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EFFECT OF LIGHT INTENSITY ON PERFORMANCE OF SILICON-BASED THIN FILM SOLAR CELLS

Ihsanul Afdi Yunaz[1], Shunsuke Kasashima[1], Sorapong Inthisang[1], Taweewat Krajangsang[1], Shinsuke Miyajima[1], Akira Yamada[1,2], and Makoto Konagai[1,2]

[1]Department of Physical Electronics, Tokyo Institute of Technology
[2]Photovoltaics Research Center (PVREC), Tokyo Institute of Technology
2-12-1-S9-9, O-okayama, Meguro-ku, Tokyo 152-8552, Japan

ABSTRACT

Theoretical and experimental studies were performed to explore the effect of light intensity on the performance of silicon-based thin film solar cells. The theoretical study was conducted using AMPS-1D (Analysis of Microelectronic and Photonic Structures) to analyze how the device structure affects the performance of silicon-based solar cells under various concentration ratios of sunlight. We calculated a-Si:H and μc-Si:H p-i-n type single-junction solar cells, and also experimentally evaluated a-Si:H, a-SiO:H and μc-Si:H solar cells. From both simulation and measurement results, we confirmed that the V_{oc} logarithmically increases with increasing the light intensity. Moreover, from simulation results, we also observed that the defect density and thickness of i-layer strongly influence the light-intensity dependence of a-Si:H solar cells.

INTRODUCTION

Silicon-based thin film solar cells are attractive candidates for further cost-reduction of solar cells. However, a remarkable efficiency improvement is urgently required for a wider practical use. It is widely known that a multi junction structure has to be employed in order to obtain much higher efficiency.

Meanwhile, it is also well considered that a concentrator solar cell is another promising approach to enhance the conversion efficiency. In concentrator solar cells, the photocurrent linearly increases with increasing the concentration ratio of incident light. At the same time, the open-circuit voltage (V_{oc}) of solar cells increases logarithmically with the photocurrent. This leads to an increase in efficiency with increasing the sunlight intensity. In GaAs based concentrator solar cells, for example, a very high efficiency of 40.8% has been reported [1].

Therefore, it is clear that silicon-based thin film solar cells with an ultra high efficiency can be realized by employing a combination of multi-junction structure and concentration of sunlight. However, there have been only a few reports on silicon-based thin film concentrator solar cells. Also, the performance of these type of solar cells under various sunlight concentrations has not been well studied. For those reasons, as a first step for the development of silicon-based thin film concentrator solar cells, we performed both theoretical and experimental studies to investigate the effect of light intensity on the photovoltaic performance of various single-junction silicon-based thin film solar cells.

SIMULATION MODEL

The theoretical study was conducted using AMPS-1D (Analysis of Microelectronic and Photonic Structures), a one-dimensional device simulator [2] to explore, for the first time, how the device structure affects the performance of silicon-based solar cells under various concentration ratios of sunlight. We calculated two types of standard single-junction p-i-n solar cells, hydrogenated amorphous silicon (a-Si:H) and hydrogenated microcrystalline silicon (μc-Si:H) solar cells. The main parameters used in the simulation were general parameters based on various measurement results and references [3-5].

In order to analyze the light-intensity dependence of the solar cells, the concentration ratio of sunlight was varied from 0.01 to 50 sun. In the case of a-Si:H solar cells, we also varied the defect density of i-layer from $2x10^{15}$ to $5x10^{16}$ cm^{-3}, and the thickness of i-layer from 200 to 400 nm.

EXPERIMENTAL DETAILS

For comparison to the simulation results, we then systematically measured the photovoltaic performance of several silicon-based thin film solar cells under various sunlight concentrations. We evaluated three types of standard p-i-n single-junction solar cells. These solar cells were a-Si:H (1.75 eV, 300 nm), a-SiO:H (1.9 eV, 120 nm), and μc-Si:H (1.1 eV, 1.0 μm) solar cells. All of these cells were fabricated on the SnO_2:F coated glass (Asahi U-Type glass) substrates. The i-layer of each solar cell was deposited using a standard 60 MHz VHF-PECVD technique. The photo J-V characteristics for the fabricated cells were measured under AM 1.5 illumination with various light intensities. The light concentration was controlled by using a combination of an optical lens and various Neutral Density (ND) filters.

SIMULATION RESULTS

Comparison of a-Si:H and μc-Si:H Solar Cells

First, the effect of light intensity on the photovoltaic performance of a-Si:H and μc-Si:H single-junction solar cells was examined. Here, the thickness and the defect density of i-layer for a-Si:H cell were 400 nm and 1×10^{16} cm^{-3}, respectively. The thickness and defect density of i-layer for μc-Si:H cell was 1.5 μm and 1×10^{15} cm^{-3}, respectively. Fig. 1 shows the calculated photovoltaic (PV) parameters of both solar cells as a function of light intensity. It should be noted that the values of short-circuit current (J_{sc}) given in Fig. 1 and also in Figs. 2-3 were divided by the light intensity.

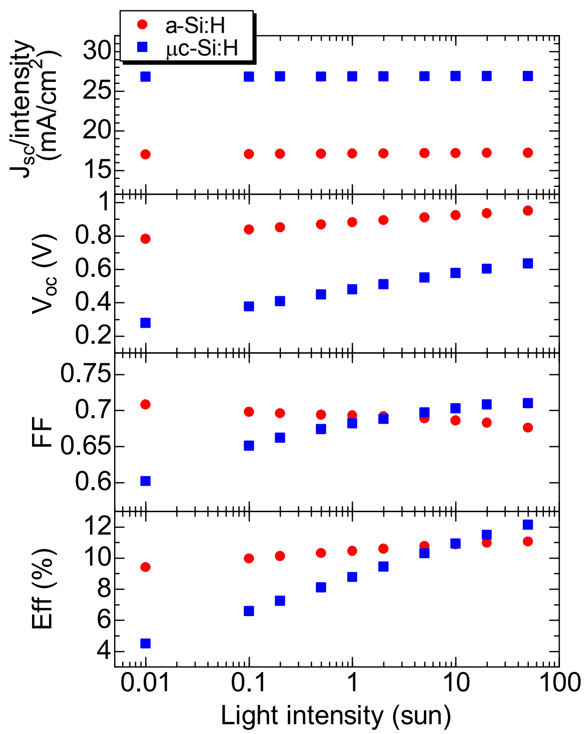


Fig. 1. Calculated PV parameters of a-Si:H and μc-Si:H solar cells as a function of light intensity.

From Fig. 1, one can see that the V_{oc} for both cells logarithmically increases with the light intensity, as previously expected. Moreover, the short-circuit current (J_{sc}) divided by the light intensity slightly increases with increasing the light intensity. In case of a-Si:H solar cell, the J_{sc} increases from 17.12 mA/cm2 at 1 sun to 17.22 mA/cm^2 at 50 sun. On the other hand, in case of μc-Si:H solar cells, the J_{sc} increases from 26.84 to 26.90 mA/cm^2. From the spectral response of both solar cells, we confirmed a slight improvement of quantum efficiency in the short-wavelength regions that leads to the Jsc enhancement, as shown in Fig. 2.

From Fig. 1 one also can notice a different tendency in the fill factor (FF) of each solar cell. In a-Si:H cell the FF slightly decreases, while in μc-Si:H cell the FF increases with increasing the light intensity. This difference tendency is probably due to the differences in the band gap and the number of defect density of i-layer for each solar cell. Therefore, it is clear that device structure affects the performance of solar cells under concentration of sunlight.

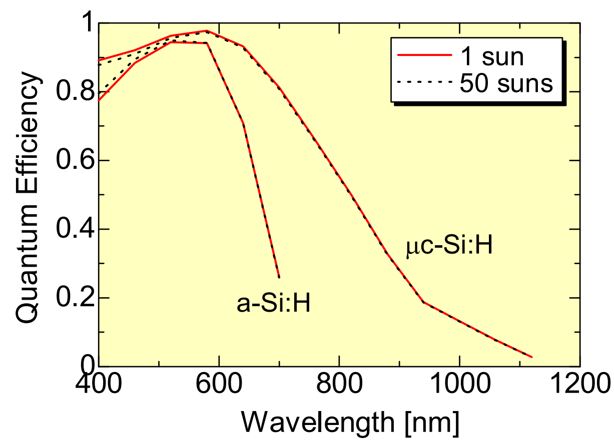


Fig. 2. Quantum efficiency of a-Si:H and μc-Si:H under 1 and 50 suns illumination.

Effect of i-layer Defect Density on Performance of a-Si:H Solar Cells

In order to further investigate how the device structure influences the photovoltaic performance of solar cells under various concentration ratios of sunlight, the effect of i-layer defect density for a-Si:H was then studied. The defect density of i-layer was changed from 2×10^{15} to 5×10^{16} cm-3. Here, the thickness of i-layer was kept constant at 400 nm.

Fig. 3 gives the calculated PV parameters of a-Si:H solar cells with various i-layer defect densities as a function of light intensity. As can be seen from Fig. 3, the change tendency of each PV parameter with increasing the light intensity strongly depends on the defect density of i-layer. The enhancement of J_{sc} (ΔJ_{sc}) with an increase in the light intensity, for instance, decreases with increasing the defect density. On the other hand, the enhancement of V_{oc} (ΔV_{oc}) with the light intensity increases with increasing the defect density. The drop of FF (ΔFF), however, decreases with increasing the defect density. As a result, there is a slight difference in the improvement of conversion efficiency (ΔEff) for each i-layer defect density.

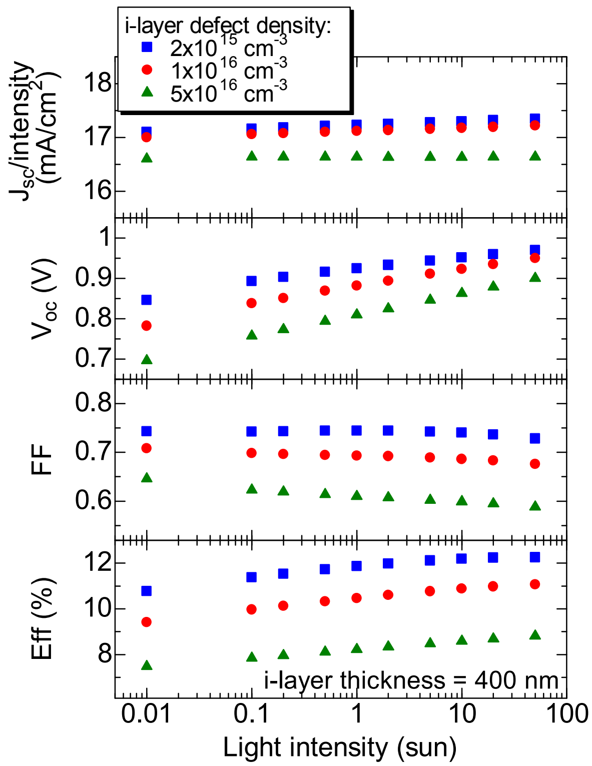


Fig. 4. Calculated PV parameters of a-Si:H solar cells with various i-layer defect densities as a function of light intensity. The i-layer thickness was 400 nm.

Effect of i-layer Thickness on Performance of a-Si:H Solar Cells

Next, the effect of i-layer thickness on the performance of a-Si:H solar cells under various concentrations of sunlight was calculated. As previously mentioned, the i-layer thickness was varied from 200 to 400 nm. Here, the i-layer defect density was assumed to be 2×10^{15} cm^{-3}.

Fig. 5 illustrates the calculated PV parameters of a-Si:H solar cells with various i-layer thicknesses as a function of light intensity. From Fig. 5 we can see that there is no much difference in the enhancement of J_{sc} (ΔJ_{sc}) for each i-layer thickness. However, the thickness of i-layer sensibly affects the changes of FF and V_{oc}. The drop of FF (ΔFF) at the light intensity of more than 1 sun as well as the enhancement of V_{oc} (ΔV_{oc}) decrease with decreasing the i-layer thickness.

To investigate the reason why the drops of FF decreased with decreasing the i-layer thickness, the recombination rates at the maximum voltage were calculated. Fig. 6 depicts the recombination rate for a-Si:H solar cells with the thicknesses of 200 and 400 nm at 1 and 50 suns. From Fig. 6 we can see that for both i-layer thicknesses, the recombination rate increased with increasing the light intensity from 1 to 50 suns, resulting a drop in FF with increasing the light intensity. Moreover, it is interesting to noticed that the increase in recombination rate due to the light intensity (shown as the blue and red arrows in Fig. 6), decreased with decreasing the i-layer thickness. As a result, the drop of FF with increasing the light intensity decreased with decreasing i-layer thickness. These results reveal that the device structure has significant influences on the light-intensity dependence of a-Si:H solar cells.

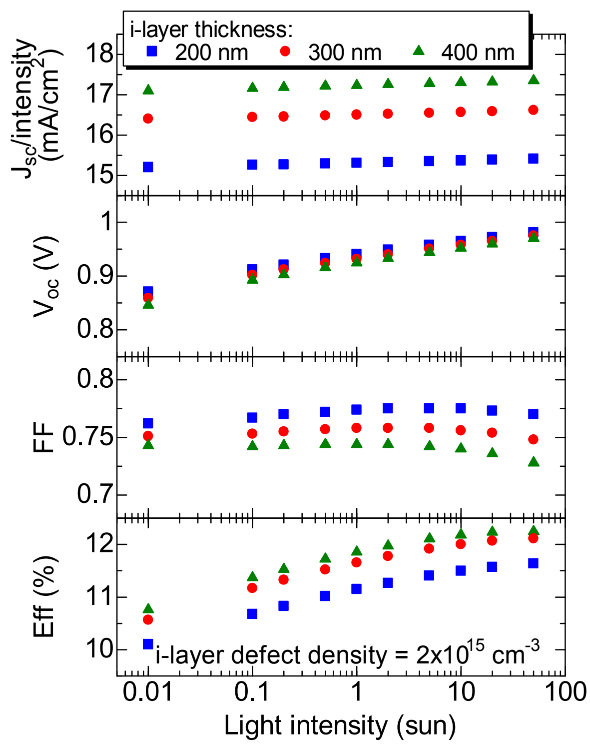


Fig. 5. Calculated PV parameters of a-Si:H solar cells with various i-layer thicknesses as a function of light intensity. The i-layer defect density was 2×10^{15} cm^{-3}.

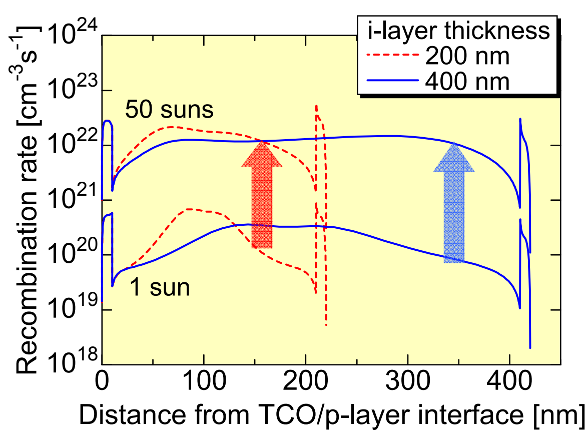


Fig. 6. Recombination rate of a-Si:H cells with various i-layer thicknesses under 1 and 50 suns illuminations at the maximum voltage.

MEASUREMENT RESULTS

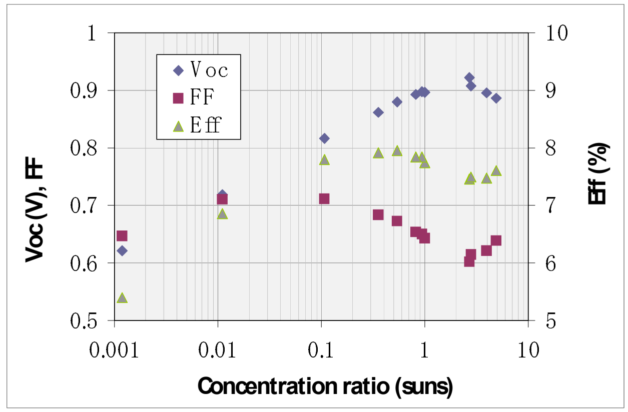
For comparison to the simulation results explained before, we also measured the photo J-V characteristics of three types of solar cells under various concentration ratios of sunlight. It should be noted that since we could not control and measure the cell temperature during the measurement, the cell temperature was probably not constant at 25°C.

Fig. 7 shows the PV parameters of a-Si:H, a-SiO:H, and μc-Si:H solar cells as a function of concentration ratio. Despite from the simulation results shown in Figs. 1-3 we confirmed that the J_{sc} increases with increasing the light intensity (concentration ratio), in the experimental study we simply assumed that the photocurrent linearly increases with increasing the concentration ratio of incident light. Thus, the concentration ratio shown in x-axis of graphs in Fig. 7 was defined as the ratio of J_{sc} under concentrated sunlight with that of under 1 sun.

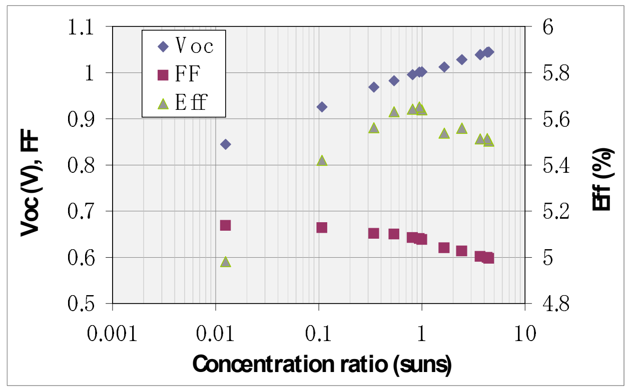
From Fig. 7 we can see that the V_{oc} of each solar cell logarithmically increases with increasing the light intensity. These results are in good agreement with the simulation results previously explained. However, the FF of all solar cells declines with increasing the concentration ratio to more than 0.5 sun. As a result, the efficiency drastically drops with increasing the concentration ratio to more than 1 sun, which obviously differs from the simulation results. These phenomena are probably because the high current density leads to the resistance loss which deteriorates the FF of the solar cells. Moreover, a high light intensity might also cause an increase in the temperature of solar cells which also deteriorates the FF. The drops of FF and efficiency at a high light intensity can be reduced, for example, by using a substrate with a low sheet resistance and by maintaining the cell temperature at 25°C. Therefore, in the development of silicon-based thin film concentrator solar cells, an optimum design of solar cell structure must be properly conducted to obtain a remarkable efficiency improvement.

CONCLUSIONS

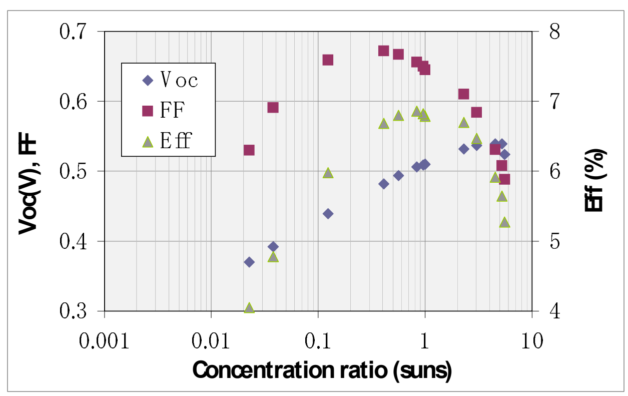
Both theoretical and experimental studies were performed to explore the effect of light intensity on the performance of silicon-based thin film solar cells. The theoretical study was conducted using AMPS-1D to examine how the device structure affects the performance of solar cells under various concentration ratios of sunlight. We theoretically analyzed a-Si:H and μc-Si:H single-junction solar cells, and also experimentally evaluated a-Si:H, a-SiO:H and μc-Si:H solar cells. From both simulation and measurement results, we observed that the V_{oc} logarithmically increases with increasing the light intensity. Moreover, from simulation results, we also found that the defect density and thickness of i-layer strongly influences the light-density dependence of a-Si:H solar cells. Thus, in the development of silicon-based thin film concentrator solar cells, the solar cell structure must be designed carefully to achieve a remarkable efficiency improvement.



(a) a-Si:H



(b) a-SiO:H



(c) μc-Si:H

Fig. 7. PV parameters of three types of silicon-based thin film solar cells as a function of concentration ratio of sunlight. (a) a-Si:H solar cell, (b) a-SiO:H solar cell, and (c) μc-Si:H solar cell.

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