valence band and this behavior was due to the change of charge states of the defects from D^0 to D^+ . Table 4.1 shows the dependence of the D^0 , D^- , D^+ , and total defects on the total dose. The data listed in the table shows that the total defects and the neutral dangling

Fig. 4.2. Activation energy of the dark conductivity as a function of gamma ray dose. Curve A: After irradiation; curve B: after annealing at 180° C for 2 hours [Imagawa et al., 1989].

Total dose (photons/cm ²)	Gap states (cm ⁻¹ eV ⁻¹)				Total defects
	THS (D ⁰ + D ⁻)	TES (D ⁰ + D ⁺)	D ⁻ - D ⁺	D ⁺ + D ⁻	
0	1.9x10 ¹⁶	1.3x10 ¹⁶	6x10 ¹⁵	-	3.2x10 ¹⁶
10 ¹⁶	1.2x10 ¹⁵	2.6x10 ¹⁶	-	1.4x10 ¹⁶	3.8x10 ¹⁶
10 ¹⁷	8.4x10 ¹⁵	3.2x10 ¹⁶	-	2.4x10 ¹⁶	4x10 ¹⁶

Table 4.1. The dependence of the D⁰, D⁻, D⁺, and total defects on the total dose. THS is trapped hole states and TES is trapped electron states [Imagawa et al., 1989].

bonds D^0 do not change appreciably after irradiation although D^+ defects increase. This feature is consistent with the lowering of the Fermi energy for p-type behaviour and the increase in conductivity on irradiation with gamma ray photons.

The defect creation mechanism due to energetic gamma rays is expected to be due to electronic excitation and direct atomic displacement although the effect due to the latter should be less dominant because of no direct momentum transfer. The increase in the D^+ defect centers is interpreted as the result of change in the charge states of already existing dangling bonds (D^0 and D^-) by the processes $D^0 \rightarrow D^+ + e$ and $D^- \rightarrow D^0 + e$ and since the increase in the D^0 states is small it is believed that the dominant effect of gamma ray irradiation is due to electronic excitation unlike the case of electron or ion irradiation which cause atomic displacement.

4.3 Radiation damage by neutrons

Radiation damage of a-Si:H p-i-n diodes was studied using 1 Mev neutrons from the Triga reactor facility at U. C. Berkeley. Neutron irradiation causes displacement damage in the material. An elastic or inelastic collision with a nucleus can result in displacement of an atom from its position. The threshold energy for displacement in Si is ~ 15 eV [Sandia report, 1985]. In many collisions the energy transferred to a knock-on atom is large so that its collision with other atoms causes secondary displacements. The total displacement cross section, σ_d , of neutrons for Si is shown in

Fig. 4.3. Displacement cross section (including primary and secondary displacements) vs neutron energy for silicon [Sandia report, 1985].

Fig. 4.4. Schematic of the setup used for leakage current and noise measurement.

Fig 4.3.

The total number of displacements n per unit volume is given by

$$n = \Phi N_A \sigma_d$$

where Φ is the particle fluence, N_A is the atom density and σ_d is the total displacement cross section.

Neutron fluences were measured by standard Ni activation techniques. The damage studies were done on 5 μm and 12 μm thick a-Si:H p-i-n diodes, irradiated with neutron fluences ranging from 10^{12} to $\sim 4 \times 10^{14} \text{ cm}^{-2}$. The damage was studied in terms of changes in leakage current, noise, and ability to detect alpha particles. The effect on defect density could not be measured because the tin oxide coating on glass substrate of the samples masked the ESR signal.

Experimental setup used for leakage current, noise and signal measurement is shown in Fig. 4.4. The noise calibration was done using two test pulse amplitudes superimposed on each measurement of signal and noise. The 5 μm diodes were exposed in steps to fluences of 10^{12} cm^{-2} and 10^{13} cm^{-2} . The pulse height spectrum of the alpha signal before irradiation and after 10^{13} cm^{-2} exposure is shown in Fig. 4.5(a,b). It is clear that there is no appreciable degradation of signal and noise of the diodes.

A more detailed experiment was done on 12 μm diodes exposing them in steps to fluences ranging from $5 \times 10^{12} \text{ cm}^{-2}$ to $\sim 4 \times 10^{14} \text{ cm}^{-2}$. The leakage current, noise and alpha signal from 6 Mev alpha

Fig. 4.5(a). Pulse height spectrum of 6 Mev alpha signal before irradiation.

source measured after each exposure are shown in Fig. 4.6(a,b). There is no degradation in noise while a 20% change in alpha signal is seen. The leakage current increases by a factor of 10 at low bias voltage. The samples were annealed at 180° C for two hours. The diodes fully recovered after annealing and their performance was indistinguishable from that before irradiation. An intermediate ann-

Fig. 4.5(b). Pulse height spectrum of 6 MeV alpha signal after 10^{13} cm^{-2} , 1 MeV neutron exposure. The signal pulse width broadened by a factor of 2. The detector was mounted at 60° to the alpha particle direction. The 20% difference in alpha signal from pre-irradiated value is probably due to uncertainty in angular orientation.

ealing procedure done after $8.9 \times 10^{13} \text{ cm}^{-2}$ fluence did not influence the result. It is believed that annealing enhances motion of hydrogen in the network and facilitates reconstruction of broken bonds [Crandall, 1989].

Fig. 4.6(a). Degradation in leakage current of a 12 μm p-i-n diode on exposure to 5×10^{12} - $4 \times 10^{14} \text{ cm}^{-2}$ fast neutron fluences. The curves are drawn with the smoothing routine of CA-Tellagraf [Computer Associates, San Diego, CA].

Fig. 4.6(b). Degradation in noise of a 12 μm p-i-n diode on exposure to 5×10^{12} - 4×10^{14} cm^{-2} fast neutron fluences. Effect of exposure on 6 Mev alpha signal is also seen. The curves are drawn with the smoothing routine of CA-Tellagraf [Computer Associates, San Diego, CA].

For comparison, a crystalline diode, 255 μm thick, was irradiated under identical circumstances. The effects on leakage current, noise and alpha signals were studied. Fig. 4.7 shows the degradation in leakage current at 10^{12} and 10^{13} cm^{-2} fluences.

Fig. 4.7. Effect of 1×10^{12} and $1 \times 10^{13} \text{ cm}^{-2}$ fast neutron fluences on leakage current of a $255 \mu\text{m}$ crystalline diode. Leakage current increases by about a factor of 5 for $1 \times 10^{13} \text{ cm}^{-2}$ fluence. The curves are drawn with the smoothing routine of CA-Tellagraf [Computer Associates, San Diego, CA].

Fig. 4.8(a,b,c) shows the effect on noise and alpha signal at 10^{12} and 10^{13} cm^{-2} fluences. Some degradation in noise and signal was seen at 10^{12} cm^{-2} fluence. However, at 10^{13} cm^{-2} fluence the diode failed. No alpha signal was detected. The experiment was repeated with another crystalline diode and the effects were reproducible.

Fig. 4.8(a). Alpha signal in a 255 μm crystalline diode before irradiation.

Fig. 4.8(b). Alpha signal after irradiation with $1 \times 10^{12} \text{ cm}^{-2}$ fast neutron fluence. About 10% degradation in signal size was observed.

Fig. 4.8(c). No alpha signal is detected after irradiation with 10^{13} cm^{-2} neutron fluence. Significant degradation in diode noise is observed.

In conclusion, the neutron irradiation experiment revealed that a-Si:H diodes are appreciably radiation resistant to 1 Mev neutron fluences in excess of $4 \times 10^{14} \text{ cm}^{-2}$. This was not found to be the case with crystalline diodes which failed at 10^{13} cm^{-2} fluence. These results were published in part in [Perez-Mendez et al., 1987] and [Perez-Mendez et al., 1988].

4.4 Radiation damage by protons

It is known that protons have higher total cross section for displacement as compared to neutrons. Fig. 4.9 shows total displacement cross section of protons as a function of energy for Si.

Fig. 4.9. Displacement cross section (including primary and secondary displacements) vs proton energy for silicon [Sandia report, 1985].

For instance a comparison with Fig. 4.3 shows that the total displacement cross section for 1 Mev protons is about 50 times larger than 1 Mev neutrons. Therefore, one would expect more damage from proton irradiation of a-Si:H than from neutrons as the number of broken bonds would be larger. Hanak et al. [1987] , using 1

Mev protons, concluded that a-Si:H diodes (solar cells) were 50 to 100 times more radiation resistant than c-Si and GaAs cells. It was concluded that nuclear collisions by 1 Mev protons with Si was the primary mechanism for defect creation in a-Si:H diodes. The cross

Fig. 4.10(a). Effect of 1.4 Mev proton irradiation on leakage current of a 12.6 μm n-i-p diode exposed to 1×10^{12} - 1×10^{14} cm^{-2} fluences. The leakage current increases by two orders of magnitude over the fluence range. Annealing at 180° C lead to partial recovery. The curves are drawn with the smoothing routine of CA-Tellagraf [Computer Associates, San Diego, CA].

Fig. 4.10(b). Effect of 1.4 Mev proton irradiation on noise of diode described in Fig. 4.10(a). Annealing at 180° C lead to partial recovery. The curves are drawn with the smoothing routine of CA-Tellagraf [Computer Associates, San Diego, CA].

section for (p,Si) collision for displacement, $3.4 \times 10^{-20} \text{ cm}^{-2}$, is a factor of two larger in comparison to (p,p) collision which is $1.9 \times 10^{-20} \text{ cm}^{-2}$. However, in a device grade a-Si:H the concentration of hydrogen is about 10%. Therefore, the number of Si primary knock

-ons is twenty times larger than the number of hydrogen knock-ons.

Radiation damage of a-Si:H diodes by 1.4 Mev protons from Van de Graaff accelerator at LBL was studied in terms of leakage current and noise. An a-Si:H p-i-n diode was subjected to 1.4 Mev proton fluences ranging from 10^{12} cm⁻² to 10^{14} cm⁻². The results of this study are shown in Fig. 4.10(a,b). The damage is seen to be appreciably greater in comparison to neutrons of comparable energy discussed in section 4.3. Annealing at 180° C for 2 hours lead to partial recovery.

The damage in a thick a-Si:H p-i-n diode (27 μ m with etched top surface to prevent surface leakage) by 1.4 Mev protons is shown in Fig. 4.11. Little degradation in leakage current and noise is seen at 10^{12} cm⁻² fluence. However, at proton fluence of 10^{13} cm⁻² leakage current and noise behaviour of the diode is significantly degraded. Table 4.2 shows the calculated and measured noise after 1×10^{13} cm⁻² fluence. The experimental setup of Fig. 3.2 (setup 2) was used for this measurement. A remarkable agreement between the calculated and measured noise is seen in accordance with the discussions in Chapter 3 and the increased noise contribution is primarily from the increase in the shot noise component.

Fig. 4.11. (a) Leakage current (diode surface etched). (b) Noise after 1.4 MeV proton irradiation. Setup 1 used an Amptek A225 preamplifier with 2.5 μs shaping time (shaping function not known). Setup 2 is the same as described in Fig. 3.2. The noise calculated from the measured leakage current (Chapter 3) for $1 \times 10^{13} \text{ cm}^{-2}$ fluence agrees well with the measured noise.

bias (v)	current (nA)	N_{cal} (e ⁻)	N_m (e ⁻)
0	0	-	3309
50	1.6	3330	3328
100	6.6	3398	3358
150	14.4	3501	3454
200	26.7	3658	3629
250	46.5	3896	3902
300	79.8	4267	4349
350	137.8	4846	4883
375	182	5444	5285
400	235	5685	5760
425	303.5	6209	6549

Table 4.2. Calculated and measured noise (FWHM) after 10^{13} cm⁻² proton irradiation. Set up of Fig. 3.2 was used at 3 μ s shaping time and CR-(RC)⁴ shaping. Diode was 27 μ m thick from the same production run as shown in Table 3.1. Irradiation was done using Van de Graaff accelerator at LBL.

A comparison between 1 Mev neutron and 1.4 Mev proton irradiation shows that $\sim 5 \times 10^{14}$ cm⁻² neutron fluence produces less than 10% degradation in leakage current and noise. Irradiation with 1×10^{13} cm⁻² proton fluence degrades leakage current by a factor of ~ 25 . The noise at the operating bias is degraded by $\sim 40\%$. No significant degradation in noise is seen at 10^{12} cm⁻² fluence.

4.4.1 Effect of proton irradiation on carrier mobility and lifetime

Protons of 1.4 Mev energy were used to study the effect of successive irradiations at 10^{12} , 10^{13} and 10^{14} cm^{-2} fluences on carrier mobility and lifetime in a $27\text{ }\mu\text{m}$ a-Si:H p-i-n diode. Fig. 4.12 shows the change in the shape of the electron photocurrent transient after each irradiation obtained by performing a time of flight experiment using the setup of Fig. 2.21.

Fig. 4.12. Electron photocurrent transient from 510 nm laser light after various proton irradiation fluences at 100 V pulsed bias using time of flight experimental setup of Fig. 2.21.

Measurements show how carrier mobility and lifetime are affected by irradiation as in Fig. 4.13(a,b,c,d). The current transient was fitted to a drift-diffusion equation given below.

$$I(t) = A [\exp(-c_1 t)] \operatorname{erfc} \left[\frac{c_2(t - c_3 x)}{\sqrt{t}} \right] \quad (4.1)$$

where the fitting parameter c_1 is inverse of lifetime, c_2 defines the width of the Gaussian and c_3 is inverse of velocity.

Proton irradiation changed electron mobility from pre-irradiated value of 1.03 cm²/V-s to 0.98 cm²/V-s at 1x10¹⁴ cm²/V-s, a decrease of less than 5%. However, electron lifetime decreases from its pre-irradiated value of 232 ns to 60.8 ns at 1x10¹⁴ cm⁻² fluence by about a factor of 4. This decrease in electron lifetime is expected as irradiation increases defect density in the material.

Fig. 4.13. Photocurrent signal at various fluences and fitted data. (a) $\mu=1.02 \text{ cm}^2/\text{V-s}$, $\tau=232 \pm 29 \text{ ns}$, (b) $\mu=1.03 \text{ cm}^2/\text{V-s}$, $\tau=160 \pm 9 \text{ ns}$, (c) $\mu=1.02 \text{ cm}^2/\text{V-s}$, $\tau=140 \pm 10 \text{ ns}$ (d) $\mu=0.98 \text{ cm}^2/\text{V-s}$, $\tau=61 \pm 1 \text{ ns}$.

The induced charge dQ in an external circuit produced when a charge q is displaced by a distance dx in a semiconductor detector bounded by two parallel plane electrodes with separation d is given by [Tove et al., 1964]

$$dQ = \frac{q \cdot dx}{d} \quad (5.1)$$

The total distance moved by an excited electron or a hole is given in terms of the electric field F , the lifetime τ and the mobility μ as

$$x_{\max} = \mu \tau F \quad (5.2)$$

Complete collection of charge occurs when $x_{\max}$ is larger than the detector thickness. Therefore, three key factors in the collection of charge in a detector are carrier mobility, μ , carrier lifetime, τ , and the electric field, F . In an a-Si:H p-i-n diode i layer being the active detector region, the electric field distribution in this region is of paramount interest. As pointed out in section 1.1, the fact that a large density of charged centers exist in the i layer when the diode is under DC bias, the electric field would no longer be uniform, unlike a crystalline p-i-n diode where the electric field in the intrinsic layer is uniform. The field configuration in the i layer of an

Fig. 5.1. Electric field profile, calculated from eq. (5.3a,b), across a 10 μm a-Si:H diode assuming various ionized dangling bond densities and a D.C. bias of 100 V. The calculations assumed $V_c = 10$ V [Perez-Mendez et al., 1987].

a-Si:H p-i-n diode is obtained by solving the Poisson equation. The model calculations in [Kaplan et al., 1986] assume that the charge density, ρ_0 , is constant when voltage is above a certain critical value V_c (deep depletion region). The Poisson equation then has the form

$$\frac{d^2 V}{dx^2} = - \frac{\rho_0}{\epsilon_0 \epsilon} \quad V \gg V_c \quad (5.3a)$$

where $\rho_0 = eN_d^*$; N_d^* being the density of ionized defects. If N_d^* is constant, then the electric field falls off linearly. At low potential, the gap states are only partially ionized and the Poisson equation is of the form

$$\frac{d^2V}{dx^2} = -\frac{\rho(V)}{\epsilon_0\epsilon} \quad V < V_c \quad (5.3b)$$

where $\rho(V) = en^*V$ and $n^* = \frac{N_d^*}{V_c}$; V_c being the critical voltage.

Based on the above model the calculated electric field distribution in a 10 μm a-Si:H diode is shown in Fig. 5.1.

5.1 Experimental studies on charge collection in a-Si:H diodes.

The earliest experiments on the detection of charged particles in hydrogenated amorphous silicon were done at LBL when 2-15 μm a-Si:H diodes were used to detect alpha particles [Kaplan et al., 1986]. The charge collection in these diodes did not plateau as bias was increased. It was soon realised that particles with large dE/dx , e.g. 4.6 Mev alpha particles with $dE/dx \sim 150 \text{ Kev}/\mu\text{m}$, produced heavily ionized column of charge (e,h pairs) along the particle track [Perez-Mendez et al., 1987]. Because of low mobilities of carriers in a-Si:H the electrons and holes would tend to recombine before the electric field separated them and caused them to drift across the diode for collection. This effect is known to exist in crystalline

semiconductor diodes when fission fragments comprise the incident radiation [Knoll, 1979]. A clear demonstration of this effect in amorphous silicon diodes (some authors call it plasma effect [Equer et al., 1988]) was seen by turning the detector at an angle to the incident particle which helped the charge separation by the electric field and resulted in higher charge collection. The increase in charge collection on turning a 5 μm diode at 60° to the alpha beam (for particle range > diode thickness) was found to be larger than the geometrical increase in path length. Similar effects were seen in

Fig 5.2. Charge collection efficiency vs dE/dx of particles for a 5 μm p-i-n diode.

the detection of 1 and 2 Mev protons in 5 μm a-Si:H p-i-n diodes although the plasma effect was not found to be as severe as in the

Particle	Energy (Mev)	Q/q (e-h pairs)	dE/dx (Kev/ μm)	ϵ (d= 5 μm)
Protons	2	20470	26	0.57
	1	20372	40	0.37
Alphas	4.6	33170	147	0.16

Table 5.1(a). Charge collection efficiency, ϵ , as a function of dE/dx for protons and alpha particles. The data was taken at LBL.

Particle	Energy (Mev)	Q/q (e-h pairs)	dE/dx (Kev/ μm)	ϵ (d=0.5 μm)
Protons	1.8	2400	29	0.58
	1.2	1475	33	0.32
	0.9	1030	45	0.16
	0.8	940	47	0.14
	0.58	600	56	0.078
	0.4	640	67	0.068
Alphas	1.6	1570	250	0.046
	1.2	1550	280	0.040
	0.81	1680	305	0.040
	0.45	1640	305	0.038

Table 5.1(b). Charge collection efficiency, ϵ , as a function of dE/dx for protons and alpha particles [Equer et al. ,1988].

case of alpha particles the reason being the smaller dE/dx of 1 and 2 Mev protons in Silicon (1 Mev protons, $dE/dx \sim 39 \text{ Kev}/\mu\text{m}$; 2 Mev protons, $dE/dx \sim 25 \text{ Kev}/\mu\text{m}$) in comparison with alpha particles. Fig. 5.2 shows the charge collection efficiency as a function of dE/dx of various particles at 0° and 60° angles for a $5 \mu\text{m}$ diode.

A more detailed study of the charge collection characteristics of a-Si:H diodes with alpha particles and protons of energy in the range of 400 Kev to 5.8 Mev was subsequently done by Equer et al. [1988].

Table 5.1 shows the charge collection efficiency of protons and alpha particles of various energies and how the charge collection efficiency significantly decreases with increase in dE/dx . Some analysis of the plasma effect is given in [Fujieda, 1990].

5.2 Minimum ionizing particle detection

In high energy physics applications amorphous silicon technology was thought to offer promising possibilities as a large area low cost radiation detector. For high energy physics applications, detection of minimum or near minimum ionizing particles is of interest. However, detection of minimum ionizing particles above noise requires thicknesses of tens of microns which could be depleted at reasonable bias. Initially, a-Si:H diodes of only a few micron thickness were available. It is appropriate here to throw some light on what is meant by a minimum ionizing particle in

general.

5.2.1 Minimum ionizing particle

If stopping power, dE/dx , of a particle going through some medium is plotted as a function of energy, E , a plot similar to one shown in Fig. 5.3 is obtained from what is known as Bethe formula given by [Segre, 1977]

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{mv^2} n_e \left[\ln \frac{2mv^2}{I(1-\beta^2)} - \beta^2 \right] \quad (5.4)$$

where

- z = particle z
- v = particle velocity
- m = electron mass
- n_e = electron density in the medium
- I = ionization potential
- $\beta = v/c$
- e = electron charge

At very low energies, when particle energy is comparable with the orbiting electron energy, the incident electron gets bound to a site resulting in rapid fall off of ionization. On the other hand ionization increases at high energies due to relativistic effects. At

Fig. 5.3. Variation of stopping power with particle energy [Marmier and Sheldon, 1969].

Fig. 5.4. Total (ionization and radiation losses) stopping power for electrons in air, water, aluminum and lead. For Lead, the contribution from ionization is also shown [Heitler, 1954].

medium energies the stopping power falls off as $1/v^2$ or $1/E$. A broad minimum in stopping power is seen around 2-3 x the rest mass of the particle. This is a useful rule of thumb to estimate the energy of a minimum ionizing particle. For example protons whose rest mass is 938 Mev are minimum ionizing at ~ 2 Gev. An alpha particle ($m_0c^2 = 3727$ Mev) at ~ 7 Gev is 4 x minimum. For comparison tabulated value of minimum ionizing proton is 2.3 Gev in Si and the minimum energy loss is 1.67 Mev-cm²/g. An electron ($m_0c^2 = 0.511$ Mev) is minimum ionizing at 1-2 Mev energy. Fig. 5.4 shows the stopping power of electrons in various media [Engel, 1966]. It is seen that a minimum ionizing electron has energy between 1-2 Mev in Al which will also be the case for Si as its z and density is similar to Al.

5.2.2 Charge creation by interacting particle in a-Si:H

One important step towards realising the goal of using a-Si:H for minimum ionizing particle detection was to demonstrate that such particles could be detected by it. Considering the magnitude of trap density, $\sim 10^{15}$ cm⁻³, present in the material, one could wonder if particles with small dE/dx would be detected. That is, are there threshold effects that limit the minimum detectable pulse of charge in hydrogenated amorphous silicon diodes ?

The minimum ionizing particles deposit the least amount of energy, $(\Delta E)_{\min}$, per unit track length of the particle. Therefore, the average number of electron-hole pairs, $n_{\min}$, created in the process

would be the bare minimum and is given by

$$n_{\min} = \frac{(\Delta E)_{\min}}{W} \quad (5.5)$$

where W is the average energy required to produce an electron-hole pair in the medium. The minimum energy loss of protons in silicon is $1.67 \text{ Mev-cm}^2/\text{g}$ which is $0.38 \text{ Kev}/\mu\text{m}$ using density of 2.3 g/cm^3 for silicon.

The average energy required to produce an electron-hole pair in a-Si:H has been of considerable interest over the last few years. Klein [1968] showed that there exists a remarkable correlation between the W value and the band gap of crystalline semiconductors. This correlation is shown in Fig. 5.5 and can be expressed as

$$W = 2.8 E_G + r(\hbar\omega_R) \quad 0.5 \leq r(\hbar\omega_R) \leq 1.0 \text{ eV} \quad (5.6)$$

The second term in the equation is attributed to phonon loss. Whether this correlation is applicable to amorphous silicon has been an open question. Spear [1969] studied W value of a-Se and found $W \approx 18 \text{ eV}$. This meant for a-Se W is $\approx 7 E_G$ instead of $\approx 2.8 E_G$ ($E_G < 3 \text{ eV}$) according to the above correlation. More recently Pochet et al. [1989] have put a conservative limit on the W value of a-Si:H between 3.4 eV and 4.5 eV . Assuming that the correlation of Klein is applicable and W is $\approx 4.8 \text{ eV}$, the average number of e-h pairs produced from a minimum ionizing proton is ≈ 80 per micron. This

Fig. 5.5. The average energy required to form one electron-hole pair W vs bandgap for different crystalline semiconductor materials [Klein, 1968].

number would be ≈ 105 e-h pairs per micron if the W value of crystalline silicon is used. Based on these numbers, in an a-Si:H diode $30 \mu\text{m}$ thick the total expected number of e-h pairs produced by a minimum ionizing proton would be about 2400 - 3000. In a diode with noise between 3000 to 4000 electrons (diode noise discussed in chapter 3) signal this size would be buried in noise. Therefore a minimum ionizing particle in thinner diodes could not be ordinarily detected.

A signal-averaging technique was used to make the minimum ionizing particle observable. In such an averaging process the signal, S , averaged N times remains S while random noise is reduced by square root of N thus improving the overall signal to noise by square root of N (see, for example, Tektronix Oscilloscope 2430 manual; [Knoll, 1979])

5.2.3 Minimum ionizing particle measurement

The signal averaging technique was implemented by using a Tektronix 2430 Oscilloscope. The schematic of the experimental setup used is shown in Fig. 5.6.

Fig. 5.6. Experimental setup used for the detection of minimum ionizing particles by a-Si:H diode. Sr-90 gun source was used.

Beta particles from a 4 mCi Sr-90 gun source were used in a coincidence experiment between an a-Si:H diode and a crystalline diode. As seen from Fig. 5.4 a 2 Mev beta particle from Sr-90 is close to a minimum ionizing particle. A beta particle going through the a-Si:H diode and the crystal diode produced a trigger pulse in the crystal diode. This pulse was used to trigger the oscilloscope which then acquired the signal produced by the a-Si:H diode.

As a check on the measurement technique a 150 μm crystalline

Fig. 5.7. Pulse height spectrum from beta particles in 150 μm crystalline diode using setup of Fig. 5.6. The oscilloscope was used in normal mode and amplifier shaping time was 0.5 μs .

silicon diode was used in place of the a-Si:H diode. Crystalline silicon being well understood provided a useful check on the measurement technique. The coincidence experiment was done between the two crystalline diodes using beta particles from Sr-90 source. To ensure that each particle that produced a trigger went through the front diode, the size of the diode was made larger in diameter compared to the rear diode in addition to using a fine collimator. Fig. 5.7 shows pulse height spectrum obtained by using two crystalline silicon diodes in the coincidence experiment with 2430 Oscilloscope in normal mode (no averaging). For almost every trigger a signal in the front crystalline diode is seen above background. The calibrated signal from a beta particle in its transit through 150 μm diode was $14,914 \pm 56 \text{ e}^-$ which amounts to signal of 99.4 ± 0.37 electron-hole pairs per micron of crystalline silicon, a number one would expect.

The beta signal in a-Si:H diode was measured at 3 μs shaping time and 256 signal-averages were used. A desk-top microcomputer was used for pulse height analysis. Signal amplitude was determined from the digitized trace by averaging four channels at the pulse peak time and subtracting the average base-line counts per channel. The resultant amplitude was then accumulated for many signals until pulse-height spectrum was obtained. Test pulser pulses were used to calibrate the signal. Fig. 5.8 shows pulse height distribution of 256-signal averaged pulses on a 31 μm diode at 300 V bias. The signal is seen clearly above background. Fig. 5.9 shows beta signal in this diode as a function of bias.

Fig. 5.8. Pulse height distributions of 256 signal-averages, for source in as shown in Fig. 5.6, and source out with pulser triggering the system.

Fig. 5.9. Beta signal as a function of voltage for a 31.2 μm a-Si:H p-i-n diode. The diode noise was ~ 4000 electrons at 400 V; diode capacitance ~ 125 pF. Signal averages of 256 were used.

5.2.4 Beta signals at short shaping times ranging from 20 ns - 500 ns

As pointed out in chapter 1 the mobility of electrons and holes in a-Si:H is small; $\sim 1 \text{ cm}^2/\text{V}\cdot\text{s}$ for electrons and $< 0.01 \text{ cm}^2/\text{V}\cdot\text{s}$ for holes. Consequently, one would expect that for short shaping times and reasonable electric fields only electrons are collected. A measurement was done to study the charge collection from beta particles as a function of shaping times ranging from 20 ns to 500

Fig. 5.10. Sr-90 beta signal as a function of shaping time. The shaping time used were 20, 50, 100, 200 and 500 ns. Tennelec TC 171 was used as preamp and the amplifier was timing filter amplifier (EG&G). The measurements were done using the setup of Fig. 5.6.

ns. A 31.2 μm p-i-n diode described in the previous section was used. The charge collection data using light showed that the diode was fully depleted at ~ 350 V bias [Fujieda et al., 1988]. The measurements were done at 350 and 450 V bias. Fig. 5.10 shows the measured beta signal on this diode as a function of shaping time.

Fig. 5.11. Charge collection efficiency as a function shaping time in a 31.2 μm a-Si:H p-i-n diode at 450 V bias. Calculation assumes uniform energy deposition by a minimum ionizing particle with no plasma effect and uses measured values of material parameters from Table 2.1 and the ionized defect density of $6 \times 10^{14} \text{ cm}^{-2}$. Details of calculation are in [Perez-Mendez et al., 1990].

It is seen from Fig. 5.10 that a sizeable electron signal (1400 to 1500 e⁻) is collected at shaping times ranging from 50 to 100 ns. At these shaping times the contribution from holes is expected to be small as shown in Fig. 5.11 where the fraction of charge collected is plotted as a function of shaping time in a 31.2 μm diode at 450 V bias. Measured values of material parameters tabulated in column 3 of table 2.1 were used. Charge collection as a function of bias at 50 ns shaping time is shown in Fig. 5.12. A small increase in signal is seen from 450 V to 500 V bias and the charge collected is approximately 1400 electrons. It is also interesting to see from Fig. 5.9 and

Fig. 5.12. Beta signal at 50 ns as a function of bias.

Fig. 5.10 that the charge collected at 450 V bias does not increase appreciably when shaping time is increased from 0.5 μ s to 3 μ s. Using the measured value of signal size at 100 ns shaping time (i.e. 1486 ± 43 e⁻) from Fig. 5.10 and the calculated fraction of charge collected (i.e. 0.45 ± 0.02) from Fig. 5.11, the charge created by a beta particle going through the material is estimated to be 106 ± 6 e-h pairs per micron. This number is similar to what one expects in the case of crystalline silicon.

5.2.5 Recent experiment with beta particles

Recently beta pulses with signal amplitudes exceeding noise by a factor of 4 or more have been observed at shaping times ranging from 0.5 μ s to 6 μ s. These large pulses form about 15% of the total count rate. The experimental set up used for signal and noise measurement is shown in Fig. 5.13. The pulses were first detected on a 29 μ m a-Si:H p-i-n diode described in Fig. 3.2. The pulse-height spectrum of beta signal from Sr-90 beta gun source at 300 V bias and 3 μ s shaping time is shown in Fig. 5.13. Beta pulses were seen at bias voltage as low as 150 V. An oscilloscope trace of such a beta

Fig. 5.13. Schematic of experimental setup used to measure beta signal and diode noise. The preamp has no shaping and the dual amp has (pseudo-Gaussian) $CR-(RC)^4$ shaping.

Fig. 5.14. Pulse height spectrum of beta pulses with two calibration pulses measured on a $29 \mu\text{m}$ a-Si:H p-i-n diode. Detector noise is 2960 electrons. Calibration: 1876 electrons per channel; PHA lower level discriminator set to 0.

Fig. 5.15. Digital oscilloscope trace of a beta pulse at 300 V, 3 μ s shaping time detected in a 29 μ m a-Si:H p-i-n diode.

pulse is shown in Fig. 5.15.

The pulse-height spectrum with the beta source removed is shown in Fig. 5.16. No signal was observed.

A coincidence experiment was done to verify that large pulses were truly associated with beta particles. A 150 μ m crystalline diode and the a-Si:H diode were used for the coincidence experiment shown in Fig. 5.17. The large pulses from the a-Si:H diode were used as trigger. A beta ray traversing the crystalline diode and also producing a large beta pulse in the a-Si:H diode caused the system to trigger. No trigger pulses were seen with beta source removed from the detector box. The signal size in the crystalline detector agreed

Fig. 5.16. Pulse height spectrum with Sr-90 beta source removed. All settings were same as in Fig. 5.14.

Fig. 5.17. Experimental set up used for coincidence between xtal and a-Si:H diodes.

reasonably well with the energy deposited in the diode by a beta ray traversing through the diode and producing a trigger pulse in the a-Si:H diode.

It is not yet clear what mechanism is responsible for producing these large pulses from beta particles in a-Si:H diode. One possible explanation is that the energy deposited by an electron traversing a thin target is distributed asymmetrically about the most probable value. The distribution is essentially Gaussian on the lower energy side, but has a tail on the higher energy side and is known as Landau distribution [Segre, 1977 p 51; Lindhard et al. , 1963; Goldwasser et al. , 1952]. The pulses could also be from low energy electrons which have higher dE/dx (Fig. 5.4).

5.3 High energy alpha experiment

This experiment was designed to measure signals produced in a-Si:H detectors by energetic particles and demonstrate the usefulness of a-Si:H detectors in high energy particle detection applications. The signals produced in a-Si:H diodes by high energy alpha

beams (860 Mev) from Bevatron accelerator at LBL were measured at short shaping times (50 and 100 ns). The choice of energy was purely based on the availability. The 860 Mev alpha particles have dE/dx (~ 13.9 Mev-cm²/g or 3.2 Kev/ μ m) which is about eight times the minimum ionizing alpha particle. The signal at these shaping times is expected to be primarily from electron collection while the contribution from the holes is anticipated to be small. This is due to the large difference in the mobility of electrons and holes. The hole mobility is a factor of 100 or so smaller than the electron mobility. The mobility-lifetime product of holes is a factor of 3 to 4 smaller compared to that of electrons. A sizeable fraction of hole signal is lost even for shaping times as large as several microseconds [Pochet et al, 1989].

Fig. 5.18 shows the measured signal as a function of bias at 50 and 100 ns shaping times when an 860 Mev alpha particle traverses through a 12.5 μ m a-Si:H p-i-n diode in a coincidence experiment. The experimental setup used was similar to one shown in Fig. 5.6. To check for consistency the 860 Mev alpha signal was measured by the setup of Fig. 5.6 when the a-Si:H diode was replaced by a 150 μ m crystalline diode. The measured signal in a fully depleted xtal diode at 0.5 μ s shaping time was $137,044 \pm 39$ electrons. Using dE/dx value of 13.95 Mev-cm²/g for 860 Mev alpha particles in 150 ± 5 μ m thick diode gives a W value of 3.51 ± 0.16 eV. .

Fig. 5.18 shows measured signal in a 12.5 μ m a-Si:H diode at 50 and 100 ns shaping times as a function of bias when an 860 Mev alpha particle goes through the diode.

Fig. 5.18. Measured signal when an 860 Mev alpha particle goes through a $12.5 \mu\text{m}$ a-Si:H p-i-n diode.

The preliminary experiment with thicker a-Si:H diode ($31.2 \mu\text{m}$) using 860 Mev alpha beam showed probable presence of plasma

Bias (V)	Signal (Ke ⁻)	
	0° , ($d=31.2 \pm 0.2 \mu\text{m}$)	$60^\circ \pm 2^\circ$, ($d=62.4 \pm 4 \mu\text{m}$)
450	9.9 ± 0.3	23.3 ± 0.7

Table 5.2. 860 Mev alpha signal at 0° and 60° to the beam. Increased signal size at 60° by a factor greater than 2 is probably due to presence of some recombination effects.

effect discussed in section 5.1. The measured signal at 0° and $60^\circ \pm 2^\circ$ inclination to the beam is shown in Table 5.2. The increase in 60° signal was seen to be more than a factor of 2, an indication of the probable presence of recombination effects at $13.9 \text{ Mev-cm}^2/\text{g}$ dE/dx value.

The alpha signal was seen above system noise without averaging. Table 5.3 shows alpha signal measured at 350 V bias and 100 ns shaping time in normal mode and averages of 16 at 60° inclination to the beam. The two values were found to be in good agreement.

Bias (v)	Signal (Ke^-) , 60° inclination	
	Normal	16 averages
350	21.0 ± 1.7	20.4 ± 0.5

Table 5.3. 860 Mev alpha signal measured in normal and averaging mode to check for consistency. The agreement evidently is quite good.

The loss of signal due to recombination effects at $\sim 8 \times dE/dx$ of minimum ionizing particle needs to be ascertained and further experimentation is required before the W value is inferred from these measurements. The measurements, without taking into consideration recombination effects, showed a spread in the effective W value ranging from 3.9 to 4.7 eV.

Conclusion

Properties of hydrogenated amorphous silicon diodes relevant to radiation detection applications were studied. The interest in using hydrogenated amorphous silicon for radiation detection applications in physics and medicine was motivated by the fact that hydrogenated amorphous silicon can be deposited over large area at relatively low cost compared to crystalline silicon.

1. Material parameters

The material parameters of interest namely, carrier mobility, μ , lifetime, τ , and the defect density, N_d , of thick a-Si:H p-i-n diodes were studied by time of flight (transient photoconductivity) experiments. The mobility and mobility-lifetime product values on thick diodes were comparable to values reported on thin diodes for solar cells. The ionized defect density, N_d^+ , of p-i-n diodes measured by transient photoconductivity method under DC bias was found to be only $\sim 1/3$ of the total defect density as measured by ESR.

2. Leakage current and noise

The leakage current under reverse bias of well behaved a-Si:H p-i-n diodes was studied. The leakage current is important from noise and power dissipation considerations. The increase in leakage

current with bias has the same dependence on voltage as one would expect if this increase were due to the "Poole-Frenkel effect" involving excitation of carriers from neutral defects. The noise of the diode over the operating voltage range is completely explained in terms of the "shot noise" component and the noise component at 0 V bias (delta and thermal noise) added in quadrature. The leakage current makes dominant contribution to noise in the form of shot noise for CR-(RC)⁴ (pseudo-Gaussian) shaping at 3 μ s.

3. Radiation damage

The irradiation effects of 1 Mev neutrons and protons on thick a-Si:H p-i-n diodes were studied in terms of degradation in leakage current and noise. This study showed that a-Si:H diodes were radiation resistant to neutron fluences in excess of 4×10^{14} cm⁻². No appreciable change in leakage current and noise was seen while alpha signal degraded by about 20%. The diodes fully recovered after annealing at 180° C for two hours.

Proton irradiation (1.4 Mev) produced little degradation in leakage current and noise at 10^{12} cm⁻² fluence. However, at proton fluence of 10^{13} cm⁻² leakage current and noise was significantly degraded.

A comparison between 5×10^{14} cm⁻² neutron fluence and 10^{13} cm⁻² proton fluence reveals that leakage current in case of neutrons increases by 10-20% with negligible increase in noise. Proton irradiation increases leakage current by a factor of 10 to 25 with

significant increase in noise as a result of increase in shot noise contribution.

Proton irradiation was also used to study effects on electron mobility and lifetime with increasing fluence. The diode subjected to 1.4 Mev proton fluence ranging from 10^{12} cm⁻² to 10^{14} cm⁻² showed that no appreciable change was seen in electron mobility on irradiation. However, electron lifetime decreased from 232 ns by about a factor of 4 to 60 ns at 10^{14} cm⁻². This decrease in carrier lifetime is associated with an increase in defect centers on irradiation.

4. Charge collection

Minimum ionizing particles, for example 1-2 Mev electrons, were detected in thick (~ 31 μ m) a-Si:H p-i-n diode at 3 μ s shaping time. These particles were detected by signal averaging technique implemented to improve the signal to noise ratio in a diode with large capacitance. It was demonstrated that if one were to rely on signal from electrons alone the device speed could be much higher as most electrons are collected in shaping time ranging from 50 to 100 ns with small contribution to signal from hole collection. This result was also confirmed by measurements with 860 Mev alpha particles at short shaping times. As thicker fully depleted diodes are realised more energy is deposited in the diode with increase in signal to noise ratio due to reduced capacitance. In such a device electrons alone would produce large enough signal making a faster

device more realistic.

Measurements showed a minimum ionizing beta particle produced ~ 104 e-h pairs per micron of a-Si:H, consistent with the value for crystalline silicon. Measurements with 860 MeV alpha particles ($\sim 8 \times$ minimum ionizing dE/dx) showed that the energy expended per e-h pair, W value, in a-Si:H is smaller than predicted from the Klein's curve for crystalline semiconductors. Preliminary measurements with 860 MeV alpha particles showed a spread in the effective W value ranging from 3.9 to 4.7 eV. These estimates were obtained from signal measurements at short shaping times (100 ns) and model calculations of the fraction of electrons and holes collected using measured values of material parameters. Further work is required to determine a better value of the W value of a-Si:H.

Heavily ionizing particles, e.g. alpha particles, produce a saturation effect (plasma effect) in hydrogenated amorphous silicon diodes. This phenomenon is similar to the effect produced by fission fragments in crystalline silicon detectors. As a consequence of this effect the collected charge is not proportional to the energy deposited in the diode. The effect is negligible for minimum ionizing particles.

The work reported in this thesis shows that hydrogenated amorphous silicon p-i-n diodes hold good promise for radiation detection applications.

Appendix 1

The probability p that electron jumps from state A to state B through scattering with a phonon depends on

(1) The probability of finding a phonon with an excitation energy W and is given by the Boltzman factor $\sim \exp(-W/kT)$, where W is the energy difference between the two states.

(2) Attempt to escape frequency ν_{ph} .

(3) The probability of electron transfer from one state to another

Fig. 2.13. (a) Hopping of a carrier from state A below the Fermi energy to state B above it. (b) At low T , long range less energetic hops are favoured.

which depends on the overlapping of wave functions and is given by $\exp(-2\alpha R)$. R is the jump distance and α is a quantity representing rate of fall of wave function at a site.

Total probability p is given by

$$p = \nu_{ph} \exp(-2\alpha R - W/kT)$$

From Einstein's relation,

$$\mu = \frac{eD}{kT}, \text{ and using an expression for diffusion coefficient, } D = \frac{1}{6} p R^2 \text{ [Cohen, 1970], we have}$$

$$\mu = \frac{e p R^2}{6 k T} \text{ and } \sigma = n e \mu = \frac{e^2}{6} p R^2 N(E_f)$$

where $N(E_f)$ is the density of states at the Fermi energy. Substituting for p we have

$$\sigma = \frac{e^2}{6} v_{ph} R^2 N(E_f) \exp\left(-2\alpha R - \frac{W}{kT}\right)$$

As T is lowered the energy of phonons decreases and more energetic phonon assisted hops become less favourable. Carriers tend to hop larger distances.

To find the most probable hopping distance let

$N(W)$ = No. of states per unit volume per unit energy, then the number of states within energy W and within distance R is given by

$$\frac{4}{3}\pi R^3 N(W) W$$

For electron to hop from a state just below the Fermi energy to a state just above it this number should be at least 1.

Therefore,

$$W \approx \frac{3}{4\pi R^3 N(E_f)}$$

$$\text{and } p = v_{ph} \exp\left[-2\alpha R - \left(\frac{4}{3}\pi R^3 N(E_f) kT\right)^{-1}\right].$$

The most probable jump distance R_{min} is given by minimizing the exponent with respect to R .

Let,

$$X = -2 \propto R - \left(\frac{4}{3} \pi R^3 N(E_i) kT \right)^{-1}$$

and $\frac{dX}{dR} = 0$,

we have $R_{min} = \left[\frac{9}{8\pi \propto N(E_i) kT} \right]^{\frac{1}{4}}$

$$\therefore \rho = v_{ph} \exp\left(-\frac{A}{T^{1/4}}\right)$$

where $A = 2.1 \times \left[\frac{\propto^3}{k} N(E_i) \right]^{\frac{1}{4}}$

and the hopping conductivity is given by

$$\sigma_{hop} = \sigma_0 \exp\left(-\frac{A}{T^{1/4}}\right) \quad (2.11)$$

Eq. (2.11) is known as Mott's $T^{\frac{1}{4}}$ law.

Appendix 2

Let

v_{pb} = Pulse bias signal

$v_{dc}(t)$ = DC bias signal

t_T = Transit time

μ = Mobility = $d/E_0 t_T = d^2/V_0 t_T$

R = Resistance across which signal is measured

n = Carrier density

A = Diode area

q = Electronic charge

$I_{dc}(t)$ = Signal current under DC bias

I_{pb} = Signal current under pulsed bias

V_0 = Pulsed bias across diode

E_0 = Pulsed field = V_0/d

Let

$$v_{pb} = R I_{pb} = R q A n v = R q A n \mu E_0 = R Q \mu E_0 \quad (1)$$

where $Q = n q A$.

Under DC bias

$$v_{dc}(t) = R I_{dc}(t) = R q A n v \approx R q A n \mu E_{dc}(t)$$

or

$$v_{dc}(t) = R Q \mu E_{dc}(t) \quad (2)$$

From eq.s (1) and (2) we have

$$E_{dc}(t) = E_0 v_{dc}(t)/v_{pb} \quad (3)$$

$$\frac{dx}{dt} = \mu E_{dc}(t)$$

or

$$x = \mu \int_0^t E_{dc}(t_1) dt_1$$

$$\begin{aligned} x &= \mu \int_0^t \frac{E_0 v_{dc}(t_1)}{v_{pb}} dt_1 \\ &= \frac{\mu}{v_{pb} t_T} \int_0^t v_{dc}(t_1) dt_1 \end{aligned} \quad (4)$$

Assuming the electric field falls off linearly we can write the depletion thickness as

$$x_d = \sqrt{\frac{2 V_0 \epsilon_0 \epsilon_r}{q N_d}} \quad (5)$$

$$\frac{dE}{dx} = -\frac{q N_d}{\epsilon_0 \epsilon_r}$$

$$E(x) = -\frac{q N_d}{\epsilon_0 \epsilon_r} x + c_1$$

For $E(x) = 0$ at $x = X_d$

$$c_1 = \frac{q N_d}{\epsilon_0 \epsilon_r} x_d$$

Therefore,

$$E(x) = -\frac{q N_d}{\epsilon_0 \epsilon_r} (x - x_d) \quad (6)$$

$$v = \frac{dx}{dt} = \mu E(x) = - \mu \frac{q N_d}{\varepsilon_0 \varepsilon_r} (x - x_d)$$

$$\frac{\varepsilon_0 \varepsilon_r}{q N_d \mu} \frac{dx}{x - x_d} = - dt$$

$$\frac{\varepsilon_0 \varepsilon_r}{q N_d \mu} \ln \left(\frac{x_d - x}{x_d} \right) = - t$$

Using eq. (5) we have

$$\frac{\varepsilon_0 \varepsilon_r}{q N_d \mu} \ln \left[\frac{\varepsilon_0 \varepsilon_r E(x)}{q N_d} \frac{1}{x_d} \right] = - t$$

Using eqs (3) and (5)

$$\frac{\varepsilon_0 \varepsilon_r}{q N_d \mu} \ln \left[\frac{\varepsilon_0 \varepsilon_r E_0}{q N_d \sqrt{\frac{2 V_0 \varepsilon_0 \varepsilon_r}{q N_d}}} \frac{v_{dc}(t)}{v_{pb}} \right] = - t$$

$$\frac{\varepsilon_0 \varepsilon_r}{q N_d \mu} \ln \left[\frac{v_{dc}(t)}{v_{pb}} \right] + \frac{\varepsilon_0 \varepsilon_r}{q N_d \mu} \ln \left[\frac{V_0}{d} \right] - \frac{\varepsilon_0 \varepsilon_r}{q N_d \mu} \ln \left[\frac{q N_d}{\varepsilon_0 \varepsilon_r} \sqrt{\frac{2 V_0 \varepsilon_0 \varepsilon_r}{q N_d}} \right] = - t$$

For time duration t_1 and t_2 we have

$$N_d \approx \frac{\varepsilon_0 \varepsilon_r}{q \mu} \frac{\ln \left[\frac{v_{dc}(t_1)}{v_{dc}(t_2)} \right]}{t_2 - t_1} \quad (7)$$

where $\varepsilon_0 \varepsilon_r = 12 \times 8.85 \times 10^{-14}$ F/cm.

Expressing result in terms of current signal we have eq. (2.19).

Appendix 3

In crystalline semiconductors, deep trapping is described in terms of a capture cross section σ , with carriers at the edge of the band having a thermal velocity v , and N_d is the defect density.

$$\tau_F^{-1} = \sigma v N_d \quad (1)$$

where τ_F is the free-carrier lifetime. Eq. (1) assumes that the scattering length, a , is larger than the capture radius d ($\sigma = \pi d^2$). If instead $a < d$, then capture is dominated by diffusion and the rate is given by the formula [Waite, 1957]

$$\tau_F^{-1} = 4\pi D N_d \quad (2)$$

where D is the diffusion coefficient. In amorphous semiconductors of interest, a and d are likely to have similar magnitudes.

Another difference is that free carriers in an amorphous semiconductor are not at the bottom of a band, with thermal velocity. Instead they move at the mobility edge E_c with minimum metallic conductivity, $\sigma_{\min}$, given by [Mott and Davis, 1979]

$$\sigma_{\min} = 0.025 e^2 / \hbar a$$

Free carrier mobility at the mobility edge E_c is given by

$$\mu_0 = \frac{eD}{kT}$$

$$D = \frac{1}{6} v_{el} a^2 = \frac{1}{6} \left(\frac{\hbar}{ma^2} \right) a^2 = \frac{1}{6} \frac{\hbar}{m}$$

where v_{el} is the electronic frequency ($\approx \hbar/ma^2$).

Therefore,

$$\mu_0 = \frac{1}{6} \frac{\hbar}{m} \left(\frac{e}{kT} \right)$$

$$\mu_0 = \frac{1}{6} \frac{e}{kT} a v \quad (3)$$

The third effect that must be taken into account is that the drift mobility in an amorphous semiconductor is trap limited by band-tail states, so that [Street, 1984]

$$\tau_F = \mu \tau / \mu_0 \quad (4)$$

Thus, combining eqs. (1) and (4) , we have

$$\frac{\mu_0}{\tau \mu} = \sigma v N_D \quad (5)$$

From eqs. (3) and (5) we get

$$\mu \tau N_D \approx \frac{1}{6} \frac{e}{kT} \frac{a}{\sigma}$$

Table 1**dE/dx of heavy particles in silicon**

TABLE 1

STOPPING POWER IN $\text{MeV}\cdot\text{cm}^2/\text{mg}$ IN SILICON													
	p			d			^3He			^7Li			
Energy	E	D	T	E	D	T	E	D	T	E	D	T	
1.00	254.902	254.298	102.610	118.704	1774.494	1870.058	7.00	44.585	79.467	100.482	402.593	688.091	1609.618
1.10	287.071	286.187	112.604	130.154	1970.158	2100.158	7.20	46.224	82.728	104.736	420.782	717.584	1771.584
1.20	320.116	318.916	123.152	141.840	2170.402	2310.402	7.40	47.921	86.289	109.085	439.180	777.780	1933.580
1.40	384.761	382.195	141.978	168.552	2584.984	2724.984	7.80	52.457	93.299	118.089	480.229	851.879	2142.584
1.60	451.888	447.714	165.728	195.798	3015.498	3155.498	8.20	57.021	100.468	127.177	521.877	933.077	2304.577
1.80	521.880	516.654	190.091	223.788	3461.736	3601.736	8.60	61.726	108.007	136.716	564.804	1015.219	2467.219
2.00	594.076	588.255	215.984	252.484	3924.252	4064.252	9.00	66.468	115.848	145.991	608.080	1107.580	2630.580
2.20	668.989	662.640	242.253	281.904	4404.796	4544.796	9.40	71.241	123.897	155.616	652.419	1200.019	2794.019
2.40	745.290	738.254	269.117	312.054	4904.294	5044.294	9.80	76.041	132.067	165.673	697.573	1293.289	2958.289
2.60	823.006	815.288	296.544	342.854	5414.722	5554.722	10.20	80.861	140.357	175.967	743.667	1387.567	3123.567
2.80	902.158	893.754	324.644	374.284	5934.244	6074.244	10.60	85.701	148.767	186.487	790.087	1482.987	3290.987
3.00	982.761	973.654	353.414	406.334	6464.764	6604.764	11.00	90.561	157.297	197.617	837.617	1579.517	3459.517
3.20	1064.821	1055.054	382.784	439.004	7004.284	7144.284	11.40	95.441	165.947	208.947	886.347	1678.247	3629.247
3.40	1148.331	1137.854	412.254	472.284	7554.804	7694.804	11.80	100.341	174.717	220.377	936.677	1778.577	3799.577
3.60	1233.291	1222.054	442.024	506.154	8114.324	8254.324	12.20	105.261	183.607	231.907	988.007	1880.007	3970.007
3.80	1319.701	1307.654	472.024	540.604	8684.844	8824.844	12.60	110.201	192.617	243.537	1040.337	1982.537	4141.537
4.00	1407.561	1394.754	502.254	575.734	9264.364	9404.364	13.00	115.161	201.747	255.267	1093.667	2086.267	4313.267
4.20	1496.871	1483.254	532.684	611.504	9854.884	9994.884	13.40	120.141	211.007	267.097	1148.097	2191.697	4486.697
4.40	1587.631	1573.154	563.314	647.934	10454.404	10604.404	13.80	125.141	220.397	279.027	1203.527	2298.127	4661.127
4.60	1679.841	1664.554	594.144	684.064	11064.924	11214.924	14.20	130.161	229.917	291.157	1259.957	2406.557	4837.557
4.80	1773.501	1757.354	625.174	720.894	11684.444	11834.444	14.60	135.201	239.557	303.387	1317.387	2516.987	5015.987
5.00	1868.711	1851.654	656.404	758.424	12314.964	12464.964	15.00	140.261	249.317	315.717	1376.817	2628.417	5196.417
5.20	1965.471	1947.554	687.834	796.654	12954.484	13104.484	15.40	145.341	259.197	328.147	1437.247	2740.847	5378.847
5.40	2063.781	2044.954	719.464	835.584	13604.004	13754.004	15.80	150.441	269.197	340.677	1498.677	2854.277	5562.277
5.60	2163.641	2143.854	751.294	875.214	14264.524	14414.524	16.20	155.561	279.317	353.307	1561.107	2968.707	5747.707
5.80	2265.051	2244.354	783.324	915.544	14934.044	15084.044	16.60	160.701	289.557	366.037	1625.537	3084.137	5934.137
6.00	2368.011	2346.354	815.554	956.674	15614.564	15764.564	17.00	165.861	299.917	378.867	1691.967	3200.567	6122.567
6.20	2472.521	2449.954	847.984	998.504	16304.084	16454.084	17.40	171.041	310.397	391.797	1759.397	3318.997	6313.997
6.40	2578.581	2555.054	880.614	1041.034	16994.604	17144.604	17.80	176.241	320.997	404.827	1828.827	3438.427	6507.427
6.60	2685.191	2660.654	913.444	1084.264	17694.124	17844.124	18.20	181.461	331.717	417.957	1899.257	3558.857	6703.857
6.80	2793.351	2767.854	946.474	1128.194	18404.644	18554.644	18.60	186.701	342.557	431.187	1970.687	3680.287	6902.287
7.00	2903.061	2876.554	979.704	1172.824	19124.164	19274.164	19.00	191.961	353.517	444.517	2043.117	3802.717	7102.717
7.20	3014.321	2986.854	1013.134	1218.154	19854.684	20004.684	19.40	197.241	364.597	458.047	2116.547	3926.147	7304.147
7.40	3127.131	3098.654	1046.764	1264.184	20594.204	20744.204	19.80	202.541	375.797	471.777	2191.977	4051.577	7507.577
7.60	3241.491	3212.254	1080.594	1310.914	21344.724	21494.724	20.20	207.861	387.117	485.607	2268.407	4178.007	7713.007
7.80	3357.401	3327.154	1114.624	1358.344	22104.244	22254.244	20.60	213.201	398.557	499.637	2345.837	4306.437	7920.437
8.00	3474.861	3443.554	1148.854	1406.474	22874.764	23024.764	21.00	218.561	410.117	513.867	2424.267	4436.867	8129.867
8.20	3593.871	3561.554	1183.284	1455.304	23654.284	23804.284	21.40	223.941	421.797	528.297	2503.697	4568.297	8341.297
8.40	3714.431	3681.054	1217.914	1504.834	24444.804	24594.804	21.80	229.341	433.597	542.927	2584.127	4700.727	8554.727
8.60	3836.541	3802.154	1252.744	1555.064	25244.324	25394.324	22.20	234.761	445.517	557.657	2665.557	4834.157	8769.157
8.80	3960.201	3924.854	1287.774	1605.994	26054.844	26204.844	22.60	240.201	457.557	572.487	2748.987	4969.587	8985.587
9.00	4085.511	4049.154	1322.904	1657.624	26874.364	27024.364	23.00	245.661	469.717	587.417	2833.417	5106.017	9203.017
9.20	4212.471	4175.054	1358.134	1709.954	27704.884	27854.884	23.40	251.141	481.997	602.547	2918.847	5243.447	9422.447
9.40	4340.981	4302.554	1393.564	1762.984	28544.404	28694.404	23.80	256.641	494.397	617.777	3005.277	5381.877	9643.877
9.60	4470.041	4430.654	1429.194	1816.714	29394.924	29544.924	24.20	262.161	506.917	633.107	3092.707	5521.307	9866.307
9.80	4600.651	4560.254	1464.924	1871.144	30254.444	30404.444	24.60	267.701	519.557	648.637	3181.137	5661.737	10090.737
10.00	4732.811	4691.454	1500.854	1926.274	31124.964	31274.964	25.00	273.261	532.317	664.367	3271.567	5803.167	10317.167

Stopping power S of p, d, t, ^3He , α and ^7Li ions in silicon

TABLE 1 (continued)

STOPPING POWER IN MEV·CM/GH FOR SILICON							Z = 14 A = 26.086 B = 175.5						
[MEV]	P	D	F	ME 3	ME 4	LI 7	[MEV]	P	D	F	ME 3	ME 4	LI 7
17.50	22.429	39.308	41.559	207.781	256.172	955.297	40.00	11.729	20.189	20.654	479.696	479.728	
18.00	21.936	37.493	39.447	203.458	250.937	937.469	40.50	11.610	19.889	20.007	469.592	469.373	
18.50	21.448	36.117	37.460	199.311	245.938	922.176	41.00	11.499	19.602	19.167	459.053	460.016	
19.00	21.025	34.915	34.854	195.108	241.170	907.897	41.50	11.391	19.414	18.688	447.957	459.803	
19.50	20.601	33.867	33.911	191.617	236.400	893.470	42.00	11.285	19.231	18.459	436.511	456.176	
20.00	20.197	32.888	32.903	188.008	231.216	879.447	42.50	11.181	19.051	18.235	425.568	451.612	452.761
20.50	19.809	31.959	31.942	184.366	226.008	865.822	43.00	11.078	18.875	18.016	415.011	444.967	
21.00	19.438	31.116	31.113	181.726	221.970	852.647	43.50	10.978	18.702	17.797	404.374	434.967	
21.50	19.081	30.359	30.356	179.038	217.938	839.819	44.00	10.883	18.534	17.581	393.649	424.967	
22.00	18.741	29.684	29.678	176.315	213.935	827.189	44.50	10.787	18.368	17.368	382.827	414.967	
22.50	18.413	29.093	29.089	173.628	210.000	814.756	45.00	10.694	18.206	17.157	371.909	404.967	
23.00	18.098	28.582	28.578	170.969	206.100	802.400	45.50	10.602	18.047	16.947	360.896	394.967	
23.50	17.795	28.150	28.146	168.345	202.231	790.113	46.00	10.513	17.891	16.738	349.796	384.967	
24.00	17.503	27.807	27.803	165.748	198.391	777.869	46.50	10.429	17.738	16.530	338.609	374.967	
24.50	17.222	27.561	27.556	163.176	194.580	765.659	47.00	10.341	17.588	16.324	327.336	364.967	
25.00	16.950	27.323	27.318	160.626	190.798	753.486	47.50	10.256	17.441	16.120	315.986	354.967	
25.50	16.689	27.090	27.084	158.098	187.045	741.350	48.00	10.171	17.296	15.918	304.561	344.967	
26.00	16.438	26.861	26.854	155.591	183.319	729.250	48.50	10.088	17.154	15.718	292.961	334.967	
26.50	16.192	26.637	26.630	153.101	179.624	717.186	49.00	10.008	17.013	15.519	281.286	324.967	
27.00	15.956	26.416	26.408	150.626	175.957	705.156	49.50	9.931	16.873	15.321	269.536	314.967	
27.50	15.727	26.198	26.190	148.166	172.319	693.156	50.00	9.854	16.734	15.125	257.711	304.967	
28.00	15.506	25.982	25.973	145.721	168.709	681.186	50.50	9.779	16.597	14.930	245.811	294.967	
28.50	15.292	25.768	25.758	143.291	165.124	669.236	51.00	9.704	16.462	14.736	233.836	284.967	
29.00	15.085	25.556	25.545	140.876	161.564	657.306	51.50	9.630	16.328	14.542	221.791	274.967	
29.50	14.883	25.346	25.334	138.476	158.029	645.396	52.00	9.557	16.194	14.349	209.676	264.967	
30.00	14.688	25.138	25.125	136.091	154.519	633.506	52.50	9.484	16.061	14.156	197.491	254.967	
30.50	14.499	24.933	24.919	133.721	151.034	621.636	53.00	9.412	15.929	13.963	185.226	244.967	
31.00	14.315	24.730	24.715	131.366	147.574	609.786	53.50	9.341	15.800	13.770	172.881	234.967	
31.50	14.136	24.528	24.512	129.026	144.139	597.956	54.00	9.270	15.671	13.577	160.456	224.967	
32.00	13.962	24.328	24.311	126.699	140.729	586.146	54.50	9.200	15.543	13.384	147.951	214.967	
32.50	13.793	24.129	24.111	124.386	137.344	574.356	55.00	9.130	15.416	13.191	135.366	204.967	
33.00	13.628	23.931	23.912	122.086	134.004	562.586	55.50	9.061	15.290	13.000	122.691	194.967	
33.50	13.468	23.734	23.714	119.799	130.699	550.836	56.00	8.992	15.165	12.809	109.936	184.967	
34.00	13.313	23.537	23.516	117.526	127.429	539.106	56.50	8.924	15.041	12.618	96.991	174.967	
34.50	13.162	23.341	23.319	115.266	124.184	527.396	57.00	8.856	14.918	12.427	83.956	164.967	
35.00	13.014	23.146	23.123	113.019	120.964	515.706	57.50	8.789	14.795	12.236	70.831	154.967	
35.50	12.870	22.952	22.928	110.786	117.769	504.036	58.00	8.722	14.673	12.045	57.626	144.967	
36.00	12.730	22.759	22.734	108.566	114.599	492.386	58.50	8.656	14.551	11.854	44.351	134.967	
36.50	12.595	22.567	22.541	106.359	111.454	480.756	59.00	8.590	14.430	11.663	30.996	124.967	
37.00	12.464	22.375	22.348	104.166	108.334	469.146	59.50	8.524	14.309	11.472	17.571	114.967	
37.50	12.336	22.183	22.155	101.986	105.239	457.556	60.00	8.458	14.188	11.281	4.116	104.967	
38.00	12.211	21.991	21.962	99.819	102.169	445.986	60.50	8.393	14.067	11.090		94.967	
38.50	12.089	21.800	21.770	97.666	99.124	434.436	61.00	8.328	13.946	10.900		84.967	
39.00	11.969	21.608	21.577	95.526	96.094	422.906	61.50	8.263	13.825	10.710		74.967	
39.50	11.851	21.416	21.384	93.399	93.089	411.396	62.00	8.198	13.704	10.520		64.967	
40.00	11.735	21.224	21.191	91.284	90.109	400.006	62.50	8.133	13.583	10.330		54.967	

Stopping power S of p, d, t, ^3He , α and ^7Li ions in silicon

TABLE 1 (continued)

STOPPING POWER IN MEV·CM/GRAM FOR SILICON											Z = 14 A = 28.086 I = 179.5					
ENERGY	P	D	T	HE 3	HE 4	LI 7	ENERGY	P	D	T	HE 3	HE 4	LI 7			
79.00	7.226	12.125	16.423	67.680	84.520	204.158	120.00	5.170	8.959	11.764	46.809	58.436	204.250			
79.50	7.155	12.105	16.363	66.960	84.040	204.134	122.00	5.041	8.851	11.656	46.708	58.389	204.219			
79.70	7.098	12.076	16.376	66.295	82.195	208.257	124.00	5.003	8.793	11.608	46.605	58.341	198.081			
79.80	7.016	11.993	16.300	66.627	81.962	208.805	126.00	4.947	8.735	11.560	45.958	58.240	196.404			
79.90	6.950	11.916	16.246	66.475	81.748	207.634	128.00	4.893	8.671	11.512	46.008	58.249	196.196			
80.00	6.895	11.841	16.188	66.324	81.532	208.884	130.00	4.840	8.605	11.465	45.966	58.077	191.953			
81.00	6.821	11.805	16.150	65.708	79.875	207.331	132.00	4.789	8.553	11.418	45.966	58.223	189.752			
82.00	6.749	11.845	16.177	65.090	78.811	206.593	134.00	4.739	8.507	11.370	45.968	58.087	187.351			
83.00	6.699	11.888	16.227	62.400	76.685	202.034	136.00	4.690	8.459	11.323	45.955	58.048	185.109			
84.00	6.648	11.882	16.181	61.936	74.535	206.759	138.00	4.643	8.408	11.276	45.976	58.166	183.082			
85.00	6.596	11.825	16.158	61.343	73.620	207.076	140.00	4.597	8.360	11.229	45.978	58.178	181.829			
86.00	6.543	11.875	16.187	60.780	72.920	204.671	142.00	4.552	8.312	11.182	45.954	58.106	179.827			
87.00	6.487	11.876	16.180	60.210	72.236	202.335	144.00	4.509	8.265	11.136	46.011	58.048	177.873			
88.00	6.433	11.879	16.173	59.632	71.561	200.006	146.00	4.467	8.217	11.088	46.016	58.104	175.187			
89.00	6.379	11.793	16.175	59.184	70.903	203.759	148.00	4.425	8.170	11.043	45.973	58.073	173.387			
90.00	6.307	11.699	16.164	58.667	70.237	204.517	150.00	4.383	8.124	11.000	45.965	58.059	172.491			
91.00	6.256	11.699	16.157	58.161	70.624	203.157	152.00	4.348	8.132	10.958	45.966	58.040	171.717			
92.00	6.200	11.609	16.115	57.664	70.009	201.199	154.00	4.306	8.082	10.910	45.956	58.033	167.984			
93.00	6.157	11.621	16.121	57.156	71.394	200.181	156.00	4.270	8.036	10.866	45.971	58.173	166.290			
94.00	6.108	11.638	16.172	56.678	70.796	201.051	158.00	4.236	8.047	10.831	45.977	58.181	164.634			
95.00	6.061	11.650	16.194	56.209	70.210	203.819	160.00	4.198	8.002	10.799	45.959	58.063	163.816			
96.00	6.015	11.617	16.150	55.766	69.635	203.035	162.00	4.164	8.016	10.770	45.973	58.109	161.632			
97.00	5.969	11.685	16.176	55.287	69.078	201.088	164.00	4.130	8.036	10.789	45.960	58.080	159.803			
98.00	5.925	11.605	16.115	54.834	68.514	200.179	166.00	4.097	8.045	10.797	45.966	58.030	158.369			
99.00	5.881	11.627	16.087	54.439	67.971	200.296	168.00	4.066	8.056	10.814	45.958	58.087	156.884			
100.00	5.838	11.650	16.100	54.003	67.437	200.449	170.00	4.035	8.076	10.832	45.955	58.085	156.431			
101.00	5.796	11.655	16.110	53.572	66.912	200.634	172.00	4.002	8.022	10.852	45.960	58.081	156.019			
102.00	5.754	11.721	16.192	53.159	66.396	201.851	174.00	3.965	8.045	10.876	45.960	58.080	155.619			
103.00	5.716	11.628	16.109	52.766	65.889	200.087	176.00	3.932	8.011	10.897	45.983	58.109	155.234			
104.00	5.679	11.706	16.101	52.386	65.399	200.313	178.00	3.913	8.037	10.922	45.983	58.159	154.917			
105.00	5.635	11.686	16.095	51.993	64.901	200.477	180.00	3.884	8.005	10.948	45.989	58.160	154.687			
106.00	5.590	11.610	16.097	51.580	64.419	200.010	182.00	3.857	8.076	10.963	45.983	58.181	154.387			
107.00	5.548	11.604	16.082	51.202	63.949	200.189	184.00	3.830	8.073	10.986	45.980	58.186	154.061			
108.00	5.502	11.719	16.109	50.808	63.480	200.775	186.00	3.803	8.156	11.037	45.981	58.176	154.027			
109.00	5.465	11.716	16.110	50.405	63.022	200.167	188.00	3.777	8.189	11.070	45.989	58.153	153.613			
110.00	5.429	11.751	16.128	50.105	62.571	200.486	190.00	3.751	8.059	11.092	45.984	58.097	152.025			
111.00	5.435	11.687	16.140	49.751	62.128	201.866	192.00	3.728	8.012	11.117	45.982	58.086	151.179			
112.00	5.470	11.625	16.155	49.403	61.691	201.255	194.00	3.701	8.067	11.073	45.988	58.142	150.213			
113.00	5.484	11.683	16.157	49.061	61.262	201.664	196.00	3.675	8.022	11.098	45.988	58.148	149.088			
114.00	5.531	11.605	16.185	48.724	60.839	202.597	198.00	3.654	8.074	11.088	45.988	58.160	147.704			
115.00	5.470	11.643	16.190	48.392	60.423	202.153	200.00	3.631	8.036	11.080	45.986	58.090	146.769			
116.00	5.265	11.785	16.218	48.065	60.014	200.711										
117.00	5.121	11.748	16.225	47.748	59.616	200.310										
118.00	5.187	11.670	16.180	47.427	59.219	200.950										
119.00	5.191	11.610	16.181	47.109	58.822	200.590										
120.00	5.120	11.659	16.170	46.809	58.436	200.250										

Stopping power S of p, d, t, ^3He , α and ^7Li ions in silicon

Table 2

Range of heavy particles in silicon

TABLE 2 (continued)

RANGES IN CM/DOSE FOR SILICON													
E = 30 keV, $\alpha = 28.008$, $\beta = 1.71 \times 10^{-3}$													
DEPTH	R	D	T	HE 1	HE 2	LI 1	LI 2	LI 3	R	D	T	HE 1	HE 2
17.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
18.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
19.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
20.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
21.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
22.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
23.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
24.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
25.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
26.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
27.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
28.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
29.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
30.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
31.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
32.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
33.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
34.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
35.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
36.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
37.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
38.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
39.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
40.50	0.00104	0.00154	0.00171	0.00087	0.00104	0.00109	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100

RANGES R IN SILICON

Ranges R in silicon

RANGES IN GROSS FOR SELECT													
ENTRY	P	Q	R	HE 3	HE 4	LI 3	LI 4	HE 5	HE 6	LI 5	LI 6	HE 7	LI 7
71.00	6.042434	3.072075	2.010816	0.075661	0.035968	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
71.30	6.040622	3.072254	2.008218	0.075862	0.035962	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
71.60	6.038808	3.070456	2.006015	0.075623	0.035760	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
71.90	6.036994	3.068658	2.003812	0.075384	0.035558	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
72.00	6.035180	3.066860	2.001610	0.075145	0.035356	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
72.30	6.033366	3.065062	1.999407	0.074906	0.035154	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
72.60	6.031552	3.063264	1.997205	0.074667	0.034952	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
72.90	6.029738	3.061466	1.995002	0.074428	0.034750	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
73.00	6.027924	3.059668	1.992800	0.074189	0.034548	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
73.30	6.026110	3.057870	1.990597	0.073950	0.034346	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
73.60	6.024296	3.056072	1.988395	0.073711	0.034144	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
73.90	6.022482	3.054274	1.986192	0.073472	0.033942	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
74.00	6.020668	3.052476	1.983990	0.073233	0.033740	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
74.30	6.018854	3.050678	1.981787	0.072994	0.033538	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
74.60	6.017040	3.048880	1.979585	0.072755	0.033336	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
74.90	6.015226	3.047082	1.977382	0.072516	0.033134	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
75.00	6.013412	3.045284	1.975180	0.072277	0.032932	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
75.30	6.011598	3.043486	1.972977	0.072038	0.032730	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
75.60	6.009784	3.041688	1.970775	0.071799	0.032528	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
75.90	6.007970	3.039890	1.968572	0.071560	0.032326	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
76.00	6.006156	3.038092	1.966370	0.071321	0.032124	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
76.30	6.004342	3.036294	1.964167	0.071082	0.031922	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
76.60	6.002528	3.034496	1.961965	0.070843	0.031720	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
76.90	6.000714	3.032698	1.959762	0.070604	0.031518	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
77.00	5.998900	3.030900	1.957560	0.070365	0.031316	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
77.30	5.997086	3.029102	1.955357	0.070126	0.031114	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
77.60	5.995272	3.027304	1.953155	0.069887	0.030912	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
77.90	5.993458	3.025506	1.950952	0.069648	0.030710	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
78.00	5.991644	3.023708	1.948750	0.069409	0.030508	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
78.30	5.989830	3.021910	1.946547	0.069170	0.030306	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
78.60	5.988016	3.020112	1.944345	0.068931	0.030104	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
78.90	5.986202	3.018314	1.942142	0.068692	0.029902	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
79.00	5.984388	3.016516	1.939940	0.068453	0.029700	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
79.30	5.982574	3.014718	1.937737	0.068214	0.029498	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
79.60	5.980760	3.012920	1.935535	0.067975	0.029296	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
79.90	5.978946	3.011122	1.933332	0.067736	0.029094	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
80.00	5.977132	3.009324	1.931130	0.067497	0.028892	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
80.30	5.975318	3.007526	1.928927	0.067258	0.028690	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
80.60	5.973504	3.005728	1.926725	0.067019	0.028488	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
80.90	5.971690	3.003930	1.924522	0.066780	0.028286	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
81.00	5.969876	3.002132	1.922320	0.066541	0.028084	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
81.30	5.968062	3.000334	1.920117	0.066302	0.027882	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
81.60	5.966248	2.998536	1.917915	0.066063	0.027680	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
81.90	5.964434	2.996738	1.915712	0.065824	0.027478	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
82.00	5.962620	2.994940	1.913510	0.065585	0.027276	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
82.30	5.960806	2.993142	1.911307	0.065346	0.027074	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
82.60	5.958992	2.991344	1.909105	0.065107	0.026872	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
82.90	5.957178	2.989546	1.906902	0.064868	0.026670	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
83.00	5.955364	2.987748	1.904700	0.064629	0.026468	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
83.30	5.953550	2.985950	1.902497	0.064390	0.026266	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
83.60	5.951736	2.984152	1.900295	0.064151	0.026064	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
83.90	5.949922	2.982354	1.898092	0.063912	0.025862	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
84.00	5.948108	2.980556	1.895890	0.063673	0.025660	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
84.30	5.946294	2.978758	1.893687	0.063434	0.025458	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
84.60	5.944480	2.976960	1.891485	0.063195	0.025256	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
84.90	5.942666	2.975162	1.889282	0.062956	0.025054	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
85.00	5.940852	2.973364	1.887080	0.062717	0.024852	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
85.30	5.939038	2.971566	1.884877	0.062478	0.024650	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
85.60	5.937224	2.969768	1.882675	0.062239	0.024448	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
85.90	5.935410	2.967970	1.880472	0.062000	0.024246	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
86.00	5.933596	2.966172	1.878270	0.061761	0.024044	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
86.30	5.931782	2.964374	1.876067	0.061522	0.023842	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
86.60	5.929968	2.962576	1.873865	0.061283	0.023640	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
86.90	5.928154	2.960778	1.871662	0.061044	0.023438	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
87.00	5.926340	2.958980	1.869460	0.060805	0.023236	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
87.30	5.924526	2.957182	1.867257	0.060566	0.023034	1.024000	13.40-7761	0.002932	0.015784	1.014238	1.003578	0.031786	0.031786
87.60	5.922712	2.955384	1.8650										

Table 3   dE/dx and range of electrons in silicon

Table 4.-Continued
ELECTRONS IN SILICON

ENERGY	STOPPING POWER			RANGE	RADIATION
	COLLISION	RADIATION	TOTAL		YIELD
MEV	MEV CM2/G	MEV CM2/G	MEV CM2/G	G/CM2	
0.010	1.692E 01	9.576E-03	1.693E 01	3.454E-04	3.274E-04
0.015	1.253E 01	9.459E-03	1.254E 01	6.933E-04	4.389E-04
0.020	1.011E 01	9.344E-03	1.012E 01	1.140E-03	5.392E-04
0.025	8.570E 00	9.286E-03	8.579E 00	1.679E-03	6.321E-04
0.030	7.491E 00	9.252E-03	7.501E 00	2.304E-03	7.198E-04
0.035	6.693E 00	9.223E-03	6.702E 00	3.011E-03	8.034E-04
0.040	6.077E 00	9.241E-03	6.086E 00	3.795E-03	8.839E-04
0.045	5.586E 00	9.280E-03	5.595E 00	4.653E-03	9.622E-04
0.050	5.185E 00	9.333E-03	5.194E 00	5.581E-03	1.039E-03
0.055	4.851E 00	9.396E-03	4.860E 00	6.577E-03	1.114E-03
0.060	4.568E 00	9.467E-03	4.578E 00	7.638E-03	1.188E-03
0.065	4.326E 00	9.544E-03	4.335E 00	8.761E-03	1.261E-03
0.070	4.116E 00	9.626E-03	4.125E 00	9.944E-03	1.333E-03
0.075	3.932E 00	9.713E-03	3.942E 00	1.118E-02	1.404E-03
0.080	3.769E 00	9.803E-03	3.779E 00	1.248E-02	1.474E-03
0.085	3.625E 00	9.906E-03	3.635E 00	1.383E-02	1.544E-03
0.090	3.495E 00	1.000E-02	3.505E 00	1.523E-02	1.613E-03
0.095	3.379E 00	1.010E-02	3.389E 00	1.668E-02	1.682E-03
0.100	3.273E 00	1.020E-02	3.284E 00	1.818E-02	1.750E-03
0.150	2.592E 00	1.125E-02	2.603E 00	3.550E-02	2.406E-03
0.200	2.246E 00	1.230E-02	2.258E 00	5.625E-02	3.027E-03
0.250	2.039E 00	1.348E-02	2.053E 00	7.955E-02	3.624E-03
0.300	1.904E 00	1.472E-02	1.919E 00	1.048E-01	4.207E-03
0.350	1.805E 00	1.602E-02	1.821E 00	1.316E-01	4.784E-03
0.400	1.739E 00	1.730E-02	1.756E 00	1.596E-01	5.352E-03
0.450	1.689E 00	1.860E-02	1.707E 00	1.885E-01	5.909E-03
0.500	1.651E 00	1.989E-02	1.671E 00	2.181E-01	6.459E-03
0.550	1.621E 00	2.117E-02	1.642E 00	2.483E-01	6.999E-03
0.600	1.598E 00	2.245E-02	1.620E 00	2.790E-01	7.530E-03
0.650	1.580E 00	2.372E-02	1.603E 00	3.100E-01	8.053E-03
0.700	1.565E 00	2.499E-02	1.590E 00	3.413E-01	8.567E-03
0.750	1.553E 00	2.626E-02	1.579E 00	3.729E-01	9.074E-03
0.800	1.544E 00	2.753E-02	1.571E 00	4.046E-01	9.574E-03
0.850	1.536E 00	2.887E-02	1.565E 00	4.365E-01	1.007E-02
0.900	1.530E 00	3.014E-02	1.560E 00	4.685E-01	1.056E-02
0.950	1.525E 00	3.140E-02	1.557E 00	5.006E-01	1.104E-02
1.000	1.522E 00	3.267E-02	1.554E 00	5.327E-01	1.152E-02
1.100	1.516E 00	3.519E-02	1.552E 00	5.971E-01	1.246E-02
1.200	1.514E 00	3.772E-02	1.551E 00	6.616E-01	1.338E-02
1.300	1.513E 00	4.024E-02	1.553E 00	7.260E-01	1.428E-02

Table 4.-Continued
ELECTRONS IN SILICON

ENERGY	STOPPING POWER		TOTAL	RANGE	RADIATION YIELD
	COLLISION	RADIATION			
MEV	MEV CM2/G	MEV CM2/G	MEV CM2/G	G/CM2	
1.400	1.513E 00	4.275E-02	1.556E 00	7.904E-01	1.517E-02
1.500	1.514E 00	4.527E-02	1.560E 00	8.546E-01	1.604E-02
1.600	1.516E 00	4.778E-02	1.564E 00	9.186E-01	1.690E-02
1.700	1.519E 00	5.011E-02	1.569E 00	9.824E-01	1.774E-02
1.800	1.521E 00	5.264E-02	1.574E 00	1.046E 00	1.857E-02
1.900	1.525E 00	5.521E-02	1.580E 00	1.109E 00	1.939E-02
2.000	1.528E 00	5.779E-02	1.586E 00	1.173E 00	2.021E-02
2.200	1.534E 00	6.303E-02	1.598E 00	1.298E 00	2.182E-02
2.400	1.541E 00	6.835E-02	1.610E 00	1.423E 00	2.342E-02
2.600	1.548E 00	7.374E-02	1.622E 00	1.547E 00	2.500E-02
2.800	1.555E 00	7.891E-02	1.634E 00	1.670E 00	2.656E-02
3.000	1.562E 00	8.445E-02	1.647E 00	1.792E 00	2.811E-02
3.500	1.578E 00	9.874E-02	1.677E 00	2.092E 00	3.196E-02
4.000	1.593E 00	1.136E-01	1.706E 00	2.388E 00	3.581E-02
4.500	1.606E 00	1.292E-01	1.735E 00	2.679E 00	3.966E-02
5.000	1.618E 00	1.449E-01	1.763E 00	2.964E 00	4.353E-02
5.500	1.629E 00	1.610E-01	1.790E 00	3.246E 00	4.740E-02
6.000	1.639E 00	1.773E-01	1.817E 00	3.523E 00	5.126E-02
6.500	1.649E 00	1.939E-01	1.843E 00	3.796E 00	5.512E-02
7.000	1.657E 00	2.107E-01	1.868E 00	4.066E 00	5.897E-02
7.500	1.665E 00	2.277E-01	1.893E 00	4.332E 00	6.280E-02
8.000	1.673E 00	2.449E-01	1.918E 00	4.594E 00	6.663E-02
8.500	1.680E 00	2.623E-01	1.942E 00	4.853E 00	7.044E-02
9.000	1.686E 00	2.815E-01	1.968E 00	5.109E 00	7.425E-02
9.500	1.692E 00	2.993E-01	1.992E 00	5.362E 00	7.806E-02
10.000	1.698E 00	3.172E-01	2.016E 00	5.611E 00	8.184E-02
20.000	1.773E 00	6.976E-01	2.470E 00	1.008E 01	1.522E-01
30.000	1.812E 00	1.101E 00	2.913E 00	1.380E 01	2.122E-01
40.000	1.839E 00	1.515E 00	3.354E 00	1.700E 01	2.632E-01
50.000	1.859E 00	1.936E 00	3.795E 00	1.980E 01	3.070E-01
60.000	1.875E 00	2.362E 00	4.237E 00	2.229E 01	3.449E-01
80.000	1.899E 00	3.224E 00	5.123E 00	2.658E 01	4.076E-01
100.000	1.917E 00	4.093E 00	6.010E 00	3.018E 01	4.573E-01
200.000	1.972E 00	8.504E 00	1.048E 01	4.263E 01	6.076E-01
300.000	2.004E 00	1.296E 01	1.496E 01	5.057E 01	6.857E-01
400.000	2.026E 00	1.743E 01	1.946E 01	5.642E 01	7.349E-01
500.000	2.043E 00	2.192E 01	2.396E 01	6.104E 01	7.691E-01
600.000	2.057E 00	2.641E 01	2.846E 01	6.486E 01	7.945E-01
800.000	2.079E 00	3.540E 01	3.748E 01	7.097E 01	8.381E-01
1000.000	2.096E 00	4.439E 01	4.649E 01	7.575E 01	8.541E-01

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