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Equivalent Noise Charge Measurements in Hydrogenated Amorphous Silicon Radiation Detectors

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Abstract

The input equivalent noise charge (ENC) of hydrogenated amorphous silicon radiation detector diodes was measured and analyzed. The noise sources of amorphous silicon diodes were analyzed into three sources; shot noise, flicker noise and thermal noise from the contact resistance. By comparing the measured ENC with the calculated signal charge in uniform generation case, the signal-to-noise ratio (S/N) for the sample diodes is estimated as a function of the detector bias and the shaping time of Gaussian pulse shaper. The maximum S/N occurred at the bias level just above the full depletion voltage for shaping time of 2~3 μsec. The developed method is useful in optimum design of amorphous silicon p-i-n diodes for charged particulate radiation spectroscopy.

1. Introduction

Hydrogenated amorphous silicon (a-Si:H) has been recently paid attention as solid state radiation detector material because of the easy fabrication of large area device, better radiation hardness in comparison with its crystalline counterpart.[1] However the internal stress build-up during the preparation of this material, typically when prepared by PECVD (plasma enhanced chemical vapor deposition) limits the thickness of this material within about 100 micrometers.[2] Another important drawback in using this material for the radiation energy spectroscopy is the detector noise due to the finite reverse current and its fluctuation.[3] In order to design the a-Si:H radiation detection system with improved signal-to-noise ratio for various applications, it is necessary to estimate the magnitude of equivalent noise charge inherent to the detector itself in addition to the statistical noise. The formulation of the equivalent noise charge was done in the system of a charge-sensitive preamplifier and general CR-(RC)^n shaping amplifier[4] based on the measured spectra of a-Si:H detector diodes.

2. Signal Charge and Collection Efficiency

The total generated charge in any semiconductor diode by a single radiation quantum is given by

$$Q_o = q\frac{\Delta E}{W} \qquad (1)$$

where q : the electronic charge
ΔE : the energy deposit by the radiation [#]
W : the average ionization energy required [eV]

W value of amorphous silicon is ~ 5 eV which is larger than that of crystalline silicon (*W* = 3.6 eV) but it is still considerably lower than that of any gas-filled ionization chamber (*W* = 26 eV for P10 gas).

The signal pulse through the external circuit is, then, induced by the drift motion of these charge carriers under the electric field due to dc bias. At the time of all the charge carriers are collected, one can expect the integration of the current pulse is equal to the total charge generated, but due to several loss mechanisms, it is not. One is that when the detector diode is not fully depleted, the charge carriers in the neutral region do not drift and finally recombine each other. Another is that when the shaping time of a pulse shaping amplifier is shorter than the collection time of charge carriers, the integration is not complete and this type of loss is often called 'ballistic deficit.'

Considering these two loss mechanisms, the signal charge collection efficiency is calculated by the following process. First, the induced current due to the drift motion of electrons generated at x_o with a fixed life-time, τ_e is

$$\frac{dI}{dx_o} = \frac{qn(x_o)v(x_o,t)\exp[-t/\tau_e]}{d} \qquad (2)$$

where $n(x_o)$: the number of electrons generated at x_o [#/cm]

$v(x_o,t)$: the velocity of electrons at time t [cm/sec]

d : the thickness of the i-layer [cm]

Then the collected electron charge for a shaping time τ, is calculated by the following equation

$$Q_e = \int_0^w dx_o \int_0^\tau \frac{dI}{dx_o} dt \qquad (3)$$

where w : the depletion width

The same method also applies to the holes. Finally the normalized collection efficiency, η, becomes

$$\eta = \eta_e + \eta_h = \frac{Q_e + Q_h}{Q_o} \qquad (4)$$

This resultant equation is used to estimate the signal size and the signal-to-noise ratio of the amorphous silicon detector diodes.

Through the amplifier system, this signal charge is converted into a voltage pulse height in spectroscopic application. However the pulse height generally fluctuates and the standard deviation of the mean pulse height is called noise in electronic sense. The overall noise of the any solid state radiation detection system as shown in Fig. 1, is due to three reasons; the statistical fluctuation of the signal charge generation process, the electronic noise of the amplifier system and the detector noise. Those noise sources are independent to each other and are summed up as squares to yield the total noise.

$$N_{\mathrm{tot}}^2 = N_{\mathrm{sta}}^2 + N_{\mathrm{det}}^2 + N_{\mathrm{amp}}^2 \qquad (5)$$

where N_{tot} : the total equivalent noise charge [#]

N_{sta} : the statistical fluctuation of the signal itself [#]

N_{det} : the input equivalent noise charge of the detector [#]

N_{amp} : the input equivalent noise charge of the amplifier [#]

One important factor to consider is that since the signal, Q, is expressed as the number of electron-hole pairs in the detector, the above three noise sources must be converted into the input equivalent noise charge (ENC) in order to directly compare with the signal charge. In the designer's point of view, the signal-to-noise ratio

(S/N) should be maximized for a given condition of fixed and variable parameters. The purpose of this study is to express the signal-to-noise ratio of the amorphous silicon detector with several operational parameters such as detector capacitance, applied bias, and pulse shaping time etc.

3. Experimental

The most common structure of the amorphous silicon radiation detector is p-i-n diodes. The p- and n-layers act as blocking barriers of the injected electrons and holes respectively under a reverse bias and should be thin enough to avoid the window effect for the incident radiation. The intrinsic layer (i-layer in short) is the main sensitive layer of which thickness should be larger than the range of charged particulate radiation to be detected and also it should be fully depleted at the operation bias. Sample diodes were prepared in PECVD facility in Lawrence Berkeley Laboratory. The intrinsic (i-layer) layer is deposited from the silane (SiH_4) plasma generated by RF glow discharge (13.5 MHz) on corning glass substrate at 250 °C. The p- and n-layers are also deposited from a mixture of silane and appropriate doping gases such as diborane and phosphine.[5]

From the measured capacitance of ~200 pF and the top metal contact area of ~ 0.07 cm^2, the estimated thickness of the sample diodes were 3.7 μm on the average. The reverse current and ENC were measured using the set-up shown in Fig. 1. ENC of the detector alone was calculated by the equation (5) where the statistical noise was neglected because the signal is simulated by a test voltage pulse through a test capacitor and the amplifier noise was measured in the same set-up except that the detector is replaced by a capacitor of the same capacitance.

4. Results and Discussion

(a) Reverse Current

The measured reverse current is shown in Fig. 2. When the p-i-n diode is reverse biased, there is a dc reverse current flow due to the contact (p-i) injection and the thermal generation in the bulk i-layer through the non-hydrogenated dangling bonds which are inherent defects in amorphous silicon. While the Shockley-Read-Hall model describes well the thermal emission in crystalline silicon with a discrete impurity level,[6] the thermal emission in amorphous silicon is known to be enhanced by the Pool-Frenkel effect (field induced Coulomb barrier lowering).[7] However the measurd reverse current of the sample diodes shows a strong dependency on the bias which is probably due to the leakage current through the free surface of i-layer betweeen doped layers.

(b) Signal Charge Collection Efficiency

The Fig. 3 shows the total, electron, and hole collection efficiency for the sample diode as a function of shaping time at a reverse bias of 10 Volts. Since the electron has a higher mobility than the holes, electron collection is fast and its ballistic deficit is negligible. However, in order to collect the holes, the shaping time should be at least 2 μsec long. Fig. 4 are the total collection efficiency at different biases. Fig. 5 shows the total collection efficiency as a function of bias voltage for 3 different shaping times.

(c) Detector Noise

The measured ENC of the detector are plotted in Fig. 6 and 7 as a function of shaping time and of reverse bias, respectively. As we see in the figures, the detector noise increases as the reverse bias, or the reverse current increases. Also the noise increases very rapidly as a function of shaping time. Therefore the detector noise source is considered not only due to shot noise but also due to flicker noise. Therefore the frequency spectra of the reverse current fluctuation is represented as follows

$$\frac{\langle i^2 \rangle}{\Delta f} = \text{shot noise} + \text{flicker noise} = 2qI + \frac{aI^b}{f^c} \qquad (6)$$

Shot noise is due to the random injection of electrons from the contact metal through the blocking p-layer and finally into the depleted i-layer and flicker noise is believed to occur due to the random trapping-detrapping processes of electrons by shallow states originated from the long-range disorder of the random network of amorphous silicon.[8]

The relation between the noise power spectra and ENC for a combination of charge-sensitive amplifier and an CR-(RC)^n shaping amplifier system is

$$N_{\mathrm{det}}^2 = N_s^2 + N_f^2 = \frac{1}{(qA_n)^2} \times \int_0^\infty \frac{\langle i^2 \rangle}{\Delta f} \times \frac{G(\omega)^2}{\omega^2} d\omega \qquad (7)$$

where A_n : the gain of CR-(RC)^n shaping amplifier for a unit step pulse input = $n^n e^{-n}/n!$

$G(\omega)$: the transfer function of CR-(RC)^n shaping amplifier

$$G(\omega)^2 = \frac{\lambda^{2n}(\omega)^2}{(\lambda^2 + \omega^2)^{n+1}} \qquad (8)$$

$\omega = 2\pi f$ and $\lambda = 1/\tau = 1/RC$

The small increase of ENC at short shaping time is due to the thermal noise of the contact resistance of the detector. Since this resistance is in series with the preamplifier, it behaves the same way as the amplifier noise, which is characterized as $1/\tau$. But in the bias region of interest, it can be neglected.

Based on the measured ENC and the calculated collection efficiency, the signal-to-noise ratio is estimated as a function of the shaping time and the bias as shown in Fig. 8 and 9. The optimum conditions are clearly definable for the sample diodes.

5. Conclusion

The detector noise of amorphous silicon p-i-n diode was analyzed as a sum of shot noise and flicker noise and both of which are found to be originated from the reverse bias current and surface leakage current. The input equivalent noise charge was formulated with several major operation parameters; reverse bias, detector capacitance and the time-constant and number of RC-integrating stages of shaping amplifier. The obtained detector equivalent noise charge expression can be used to design the various size of amorphous silicon radiation detector and the appropriate shaping amplifier system depending on the applications, such as alpha and beta spectroscopy.

Acknowledgement

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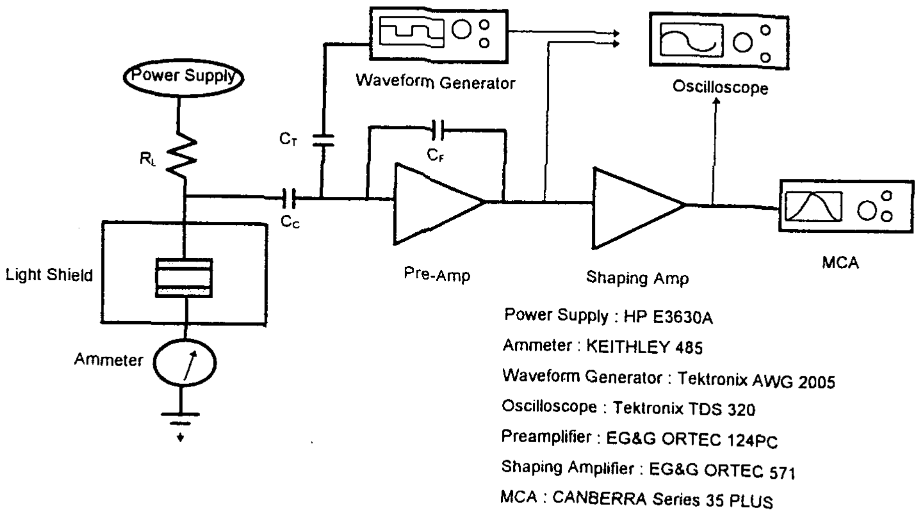
Figures



Power Supply : HP E3630A
Ammeter : KEITHLEY 485
Waveform Generator : Tektronix AWG 2005
Oscilloscope : Tektronix TDS 320
Preamplifier : EG&G ORTEC 124PC
Shaping Amplifier : EG&G ORTEC 571
MCA : CANBERRA Series 35 PLUS

Fig. 1 Measurement set-up

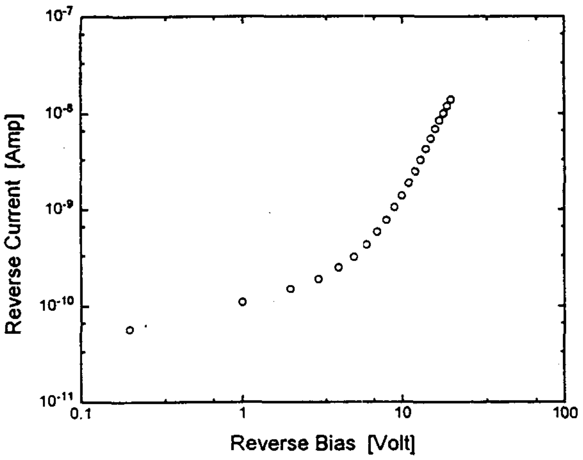


Fig. 2 Reverse current versus applied voltage

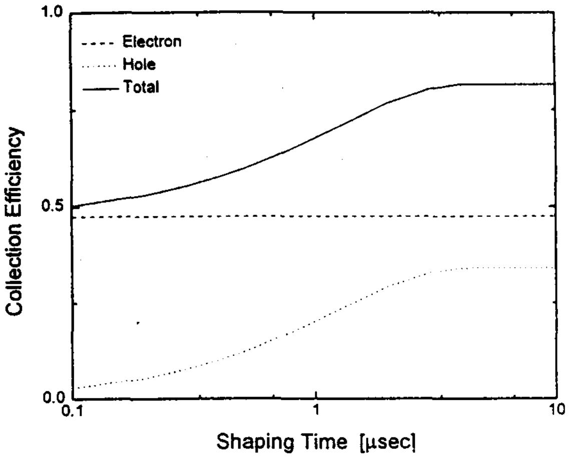


Fig. 3 Collection efficiency ; total, electron and hole

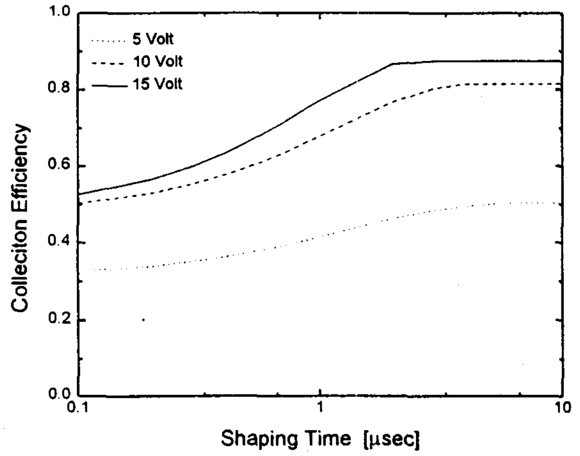


Fig. 4 Total collection efficiency as a function of shaping time at different biases

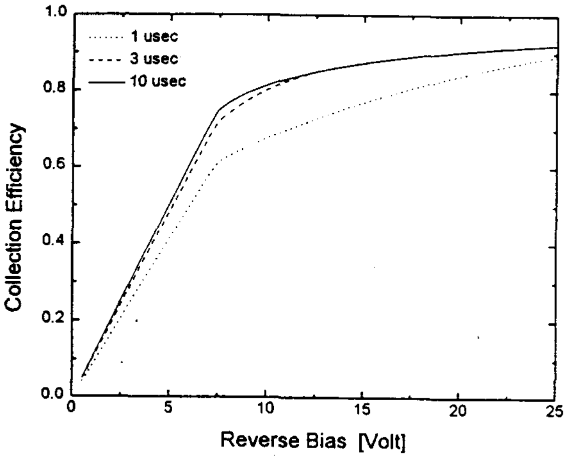


Fig. 5 Collection efficiency as a function of bias

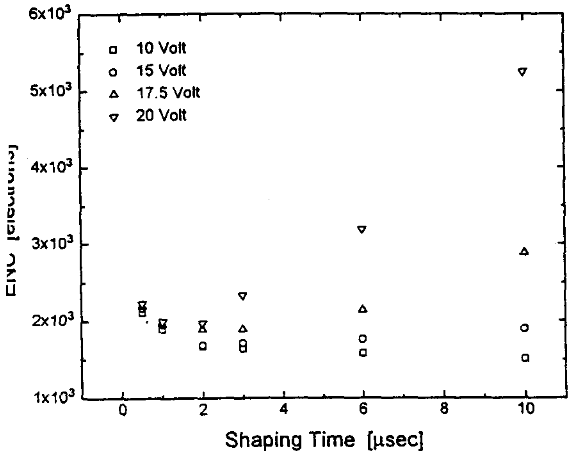


Fig. 6 Measured ENC as a function of shaping time

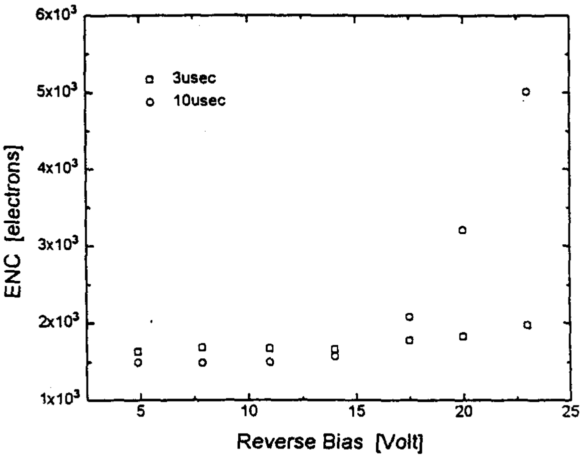


Fig. 7 Measured ENC as a function of reverse bias

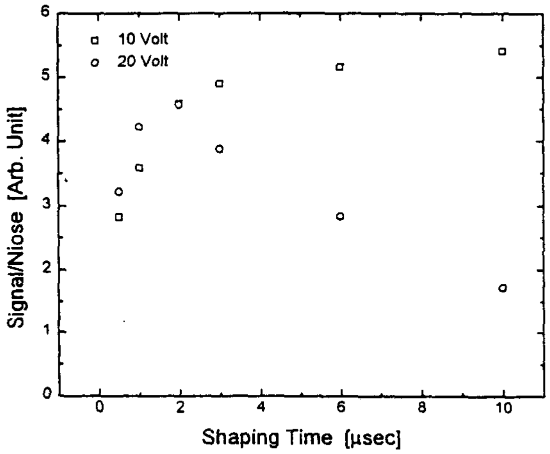


Fig. 8 Signal-to-noise ratio as a function of shaping time

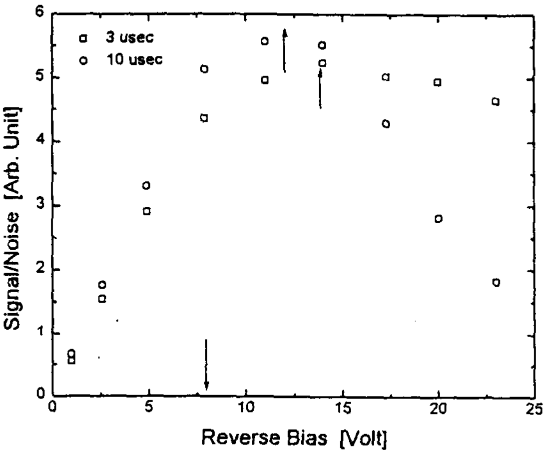


Fig. 9 Signal-to-noise ratio as a function of reverse bias