Research Article

Experimental Investigation of the Effects of Partial Shading on Photovoltaic Cells' Electrical Parameters

W. B. Xiao,^{1,2} F. Y. Hu,^{1,2} H. M. Zhang,^{1,2} and H. M. Wu^{1,2}

¹Jiangxi Engineering Laboratory for Optoelectronics Testing Technology, Nanchang Hangkong University, Nanchang 330063, China

²Key Lab of Non Destructive Test (Ministry of Education), Nanchang Hangkong University, Nanchang 330063, China

Correspondence should be addressed to W. B. Xiao; xiaowenbo1570@163.com

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The short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}), and the maximum power point (V_{MPP} , I_{MPP}) of monocrystalline and multicrystalline silicon solar cells under three kinds of partial shading patterns have been investigated experimentally. The partial shades are, respectively, the nine shelter locations by $1\text{ cm} \times 1\text{ cm}$ black card, the six shelter locations by $2\text{ cm} \times 1\text{ cm}$ black card, and the center shelters with isosceles triangle, circle, square, and two rectangles black cards whose areas are 2 cm^2 . Firstly, the results show that the partial shading causes disproportional high losses on those parameters of both cells but will have a minimal effect on V_{oc} . Secondly, it is found that those parameters of the monocrystalline cell are less dependent on the shading than that of the multicrystalline cell. Thirdly, it is noted that I_{sc} and I_{MPP} of both cells will be decreasing dramatically as a rectangular black shading card with a long side parallel to cell's finger, compared with that normal to cell's finger. Finally, it can be seen that the effects of shading on the electrical parameters of both cells will be suppressed when the border lines of shading match the size of the shaded cell.

1. Introduction

Photovoltaic (PV) power is now becoming an important energy source. Not only is PV power environmentally friendly but also it has been becoming economically competitive with conventional fuels [1, 2]. However, PV energy production is easily influenced by the shadow of natural and human made objects [3–5]. The shaded cells absorb electric power generated by the unshaded cells, causing hot spots that can irreversibly damage PV cells. Therefore, the output performances of PV cells under partial shading conditions have been drawing increasing attention [6–11]. Over the years, the theoretical researches are mainly based on the single-diode model [12–15] and the double-diode model [16–18]. However, it is obvious that those theoretical models do not always fit to complex and changeable shading environments. In addition, several researchers have adopted an experimental approach to study the characteristics of PV cells under partial shading conditions. The behaviors of the solar cell electrical parameters have been compared with the central and edge shading [19, 20]. It was found that edge shading is a problem

occurring in PV concentrator systems. The effects of shading percentage on electrical parameters of solar cells have been analyzed [21, 22]. The results showed that the generated current is decreasing as the shading profile is increasing. However, none of the above researches clarifies the effects of shading shape on cell's performances. Furthermore, there are also lacks of detailed comparative studies of different kinds of solar cells under same shading condition. As a result, the nonlinear characteristics of electrical parameters of PV cells under partial shading still remain elusive.

In this paper, the electrical parameters (the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}), and the maximum power point (V_{MPP} , I_{MPP})) of monocrystalline and multicrystalline silicon solar cells under three kinds of partial shading patterns have been investigated experimentally. The results firstly show that the partial shading causes disproportional high losses on electrical parameters of monocrystalline and multicrystalline cells. But the shading will have a minimal effect on the open-circuit voltage of both cells. Secondly, it is found that the electrical parameters of the monocrystalline cell are less dependent on the shading than those parameters

FIGURE 1: Experimental samples (a), the nine shelter locations by using $1\text{ cm} \times 1\text{ cm}$ black square card (b), the six shelter locations by using $2\text{ cm} \times 1\text{ cm}$ black rectangle card (c), and the center shelters with isosceles triangle, circle, square, and two rectangles black cards whose areas are 2 cm^2 (d). The dashed lines are the cell's fingers (not to scale).

of multicrystalline cell. Thirdly, it is noted that the short-circuit current and current at maximum power point of both cells will be decreasing dramatically as a rectangular black shading card with a long side parallel to cell's finger, compared with that normal to cell's finger. Finally, it can be seen that the effect of shading on the electrical parameters of both cells will be significantly suppressed when the border lines of shading match the shaded cell.

2. Experimental Samples, Setup, and Shading Patterns

The experimental samples are $2.8\text{ cm} \times 2.5\text{ cm}$ monocrystalline and multicrystalline silicon solar cells manufactured by QS Solar Company (Figure 1(a)). The distance between fingers of monocrystalline and multicrystalline cells is about 0.25 cm . The PV testing system (number SAC- III + G

FIGURE 2: I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of monocrystalline ((a) and (b)) and multicrystalline ((c) and (d)) silicon solar cells against nine square shelter locations.

made by Chengdu ZKY Instrument Co. Ltd.) is used for data acquisition. The testing system mainly includes a solar simulator, an electric signal reading device, and temperature control equipment, which are enclosed in a dark box. The simulated sunlight is achieved by Xenon light source. The beam impinges perpendicularly on the cell. The cell is placed in a temperature control room wherein temperature can be controlled by temperature control equipment, a semiconductor refrigeration device. The photoelectric signal of cell is recorded by the electric signal reading device. All the experiments were done at a temperature of 25°C and a light intensity of 1000 W/m². In the above condition, I_{sc} , V_{oc} , I_{MPP} , and V_{MPP} of unshaded monocrystalline (multicrystalline) cell are 30.5 (30.1) mA, 3.02 (2.99) mV, 27.6 (29.3) mA, and 2.49 (2.48) mV.

In order to study the effects of shading on solar cell's performances, three kinds of partial shading patterns are designed as shown in Figures 1(b), 1(c), and 1(d). Those

configurations are not scaled in relation to cell dimensions, which purpose is to mark all the shading parts in a schematic diagram of a solar cell. The partial shades are, respectively, the nine shelter locations by 1 cm × 1 cm black card, the six shelter locations by 2 cm × 1 cm black card, and the center shelters with isosceles triangle, circle, square, and two rectangles black cards whose areas are 2 cm². In the real experiment, the numbers of measurements are, respectively, nine for the square shelter configuration, six for the rectangle shelter configuration, and five for the center shelter configuration.

3. Results and Discussion

3.1. Nine Square Shelter Locations. In Figure 2, I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of monocrystalline and multicrystalline cells are measured against nine square shelter locations. Firstly, it can be seen that I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of both cells are obviously less than those of the unshaded cells. The reason is that the

FIGURE 3: I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of monocrystalline ((a) and (b)) and multicrystalline ((c) and (d)) silicon solar cells against six rectangle shelter locations.

light-receiving area of the cell is reduced. The average I_{sc} of monocrystalline and multicrystalline cells under nine square shelter locations are about 21.75556 mA and 20.96667 mA. In fact, PV cell can be divided into a number of subcells by the cell's fingers. In other words, cell can be regarded as subcells in series. The I_{sc} of unshaded monocrystalline and multicrystalline cells are 30.5 mA and 30.1 mA. Namely, the I_{sc} of each subcell of monocrystalline and multicrystalline cells are about 30.5 mA and 30.1 mA. When the cell is sheltered by using $1\text{ cm} \times 1\text{ cm}$ black square card, the light-receiving area of each sub-cell is 0.45 cm^2 but not 0.7 cm^2 . According to previous research work [21, 22], it is known that the I_{sc} are approximately proportional to the light-receiving area. As a result, the short-circuit current under shaded condition should be equal to 19.6 mA and 19.3 mA for the monocrystalline and multicrystalline cells, which are very close to the above experimental results. Therefore, the above conclusion is correct. Secondly, it is observed that those parameters vary

with the shading positions. It is due to the fact that the devices themselves owned uniform defects [23]. Thirdly, it is noted that the standard deviations of I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of monocrystalline (multicrystalline) cell are, respectively, 0.579032 (0.705337) mA, 0.486769 (0.499444) mA, 0.013333 (0.01424) mV, and 0.02 (0.044441) mV. Those show that shading locations have a minimal effect on V_{oc} , which also can be seen in Figure 2. The reason is that V_{oc} is mainly determined by the band gap of the solar cell material, the device temperature, and the incident light intensity [24, 25]. In addition, it is found that the shading has more influence on the electrical parameters of the monocrystalline cell than that of the multicrystalline cell from the standard deviation. The differences can be regarded as the multicrystalline cell has much more nonuniformity defects.

3.2. Six Rectangle Shelter Locations. In Figure 3, I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of monocrystalline and multicrystalline cells

FIGURE 4: I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of monocrystalline ((a) and (b)) and multicrystalline ((c) and (d)) silicon solar cells against center shelters with isosceles triangle, circle, square, and two rectangles black cards.

are measured against six rectangle shelter locations. It can also be seen that I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of both cells are changing with the shading positions. The standard deviations of I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of monocrystalline (multicrystalline) cell are, respectively, 5.105865 (5.505853) mA, 6.1555 (6.146448) mA, 0.01633 (0.026646) mV, and 0.054772 (0.121888) mV, which also show that the shading has a minimal effect on V_{oc} for both cells and on electrical parameters of monocrystalline cell. Those experimental results give a direct proof verifying the above conclusions. What should be noticed is that there are mutation process of I_{sc} and I_{MPP} for both cells between the third and fourth locations as arrows shown in the Figures 3(a) and 3(c). This may be the differences between the long side of rectangular shading card normal to cell's finger and the long side of rectangular shading card parallel to cell's finger. When PV cell is covered by a black rectangular shading card with a long side normal to cell's finger, only 1 cm length is sheltered along the longitudinal

direction for each subcell. The results of this shading mode are similar to the above case. So the short-circuit current under shaded condition should be equal to 19.6 mA and 19.3 mA for the monocrystalline and multicrystalline cells, which are also very close to the above experimental data. When PV cell is covered by a black rectangular shading card with a long side parallel to cell's finger, the 2 cm length is sheltered along the longitudinal direction for each subcell. Therefore, the short-circuit current under shaded condition should be equal to 8.7 mA and 8.6 mA for the monocrystalline and multicrystalline cells, which are also roughly consistent with experimental observation. As a result, the short-circuit current of cell is determined by the weakest subcell when the cell is partially shaded.

3.3. Center Shelters with Different Shapes. In Figure 4, I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of monocrystalline ((a) and (b)) and multicrystalline ((c) and (d)) silicon solar cells are measured

against isosceles triangle, circle, square, and two rectangles black cards whose areas are 2 cm^2 . As it can be seen, the impacts of shading shapes on the electrical parameters of both cells are different. The standard deviations of I_{sc} , I_{MPP} , V_{oc} , and V_{MPP} of monocrystalline (multicrystalline) cell are, respectively, 3.432929 (4.304997) mA, 4.145301 (4.411136) mA, 0.024083 (0.035355) mV, and 0.070143 (0.112116) mV. The above conclusion can also be drawn from those results. It is particularly noticed that I_{sc} and I_{MPP} of both cells under square shading are maximum values for isosceles triangle, circle, and square shading, as shown in Figures 4(a) and 4(c). This can be explained by the fact that the border lines of square shading match the shaded cell's size. In addition, it is found that I_{sc} and I_{MPP} of both cells under a rectangular shading card with a long side parallel to cell's finger are minimum values. It is because of the combined effect of the above two factors. One factor is that a greater portion of each subcell is shaded in the above condition. Another is that the border lines of rectangle shading do not match the shaded cell's size. Therefore, I_{sc} and I_{MPP} of both cells under rectangles black card with a long side normal to cell's finger present a peak, as arrows shown in Figures 4(a) and 4(c).

4. Conclusion

In order to explain clearly the shading effects on the solar cell's performances, experiments under three kinds of partial shading patterns were carried out. Firstly, the results show that the partial shading causes disproportional high losses on electrical parameters of monocrystalline and multicrystalline cells but will have a minimal effect on V_{oc} for both cells. The reason is that V_{oc} is mainly determined by the band gap of the solar cell material, the device temperature, and the incident light intensity. Secondly, it is found that electrical parameters of the monocrystalline cell are less dependent on the shading than that of multicrystalline cell. The differences can be regarded as the multicrystalline cell has much more nonuniformity defects. Thirdly, it is noted that the I_{sc} and I_{MPP} of both cells will be decreasing dramatically as a rectangular black shading card with a long side parallel to cell's finger, compared with that normal to cell's finger. The reason of this behavior is due to the subcell in series being much more sheltered while card's long side parallel to cell's finger. Finally, it can be seen that the effects of shading on the electrical parameters of both cells will be suppressed when the border lines of shading match the size of the shaded cell.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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