IOP Conf. Series: Earth and Environmental Science **59** (2017) 012066 doi:10.1088/1755-1315/59/1/012066

The effect of substrate morphological structure on photoelectrical conversion performance of silicon solar cell

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Abstract. A novel method is proposed to evaluate electrical characteristics of silicon solar cell at real operating conditions. Silicon solar cells with different substrate morphological structures have various photoelectrical performances. The effect of substrate morphological structure on photoelectrical conversation performance of silicon solar cell has been investigated by illustration analysis, mathematical model and I-V test system. Results show that the solar cell with the porous-sponge like substrate has better electrical characteristics than those with conical like substrate morphological structure. The output power of porous substrate solar cell can exceed by 11% at 40 degree incident angle of sunlight compared to conical substrate solar cell.

1. Introduction

The study on photoelectrical conversion performance of solar cell is an importance research subject of photovoltaic industry. Many researches have been performed to assess electrical characteristics of solar cell in recent years [1-8]. But most of these evaluation methods focus on models of solar cells under the standard test conditions (STC), which means the incident simulated sunlight beam is directed at an angle of 90° relative to the solar cell plane. However these conditions only represent a very limited fraction of actual, realistic operating conditions for solar cells. The incidence angle of the sunlight indeed varies between different geographical locations and throughout the duration of a day and a year. Silicon solar cells, which boast more than 70% of the market share of the photovoltaic products, show a more cosine like angular dependence [9].

This paper presents an angle-resolved characterization approach of silicon solar cell and measured angle-resolved photovoltaic properties of porous substrate solar cells in comparison with conical substrate solar cells.

2. Experiments and model

The texturing of the solar cell surface has been shown to yield superior reflectance properties over a broad range of incident angles [10–12]. In our previous work, plasma immersion ion implantation (PIII) has been put forward to produce black silicon to texture the silicon solar cell surface. Hence, the silicon solar cells used for this work was commercially available boron-doped p-type multi-crystalline silicon wafers obtained from the ingot by wire sawing with thickness ~200 μm, area 156mm × 156 mm, and resistivity 1~3Ωcm. The black silicon was prepared by plasma immersion ion implantation process on domestic equipment and subsequently subjected to acid etching in HF/HNO3 solutions.

After that, the black silicon wafers were phosphorus doped using phosphorous oxychloride (POCl3) as the dopant source and then subjected to edge etching through reactive ion etching and removing phosphosilicate glass (PSG) layer with diluted HF. Silicon-nitride layer for passivation was grown by plasma enhanced chemical vapor deposition (PECVD) process. Finally, the front and back metallization of all the wafers were carried out by screen-printing technique and followed by baking and co-firing in a conveyer belt furnace.

The microstructure of the silicon solar cells were characterized by scanning electron microscope (SEM). Figure 1 and figure 2 shows different substrate surface of solar cells respectively. The microstructures seen in figure 1 are porous-sponge like concaves arbitrarily spread throughout the solar cell surface. The microstructures seen in figure 2 are conical-like hillocks randomly distributed across the entire solar cell surface.

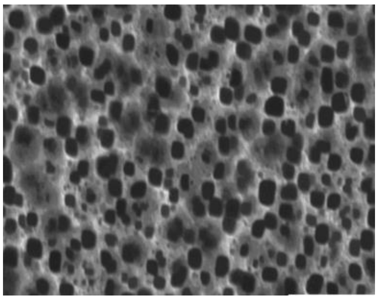

Figure 1. SEM-image of porous-sponge like substrate surface of solar cell.

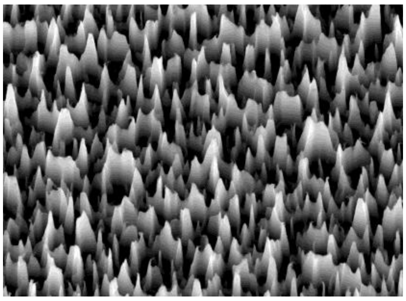

Figure 2. SEM-image of conical like substrate surface of solar cell.

The electrical equivalent circuit module of solar cell is depicted in figure 3, which contains a photocurrent source, a p-n junction diode, a p-n junction capacitance, a series resistor and a shunt resistor. Due to the p-n junction capacitance is relatively small, and the time constant of the PV system is large enough, the influence of the p-n junction capacitance can be ignored. Applying Kirchhoff's current law (KCL) and Shockley equation to the junction point of these two resistors gives the characteristic equation of the solar cell, which is a nonlinear transcendental equation, as follows:

$$I = I_{ph} - I_0 \left\{ \exp[\frac{q(U + IR_s)}{AKT_c}] - 1 \right\} - \frac{U + IR_s}{R_{sh}} \tag{1}$$

Where U and I are respectively the output voltage and current of the solar cell, I_{ph} is the photocurrent which is proportional to the irradiance; I_0 is the diode saturation current, R_s is the series resistance, R_{sh} is the parallel resistance, A is the ideality factor of the diode which change with the output voltage, K is the Boltzmann constant (1.38×10^{-23} J/K) and T_c is the absolute temperature.

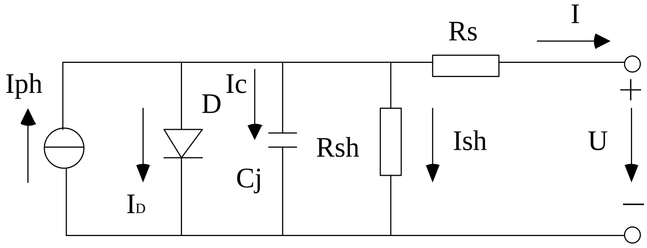

Figure 3. Electrical equivalent circuit model of solar cell

The presence of R_{sh} corresponds to the leakage current in the p-n junction. In practice, R_{sh} is much larger than $U+IRs$ .Therefore R_{sh} was ignored. The exponential term is much larger than 1. Thus, Equation (1) can be further simplified as equation (2):

$$I = I_{ph} - I_0 \exp[\frac{q(U + IR_s)}{AKT_c}] \tag{2}$$

For a given PV module, in order to evaluate A, R_s, I_{ph}, I_0 in a particular environmental condition, a system of non-linear equations is generated by forcing to fit the I-V curve expressed by equation (2) in four points. Two particular points are used to determined two equations: open circuit point ($V=V_{oc}$, $I=0$), short circuit point ($V=0, I = I_{sc}$). In these cases, equation (2) becomes:

$$0 = I_{ph} - I_0 \exp[\frac{qU_{oc}}{AKT_c}] \tag{3}$$

$$I_{sc} = I_{ph} - I_0 \exp[\frac{qI_{sc}R_s}{AKT_c}] \tag{4}$$

In equation (4), because the equivalent series resistance R_s is relative smaller than the p-n junction on-resistance, the exponential term approximates to 0. Then the equation becomes:

$$I_{sc} \approx I_{ph} \tag{5}$$

The diode saturation current can derived from equation (3).

$$I_0 = I_{ph} \exp[-\frac{qU_{oc}}{AKT_c})] \tag{6}$$

From equation (5) and (6), equation (2) becomes:

$$I = I_{ph}(1 - \exp[\frac{q(U + IR_s - U_{oc})}{AKT_c}]) \tag{7}$$

The photocurrent I_{ph} can be influenced by the irradiance as the equation (9) described:

$$I_{ph} = I_{phref} F(\theta) \tag{8}$$

Where I_{phref} is the photocurrent under one sun illumination (1000 W/m^2, AM1.5G) at 298K temperature, $F(\theta)$ is defined as a function of the sunlight incident angle θ on the surface of solar cell, θ is incident angle of the sun light due to solar cell normal axis, seen in figure 4 and figure 5.

In equation (7), because product item IR_s is much smaller than the difference of U and U_{oc}, combined with equation (8), equation (7) becomes:

$$I \approx I_{phref} (1 - \exp[\frac{q(U - U_{oc})}{AKT_c}])F(\theta) \tag{9}$$

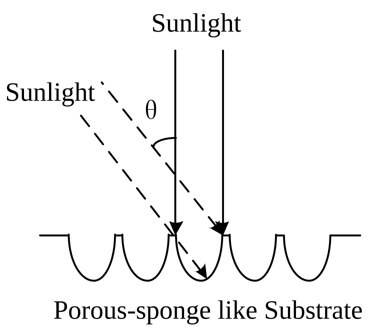

Figure 4. Schematic view of porous substrate solar cell radiated at various incident angle of sunlight

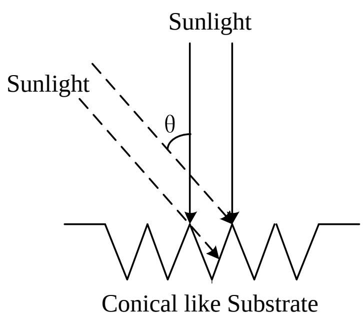

Figure 5. Schematic view of conical substrate solar cell radiated at various incident angle of sunlight

Figure 4 shows schematically the porous substrate solar cell radiated at various incident angle of sunlight, and figure 5 shows schematically the conical substrate solar cell radiated at various incident angle of sunlight. When sunlight is deflected a contain angle, i.e. incident angle θ, the irradiance area on the solar cell changes. The bigger the incident angle θ, the smaller the irradiance area. It results in photocurrent I_{ph} declines. Thus, $F(\theta)$ is a monotone decreasing function of θ.

It is seen in figure 4 and 5 that the irradiance area of the porous substrate solar cell is a bit larger than that of the conical substrate solar cell at the same of incident angle θ. Accordingly, it should be inferred that the photoelectrical conversion performance of porous substrate solar cell is superior to the conical substrate solar cell.

3. Results and discussion

The I–V curves and photoelectrical conversion properties including short circuit current I_{SC}, open circuit voltage V_{OC}, fill factor, and output power P, were measured on solar cells under one sun illumination (1000W/m2, AM1.5G) using a Newport Oriel solar simulator and a Keithley 2400 source meter. The solar simulator was fixed during all measurements. The solar cell test stage consists of an upper probe station and a bottom rotating table. The incidence angle was varied using two PMC100 stepping motors connected to the bottom rotating table.

Based on the experiment data, it is found that the open circuit voltage V_{OC} and fill factor do not change significantly for the incident angles below 80 degree. However, the short circuit current I_{SC} and consequently output power P decrease with increasing incident angle.

The measured angle-dependent short circuit currents for different substrate solar cells are plotted in figure 6. The I_{SC} of the porous substrate solar cell is always higher than that of the conical substrate solar cell below 60 degree incident angle of sunlight. The difference between the short circuit currents of two kinds of solar cells achieves the maximum at 40 degree, about 0.538 A.

Figure 7 shows the measured angle-dependent output power for different substrate solar cells. The P of the porous substrate solar cell is always higher than that of the conical substrate solar cell below 70 degree incident angle of sunlight. The difference between the short circuit currents of two kinds of solar cells achieves the maximum at 40 degree, about 0.38 W. The maximum 0.38W takes up 11% of the output power of the conical substrate solar cell.

Therefore, the solar cell with the porous-sponge like substrate has better electrical characteristics than those with conical like substrate morphological structure.

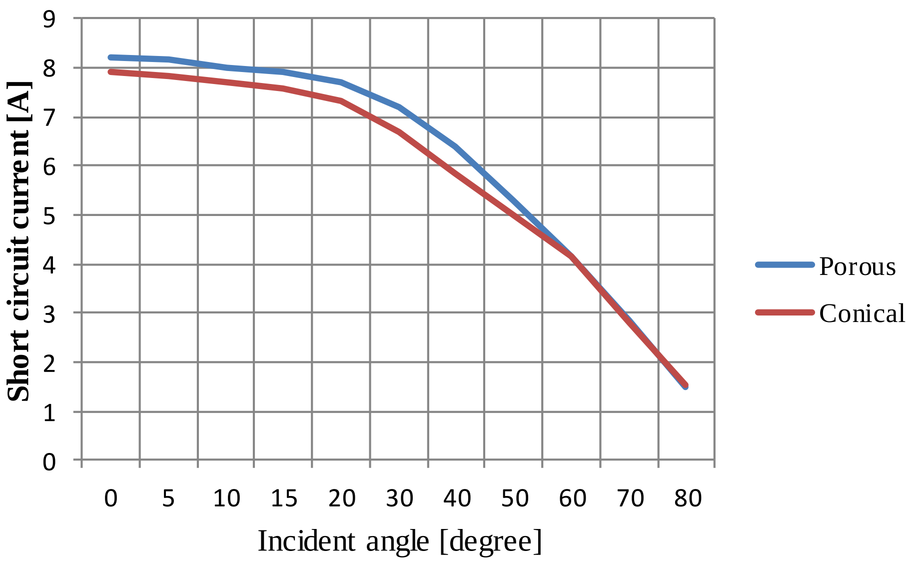

Figure 6. Short circuit current curves of different solar cells at various incident angle of sunlight

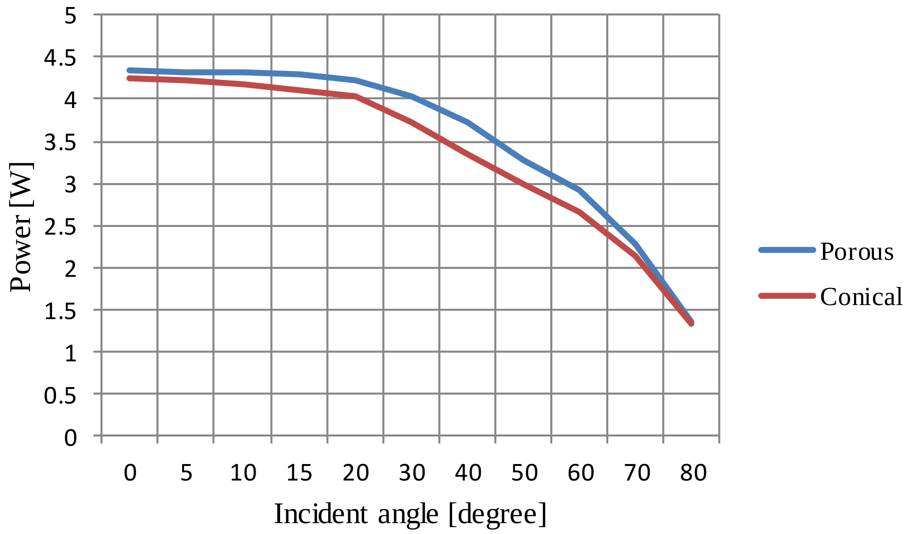

Figure 7. Power output curves of different solar cells at various incident angle of sunlight

4. Conclusions

A novel method for angle-resolved characterization of solar cells and estimated angle-dependent photoelectrical conversion performances of different substrate surface of solar cells has been presented. Silicon solar cells with different substrate morphological structures have various photoelectrical performances at real operating conditions. Compared to the solar cell with conical like substrate morphological structure, the solar cell with the porous-sponge like substrate has better photoelectrical characteristics over a broad range of incident angles due to larger irradiance area in general. The short circuit current and the output power of porous substrate solar cell can respectively exceed by 0.538A and 0.38W at 40 degree incident angle of sunlight.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (Grant No. 61274059).

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