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Signal Generation in a Hydrogenated Amorphous Silicon Detector

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The signals produced in thick hydrogenated amorphous silicon p-i-n detectors were measured using incident light pulses with different mean free paths. The signal shapes as a function of bias potential were analyzed in terms of the relevant parameters: mobilities and mean free paths of the electrons and holes. These latter were measured by transient photoconductivity methods using a pulsed nitrogen-dye laser system.

I. Introduction

In this paper we analyze the characteristics of the signals produced in an amorphous silicon p-i-n detector subjected to various particle and photon radiations. Previously we and others have shown that alpha particles and low energy protons produce signals in which there is some amplitude loss due to charge recombination in the detector. In later papers we give the value for W, the average energy used in producing 1 e-h pair, measured using pulsed x-rays. We also show that minimum ionizing particles (1.5 MeV electrons) produce a mean free path simulates that of a minimum ionizing particle. The 510 nm light produced in an amorphous silicon detector region, it is of interest to know the electric field and charge collection, which allows the performance of a-Si:H particle detectors to be predicted.

The material parameters: mobilities, and lifetimes for the electrons and holes, and the density of ionized dangling bond states were measured using the transient photoconductivity method and were done with a pulsed dye laser as described below.

II. Signals Produced by Light Pulses

Figure 1 shows signals from 510 and 760 nm light in a 27 μm p-i-n detector as a function of bias. 510 nm light incident on the p side of the detector produces a signal where the holes are collected promptly and the electrons drift to the n side. The signal increases with bias as the depletion layer extends from the p side to the n side of the detector. No appreciable hole signal is measured when light is incident from the n side of the detector at low bias. This is due to the fact that the depletion layer does not extend to the n side until a sufficiently large bias is applied across the detector. The full depletion is indicated by the onset of hole collection and occurs at ~ 375 V, as shown in Fig. 1. We have used model calculations that use measured values of mobility μ, carrier lifetime τ, and the ionized dangling bond density N_d as fitting parameters. The model is used to explain the signal shape of Fig. 1 and is described in Section V.

III. Derivation of Signal Produced by 510 nm Light Pulses

The induced charge dQ in an external circuit produced when a charge q is displaced by a distance dz in a semiconductor detector bounded by two parallel plane electrodes with separation d is

\[ dQ = \frac{qdx}{d} \]  

Equation (1) differs from the expression \( dQ = \frac{qdV}{V_D} \) frequently used in gas detectors which assumes a uniform electric field in the sensitive volume. The total distance moved by an excited electron or hole is given in terms of the electric field E and the lifetime τ by

\[ x_{max} = \mu \tau E. \]

Complete collection occurs when \( x_{max} \) is larger than the sample thickness. In general, however, the electric field is not uniform in the material. In an a-Si:H detector the i layer being the active detector region, it is of interest to know the electric field distri-
bution in it. Under reverse DC bias, the electric field distribution in the i layer is obtained by solving the Poisson equation. The model calculation assumes that, under sufficient DC bias, the dangling bonds are almost fully ionized and the Poisson equation has the form [deep depletion model]

\[
\frac{d^2V}{dz^2} = - \frac{\rho_0}{\epsilon_0 \epsilon_V} \quad V \gg V_c
\]

where \( \rho_0 = eN_d^* \); \( N_d^* \) being the density of ionized defects. If \( N_d^* \) is constant, then the electric field falls off linearly. At low potential, the gap states are only partially ionized and the Poisson equation is of the form

\[
\frac{d^2V}{dz^2} = - \frac{\rho(V)}{\epsilon_0 \epsilon_V} \quad V < V_c
\]

where \( \rho(V) = en'V \) and \( n' = \frac{N_d^*}{V_c} \); \( V_c \) being the critical voltage. The solution of this equation gives an exponentially dropping off field. Based on this calculation, Fig. 2 shows the electric field distribution in a 27 \text{ pm} \text{-i-n} sample (ionized dangling bond density \( N_d^* \sim 7 \times 10^{14} \text{cm}^{-3} \), \( V_c = 1 \text{ volt}) \).

\[\text{Fig. 2. Calculated electric field profiles in 27 \text{ pm} \text{-i-n} detector at various bias voltages. The calculation is based on measured ionized dangling bond density \( N_d^* \sim 7 \times 10^{14} \text{cm}^{-3} \).}\]

In order to calculate the charge collection due to one type of carrier injected near the appropriate contact (for example, holes at n contact), several assumptions are made. First, the exponentially varying electric field has negligible effect on the signal in comparison with the linear part so that the deep depletion model with linear electric field is assumed to be valid through the entire i layer.

\[
E(z) = \frac{eN_d^*}{\epsilon_0 \epsilon_V}(W - z)
\]

where \( W \), the depletion thickness is

\[
W = \sqrt{\frac{2\epsilon_0 \epsilon_V V_b}{eN_d^*}}
\]

Secondly, the distribution of photo generated carriers is of the form

\[
n(z) = n_0 \exp(-\frac{z}{X_0})
\]

where \( X_0 \) is mean absorption depth in a-Si:H (for \( \lambda = 510 \text{nm} \), \( X_0 \sim 0.2 \text{um} \)) so that the total charge from the carriers is

\[
Q_0 = e \int_0^d n(x)dx = eN_0 X_0 \left[ 1 - \exp\left(\frac{-d}{X_0}\right) \right] \approx eN_0 X_0
\]

Thirdly, mobility of the carriers is assumed constant in the region of interest, independent of electric field, so that the velocity of carriers at any position, \( x \), is simply proportional to the electric field at that position.

\[
v(x) = \mu E(x)
\]

Fourthly, the density of deep traps \( N_d \) is much larger than the density of carriers and the detrapping time is very long in comparison with the shaping time, \( T_T \), of the electronics so that the density of carriers decays exponentially with time

\[
n(t) = n(0) \exp\left(-\frac{t}{r}\right)
\]

where \( r \) is the carrier lifetime.

Finally, there is no loss of collected charge at the preamplifier. With these assumptions, the collected charge is expressed by

\[
Q = e \int_0^d dx \int_0^T n(t) v(x) dt
\]

where \( v(x) \) is the drift velocity of the carriers generated at \( x \). The normalized charge collection efficiency, \( \epsilon \), is basically a function of the following parameters.

\[
\epsilon \equiv \frac{Q}{Q_0} = f(\mu, r, N_d^*, T_T, V_b, d, X_0)
\]

Only the first three parameters are material related which we measured by standard transient photoconductivity experiments.

**IV. Measurement of Mobility, Mobility-Lifetime Product, and Dangling Bond Density**

We have used transient photoconductivity experiments to measure carrier mobility \( \mu \), the mobility-lifetime product \( \mu \tau \), and the ionized dangling bond density \( N_d^* \) in thicker (27 \text{ pm}) detectors. A pulsed nitrogen-dye laser system with 3-ns pulse width is used for this purpose at a wavelength of 510 nm, which has an absorption mean free path of \( \sim 0.2 \text{um} \) in a-Si:H.

In a conventional time-of-flight experiment, the drift mobility is determined by measuring the carrier transit time by applying a biased pulse a few tens of microseconds before photo-injection of carriers. This ensures that at these short times very few dangling bonds are ionized. Hence, to a good approximation, the electric field is uniform through the bulk of the i layer. The photocurrent J resulting from the applied field is

\[
J = \eta n e \mu \frac{E}{d}
\]

where \( n \) is the number of photons absorbed, \( \eta \) is the carrier generation efficiency, \( \mu \) is the drift mobility of the carrier moving across the sample, and \( d \) is the thickness of i layer.

The mobility is obtained from the transit time \( T_T \),

\[
\mu = \frac{d}{ET_T} = \frac{d^2}{VT_T}
\]

For nondispersive transport \( T_T \) is defined as the time at which J drops by 50%, while for dispersive transport in which the mobility
is time-dependent, it is given by the change of slope in a log \( J \) - log \( t \) plot.

The mobility-lifetime product \( \mu \tau \) is determined by measuring charge collection (equal to \( \int \mu t \) at a uniform electric field when a uniform electric field is applied. The charge collection is given by the Hecht equation,

\[
Q = \frac{\eta e \mu E}{d} \left[ 1 - \exp \left( -\frac{d}{\mu \tau E} \right) \right]
\]

where \( Q = Q_0 = \eta e \) corresponds to complete transit of all carriers.

The ionized dangling bond density is determined by measuring the transient photoconductivity current signal from the sample with equilibrium DC bias as follows. The depletion field depends on the distance \( \tau \) into the sample, so that the photocurrent is time dependent, corresponding to the drift of the charge packet down the field.

\[
J(t) = \frac{\eta e \mu E(t)}{d}
\]

For the carriers that start at \( x = 0 \) and \( t = 0 \), \( x \) is related to \( t \) by

\[
x = \int_0^t \mu E(t')dt'
\]

\( E(x) \) can therefore be obtained directly from measurement of \( J(t) \) using equation (15), provided \( E(t) \) and the mobility are known.

Since the current is proportional to the field, \( E(t) \) can be found by comparing the current to that obtained for a known applied field and using equation (10). In this way, \( \eta e \) does not need to be known, provided it is the same for pulsed and DC bias experiments. The ionized dangling bond density is deduced from the slope of linearly decreasing part of the DC bias photo-current transient by using equation (2).

Table 1 shows the measured parameters from 4 samples.

<table>
<thead>
<tr>
<th>Type</th>
<th>Maker</th>
<th>( \mu_e ) (cm²/Vs)</th>
<th>( \mu_\tau e ) (cm²/V)</th>
<th>( \mu_h ) (cm²/Vs)</th>
<th>( \mu_\tau h ) (cm²/V)</th>
<th>( N_0^* ) (cm⁻³)</th>
<th>( N_0^* \mu_\tau e ) (1/cmV)</th>
<th>( N_0^* \mu_\tau h ) (1/cmV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-i-n</td>
<td>GSI</td>
<td>1.2</td>
<td>1.1 × 10⁻⁷</td>
<td>0.004</td>
<td>1.0 × 10⁻⁸</td>
<td>7 × 10¹⁴</td>
<td>7.7 × 10⁷</td>
<td>7.0 × 10⁵</td>
</tr>
<tr>
<td>n-i-p</td>
<td>GSI</td>
<td>1.2</td>
<td>1.1 × 10⁻⁷</td>
<td>0.004</td>
<td>1.6 × 10⁻⁸</td>
<td>7 × 10¹⁴</td>
<td>8.4 × 10⁷</td>
<td>8.4 × 10⁵</td>
</tr>
<tr>
<td>n-i-p</td>
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<td>1.1</td>
<td>1.5 × 10⁻⁷</td>
<td>0.004</td>
<td>2.7 × 10⁻⁸</td>
<td>6 × 10¹⁴</td>
<td>9.0 × 10⁷</td>
<td>9.6 × 10⁶</td>
</tr>
<tr>
<td>n-i-p</td>
<td>Xerox</td>
<td>1.4</td>
<td>1.1 × 10⁻⁷</td>
<td>0.003</td>
<td>6.6 × 10⁻⁸</td>
<td>6 × 10¹⁴</td>
<td>6.6 × 10⁷</td>
<td>1.6 × 10⁷</td>
</tr>
</tbody>
</table>
Fig. 5. Electron and hole mobility vs electric field in 27 μm p-i-n detector. a) Electron mobility; b) hole mobility.

Fig. 6 shows charge collection for sample of Fig. 3 at various DC biases from which the field profile and ionized dangling bond density is obtained.

Fig. 6. Transient photo current electron signal at different DC bias voltages from 27 μm p-i-n detector using 510 nm light.

V. Fit to Hole Signal Using Measured Parameters $\mu$, $\tau$ and $N_d$

Fig. 7 shows the fit to the measured hole signal of Fig. 1 using the model calculation of signal discussed in Section III. The dots in Fig. 7 are experimental data points for 510 nm light. The fit uses the measured values

$$\mu_h = 0.004 \text{ cm}^2/\text{Vsec} \quad \mu \tau_h = 1.2 \times 10^{-8} \text{ cm}^2/\text{Vsec}$$

Fig. 7 also shows calculated hole signal for three values of $N_d$. A value of $N_d = 7.1 \times 10^{14} \text{cm}^{-3}$ fits the measured signal best. This value of $N_d$ is in good agreement with the measured dangling bond density obtained from the transient photoconductivity experiments.

Summary and Conclusions

The transient photoconductivity measurements on relatively thick samples of a-Si:H show ionized dangling bond densities in the range of $6-7 \times 10^{14} \text{cm}^{-3}$. The electron transport on the samples is found to be nondispersive with high field electron mobility in the range of $1.1-1.3 \text{cm}^2/\text{Vsec}$. The hole mobility ranging from 0.003 - 0.007 \text{cm}^2/Vsec is dispersive with $\alpha \sim 0.6$. While the electron mobility increases by $\sim 20\%$ at high field, hole mobility increases by $\sim 40\%$ from the low field values. This increase in mobility is attributed to dispersion of the transport, but there may be the Poole-Frenkel effect with the non-dispersive electrons. ($\mu \tau N_d$) values range from $6.6 \times 10^7$ to $9 \times 10^7$ and ($\mu \tau N_d$)$_h$ range from $7 \times 10^6$ to $1.6 \times 10^7$. These values are in good agreement with values reported on thinner samples. We find that the fit to the hole signal based on model calculation discussed in Section III is very sensitive to the ionized dangling bond density value $N_d$. This sensitivity and a good agreement between measured dangling bond density value from the transient photoconductivity experiment and the one obtained from the calculated fit suggests that this provides a useful method for the measurement of ionized dangling bond density in thick samples.
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