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Hole-mobility limit of amorphous silicon solar cells

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We present temperature-dependent measurements and modeling for a thickness series of hydrogenated amorphous silicon *nip* solar cells. The comparison indicates that the maximum power density (P_{MAX}) from the as-deposited cells has achieved the hole-mobility limit established by valence bandtail trapping, and P_{MAX} is thus not significantly limited by intrinsic-layer dangling bonds or by the doped layers and interfaces. Measurements of the temperature-dependent properties of light-soaked cells show that the properties of as-deposited and light-soaked cells converge below 250 K; a model perturbing the valence band tail traps with a density of dangling bonds accounts adequately for the convergence effect. © 2006 American Institute of Physics.

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Solar cells based on hydrogenated amorphous silicon (*a*-Si:H) and related materials are now manufactured in large quantities, so it is remarkable that there is no consensus regarding the optoelectronic processes that determine their photovoltaic conversion efficiency. There are at least two broad issues that have led to ambiguities regarding the device physics. First, the solar cells are *nip* or *pin* structures, and the cell efficiency is potentially affected by the properties of the intrinsic and doped layers and also by the interfaces between them. Second, at least for the intrinsic layer, both disorder limitation of carrier mobilities, and also carrier capture by deep levels such as dangling bonds, are each known to be important, but it is difficult to distinguish the two effects on the cell's efficiency.

In this letter, we present temperature-dependent measurements and analyses for a series of *a*-Si:H *nip* solar cells prepared at United Solar Ovonic Corporation that indicate that the efficiencies of these cells at solar intensities are mostly determined by the hole mobility of the intrinsic layer. Essentially the same conclusion (of mobility or space-charge limited photocurrent) was reached recently for polymer-fullerene blend solar cells.¹ Temperature-dependent measurements are useful for exploring hole mobility effects in *a*-Si:H solar cells because the strong temperature dependence of the hole drift mobility in *a*-Si:H gives a fairly distinctive temperature dependence for the cell efficiency. The statement that the efficiencies are near the hole mobility limit implies that the density of deep levels is sufficiently low that it has a minor effect on the efficiency, and that the *p/i* and *n/i* interfaces are sufficiently good that they are behaving nearly ideally. We also present measurements for the light-soaked state, where deep levels do have a clearly measurable effect; the mobility-limitation idea remains roughly applicable. We conclude that improved efficiencies of *a*-Si:H solar cells will likely require further improvements in the hole drift mobility.

For these experiments, six *a*-Si:H *nip* solar cells were deposited using rf glow discharge on stainless steel substrates. The *n* and *p* layers were the same in all depositions; the deposition time for the intrinsic layer was chosen to give

intrinsic layer thicknesses from 185 to 893 nm. The cells were not optimized for the best efficiency, and in particular do not have a highly reflecting back contact. Special attention was paid to the hydrogen dilution in the intrinsic layer and to avoid nanocrystallite inclusion. Details of the deposition procedures have been given elsewhere.² As-deposited properties of the cells were measured under a solar simulator; for the thickest intrinsic layer (893 nm) a typical cell had an open-circuit voltage (V_{OC}) of 0.982 V, a short circuit current density (J_{SC}) of 14.4 mA/cm², a fill factor (FF) of 0.559, and a maximum power density (P_{MAX}) of 7.9 mW/cm².

Further studies were done using a 30 mW, near-infrared (685 nm wavelength) laser. We chose to use this laser because its wavelength is absorbed fairly uniformly throughout the intrinsic layers of the cells, which simplifies modeling of the measurements. In Fig. 1 we present the temperature dependent normalized maximum power density $P_{\text{MAX}}(T)/J_s(T)$ and $V_{\text{OC}}(T)$ for four cells with differing intrinsic-layer thickness. J_s is the photocurrent density measured at -2 V, which is a good approximation to the saturated reverse-bias photocurrent over most of the temperature range. The measurements were done at constant laser flux. The average photo-generation rate at 295 K was $G=3.3 \times 10^{20}$ cm⁻³ s⁻¹; G does vary with T due to the temperature-dependent band gap of *a*-Si:H.

As has been reported by most previous workers, V_{OC} is nearly thickness independent. P_{MAX}/J_s declines markedly with thickness, which indicates that photocarriers generated deep inside a thick cell are likely to recombine instead of contributing to power generation. The solid lines in Fig. 1 represent computer calculations (AMPS-1D code³) using what we consider to be the simplest reasonable model for an *a*-Si:H *nip* solar cell. The crucial electrical parameters describe hole transport in the intrinsic layer. The code uses the exponential valence bandtail trapping model^{4,5} to describe hole transport. The parameters we used are given in Table I; as described elsewhere,⁶ they have been chosen for consistency with hole drift mobility ("time-of-flight") measurements.⁷ The electron parameters are given in Table I

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FIG. 1. Temperature-dependent measurements of V_{OC} and the P_{MAX}/J_s for four as-deposited a -Si:H nip solar cells with varying intrinsic layer thickness are indicated by the symbols. Measurements were done at constant laser flux; the average photogeneration rate G at 295 K was $3.3 \times 10^{20} \text{ cm}^{-3} \text{ s}^{-1}$. The lines indicate corresponding calculations for a model based primarily on hole drift-mobility measurements.

for completeness, but the calculations are fairly insensitive to them. This is expected because electron drift-mobilities are hundreds of times larger than hole drift mobilities in a -Si:H.^{5,8} Deep levels were not included in the calculations of Fig. 1. We used idealized p and n layer parameters for which the precise values have little effect on calculated cell properties; prior experiments indicate that doped layers and interfaces are not limiting V_{OC} in contemporary cells.⁹ The temperature-dependent photogeneration rate $G(T)$ was determined from the measured, temperature-dependent photocurrent under reverse bias for the thinnest cell (186 nm). The temperature-dependent bandgap $E_g(T)$ was determined from measurements of the electroabsorption spectrum that are not shown here; this method¹⁰ gave results consistent with earlier reports.¹¹

As can be seen from the figure, these calculations give a good account for the temperature-dependent magnitudes of V_{OC} and P_{MAX}/J_s . The near thickness independence of V_{OC} and its increase with decreasing temperature may be roughly understood using the model that equates eV_{OC} (e is the electronic charge) to the separation of electron and hole quasi-Fermi levels in the intrinsic layer.^{4,8} For the thicker samples,

FIG. 2. Temperature-dependent calculations for P_{MAX}/J_s of an a -Si:H nip solar cell based on a deep-level model are shown as the dashed line; the intrinsic layer thickness is 893 nm. The corresponding experimental measurements (symbols) and valence band tail based calculations from Fig. 1 are also shown for reference.

the decline in P_{MAX}/J_s with decreasing temperature is a consequence of the rapid decline in the hole drift mobility with temperature in a -Si:H.⁵ As the hole drift mobility declines, the region from which holes can be collected shrinks, and leads to reduced power from a thick cell.⁸ At the highest temperatures, there is evidently a discrepancy between the model and the P_{MAX}/J_s measurements; we believe that this reflects the onset of the effects of deep levels (dangling bonds).

Modelers generally include deep levels when they study a -Si:H solar cells,^{12,13} but we do not believe that deep levels dominate the values of P_{MAX} and V_{OC} of the as-deposited cells studied here. One reason for our view is that the measured drift mobilities of holes in a -Si:H essentially establish the largest values of P_{MAX} that can be obtained from the cells, and Fig. 1 indicates that the actual power from cells is close to these maximum values. If the densities of deep levels were large enough, they would lower P_{MAX} and V_{OC} noticeably below the calculated values of Fig. 1. A second reason for believing that a density of deep levels is not dominating V_{OC} and P_{MAX} is illustrated in Fig. 2, where the dashed line is a calculation of P_{MAX}/J_s based on the assumption that deep levels do dominate hole trapping. P_{MAX}/J_s calculated using deep levels decreases as the temperature T increases; both the measured P_{MAX}/J_s and the calculation based on hole mobilities increase with T .

For the deep level calculation in Fig. 2, we set the band-tail trap densities to zero. We used a donor-type ($0/+$) deep level that was electrically neutral in the dark. The coeffi-

TABLE I. a -Si:H solar cell modeling parameters (see Ref. 6, 8, and 11). Solar cell performance is mainly sensitive to the first 5 parameters, governing the hole drift mobility and the bandgap.

μ_p	$0.3 \text{ cm}^2/\text{V s}$	Band mobility of holes
ΔE_v	0.04 eV	Width of exponential valence band tail
N_v	$4 \times 10^{20} \text{ cm}^{-3}$	Valence band effective density-of-states
b_{vp}	$1.3 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$	Trapping coefficient $h^+ \rightarrow V^0$ (valence band tail)
E_g	1.74 eV	Electrical band gap
dE_g/dT	$-4.7 \times 10^{-4} \text{ eV/K}$	
b_{vn}	$1.0 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$	Trapping coefficient $e^- \rightarrow V^+$ (valence band tail)
μ_n	$2 \text{ cm}^2/\text{V s}$	Band mobility of electrons
ΔE_c	0.02 eV	Width of exponential conduction band tail
N_c	$4 \times 10^{20} \text{ cm}^{-3}$	Conduction band effective density-of-states
b_{cn}	$1.3 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$	Trapping coefficient $e^- \rightarrow C^0$ (conduction band tail)

FIG. 3. Symbols indicate temperature-dependent measurements of V_{OC} and P_{MAX}/J_s for an 893-nm-thick cell in its as-deposited and light-soaked (200 h at 295 K) states. The calculated line through the as-deposited measurements is from the hole drift-mobility based calculation of Fig. 1; for the light-soaked state, the calculation also includes a density of deep levels.

cients for hole and electron capture by the deep level chosen to be $b_{dp}=7.5 \times 10^{-9}$ and $b_{dn}=4 \times 10^{-8} \text{ cm}^3 \text{ s}^{-1}$, respectively. Given $\mu_p=0.3 \text{ cm}^2/\text{V s}$, they are consistent with hole deep-trapping experiments.¹⁴ We neglected the slight temperature dependences. The defect density N_d is $5.7 \times 10^{16} \text{ cm}^{-3}$ for Fig. 2, which fits the measured power at 230 K.

While deep levels do not seem to have a noticeable effect on the as-deposited state of these cells, a growth in deep-level density during illumination is the most plausible mechanism for the degradation of *a*-Si:H based solar cells during light soaking.¹⁵ In Fig. 3 we present the measurements for V_{OC} and P_{MAX}/J_s for an 893 nm cell before and after 200 h of light soaking at 295 K ($G=3.3 \times 10^{20} \text{ cm}^{-3} \text{ s}^{-1}$). The P_{MAX} measured at 295 K degraded about 30%, which is comparable to the saturated degradation of thick cells after long-term exposure to solar illumination.¹⁶ It is interesting that there is little difference in the light-soaked and the as-deposited states when measured at 230 K. This convergence of the two states at lower temperatures has not been noted in previous solar cell studies.

We were able to account for the convergence effect using the modeling procedures described earlier. For the light-soaked state, we added a density of deep levels to the band tail traps that were used to calculate the properties of the as-deposited state.¹⁷ The deep level trapping coefficients b_{dp}

and b_{dn} were noted earlier; the density of defects N_d was adjusted to $2 \times 10^{16} \text{ cm}^{-3}$ in order to fit the measured value of V_{OC} at 295 K after light soaking. This calculation gives a satisfactory account for the magnitude of P_{MAX}/J_s (no parameters were further adjusted), as well as for the temperature-dependences of V_{OC} and of P_{MAX}/J_s . The measurements of V_{OC} at lower temperatures are somewhat smaller than the calculated values. We speculate that this effect is due to a nonideal *p* layer.

Heuristically, the convergence effect may be understood from the splitting of the electron and hole quasi-Fermi levels in the intrinsic layer. This splitting increases as T falls [as evidenced by $V_{OC}(T)$]. While the density of deep levels is constant, the density of bandtail states between the two quasi-Fermi levels increases with this splitting—thus accounting qualitatively for the increased importance of bandtails at lower T .

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