Hole-mobility limit of amorphous silicon solar cells

Jianjun Liang, E. A. Schiff

Department of Physics, Syracuse University, Syracuse, New York 13244-1130

S. Guha, Baojie Yan, and J. Yang

United Solar Ovonic Corporation, Troy, Michigan 48084

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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 ($P_{\text{MAX}}$) from the as-deposited cells has achieved the hole-mobility limit established by valence bandtail trapping, and $P_{\text{MAX}}$ 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-change limited photocurrent) was reached recently for polymer-fullerene blend solar cells. 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 notoptimized 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 to maintain a good material quality throughout the entire intrinsic layer and to avoid nanocrystallite inclusion. Details of the deposition procedures have been given elsewhere. 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 ($V_{\text{OC}}$) of 0.982 V, a short circuit current density ($J_{\text{SC}}$) of 14.4 mA/cm$^2$, a fill factor (FF) of 0.559, and a maximum power density ($P_{\text{MAX}}$) of 7.9 mW/cm$^2$.

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 $P_{\text{MAX}}/(J_{\text{SC}})$ and $V_{\text{OC}}/T$ for four cells with differing intrinsic-layer thickness. $J_\infty$ 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 photogeneration rate at 295 K was $G=3.3\times10^{20}$ 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, $V_{\text{OC}}$ is nearly thickness independent. $P_{\text{MAX}}/J_{\infty}$ 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 code) 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 to describe hole transport. The parameters we used are given in Table I; as described elsewhere, they have been chosen for consistency with hole drift mobility (“time-of-flight”) measurements. The electron parameters are given in Table I.
Fermi levels in the intrinsic layer. For the thicker samples, temperature-dependent photogeneration rate hole drift-mobility measurements. The lines indicate corresponding calculations for a model based primarily on reports. Interfaces are not limiting properties; prior experiments indicate that doped layers and which the precise values have little effect on calculated cell electronic charge. 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. For the thicker samples, 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. As the hole drift mobility declines, the region from which holes can be collected shrinks, and leads to reduced power from a thick cell. 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, 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 \( P_{MAX}/J_s \) 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 bandtail trap densities to zero. We used a donor-type (0/+ deep level that was electrically neutral in the dark. The coeffi-

![FIG. 1. Temperature-dependent measurements of \( V_{OC} \) and the \( P_{MAX}/J_s \) for four as-deposited \( a\)-Si:H \( n\) \( p\) 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.](image1)

![FIG. 2. Temperature-dependent calculations for \( P_{MAX}/J_s \) of an \( a\)-Si:H \( n\) \( p\) 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.](image2)

### 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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_p )</td>
<td>( 0.3 \text{ cm}^2/\text{V s} )</td>
</tr>
<tr>
<td>( \Delta E_g )</td>
<td>( 0.04 \text{ eV} )</td>
</tr>
<tr>
<td>( N_v )</td>
<td>( 4 \times 10^{20} \text{ cm}^{-3} )</td>
</tr>
<tr>
<td>( b_{vp} )</td>
<td>( 1.3 \times 10^9 \text{ cm}^3\text{s}^{-1} )</td>
</tr>
<tr>
<td>( E_g )</td>
<td>( 1.74 \text{ eV} )</td>
</tr>
<tr>
<td>( dE_g/dT )</td>
<td>( -4.7 \times 10^{-4} \text{ eV/K} )</td>
</tr>
<tr>
<td>( b_{vn} )</td>
<td>( 1.0 \times 10^9 \text{ cm}^3\text{s}^{-1} )</td>
</tr>
<tr>
<td>( \mu_n )</td>
<td>( 2 \text{ cm}^2/\text{V s} )</td>
</tr>
<tr>
<td>( \Delta E_c )</td>
<td>( 0.02 \text{ eV} )</td>
</tr>
<tr>
<td>( N_c )</td>
<td>( 4 \times 10^{20} \text{ cm}^{-3} )</td>
</tr>
<tr>
<td>( b_{cn} )</td>
<td>( 1.3 \times 10^9 \text{ cm}^3\text{s}^{-1} )</td>
</tr>
</tbody>
</table>

Band mobility of holes
Width of exponential valence band tail
Valence band effective density-of-states
Trapping coefficient \( h^+ \rightarrow V^0 \) (valence band tail)
Electrical band gap
Trapping coefficient \( e^- \rightarrow V^+ \) (valence band tail)
Band mobility of electrons
Width of exponential conduction band tail
Conduction band effective density-of-states
Trapping coefficient \( e^- \rightarrow C^0 \) (conduction band tail)
After 200 h of light soaking at 295 K, the open-circuit voltage of the solar cell was 0.95 V for the as-deposited state and 0.85 V for the light-soaked state. The density of defects, $N_D$, was adjusted to $2 \times 10^{16}$ 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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7. Actual calculations require the densities of valence and conduction band tails at lower temperatures are somewhat
8. independent parameters since we use the assumption that the bandedge lies within the band tail (see Refs. 6 and 8).