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Comparison of Alpha Particle Signals with respect to Incident Direction onto a-Si:H pin diodes

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Abstract

For the application of hydrogenated amorphous silicon (a-Si:H) p-i-n structural diode as the alpha particle spectroscopy, the induced charge collection was simulated based on a relevant non-uniform charge generation model. The simulation was accomplished for two extreme cases of the incident direction of alpha particle, p- and n-side, respectively. As expected, for the complete charge collection, the hole collection should be severely considered due to its poor mobility and the full depletion bias required. For the comparison of signal corresponding to the detector configuration or structure, although n-i-p configuration shows a wider range of linearity to the energy, p-i-n configuration is more suitable in the viewpoint of linearity and signal value for the considering energy range.

1. Introduction

The hydrogenated amorphous silicon (a-Si:H) has a potential as the application of radiation detection due to better material properties over its crystalline counterpart, such as easy fabrication of large area with low cost and good radiation resistance. In addition, the thickness of films produced by the current state-of-the art is thick enough to use this material as alpha or heavy charged particle spectroscopy. It was reported that a-Si:H diodes of the Schottky or p-i-n structure can detect charged particle radiation such as alpha and beta particles.[1, 2]

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.

Alpha radiation is highly toxic when it irradiates the inside of the body from internally deposited radioisotopes by inhalation, ingestion, entering through a wound etc. For common alpha-emitting radioisotopes, the typical energy of emitted alpha particles has a limited range between about 4 and 7 MeV energy, a silicon detector should be at least 40 μm in thickness.[4]

2. Charge Collection Efficiency

An alpha particle losses 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. 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 known as a Bragg curve. So the curve should be obtained before the calculation of the signal in a detector.

From the information of mass stopping power in the reference [5], Bragg curve and the range of alpha particle are simplified as follows

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

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

where

$\lambda = 0.2154$ [MeV^{-1}]

$S_o = 497$ [MeV/cm]

$A_o = 5.47$

$B_o = A_o + e^{\lambda E_o}$

From the above equation, Bragg curve means the mass stopping power expressed as a function of the initial energy of the alpha particle and the penetration distance. 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

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

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 ~ 5 eV which is larger than that of crystalline silicon (~ 3.6 eV) but is still considerably lower than that of a typical gas-filled detector (~ 30 eV).

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, several approximations are used; (a) one-side abrupt junction model (b) one-region approximation (c) instant charge generation and simple trapping approximation (d) neglect of the diffusion process.

The induced current at the external circuit of detector when a charge, q, is displaced by a small distance dx in a diode of thickness, d, becomes [6]

$$i(t) = \frac{q}{d} \times v(x,t)$$

The collected signal charge is calculated by integrating the above equation with the initial electron-hole pair distribution.

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

For each direction of incident alpha particle toward a-Si:H pin diode, various calculations are accomplished for different electric field configuration, and different depletion widths and the different range of alpha particles. The electron and hole charge collection should be carefully formulated for four different cases as follows.

	Partial Depletion (w < d)	Full Depletion (w > d)
Full Energy Deposition (R < d)	case 1	case 3
Partial Energy Deposition (R > d)	case 2	case 4

Fig 1. shows, for example, the schematic diagram of calculation procedure for n-i-p configuration.

Finally the collection efficiency is defined and calculated as

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

3. Results and Discussion

From the reference [3], several material parameters of the detector were used for the input parameters; electron and hole mobility, electron and hole life time and dangling bond density. Since the detector thickness, initial energy of alpha particle, applied reverse bias and shaping time were used as the input variables, the calculation results are shown for each operational parameters.

40 μm detector thickness was considered for the full detection of 7 MeV alpha particle which is a reasonable maximum value from the common-alpha emitting source and the corresponding full depletion bias was about 860 Volts.

Fig. 2 shows the total collection efficiency as a function of reverse bias for each configuration at 10 μsec shaping time. There are two distinct regions divided by the full depletion bias. The collection efficiency is saturated at certain value above the full depletion bias, but it never reaches to unity because of the exponential trapping approximation as discussed in section 2. Over certain range of reverse bias, it could be known that the collection efficiency is higher for n-i-p configuration than for the opposite p-i-n configuration. That is explained by the longer drift motion of electron with high mobility for n-i-p configuration.

Similar result should be noticed by Fig. 3 showing the total collection efficiency as function of shaping time for each configuration at a reverse bias voltage of 1000 Volts. The increase region of Fig. 3 is due to the hole collection, which may affect the determination of shaping time for the spectroscopy system. The calculated signal pulse peaking times are ~ 0.02 and ~ 6.5 μsec for electron and hole case, respectively, independent upon the diode configuration. Thus, it needs the shaping time of more than 6.5 μsec to detect the common alpha-emitting source.

Fig. 4 and Fig. 5 show the energy collection efficiency as a function of initial energy of incident alpha particle with various detector thickness for p-i-n and n-i-p configuration, respectively. There is a definite difference between Fig. 4 and Fig. 5. While p-side incidence case shows a monotonous decreasing feature, n-side incidence case has a peak value. This difference is well understood by two figures in the right-hand side of Fig. 1. For p-i-n configuration, the drift length of electron is shorter when the range of alpha particle is longer. For n-i-p configuration, on the other hand, the drift length is also longer when the range is longer. The decreasing feature after a peak value in Fig. 5 is due to that the collection efficiency decreases after the range of alpha particle is greater than the detector thickness.

Fig. 6 and Fig. 7 show the signal output as a function of initial energy of incident alpha particle with various detector thickness. Comparing Fig. 6 with Fig. 7, p-i-n configuration shows better features of the good linearity and the high signal for energy range. As shown by the figures, the energy spectroscopy of alpha particles should be accomplished with a 30 ~ 70 μm thick detector for the common energy range.

4. Conclusion

The induced charge collection efficiency for alpha particle was calculated based on the relevant non-uniform charge generation model using a simplified Bragg curve. From the simulation, the following conclusions are derived. For reasonable charge collection, the shaping time should be at least ~ 6.5 μsec or larger and the full depletion reverse bias required. Comparing p-i-n diode with n-i-p diode, there is a wider region of linearity to the energy in the case of n-side incidence of alpha particle. However, incidence toward p-side is better than the opposite case because of a good linearity in the range of interesting energy and the higher signal value. As a result of simulation, it is said that the energy spectroscopy of alpha particles can be done with a-Si:H detector, and 70 μm thick diode should be prepared for natural common alpha emitters.

References

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Figures

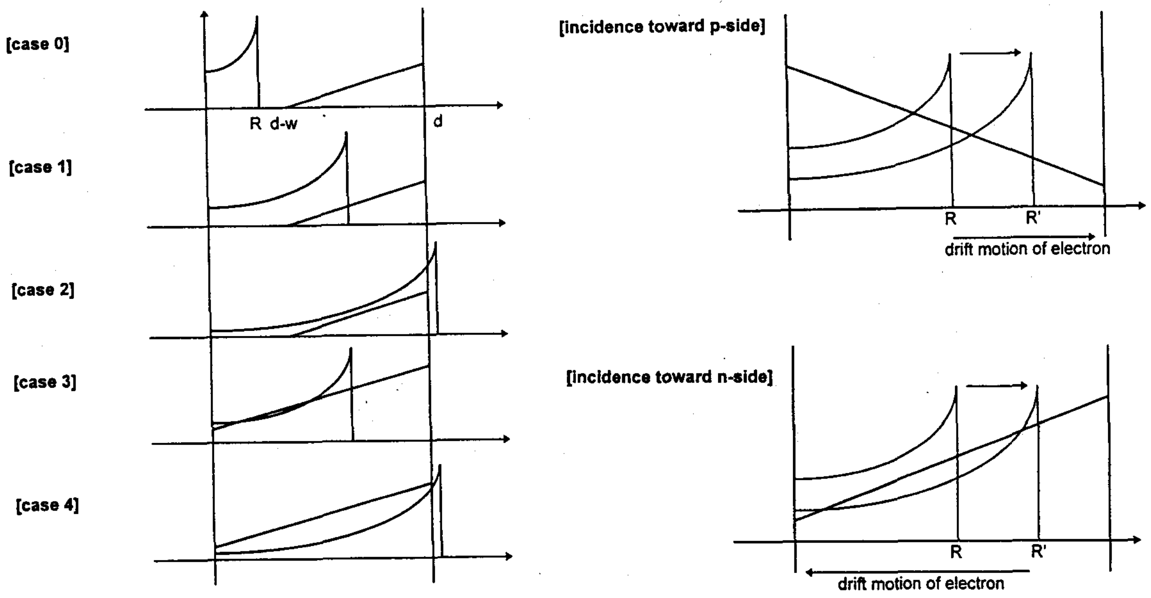

Fig. 1 Calculation algorithm for n-i-p configuration

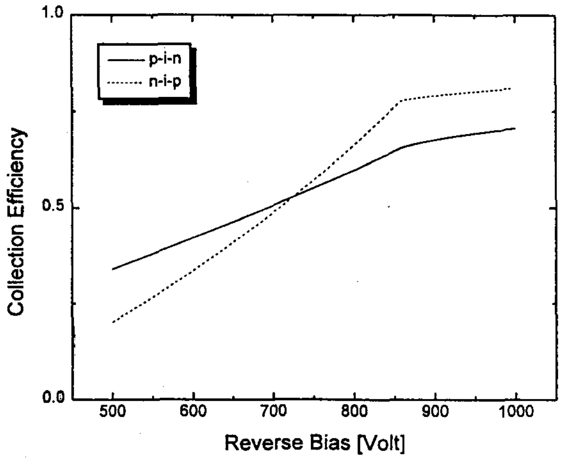

Fig. 2 Collection efficiency as a function of reverse bias for each configuration

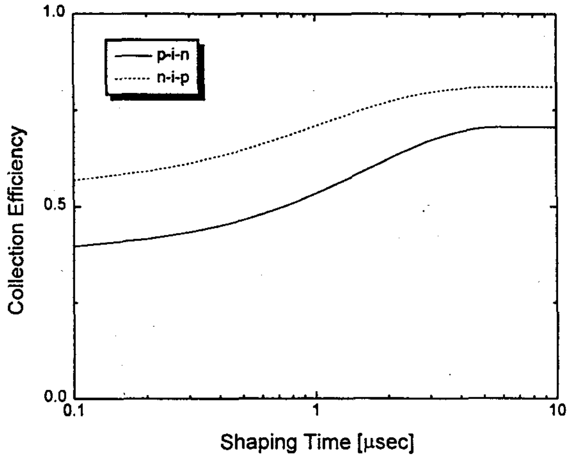

Fig. 3 Collection efficiency as a function of shaping time for each configuration

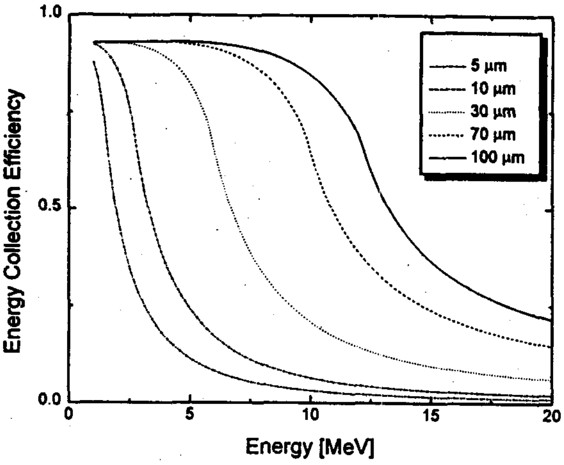

Fig. 4 Energy collection efficiency for p-i-n configuration

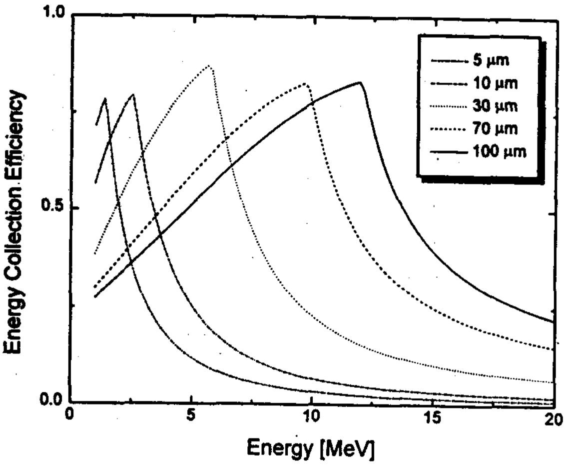

Fig. 5 Energy collection efficiency for n-i-p configuration

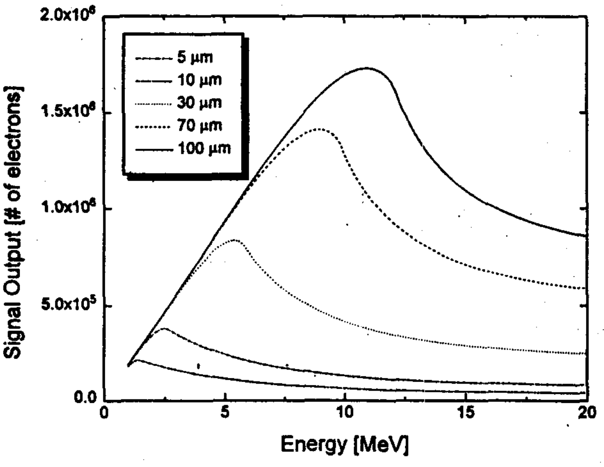

Fig. 6 Siganl output for p-i-n configuration

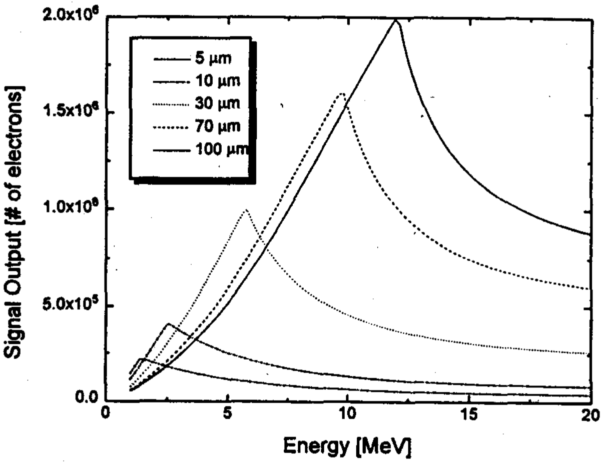

Fig. 7 Signal output for n-i-p configuration