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MATERIAL PARAMETERS IN A THICK HYDROGENATED AMORPHOUS SILICON DETECTOR AND THEIR EFFECT ON SIGNAL COLLECTION*

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ABSTRACT

Transient photoconductivity and ESR measurements were done to relate the ionized
dangling bond density and the spin density of thick hydrogenated amorphous silicon (a-Si:H)
detectors. We found that only a fraction (~30 - 35%) of the total defect density as measured by
ESR is ionized when the detector is biased into deep depletion. The measurements on annealed
samples also show that this fraction is about 0.3. An explanation based on the shift of the
Fermi energy is given. The measurements show that the time dependence of relaxation is a
stretched exponential.

I. INTRODUCTION

Charge collection in hydrogenated amorphous silicon p-i-n detectors depends on various
material parameters such as carrier mobility and carrier mobility-lifetime product. Another
material parameter vital to charge collection in amorphous silicon detectors is the ionized
dangling bond density, as this determines how rapidly the electric field falls off in the active
region of the detector. In this paper we describe measurements of these material parameters in
thick (>25 µm) amorphous silicon 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 ~ 0.2 µm in a-Si:H and is used to provide information on the individual contribution
to the signal of the electron and hole motion. This is done by having the laser light incident on
the p or n side of the p-i-n detector. These kinds of experiments provide detailed information
about the internal electric field and charge collection which allows the performance of a-Si:H
particle detectors to be evaluated.

II. DERIVATION OF SIGNAL PRODUCED BY 510 nm LIGHT PULSES

Previously [1], we have analyzed signals from 510 nm light in terms of material parameters
measured by transient photoconductivity experiments. The analysis assumes that the detector is
biased into deep depletion. Assuming the electric field profile is linear based on the model
calculation [2,3] it is shown in [1] that the normalized charge collection efficiency, \( \varepsilon \), is a
function of the following parameters

\[
\varepsilon \equiv \frac{Q}{Q_0} = f\left( \mu, \tau, N_d^*, T_s, V_b, d, X_0 \right)
\]

where \( \mu \) is the carrier mobility, \( \tau \) the carrier lifetime, \( N_d^* \) the ionized dangling bond density, \( T_s \)
the shaping time of electronics, \( V_b \) the bias, \( d \) the detector thickness and \( X_0 \) the mean
absorption depth in a-Si:H for 510 nm light (\( X_0 \sim 0.2\mu m \)). The first three parameters are
material related.

III. MEASUREMENT OF MOBILITY, MOBILITY-LIFETIME PRODUCT, TOTAL
DANGLING BOND, AND IONIZED DANGLING BOND DENSITY

We use transient photoconductivity experiments to measure carrier mobility \( \mu \), the mobility-
lifetime product \( \mu \tau \) and the ionized dangling bond density \( N_d^* \) in thick (>25 mm) detectors [4].
The electron and hole mobilities are obtained by measuring transit time in a conventional time of
flight experiment. The electron transport in the samples reported in this paper is nondispersive. The mobility-lifetime product \( \mu \tau \) is obtained from the field dependence of charge collected (\( J/dt \)) and the Hecht equation. The ionized dangling bond density is determined from the transient photocurrent signal when equilibrium DC bias is applied[1].

Table 1 shows \( \mu_e, \mu_h, \mu_e \tau_e, \mu_h \tau_h \) and the ionized dangling bond density \( N_d \) for various measured samples. The dangling bond densities of the Xerox samples measured by ESR are listed also. All the samples were made by Xerox PARC except the one marked by an asterisk which was made by Glasstech-Solar, Inc. (GSI).

<table>
<thead>
<tr>
<th>Thickness (( \mu m ))</th>
<th>27†</th>
<th>28</th>
<th>48</th>
<th>27*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>n-i-p</td>
<td>n-i-p</td>
<td>n-i-p</td>
<td>p-i-n</td>
</tr>
<tr>
<td>( \mu_e (cm^2/Vs) )</td>
<td>1</td>
<td>1.1</td>
<td>1.4</td>
<td>0.56</td>
</tr>
<tr>
<td>( \mu_e \tau_e (cm^2/V) )</td>
<td>8x10^-8</td>
<td>1.1x10^-7</td>
<td>1.1x10^-7</td>
<td>9x10^-8</td>
</tr>
<tr>
<td>( \mu_h (cm^2/Vs) )</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>( \mu_h \tau_h (cm^2/V) )</td>
<td>1x10^-8</td>
<td>1x10^-8</td>
<td>2.7x10^-8</td>
<td>&lt;3.8x10^-8</td>
</tr>
<tr>
<td>( N_d (cm^{-3}) )</td>
<td>8x10^14</td>
<td>6x10^14</td>
<td>6x10^14</td>
<td>7x10^14</td>
</tr>
<tr>
<td>( N_d (cm^{-3}) )</td>
<td>2.6x10^15</td>
<td>2x10^15</td>
<td>2x10^15</td>
<td>2.3x10^15</td>
</tr>
<tr>
<td>( N_d^*/N_d )</td>
<td>31%</td>
<td>30%</td>
<td>30%</td>
<td>29%</td>
</tr>
<tr>
<td>( \mu_e \tau_e N_d (1/cmV) )</td>
<td>2x10^8</td>
<td>2.2x10^8</td>
<td>2.2x10^8</td>
<td>2.1x10^8</td>
</tr>
<tr>
<td>( \mu_e \tau_e N_d (1/cmV) )</td>
<td>2.5x10^8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Measured parameters of different samples.

† Sample was subsequently heat treated (Section IV and V).
* GSI sample, ** Estimated from \( \mu_e \tau_e N_d \).

It is seen that the ionized dangling bond density values are a small fraction of the spin density. This observation is also corroborated by making fits to the measured hole signal of Fig. 1 using measured values of \( \mu_h \) and \( \mu_h \tau_h \) and the model calculation of signal mentioned in Section II. The dots in Fig. 1 are experimental data points for 510 nm light. The fit uses the measured value of

\[
\mu_h = 0.004 \frac{cm^2}{Vs} \quad \text{and} \quad \mu_h \tau_h = 1.2 \times 10^{-8} \frac{cm^2}{Vs}
\]

A value of \( N_d^* = 7.1 \times 10^{14} \text{cm}^{-3} \) fits the measured data best. This value of \( N_d^* \) is in good agreement with the ionized dangling bond density value obtained from the transient photoconductivity experiments.

The dangling bond density of a 27 \( \mu \)m p-i-n (GSI) sample with tin oxide film on substrate was obtained from \( \mu_e \tau_e N_d \) product which follows from the basic expressions relating the capture process with the trap - limited transport of amorphous semiconductors. Street [5,6] has shown that this product is given by

\[
\mu \tau N_e = \frac{e}{6 KT} \frac{a}{\sigma}
\]
where $a$ is the scattering length of carrier (in a-Si:H $a \sim 10 \text{ Å}$ for electrons and for holes $a \sim 5 \text{ Å}$), $\sigma$ is the capture cross section and $T$ is the temperature. The mobility-lifetime product $\mu\tau$ is measured by transient photoconductivity experiments and $N_d$ by ESR. An average value of $\mu_e\tau\varepsilon N_d = 2.5$ was obtained from the values reported by Street [7] and the ones measured by us as shown in Table 1. We have also used $\mu\tau N_d$ product to estimate $N_d$ for the annealed sample discussed in Section IV.

To eliminate possible effects of impurity variations from sample to sample in relating the ionized dangling bond density and the spin density, measurements were done on a sample whose dangling bond density was increased by heating. The initial spin density of a $27 \mu\text{m}$ n-i-p sample before heat treatment was $2.6 \times 10^{15}$ cm$^{-3}$ (ESR) and the ionized defect density $8 \times 10^{14}$ cm$^{-3}$ (TOF). The sample was heated to $300\text{°C}$ to increase the spin density to $6.5 \times 10^{15}$ cm$^{-3}$; the ionized defect density was measured to be $2 \times 10^{15}$ cm$^{-3}$. The fraction of defects ionized ($\sim 30\%$) before and after the heat treatment remained unchanged.

IV. DEFECT RELAXATION ON ANNEALING

The heat treated sample was annealed at $175\text{°C}$ and the ionized dangling bond density measured as a function of annealing time. Fig. 2 shows the measured ionized defect density versus annealing time. Also shown are the defect density values derived from the measured
μeτe values and μeτeNd ≡ 2x10^8. The time dependence of relaxation is non-exponential and is a stretched exponential of the form [8]

\[ N_d - N_{deq} = N_{do} - N_{deq} \exp\left[-\left(\frac{t}{\tau_s}\right)^\beta\right] \] (3)

where \(N_{do}\) and \(N_{deq}\) are the initial and equilibrium dangling bond density. \(β\) is a dispersion parameter and \(τ_s\) is the time required for structural relaxation. The plot of this curve for 175°C is shown in Fig. 2. It is seen that the curve is in good agreement with the derived values of \(N_d\).

In Fig. 3 the normalized defect density is shown as a function of annealing time. The data is normalized to the initial and the equilibrium defect density values. From Figs. 2 and 3 it is seen that the ionized defect density as a function of annealing time also has the dependence of the same stretched exponential but reduced by about a factor of 3. This confirms that we are looking the same effect.

![Graph showing ionized defect density Nd* vs annealing time](image)

**Fig. 2** Ionized defect density \(N_d^*(\text{TOF})\) vs annealing time. Also shown is defect density \(N_d\) from \((μeτeNd ≡ 2x10^8)\) vs annealing time. Solid line, -, shows stretched exponential at 175°C anneal temperature.

V. IONIZED DEFECT DENSITY AND FERMI ENERGY

Our results show that only about one third of the defects are ionized when the samples are biased into deep depletion. The ionization fraction depends on the energy of the defect states and on the shift of the Fermi energy which results from the depletion bias. We analyze a simple density of states model illustrated in Fig. 4. The singly and doubly occupied defect states are
Fig. 3 Relaxation data at 175°C for a 27 μm sample after heat treatment. \(N_d^*\) and \(N_d\) follow same stretched exponential.

Fig. 4 Fraction of defects ionized vs. shift in Fermi energy on depletion.
represented by gaussian bands of width \( \sigma \). The two bands are separated by the correlation energy \( U \). It is assumed that the equilibrium Fermi energy, \( E_{F0} \) is pinned by the defects and so lies symmetrically between the two bands at zero bias. The Fermi energy will move to the center of the gap, \( E_{Fd} \) under condition of deep depletion. The fact that electrons are depleted rather that holes implies that \( E_{Fd} \) is below \( E_{F0} \), so that the average energy of the defect levels is above mid-gap. The density of ionized defects is given by

\[
N_d^* = N_d - \int N_d(E) f(E_{Fd}, T) dE
\]

where \( f \) is the Fermi function. Fig. 4 shows the calculated fraction of ionized defects as a function of the shift of the Fermi energy, \( E_{Fd} - E_{F0} \), for different assumed values of \( \sigma \) and \( U \) which cover the usually accepted range of these values. The experimentally observed ionization fraction of about 0.3 corresponds to a shift of the Fermi energy of 0.05-0.1 eV. These results place some constraints on the defect energy levels, although they cannot uniquely determine the positions. For example, a correlation energy of 0.02 eV and a mobility gap of 1.8 eV places the upper defect level in the range of 0.7-0.75 eV below the conduction band.

VI. SUMMARY

Transient photoconductivity measurements on relatively thick samples of a-Si:H have been made to measure the fraction of defects ionized on biasing a detector to deep depletion. The measurements show that 30% of the defects are ionized. This observation is further corroborated by measurements on a sample whose spin density was initially increased by heat treatment and reduced subsequently by annealing. The defect relaxation on annealing follows a stretched exponential behavior and is the same for the ionized and the total defect density. The ionization fraction depends on the energy of the defect states and on the shift of the Fermi energy which results from the depletion bias. Analysis of a simple density of states model shows that the experimentally observed ionization fraction corresponds to a shift of the Fermi energy of 0.05-0.1 eV.

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