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Authors

Lee, H.
Cho, G.
Drewery, J.S.
et al.

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FOR LONG-TERM CHARGE STORAGE

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Physics Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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NEW a-Si:H PHOTO-DETECTORS
FOR LONG-TERM CHARGE STORAGE

H. LEE, G. CHO, J. S. DREWERY, W. S. HONG, T. JING, S. N. KAPLAN, A. MIRESHGHI, V. PEREZ-MENDEZ AND D. WILDERMUTH
Lawrence Berkeley Laboratory, Berkeley, CA 94720

ABSTRACT

Using the high light absorption properties of amorphous silicon, we developed a new device configuration that can detect photons and store the induced charges for relatively long time. This device, coupled to a scintillator such as CsI(Tl) in an array form, could be used as a scintillation camera, or for long-term photo-detection such as radionuclide labeled chromatography. The detector has a simple sandwich structure consisting of a scintillator followed by a top metal layer, p-i-n layers of hydrogenated amorphous silicon (a-Si:H), a second metal layer, a thin insulating layer and a bottom metal layer. The electron-hole pairs generated in the i-layer by the interaction with the incident light will be separated by the imposed electric field and be stored in the central metal-insulator interface. Readout will be done by switching the external bias to ground after the storage time, which depends on the needs for the specific application. Prototype devices were fabricated and tested. The performances of the devices were analyzed in connection with the storage time and the background signal produced by the thermally generated charges.

INTRODUCTION

Hydrogenated amorphous silicon (a-Si:H) devices have been described for radiation detection applications.[1] Due to the large area and high radiation resistivity, a-Si:H radiation detectors have some advantages over the crystalline devices. There are many applications of a-Si:H radiation detectors which include detection of visible light, x-rays, γ-rays, charged particles and neutrons.[1-4] For example, for the imaging of γ-ray distribution in nuclear medicine we can replace a conventional scintillation camera with an a-Si:H pixel detector combined with a scintillator. CsI(Tl) is known to be an appropriate scintillator for this purpose because of its high light yield and high interaction efficiency for γ rays.[4] While the intrinsic spatial resolution of conventional scintillation cameras is more than 3 mm, a-Si:H pixel devices can be made to have much higher spatial resolution if required. Moreover, these devices do not utilize photomultiplier tubes (PMTs) unlike the conventional cameras and accordingly have the advantage of compactness and light weight. With ordinary p-i-n a-Si:H pixel detectors for this purpose we would have to record each incoming γ ray by low noise multistage amplifiers at each pixel because of the low counting rate. Storage and integration of the individual counts to give a larger signal can eliminate the need for pixel level amplifiers thus making the readout scheme much simpler.

In this paper we describe a device which is appropriate for this purpose. This consists of a scintillator placed on the top transparent conducting layer followed by p-i-n a-Si:H layers, a second metal layer, an insulating layer and a bottom metal layer as shown in Fig. 1. By applying a reverse bias the i-region is under an electric field. When the light is incident on it, it produces electron-hole pairs and these carriers will
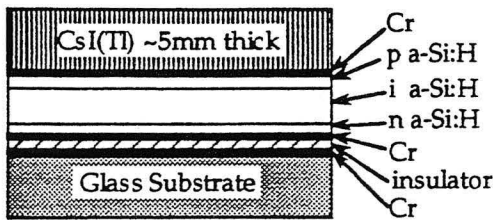
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Fig. 1   A schematic diagram of a charge storing detector. Top Cr is made semitransparent for light penetration. Silicon dioxide or silicon nitride was used for the insulator.

drift to the top and middle metallic layers and remain there until the electric field is reversed. In order to read out the amount of stored charges the applied bias is switched to ground and by integration of the measured current we can obtain the charge information.

EXPERIMENTS

Oxide(SiO_2) or nitride(Si_3N_4) were used as the insulators and the thicknesses were 200~300 nm. Thin insulators are preferred in order to make a high capacitance of the metal-insulator-metal which can accommodate a large amount of charge. The p- and n-layer of a-Si:H were 30 nm and 20 nm thick respectively and the i-layer was 1μm thick which was calculated to absorb ~ 96% of the light emitted from the CsI(Tl) using the emission spectrum of CsI(Tl)[4] and optical absorption coefficient of a-Si:H.[5] The capacitance of the insulator, C_i, was 1700 ~ 3300pF and that of the p-i-n diode, C_d, was ~1150pF for a pixel size of 3mm x 3mm.

The experimental system and the pulse configuration from each pulse generator are shown in Fig. 2. The p-i-n diode in the device is indicated as a capacitor C_d with a resistor R_d in parallel and the metal-insulator-metal layer is indicated as a capacitor C_i. In the system configuration there is another capacitor C_c and a resistor R_c, which are used to cancel out the RC transients when the bias from PG1 changes. The capacitance of C_c is equal to the total capacitance of C_d and C_i in series and the resistance of R_c is equal to the forward resistance of the p-i-n diode which is ~100kΩ. By applying pulses of the same magnitude but opposite polarities on the charge

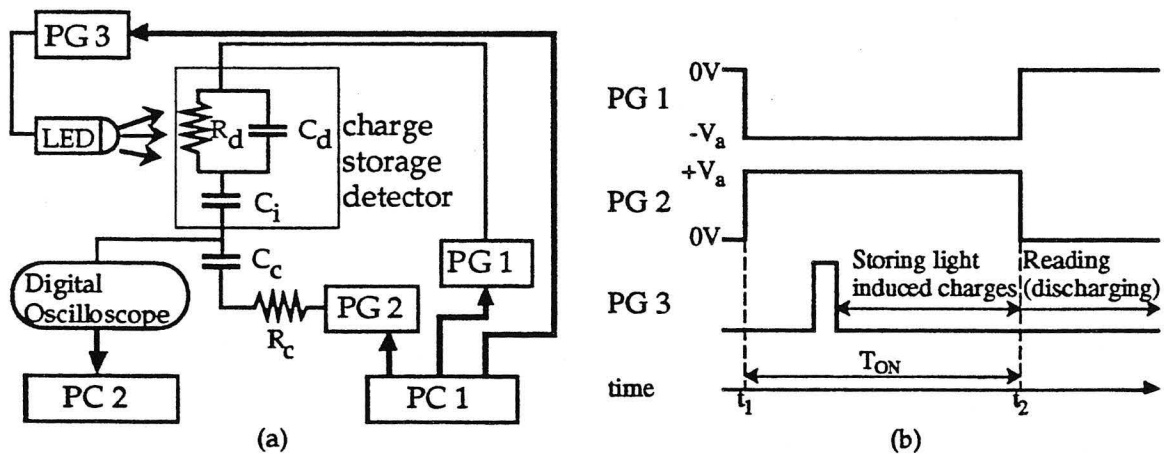Fig. 2   (a) Schematic representation of the experimental system. IBM PC 1 controls the pulse generators and PC 2 is used for data acquisition. The p-i-n a-Si:H diode is indicated as a resistor R_d and a capacitor C_d in parallel.

(b) The time sequence of the pulses from the pulse generators. At t_1 the charge storing detector begins to store the charges generated by either incident light or thermal excitation.

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storage detector and on the R_c-C_c components simultaneously the switching transients were canceled up to 98%. The residual transients were measured separately and subtracted from the signal. The time sequence of the operation is shown in Fig. 2 (b). During T_{ON} a reverse bias, V_a, is applied on the device. The light incident during this interval generates electron-hole pairs, which will be stored until time t_2. Then the stored charges are discharged by switching the bias to 0V. The discharging current is read by the digital oscilloscope and the amount of the stored charges is obtained by integration of the current.

RESULTS

When a step pulse of the reverse bias, V_a, is applied on the device, the p-i-n diode acts like a capacitor and charges build up on its surfaces as well as on the insulator surfaces in a few system RC times, then the voltage across the p-i-n diode, V_d, and across the insulator, V_i, is set by the corresponding capacitance ratio, i. e., $V_d = V_a C_i/(C_d+C_i)$ and $V_i = V_a C_d/(C_d+C_i)$. Due to the reverse bias V_d, thermally generated carriers in the i-region flow along the electric field and are stored on the insulator surfaces. As the thermal generation current flows, charges will accumulate on the insulator capacitor and correspondingly V_d will decrease. This thermal generation current will flow until $V_i = V_a$, when the insulator capacitor is saturated with charges and the amount is given by $Q_{sat} = V_a C_i^2/(C_d+C_i)$. To measure the light induced charges we should read them out before the electric field in the p-i-n diode drops below full depletion, then these charges are obtained by subtracting the thermally generated charges from the total collected charges. If the thermal generation current is too large the insulator capacitor will be saturated with charges in a short time and the light induced charges cannot be stored with full efficiency.

One way to store the light induced charges for a long time is to have a high value of Q_{sat} by applying high V_a and making C_i high and C_d low. The values of C_i and C_d can be manipulated by adjusting the areas and the thicknesses of the corresponding layers. Another way of having a long storage time is to reduce the thermal generation current. This can be accomplished by lowering the ambient temperature. Fig. 3 shows the temperature effects on the thermal generation current and correspondingly stored charges. At room temperature, 10 min. after 10V of V_a is applied the thermal generation charges are accumulated almost up to the saturation level and there is
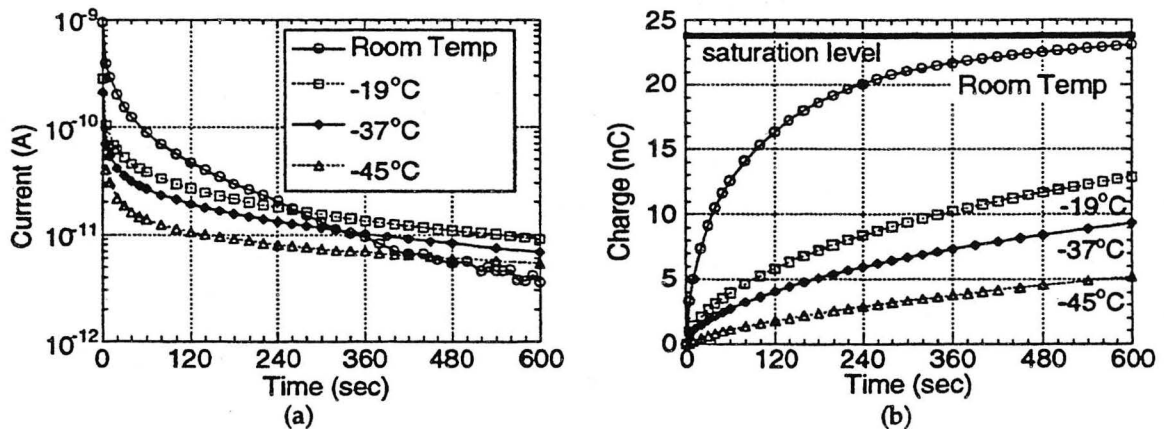

Fig. 3   Time dependent thermal generation current (a), and stored thermal generation charges (b) after applying 10V on the charge storing detector at various temperatures. ($C_i = 3200$pF and $C_d = 1150$pF).
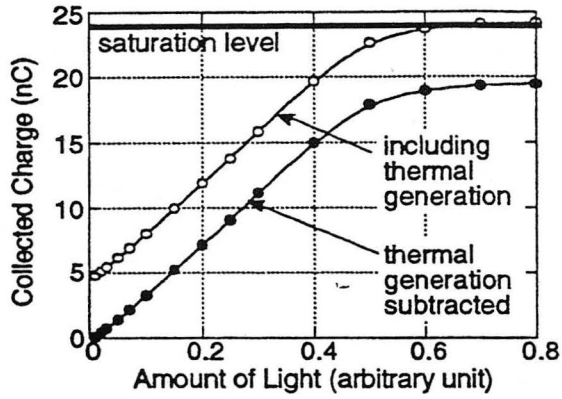
Fig.4 Relationship between the input light amount and the collected charges after 5 min storage time with a bias of 10V at T = -37°C.

little room for the light induced charges. At T=-45°C, however, the amount of the stored thermal generation charge after 10 min. is about 21% of the Q_{sat} and it takes as long as 9 hours to reach the saturation level.

As a test light source an LED of λ = 665nm was used. With a pulse width of 100ms it produced about 3nC of charges in the i-region. A relationship between the input light amount and the collected charges after 5 min. of storage time at T = -37°C is shown in Fig. 4. We can see that there is a linear relationship between the input and the output up to ~80% of saturation charge amount.

DISCUSSION

It is generally known that the thermal generation current is due to the carriers which are excited from deep states to the band edges and drift along the depletion field. Theoretical models of the thermal generation current have been developed using a single trap level and a Shockley-Read-Hall formalism.[6,7] The thermal generation current is also significantly dependent on voltage and this is due to the field enhanced emission such as Poole-Frenkel effect, tunneling and phonon assisted tunneling.[8-10] In the range of bias and temperature with which our experiments were performed, the Poole-Frenkel effect was found to be the dominant one, and the other effects may be neglected.

The thermal generation current with Poole-Frenkel effect only can be expressed as

$$I_R = \alpha (kT)^4 \frac{\sqrt{F}}{\beta_{PF}} \exp\left[\frac{-E_i + \beta_{PF}\sqrt{F}}{kT}\right] \tag{1}$$

where α is a parameter which depends on the geometry and material properties of the device, F is the electric field, β_{PF} is the Poole-Frenkel constant, E_i is the difference between conduction band mobility edge and quasi-Fermi energy.

By finding a time dependence of the electric field F in Eq. (1) we can obtain the time dependence of the thermal generation current also. By approximation the p-i-n diode in Fig. 2 (a) may be considered as a voltage dependent current source with a capacitor, C_d, in parallel. Then by a circuit analysis with Eq. (1) as the current source expression we can get the time dependence of F which is assumed to be uniform, i. e., $F = V_d/d_r$. The resulting electric field is expressed as
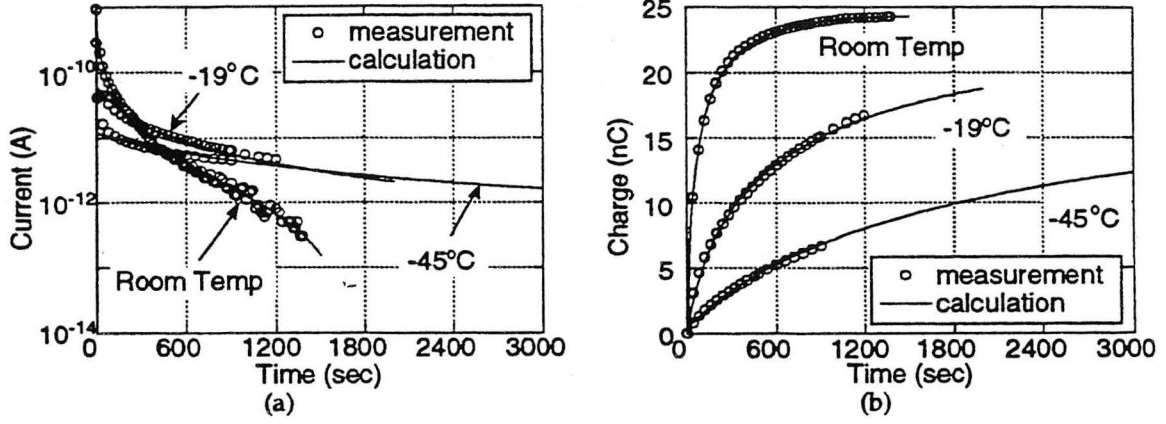
Fig. 5 Comparisons of measurements and theoretical calculations for the time dependent thermal generation current (a), and stored charges (b) at various temperatures. α=0.15, β_{PF}=0.04 and E_i=0.34 were used in Eq. (1) and (2) for the fittings.

$$F(t)^{1/2} = \frac{kT}{\beta_{PF}}\ln\left[\exp\left(-\frac{\beta_{PF}}{kT}\sqrt{\frac{C_iV_a}{(C_i+C_d)d}}\right) + \frac{\alpha t}{2C_id}(kT)^3\exp\left(-\frac{E_i}{kT}\right)\right] \quad (2)$$

where d is the thickness of the i-layer.

By assigning proper values to the parameters α, β_{PF} and E_i in Eq. (1) and (2) good fits to the measurements were obtained. For the best fit α=0.15 Amp·μm/V·eV^3, β_{PF} = 0.04 eV$\sqrt{\mu m/V}$ and E_i = 0.34 eV were given and the comparisons of the calculated thermal generation currents and the stored charges and those obtained from measurements are shown in Fig. 5. The value of β_{PF} is about twice larger than the theoretical value of 0.022. This increase may be interpreted that the Poole-Frenkel effect is enhanced because the surrounding defect states give screening effect resulting in lowering of the barrier height further.[10] E_i has been measured by many workers and is 0.9~0.95eV at steady state and 0.75~0.8eV at initial transient of applying reverse bias.[6,7] The value of E_i for our fitting was 0.41~0.61eV lower than the conventional values. This may be due to significant emissions from the shallow states.

The time to reach 90% of the saturation level by thermal generation current, using the above model with V_a=10V, C_d=1150pF and C_i=3200pF, is plotted as a function of temperature in Fig. 6. As the temperature decreases the saturation time increases exponentially with the activation energy of 0.38eV and at T=-50°C the saturation time is about 13 hours. As the saturation time is so sensitive to the temperature, the
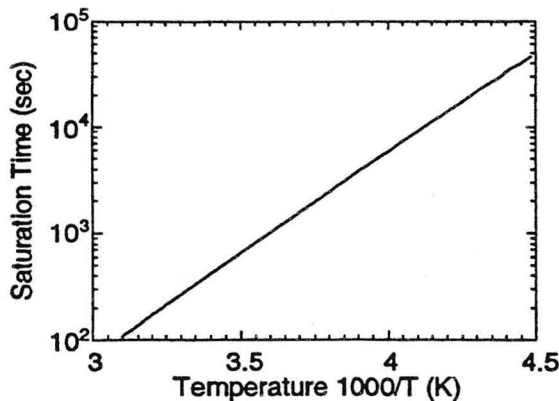

Fig.6 Temperature dependence of the saturation time which is defined as the time needed to store the thermal generation charges up to 90% of Q_{sat}.

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maximum storage time can be easily manipulated by controlling the temperature.

CONCLUSION

We have given a discussion of our studies of a detector which is able to store the light induced charges for a long time. With our prototype devices at room temperature, significant thermal generation current flows and saturates the insulator capacitor in 10 min. with 10V of applied bias. The thermal generation current, however, could be lowered by reducing the ambient temperature, and after 10 min. at T=-45°C the stored thermal generation charges were about 21% of the saturation charge amount. Another way to reduce the thermal generation current is to make the volume of p-i-n diode smaller by reducing the contact area, but the thickness should be thick enough to ensure low capacitance of p-i-n diode because lower capacitance of the p-i-n diode require a higher initial bias on it and a higher Q_{sat}. By the same reasons high capacitance of the insulator, i. e., thin insulator, is preferred. A high value of the V_a also provides a long storage time. A good linear relationship between the input light and the output charges was acquired up to ~80% of Q_{sat} with a storage time of 5 min.

A time dependent thermal generation current model based on the previous models was developed for our experiments and it gave good fits to the measurements. Using this model the amount of stored thermal generation charges and the maximum storage time at any temperature can be predicted. The time needed to saturate the insulator capacitor with thermal generation charges has an exponential dependence on the reciprocal of the temperature and with slight decrease in temperature much longer storage time can be obtained.

ACKNOWLEDGEMENTS

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720