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Omni-direction PERC solar cells harnessing periodic locally focused light incident through patterned PDMS encapsulation†

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Photovoltaic panels based on crystalline Si solar cells are the most widely utilized renewable source of electricity, and there has been a significant effort to produce panels with a higher energy conversion efficiency. Typically, these developments have focused on cell-level device modifications to restrict the recombination of photo-generated charge carriers, and concepts such as back surface field, passivated emitter and rear contact (PERC), interdigitated back contact, and heterojunction with intrinsic thin layer solar cells have been established. Here, we propose quasi-Fermi level control using periodic local focusing of incident light by encapsulation with polydimethylsiloxane to improve the performance of solar cells at the module-level; such improvements can complement cell-level enhancements. Locally focused incident light is used to modify the internal quasi-Fermi level of PERC solar cells owing to the localized photon distribution within the cell. Control of the local focusing conditions induces different quasi-Fermi levels, and therefore results in different efficiency changes. For example, central focusing between fingers enhances the current density with a reduced fill factor, whereas multiple local focusing enhances the fill factor rather than the current density. Here, these effects were explored for various angles of incidence, and the total electrical energy production was increased by 3.6% in comparison to a bare cell. This increase is significant as conventional ethylene vinyl acetate-based encapsulation reduces the efficiency as short-wavelength light is attenuated. However, this implies that additional module-scale studies are required to optimize local focusing methods and their synergy with device-level modifications to produce advanced photovoltaics.

1. Introduction

Photovoltaics based on crystalline Si solar cells are a promising source of renewable energy owing to their relatively high conversion efficiency and the maturity of the manufacture process.[1] Many researchers have aimed to improve the efficiency of crystalline Si-based solar cells; some of the most important device structure improvements include the back surface field (BSF), heterojunction with intrinsic thin layer (HIT), passivated emitter and rear contact (PERC), tunneling oxide-passivated contact (TOPCon), and interdigitated back contact (IBC) structures.[2–15]

Developments in crystalline Si-based solar cell technology aim primarily to reduce the premature recombination of photo-generated charge carriers as they are transported to the metal contacts that are connected to the external circuit,[2–8,13–15] and maximize the light incident on the solar cells by placing the emitter and collector contacts on the back side.[9–12] Oxide surface passivation can be used to eliminate Shockley–Read–Hall (SRH) recombination sites in PERC and TOPCon structures, which produce internal fields that prevent generated charge carriers from reaching SRH sites.[2–8] Furthermore, HIT cells were introduced to reinforce the internal field and form a selective barrier.[13–15] IBC structures are used to remove the metal grid and fingers from the front face as they form a physical barrier between incident light and the solar cells.[9–12] By combining these developments, the efficiency of a HIT–IBC crystalline Si-based solar cell can exceed 26.7% under 1 sun, AM1.5.[13]

The efficiency of crystalline Si solar cells can be improved further by controlling the current path of photo-generated carriers *via* modification of the quasi-Fermi level of each charge carrier so that low-loss paths are selected until collection and a greater external voltage load is required to compensate for the generated diode current.[1] However, controlling the quasi-Fermi level distribution in solar cell devices by modifying only the junction structure and doping concentration is very difficult and can be inefficient. The charge carrier concentration can be used to control the quasi-Fermi level within the solar cell.

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Control over the microscopic light intensity within the solar cell device can allow control over the generation rate and excess charge carrier concentration. Recently, silicone-based encapsulation methods have been proposed as they overcome the efficiency losses that result from conventional encapsulation materials[16–22] such as ethylene vinyl acetate (EVA)–glass or EVA–polymer films that attenuate short-wavelength light.[23–26] Optical geometries that modify the light distribution across solar cells can be easily patterned into the encapsulating material during casting.

In this study, we investigated the effects of periodic local focusing of incident light using cylindrical lens structures cast into polydimethylsiloxane (PDMS) used to encapsulate PERC solar cells (see ESI Fig. S1†), and the performance of these cells was measured for various angles of incidence (AOIs). The periodic locally focused light between each finger provided microscopic modification of the quasi-Fermi level of each photo-generated carrier, which altered the current distribution within the cells. Analysis of the light focusing function and performance of crystalline Si solar cells presents new opportunities for photovoltaic efficiency improvements. Specifically, we expect that the combination of cell-level structural improvements and module-level light conditioning will enable the production of advanced photovoltaic modules.

2. Experimental details

2.1 Fabrication of optical patterns

For optical patterns, glass substrates were spin-coated with dry film photoresist (MS7100, Mitsubishi). Photoresist was patterned photolithographically by exposure to ultraviolet light using a mask aligner. Patterns were then etched using a micro-blast with 600-mesh powder and the photoresist was removed using 1% sodium hydroxide. Patterns were then etched using a hydrofluoric acid solution.

2.2 Fabrication of PDMS stamps

To replicate etched patterns, PDMS (SR-580, Heesung STS) was poured over and cured on the etched glass substrate in an oven for 40 min at 70 °C. Cured PDMS replicas (PDMS mold) were ozone-treated using a UV ozone cleaner (AT-6, AhTech LTS) for 10 min, followed by treatment with trichloro(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)silane (Sigma-Aldrich) in a vacuum oven to easily separate the PDMS mold and stamp.

Optical PDMS stamps were fabricated by replicated the PDMS mold using PDMS (Sylgard 184, Heesung STS), which was cured using the same conditions and then ozone-treated and silane-treated with the same solution in a vacuum oven to produce a Si solar cell encapsulation layer.

2.3 PDMS encapsulation of a Si solar cell

PDMS (SR-580, Heesung STS) was prepared for the encapsulation of PERC (LWM5BB, Lightway) solar cells using a casting process. A PDMS stamp was attached by stamping the masked area with PDMS (SR-580, Heesung STS) and curing for 1 h at 70 °C in an oven. The stamp was removed from the cells after curing.

2.4 Characterization

Field-emission scanning electron microscopy (S4800; Hitachi) was used to image the surface and cross-sections of the patterned PDMS encapsulation layer. The photovoltaic performance of the encapsulated solar cells was measured by first calibrating a solar simulator (Sun 2000, 1000 W xenon source; Abet Technologies; 2400 Keithley source meter) with a KG-3 filter and an NREL-certified reference cell, and then setting the simulator to 1 sun, AM1.5 conditions. Photovoltaic performance was measured with respect to the AOI using a custom jig that was designed to accurately tilt the plane.

2.5 Calculation of internal quasi-Fermi level

The charge carrier concentration and induced quasi-Fermi level within the PERC type solar cells were calculated by PC2D, which is well-known spread-sheet based simulation tool for mono-crystalline Si based solar cells suitable for 2D simulation. In order to simulate periodically local focusing of incident light, the input light intensity according to the location were modified considering the focusing situations given by silicone encapsulation patterns. The basic device parameters, such as doping concentration and thickness of wafers, were obtained by catalog of purchased PERC solar cells.

3. Results and discussion

3.1 Theoretical calculations

The efficiency of crystalline Si solar cells has been improved by suppressing SRH recombination and reducing the shadows cast by indigitated fingers or grids at the device and cell levels.[1–15] Modification of the quasi-Fermi level within the device can also affect cell performance as the recombination rate loss is altered by the current flow path and the required external load voltage required to compensate the photo-generated current. Without complex junction modifications or doping controls, the quasi-Fermi level can be modified by controlling the charge carrier concentration distribution with the aid of light focused by the optical geometry of an encapsulation layer. As shown in Fig. 1(a) and (b), PC2D tools were used to calculate the modification of the quasi-Fermi level of PERC solar cells using focused light[23] in short and open circuit conditions. Light was focused on the center of the space between fingers and was closer to the fingers compared to that of homogeneous incident light (see ESI Fig. S2† for more calculated values). Using local focusing, the current distribution and quasi-Fermi level difference of the electrons and holes differed from that under homogeneous illumination for both short and open circuit conditions, as shown in Fig. 1(a) and (b), respectively. The current density in the device was determined using the charge carrier concentration and the gradient of the quasi-Fermi level as described in eqn (1), where e is the charge on an electron, and n and p are the electron and hole concentration of E_{Fn} and E_{Fp}, which are the quasi-Fermi potential of each charge carrier.

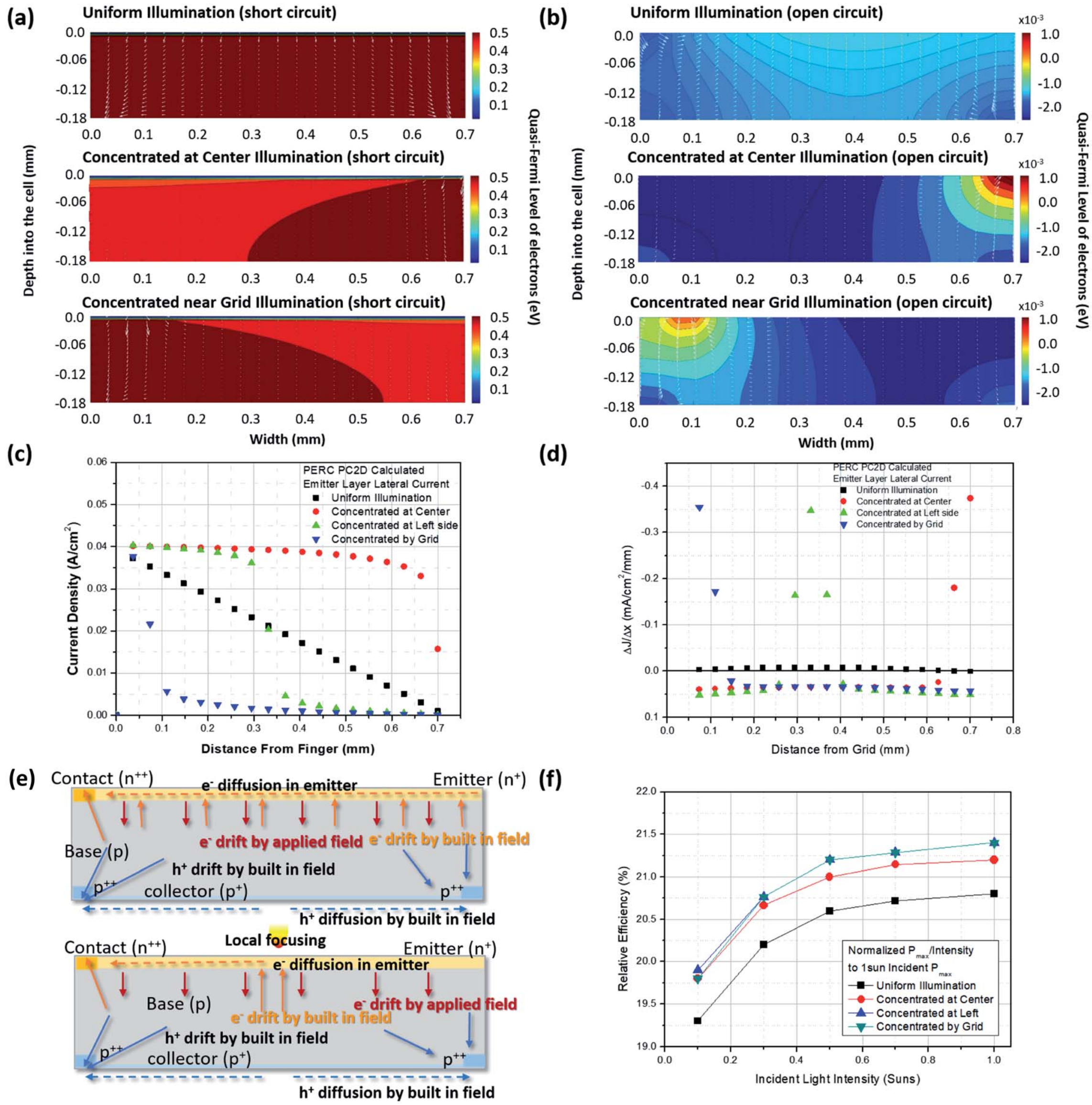

Fig. 1 The difference between the quasi-Fermi levels of electrons and holes calculated by PC2D under (a) short and (b) open circuit applied voltage conditions with homogeneous illumination, focused at the center of the gap between fingers, and focused near the fingers. (c) The calculated lateral current and (d) gradient of lateral current through the passivated emitter and rear contact (PERC) emitter layer for a short circuit under various local focusing conditions. (e) Schematic of the estimated charge carrier movement under homogeneous illumination and local focus. (f) Calculated efficiency of the PERC solar cell according to the incident light intensity and local focus.

$$J = J_n + J_p = e(n\nabla E_{Fn} - p\nabla E_{Fp}) \quad (1)$$

Therefore, the space distribution of the electrons, holes, and the resulting quasi-Fermi levels changed the current path as shown in Fig. 1(c), in which the lateral current in the emitter layer of a PERC solar cell is shown under focused and homogeneous illumination. This indicates that the current from the bulk to the emitter is dependent on the location of the focus, and the focus induced a localized current density within the device that did not spread into the bulk. The lateral current path in the emitter layer, shown in Fig. 1(d), was microscopically localized according to the light focusing control. As shown in Fig. 1(e), the module-scale modification of light incident on the solar panel can modify the current path within the solar cell device, which makes it a powerful tool for performance enhancement. Alteration of the current path not only affects the current density in a short circuit, but also the external voltage load required to compensate the photo-generated current by a diode current to establish open circuit conditions. Therefore, localized focused light can affect the short circuit current density, fill factor, and open circuit voltage of the solar cell. Interestingly, local focusing resulted in greater performance enhancement than homogenous illumination, as shown in Fig. 1(f). See ESI Table S1† for detailed performance values. Therefore, additional studies are required to identify mechanisms that would allow optimal cell conditions to be obtained using this new control tool.

3.2 Effect of periodic local focusing under vertical illumination

The calculated results were verified using silicone-based encapsulation technology.[24–26] Four surface geometries of PDMS encapsulation layers, identified as Cases 1 to 4, were prepared on PERC solar cells, as shown in Fig. 2. The PDMS encapsulation geometries were prepared by stamping during the PDMS casting process, and the light distribution produced by each geometry was simulated using raytracing methods, as shown in Fig. 2(a). In Case 1, notches were introduced to the finger regions of the PERC solar cell so that light incident on the finger was refracted into the solar cell region and reduced light loss due to obstruction by the fingers. In Case 2, a parabolic lens was added to the Case 1 geometry so that incident light was focused on the spaces between fingers. In Case 3, two lens shapes were introduced and Case 4 incorporated four lenses that were used to change the focus locations. Photographs of the encapsulated PERC solar cells of Cases 1 to 3 are presented in Fig. 2(b), which indicate that the patterns were well-aligned. Furthermore, the micrographs of each geometry shown in Fig. 2(c) prove that each geometry was well-constructed according to the design.

Local focusing by optical structures incorporated in a PDMS encapsulation layer can modify the performance of PERC solar cells as indicated by the relation between the current density and applied voltage (*I–V* behavior), as shown in Fig. 3(a). In comparison to bare solar cells, the short circuit current density (J_{sc}), fill factor (FF), open circuit voltage (V_{oc}), and resulting energy conversion efficiency were modified according to the PDMS geometry. In all cases, as expected from our PC2D calculations, the efficiency was increased compared to that of a bare cell. Furthermore, local focusing using PDMS structures is a method suitable for improving the performance of crystalline Si-based solar cells compared to that of conventional EVA-based encapsulation, which reduces efficiency. Therefore, the module-level efficiency improvement of silicone-based encapsulation is increased further. It is interesting to note that the *I–V* behavior differed with local focusing. The relationship between the logarithm of the current density and the applied voltage indicates the device status under the applied load according to an 'ideality factor.' As shown in Fig. 3(b), this relationship can be divided into three categories according to the focusing geometry: the bare cell and Case 1, Case 2, and Cases 3 and 4. In Case 1, the illumination is similar to that of a bare cell, except that the light incident on the finger region is refracted onto the active region. Therefore, the efficiency increased as a result of the increase in current density with little change in the V_{oc} and FF, as shown in Fig. 3(c). In Case 2, the current density increased more than in Case 1, but the FF decreased, as shown in Fig. 3(d). In Cases 3 and 4, the efficiency improvement was a result of the increased FF rather than the current density, as shown in Fig. 3(e) and (f). This indicates that the light distribution within the solar cell device can produce different operating conditions, charge carrier movements, and loss mechanisms. Therefore, microscopic and periodic local

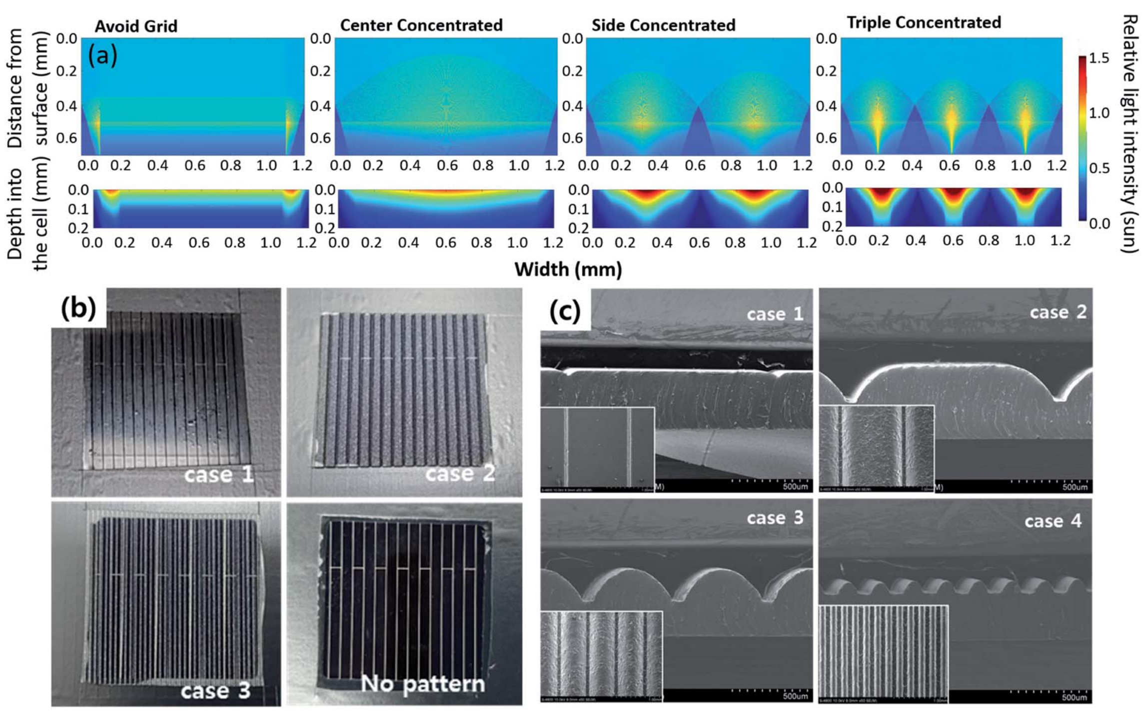

Fig. 2 (a) Light distribution on a solar cell and the photon distribution within the cell according to local focusing optical structures in the polydimethylsiloxane (PDMS) encapsulation calculated using raytracing methods. (b) Photographs of PERC solar cells encapsulated by PDMS optical structures. (c) Scanning electron micrographs (SEM) of each PDMS optical structure on PERC solar cells.

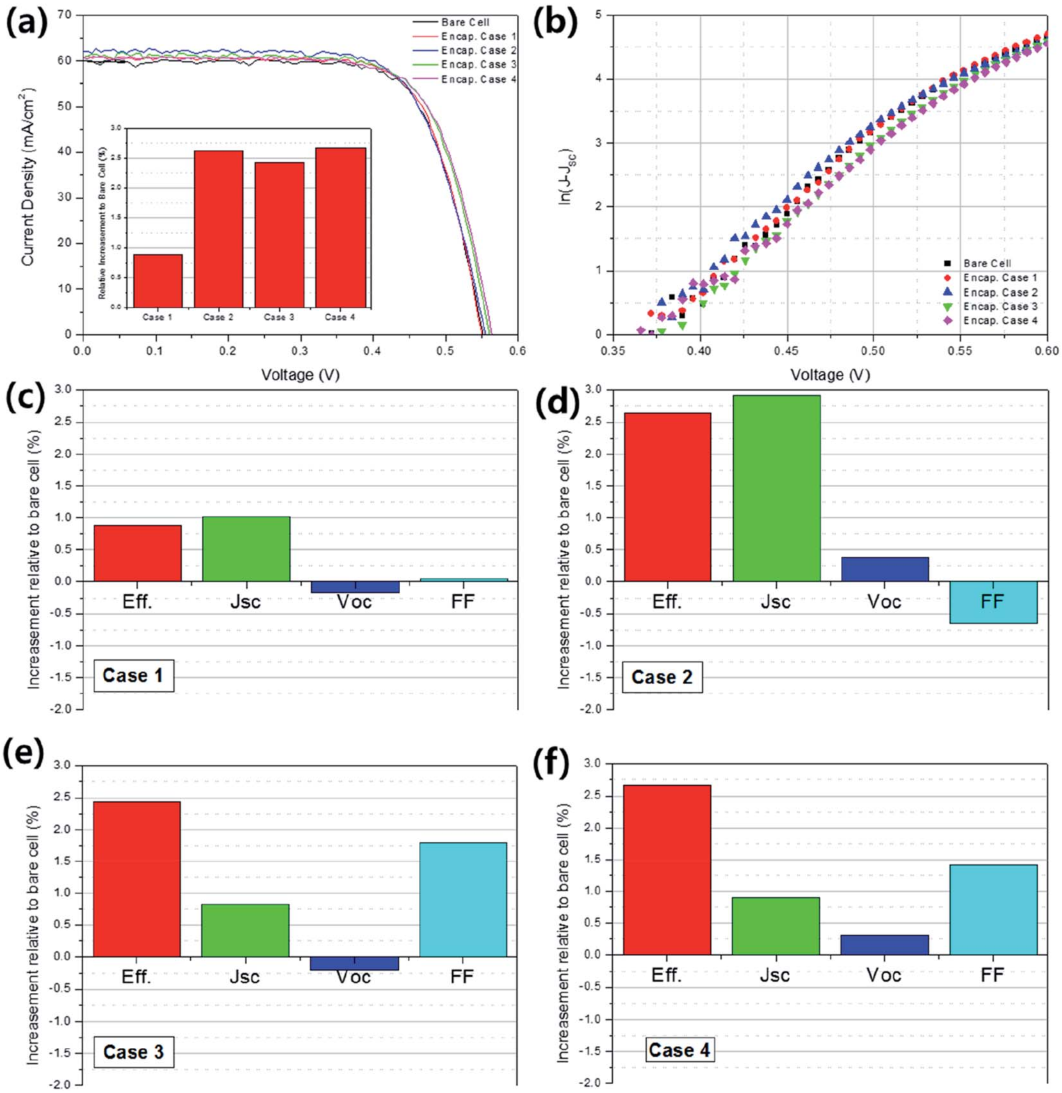

Fig. 3 (a) The relationship between current density and applied voltage for each PDMS-encapsulated PERC solar cell measured under 1 sun, AM1.5, and (inset) measured efficiency. (b) The relationship between the logarithm of current density and applied voltage of each Case. The relative change in efficiency, short circuit current density, open circuit voltage, and fill factor compared to those of a bare cell when (c) Case 1, (d) Case 2, (e) Case 3, and (f) Case 4 PDMS structures were used to encapsulate PERC solar cells are shown.

focusing and the resulting photon distribution control enables a new method of solar cell modification and enhancement that cannot be obtained using conventional device controls. Furthermore, these results are achieved using encapsulation processes that are independent of the crystalline Si solar cell type at the module level, and therefore can compliment improvements in the device or cell structure. However, this study has only indicated the potential of this technique; additional studies must be carried out to determine optimal photovoltaic structures.

3.3 Effect of periodic local focusing for oblique illumination

When optical structures are incorporated into the encapsulation layer for controlled local focusing, an obliquely incident light can alter the focus location and photon distribution in the solar cell. A half-cylindrical-shaped PDMS encapsulated solar cell can have two different AOIs. One AOI is in the direction of rotation, which is perpendicular to the rotation axis and parallel to the cylindrical axis, and perpendicular to the other AOI. When the rotation direction is parallel to the cylindrical direction it is expected that the local focusing location is unchanged. However, localized focusing conditions are expected to vary significantly according to the AOI and cylindrical geometries calculated using two-dimensional raytracing, as shown in Fig. 4. Fig. 4(a) shows an example for Case 2 in which the AOI was varied. The other cases are shown in Fig. 4(b). Fig. 4(c) shows the light distribution as a function of AOI for Case 3, which indicates that the focus location and concentration change as a function of AOI. As shown in Fig. 4(d), the focusing point appears to be split as a function of AOI in Case 2. These changes and the resulting photon distribution in the solar cell devices were calculated as shown in Fig. 4(e). The internal quasi-Fermi

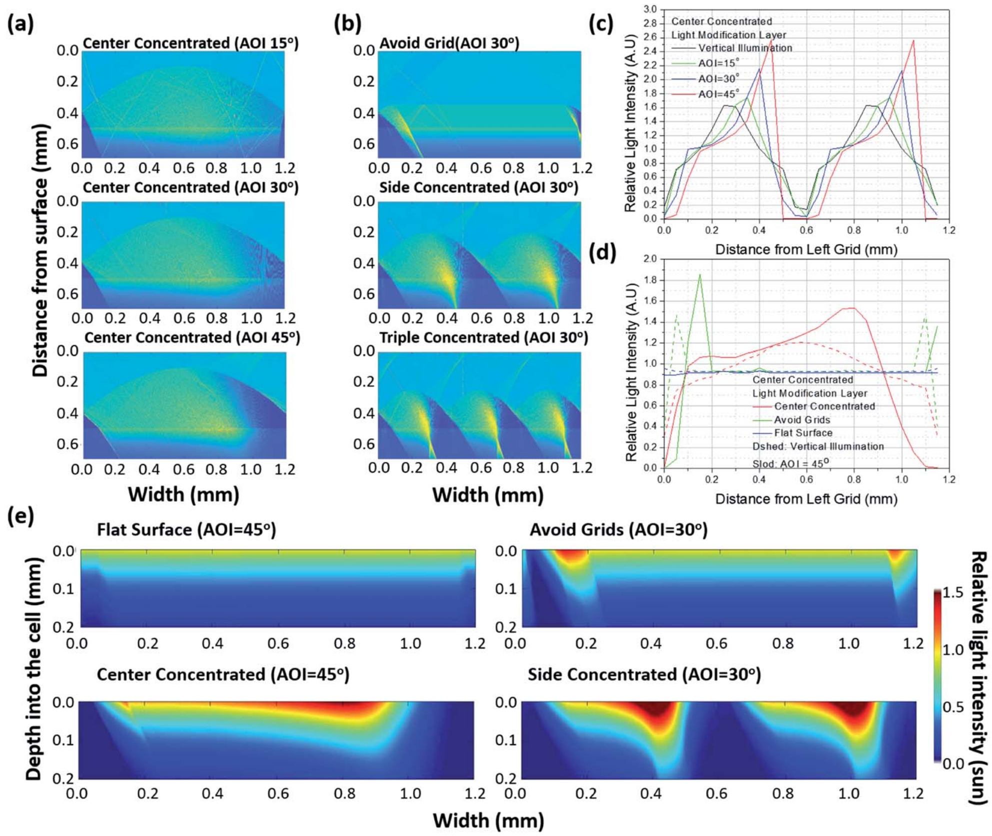

Fig. 4 Raytracing calculation results for light distribution in (a) the Case 1 PDMS structure on PERC solar cells according to the angle of incidence (AOI) and (b) each geometry at a 30° AOI. (c) Light intensity on the PERC solar cell surface encapsulated with a Case 3 structure according to AOI calculated using raytracing. (d) Light intensity on the PERC solar cell surface for different PDMS encapsulation geometries at a 45° AOI calculated using raytracing. (e) Light distribution within PERC solar cells for different PDMS encapsulations and AOIs, calculated using raytracing.

level was modified as a function of the AOI and the encapsulation optical geometries, and it is expected that solar cell performance is dependent on the AOI.

The photovoltaic panel was operated under various AOI conditions. The electricity produced by a photovoltaic panel depends not only on the efficiency under strong, vertical light, but also on its performance with a varying AOI. The half-cylindrical optical structure patterned in the PERC solar cell encapsulation material modified the AOI-dependent properties with respect to the properties of a bare cell, as shown in Fig. 5 (see ESI Fig. S3† for more detailed data). In general, the efficiency of crystalline Si-based solar cells decreases with an increasing AOI because a decreased area of light interception results in a smaller current density and V_{oc}.[27–29] Therefore, changes in the quasi-Fermi level within the solar cell owing to local focusing can produce a more significant effect on the performance for a large AOI. When the direction of rotation was parallel to the cylindrical direction of the PDMS structure, the local focus location was not expected to differ from that of vertical illumination. As shown in Fig. 5(a), the efficiency of a PDMS-encapsulated solar cell is greater than that of bare cells for a range of AOIs, and the degree of enhancement is like that resulting from vertical illumination, as shown in Fig. 3. However, the results differed as the AOI was rotated in a direction perpendicular to the pattern axis as the local focus point moved, as shown in Fig. 4. As a result, the electrical energy expected to be produced as a light source moved from 0 to 60° was different, as shown in Fig. 5(b). In all cases, electricity production increased owing to the introduction of notches in the contact fingers. The most electricity was generated using the Case 2 geometry as the AOI was varied parallel to the pattern axis. However, Case 4 produced the most electricity when the AOI was varied perpendicular to the pattern axis. In Case 2, local focusing was most affected by perpendicular movement relative to the pattern axis, so it was expected that various quasi-Fermi level conditions were generated as a function of AOI, as shown in Fig. 5(c). When vertically illuminated, the efficiency of the Case 2 design was improved by the increased current density and decreased FF. Typically, when the AOI was changed, the FF increased, and the current density and V_{oc} decreased, which is true in general for crystalline Si solar cells. The increase in FF occurs when the local focusing point is near the fingers, as shown in Cases 3 and 4 under vertical illumination. Therefore, a change in local focus increases the FF, and maintains an improved performance for all AOI conditions. In Case 4, as shown in Fig. 5(d), the change in FF was not large, and the performance was not affected by light distribution.

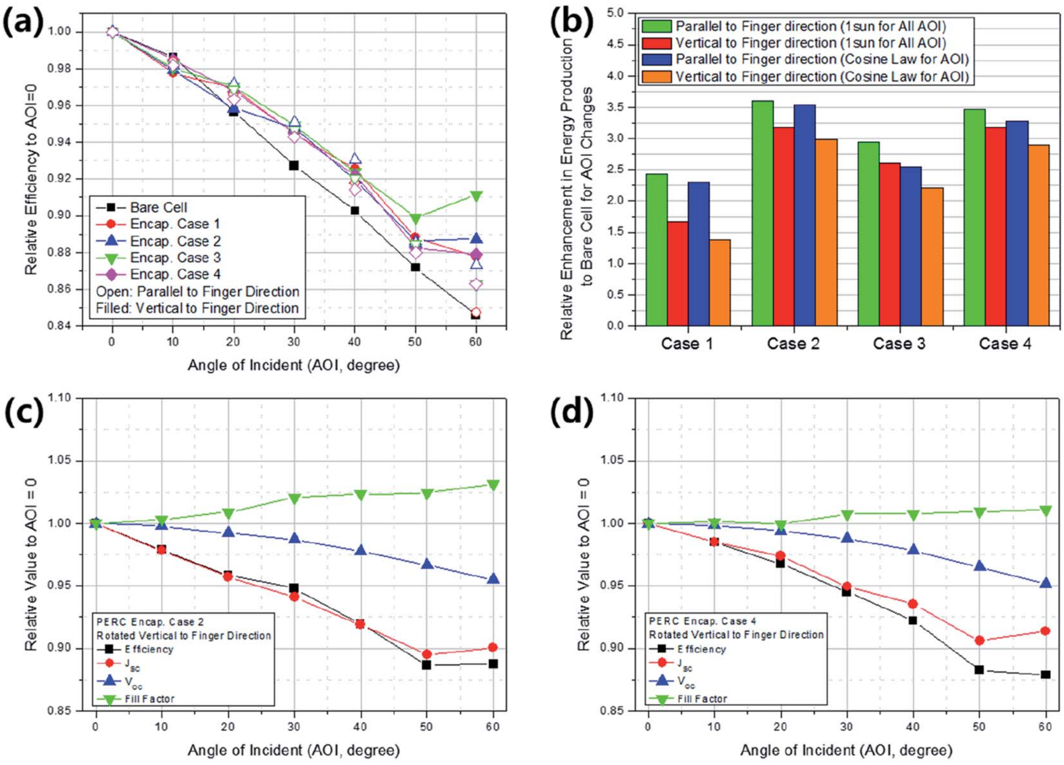

Fig. 5 (a) Efficiency relative to vertical illuminated conditions as a function of the AOI for each PDMS encapsulation geometry on a PERC solar cell. (b) The expected electric energy production relative to bare cells for each geometry of PDMS encapsulation on PERC solar cells. The variation in efficiency, short circuit current density, open circuit voltage, and fill factor according to the AOI for (c) Case 2 and (d) Case 4 PDMS structures on PERC solar cells.

We have proven the validity of quasi-Fermi level control by light distribution modification induced by periodic local focusing obtained using half-cylindrical structures in PDMS encapsulation on PERC solar cells under vertical and obliquely incident light. These new tools can be used to further advance the development of crystalline Si-based solar cells. This technique is applied at a module-level and can therefore be combined with cell-level developments to synergize with IBC and HIT devices. However, this study is limited to the simple case of half-cylindrical geometries, and the interesting improvements in performance should not be considered to have been optimized. Future studies should explore more efficient designs using a theoretical or experimental approach.

4. Conclusion

We suggest a new tool to improve the efficiency of crystalline Si-based solar cells using periodic local focusing of incident light so that the internal quasi-Fermi level can be modified with a controlled photon distribution. This tool was implemented at the module-level by introducing half-cylindrical optical structures in PDMS-based encapsulation during the casting process. The periodic local focusing of incident light has improved the efficiency of PERC solar cells owing to different mechanisms according to the focus location. When focused centrally between the fingers, the efficiency was increased by an enhanced current density with little degradation of the FF, whereas the FF was increased if multiple foci were formed between the fingers. This shows that changes in light focus produce different quasi-Fermi level distributions within solar cells, which can be used to modify solar cell properties. Furthermore, changes in the AOI further enhance performance so that the overall expected energy production was increased relative to that of a bare cell. Given the efficiency losses that result when conventional EVA-based encapsulation is used in module fabrication, PDMS encapsulation has considerable advantages, including the possibility of incident light conditioning using a simple stamping process. This new tool can be used to develop advanced photovoltaic modules from crystalline Si solar cells, which can be combined with cell-level technologies to prohibit recombination. However, additional theoretical and practical studies are needed to further optimize the conditions and process.

Conflicts of interest

There are no conflicts of interests to declare.

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