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

Yongtao Li\textsuperscript{1,2,3}, Xiaomeng Sun\textsuperscript{2}, Yang Xia\textsuperscript{1,2}

1 Key Laboratory of Microelectronics Devices & Integrated Technology, Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China
2 Beijing Key Laboratory of IC Test Technology, 100088, Beijing, China
3 liyongtao@ime.ac.cn

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\degree 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 \textasciitilde200 \mu m, area 156mm \times 156 mm, and resistivity 1-3\Omega cm. 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.

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:

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

(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.

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

\[
I = I_{ph} - I_0 \left\{ \exp\left[ \frac{qU}{AKT_c} \right] - 1 \right\} - \frac{U}{R_s}
\]  

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

\[ 0 = I_{ph} - I_0 \exp\left[\frac{qU_{oc}}{AKT_c}\right] \] (3)

\[ I_{sc} = I_{ph} - I_0 \exp\left[\frac{qI_{sc}R_s}{AKT_c}\right] \] (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:

\[ I_{sc} \approx I_{ph} \] (5)

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

\[ I_0 = I_{ph} \exp\left[-\frac{qU_{oc}}{AKT_c}\right] \] (6)

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

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

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

\[ I_{ph} = I_{phref} F(\theta) \] (8)

Where \( I_{phref} \) is the photocurrent under one sun illumination (1000 W/m², AM1.5G) at 298K temperature, \( F(\theta) \) is defined as a function of the sunlight incident angle \( \theta \) on the surface of solar cell, \( \theta \) 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:

\[ I \approx I_{phref} (1 - \exp\left[\frac{q(U - U_{oc})}{AKT_c}\right]) F(\theta) \] (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 $\theta$, the irradiance area on the solar cell changes. The bigger the incident angle $\theta$, the smaller the irradiance area. It results in photocurrent $I_{ph}$ declines. Thus, $F(\theta)$ is a monotone decreasing function of $\theta$.

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 $\theta$. 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.

![Graph showing short circuit current curves of different solar cells at various incident angle of sunlight](image-url)

Figure 6. Short circuit current 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 photovoltaic conversion performances of different substrate surface of solar cells has been presented. Silicon solar cells with different substrate morphological structures have various photovoltaic 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 photovoltaic 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.

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References
[1] Saloux Etienne, Teysse d’Alberto, Sorin Mikhail 2011 Solar Energy 85 713.
[2] Nema RK, Nema Savita, Agnihotri Gayatri 2009 International Journal of Recent Trends in Engineering 1 151.
[3] Khazaei J, Miao Z, Piyasinghe L, Fan L 2015 Electric Power Systems Research 123 85.
[4] Lo Brano V, Orioli A, Ciulla G, Di Gangi A 2010 Solar Energy Materials and Solar Cells 94 1358.
[5] Laudani A, Mancilla-David F, Riganti-Fulginei F, Salvini A 2013 Solar Energy 97 122.
[6] Orioli A, Di Gangi A 2013 Applied Energy 102 1160.
[7] Kashif Ishaque, Zainal Salam, Hamed Taheri, Amir Shamsudin 2011 Solar Energy 85 1768.
[8] Xiaofang Yuan, Yongzhong Xiang, Yuqing He 2014 Solar Energy 108 238.
[9] Balenzategui J L, Chenlo F, 2005 Solar Energy Materials and Solar Cells 86 53.
[10] X. Liu, Coxon P R, Peters M, Hoex B, Cole J M, Fray D J 2014 Energy & Environmental Science 7 3223.
[11] Rahman A, Ashraf A, Xin H, Tong X, Sutter P, Eisaman M D, Black C T 2015 Nature Communications 6 5963.
[12] Jihun Oh, Hao-Chih Yuan, Howard M B 2012 Nature Nanotechnology 7 743.