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FIELD COLLAPSE DUE TO BAND-TAIL CHARGE IN AMORPHOUS SILICON SOLAR CELLS

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ABSTRACT

It is common for the fill factor to decrease with increasing illumination intensity in hydrogenated amorphous silicon solar cells. This is especially critical for thicker solar cells, because the decrease is more severe than in thinner cells. Usually, the fill factor under uniformly absorbed red light changes much more than under strongly absorbed blue light. The cause of this is usually assumed to arise from space charge trapped in deep defect states. We model this behavior of solar cells using the Analysis of Microelectronic and Photonic Structures (AMPS) simulation program. The simulation shows that the decrease in fill factor is caused by photogenerated space charge trapped in the band-tail states rather than in defects. This charge screens the applied field, reducing the internal field. Owing to its lower drift mobility, the space charge due to holes exceeds that due to electrons and is the main cause of the field screening. The space charge in midgap states is small compared with that in the tails and can be ignored under normal solar-cell operating conditions. Experimentally, we measured the photocapacitance as a means to probe the collapsed field. We also explored the light intensity dependence of photocapacitance and explain the decrease of *FF* with the increasing light intensity.

INTRODUCTION

The key feature of a-Si:H *p-i-n* solar cells is that photogeneration occurs in the region with a high electric field (i.e., the i layer). The carrier drift length is a unique parameter in the operation of *p-i-n* solar cells that distinguishes them from the other types of solar cells. To achieve a high-efficiency solar cell, it is highly desirable that the drift length be greater than the i-layer thickness so that photogenerated carriers can be collected effectively. Therefore, a probe of the electric field in the i layer is crucial because the drift length is proportional to the electric field. We observe that the fill factor (*FF*) of a-Si:H *p-i-n* solar cells decreases as the light intensity increases. As we increase the illumination intensity from low levels to one-sun, we observe a decrease in fill factor of approximately 15% in as-grown cells.

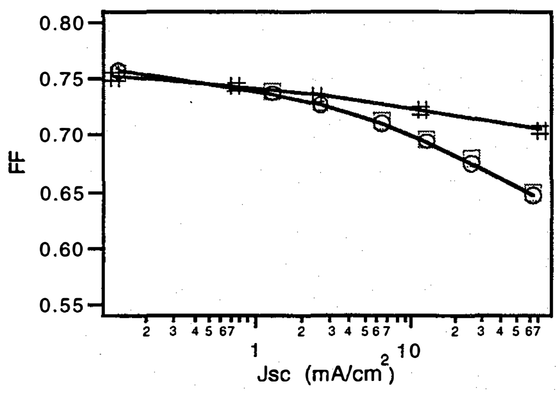
Illumination generates electrons and holes. The recombination of electron and hole leads to a loss of carriers. The drift of carriers and the nature of blocking contacts lead to the photogenerated space charge. The space charge is mainly due to the free carriers, to the trapped charge in the midgap states, and to the trapped charge in band-tail states. This space charge screens the applied field and reduces the internal field. As the light intensity increases, more electrons and holes are produced. This causes more photogenerated space charge, further decreasing the electric field in the i layer. We propose that a decrease in the electric field causes the *FF* to decrease with increasing light intensity. Photogenerated space charge in traps is the main cause of the electric field reducing. We use AMPS modeling and photocapacitance experiments to verify this.

SIMULATION

In general, a complete approach to this problem entails solving the transport equations of electrons and holes in an a-Si:H solar-cell device. Although a simple closed-form solution is not available, we could solve the transport equations numerically [1,2]. We model the behavior of a-Si:H *p-i-n* solar cells using the AMPS simulation program [2]. The details of the use of AMPS has been published elsewhere [3]. To test our hypothesis, we model the light intensity dependence of *p-i-n* solar cells and emphasize the effect on *FF* due to the band-tail states and the midgap states.

The modeled devices have a homojunction *p-i-n* structure with the energy gap of 1.72 eV. The thickness of the p layer is 100 Å, the thickness of thei layer is 5000 Å, and the thickness of the n layer is 250 Å. The thicknesses are close to the experimental solar cells fabricated at the National Renewable Energy Laboratory (NREL). The modeling uses a Gaussian distribution of midgap states and an exponential distribution of the band-tail states in the i layer. The simulated experiment is to simulate the modeled cell with increasing light intensity from 1/1000 th of a sun to 8 suns. We change only i layer parameters, such as the band-tail width and the density of the midgap state, for each simulation.

Figure 1 summarizes the modeling results. We plot the *FF* as a function of the short-circuit current (J_{sc}) for three experiments. We use the short-circuit current to reflect the light intensity. For example, a current of 12 mA/cm^2 corresponds to 1-sun light intensity. The parameters of the i layer used in each experiment is listed in the table below the figure.



	Cell □	Cell ○	Cell #
Nd	$5x10^{15}$	0	0
Ea (meV)	27	27	0
Ed (meV)	44	44	0

Figure 1. The simulation results of fill factor as a function of illumination intensity for three experiments. The designed cell has a *p-i-n* structure with i layer thickness of 0.5 mm. The table shows the i layer parameters for each experiment.

The first experiment is to run a standard cell with i-layer parameters close to the real cell. For example, the conduction-band tail width (Ea) is 27 meV, and the valence-band tail width (Ed) is 44 meV. We choose a midgap defect density (Nd) of 5×10^{15} cm^{-3} ,which is close to the defect density in an as-grown cell. As expected, we observe a decrease of *FF* with increasing light intensity, as in the actual cell. The symbol □ represents this experiment.

To test whether or not this decrease in *FF* is caused by the space charge trapped in the midgap defects, we remove the defects. We do the second experiment on this new cell without the defect states. We use symbol ○ to denote this run. We find that it has little effect on *FF*. It also shows a decrease of *FF* with the increasing of light intensity. The data of the second experiment are almost identical to the first one. This implies that the space charge in midgap defect states is so small that it causes insignificant changes in the electric field in the dark. In fact, we find that the midgap defect density must be as high as 1×10^{17} to reduce the fill factor below that in the standard cell for just AM1 illumination (J_{sc}=12 mA/cm^2) from the simulation.

We proposed that the decrease in *FF* is mainly caused by the space charge in the band-tail states. We hypothesized that if the cell has no band-tails, there is no light dependence of the fill factor. The third designed cell is the one without the midgap defects and band-tails. The third experiment is denoted by the # symbol. The results support our ideas. It really shows less dependence on light intensity than the standard cell. This indicates that most photogenerated space charge is trapped in the band-tails. On the other hand, there is a slight but significant illumination dependence of *FF* at high light intensity. We attribute this effect to the space charge of free carriers.

EXPERIMENTAL

Experimentally, we cannot easily measure the electric field in the i layer, but we can measure the effect of space charge using the well-established capacitance technique. We can measure the photocapacitance (C_{ph}) [4-6], which is a sensitive probe of the i-layer field distortion. It measures the response of space charge to the applied voltage. We measure capacitance in the dark and under illumination. We define the photocapacitance by subtracting the capacitance in the dark (C_{dk}) from its value in the light. In the following section, we address the photocapacitance theory first and then show the experimental results.

It is well known that any space charge has an associated capacitance [7]. There are two capacitances in the *p-i-n* configuration: one for electrons and one for holes. For simplicity, one can think of the total photocapacitance as the two capacitances added in series. Crandall modeled the photocapacitance previously [8,9]. The Regional Approximation was applied to solve the transport equations and analytical solutions could be obtained only for two extreme cases. If perturbation to the system is small, the photogenerated space charge is so small that the electric field is little changed from its dark value. In this case, C_{ph} is given by

$$C_{ph} = \frac{ed^3}{2(\mu_h + \mu_e)} \frac{G}{V^2}. \quad (1)$$

If the perturbation to the system is large enough that it determines the shape of the electric field, C_{ph} is given by

$$C_{ph} = c \frac{\mu_h^{0.75}}{\mu_e^{0.5}} \frac{G^{0.25}}{V^{0.5}}, \quad (2)$$

where *e* is the electron charge, *G* is the photogeneration rate, *V* is the applied voltage plus the built-in voltage, *d* is the sample thickness, μ_e is the electron drift mobility, μ_h is the hole drift mobility, and *c* is a constant. The beauty of having an analytical solution is that the relationship between the cause and effect is clearly presented. The theory predicts that at low light intensity, C_{ph} increases linearly with the generation rate and is reciprocal to the square of the applied voltage. At high light intensity, C_{ph} increases with a quarter power of the generation rate and is reciprocal to the square root of the applied voltage. Photocapacitance also depends on the drift mobility, but that is not the subject of this study. Unfortunately there is not an analytic expression to connect the two regimes.

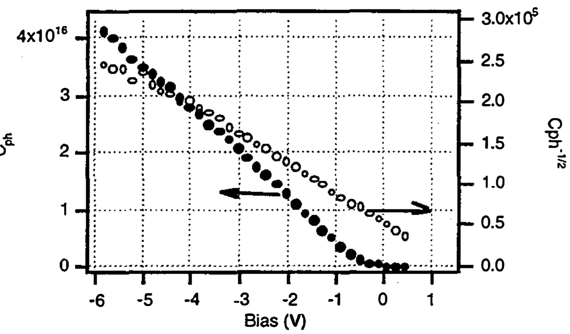


Figure 2. The voltage dependence of photocapacitance plotted as $C_{ph}^{-1/2}$ and C_{ph}^{-2} versus voltage. The sample has a *n-i-p* structure with i-layer thickness of 1.5 µm, and the measurement is done at room temperature with a modulation frequency of 10 kHz.

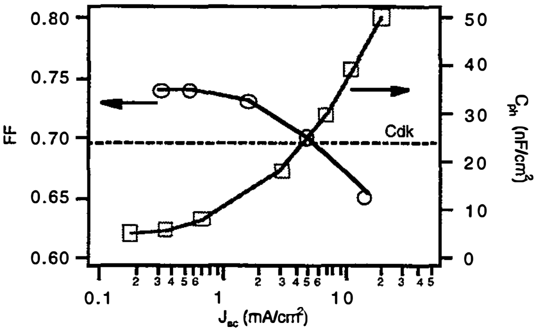


Figure 3. The light-intensity dependence of FF and photocapacitance in one sample. The sample has a *p-i-n* structure with i-layer thickness of 0.5 µm. The photocapacitance is measured at zero bias.

In Figure 2 we select two extreme cases to test the theory. The theory also works for the *n-i-p* structure sample. The sample has a nip structure and is deposited on a transparent conductive oxide (TCO) coated glass substrate with an i-layer thickness of 1.5 µm. We chose a thicker sample than the normal solar cell because it is more affected by the space charge. The open circles are the data measured at low red-light intensity. The ratio of C_{ph} to C_{dk} is about 4%, which is a small perturbation. We plot $C_{ph}^{-1/2}$ versus voltage using the right-hand axis. The linear relation is what we expected from Eq. (1). The solid circles are the data taken at high red-light intensity. The ratio of C_{ph} to C_{dk} is about 650% and the perturbation is large. We plot C_{ph}^{-2} versus voltage using the left-hand axis. It also shows a linear dependence on the voltage. The data support the theoretical prediction of the voltage dependence of C_{ph}. It is worth mentioning that C_{ph} can be greater than C_{dk} for moderate light intensity although an analytical solution is not available in that case.

DISCUSSION

In this section, we first discuss the qualitative explanation for the decrease of *FF* with increasing light intensity in a-Si:H solar cells. We use photocapacitance as an indicator of the electric-field distortion in the i layer. The larger is C_{ph}, the more field distortion. Then we discuss the effect of recombination on the *FF*.

In Figure 3, we plot the *FF* and C_{ph} measured at zero bias as a function of the short-circuit current measured in one sample. A current of 14 mA/cm^2 corresponds to AM1 light intensity. The sample has a structure of glass/TCO/p/i/n/Pd. The p-layer thickness is about 150 Å. The i-layer thickness is about 4500 Å, and the n-layer thickness is about 300 Å. The cell has an efficiency over 8 % in the as-grown state. We show the dark capacitance to indicate the thermal equilibrium condition. At low light, C_{ph} is only a small fraction of C_{dk}. This implies that at these light intensities, the system is near its equilibrium condition and the perturbation of the electric field is small. As the light intensity increases, C_{ph} increases and is comparable to C_{dk}. In this case, the perturbation is no longer small. At high light intensity, C_{ph} is many times larger than C_{dk}. In this case the perturbation is enormous. The electric field is near collapse.

This observation and interpretation agrees well with our idea that the decrease of electric field causes the decrease of *FF* with the increase of light intensity, as we see in Fig. 3. We interpret the small *FF* change at low light intensity as a result of a small perturbation of the electric field by photogenerated space charge. We explain the *FF* decrease at high light intensity as a result of a large perturbation of the field.

To conclude, we have studied the field collapse in a-Si:H *n-i-p* and *p-i-n* solar cells. The simulation shows that the decrease in fill factor is caused by photogenerated space charge trapped in the band-tail states rather than in defects. The photocapacitance measurement clearly demonstrates the effect of the photogenerated space charge. Photocapacitance theory in two extreme cases has been successfully tested on one sample at room temperature. We qualitatively explain the decrease of *FF* with increasing light intensity, using C_{ph} as a measure of electric-field distortion. We expect this technique will become a useful diagnostic tool for a-Si:H solar cells.

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