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Built-in Potential Measurements in a-Si:H p-i-n Solar Cells

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Abstract

We have measured the open-circuit voltage V_{oc} and the short-circuit current density J_{sc} of amorphous silicon (a-Si:H) p-i-n solar cells deposited by radio-frequency plasma-enhanced chemical vapor deposition (RF-PECVD) at different monochromatic illuminations, and temperatures. From the measurements, the built-in potential V_{bi} was determined by using two different methods: activation energy and differential temperature. The results from both methods were analyzed and compared as a function of excitation wavelength. It was observed that there is good agreement between the two methods. We found that V_{bi} increases until about 650 nm, and then decreases with increasing wavelength. This behaviour is explained and interpreted in different ways.

Key Words: 73.50.Pz; 72.80.Ng;/photovoltaic effects; amorphous thin films; built-in potentials.

1. Introduction

Hydrogenated amorphous silicon (a-Si:H) p-i-n solar cells have been extensively investigated for use as low-cost solar cells [1]. Practical use of a-Si:H p-i-n solar cells as an electric power source requires improvements in collection efficiency and stability.

The internal or built-in potential (V_{bi}) across a solar cell is usually described as an upper limit to the open-circuit voltage (V_{oc}) of the cell under illumination. It is originating

*Present address: Physics Department, University of Mersin, 33342 Mersin, Turkey from the Fermi energy difference between p- and n-layers. For amorphous silicon based p-i-n solar cells incorporating wide bandgap intrinsic layers it has recently been proposed that this limitation has in fact been reached for some device designs [2]. However, there is currently no consensus among amorphous silicon researchers regarding either the values for V_{bi} or procedures for measuring this parameter.

In this work, we measure the built-in potential of a-Si:H p-i-n solar cells under short-circuit and open-circuit conditions. This measurement gives important information about charge carrier collection due to the maximum field and its spatial distribution by V_{bi}.

1. Experimental

The standard a-Si:H p-i-n solar cells were deposited by radio-frequency (13.56 MHz) plasma-enhancement chemical vapour deposition (RF-PECVD) on 7059 glass substrate coated with transparent conducting oxide. The i-layers were prepared by decomposition of pure silane at $P_R = 40mT$orr (gas pressure), $P_{RF} = 5mW/cm^2$ (radio-frequency power) and $T_s = 250°$C (substrate temperature). The structure was $glass/SnO_2/$**p**(a $- SiC : H)/$**buffer**(a $- Si : H)/$**i**(a $- Si : H)/$**buffer**(a $- Si : H)/$**n**(a $- Si : H)/Cr$, with light incident from the p side of the cell. For electrical measurements, copper wire contacts were made on the p- and n-layers with electrically conductive silver paint. The thickness of the i-layer was 2.2μm. The optical band gap (or Tauc gap) E_g was 1.7 eV. The doped-Fermi energy levels were $E_{fv} = 0.3\ eV$ and $E_{fc} = 0.2\ eV$ for p- and n-layers, respectively. Further details concerning the deposition conditions have been given elsewhere [3].

Basically, the experimental set-up includes an optical excitation (tungsten halogen lamp, Oriel Corporation, Model 6140-1), a monochromator (M25), a liquid nitrogen cryostat (Oxford 102 series), rotary (Elnor, Type 350 C) and diffusion (Alcatel) pumps, a programmable temperature controller unit (ITC 502 Oxford: Intelligent Temperature Controller), optical fiber cables, an amplifier (S6) and a photodiode, a Keithley 617 electrometer (programmable in both current and voltage modes) and microcomputers (IBM PC). They are combined suitably to measure the short-circuit current density J_{sc} and the open-circuit voltage V_{oc} of the solar cell as a function of excitation intensity and wavelength, and temperature. The cell under study was placed in a cryostat which allowed us to set the required temperature between 90 K and 500 K. The light beam from the excitation source was passed through the monochromator, which had two adjustable slits (entrance and exit) to vary the light flux. The light flux was measured by a photodiode placed at the exit of the monochromator. The electrical measurements were carried out with a Keithley 617 electrometer. Most of the experiments were made and controlled automatically by programs written in quick basic. Further details and measurements concerning the experimental set-up have been given elsewhere [4].

2. Analysis and Results

There have been several methods described to measure the built-in potential of standard a-S:H p-i-n solar cells. One approach to estimate V_{bi} is the electroabsorption technique developed by a Osaka University group [5]. Another attractive method to determine V_{bi} is the differential temperature method (DTM) developed by Hegedus et al. [6]. In this work we have followed this last method to find V_{bi} under monochromatic very low illumination levels. The DTM method does not assume that V_{bi} is independent of intensity wavelength or temperature. Therefore it can be used to investigate the effects of these experimental variables on V_{bi}. The method requires data at a relatively few temperatures, but also assumes linearity in $V_{oc} - T$ (temperature) over a limited range rather than all the way to $T = 0$. Moreover, the method accounts for any temperature-dependence of the a-Si:H p-i-n diode (solar cell) quality factor A_L rather than assuming a single, unique value of A_L can be used.

Hegedus et al. [6, 7] empirically demonstrated the applicability of the standard functional form of the illuminated diode forward current-voltage relation,

$$J_f = J_{OL} \exp\left[(qV)/(A_L kT)\right] \tag{1}$$

and

$$V_{oc} = (A_L kT/q) \ln(J_{sc}/J_{OL}). \tag{2}$$

where A_L is the diode factor and J_{OL} is the saturation current in light. Equation (2) assumes superposition, which is likely not to strictly apply in a-Si:H p-i-n cells due to the space-charge trapping and field dependence of the light generated current. Series and shunt resistance is also neglected. However, Hegedus et al. [6] found that equations (1) and (2) provided a good description of these devices by finding close agreement between measured and calculated V_{oc} values. Based on the temperature dependence of J_{OL}, A_L, and V_{oc}, they proposed that the forward diode in the illuminated a-Si:H p-i-n solar cell was controlled by recombination at or very near the interfaces with the p-i junction recombination dominant. Bulk recombination does not appear to be significant.

In the light of the above assumptions, Hegedus et al. [6] adopted a form of J_{OL} appropriate for interface recombination

$$J_{OL} = J_{oo} \exp\left[-(qV_{bi})/(kT)\right]. \tag{3}$$

Here it is assumed that J_{OL} is composed of the sum of interface recombination currents at both p-i and i-n junctions. Also it should be noted that details of the form J_{oo} are irrelevant to both the $\ln(J_{sc}) - V_{oc}$ and $V_{oc} - T$ calculations to obtain V_{bi} so long as J_{oo} is nearly temperature independent. Equation (3) assumes a built-in voltage exists at each junction (p-i and i-n). The total V_{bi} is the sum of values from each junction, consistent with the series connected double junction model [8] as well as photovoltage profiling experiments [9].

Figure 1 shows the measured J_{sc} and V_{oc} of a-Si:H p-i-n solar cell (illuminated through the p-layer) at several temperatures between 274 K and 364 K at low intensities (640 nm) from about 10^{16} to 10^{12} photons $\cdot$ $\mathrm{cm}^{-2}\cdot$ sec^{-1} at each temperature. From equation (2), J_{OL} and A_L are calculated from the intercept and slope, respectively, of the $\ln J_{sc} - V_{oc}$ data. Figure 2 shows the diode (cell) factor under illumination (A_L) as a function of temperature. Conventional diode analyses assume A or A_L to be independent of temperature. We account for this behaviour explicitly in the DTM method derived later.

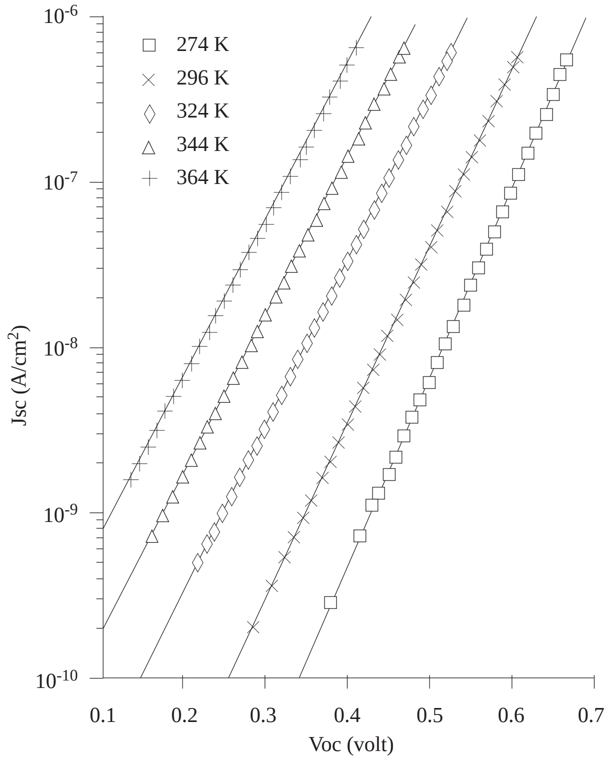

Figure 1. $J_{sc} - V_{oc}$ for a-Si:H p-i-n solar cell illuminated (640 nm) through p-layer at several temperatures.

Figure 3 shows an activation energy plot of J_{OL} for a-Si:H p-i-n solar cell. Here, using equation (3), we found $V_{bi} = 0.84$ volt.

We now derive the DTM method to obtain V_{bi} from $J_{sc} - V_{oc} - T - F(light - flux) - data$. Combining equations (2) and (3) gives

$$V_{oc} = (A_L kT/q)\ln(J_{sc}/J_{oo}) + A_L V_{bi}. \tag{4}$$

Equation (4) can be written as

$$V_{bi} = V_{oc}(T)/A_L(T) - (kT/q \times constant) \tag{5}$$

which explicitly recognizes the temperature dependence of A_L as shown in Figure 2. The constant term in equation (5) is negative since J_{sc} is less than J_{oo}. This allows V_{bi} to be determined from $J_{sc} - V_{oc}$ measurements at just 2 temperatures as

$$V_{bi} = \frac{V_{oc}(T_1)}{A_L(T_1)}\left[\frac{T_2}{(T_2 - T_1)}\right] - \frac{V_{oc}(T_2)}{A_L(T_2)}\left[\frac{T_1}{(T_2 - T_1)}\right], \tag{6}$$

where $A_L(T)$ is found from $\ln J_{sc} - V_{oc}$ relation at a given T, as shown in Figure 2. Equation (6) is called the differential temperature method (DTM). It only requires that A_L can be calculated from $\ln J_{sc} - V_{oc}$ and that V_{oc} is proportional to T over the range of T measured, not beyond.

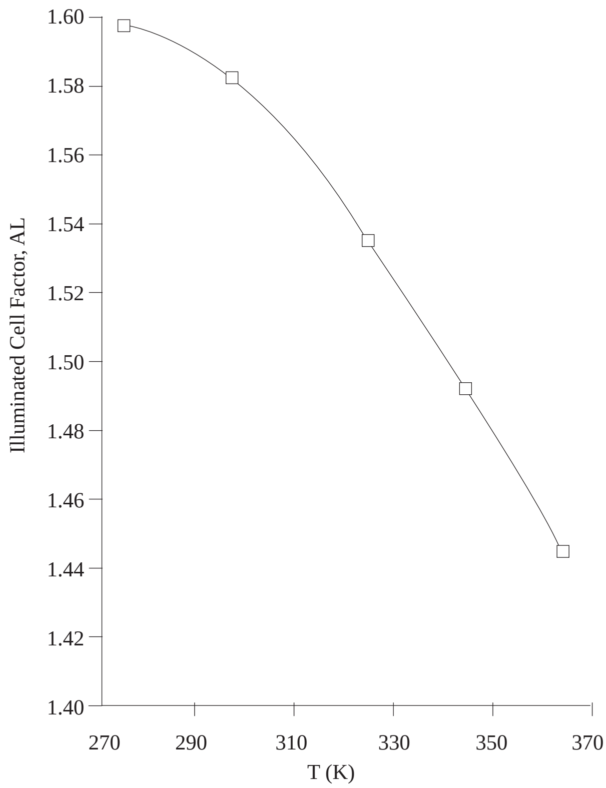

Figure 2. Illuminated (640 nm) diode (cell) factor as a function of temperature. The solid line serves as guides to the eyes.

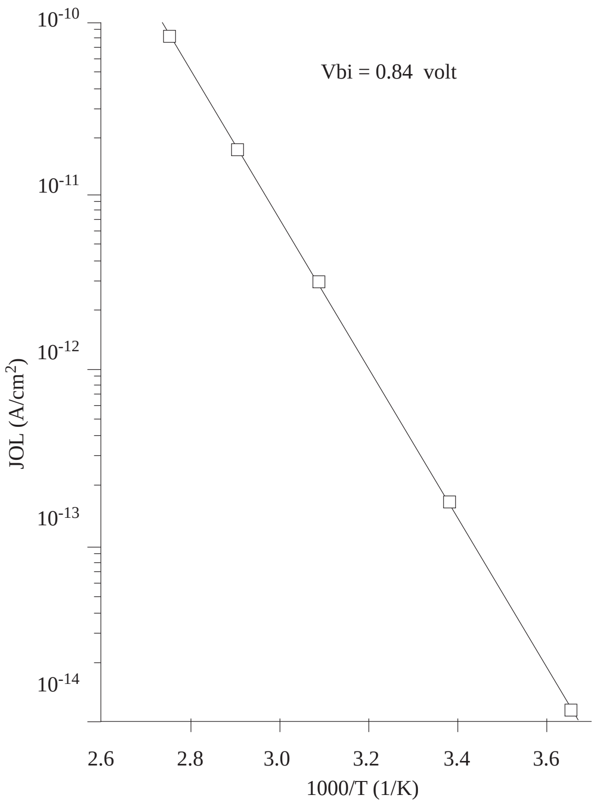

Figure 3. V_{bi} from activation energy of J_{OL}. $\lambda = 640$ nm.

Figure 4 shows the results of applying Equation (6) to data from a-Si:H p-i-n solar cell. For each pair of temperatures (T_1 and T_2) and A_L factors (A_{L1} and A_{L2}), V_{bi} is calculated from V_{oc1} and V_{oc2} at several intensities. As can be seen, V_{bi} is almost independent of intensity, and only weakly dependent on the choice of temperatures T_1 and T_2.

In our data analysis, we used the curve-fitting and statistical analysis features of "Kaleida Graph" application for Macintosh. The V_{bi} values obtained from many temperature couples (see Figure 4, in DTM method) were averaged. In Figure 5, we compared these averaged V_{bi} values with those of $\ln J_{OL} - 1/T$ method (activation energy plot) for many wavelengths. Here, first, we find the agreement between the two methods to be excellent. Values from both methods have error bars of at least ± 20 mV, especially since the DTM value is the average over a range of intensity giving a similar range in values. The values differ by about 10-15 mV, which is $1 - 2\%$, and they have identical trends. This is really very good agreement and confirmation of the two methods.

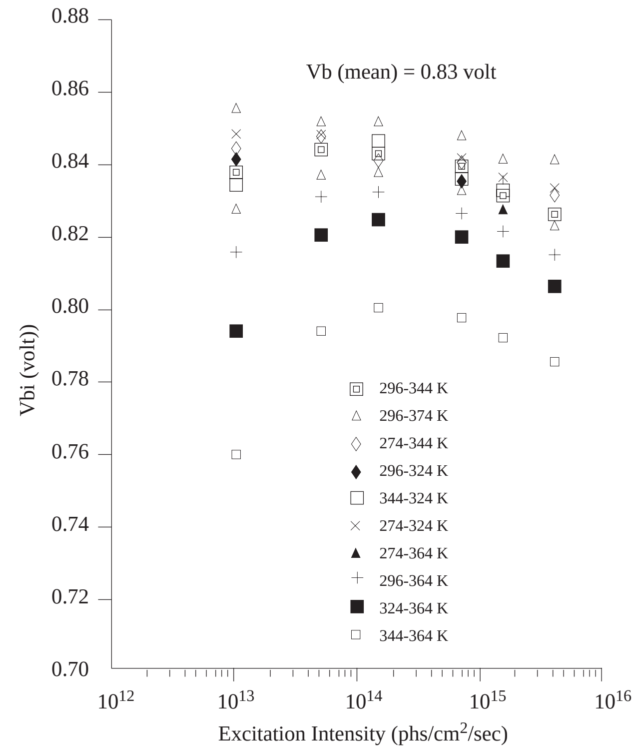

Figure 4. V_{bi} versus excitation intensity (640 nm) for several temperature-couples.

Second, the behaviour of peaking then decresing beyond 650 nm could have several interpretations. At short wavelengths, the photocarriers are generated in the p-i junction region, and hence see its potential difference. As the light penetrates deeper, it begins to excite carriers at the back of the n-i junction, which is much smaller and probably only contributes $< 0.1V$ to V_{bi}. This would explain the increase. Similar small increases in V_{bi} have been seen with electroabsorption [10] but have been attributed to totally different mechanisms (the ac field varying in the p-layer). But one must remember that measurements at short wavelengths on devices with such very thick i-layers (2.2 μm) are very difficult to interpret since most of the i-layer is in the dark. We are not measuring a bulk i-layer property. Severe distortion of the field can result.

The decrease beyond 650 nm might be due to reduced absorption throughout the i-layer, pushing the quasi-fermi levels back closer to mid-gap. However, this does not agree with data shown in Figure 4 where V_{bi} decreases with increasing intensity. Another possibility is that generation and transport path change as sub-bandgap light is used. Carriers are increasingly trapped in bandtail states then percolate up to the extended conduction states. This will effectively lower the energy needed to excite a carrier, effectively reducing V_{bi}. But this is not easy to show. So we do not have a good, clear, well-supported explanation of the decrease beyond 650 nm.

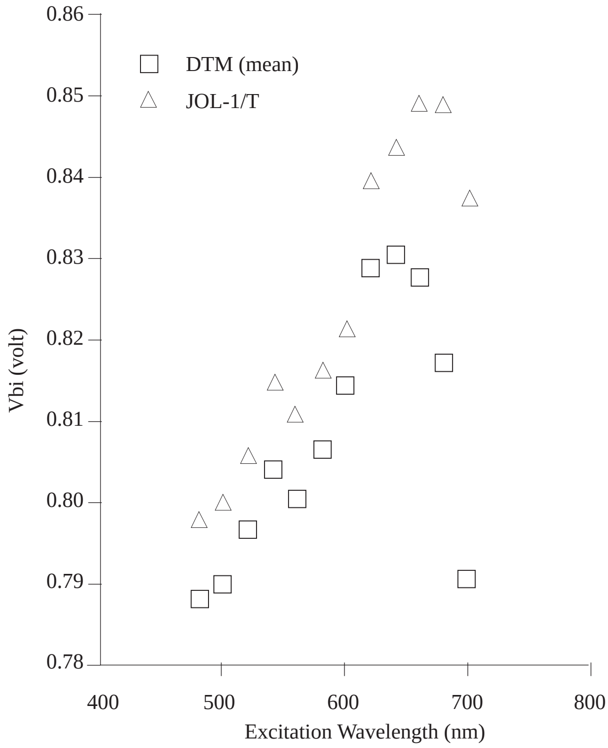

Figure 5. V_{bi} versus wavelength, calculated from $J_{OL} - 1/T$ and differential temperature methods.

3. Conclusion

We have estimated V_{bi} using two methods: $J_{OL} - 1/T$ and differential temperature. These methods are based on a simple interface recombination model for the forward diode current under illumination. The differential temperature method is easy to implement requiring J_{sc} and V_{oc} measurements at a few temperatures and intensities. We found very good agreement and confirmation between the two methods. In both methods, the V_{bi} behavior has almost identical trends in wavelength. There is a peak (maximum) at around 650 nm. At short wavelengths (below 650 nm), the photocarriers are generated in p-i junction region, and hence there is a potential difference. As the light penetrates deeper, it begins to excite carriers at the back n-i junction, which is much smaller and probably only contributes very small amount ($< 0.1V$) to V_{bi}. This would explain the increase. Above 650 nm, the decrease in V_{bi} might be due to reduced absorption throughout the i-layer, pushing the quasi-fermi levels back closer to mid-gap. However, we found that this does not agree with other data in which V_{bi} decreases with incresing intensity. Another possibility is that generation and transport path change as sub-bandgap light is used. Carriers are increasingly trapped in bandtail states then percolate up to the extended conduction states. This will effectively lower the energy needed to excite a carrier, effectively reducing V_{bi}.

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