Journal of the Korean Nuclear Society
Volume 28, Number 4, pp. 397~405, August 1996

Signal Generation Due to Alpha Particle in Hydrogenated Amorphous Silicon Radiation Detectors

Ho Kyung Kim and Gyuseong Cho
Korea Advanced Institute of Science and Technology
373-1 Kusong-dong, Yusong-gu, Taejon 305-701, Korea

(Received March 5, 1996)

Abstract

The hydrogenated amorphous silicon (a-Si : H) holds good promise for radiation detection from its inherent merits over crystalline counterpart. For the application to alpha spectroscopy, the induced charge collection in a-Si : H pin detector diodes was simulated based on a relevant non-uniform charge generation model. The simulation was performed for the initial energy and the range of incident alpha particles, detector thickness and the operational parameters such as the applied reverse bias voltage and shaping time. From the simulation, the total charge collection was strongly affected by hole collection as expected. To get a reasonable signal generation, therefore, the hole collection should be seriously considered for detector operational parameters such as shaping time and reverse voltage etc. For the spectroscopy of alpha particle from common alpha sources, the amorphous silicon should have about 70μm thickness.

1. Introduction

The hydrogenated amorphous silicon (a-Si : H) has been recently paid attention as a solid-state material for radiation detectors because of the easy fabrication of large area devices and the high radiation-hardness in comparison with its crystalline counterpart. It was reported that a-Si : H diodes of the Schottky or p-i-n structure can detect charged particles such as alpha and beta ray.[1, 2] In many applications such as radioisotope analysis and physics experiments, it is necessary to relate the magnitude of the signal from the detectors with the radiation type and its energy.

In the case of detecting high energy particles by thin semiconductor diodes often arisen in particle accelerator experiments, it is common to assume the uniform charge generation along the track of the radiation[3] because the range of passing particle is typically much larger than the detector thickness. In the case of detecting nuclear radiation, however, it is necessary to consider the non-uniformity of the charge generation along the track. Especially for the alpha spectroscopy by amorphous silicon diodes, the analysis of the detector signal can be very complicated due to three factors ; (1) the detector thickness : the range is a strong function of the alpha energy and the detector thickness is limited by the preparation. So far the maximum thickness obtained by the PECVD(plasma enhanced chemical vapor deposition) is about 100μm and is due to the build-up of the internal stress in the film during the deposition.[4] (2) the applied bias : the space charge in the intrinsic layer exposed under the reverse bias is mostly due to the ionized dangling bonds of silicon atoms and its magnitude is about 7×10^{14}bonds/cm^3 in a device quality films. This makes the diode need a high voltage for full depletion of the intrinsic layer, and (3) the low hole mobility and the noise: the mobilities of charge carriers in the amorphous silicon are low so the charge collection time should be long enough to yield a reasonable signal size. This also increases the electronic noise of the detector itself mainly due to the fluctuation of the reverse leakage current of diodes. [5]

Therefore, in order to design and operate a-Si : H diode detectors with a high signal-to-noise ratio (S/N), the operation parameters, such as the bias, shaping time etc., should be optimized. In this paper, a simplified calculation of the charge collection efficiency in a-Si : H pin diodes when they are used for the alpha spectroscopy is performed.

2. Charge Collection Efficiency for Alpha Particle

2.1 Energy Loss along the Alpha Particle Track

An alpha particle loses its energy continuously in a medium through the Coulomb interaction and the interaction density is high in a solid due to the high electron density. Therefore, its specific energy loss is large and it has a specific track range in a material depending on the energy. For common alpha-emitting radioisotopes, the typical energy of emitted alpha particles has a limited ranges between about 3 and 7 MeV. [6] For the full collection of signal from alpha particles of 7 MeV, a silicon detector should be at least 40μm in thickness. The charge generation in a detector medium by an alpha particle is proportional to the energy loss at a specific distance of penetration, that is corresponding to the peak of a Bragg curve. So the curve should be obtained before the calculation of the signal in a detector.

From the data given by Qureshi [7], the mass stopping power, S_m, for alpha particles in a silicon, of which density is $\rho = 2.3\text{g/cm}^3$, is plotted as a function of energy and then it is fitted to the following equation

$$S_m \equiv -\frac{1}{\rho}\frac{dE}{dx} = S_2 + S_1 e^{-\lambda E} \quad (1)$$

where

$S_1 = 1209$ [MeVcm^2/g]
$S_2 = 221$ [MeVcm^2/g]
$\lambda = 0.2154$ [MeV^{-1}]

In Fig. 1, the relative error is 1~2% in the interest region and the average standard deviation is 20.56 [MeVcm^2/g].

Then, Eq. (1) is modified for amorphous silicon, whose density is $\rho = 2.25\text{g/cm}^3$, and rearranged as a function of the initial energy of the particle, E_o, and the penetration distance, x measured from the injection surface as follows

$$S(E_o, x) = -\frac{dE}{dx} = S_o \frac{B_o}{B_o - A_o e^{\lambda S_o x}} \quad (2)$$

where

$S_o = 497$ [MeVcm]
$A_o = 5.47$
$B_o = A_o + e^{\lambda E_o}$

From the Eq. (2), the range of alpha particle is given by

$$R(E_o) = \frac{1}{\lambda S_o} \ln\left(\frac{A_o + e^{\lambda E_o}}{A_o + 1}\right) \quad (3)$$

The generated charge due to an incident alpha particle with initial energy, E_o, and range, R, in a-Si : H pin detector with thickness, d, is given by

$$Q_r = \int_0^L q\frac{S(E_o, x)}{W}dx = qA\int_0^L n_o(E_o, x)dx \quad (4)$$

where L is the smaller value between R and d. q is an electronic charge, A is the area of the detector and W is the average ionization energy needed to produce an electron-hole pair by the incident radiation. W value of amorphous silicon is ~5eV which is larger than that of crystalline silicon(~3.6eV) but it is still considerably lower than that of a typical gas-filled detector(~30eV). $n_o(E_o, x)$ is the initial distribution of generated charges and is directly proportional to the Eq. (2).

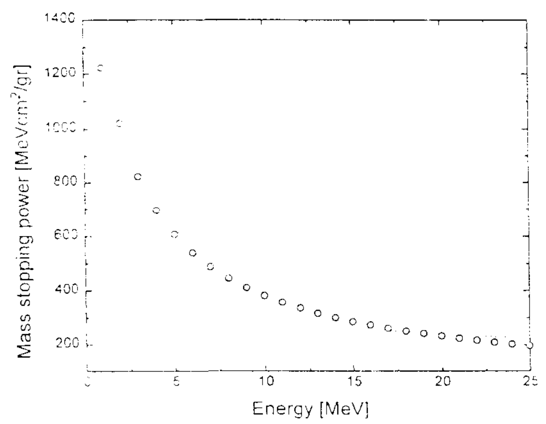

Fig. 1. Mass stopping power of a-Si : H against alpha particles as a function of energy : the data is fitted by Eq. (1) which is shown by the dot-line.

2.2 Governing Equations and Approximations

When a-Si : H pin diode is used as a radiation detector, the area of detector is very large compared to the thickness of the detector. So that one-dimensional approximation can describe the problem properly. To calculate the collection efficiency of induced charges in a-Si : H pin diode, there are three relevant governing equations which are a Poisson's equation for the potential distribution, V(x), and two continuity equations of charge carriers, electrons and holes.

$$\frac{d^2V}{dx^2} = -\frac{q}{\varepsilon_o\varepsilon_{asi}}(n_e - n_h + n_c + N^*_d) \quad (5a)$$

$$\frac{dn_e}{dt} = \frac{1}{q}\frac{dj_e}{dx} + g_e \quad (5b)$$

$$\frac{dn_h}{dt} = -\frac{1}{q}\frac{dj_h}{dx} + g_h \quad (5c)$$

where

$j_e = q\mu_e n_e \mathrm{E} + qD_e\frac{dn_e}{dx}$: the electron current density (6a)

$j_h = q\mu_h n_h \mathrm{E} - qD_h\frac{dn_h}{dx}$: the hole current density (6b)

where, ε_o is the permittivity in vacuum and ε_{asi} is the relative dielectric constant of amorphous silicon. μ, D, and E stand for the mobility, diffusion coefficient and the electric field strength, respectively. n means the number of density and subscripts e, h and c correspond to electron, hole and ionized dopant, respectively. Similarly, the net generation rate is symbolized by g.

For simple calculation, several assumptions are made as follows.

(1) One-sided abrupt junction : Amorphous silicon radiation detectors are reverse-biased pin diode in which i-layer is slightly n-type due to the ionized dangling bonds. Therefore it behaves like a p-n junction diode. Also the doped p-layer(~nm) is much thinner than the undoped i-layer(~μm) so the diode can be approximated as a one-sided abrupt p-i junction. The maximum ionizable dangling bond density, N^*_d is assumed to be constant over the spatial variable, x, so the electric field is linear through the diode and it drops to zero at the end of the depletion layer.

(2) One region approximation : Since the electric field in the n-layer is low due to high trapping and recombination processes, the transport of charge in that region does not contribute to the radiation signal. Therefore the i-layer is only considered and used for charge collection calculation. Since the density of generated electrons and holes due to the incident alpha particle is smaller than the ionized dangling bond density and the dopant density, n_c, is zero, the Eq. (5a) becomes the following simple equation,

$$\frac{d^2V}{dx^2} = -\frac{qN^*_d}{\varepsilon_o\varepsilon_{asi}} \equiv -a \quad (7)$$

where the defined value "a" means the slope of the electric field in the i-layer.

(3) Instant charge generation and simple trapping approximation : It is assumed that the charge carriers are generated in the detector instantly at time $t=0$. And the direct recombination of generated charge carriers is neglected because of the small cross section. Also the plasma effect due to the high density of charge carriers at the end of range of alpha particles is neglected. However, the number of charge carriers decreases due to the trapping by defect states

during the transit time and it is characterized by a lifetime, τ_i where the subscript i means the type of charge carrier. Therefore, the generation and recombination term in Eqs. (5b) and (5c) becomes

$$g_i(x, t) = n_o(E_o, x)\delta(t) - \frac{n_i(x, t)}{\tau_i} \tag{8}$$

where $n_i(x, t)$ is electron density, $n_e(x, t)$ or hole density, $n_h(x, t)$. $\delta(t)$ stands for the delta function.

(4) Neglecting the diffusion process of generated charge : The diffusion of charge carriers during the transit time is neglected because the diffusion length, L, is much shorter than the depletion width, w, for the range of applied reverse bias, V_a, of interest, i. e.

$$\frac{w}{L} = \left(\frac{2V_a}{a}\right)^{1/2} (D_i\tau_i)^{-1/2} \gg 1 \tag{9}$$

Then, since the drift motion of charge carriers is only considered, the Eqs. (6a) and (6b) become

$$j_e = q\mu_e n_e \mathrm{E} \tag{10a}$$

$$j_h = q\mu_h n_h \mathrm{E} \tag{10b}$$

Also the mobilities of electrons and holes are assumed to be constant in the range of interest and independent of the electric field strength in the i-layer. [8]

Fig. 2 shows schematic distributions of the space charge density, the electric field with increasing applied reverse-bias, V_a, and the generated charge density due to an incident alpha particle with initial energy, E_o. It is assumed that the alpha particle is incident toward p-side of a-Si : H pin diode.

2.3 Calculation Procedure of the Charge Collection Efficiency

The charge, dQ is induced at the external circuit of detector when a charge q is displaced by a small distance dx in a diode of thickness, d. [9]

$$dQ = \frac{q}{d} \times dx \tag{11}$$

Then, the induced current becomes

$$i(t) = \frac{dQ}{dt} = \frac{q}{d} \times \frac{dx}{dt} = \frac{q}{d} \times v(x, t) \tag{12}$$

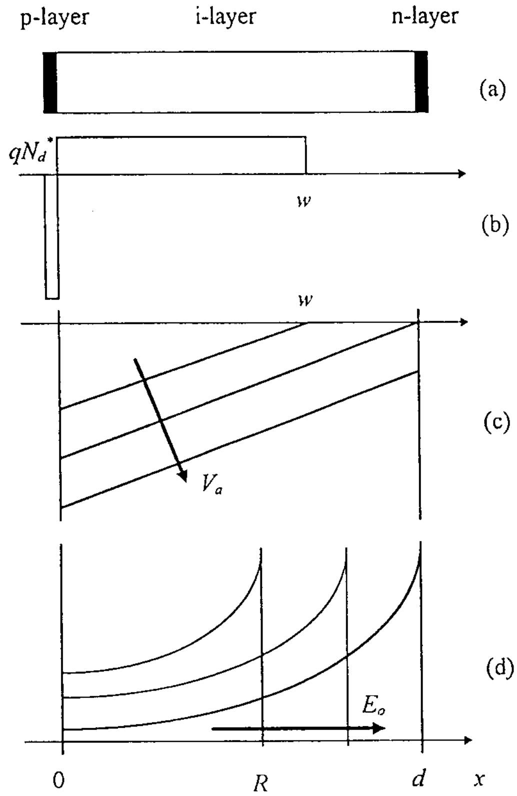

Fig. 2 (a) Schematic view of a pin diode (b) the space charge distribution (c) the electric field distribution inside the diode at different applied reverse-bias (d) the generated charge distribution due to alpha particle at different initial energy

where $v(x, t)$ is the velocity of charge carriers at position x in time t.

Thus, the total charge can be obtained by the integration of the velocity of generated charge carriers in a detector.

$$Q_c(t) = \int_0^t i(t)dt = \int_0^t [i_e(t) + i_h(t)]dt = Q_e(t) + Q_h(t) \tag{13}$$

The collected signal charge is calculated for various cases of different electric field configuration, E(x), and different depletion widths and the different range of alpha particles. For a convenient calculation, the following parameters are defined as a normalized value by the detector thickness, d ;

Depletion parameter, $Y \equiv \frac{w}{d}$

Range parameter, $Z \equiv \frac{R}{d}$

The electron and hole charge collection should be carefully formulated for four different cases as shown in Table 1. Here, only the formula for case 1 will be given.

Table 1. Four different cases for the electron and hole collection

	$Y<1$ Partial depletion	$Y>1$ Full depletion
$Z<Y$	case 1	case 2
$Z>Y$	case 3	case 4

The electric field is represented as

$$E(x) = a(x-w) \quad \text{for } 0 \leq x \leq u \tag{14}$$

The electron drift velocity as a function of time, t, and the initial position, x_o, is given by

$$v_e(x_o, t) = \frac{(w-x_o)}{\tau_n} e^{-t/\tau_n} \tag{15}$$

where the electron characteristic time, $\tau_n = \frac{1}{a\mu_e}$, and is determined by the amorphous silicon material property. Note that the electron transit time, t, from the initial position, x_o, to w is infinite or the electron never reaches w theoretically. The induced current due to electron drift motion is given as follows

$$\Delta I_e(x_o, t) = qn(E_o, x_o) e^{-t/\tau_e} \frac{v_e(x_o, t)}{d} \tag{16}$$

where the exponential term is due to the trapping process. Therefore the total induced charge due to electrons generated at x_o during a collection or shaping time, τ, is

$$Q_e = \int_0^R dx_o \int_0^\tau \Delta I_e(x_o, t) dt \tag{17}$$

The hole drift velocity and the induced current have similar expressions to the electron case such as

$$v_h(x_o, t) = -\frac{(x_o-w)}{\tau_p} e^{t/\tau_p} \tag{18}$$

$$\Delta I_h(x_o, t) = -qn(E_o, x_o) e^{-t/\tau_h} \frac{v_h(x_o, t)}{d} \tag{19}$$

where τ_p and τ_h are the hole characteristic time and hole life-time, respectively and τ_p is defined by

$$\tau_p = \frac{1}{a\mu_h}$$

In order to calculate the induced charge due to holes, some parameters should be defined such as t_{ro} = the hole transit time from R to 0 and x_{tp} = the boundary position between holes which can reach x=0 and which can not reach x=0 during time, t_{ro}.

$$t_{ro} = \tau_p \ln\left(\frac{Y}{Y-Z}\right)$$

$$x_{tp} = Y(1-e^{-\tau/\tau_p})$$

If the collection time, τ, is smaller than t_{ro}, some of holes can reach x=0 and others cannot reach x=0, then, the induced charge due to all holes is

$$Q_h = \int_0^{x_{tp}} dx_o \int_0^{t_{xo}} \Delta I_h(x_o, t) dt + \int_{x_{tp}}^R dx_o \int_0^\tau \Delta I_h(x_o, t) dt \tag{20}$$

where $t_{xo} = \tau_p \ln\left(\frac{Y}{Y-X_o}\right)$

If the collection time is larger than the t_{ro}, all the holes can reach x=0, so

$$Q_h = \int_0^R dx_o \int_0^{t_{xo}} \Delta I_h(x_o, t) dt$$

Finally the collation efficiency is defined and calculated as

$$\eta \equiv \frac{\text{collected charge}}{\text{total generated charge}} = \frac{Q_c}{Q_o} = \frac{Q_e + Q_h}{Q_o} \tag{22}$$

3. Results and Discussion

In order to calculate the charge collection efficiency, several material parameters of the detector and operational parameters are required. Table 2 shows the input parameters for the calculation and the calculation results are shown for each operational parameters, such as the bias voltage and the shaping time.

As discussed in section 2.1, the range of alpha particles from common alpha-emitting radioisotopes is approximately between 3 MeV and 7 MeV. From the Eq. (5a), the required detector thickness should be about 40 μm to fully collect the signal charge carriers from a 7 MeV alpha particle. The full depletion bias is about 860 V for this case.

Fig. 3 shows the electron, hole, and total collection efficiency for the 40μm thickness detector as a function of shaping time at a reverse bias of 950V which is 10% higher than the full depletion bias. Since the electron has a higher mobility than the holes by about 40μm to fully collect the signal charge carriers that its ballistic deficit is negligible. However, in order to collect the holes, the shaping time should be at least as long as 5μsec. The total collection efficiency is strongly dependent upon the hole collection. It is noted that the total collection never reaches to unity because of the exponential trapping approximation as discussed in section 2. 2.

Fig. 4 shows the total collection efficiency as a function of shaping time for the 40μm thickness detector at different bias voltages for the partial depletion and full depletion cases. At the partial depletion bias, the collection efficiency is poor (<0.5), but at the full depletion bias condition, the collection efficiency

Table 2. Input parameters for the calculation of charge collection efficiency

Parameters	Value
Electron mobility, μ_e	1.2cm^2/Vsec
Hole mobility, μ_h	0.4cm^2/Vsec
Electron life time, τ_n	9×10^{-8}/sec
Hole life time, τ_p	3×10^{-6}/sec
Dangling bond density, N_d^*	7×10^{14}cm^{-3}
Detector thickness, d	variable
Initial energy of alpaha particle, E_o	variable
Applied reverse bias, V_a	variable
Shaping time, τ_e	variable

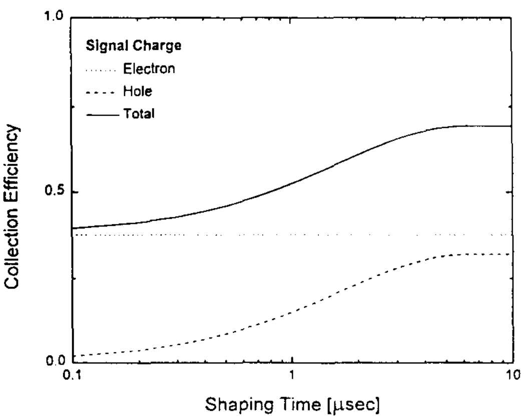

Fig. 3 Collection efficiency of total, electron and hole for the 40μm thickness detector at 950 V

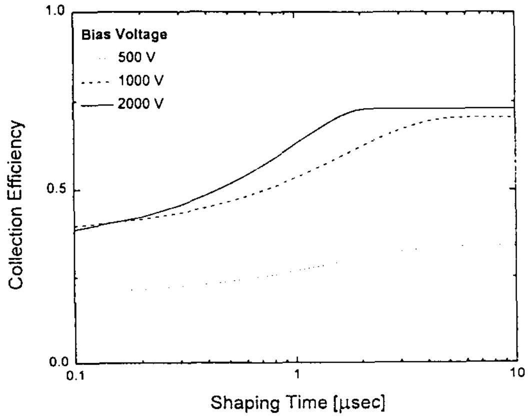

Fig. 4 Total collection efficiency as a function of shaping time for the 40m thickness detector at different bias voltages

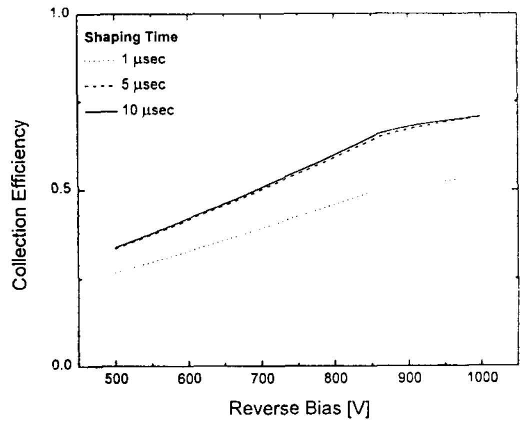

Fig. 5 Total collection efficiency as a function of reverse bias voltage for the 40μm thickness detector at different shaping times

is reasonably high, 70%, and the saturation level is almost same. However, the time of saturation is faster as the reverse bias voltage increases due to the slow hole collection.

Fig. 5 shows the total collection efficiency as a function of the bias voltage for three different shaping times. From the figure, it is noted that 5 μsec would be a reasonable shaping time and the collection efficiency becomes saturated above the full depletion bias voltage, ~860V.

Figs. 6 and 7 show the total collection efficiency and signal output as a function of the initial energy of incident alpha particle for the detector with various thickness, respectively. As expected, the collection efficiency is a decreasing function of the initial energy and the signal output has a maximum value due to the finite range of the incident particle. As shown in Fig. 7, the alpha particle energy spectroscopy can be accomplished with 30~70μm thick detector for the energy range up to 7 MeV because the output signal is linear in that region.

4. Conclusions

Hydrogenated amorphous silicon is a good candidate in making radiation detectors due to many attractive merits; easy fabrication of large-area devices with low cost and good radiation resistance. The thickness of films produced by the current state of arts is large enough to use this material as alpha or heavy charged particle spectroscopy.

The induced charge collection efficiency for alpha particle was calculated based on the non-uniform charge generation model using a simplified Bragg curve. The charge collection was mainly limited by the hole drift motion due to its poor electronic properties in hydrogenated amorphous silicon. For the complete hole collection, shaping time should be at least about 5μsec or longer. As far as the reverse bias is concerned, the full depletion bias is required for a reasonable collection efficiency. As a result of simulation, it is said that the energy spectroscopy of alpha particles can be done with a-Si : H detector, and 70μm thick diode should be prepared for natural alpha sources.

In conclusion, it is shown that hydrogenated amorphous silicon pin diode can be used for the alpha particle spectroscopy.

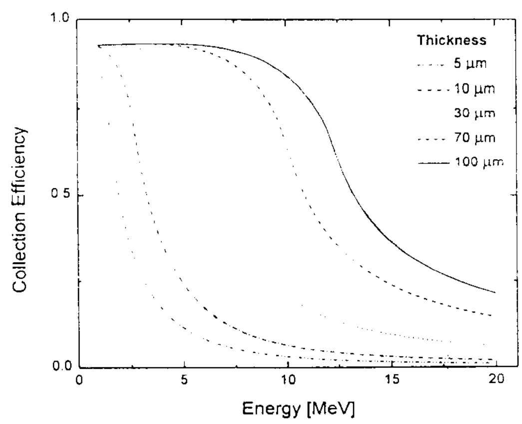

Fig. 6 Total collection efficiency as a function of the initial energy of incident alpha particle for the detector with various thickness

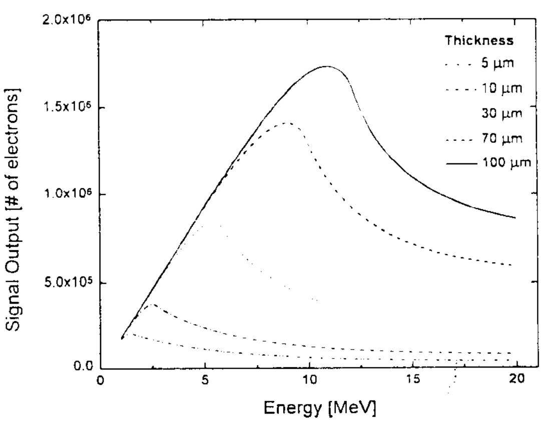

Fig. 7 Signal output as a function of the initial energy of incident alpha particle for the detector with various thickness

References

1. S. N. Kaplan et al. , "Detection of Charged Particles in Amorphous Silicon Layers," *IEEE Trans. Nucl. Sci.*, **33**(1), 351(1986)
2. V. Perez-Mendez et al. , "Hydrogenated Amorphous Silicon Pixel Detectors for Minimum Ionizing Particles," *Nucl. Instr. and Meth.*, **A273**, 127-134 (1988)
3. G. Cho, *Signal and Noise Analysis of a-Si : H Radiation Detector-Amplifier System*, Ph. D. Thesis, UC Berkeley(1992)
4. W. S. Hong, *Development of Radiation Detectors Based on Hydrogenated Amorphous Silicon and Its Alloys*, Ph. D. Thesis, UC Berkeley(1995)
5. G. Cho et al. , "Noise in a-Si:H p-i-n Detector Diodes," *IEEE Trans. Nucl. Sci.*, **39**(4), 641 (1992)
6. G. F. Knoll, *Radiation Detection and Measurement*, 2nd Ed. , John Wiley & Sons, 9(1989)
7. S. Qureshi, *Hydrogenated Amorphous Silicon Radiation Detectors : Material Parameters ; Radiation Hardness; Charge Collection*, Ph. D. Thesis, UC Berkeley(1991)
8. S. M. Sze, *Physics of Semiconductor Devices*, 2nd Ed., John Wiley & Sons., 448-450(1981)
9. P. A. Tove and K. Falk, "Pulse Formation and Transit Time of Charge Carriers in Semiconductor Junction Detectors," *Nucl. Instr. and Meth.*, **29**66 (1964)