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by Field Profile Tailoring**

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IMPROVEMENT OF THICK a-Si RADIATION DETECTORS BY FIELD PROFILE TAILORING

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ABSTRACT

Application of thick ($\sim 50 \mu\text{m}$) a-Si p-i-n diodes as a direct radiation detector for minimum ionizing particles is hampered by the need to apply large bias voltages in order fully to deplete the detecting intrinsic layer, which typically contains $5-10 \times 10^{14}$ ionizable dangling bonds per cm^3 . By insertion of thin p-type layers at intervals within the intrinsic layer, the required depletion voltage can be reduced by a factor of at least $1/(n+1)$ where n is the number of layers inserted. This principle is demonstrated for devices approximately $12 \mu\text{m}$ in thickness. It is shown that electron losses within the p type layer can be kept to minimum by choice of a low doping concentration for the introduced p layers.

INTRODUCTION

Direct detectors for minimum ionizing particles can be fabricated from amorphous silicon diodes[1-3]. Typically, an 'intrinsic' detecting layer is sandwiched between thin p and n blocking layers. Under reverse bias the intrinsic layer is depleted. Ionizing radiation gives rise to electron-hole pairs in this layer which may be collected at the input of a charge-sensitive amplifier.

Device quality a-Si:H is, however, slightly n type, with a density of ionizable defects of $5-10 \times 10^{14} \text{ cm}^{-3}$. As a result a bias voltage of 1300V would be required to deplete a $50 \mu\text{m}$ thick layer. Furthermore the high electric field (520 kV/cm) at the p/i interface gives rise to a leakage current by Poole-Frenkel and other mechanisms, which may become excessive. The electric field profile expected is plotted in fig. 1(a). The thickness of the metal contacts and the blocking doped layers has been exaggerated for clarity. The voltage required to deplete such a device is

$$V_d = \frac{N_d^* q L^2}{2 \epsilon \epsilon_0} \quad (1)$$

Here q is the magnitude of the charge on the electron and ϵ is the relative dielectric constant. N_d^* is the density of ionizable defects and L the 'intrinsic' layer thickness. The electric field required to deplete the device may in principle be reduced by addition of thin p layers at intervals within the device as shown in fig. 1(b). When ionized these layers give rise to a reduction in the magnitude of the electric field. These layers are expected to act as electron trapping centers; however it is shown that losses due to these centers can be made insignificant.

DEVICE DESIGN

Integration of the electric field under the field profile of fig. 1(b) reduces the voltage necessary to deplete the device by a factor

$$f = \frac{(L-d)}{2L} \quad (2)$$

where L is the total device thickness and d the thickness of the p layer, which is doped such that the concentration of acceptors is equal to the number of donors in the 'intrinsic' layer. If this doping level is exceeded the voltage required to deplete the device is unchanged but unnecessary losses of electrons will occur.

Electric field intensity

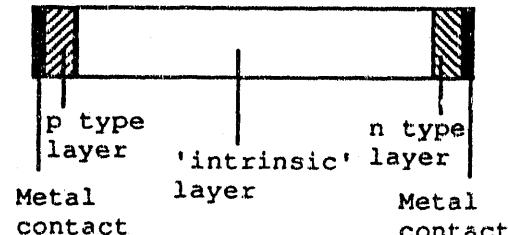


Fig. 1(a); conventional p-i-n diode and electric field profile, shown for bias greater than the depletion voltage.

Electric field intensity



Introduced p type layer

Fig. 1(b); device with single introduced 'p' layer. The field profile shown is for bias equal to the depletion voltage.

The p type layers are expected to act as traps for electrons. All electrons except those generated between the final introduced p layer and the n layer are subject to trapping at at least one introduced layer. This trapping must be minimized if the device is to be of practical use. For a single p layer, the proportion of electrons which pass through the p layer can be shown to be given by

$$f_e = \left(\frac{2V - \alpha d L}{2V + \alpha d L} \right)^{\frac{1}{\alpha(\mu\tau)_a}} \quad (3)$$

for forward voltage V (greater than the depletion voltage) and where if N_a is the acceptor density in the inserted p layer, $(\mu\tau)_a$ is the mobility-lifetime product for electrons in the layer, and $\alpha = N_a q / \epsilon \epsilon_0$.

In figure (2), this equation is plotted. A total thickness equal to 25 μm was used with $N_d^* = 7 \times 10^{14}$. The value of $N_a(\mu\tau)_a$ from Street[4] ($3.5 \times 10^8 \text{ cm}^{-1}\text{V}^{-1}$) is used. N_a is taken as $10^{19} \sqrt{c}$ where c is the B_2H_6 dopant gas concentration based on Stutzmann[5]. The measurements of Street were carried out in such a way that the p type material studied

was not depleted, whereas in our case the material is depleted; however the effect of depleting the material on this quantity should be small. This is because most trapping in the undepleted material occurs at Si^{3+} sites arising from the dopant-valence alternation pair reaction[4,6] ; depletion of the material causes these sites to become singly occupied but this has little effect on their cross section for trapping. It can be seen from fig (2) that electron losses are minimized if the introduced layer is as lightly doped as possible. A fully-compensated sample would be ideal but this cannot as yet be achieved in practice. Losses of <2% should be readily obtainable.

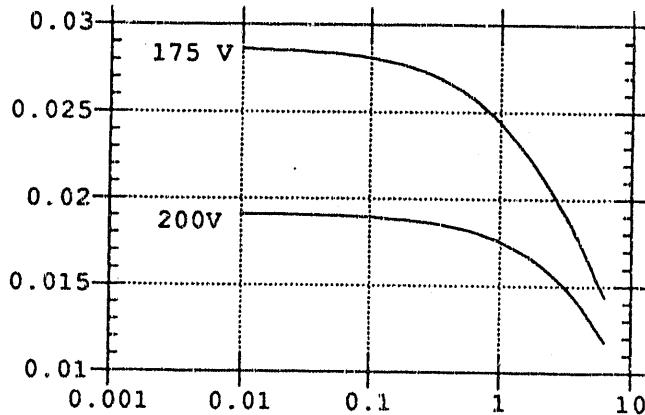


Fig. 2. Calculated electron loss as a function of inserted p layer thickness (μm) for a 25 micron thick sample (depletion voltage 165V) at 10V and 35V above the depletion voltage. Note the small losses (max 3%).

EXPERIMENTAL

Sample preparation

In order to test these ideas a number of samples were prepared. A PECVD deposition system with load lock, originally supplied by Glastech Solar Inc., which has been modified for improved gas handling and high frequency PECVD deposition, was used. The conditions for deposition of each device were as shown below. The substrates were Corning 7059 glass which was cleared and coated with a semi transparent Cr layer. To minimize problems due to film stress material was deposited in dots about 15mm in diameter through a shadow mask. In order to prevent contamination of 'intrinsic' layers by phosphorus the sample was moved to the load lock and a burial process carried out in the reaction chamber after the n type layer was deposited.

Deposition conditions were:

SiH₄ flow : 40 sccm except for 90 sccm during deposition of the introduced p layers.
 Pressure : 300mT pressure; 260°C nominal substrate temperature.
 Discharge : 85 MHz 7W
 n layer : 1500ppm PH₃ doped layer 250 nm thick
 Top p layer: 500 ppm B₂H₆ doped Si:C alloy layer 250nm thick.

The 'intrinsic' layers were deposited for a total of 6 hours giving a nominal thickness of 12 μm . In run A this deposition was uninterrupted; however in run B the deposition was halted after 3 hours and a layer containing 114 ppm B₂H₆ deposited for 81s. The chamber was then purged with argon for 5 minutes and the 'intrinsic' layer deposition resumed. It is important that the gas handling be carried out in such a way that the sample is in contact with the B₂H₆ doped gas for the minimum time except when the plasma is operating or deadhesion of the overgrown 'intrinsic' layer occurs.

Following deposition a semi transparent Cr top contact 3.15mm in diameter was deposited on each device. 21 devices were prepared in each run.

Hole onset measurements

The voltage required to deplete the devices was measured by plotting the charge produced upon illumination of the n/i interface by strongly absorbed light as a function of applied DC reverse bias. The method is described elsewhere [2].

In fig. 3(a), a plot of the hole signal against bias is shown for a sample A1 from run A with no introduced p layer, of thickness 15.0 μm as deduced from a measurement of the device capacitance. The depletion voltage is estimated by extrapolating the steeply rising part of the curve to the base level. Using the formula (1) for the depletion voltage as a function of N_d^* , it is found that $N_d^* = 7.6 \times 10^{14}$. This value has been found consistently for many samples prepared under the conditions specified.

Fig. 3 (b) shows the hole signal onset for device B1 from run B. The x axis has been normalized so that 1.0 represents the depletion voltage for a sample with the same N_d^* as the sample in fig. 4(a) and the same thickness as the sample under consideration. The hole signal appears at 72V instead of the 88V expected for a sample of this thickness with $N_d^* = 7 \times 10^{14}$. A feature of the curve is the discontinuity in the slope at 80V. This may arise because about 30% too many acceptor sites were present in the introduced p layer. As a result the introduced p layer is not fully depleted when depletion of the 'intrinsic' layers is complete. As a result additional bias appears only between the introduced p layer and the n type layer. When depletion of the p layer is complete voltage appears across the whole detecting layer and the rate of increase of field at the n type layer with bias falls.

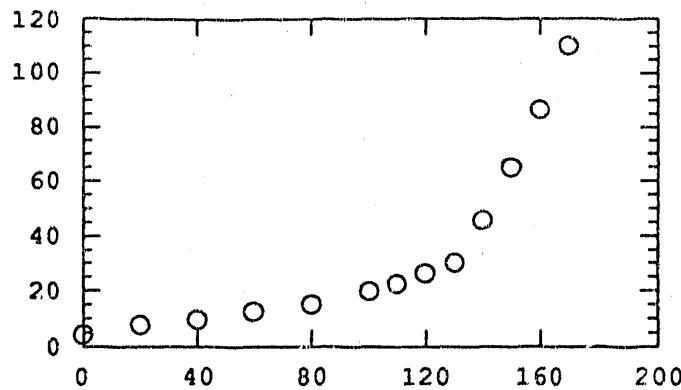


Fig. 3(a) Hole signal (arb. units) vs. bias voltage for sample from run A (no introduced p layer). Sample thickness 15.0 μm .

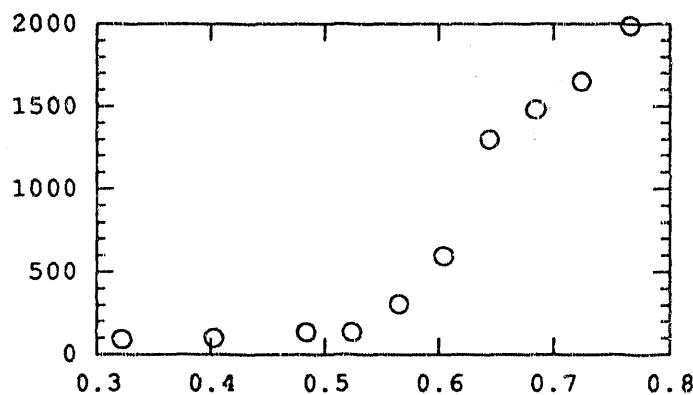


Fig. 3(b): hole signal (arb. units) vs. normalised bias voltage for sample B1 with included p layer.

Electron and hole mobility-lifetime product measurements

In order to check that electron losses in the devices were as expected, mobility-lifetime product measurements were carried out. The method has been described elsewhere [2] and is adapted from similar measurements by other authors. The charge collected after a strongly absorbed laser pulse is applied to a sample which is briefly reverse biased is measured as a function of bias voltage. For the inserted p layer sample it can be shown that provided that the p layer is thin, the Hecht relationship for the charge collected as a function of voltage applies;

$$Q(V) = \frac{(\mu\tau)_{\text{eff}} V}{L^2} Q_0 \left[1 - \exp \left(\frac{-L^2}{(\mu\tau)_{\text{eff}} V} \right) \right] \quad (4)$$

Here $(\mu\tau)_{\text{eff}}$ is an averaged quantity,

$$\frac{1}{(\mu\tau)_{\text{eff}}} = \frac{1}{(\mu\tau)_e} + \frac{1}{(\mu\tau)_a} \left(\frac{d}{L} \right) \quad (5)$$

Measurements showed the expected behavior. The values of $\mu\tau$ found were $1.1 \times 10^{-7} \text{ cm}^2/\text{V}$ for the samples with no introduced p layer and $2.47 \times 10^{-8} \text{ cm}^2/\text{V}$ for samples with an introduced p layer. Using (5) we find $(\mu\tau)_a = 1.1 \times 10^{-10} \text{ cm}^2/\text{V}$. This gives a value of $N_a(\mu\tau)_a$ of 1.1×10^7 which is somewhat higher than Street's value. Since measurements of $\mu\tau$ often vary by 50% between samples our value is within reasonable bounds.

Hole $\mu\tau$ measurements were also carried out. In this case we expect little effect from the introduced p layer as the position of the Fermi energy in the undepleted p layer is below the Si^{3+} states so that little hole trapping is expected. Depletion, however, may lead to increased trapping of holes at Si^{3+} centers. Values of $6.4 \times 10^{-9} \text{ cm}^2/\text{V}$ and $2.7 \times 10^{-8} \text{ cm}^2/\text{V}$ were found for the layers with and without the introduced p layer.

CONCLUSION

We have demonstrated the use of introduced p type layers to reduce the bias voltage necessary to deplete amorphous silicon detectors. These preliminary results indicate that electron losses owing to the introduced p layers will be within reasonable limits when suitable dopant concentrations are used. We are at present modifying our deposition system to allow these doping concentrations and to simplify production of devices with multiple introduced p layers.

Acknowledgements

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