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INVESTIGATION OF HETERO-INTERFACE AND JUNCTION PROPERTIES IN SILICON HETEROJUNCTION SOLAR CELLS

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ABSTRACT

The amorphous silicon (a-Si:H) – crystalline silicon (c-Si) heterojunction (SHJ) solar cell fill factor (FF) is very sensitive to the properties of c-Si surface, process parameters of thin a-Si:H layers, properties of transparent conducting front electrode, and all of their interfaces. In this work, quality of hetero-interface and junction properties in n-type SHJ solar cells were investigated by; (i) suns V_{OC} under white, blue, and infrared light; (ii) dark and light JV; and (iii) quantum efficiency (QE) with and without voltage and light bias. Analysis of all these measurements suggest an anomalous “S” shape JV curve can arise due to at least two separate reasons; (a) existence of a large barrier for hole transport with excellent front surface passivation, and (b) existence of an opposing diode/Schottky barrier in the hetero emitter side of a SHJ solar cell. Both of the above-mentioned interface and/or junction properties severely affect minority carrier collection in SHJ cells.

INTRODUCTION

Silicon heterojunction (SHJ) structures using low temperature deposited amorphous silicon (a-Si:H) have demonstrated high open circuit voltage (V_{OC}) and efficiency in crystalline silicon (c-Si) solar cells [1]. The increase in V_{OC} is achieved by reducing surface recombination and emitter saturation currents using a thin intrinsic a-Si:H passivation layer (i-layer) on both surfaces of c-Si wafer. Furthermore, SHJ in an interdigitated back contact (IBC) structure combines the potential of high V_{OC} with improved short circuit currents (J_{SC}) of a rear junction back contact solar cell due to reduced optical losses [2]. Despite the progress towards high efficiency values, the device physics and the carrier transport mechanism are poorly understood in part due to the extreme complexity and surface / interface sensitivity in SHJ structures. The complexity arises from presence of numerous thin (5 – 10 nm) a-Si:H layers, transparent conductive oxides in the front, rear metal contacts and all of their interfaces. Therefore, both SHJ and IBC-SHJ solar cells often exhibit a low fill factor (FF) with an anomalous current density – voltage (JV) curve, “S” shape, under illumination due to poor carrier transport. In this work, we have investigated the hetero-interface and junction properties in SHJ solar cells by analysis of illuminated and dark JV, quantum efficiency (QE) under different voltage and light biases and Sinton suns V_{OC} tester with white and filtered lights.

EXPERIMENTAL

The front junction SHJ solar cells were fabricated on 150 μm thick polished n-type c-Si (100) float zone (FZ) wafers with high bulk lifetime (> 5 msec) and resistivity of 2.0 Ω.cm. The details of the solar cell fabrication process are described elsewhere [3]. The structure of SHJ solar cells was ITO / p.a-Si:H / i.a-Si:H / n.c-Si / i.a-Si:H / n.a-Si:H / Al. All the SHJ solar cells thus fabricated can be broadly categorized into three different groups from their dark and light JV performances; a) cells with good FF (>75%), b) Type I “S” shape, and c) Type II “S” shape. The representative dark JV curves of these three types of solar cells are shown in Figure 1. The figure clearly distinguishes Type I and Type II “S” shape cells from the others with the good FF. The variation in FF is caused by changing process parameters of a-Si:H layers and their interfaces as reported elsewhere [4, 5]. Such SHJ solar cells were characterized by two complimentary techniques. The suns V_{OC} measurement predicts series-resistance-free pseudo JV and FF, which is an excellent measure of diode quality determined by shunt and junction recombination. Additionally, illumination by blue (< 580 nm) and infrared (> 780 nm) filtered light was used to identify front surface and bulk plus rear surface properties, respectively, in SHJ solar cells. The QE measurement was performed under different voltage and light bias to comprehend the carrier collection losses.

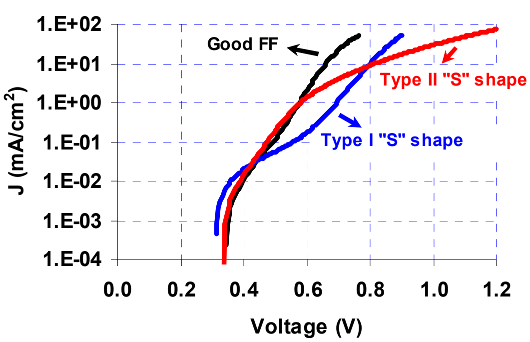

Figure 1: Dark JV curves of three types of SHJ solar cells, one with good FF and the other two with different types of “S” shape light JV curve.

RESULTS AND DISCUSSIONS

Figure 2 shows a schematic of SHJ solar cell investigated in this work. Figure 3 shows an equilibrium band diagram of such solar cells simulated by AFORS-HET [6]. In simulation, the input parameters for a-Si:H layers and ITO film were chosen as reported in literature [2,7]. The simulated band diagram exhibits an induced p-n junction diode with a type conversion at the c-Si surface (i.e., n-type wafer converted to p-type at the surface due to band alignment). A space charge region extends 200 – 500 nm deep into the c-Si wafer. Therefore, recombination in the space charge region is expected to be very low due to high quality wafer and absence of any extrinsic impurities, such as dopant diffusion in a diffused junction solar cell. However, the minority carrier, hole, needs to tunnel through the a-Si:H layers to be collected as described by Kanevce et al. [6]. The properties of a-Si:H layers and their interfaces will affect the carrier collection and hence the solar cell FF.

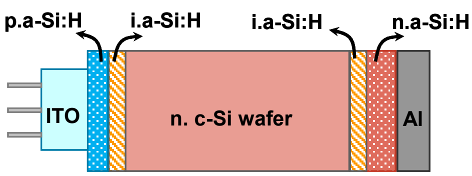

Figure 2: Schematic of SHJ solar cell on n-type c-Si wafer.

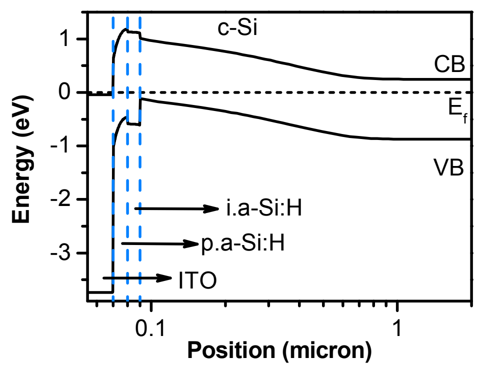

Figure 3: Equilibrium band diagram of SHJ solar cell at hetero-emitter side on n-type wafer simulated by AFORS-HET. The x-axis is plotted in logarithmic scale to emphasize the junction.

Suns V_{OC} and ideality factors

The suns V_{OC} is a well-established and widely adopted technique to characterize the junction quality in c-Si diffused homojunction solar cells and to predict efficiency and FF without the effect of series resistance [8]. Furthermore, comparison of front and back illumination or a blue and infrared illumination allows identification of a limiting recombination mechanism in the device [8, 9]. However, only limited efforts have been reported to characterize SHJ solar cells in detail using a suns V_{OC} technique [10]. Figure 4 shows the V_{OC} and ideality factor, n, at 1 sun white light illumination from suns V_{OC} measurements and plotted against the measured V_{OC} from standard light JV for a number of SHJ solar cells both with and without the i-layer passivation of the c-Si surface. The figure clearly demonstrates accuracy and effectiveness of V_{OC} estimation from suns V_{OC} measurements in SHJ solar cells. Page et al. have also reported such excellent correlation between suns V_{OC} and measured V_{OC} from light JV [10].

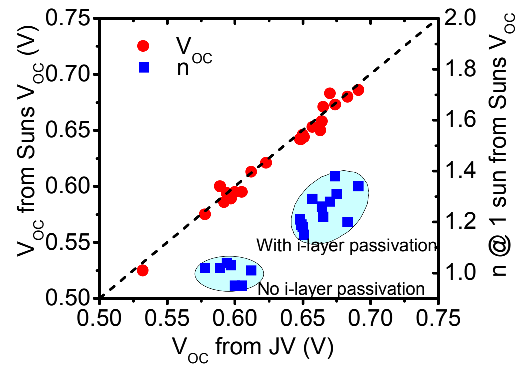

Figure 4: The V_{OC} (circles) and ideality factor (squares) of SHJ solar cells at 1 sun white light illumination as obtained from suns V_{OC} curve is plotted against the measured V_{OC} from light JV.

The ideality factor, n, at 1 sun illumination estimated from suns V_{OC} curve is close to unity (n = 1.0) for all SHJ solar cells with no i-layer passivation. However, the cells with i-layer passivation exhibit higher n-values and appear to have an increasing trend with increase of V_{OC} as shown in Figure 4. Such a variation of n-values can be explained by neglecting bulk recombination in the solar cell, which is a realistic assumption since bulk lifetime of minority carrier in the FZ wafers were over 5 msec. Suns V_{OC} curve will then be determined by surface recombination that is best represented by front and back surface saturation current densities (J_{0front} and J_{0back}) as described by Cuevas et al. [9]. The SHJ solar cell without any i-layer passivation is limited by the surface recombination in the front emitter side of the solar cell. The emitter layer p.a-Si:H was found to have poorer passivation quality than n.a-Si:H layers on n-type wafer [11]. Therefore, most recombination will occur at the front surface with a negligible diffusion of photogenerated carriers towards the rear. The V_{OC} will then be written as [9],

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{sunsJ_{ph}}{J_{0\,front}}\right) \tag{1}$$

Where, kT/q is the thermal voltage and J_{ph} is the photogenerated current density. The expression in equation 1 represents a constant ideality factor, n = 1. However, when the front c-Si surface is passivated by i-layer, the photogenerated carriers will diffuse towards rear and the expression for V_{OC} will include a diffusion term as described by Cuevas et al. [8];

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{sunsJ_{ph}}{J_{0back}} + sunsJ_{ph} \frac{W}{qn_i D} \sqrt{\frac{sunsJ_{ph}}{J_{0back}}} \right) \qquad (2)$$

Where, W is the cell thickness, n_i is the intrinsic carrier concentration of the wafer and D is the minority carrier diffusion coefficient. This additional diffusion term will lead to an increasingly higher V_{OC} than an ideal case with increase of light intensity and result in n > 1.

Suns V_{OC} of different types of SHJ solar cells

Figure 5(a) compares the light JV measured under standard conditions and pseudo JV curve obtained from suns V_{OC} measurements for a good FF cell. A higher pseudo FF predicted from suns V_{OC} is due to the absence of series resistance factor. Figure 5(b) shows the suns V_{OC} curve under white, blue and infrared light. The V_{OC} with blue light is about 10 mV lower than the white and red illumination, which suggests about 40 – 50% of blue light loss in test cell compared to the reference cell. The absorption loss in a-Si:H layers [12] coupled with a possible difference in reflectance between test and reference cell accounts for such a lower V_{OC} under blue light. An identical ideality factor (n) is obtained from the slope for all light spectra indicating a uniform surface passivation in both front and back surface.

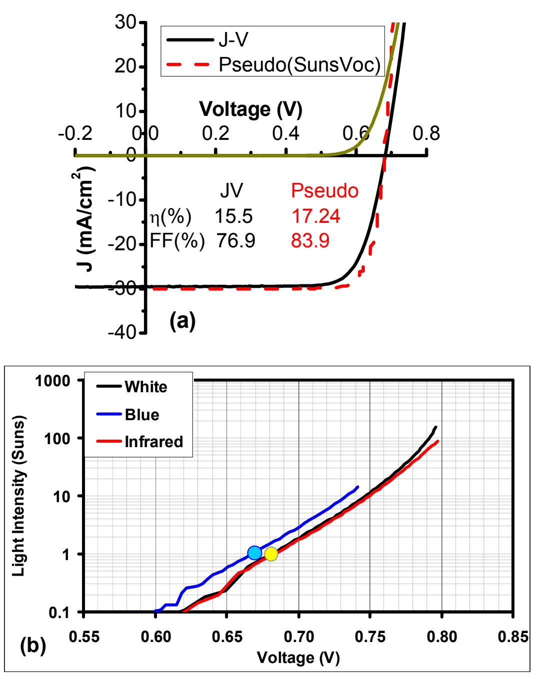

Figure 5: (a) Comparison of light JV and pseudo JV predicted from suns V_{OC}, and (b) Suns V_{OC} curve with white, blue, and infrared light.

Figures 6(a) and (b) are the corresponding light JV and suns V_{OC} curves for the Type I "S" shape solar cells. Here, it is clearly seen that the predicted pseudo JV curve from suns V_{OC} does not match the "S" shape light JV curve in Figure 6(a). In fact, the pseudo JV curve is identical to the solar cell with good FF shown in Figure 5(a). The suns V_{OC} curve in Figure 6(b), however, shows a strong spectral dependence. Much higher V_{OC} with blue light (700 mV) compared to white or red light (< 650 mV) indicates a good front surface passivation and low J_{0front}. Low V_{OC} under infrared light suggests that the suns V_{OC} curve is dominated by the recombination at the rear surface. Hence the carriers generated near the front surface must diffuse and recombine towards the rear surface, which will result in high n-values due to an additional diffusion current as described by equation (2). Differences between the JV and pseudo JV curve from suns V_{OC} may arise due to existence of a large barrier for holes in the front, such as increased valence band offset, by an unoptimized i.a-Si:H passivation layer that prevents them from tunneling through and reach the ITO contacts. The dark JV curve in Figure 1 shows identical characteristics with a good FF cell at a forward bias > 0.6 V, which implies carrier injection is not affected due to any non-ohmic behavior in the cell. However, the carrier collection under light is severely affected at a forward bias > 0.2 V [Figure 6(a)].

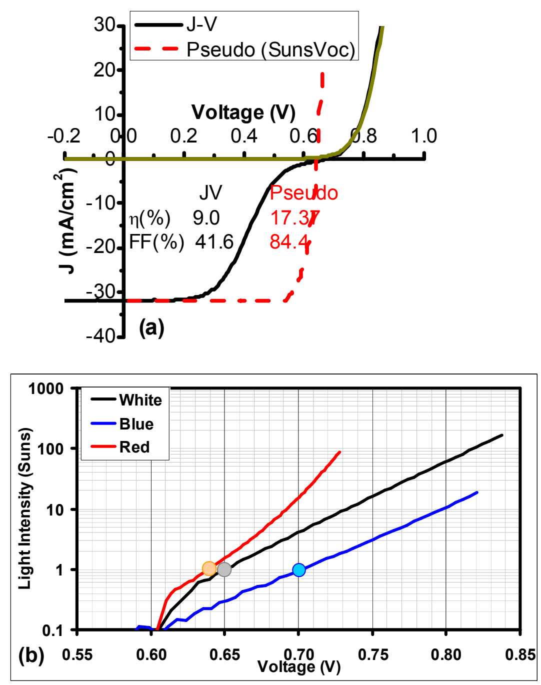

Figure 6: (a) Comparison of light JV (Type I "S" shape) and pseudo JV predicted from suns V_{OC}, and (b) Suns V_{OC} curve with white, blue, and infra-red light of Type I "S" shape cell.

Figure 7(a) and (b) are the corresponding light JV and suns V_{OC} curves for the Type II "S" shape cells. Similar to the Type I "S" shape cells, the pseudo JV curve predicted from suns V_{OC} appears to be identical to the solar cell with good FF as shown in Figure 5(a). The suns V_{OC} curves under different filtered lights, however, are very different than that of cells with good FF and Type I “S” shape cells. The curves at low light intensity seem similar to the cell with good FF, but the curves tend to bend back under white and blue light illumination at high intensities (>10 suns). This effect leads to anomalous negative n-values at high light intensities. Such negative n-values are expected to arise from an opposing diode or Schottky barrier as can be seen in homojunction cells with poor back metal contacts [8, 13]. For Type II “S” shape devices as in Figure 7(b), it appears that the opposing diode is in front of the cell, since the high blue light intensity enhances the effect of the opposing diode, while infrared illumination does not result in negative n-values even at 100 suns intensity. The opposing diode can arise due to a Schottky junction between p-type doped a-Si:H and n-type degenerate ITO layers under an unoptimal condition such as lower effective doping density [4] and/or thinner p-type doped a-Si:H or by reduced work function of ITO as described by numerical simulation of n-type SHJ solar cells [7]. Our recent work elucidates that a non-ideal p.a-Si:H / i.a-Si:H interface can also lead to such non-ohmic contact in the front side, and a simple modification of that interface in SHJ solar cell eliminates the blocking junction and leads to FF > 75% [5]. Such an opposing Schottky junction affects carrier injection in both dark and light JV curve under forward bias as shown in Figure 1 and Figure 7(a). This is distinguished difference between Type I and II.

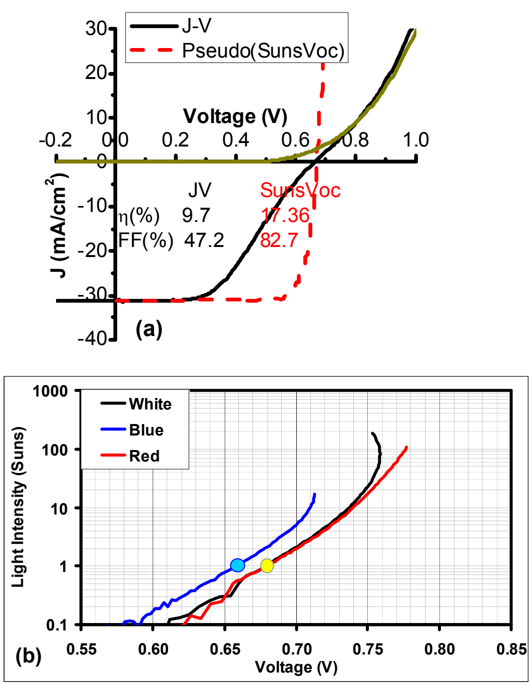

Figure 7: (a) Comparison of light JV (Type II “S” shape) and pseudo JV predicted from Suns V_{OC}, and (b) Suns V_{OC} curve with white, blue, and infra-red light of Type II “S” shape cell.

Quantum efficiency and collection losses

The ratio of QE at +0.45V to the 0V bias [QE(0.45V / 0V)] is indicative of carrier collection losses under forward bias in the device. Typically, c-Si solar cells do not suffer voltage dependent collection losses since collection is by diffusion not drift. The QE ratio of above mentioned three types of SHJ solar cells are characterized under dark and white light bias conditions and are plotted in Figure 8. For good FF (>75%) cells, this QE ratio is almost unity with or without light bias, indicating no loss of carrier collection as expected for an ideal Si solar cell. The Type I “S” shape cells have a very low QE ratio in the dark that slightly improves with light bias. The excess carrier generated by bias light may enhance hole tunneling across a large barrier in the front emitter side, the presence of this barrier was proposed from suns V_{OC} curve (Figure 6). The excess carriers may also change the space charge density hence field profile at the interface. However, Type II “S” shape cells exhibit a strong decrease in QE ratio under light bias compared to the dark. This result can be explained by the existence of an opposing diode at either ITO / p.a-Si:H or p.a-Si:H / i.a-Si:H interface, which inhibits photocurrent collection. In the dark, its presence reduces the forward injected current as seen in Fig. 1. In the light, its photoresponse reduces both V_{OC} and current collection. This effect becomes more pronounced with blue light due to even higher generation in the p-layer. It is important to note that the QE bias ratios in Figure 8 for Type I and II cells are essentially wavelength independent, confirming that the loss is due to an interfacial, not bulk collection effect.

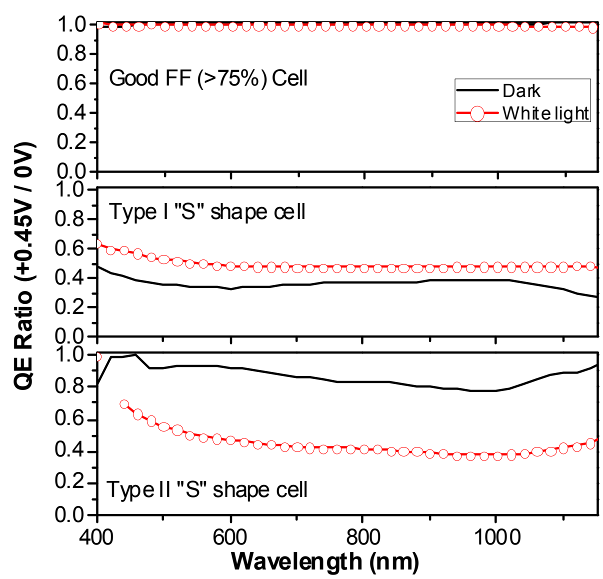

Figure 8: The quantum efficiency ratio at +0.45V to 0V bias [QE ratio (+0.45V/0V)] under dark and white light bias as a function of photon wavelength for three types of SHJ solar cells.

CONCLUSION

The hetero-interface and junction quality in SHJ solar cells are investigated by suns V_{OC} under different spectral illumination and by quantum efficiency measurements with and without voltage and light biases. The V_{OC} values at 1 sun white light illumination obtained from suns V_{OC} measurements correlate well with the measured V_{OC} from JV curve. The SHJ solar cell with good FF (77%) behaves as a normal diode with similar front and back surface passivation quality, which determines V_{OC}. The QE and dark JV exhibit uninhibited carrier transport in the solar cell. For cells with the “S” shape curve, there are two reasons that result in a low FF. In one case, existence of a large barrier for hole transport with excellent front surface passivation is hypothesized from spectral dependent suns V_{OC} curve. In the second case, existence of an opposing diode/Schottky barrier in the front emitter contact is evident from a negative ideality factor at high light intensity observed in suns V_{OC} measurements. Both of the above interface and/or junction properties will severely affect minority carrier collection in SHJ cells and their effect is consistently observed in voltage and light bias dependent QE results. The distinct feature between the two types of solar cells is, in the first case, only the carrier collection under light (but not the injection in dark) is affected at a forward bias and in the second case, carrier injection in both light and dark exhibits aberrant behaviors.

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