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A compact and high-power silicon-wafer solar strip-cells-array module integrated with an array concentrator*

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A compact, low-cost and high-output-power silicon-wafer solar strip-cells-array module (SCAM) was experimentally demonstrated. The proposed SCAM consisted mainly of a silicon-wafer strip-cell sparse array and low-concentration-ratio array concentrator based on an epoxy resin polymer (ERP) cylindrical plano-convex lens. A polymer replication process based on a polydimethylsiloxane mold was used to fabricate the ERP lens array concentrator. The results show that 46.94% of the silicon-wafer cell was saved in the designed SCAM. Moreover, the output power of the SCAM with a low concentration ratio of 8 suns was improved by 8.6%, compared with a whole piece of a conventional silicon-wafer solar cell with the same area as the module. The proposed method encapsulating solar cells provides a means to reduce the usage of silicon cells in modules as well as improving the output power of modules.

Keywords: epoxy resin polymer lens, strip-cell array, low concentration ratio

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1. Introduction

Solar energy is one of the most promising renewable energy sources because it is both free and provides an unlimited supply. The solar cells, including flat-plate photovoltaic (PV) and concentrated PV (CPV) cells, directly convert solar radiation into electrical energy by the PV effect. Concentrating photovoltaic systems are based on the concept of concentrating sunlight and have the potential to play the role of a major contributor to the future clean electricity.[1] The non-contact CPV has the following advantages:[2] (i) solar cells are more efficient at high concentrations; (ii) electricity production by CPV can start earlier and extend later in the day due to tracking; (iii) concentrators use less cell materials, either silicon or GaAs in a PV system; (iv) CPV replaces the expensive silicon or GaAs used in solar cells with low-cost materials such as glass, mirror, and plastic. This reduces the total solar cell area. The traditional non-contact highly-concentrated CPV systems generally consist of four parts including a concentrator, cell, tracker, and cooler.[3–9] The theoretical limit of a high-concentration silicon solar cell was predicted to be 53% under a solar concentration of 46200 suns.[10] Unfortunately, the high-concentration solar cell system requires very complicated installations, as the use of high-concentrating optics, cooling systems, and very precise sun trackers are required. One of the challenges in CPV is the generation of large amounts of heat due to the illumination of concentrated sunlight, resulting in heating of the solar cell. High solar cell temperatures cause losses in the photoelectric conversion efficiency and should therefore be avoided. To keep the temperature of the CPV cells reasonably low, passive or active cooling elements are typically employed.[11]

Although the high-concentration PV concept has been theoretically studied for many years, it has not been considered in commercial applications because of the lack of a suitable solar cell capable of withstanding the punishing environment produced by highly concentrated sunlight.[12] Conversely, low-concentration-ratio PV solar cells have attracted a great deal of interest due to their cost-effectiveness in recent years.[13–18] Low-concentration CPV systems concentrate the sunlight within several tens of suns,[15–18] avoiding the need for expensive and complex optical and thermal management systems that are required for high concentration systems.[3–9] Various contact low-concentrating thin-film solar cells and/or cell arrays hold significant promise.[19–23] However, the silicon-wafer PV industry controls almost 85% of the global market because of the relatively high efficiency of silicon-wafer PV cells and the gradually reducing fabrication cost.[11,24–26] Therefore, many opportunities continue to exist for research into unconventional means of exploiting advanced silicon-wafer photovoltaic systems.[27–29]

In this paper, we demonstrate a compact silicon-wafer strip-cell-array module (SCAM) encapsulated with a low-concentration lens array concentrator. The ability to define the spacings between strip-cells in sparse arrays and to concentrate the sunlight in an array form provides a method of producing modules with engineered levels, reducing the usage of

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silicon cells and at the same time improving the output power of the modules. Figure 1 shows a cross-sectional schematic diagram of the SCAM with three periods. The basic idea is to partition a bulk silicon-wafer cell into narrower strip-cells and then to arrange them in a sparse array. The solar cells array is covered with a thin array concentrator. The cylindrical plano-convex macro-lens array collects all incoming sunlight and focuses it onto the strip-cells. Thereby, all incoming sunlight is absorbed by the strip-cells that only cover a fraction of the substrate surface. This creates significant material savings in the silicon-wafer solar cell and improves the efficiency of the cell because of the use of the concentrator.

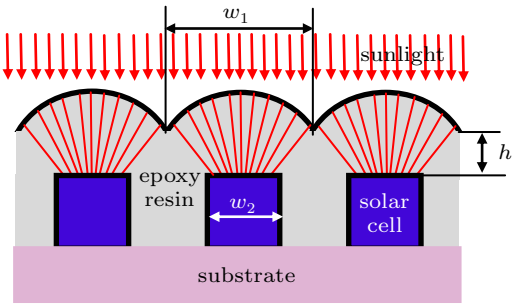


Fig. 1. Concept of the concentrated solar cells array module with three strip-cell periods and geometric parameters.

2. Experiments

The fabrication procedures are schematically shown in Fig. 2. The preliminary millimeter-sized-in-width glass-based cylindrical plano-convex lenses were purchased from commercial corporations. The radius of curvature, edge thickness, center thickness, width, and length of each glass lens shown in Fig. 2(a) were 1.8, 0.8246, 1.8, 3.2 and 30 mm, respectively. After rinsing with 70% alcohol and being dried, 6 glass-based lenses were glued side by side to a substrate of glass, forming a prototype mold of the lens array, as shown in Fig. 2(b). The lens array mold was placed into a plastic container. The polydimethylsiloxane (PDMS) solution, which was obtained by mixing a prepolymer (Sylgard 184 A, Dow Corning) mixed with a curing agent (Sylgard 184 B, Dow Corning) at a weight ratio of 10 : 1, was poured into the container, as shown in Fig. 2(c). After vacuumizing at 0.1 Pa to expel air bubbles, the mixture was thermally cured in a vacuum drying oven at 80 °C for 6 h. The PDMS imprint stamp with a concave array structure was fabricated by peeling it off from the glass-based prototype mold, as shown in Fig. 2(d).

The bare silicon-wafer solar cell was bought from a commercial company. The array solar cell module and encapsulation process were as follows. Firstly, a whole piece of silicon-wafer solar cell (WSSC) with an area of 19.6×26 mm^2 was equally laser-cut into 12 strips of solar strip-cells, where only one fingerprint electrode on the front surface of each strip-cell was retained in the cutting and every electrode wire was located as close to the edge of every strip-cell as possible. The width and area of each solar strip-cell were 1.6 mm and 1.6×26 mm^2, respectively, and the cutting-loss area of the silicon solar cell was $\sim 0.44 \times 26$ mm^2. Secondly, the 6 strip solar cells connected in parallel were periodically mounted on a substrate of glass, where the interval of the solar cells was fixed at 1.6 mm forming a bare silicon-wafer solar cell array (BSSCA). After cleaning with nitrogen, the BSSCA was placed into a plastic container. Thirdly, an epoxy resin A (BS-1202A) was mixed with a curing agent (BS-1202B) at a weight ratio of 2 : 1. After stirring for 5 min, the mixed epoxy resin solution was poured into the container to cover the BSSCA. The thickness of the epoxy resin film was controlled by the amount of the poured epoxy resin solution. Fourthly, the PDMS stamp was gently placed onto the epoxy resin solution and the center of every strip-cell was placed at the center of every concave lens in the PDMS stamp as close as possible, as shown in Fig. 2(e). This was followed by vacuumizing at 0.1 Pa to expel the air between the PDMS and the epoxy resin. After 8 h of curing at 100 °C, the PDMS stamp was gently peeled off from the epoxy resin polymer (ERP) and finally a SCAM encapsulated by the ERP film with a convex cylindrical lens array structure surface was formed, as shown in Fig. 2(f).

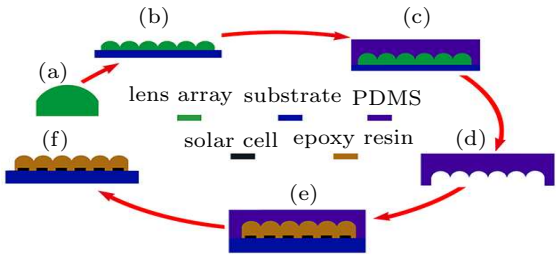


Fig. 2. Schematic plot of the fabrication procedure.

The solar cell I–V curves were measured using the test system (Keithley 2420+Newport Class 3A solar simulator + the PVIV software package from Newport) under AM1.5G simulated illumination. The electrical performances of the SCAMs were characterized by the output power P, maximum output power P_{max}, short-circuit current I_{sc}, short-circuit current density J_{sc}, open-circuit voltage V_{oc}, fill factor FF, series resistance R_{sc} at short-circuit current, shunt resistance R_{oc} at open-circuit voltage, and the I–V curve. The isotropic and cross-sectional images of the fabricated polymer lenses array and silicon solar cell array system were obtained with a digital camera using a macro lens.

3. Results and discussion

To achieve a low-cost, compact, and contact concentrating solar cell, the concentrator cannot be too thick, otherwise the cost and weight of the SCAM increases, which is disadvantageous for solar cell applications. Taking this factor

into account, we designed the thin concentrator of the cylindrical plano-convex lens array with the structure presented in Section 2. In this experiment, the curvature radius and bottom width of the designed cylindrical lens were 1.8 mm and 3.2 mm, respectively, and therefore the contact angle of the lens was $T = 62.73$. Such a contact angle can decrease the reflectance and improve the conversion efficiency of the solar cell.[20,28] The light transmittance of the ERP with a refractive index of 1.58 was 92% for a 500-nm wavelength and its stiffness was quite strong (Yung's modulus is 3.43 GPa).[31] These characteristics are useful for improving the efficiency and protecting the silicon solar cell from environmental damage. Therefore, transparent epoxy resin was chosen as the material of the lens and supporting layer. According to the structure parameters and material of the lens, the calculated focal length of the lens was $f = 4.903$ mm in the ERP and therefore the maximum height of the supporting ER layer was $h = 3.928$ mm. According to the ray optics, we calculated the concentration factor of the device as a function of h, as shown in Fig. 3, where $\gamma = w_1/w_2$, w_1 is the width of incoming sunlight onto the lens, and w_2 is the width of the focused light area on the surface of the strip cell.

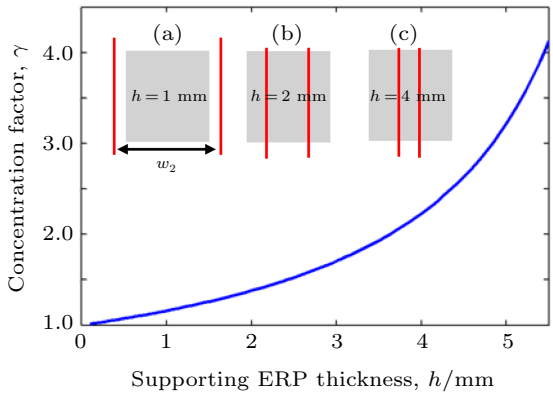


Fig. 3. Calculated concentration factor γ as a function of the supporting ERP height h (inset: schematic illustration of the width w_2 of the strip area of light focused onto the top surface of the strip cells).

Figure 4(a) shows a digital image of the PV performance test system. All tests were executed under the AM1.5 simulated illumination. Figure 4(b) shows the measured output power P of the SCAM for several different values of $h = 1.95$, 2.60, 2.93, 3.12, 3.25, 3.35, 3.42, 3.47, and 3.51 mm (the corresponding values of γ were from 2 to 10). For comparison, the measured output power of the WSSC cell packaged with a flat ER film 2 mm thick is plotted as the straight blue line shown in Fig. 4(b). In Fig. 4(b) the P of the SCAM showed nonmonotonic behavior with h. As h began to increase, γ slowly increased and a part of the focused light was outside of the upper surface of each strip cell, as the schematic inset on the left shows in Fig. 3, and consequently P of the SCAM slowly increased. For two small values of $d = 1.95$ and 2.60 mm, P of the SCAM were smaller than 131.08 mW of the output power of the WSSC with flat ER film. As h increased to > 2.6 mm ($\gamma > 3$), all of the light was focused within the upper surface of each strip cell and γ exponentially increased with h. Therefore, P of the SCAM steeply increased with h, similar to the results of bulky solar cells with a non-contact concentrator.[5] For $h > 2.92$ mm ($\gamma > 4$) the rapid increase of γ with h enhanced the conversion efficiency of the silicon photovoltaic material illuminated by the focused light but the area of photovoltaic conversion in each strip solar cell decreased, as shown in the schematic inset on the right in Fig. 3. These results showed that there was a slow increase of P of the SCAM with h, with P reaching its maximum value of 142.38 mW at $h = 3.42$ mm ($\gamma = 8$). For large values of h, for example, $h = 3.47$ and 3.51 mm, the conversion efficiency reached a saturated value and P no longer increased. In fact, P decreased slightly with h, probably due to the increase of the ERP adsorption with h.

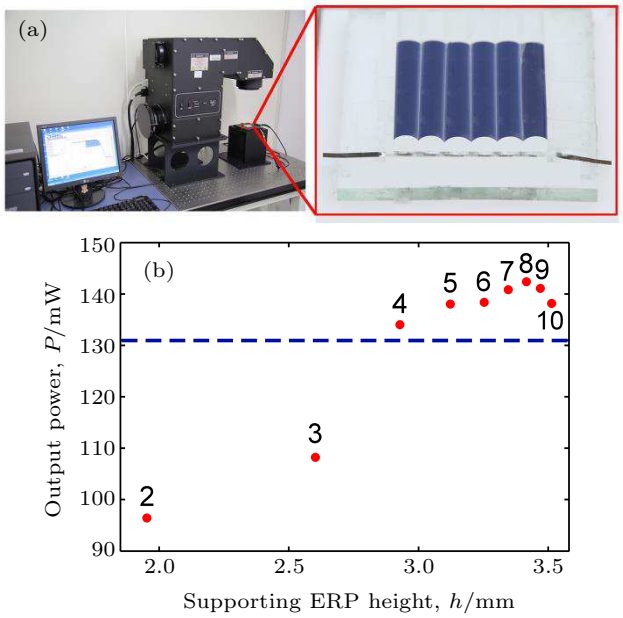


Fig. 4. (a) Digital image of the measurement setup, and (b) output power of the SCAM solar cell systems as a function of the supporting ERP height. The straight blue line indicates the output power of the WSSC cell packaged by a flat ERP film 2 mm thick, and the number above each output power (red dot) indicates the value of γ corresponding to h. The inset in panel (a) is the enlarged image of the measured SCAM.

Figure 5 shows the I–V curve of the SCAM with 6 strip-cells at $h = 3.42$ mm ($\gamma = 8$). For comparison, the I–V curve of the WSSC cell packaged by a flat ERP film 2 mm thick is also shown in Fig. 5. The test conditions for the two modules were kept unchanged and the area of illumination for the SCAM cell was the same as that for the WSSC cell. The measured electrical performance parameters of the two cells are presented in Table 1. It was found from the table that V_{oc}, J_{SC}, FF, P_{max}, and P of the SCAM cell were larger than those of the WSSC cell, due to the effect of the focused light incident onto

strip-cells.[5,20] Although both large R_{sc} and small R_{oc} of the SCAM cell, due to the reduction of strip-cells cross sectional area, resulted in a decrease of the short-circuit current I_{sc}, the overall effect was that the output power of the SCAM was improved by 8.6% over the WSSC. In addition, taking the cutting loss into account, 46.94% of the silicon-wafer cell usage in the WSSC was saved in the designed SCAM with the same module area. In addition, the low-cost and high output-power SCAM modules can be easily fabricated by a simple single-step replication process using a PDMS mold with a cylindrical plano-concave lens structure.

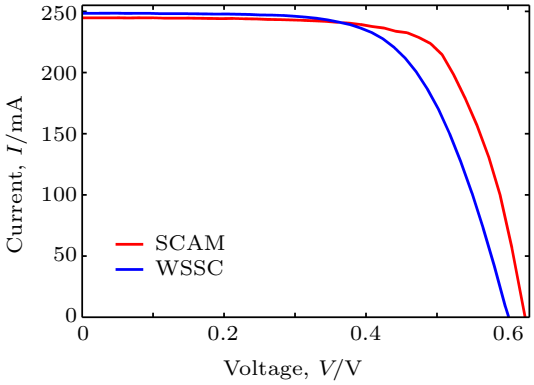


Fig. 5. I–V curves and performance parameters of the SCAM using the concentrator with $\gamma = 8$ at $h = 3.42$ mm, and WSSC without any concentrator under 1-sun AM1.5 illumination.

Table 1. Electrical performance parameters of the SCAM and WSSC cells.

Cell	J_{sc}/mA·cm^{-2}	I_{sc}/mA	V_{oc}/V	P_{max}/mW	P/mW	FF/%	R_{sc}/Ω	R_{oc}/Ω
SCAM	74.17	244.79	0.62	112.11	142.38	67.34	1448.71	0.76
WSSC	50.58	248.54	0.61	96.89	131.08	65.12	1234.59	0.62

4. Conclusion

In this work we have presented a compact silicon-wafer solar strip-cell array module integrated with a low-cost and low-solar-concentrating ERP lens array using a plano-concave PDMS-mold replication process. When the supporting ERP height was 3.42 mm, corresponding to a low concentration ratio of 8 suns, a maximum output power was obtained. Compared to the WSSC cell with the same illuminated area, our module can save the usage of bare silicon-wafer cell by 46.94% and improve the output power by over 8.6%. The SCAM module could have many practical applications due to its advantages such as its compact architecture, simplicity and cost-effectiveness in manufacturing, as well as saving the consumption of solar-wafer cells and enhancing power conversion performance.

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