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April 1989

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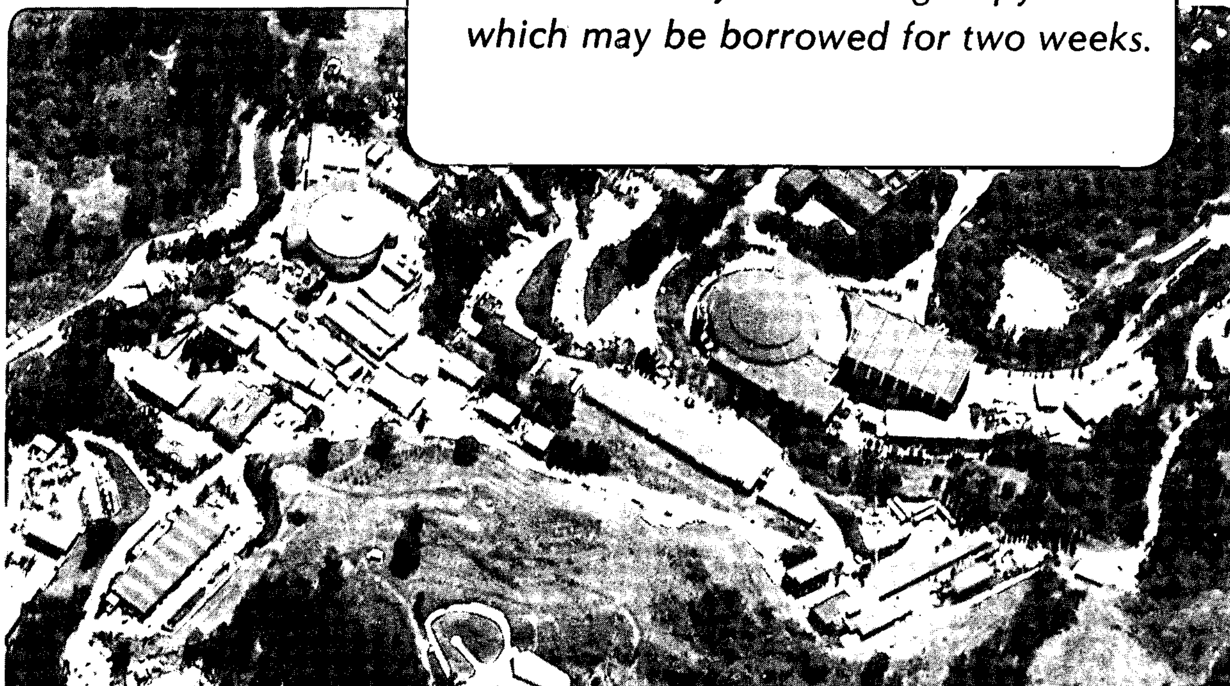

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MATERIAL PARAMETERS IN A THICK HYDROGENATED AMORPHOUS SILICON DETECTOR AND THEIR EFFECT ON SIGNAL COLLECTION*

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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, ε, is a function of the following parameters

$$\varepsilon \equiv \frac{Q}{Q_0} = f\left(\mu, \tau, N_d^*, T_s, V_b, d, X_0 \right) \tag{1}$$

where μ is the carrier mobility, τ 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 ~ 0.2μm). 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 μ, the mobility-lifetime product μτ 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 ($\int Jdt$) 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 μ_e, μ_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).

Thickness (μm)	27†	27	28	48	27*
Type	n-i-p	n-i-p	n-i-p	n-i-p	p-i-n
μ_e(cm^2/vs)	1	1.1	1.4	0.56	1.2
$\mu_e\tau_e$(cm^2/v)	8x10^{-8}	1.1x10^{-7}	1.1x10^{-7}	9x10^{-8}	1.2x10^{-7}
μ_h(cm^2/vs)	0.003	0.003	0.003	<0.003	0.004
$\mu_h\tau_h$(cm^2/v)	1x10^{-8}	1x10^{-8}	2.7x10^{-8}	<3.8x10^{-8}	1.2x10^{-8}
N_d^*(cm^{-3})	8x10^{14}	6x10^{14}	6x10^{14}	7x10^{14}	7x10^{14}
N_d(cm^{-3})	2.6x10^{15}	2x10^{15}	2x10^{15}	2.3x10^{15}	2.1x10^{15}
N_d^*/N_d	31%	30%	30%	29%	33%**
$\mu_e\tau_eN_d$(1/cmv)	2x10^8	2.2x10^8	2.2x10^8	2.1x10^8	2.5x10^8

Table 1. Measured parameters of different samples.

† Sample was subsequently heat treated (Section IV and V).

* GSI sample, ** Estimated from $\mu_e\tau_eN_d$.

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 μ_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

$$\mu_h = 0.004 \frac{cm^2}{VSec} \quad \& \quad \mu_h \tau_h = 1.2\,x10^{-8} \frac{cm^2}{V}$$

A value of $N_d^* = 7.1x10^{14}cm^{-3}$ 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 μm p-i-n (GSI) sample with tin oxide film on substrate was obtained from $\mu_e\tau_eN_d$ 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

$$\mu\tau N_d = \frac{e}{6\,KT}\frac{a}{\sigma} \qquad (2)$$

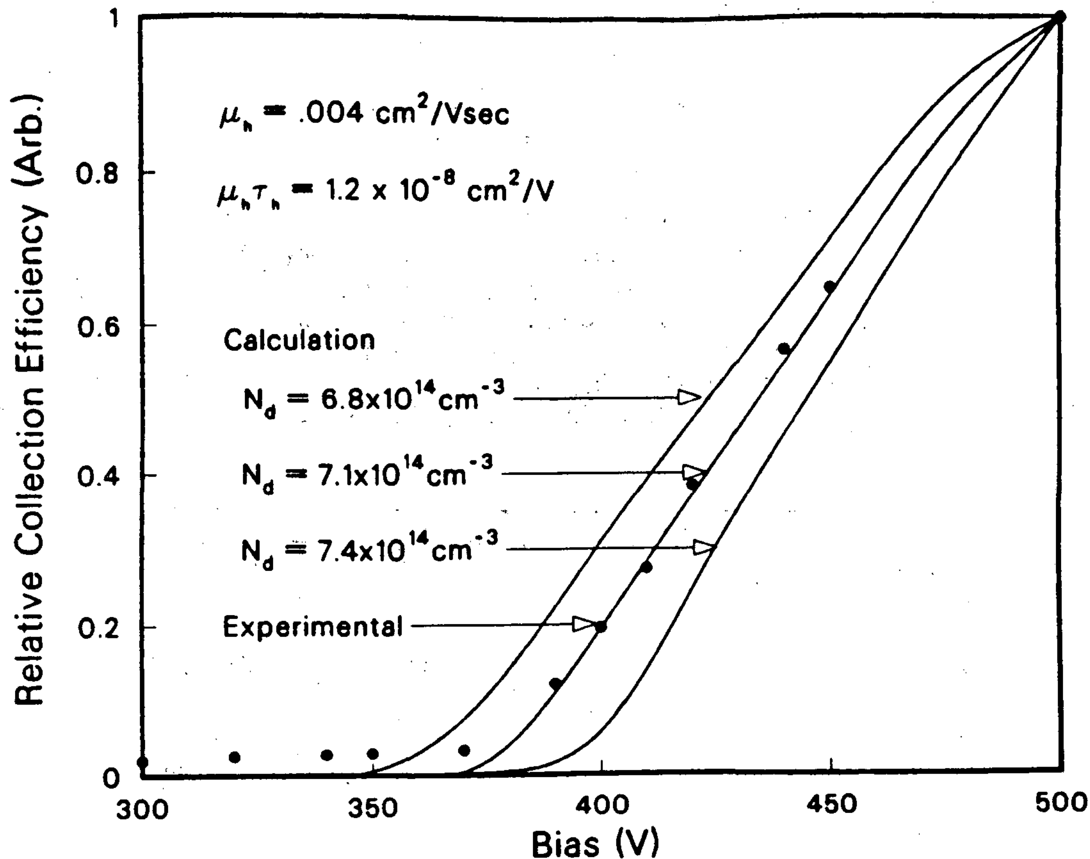

Fig. 1 Measured, •, and calculated hole signal threshold using 510 nm light pulses for different assumed values of ionized dangling bond density.

where a is the scattering length of carrier (in a-Si:H $a \sim 10$ Å for electrons and for holes $a \sim 5$ Å), σ 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 $\mu_e\tau_e N_d \approx 2.5$ 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 μm n-i-p sample before heat treatment was 2.6 x 10^{15} cm^{-3} (ESR) and the ionized defect density 8x10^{14} cm^{-3} (TOF). The sample was heated to 300C° to increase the spin density to 6.5 x $10^{15}cm^{-3}$; the ionized defect density was measured to be 2 x $10^{15}cm^{-3}$. The fraction of defects ionized (~30%) before and after the heat treatment remained unchanged.

IV. DEFECT RELAXATION ON ANNEALING

The heat treated sample was annealed at 175C° 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

$\mu_e\tau_e$ values and $\mu_e\tau_e N_d \equiv 2\times10^8$. The time dependence of relaxation is non-exponential and is a stretched exponential of the form [8]

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

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 175C° 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.

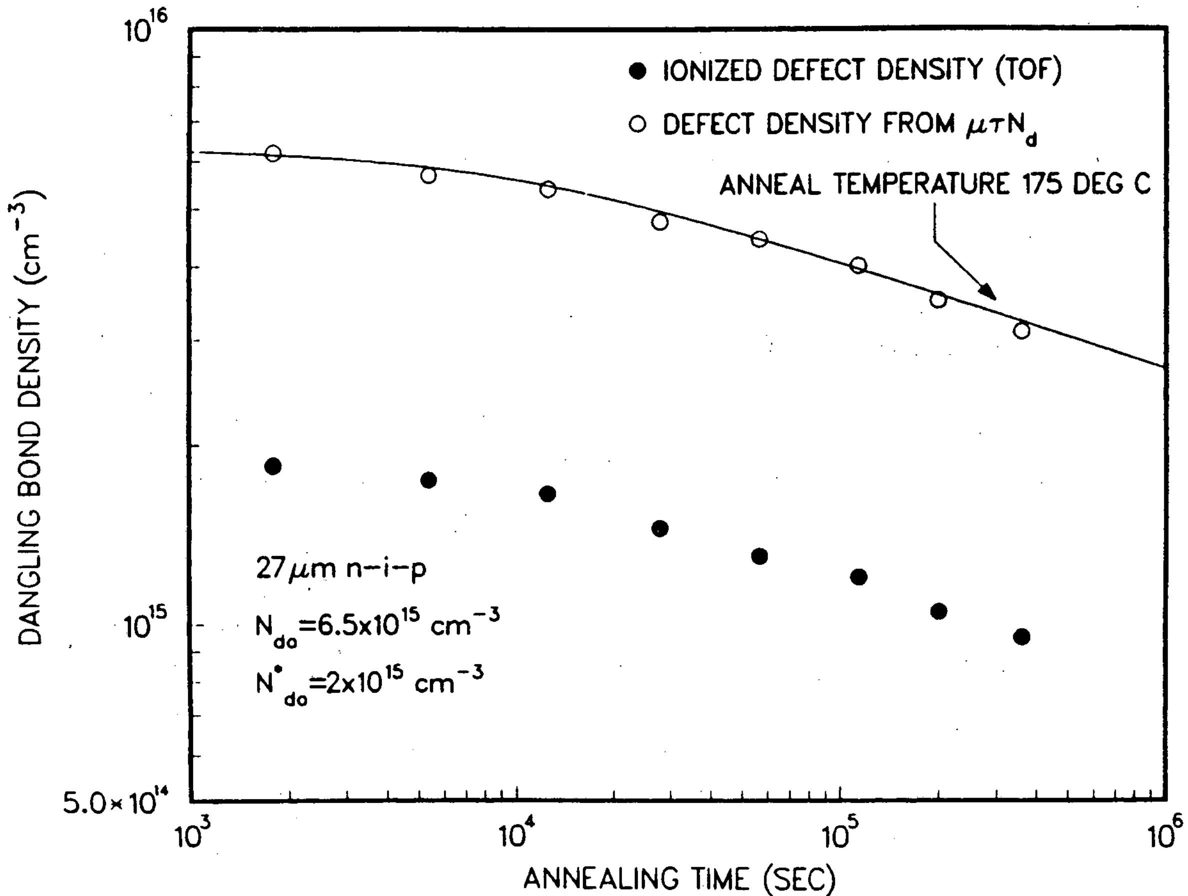

Fig. 2 Ionized defect density N_d* (TOF) vs annealing time. Also shown is defect density N_d from ($\mu_e\tau_e N_d \equiv 2\times10^8$) vs annealing time. Solid line, –, shows stretched exponential at 175C° anneal temperature.

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

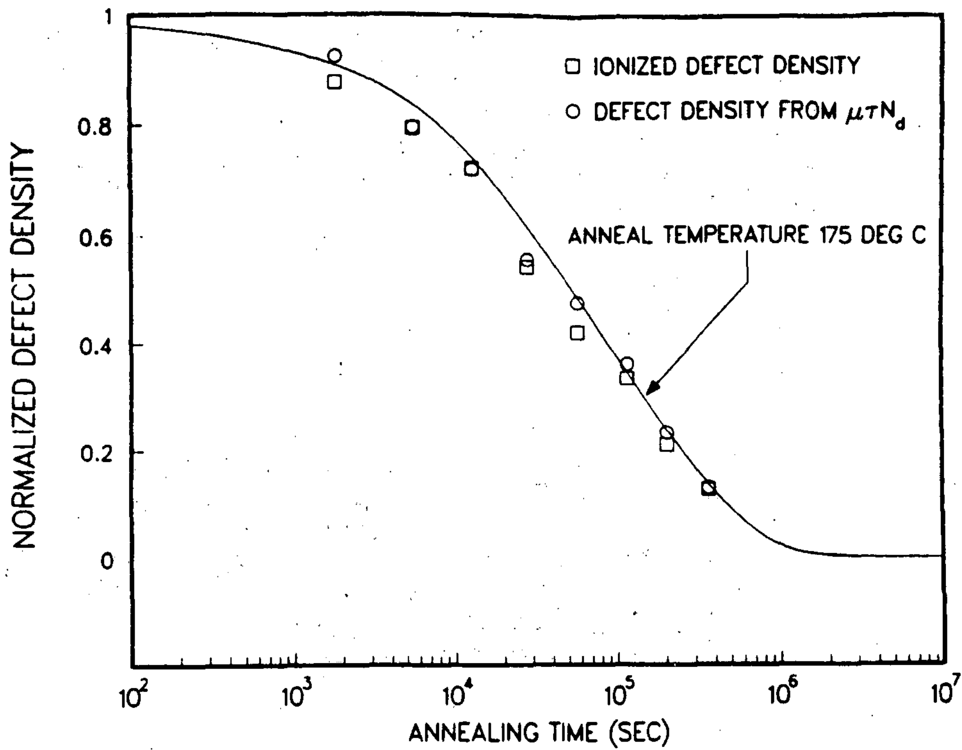

Fig. 3 Relaxation data at 175C° for a 27 μm sample after heat treatment. N_d* and N_d follow same stretched exponential.

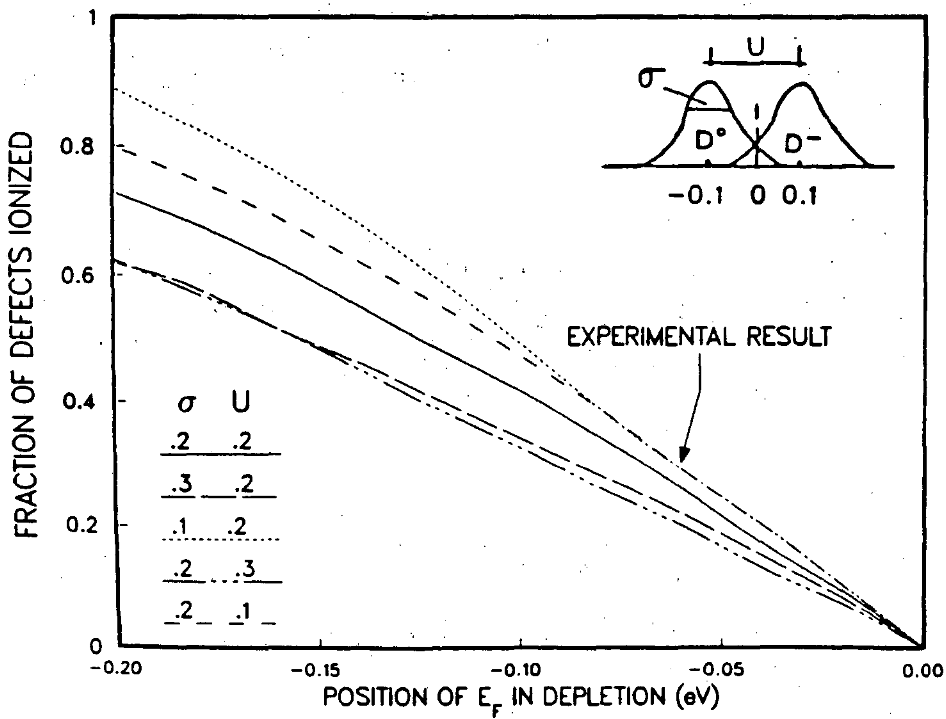

Fig. 4 Fraction of defects ionized vs. shift in Fermi energy on depletion.

represented by gaussian bands of width σ. The two bands are separated by the correlation energy U. It is assumed that the equilibrium Fermi energy, E_{Fo} 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_{Fo}, 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_{Fo}, for different assumed values of σ 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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