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Full Length Research Paper

Effects of introducing periodical polymer gratings on the solar cell

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Effects of the light-collecting solar cell with high polymer reflecting gratings and experimental accomplishment of periodical gratings on the solar cell surface are studied. It mainly discusses the way and advantage to enhance the solar cell efficiency by using holographic interference lithography to produce high polymer reflecting gratings on the solar cell. Based on the easy processing method, the theoretically calculated open-circuit voltage, V_{oc}, can be raised from 2.62 - 3.618 V, and the maximum voltage, V_m, increases from 2.5 - 3.5 V for a standard commercial Si solar cell. From experiment, the power conversion efficiency for the solar cell is also enhanced from 27 - 35.67%, corresponding to the relative increase of efficiency up to 32.1%. The theoretical analyses are in good agreement with the experimental findings.

Key words: Polymer reflecting gratings, solar cell, holographic interference lithography, power conversion efficiency.

INTRODUCTION

Nowadays, low power conversion efficiency is still the major drawback in the solar cell and is the key technology needed to be exploited (Yerokhov and Melnyk, 1999). To enhance the solar efficiency, there are two methods in the literature and they are described as followings. Firstly, the passivated emitter rear locally-diffused (PERL) structure is used in the silicon solar cell which has inverted pyramids on the top that are formed by using anisotropic etching to expose the slowly etching crystallographic planes. The pyramids reduce reflections of light incident on top surface, since light incident perpendicularly to the cell will strike one of the incident plans obliquely, and will be refracted obliquely into the cell. The rear contact is separated from the silicon by an intervening oxide layer. This gives much better rear reflection than an aluminum layer. To date, the PERL cell shows the highest conversion efficiency of 24% (Green, 1995). Second, sunlight can be focused by using external optical mirrors and lenses. Optical concentration offers an attractive and flexible approach to reducing high cell costs by substituting a concentrator area for much of the cell area. It also offers other advantages, such as a 20% increase in efficiency for a concentration of 1000 suns (an intensity of 963KW/m^2) (Wohlgemuth, 1991). These severe limitations and technical methods have created substantial potential in another alternative techniques based on the formation of other materials on the solar cell.

Generally, Si is the main substrate material to fabricate the solar cells. But, the reflective rate of Si surface is as high as 30 ~ 35% under light illumination (Hwang, Lin and Sun, 1994). If we can reduce the percentage of the reflected light, then we can hence raise the efficiency of solar cell. In this study, the high polymer reflecting grating is used on the top of solar cell surface, due to the intrinsic of reflecting light, it will flash back the light which is reflected by the solar cell surface. Thus, we can enhance the light-collecting rate of solar cell and increase power conversion efficiency just by recollecting the reflected light. Therefore, how to use the easiest and cheapest method to recollected light and then enhance the efficiency is the key purpose in this research. In experiment, we use micro electricity process, optics interferences and polymer reflecting gratings to flash back the light which is reflected by solar cell surface, so the incident light is repeatedly re-

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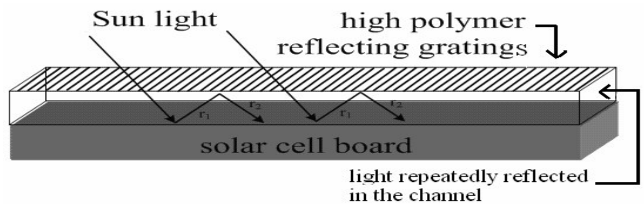

Figure 1. Schematic structure of surface gratings and reflecting ratios on the solar cell.

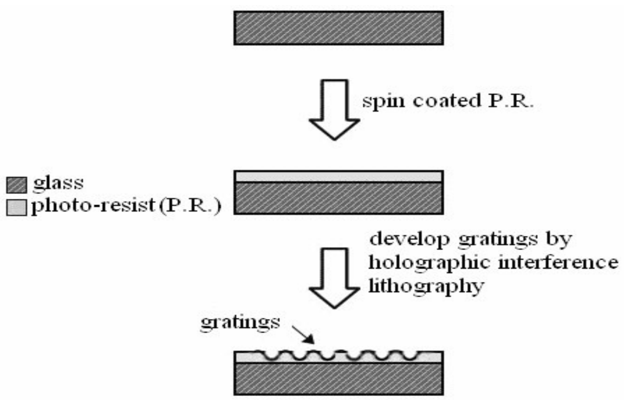

Figure 2. Process flow of periodical photo-resist grating.

flected and raises the light-collecting rate. Surely, the efficiency of solar cell will be increased. Up to now, the fabrication of periodical gratings on the solar cell surface is almost accomplished by semiconductor etching process. The method of using polymer gratings on the solar cell to reduce light reflection and enhance efficiency is still limited in the literature. The use of coating surface gratings by polymer material on the solar cell has many advantages including easy process, low cost and no additional technology in need. Figure 1 is schematic device structure with periodical surface gratings and illustrates the working theorem. The r_1 in the figure is the reflecting ratio of solar cell and r_2 is the reflecting ratio of high polymer reflecting grating. The influence of surface gratings on the solar cell is investigated by two ways that is, the experimental formation of polymer reflecting gratings on the Si solar cell surface and then confirms that it will enhance the power conversion efficiency of the solar cell. In addition, the influence of reflection ratios, r_1 and r_2, on the solar cell is also theoretically analyzed.

EXPERIMENTAL

To date, there are many studies of discussing about enhancing solar cell efficiency, and can be divided them into two ways, that is, (1) changing the elements of solar cell (2) concentration light solar cell. In this research, we match up micro electricity and optics interferences to make a layer of reflecting grating on the solar cell substrate. By this way, it does not change anything of the solar cell elements but uses the character of reflection to collect more light which is reflected from the solar cell. The reflected light will travel in the channel composed by the reflected gratings and solar cell. And we can also increase the light-collecting efficiency and power conversion efficiency (η) by increasing electron-hole pair in the channel. This research is using high polymer material to produce reflecting diffractive-mode grating elements. There are many merits for the high polymer material in this study that is, adjustable reflecting rate, good light-transmitting, heat stability. The experimental process in this work indicates how to make the sharp outward high polymer gratings on solar cell substrate (Chang et al. 2006; Chang et al. 2009). Step 1: using holographic interferometry technology to fabricate the reflecting diffractive-mode gratings. We use glass to be the substrate of reflecting diffractive grating, and spin positive photo-resist (Ultral 123) on the substrate. The lithographic photo-resist process flow is shown in Figure 2. In the experiment, a He-Cd laser with a wavelength of 325 nm and the power of 60mW is used in a holographic interferometry technology system (Chang et al., 2006). The laser beam is divided into two same beams by beam splitter. These two waves travel on the cross direction and meanwhile they interfere with each other and form the pattern of reflecting grating on the sample. The relation between diffractive grating period T and the incident angle of light θ_1 and θ_2 is given in equation (1). T is grating period, θ_1 and θ_2 are incident angles of light, λ is the laser wavelength, respectively.

$$T = \frac{\lambda}{\sin\theta_1 + \sin\theta_2} \quad (1)$$

Step 2: To reprint the gratings on the solar cell substrate. We use high polymer (Poly dimethyl siloxane, PDMS) to reprint. We spin thin film of PDMS on the photo-resist substrate which has the sensibility of diffractive grating. Because of the characteristic of PDMS, we can easily separate them. After separation, the stripe pattern of grating is transmitted on PDMS thin film. And we can also transmit the patter from PDMS thin film into high polymer substrate. First, we take PDMS thin film and put it on glass substrate, and then, we put two boards on each side of the substrate. Next, we place a glass substrate over it. After these steps, PDMS thin film is placed between two glass substrates, and there will be a revealed interval inside. After that, we fill OG into the middle of the two glasses, and then OG will adhere on the model. OG is a sensitive polymer material; the UV light is then applied to solidify it. At last, the reflecting gratings are produced on the solar cell substrate. The total processing procedures is schematically shown in the Figure 3. The attempt of introducing gratings by the interference of two beams holography is simple and first investigated in the literature. But, when these gratings are introduced to big solar panels, another process technology using photolithography with big mask is needed to expose UV on the solar panel. This research is under proceeding.

THEORETICAL ANALYSES

The theoretical simulation of the solar cell with gratings is calculated as followings.

Calculation of the maximum output power (P_m)

Calculation of total current in the solar cell is given in equation (2):

$$I = I_o\left[e^{\frac{V}{nV_T}} - 1\right] - I_{ph} \quad (2)$$

Where; I_o, I_{ph} are the reverse saturation current and photo current

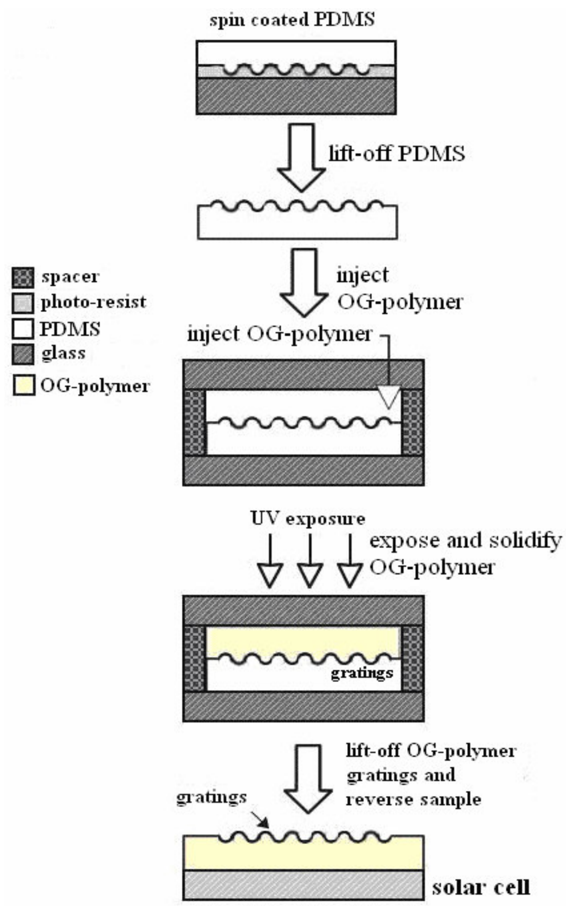

Figure 3. Process flow of transferring polymer gratings to reprint on the solar cell.

resulted from the excitation of excess carriers by solar radiation in the solar cell, respectively. For a solar cell diode with a series resistance circuit, the short-circuit current (I_{sc}) should be equal to the photo current (I_{ph}), that is $I_{sc} = I_{ph}$. Thus, the output power is given as

$$P = IV = I_o V\left[e^{\frac{V}{nV_T}} - 1\right] - I_{sc} V \tag{3}$$

Then, the maximum output power condition can be found from $dP/dV = 0$, and obtained as (Sze, 1981)

$$V_m = V_{oc} - V_T \ln\left(1 + \frac{V_m}{V_T}\right) \tag{4}$$

$$I_m = I_{sc}(1 - \frac{V_T}{V_m}) \tag{5}$$

Where; V_m, V_{oc} are maximum output and open-circuit voltages in the solar cell, respectively. I_m, I_{sc} are maximum output and short-circuit currents in the solar cell, respectively.

Then, the maximum output power (P_m) (Snyman and Enslin, 1993) is given in equation (6)

$$P_m = I_m V_m \cong I_{sc}\left[V_{oc} - V_T \ln\left(1 + \frac{V_m}{V_T}\right) - V_T\right] \tag{6}$$

Current-voltage characteristics after grating reflection

The I-V characteristic curve of the illuminated solar cell is given by the equation (7). Considering the open-circuit, we assume I = 0

$$I = -I_{ph} + I_o[e^{\frac{V_{oc}}{nV_T}} - 1] = 0 \tag{7}$$

Then, the formula results in the V_{oc} in equation (8) is

$$V_{oc} = V_T \ln\left(\frac{I_{ph}}{I_o}\right) \tag{8}$$

In equation (8), I_{ph} is photoelectric current decided when solar cell is illuminated by light intensity I, I_{ph} = rKI, where r is the reflection ratio, K is the device constant, respectively. Therefore, when an incident light is shown in figure 1, the solar cell surface is repeatedly illuminated resulted from the reflected light propagating between the solar cell board and the gratings where r_1 is the reflecting ratio of solar cell substrate and r_2 is reflecting ratio of the polymer gratings. According equation (8), then the V_{oc} can be reasonably changed and given as equation (9)

$$V_{oc2} = V_{Oc1} + V_T \ln\left(\frac{I_{ph2}}{I_{Ph1}}\right) = V_{oc1} + V_T \ln\left(\frac{r_1 r_2 KI}{KI}\right)$$
$$= V_{oc1} + V_T \ln\left(r_1 r_2\right) \tag{9}$$

Where; the I_{ph2} is defined as the product of KI and double reflection factor of r_1r_2.

Therefore, the total average open-circuit voltage, V_{ocav} , of the solar cell is given as equation (10)

$$V_{ocav} = \sqrt{V_{oc1}^{\ 2} + V_{oc2}^{\ 2}} \tag{10}$$

Although the 2nd open-circuit voltage,V_{oc2}, resulted from the repeated reflection light between solar and gratings are less than the 1st open-circuit voltage,V_{oc1}. But, from equation (10), the final V_{ocav} which is greater than V_{oc1} and V_{oc2} is calculated by the geometry sum of open-circuit voltages.

Similarly, because the short-circuit current is a photoelectric current, the intensity of short-circuit current is changed along with light and is given in equation (11)

$$I_{sc2} = I_{sc1}\left(\frac{r_1 r_2 KI}{KI}\right) = I_{sc1} r_1 r_2 \tag{11}$$

Where the suffix 1 and 2 for the I and V represent the first and second reflection parameters. The total average short-circuit current

Table 1. The specification of the commercial Si solar cell used in this study.

Items	Specification
Open-circuit voltage (V_{oc})	2.62 V
Short-circuit current (I_{sc})	109.1 mA
Maximum output voltage (V_m)	2.5 V
Maximum output current (I_m)	108 mA
Fill factor (FF)	94%
Power conversion efficiency (η)	27%
surface reflection ratio (r_1)	0.14

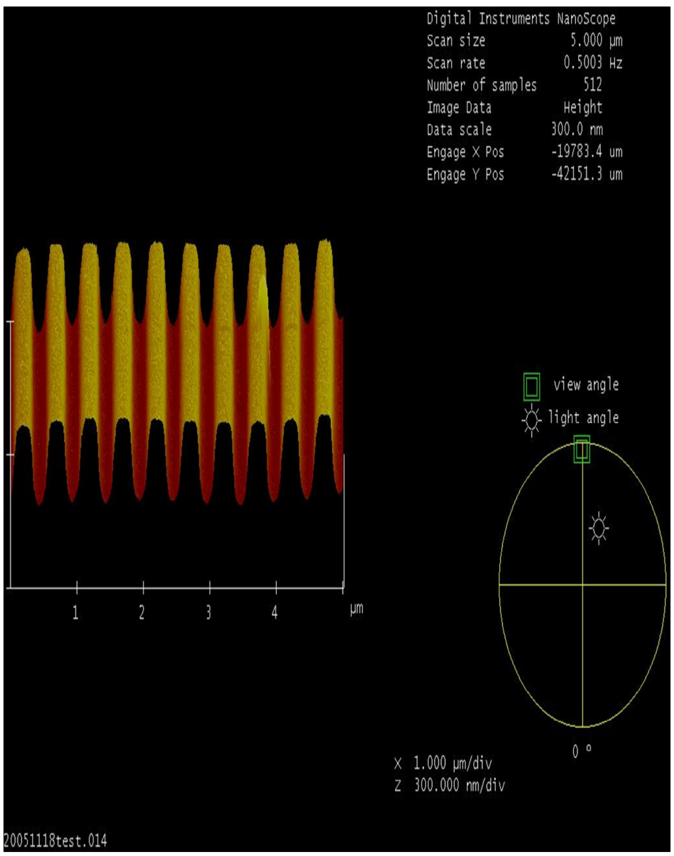

Figure 4. Surface reflecting gratings under AFM measurement.

(I_{scav}) is then given as;

$$I_{scav} = \sqrt{I_{sc1}^{2} + I_{sc2}^{2}} \qquad (12)$$

From equation (12), the final I_{scav} which is also greater than I_{sc1} and I_{sc2} is calculated by the geometry sum of short-circuit currents.

Finally, the power conversion efficiency (η) and fill factor (FF) in the solar cell are also given in equation (12 - 13)

$$\eta = \frac{I_m V_m}{P_{in}} \qquad (13)$$

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} \times 100\ \% \qquad (14)$$

RESULTS AND DISCUSSION

In this work, two kinds of solar cells are compared with each other, one with high polymer reflecting diffractive-mode gratings and the other without gratings. The calculation between two type of solar cells including short-circuit current (I_{sc}), open-circuit voltage (V_{oc}) and power conversion efficiency (η) are discussed. During the experiment, a commercial Si-based solar cell is used to form the gratings on its surface and its specification is listed in Table 1. Firstly, the Figure 4 is the result of AFM measurement in fabricating the surface polymer gratings (Yen et al., 2005). In Figure 4, the polymer grating period of 0.5 µm and depth of 184.61 nm in the OG polymer condition can be seen. From experiment, it is found that the periods in the photo-resist and OG polymer conditions are 0.52 and 0.5 µm, respectively. But, the depths in the photo-resist and OG polymer conditions are 212.24 and 184.61 nm respectively. The resulted minor deviation and decrease in dimension is mainly due to the PDMS residual during reprint process from photo-resist into OG polymer process. In addition, the reflection ratios of 0.14 and 0.06 for the independent solar cell surface and polymer gratings are measured by PL spectrometer for measuring solar cell surface optical characteristics. It implies that the reflection ratio r_1 is equal to 0.14 and the reflection ratio r_2 is 0.06 in this research, respectively.

When the parameter data of the solar cell listed in Table 1 are put into equation (2) to (14) and set the solar cell surface reflection ratio as a constant of r_1 = 0.14 (when investigating the same solar cell), then the relation of I_{sc}, V_{oc}, η vs. r_2 can be plotted by MATLAB software. The reflection ratio r_2 acts as a parameter which is dependent on the polymer grating depth and width. The relation of I_{sc} vs. r_2 is shown in Figure 5. It is found that I_{sc} increases with increasing r_2 and the value is 109.1 mA while r_2 is equal to the grating reflection ratio of 0.06. This value is almost unchanged compared with that in r_2 = 0. The range of calculated I_{sc} is just varied from 109.1 - 110.1 mA. On the other hand, Figure 6 shows the relation of V_{oc} vs. r_2 and the V_{oc} also increases with the increase of r_2. From Figure 6, it is found that the V_{oc} is rapidly increased from r_2 = 0 - 0.1 but gradually approaches 3.67 V. At the point (V_{oc}, r_2) = (3.618, 0.06), it represents the open-circuit voltage is equal to 3.618V after coating surface gratings on the solar cell. The range of calculated V_{oc} is varied from 2.62 - 3.67 V. Finally, the relation of η vs. r_2 is shown in Figure 7. It is worth to note that the rapidly increased trend of power conversion efficiency is the same with that of V_{oc} at r_2 = 0 - 0.1. When increasing the grating ratio (r_2) up to unity, the power conversion efficiency (η) will approach 39%, that is, the power conversion efficiency without coating surface gratings is 27% which is listed in

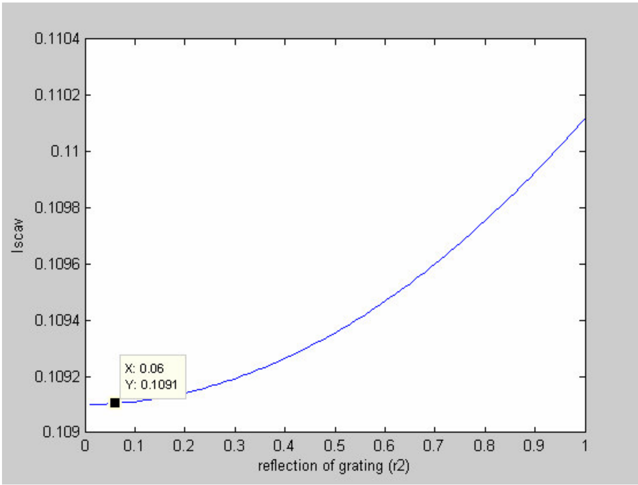

Figure 5. Polymer grating reflecting ratio (r_2) vs. I_{sc} under $r_1 = 0.14$.

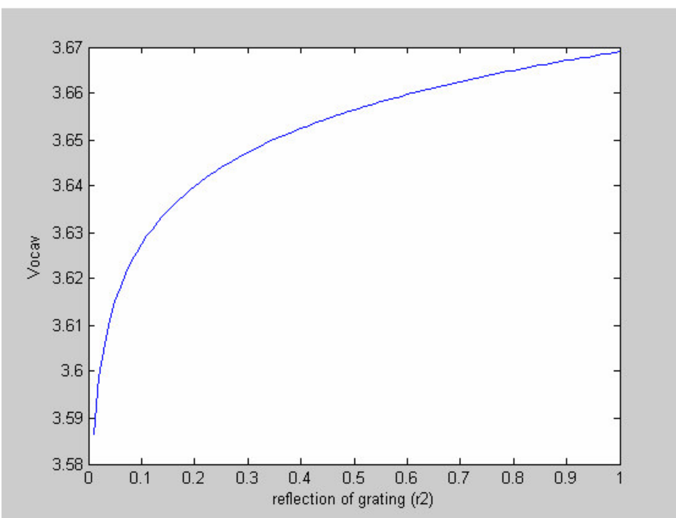

Figure 6. Polymer grating reflecting ratio (r_2) vs. V_{oc} under $r_1 = 0.14$.

Table 1, but can be 39% after coating surface polymer gratings at r_2 approaching unity. Thus, the maximum variation predicted in power conversion efficiency can be as high as 12%. In addition, the theoretical calculation and experimental results are compared. All the parameters in the I-V characteristics of the surface-grated solar cell are measured by the solar cell analyzer under standard light source simulator. The measured parameters, I_{sc}, V_{oc}, I_m, V_m, FF and η, are listed in Table 2. From Table 2, it is found that the theoretical power conversion efficiency is 37.91%, but 35.67% in experiment under $r_1 = 0.14$, $r_2 = 0.06$. The inaccuracy between theoretical calculation and experimental data is minor and its error is less than 4.6%. It also represents

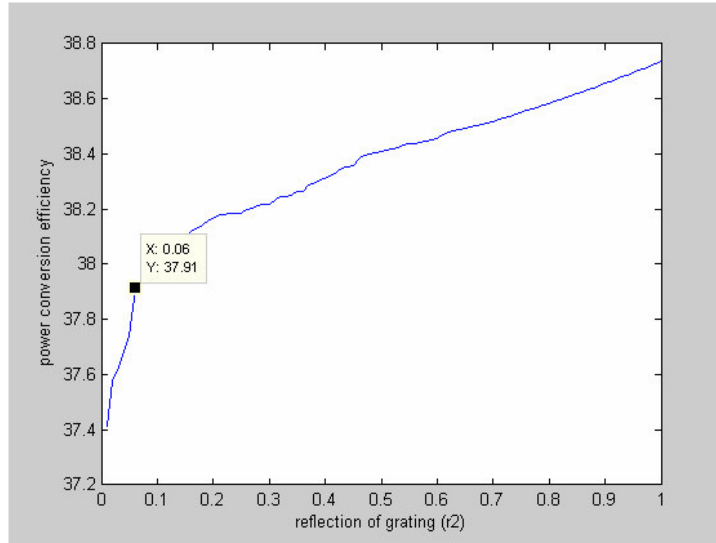

Figure 7. Polymer grating reflecting ratio (r_2) vs. power conversion efficiency (η%) under $r_1 = 0.14$.

that the theoretical calculation well predicts the experiment results and is very reasonable for each other.

Conclusion

A high polymer grated solar cell with excellent periodicity and uniformity is fabricated for the first time. From theoretical analyses and experimental results, the predicted power conversion efficiencies after coating surface gratings are both enhanced and nearly matched. The power conversion efficiency for the solar cell with surface gratings is theoretically enhanced from 27 - 37.91%, corresponding to the relative increase of efficiency up to 40.4%, but experimentally enhanced from 27 - 35.67%, corresponding to the relative increase of efficiency up to 32.1%. For a solar cell with high surface reflection ratio (r_1), it is possible to promote its power conversion efficiency (η) just through coating the surface polymer gratings to recollect the repeatedly reflected light in this study. The grating reflection ratio (r_2) is adjustable and can be changed by varying the width and depth of surface gratings to look for the suitable perimeter ratio for the optimal design. Based on the physical understanding the concept of coating surface polymer gratings on the solar cell, it may be possible to develop a high-efficiency solar cell in the future.

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Table 2. Comparative specifications of the solar cell with gratings after calculation (at $r_1 = 0.14$, $r_2 = 0.06$) and experimental measurement.

Items	Specifications after calculation	Specifications after measurement
Open-circuit voltage (V_{oc})	3.62 V	3.6 V
Short-circuit current (I_{sc})	109.1 mA	108.5 mA
Maximum output voltage (V_m)	3.5 V	3.35 V
Maximum output current (I_m)	108 mA	106.5 mA
Fill factor (FF)	95.71%	91.34%
Power conversion efficiency (η)	37.91%	35.67%

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