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Corrugation Architecture Enabled Ultraflexible Wafer-Scale High- Efficiency Monocrystalline Silicon Solar Cell

A corrugation architecture enabled ultraflexible, high performance crystal-line-silicon solar cells on a 5 inch wafer via a lithography less complementary metal oxide semiconductor compatible technique shows power conversion efficiency of 17.2%, a bending radius lower than 140 μm with the groove width of 0.86 mm, and a high mechanical stability over 1000 cyclic bending.

Corrugation Architecture Enabled Ultraflexible Wafer-Scale High-Efficiency Monocrystalline Silicon Solar Cell

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Advanced classes of modern application require new generation of versatile solar cells showcasing extreme mechanical resilience, large-scale, low cost, and excellent power conversion efficiency. Conventional crystalline silicon-based solar cell offers one of the most highly efficient power sources, but a key challenge remains to attain its mechanical resilience while preserving electrical performance. A complementary metal oxide semiconductor-based integration strategy where corrugation architecture enables an ultraflexible and low-cost solar cell modules from bulk monocrystalline large-scale ($127 \times 127 \text{ cm}^2$) silicon solar wafer with 17% power conversion efficiency. This periodic corrugated array benefit from an interchangeable solar cell segmentation scheme which preserves the active silicon thickness of $240 \mu\text{m}$ and achieves flexibility via an interdigitated back contacts. These cells can reversibly withstand high mechanical stress and can be deformed to zigzag and bifacial modules. These corrugation silicon-based solar cells offer ultraflexibility with high stability over 1000 bending cycles including convex and concave bending to broaden the application spectrum. Finally, the smallest bending radius of curvature lower than $140 \mu\text{m}$ of the back contacts is shown that carries the solar cells segments.

1. Introduction

Flexible solar cell technology has paved the way for wide application spectrum ranging from wearable and implantable electronics, robotics, and infrastructure/vehicle-integrated solar

panels on curved surfaces to space applications.^[1–4] This is mainly triggered by the need of self-powered technologies which abandons cords and benefit from wireless technologies for the sheer feasibility and convenience of the wearer.^[5–10] Recent research efforts have investigated the development of inorganic and organic flexible thin-film solar cells (TFSCs) through materials innovation and device engineering. Silicon-based solar cells is one of the most investigated materials in photovoltaics technology due to its natural abundance, nontoxicity, excellent reliability, mature manufacturing, and high performance.^[11] Flexible thin film Si-based solar cells have shown their advantage in applications in which weight is a critical factor. However, thin film Si-based solar cells seem to be disadvantageous over thick Si solar cells due to the reduction of the optical absorption with less active Si material. Nevertheless, these technologies can provide higher power conversion effi-

ciencies as compared to polycrystalline compounds or organic solar cells, due to high material quality.^[12,13]

In this regard, two main approaches are explored extensively for producing TFSCs. The first approach includes direct deposition of the TFSCs on flexible substrate, such as polymers,

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fabrics, and paper.^[14,15] Such method is restricted by the maximum temperature of the substrate materials, impacting the solar cells performance.^[12] The second approach is the transfer printing technique which utilizes the conventional rigid substrates for the fabrication and then transfer the TFSCs onto resilient substrate.^[16,17] Thus, the second method overcomes the performance limitation associated with the substrate thermal incompatibility with fabrication of high-efficiency TFSCs. However, it suffers from both of low throughput and high cost. Thus, a trade-off between mechanical compliance, performance, and robustness of flexible photovoltaic cells remains as a major challenge, especially in high volume production for large surface coverage applications.

Here, we show a novel approach for flexing crystalline (c-Si) solar cells which overcome the previous major limitations associated with the material thickness reduction and the high cost of flexing process. Our approach is inspired by the corrugated architecture where thin areas are grooved between thicker areas which eventually makes the platform in-hand flexible. We have grooved series of linear channels (≈ 1 mm wide) without photolithography to reduce the thickness of silicon in those areas while keeping the remaining areas intact in silicon solar cell (≈ 6.2 mm wide). This corrugated architecture silicon solar cells show extreme bending radius < 140 μm of the back contacts with one of the highest power conversion efficiency among c-Si flexible solar cells that reaches 17.2% on a wafer scale (127×127 mm). We also demonstrate high mechanical stability of the cells during 1000 cycles of bending. Finally, the integration of the flexible solar cells is demonstrated on a curved surface for supplying power both flexible 8×8 LED Matrix and paper-based fully functional system using indoor illumination.

2. Results and Discussion

2.1. Ultraflexible c-Si Solar Cell

The mechanical adaptability of the corrugated c-Si solar cells concept is illustrated in **Figure 1**. We have used interdigitated back contact (IBC) solar cells with an area of 127×127 mm². Each wafer comprises an interdigitated p and n regions on a bulk silicon wafer with ≈ 260 μm thickness as depicted in **Figure S1** (Supporting Information).^[18] The IBC solar cell modules are highly attractive due to their high efficiency and advanced photons absorption attributed to less contact shading compared to the standard front-side contacts modules. Additionally, the IBC configuration simplifies our flexing process without the utilization of expensive lithography techniques where the silicon thinning process is executed on the whole front side without any precautions needed for handling the contacts. In order to achieve extreme flexibility, corrugation architecture or segmentation was utilized on the IBC wafers with an alternating regions of thinned and rigid Si discontinuities as shown in **Figure 1a,b** and **Figure S2** (Supporting Information). The optical image of the corrugated c-Si solar cell is shown in **Figure 1c** demonstrating extreme mechanical bending flexibility. It cannot only be bent but also can be deformed into different configurations including a zigzag and bifacial modules

as shown in **Figure 1e,f**, respectively. An optical front view image of the zigzag configuration depicted in **Figure 1g** in which an extraordinary flexibility and plastic deformation of the interdigitated back contact with the acute bending angle of 71.4° as observed using scanning electron microscopy imaging (SEM) (**Figure 1h**). Further SEM imaging of the top view of the sample is revealed in **Figure 1i** showing both of the negative and positive IBC electrodes with a width of 0.42 and 1.6 mm, respectively. **Figure 1j** demonstrates the extreme bending flexibility of the back contacts which carries the solar cells segments that can be folded around a radius < 140 μm . Moreover, the microstructure of the active solar cell and the bent contact is shown in **Figure 1k** with no presence of microcracks in the contact region.

In order to facilitate the industrial c-Si solar cells with the flexible version of the modules and a comparable efficiency, our corrugated flexing technique is designed to be applied on 5" wafer size with a lithography less approach. The main flexing steps are depicted in **Figure 2a** (see Experimental Section for details). The combination of the photoresist (PR) and the Kapton tape which has been applied manually work as a hard mask against the plasma etching. Moreover, the PR layer enables smooth peel-off of the Kapton with no residues on the active solar area after the flexing process is completed. To assess the plasma etching effect of the silicon etching progression and the underlying IBC surface, cross-section SEM imaging, Zygo profiler measurements, for IBC surface roughness, and secondary ion mass spectrometry (SIMS) spectra analysis, were carried out. **Figure 2b** shows the optical photo of the wafer after the plasma etching is completed. **Figure 2c** presents the optical microscopy image of upper side of the IBC contacts with the root mean square average of 1.269 μm . The silicon thickness reduces during the deep reactive ion etching (DRIE) process from 240 μm at the start, to 170 μm at 250th cycle (54 min), to 71 μm at 450th cycle (99 min), and finally the silicon is etched totally at 650th cycle. Thickness reduction against DRIE etching cycles along with consumed etching time is plotted in **Figure 2e**. In addition, SEM images are carried out in **Figure 2f,g** after 54 and 99 min of DRIE etching, respectively. In order to verify the silicon etching process, the etched grooves were analyzed using SIMS in both positive and negative modes. In **Figure 2h**, the analyzed film is composed mainly of aluminum, in addition to alkali and alkaline earth (Na, K, and Ca) and halogen metals (F) commonly detected as contaminant in SIMS. The positive and negative spectra are complementary since the most intense peak in the positive mode is Al^+ (mass 27), whereas AlO^- (mass 43) is the most intense peak in the negative mode. Although the aluminum film is expected to oxidize after contact with air, the intense aluminum oxide signals detected in both modes are also due to the usage of oxygen as a sputtering beam.

2.2. Solar Cell Efficiency

The current density—voltage (J – V) characteristics are measured under a solar simulator (approximately the AM 1.5 Global Spectrum with 100 mW cm⁻² intensity and spectral mismatch correction at the room temperature), and in the dark using a four-point probe setup to reduce the resistance associated

Figure 1. Ultraflexible c-Si solar cells on a 5 inch wafer scale. Schematic representation of a) the ultraflexible corrugated c-Si solar cell. b) The common electrodes of the interdigitated back contact corrugated c-Si solar cell. Optical images of 5" wafer of c-Si IBC solar cell illustrates: c) high bending flexibility, d) flat, e) zigzag module, f) folded wafer in half to obtain bifacial demonstration, and g) the zigzag side view and the internal angle (θ). Scanning electron microscopy images: h) Cross-sectional shows zigzag deformation with $\theta = 71.4^\circ$ and i) top view reveals the deformation of the interdigitated contacts. j) Optical image illustrates the view of the corrugated architecture consists of ≈ 6.2 mm active solar cell segments and 0.8 mm grooves width. SEM images of: k) the minimum bending radii of curvature of the back contacts ($R < 140 \mu\text{m}$) during folding, and l) pop view of the folded aluminum contact and the silicon segments.

with the high current collected from $15 \times 127 \text{ mm}^2$ c-Si solar cell. The measured cells were diced using laser with power of 100%, speed of 60%, and 500 kHz (see Figure S3, Supporting Information for laser optimization). For each cell, the reported

figures of merit for calculating each of the current density (J), power density (P), and power conversion efficiency (η) are based on active solar cells area only excluding the area of grooves where no photocurrent is generated which was found

Figure 2. Progression of the DRIE and corrugation technique process. a) Schematic representation of the corrugation flow. b) Optical images of the 5" wafer post the DRIE process and during peeling off the Kapton tape. c) Optical microscope image of the IBC upper side after the DRIE. d) Optical profiler measured on the IBC for surface roughness analysis. e) DRIE effect on the silicon thickness at the exposed area (each groove area = $127 \times 0.86 \text{ mm}^2$). f) and g) Cross-sectional SEM images taken after 250 and 450 etching cycles, respectively. h) SIMS spectra of the IBC post the DRIE in both positive and negative modes.

to be around 16.65 cm^2 . The J - V characteristics of averaged optimized flexible cells are shown in Figure 3a compared to rigid ones on flat surface where the error is the standard deviation from 10 devices. The J - V and P - V characteristics of the optimized devices are shown in Figure 3a,b, respectively. The open circuit voltage (V_{oc}) = $0.620 \pm 0.02 \text{ V}$, short circuit current (J_{sc}) = $38.055 \pm 1.2 \text{ mA cm}^{-2}$, fill factor (FF) = $72.0139 \pm 1.5\%$, η = $17.017 \pm 0.8\%$, and P = 17.00 mW cm^{-2} under 1 sun illumination compared to the rigid IBC solar cells which gives

the following performance in average: V_{oc} = $0.622 \pm 0.02 \text{ V}$, J_{sc} = $38.607 \pm 1.2 \text{ mA cm}^{-2}$, FF = $71.9413 \pm 1.5\%$, η = $17.294 \pm 0.8\%$, and P = 17.30 mW cm^{-2} as illustrated in Figure 3c. On the other hand, the total power (mW) which is generated from each flexible cell ($15 \times 127 \text{ mm}^2$) is reduced with 13.7% compared to the rigid ones as the total power generated from the rigid cell is 328 mW and reduced to 283 mW for the flexible corrugated architecture ones as plotted in Figure 3d. This is attributed to the active solar cell loss at the grooves area where

Figure 3. Electrical performance of the flexible c-Si solar cells compared to the rigid ones. a) J - V performance of the flexible cells enabled via the corrugation technique compared to the rigid devices under solar simulator illumination (1 sun) at the room temperature. b) Power density (mW cm^{-2}) compression. c) Electrical characteristics comparisons of: open circuit voltage (V_{oc}), efficiency (η), short circuit current (J_{sc}), and FF. d) Weight and total power (mW) measured of devices of an area = $127 \times 15 \text{ mm}^2$. Note that all the J - V characteristics measured when the devices are flat.

total weight loss is 13.3% of each cell as the rigid cells weight is reduced from 1.5 g into 1.3 g for the flexible cells. Figure S4a,b (Supporting Information) shows the optical photos of the individual subcells ($15 \times 127 \text{ mm}^2$): (a) rigid and (b) corrugated architecture. Comparison of the weight of the rigid and flexible 5" wafer is shown in Figure S4c (Supporting Information).

2.3. Mechanical Flexibility of Interdigitated Back Contact

Our corrugation design consists of several active solar cell segments connected through the IBC (screen printed aluminum) which serves the purpose of the carrier substrate. The segmentation approach has been used recently to obtain flexibility and stretchability even with brittle materials as Si (fracture strains $<1\%$) as the stretchable electronics is attracting tremendous attentions.^[19,20] In our lithography less corrugated approach, the interconnects (grooves) width are $\approx 0.86 \text{ mm}$. To obtain the minimum bending radius for the interconnect, we assume that its length (L) is the perimeter of a circle with radius (R_{bending})

$$R_{\text{bending}} = \frac{L}{2\pi} \quad (1)$$

Hence, R_{bending} is $137 \mu\text{m}$, which is consistent with the experimental value obtained via folding the solar cell as SEM image reveals in Figure 11. As the device is bent with the previous bending radii, its fundamental strain (ϵ) can be estimated from

$$\epsilon_{\text{max}} = \frac{t}{2R_{\text{bending}}} \quad (2)$$

where t is the interconnects thickness ($\approx 25 \mu\text{m}$) and ϵ_{max} is the maximum strain. Hence, the obtained strain is below 10% which remains below the rupture strain of the screen printed metals that is $>20\%$.^[21,22] Comparative simulation study is carried out with COMSOL for the maximum stain in the interconnects as a function of bending angles (θ) which is defined by the angle between the active solar cells segment during bending and the neutral axis as shown in Figure 4a–c. In Figure 4a, the maximum strain is below 8% in the interconnects even with the maximum bending angle is equal to 180° when both of the active solar cells are folded (see Figure S5, Supporting Information for detailed 3D modeling).

For further enhancement and future work, the lowest estimated bending radius which can be achieved without exceeding 20% of the interconnects stain would be $62.5 \mu\text{m}$ with a length of $393 \mu\text{m}$ as designed using the Equations (1) and (2). In Figures S6 and S7 (Supporting Information), the flexible solar cells show little hysteresis in J_{sc} as the bending radius decreases with light illumination for both of the concave and convex bending. However, both of the FF and V_{oc} remains in the average value of 72% and 0.62 V, respectively. We consider that the reduction of the J_{sc} is due to the variation of the projected area of the bent cells. Given the length of the solar cells L_0 in its flat state (11.3 cm), the projected area S of the rectangular device under light illumination is

$$S = S_0 \frac{\sin(L_0/2R_{\text{ct}})}{L_0/2R_{\text{ct}}} \quad (3)$$

Figure 4. Extreme mechanical flexibility: 3D strain modeling of the IBC (width = 1 mm and 25 μm thickness) located between silicon solar cells with thickness of 250 μm during bending with different angles (θ). a) The maximum and minimum strain of IBC as a function of the bending angle. b) and c) Strain compression of $\theta = 0$ and 180° , respectively. d) Schematic representation of projected area key components. e) Optical photo of the flexible cells installed on concave and convex glass curvatures ($R_{\text{bending}} = 6$ cm). f) Projected area as a function of the bending radii. The scatter points are calculated with Equations (3) and (4). g) Electrical characteristics of the devices using concave and convex bending compared to the flat devices. h) Optical image of the 3D printed cyclic bending apparatus in both cases: prebent (top) and after bending (bottom). i) Electrical characteristics of the devices as a function of the bending cycles.

where S_0 is the area of the solar cell when it's flat (16.65 cm^2), R_{cave} is the concave curvature bending radius as illustrated in Figure 4d. On the other hand, the convex curvature bending radius (R_{vex}) of the same glass curvature is smaller than R_{cave} due to the glass thickness (≈ 3.6 mm). Therefore, an approximation of R_{cave} is expressed as

$$R_{\text{cave}} = R_{\text{vex}} - 2 \times t \quad (4)$$

where t is the thickness of the glass. Figure 4e shows the optical image of both of the bent cells using convex and concave glass curvatures. Figure 4f displays the projected area associated with the bending radius of 6, 5.5, 5, and 4.4 cm for

the convex and concave bending. Figure 4g demonstrates the electrical characterization of a flexible cells with an excellent bending durability after considering the projected area in the J_{sc} calculations which eliminates any hysteresis and confirms that the projected area is the one key factor of changing of the flexible device performance.^[23] In addition, the performance of the zigzag model is measured under illumination as a function of the interior angles of the zigzag without taking in consideration the projection area variation in Figures S7b,c,d (Supporting Information).

The flexible cells are bent for 100, 250, 500, 750, and 1000 cycles to investigate the durability under repeated cyclic bending. Figure 4h displays the optical images of the 3D printed test apparatus in both cases: prebent (top) and after bending (bottom). The electrical characterization of the cells under illumination versus the bending cycles are shown in Figure 4i. It showed a robust performance of the cells without any gradual decrease in the output characteristics.

2.4. Flexible LEDs Matrix and System on Chip Integrated with the Flexible c-Si Solar Cells Using Indoor Illumination

The integration of a system consists of five flexible solar cells (each cell area $\approx 127 \times 15 \text{ mm}^2$) connected in series is demonstrated to explore a seamless integration of the developed

corrugation cells using indoor illumination. The integration is explored with both of LEDs matrix and a paper based humidity sensor while the flexible cells are installed on convex curvatures.

Figure 5a displays the output voltage (3–2.9 V) of the five cells connected in series using two (light bulb) office lamps installed on convex bending glass substrate ($R = 6 \text{ cm}$). Figure 5b presents the system connected to 8×8 LEDs matrix displaying KAUST logo using (blue, yellow, green, and red) LEDs (additional display of the LEDs matrix using the flexible solar cells can be seen in the Video S1, Supporting Information). Furthermore, the cells connected in series are installed on a glass mug used to supply power to a fully functional system as shown in the optical image in Figure 5c. We interfaced a paper based humidity sensor^[24,25] with Cypress's Bluetooth Low Energy (BLE) PSOC 4 BLE system-on-chip (SoC) (see Experimental Section for details). The system was then placed on a leaf of a plant and subjected to humid conditions by blowing air from the mouth on the sensors via a pipette. The humidity sensor changes capacitance based upon the relative humidity of the environment. PSOC's Current Digital to Convertor (IDAC) was used to find the capacitance changes of the humidity sensor. For the purpose of demonstration, we only show the detection of a humid condition both with a red LED on the flexible board and notification on the smartphone (as can be seen in the Video S2, Supporting Information). Figure 5d illustrates

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Figure 5. Integration of the corrugated c-Si solar cells. Five cells are connected in series and installed on convex glass curvature. Optical images of: a) output voltage using two bulb lights. b) KAUST logo display using LEDs matrix powered by the flexible solar cells via a desk light. c) Flexible cells are installed on a glass mug used to supply power to a fully functional system placed on a plant leaf and subjected to a humid condition. d) Circuit diagram. e) Humidity sensor response. f) Red LED on a flexible board with notification of the smartphone upon the humidity sensor response.

the full circuit diagram. When the sensor sensed humidity, its capacitance changes which is recorded by IDAC in PSOC as demonstrated in Figure 5e. PSOC then turns on the LED and sends notification to a smartphone as shown in Figure 5f. Finally, our achieved efficiency using the measured area of the flexible c-Si solar cells is compared with the data literature in Figure S8 (Supporting Information).^[14,17,26–31]

3. Conclusion

In conclusion, corrugation architecture enabled ultraflexible, high performance c-Si solar cells were demonstrated on a 5 inch wafer via a lithography less complementary metal oxide semiconductor compatible technique. The flexible cells have the power conversion efficiency of 17.2% which is comparable to the rigid IBC module efficiency. The corrugation approach consists of active solar cells array (each cell area $\approx 127 \times 6.2 \text{ mm}^2$) and array of grooves (each groove area = $127 \times \approx 0.86 \text{ mm}^2$) while the active solar cells are connected via IBC screen printed aluminum which plays the key role as the carrier for the solar cells segments. The screen printed metals can withstand high strain exceeds 20%. Moreover, a bending radius of the back contacts lower than 140 μm can be achieved with the groove width of 0.86 mm. Hence, the flexible cells showed a consistent electrical performance for the convex and concave bending after the projection area calculations are taken in consideration. Furthermore, the whole 5 inch wafer can be deformed in zigzag and a bifacial module. Moreover, the flexible cells show a high mechanical stability over 1000 cyclic bending. We have demonstrated the integration of the several flexible cells in series with a flexible LEDs matrix and full functional system using indoor illumination. Our corrugation flexible solar cells can broaden the application spectrum and may lead toward unconventional areas of applications.

4. Experimental Section

Corrugation Architecture Technique: This technique was applied on 5" industrial supplied ion implanted monocrystalline n-type silicon solar cells with IBC configuration. First, positive PR 9260 was spun on the front side at 2400 r.m.m for 60 s. Pyrolysis bake was then carried out at 110 °C for 180 s. The same previous step used on the backside yielding 10 μm thick PR on both faces. After that double layer of Kapton (1/4" polyimide film with silicon adhesive) tape was applied in perpendicular lines (15 lines) across the wafer with $\approx 1 \text{ mm}$ gap between the tapes and with wider tapes located at the wafer edges ($\approx 0.9 \text{ mm}$) to prevent thinning the silicon located on top of the IBC common electrodes. The wafer was exposed to broadband stepper at 1.800 mJ cm^{-2} followed by development using AZ 726 MIF for 6 min. DRIE step was executed on the top side including SiN ($\approx 100 \text{ nm}$) layer and where the whole silicon was etched using Bosch process of successive deposition and etching cycles (≈ 650 cycles) using cryogenic cooling at $-20 \text{ }^\circ\text{C}$ for smooth sidewalls. The initial Ar plasma strike was performed at 10 sccm SF_6 , 20 sccm SF_6 , and 50 sccm Ar at 15 mTorr, 2000 W and 20 W for 10 s. Principal etching of Si surface takes the following reaction

The deposition step was composed of 100 sccm C_4F_8 and 5 sccm SF_6 at 30 mTorr, 1300 W ICP, and 5 W RF for 3 s and the etching step was composed of 5 sccm C_4F_8 and 100 sccm SF_6 at 30 mTorr, 1300 W ICP, and 35 W RF for 8 s. Plasma polymerization reaction is

Finally, Kapton tape was peeled out and the wafer was cleaned using acetone and IPA for PR removal.

Material Investigation: The mass spectra were recorded on interconnects post the DRIE process using dynamic SIMS instrument from Hiden Analytical company (Warrington-UK) operated under ultrahigh vacuum conditions, typically 10^{-9} Torr. A continuous O_2^+ beam of 2 keV energy was employed to sputter the surface while the selected ions were sequentially collected using an MAXIM spectrometer equipped with a quadrupole analyzer.

The Laser-Based Dicing Method: To dice the solar cells into area of $127 \times 15 \text{ mm}^2$, we used 1.06 μm ytterbium-doped fiber laser (PLS6MW Multi-Wavelength Laser Platform, Universal Laser Systems, USA). The laser interacting with the material strongly depended upon the wavelength, speed, power level of the laser, and the absorption characteristic of the material. The calibration of the laser dicing parameters was carried out to obtain sufficient beam penetration through the entire thickness (260 μm) of the device as shown in Figure S3, Supporting Information. Based on the sharp profile of the laser beam with power with 100%, speed of 60%, and 500 kHz was used for the cells dicing. Finally, we gently cleaved cells by hand.

Device Characterization: The devices were first characterized in the dark and under illumination of a solar simulator (ORIEL AM 1.5 Global Spectrum with 100 mW cm^{-2} intensity). Prior to each measurement, the intensity of the solar simulator was calibrated with a reference Si solar cell and a readout meter for solar simulator irradiance (Newport). J–V characteristics were recorded using a Keithley 2420-C Source Meter. Glass bending curvatures with radius of 9, 6, 3, and 2.5 cm were used for the electrical bending study. Scanning electron microscopy imaging was used at acceleration voltage of 5 kV.

SOC: The BLE module comes with integrated antenna, crystal, and flash/EEPROM. The circuit was printed on a flexible polyimide substrate, followed by bonding of paper sensor and BLE chip on the substrate.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

CMOS devices, c-Si solar cells, flexible PV, high efficiency, large-scale photovoltaics

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