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RESEARCH ARTICLE

Highly Efficient Bifacial Silicon/Silicon Tandem Solar Cells

JAEUN KIM[1], SUNHWA LEE[1], SOMIN PARK[1], MINKYU JU[2], YOUNGKUK KIM[2], EUN-CHEL CHO[2], SURESH KUMAR DHUNGEL[2], AND JUNSIN YI[2]

[1]Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon 16419, South Korea
[2]College of Information and Communication Engineering, Sungkyunkwan University, Suwon 16419, South Korea

Corresponding author: Junsin Yi (junsin@skku.edu)

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ABSTRACT Silicon-based tandem solar cells with efficient use of the solar spectrum are desirable for a next generation-commercial photovoltaic system. It has been widely investigated elsewhere using perovskites or III-V cells as top cell materials for high efficiency and stability. However, perovskite and III-V top cells are still unsuitable for mass production as well as expansion and integration with silicon solar cell production processes so far. Two-terminal bifacial Si/Si tandem cell by bonding with transparent conductive adhesive (TCA) is reported here. The current matching can maximize the efficiency by controlling the opening area of the top cell, which makes the bottom cell also able to absorb sunlight in the short wavelength region that is absorbed by the top cell as well, without being limited to the thickness or bandgap of the top cell. The Si/Si tandem solar cell achieved short circuit current density of 25.195 mA/cm^2 after current matching by 36% opening ratio of top cell.

INDEX TERMS Tandem solar cell, two-terminal, silicon solar cell, transparent conductive adhesive (TCA), current matching.

I. INTRODUCTION

Silicon (Si) solar cells dominate the photovoltaic market because of their high efficiency and stability [1], [2]. Studies have been conducted to improve the fabrication processes by comprehending the principles of solar cells in order to approach the theoretical limit of efficiency of single junction Si solar cells [3]. The highest efficiency of 26.7% has been achieved by Kaneka Corporation for silicon wafer-based solar cells employing an integrated back contact heterojunction with intrinsic thin layer (IBC-HIT) solar cells [4], [5]. Therefore, a novel structure is required to surpass the efficiency constraints of crystalline silicon solar cells [6], [7], [8].

To overcome the limitations of conversion efficiency of solar cells, the strategy under investigation is multijunction structure using sub-cells with different bandgaps. A multijunction structure can minimize thermalization loss while also achieving high efficiency by appropriately dispersing the incident solar spectrum to each cell. Various multijunction solar cells have been studied using III-V materials, which achieved highest efficiency [9], [10]. Although III-V multijunction solar cells are more efficient than other materials, their applications are limited due to their high cost. Progress has been made in the development of Si-based tandem solar cells in recent years, with efficiencies of at least 30% obtained by utilizing existing Si solar cell production lines. The present focus of Si-based tandem solar cells is on III-V and perovskite-based top cells [11], [12], [13], [14]. Solar cell based on III-V compound semiconductor have already been proven to be highly efficient and stable. The fabrication of III-V//Si tandem solar cells may be done in two ways. Direct epitaxial growth on Si is the first way. However, because of the lattice mismatch and discrepancies in thermal expansion coefficients between Si and III-V materials, this approach produces defects [15], [16] as a result of which tandem solar cells have demonstrated the

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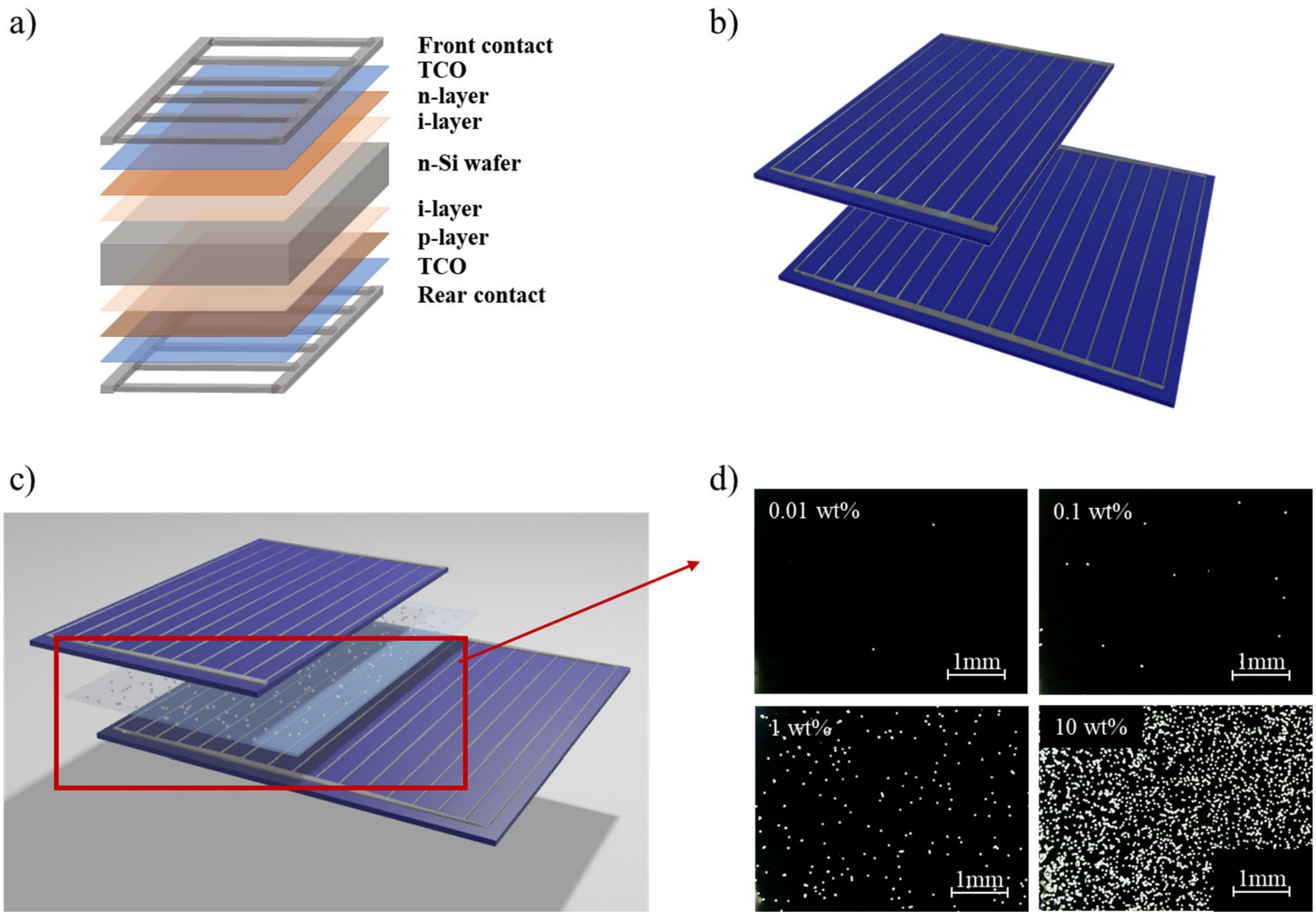

FIGURE 1. The schematic image of (a) RE-SHJ cell, (b) before and (c) after bonding top and bottom cells, and (d) structure of the bonding layer.

efficiency of only 22.3%. The second method is related to the fabrication and stacking of Si solar cells and III-V solar cells, respectively. Wafer bonding and mechanical stacking can be used to fabricate two-terminal and four-terminal solar cells [17], [18], [19]. Materials such as electrically conductive adhesive (ECA), metal nanoparticles, Poly [3,4-ethylenedioxythiophene] (PEDOT), and transparent conductive adhesive (TCA) are being studied as a method for wafer bonding and mechanical stacking [20], [21], [22], [23], [24], [25], [26], [27], [28]. Currently, two-terminal and four-terminal III-V//Si multijunction solar cells both have achieved 35.9%. However, perovskite and III-V top cells are still unsuitable for mass production as well as for the expansion and integration with silicon solar cell production processes so far.

In this article, the two-terminal bifacial Si/Si tandem solar cell is reported using Ag-coated PMMA for bonding. The bifacial solar cell improves the current density, and the efficiency can be maximized by controlling the opening ratio of top cell without being limited to the thickness or materials of the top cell. It provides the benefits to improve efficiency without instability and defects caused by lattice mismatch and differences in thermal expansion coefficients of the different materials used in tandem configuration.

II. EXPERIMENTAL DETAILS

A. DEVICE FABRICATION

A solar grade n-type Czochralski (CZ)-grown single crystalline silicon wafer of 148 μm thickness and 1.5 Ω·cm resistivity was employed in the device fabrication after cutting to 4 cm by 4 cm size. A solution of sodium hydroxide (NaOH) was used to texturize the surface. Standard cleaning from the Radio Corporation of America (RCA) was used to remove surface imperfections from the texturing wafers in two stages: standard cleaning 1 and 2. On both the surfaces of the Si-wafer, thin passivation layers of a-Si:H were then deposited. The doped n-type layer was deposited on the front side, while the p-type layer was deposited on the back side. A typical multi plasma-enhanced chemical vapor deposition (PECVD) system developed by SNTEK (Korea) was used to deposit these layers at a pressure of 0.2 Torr and temperature of 300°C. The front and rear transparent conductive oxide (TCO) layers were deposited using RF/DC sputtering system having 300/200 W power with a target, which was made up of 90 wt.% of In_2O_3 and 10 wt% SnO_2 with 99.999% purity (purchased from baco solution). During the sputtering, there was supply of Ar gas in the sputtering chamber and the substrate temperature was maintained at around 200°C during deposition. The front metal grid and back contact electrodes were also printed using Ag paste by screen printing. Front electrode/TCO/n-type carrier selective front contact (CSFC) layer/a-Si:H passivation layer/c-Si wafer /a-Si:H passivation layer/p-layer emitter/TCO/back electrode were the components of the rear-emitter silicon heterojunction (RE-SHJ) cell, as illustrated in Fig. 1 (a).

B. TANDEM CELL BONDING

The TCA was synthesized by combining polydimethylsiloxane (PDMS) and silicon elastomer curing agent in a 10:1 ratio by volume and mixing on a vortex mixer for 10 minutes. In the mixture of PDMS and silicon elastomer curing agent, Ag-coated PMMA microspheres (PMPMS-Ag-1.53, diameter range of 45-53 μm) were mixed by taking 0.01, 0.1, 1, 10 wt% on a vortex mixer for 30 minutes. The TCA mixture was then deposited by spin coating at 3000 rpm for 15 seconds. This was followed by curing conducted with the pressure of 50 kPa (0.5 bar) at 120°C for 20 minutes [27].

III. RESULTS AND DISCUSSION

Figure 1 (a) shows the schematic image of the rear-emitter silicon heterojunction (RE-SHJ) solar cell with a bifacial structure.

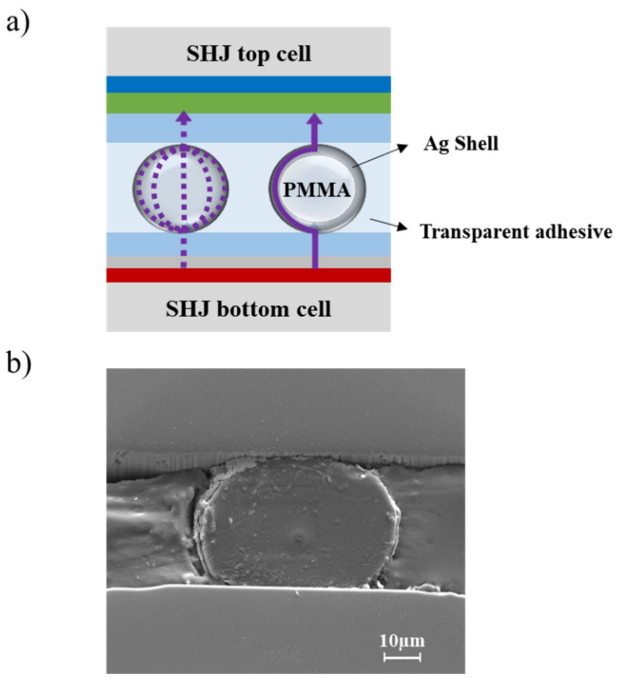

FIGURE 2. **(a) The schematic diagram of the bonding structure. (b) The FE-SEM micrograph showing cross-sectional image of the bonding.**

The short circuit current densities of the front and rear cell made with this structure are 39.77 mA/cm^2 and 37.72 mA/cm^2, respectively, with a bifaciality of 94.8%. The top cell was cut after calculating the optimal opening ratio of the top cell compared to the bottom cell based on the global average albedo of 30%. The opening ratio is the rate of the light receiving area between the top cell and the bottom cell, and the top cell is cut perpendicular to the bus bar. The optimal opening ratio (A) was controlled by the albedo (R_a) and the bifaciality (b), and was calculated through the following equation.

$$A = \{(1 - R_a \times b)/2\} \times 100 \quad (1)$$

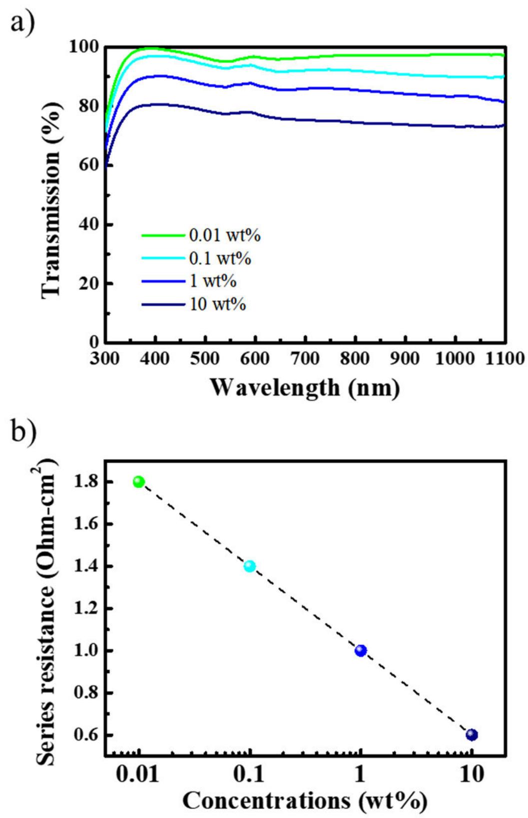

FIGURE 3. **The variation of (a) transmittance and (b) series resistance of the bonded contract layer with variation in according to weight percent of Ag-coated PMMA in TCA.**

The optimal opening ratio was calculated to be about 36%, and after cutting the top cell, it was aligned as shown in Figure 1 (b). The TCA was then used for the bonding of top and bottom cells verifying the weight percent of Ag-coated PMMA in the PDMS as shown in Figure 1 (c). The structure of the bonding layer according to the weight percentage of Ag-coated PMMA was confirmed as in Figure 1 (d) through optical microscopy (OM).

The image of the bonding layer is shown in Figure 2 with (a) the schematic diagram and (b) the cross-sectional image. The contact area varies with pressure as the Ag-coated PMMA is flexible. If the pressure is small, the contact may not be good, and if the pressure is too large, the PMMA may break, and the conductivity may decrease. In this study, it was confirmed using an FE-SEM micrograph that the contact area with the cell was about 35 μm in diameter after bonding at a pressure of 50 kPa.

The top and bottom cells must be electrically connected, and the bonding layer must be transparent enough for solar spectrum with photons of energy greater than the bandgap of the lower cell in the case of a tandem solar cell. The TCA is a conductive material with high transmittance because PDMS is a transparent medium and Ag-coated PMMA is a small particle of about 50 μm. Figure 3 shows the transmittance and the series resistance offered by TCA at various concentration of Ag-coated PMMA in terms of weight percentage. The transmittance of the TCA is 97.02%, 92.19%, 85.63%, and 75.65% in the wavelengths range from 400 nm to 1100 nm with 0.01 wt%, 0.1 wt%, 1 wt% and 10 wt% of the Ag-coated PMMA in the TCA, respectively. The series resistance decreased linearly when the conductive particle increased, starting at 1.8 $\Omega\cdot cm^2$. The transmittance decreased significantly as the concentration of Ag-coated PMMA in TCA was increased, but conductivities in all cases were found to have significantly low values.

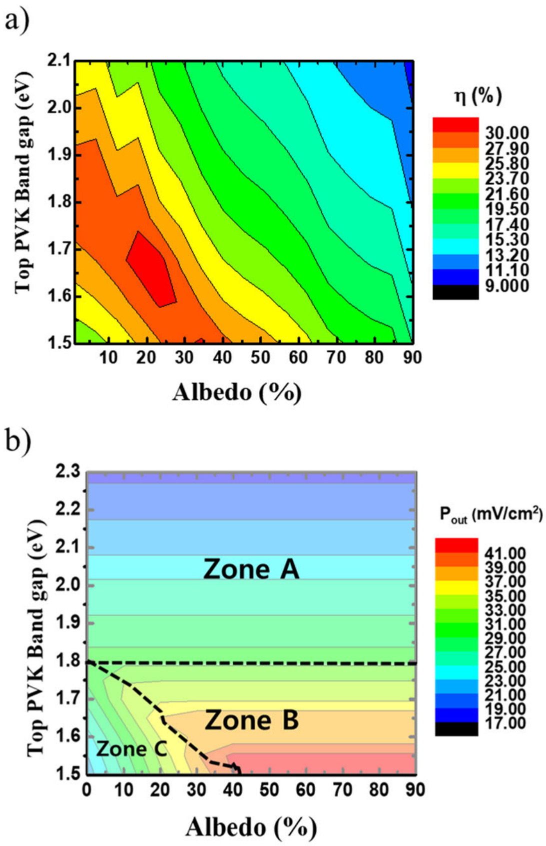

FIGURE 4. Optimal Bandgap of top perovskite (PVK) cell on various albedo (0~90%) as function of (a) efficiency (η) and (b) output power (P_{out}) of bifacial tandem cell.

A solar cell with an area of 10.24 cm^2 was fabricated and then light-induced current-voltage (LIV) measurement of the cell was performed using a zig designed to receive the sunlight from both the front and rear parts. The performance parameters were measured by irradiating the cell with 1 sun by the upper solar simulator and 0.3 sun by the lower solar simulator after cutting the top cell according to each opening ratio and attaching it to the bottom cell. The efficiency of a bifacial tandem cell is different from the monofacial tandem solar cell. Since both front and rear sun must be considered for input power, its efficiency is calculated as follows [29].

$$\eta = \frac{V_{OC} \cdot J_{SC} \cdot FF}{P_{sun}(1 + R_a)} \tag{2}$$

It is necessary to study to secure the optimal bandgap of the top cell according to Albedo in terms of efficiency as shown in Fig. 4 (a). On the other side, Fig. 4 (b) shows in terms of output power. It can be observed that when the Albedo grows, a top cell with a lower bandgap is required. However, for the investigation reported in this paper, there is no need for bandgap engineering because Si-based solar cells are used as the top as well as the bottom cells.

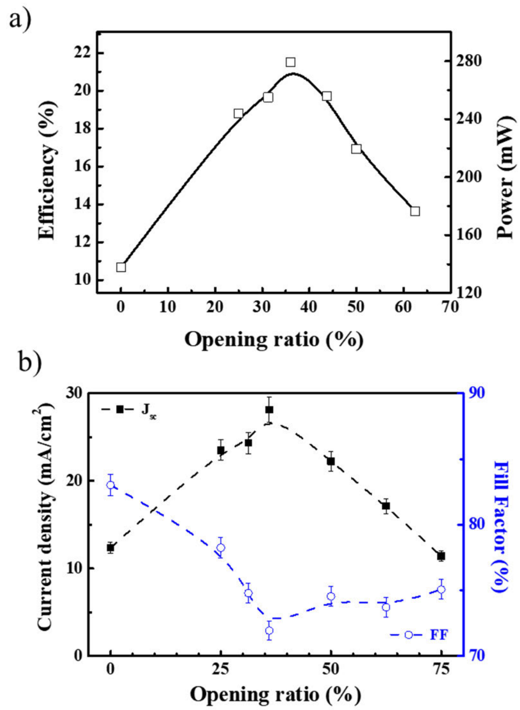

FIGURE 5. Performance of the fabricated Si/Si tandem solar cells with various opening ratio of the top cell and the bottom cell.

The performance parameters such as efficiency, power, current density, and fill factor of the fabricated Si/Si tandem solar cell are shown in figure 5. It can be seen that the experimentally determined power change result of each tandem solar cell agrees well with the calculated optimal opening ratio. It can be confirmed that the Si/Si tandem solar cell of conversion efficiency 21.50% can be achieved with a maximum power of 279.45 mW at the opening ratio of 36%. The efficiency of the bifacial solar cell is a value obtained by calculating the output versus the input as mentioned in Equation 2 above. Thus, in terms of efficiency, it can be evaluated that it is lower than 21.74% of a single monospecific cell. But since it is a bifacial cell, it is appropriate to view that the power generation is significantly higher in the same area compared to the output power of 222.62 mW. Although the Si/Si tandem solar cell with the optimal opening ratio showed the lowest fill factor of 71.94%, it showed the highest power value because it had an exceptionally high current density of 28.14 mA/cm^2.

It was conducted with a simple cutting of the top cell to obtain targeted area in order to simplify the experiment for this study. The same method used in this study can be commercialized by using the same previously designed cell manufacturing process by adding the cell cutting and bonding processes in the modularization process. However, it can be fabricated as shown in Figure 6 by drilling a hole suitable for the opening ratio while manufacturing suitable for photovoltaic system in the future. The sunlight corresponding to the area of each hole was irradiated to the bottom cell to generate current. The generated current of the bottom cell was found to match with that of the top cell in the same way as the tested sample with simple cut.

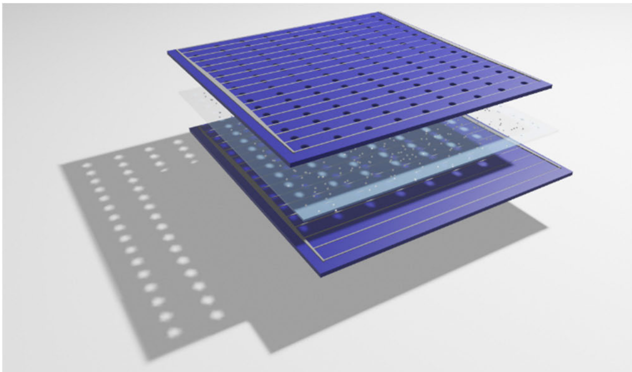

FIGURE 6. Performance of the fabricated Si/Si tandem solar cells with various opening ratio of the top cell and the bottom cell.

IV. CONCLUSION

A new direction of the next-generation silicon tandem solar cell has been reported in this article. To fabricate a tandem solar cell by bonding two RE-SHJ cells, the top cell was cut to an optimal opening ratio and TCA was used as a bonding layer. It has a contact area of about 35 μm diameter under a pressure of 0.5 kPa because of the flexibility of PMMA. Measurements of optical and electrical properties by varying the concentration of Ag-coated PMMA in TCA showed that when the concentration was increased, the conductivity improved to 0.6 $\Omega\cdot$cm^2, but the transmittance decreased to 75.65% as expected. Experimental results obtained by varying the opening ratio of the top cell confirmed that the highest output power of 279.45 mW at the opening ratio of 36%, which is the same as the value calculated theoretically. In this study, an experiment was conducted by changing the area of the top cell by simple cutting, but a next-generation solar cells can be manufactured by opening holes on the front mechanically for mass production. This paves the way to overcome the existing efficiency limitations of solar cell and manufacture stable and high-efficiency solar cells using the Si/Si tandem configuration.

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JAEUN KIM received the B.S. degree in advanced materials engineering from Chungbuk National University, Cheongju, Republic of Korea, in 2020, and the M.S. degree in electrical and computer engineering from Sungkyunkwan University, Suwon, Republic of Korea, in 2022.

From 2018 to 2020, she was a Research Student with the Multi-Functional Nanoelectronics Laboratory. Since 2020, she has been a Research Student with the Information and Communication Devices Laboratory. Her research interests include photovoltaics and thin film transistor.

SUNHWA LEE received the B.S. degree in material science and engineering from Soonchunhyang University, Asan, South Korea, and the Ph.D. degree in photovoltaic system engineering from Sungkyunkwan University, Suwon, South Korea. She is currently a Senior Researcher with Hanwha Qcells, Seongnam, South Korea. Her research interests include photovoltaics and renewable energy.

SOMIN PARK received the B.S. degree in solar and energy engineering from Cheongju University, Cheongju, South Korea. She is currently pursuing the M.S. degree with Sungkyunkwan University, Suwon, South Korea. Her research interests include solar cells and energy.

MINKYU JU was born in Busan, South Korea, in 1981. He received the master's and Doctoral degrees in photovoltaic system engineering from Sungkyunkwan University, in 2009 and 2018, respectively. He has started solar cell research and development with KPE Company Ltd., in 2006. He is currently a Senior Researcher with Hyundai Energy Solution. His research interests include solar cells and high-efficiency mass production technology.

YOUNGKUK KIM received the B.S. and M.S. degrees in physics from Kyung Hee University, Seoul, South Korea, and the Ph.D. degree in photovoltaic system engineering from Sungkyunkwan University, Suwon, South Korea. He is currently a Research Professor with Sungkyunkwan University. His research interests include photovoltaic and renewable energy.

EUN-CHEL CHO received the B.E. and M.E. degrees in electronics engineering from Kwangwoon University, South Korea, in 1991 and 1993, respectively, and the Ph.D. degree in electrical engineering from the University of New South Wales, Australia, in 2003. He is currently a Senior Vice President with Hyundai Heavy Industries Power Systems. His research interests include solar cell, photovoltaic module, and PV systems.

SURESH KUMAR DHUNGEL received the M.Sc. degree in solid state physics from the Tribhuvan University of Nepal, in 1994, and the Ph.D. degree in engineering with major in electronics and electrical engineering from Sungkyunkwan University, Suwon, South Korea, in 2007. He is currently a Research Professor with Sungkyunkwan University. His research interests and expertise include solar cell related materials and processes.

JUNSIN YI received the B.S. degree in electronic and electrical engineering from Sungkyunkwan University, South Korea, in 1989, the M.S. degree in electronic and electrical engineering from the State University of New York, USA, in 1991, and the Ph.D. degree in electronic and electrical engineering from University at Buffalo, USA, in 1994. He is currently a Professor with Sungkyunkwan University, Suwon, South Korea. His main research interests include solar cells and thin film transistor.

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