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# Heterogeneous Integration of Thin-Film InGaN-Based Solar Cells on Foreign Substrates with Enhanced Performance

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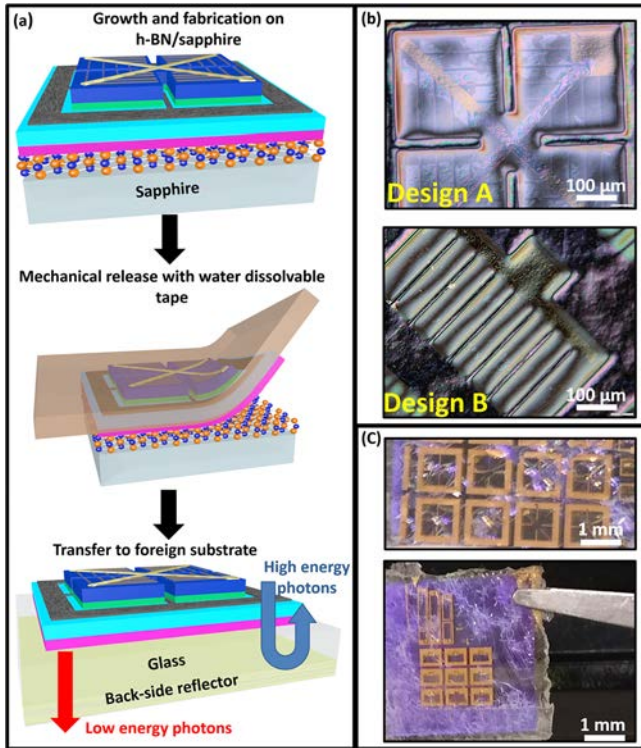
**ABSTRACT:** A practical III-nitride photovoltaic (PV) application consists of transfer to a foreign substrate with enhanced functionality and integration with mature group IV or III–V based solar cell technologies. This requires a lift-off technique compatible with good quality III–N materials, with photovoltaic device fabrication and with subsequent bonding on a heterogeneous substrate. Here, we demonstrate the first InGaN-based solar cells on a 2 in. h-BN/sapphire wafer and their transfer to glass with a backside reflector. III–N solar cells with various sizes and designs are processed and characterized on a full 2 in. wafer giving performances comparable to similar devices on sapphire. The subsequent crack-free transfer of the solar cells, enabled by Van der Waal bonded 2D layered h-BN, to a substrate with a backside reflector yields an increase in the short circuit current density of up to 20%. This demonstration of transferred InGaN-based solar cells on foreign substrates while increasing performance represents a major advance toward lightweight, low cost, and high efficiency photovoltaic applications.

**KEYWORDS:** *Heterogeneous integration, Van der Waal epitaxy, 2D h-BN, InGaN solar cells, photovoltaics*

The integration of hybrid electronics consists of assembling several devices, fabricated separately using different and potentially noncompatible processes, onto one common platform to achieve a functional heterogeneous system. This concept can be applied for cost-effective and high performance III-Nitride (III–N) based solar cell applications. InGaN alloys exhibit many favorable photovoltaic properties such as broadband absorption with a tunable bandgap (0.7 eV - 3.4 eV), superior radiation resistance, large absorption coefficients and high saturation velocities.<sup>1,2</sup> Thanks to the high absorption coefficients, InGaN Muti-Quantum well (MQW) based solar cells reported in the literature use between 4 to 30 QWs.<sup>3,4</sup> Theoretically, efficiency greater than 40% can be achieved by a multijunction solar cell composed of four InGaN subcells with different In content.<sup>5</sup> However, so far the large lattice mismatch between InN and GaN makes it experimentally difficult to grow good-quality, high In-composition InGaN films and currently impedes the realization of an all InGaN multijunction solar cell. Thus, a practical use of III–N solar cells could be their combination with mature group IV and III–V based solar cell technologies that work well at bandgaps <2 eV. Simulations carried out for an InGaN/Si 4-terminal

tandem device predicts an efficiency increase around 13% when adding a nitride solar cell with 20% In content.<sup>6</sup>

One interesting way to make these hybrid systems is to grow and process the InGaN-based solar cell, release it from the growth wafer and bond it to a foreign substrate. Different approaches for the separation of epi-layers have been demonstrated including laser lift-off<sup>7</sup> and chemical etching of the growth substrate<sup>8</sup> or a sacrificial layer.<sup>9</sup> These techniques have many limitations in practice, notably high cost, long process times, and limitations in size.<sup>10–12</sup> A more recent 2D h-BN-based mechanical liftoff technique<sup>13</sup> has attracted much attention and has been demonstrated for some key GaN-based devices such as HEMTs and LEDs.<sup>14–16</sup> A few nanometer thick sp<sup>2</sup>-bonded h-BN layer acts as a template for subsequent 3D (bulk) materials growth and also allows for the mechanical separation of the epi-layers from the growth substrate. In this work, we apply this epitaxial liftoff technique to grow, fabricate and transfer InGaN-based solar cells from a 2 in. h-BN/sapphire template to a glass slab with a dielectric mirror (DM) reflecting only high energy photons, as illustrated in Figure 1a.



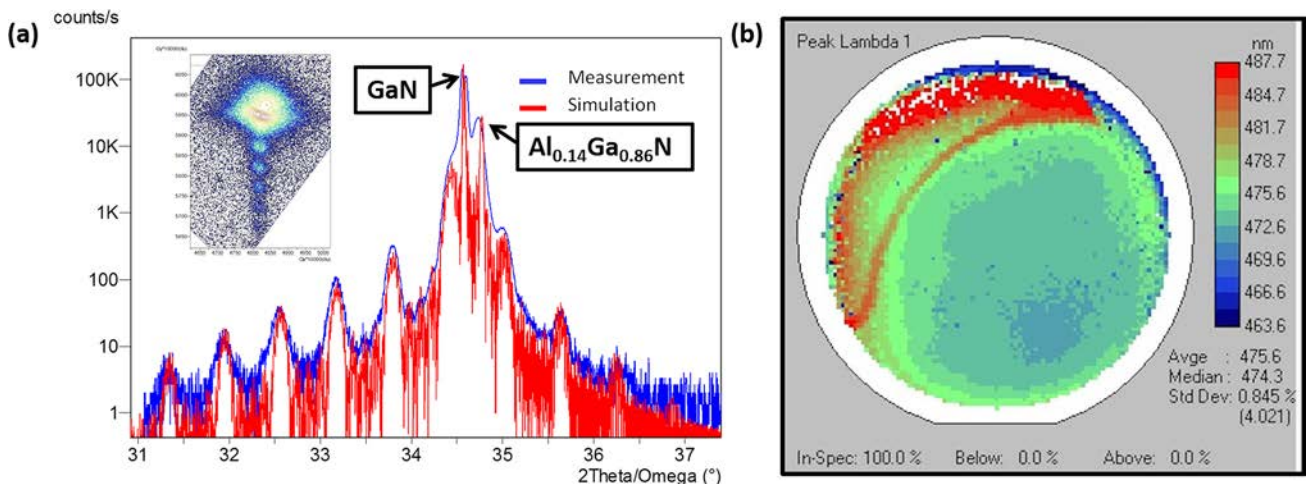
**Figure 1.** (a) Schematics of fabrication steps for releasing InGaN-based solar cells from sapphire and transferring them onto foreign substrates. (b) Optical microscopy images from the back side of  $\sim 1$  mm<sup>2</sup> solar cells with two different designs on a water dissolvable tape after release. (c) Photographs of devices with different sizes and designs transferred to glass with a DM as a back-side reflector (the purple background is due to the reflected wavelength between 375 and 465 nm).

The choice of this final substrate enhances the performance of the InGaN-based solar cells thanks to the increased light absorption from to the reflected high energy photons. At the same time, the DM transmits longer wavelengths that allow the operation of a 4-terminal tandem device after bonding with Si or GaAs-based solar cells. Figure 1b shows microscope images of two crack-free  $\sim 1$  mm<sup>2</sup> devices after their mechanical

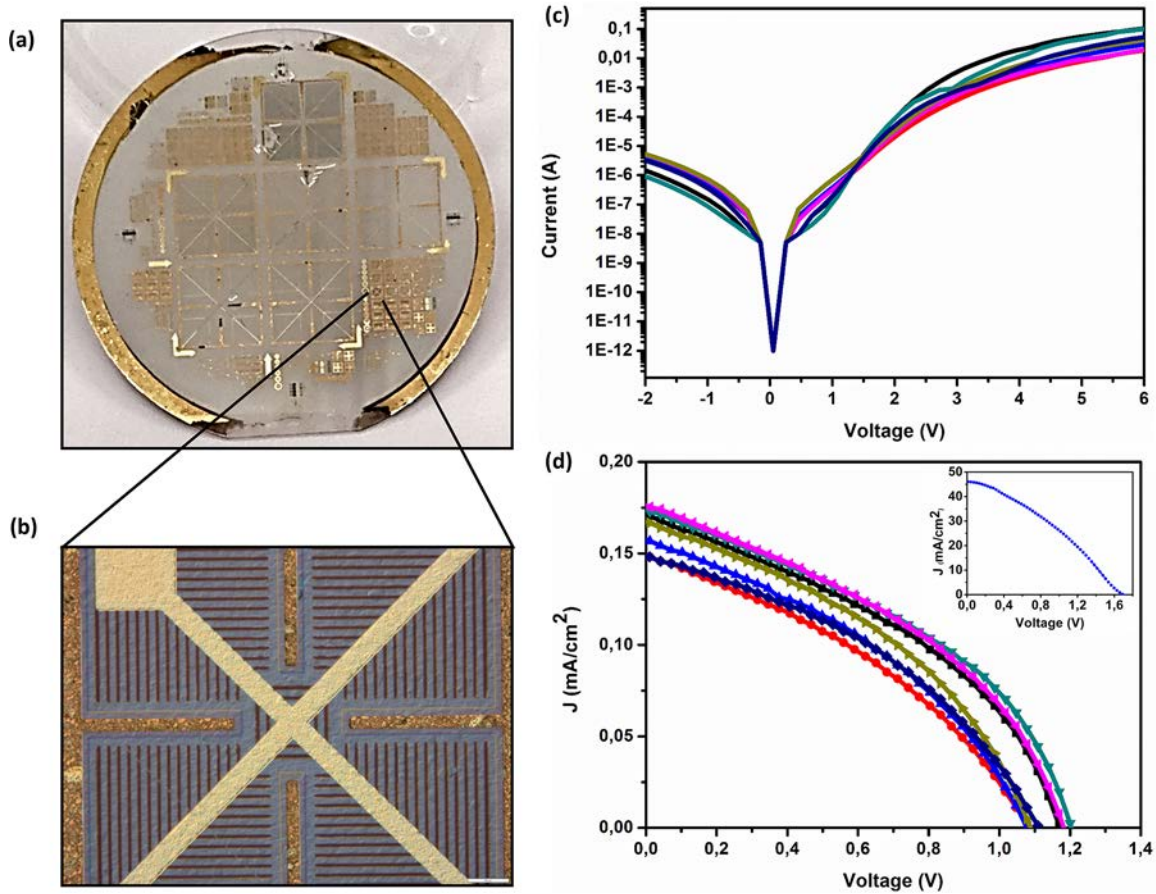
separation from the sapphire by means of a water-dissolvable tape. After liftoff, devices with design B are bonded on glass with a backside reflector using a polyurethane-based transparent resin, as shown in Figure 1c. Devices with design A have been transferred on glass with an Al back reflector.

The solar cells structure consists of a 5 InGaN/GaN quantum wells absorber sandwiched between 0.5  $\mu\text{m}$  n-GaN and 0.3  $\mu\text{m}$  p-GaN layers. This structure was grown on 3 nm h-BN using a 300 nm  $\text{Al}_{0.14}\text{Ga}_{0.86}\text{N}$  nucleation layer. The growth of the GaN-based layers on the ultrathin h-BN layer is governed by van der Waals epitaxy (vdWE).<sup>17</sup> As opposed to conventional 3-D crystals, vdWE does not involve strong chemical bonds between the epi-layer and the substrate, instead it only requires either the substrate or the overlayer to have a surface free of active dangling bonds,<sup>18</sup> which is the case for h-BN. The high-resolution X-ray diffraction (HR-XRD)  $2\theta - \omega$  scan around the (002) reflection of the grown structure is shown in Figure 2a. The scan clearly delineates the InGaN satellite peaks up to the fifth order as well as the peaks from the GaN and  $\text{Al}_{0.14}\text{Ga}_{0.86}\text{N}$  layers. Reciprocal space mapping shows a strained MQW structure (inset of Figure 2a). The In content extracted from X-ray simulation is around 18%. Figure 2b is the photoluminescence (PL) mapping performed at room temperature. Over the entire 2 in. wafer, the average emission wavelength is 475 nm, which is in agreement with the HR-XRD In content, and the standard deviation of the peak wavelength is 0.8%. This series of structural and optical characterizations demonstrate the ability to grow epitaxial InGaN-based structures on a Van der Waal surface with good quality that can operate as photovoltaic devices. Furthermore, if we consider the total device thickness that is only around 1.2  $\mu\text{m}$ , as compared to the standard structures grown on sapphire, thick GaN template is needed ( $\sim 4$  microns) to achieve good material quality. This could be considered as an advantage for cost reduction.

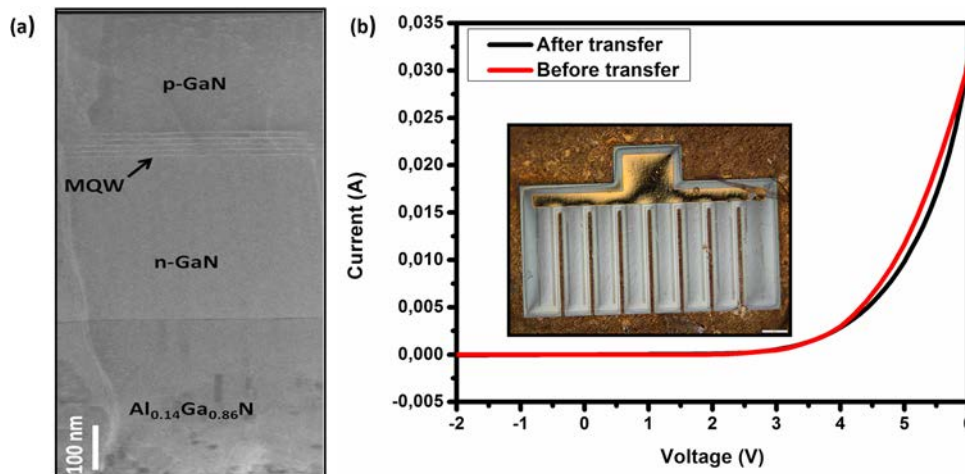
Several solar cells with different designs and sizes were fabricated using a 2 in. grown sample, as shown in Figure 3a. The use of sacrificial h-BN for wafer-scale fabrication poses a processing challenge because spontaneous delamination of the grown structure can occur during device fabrication.<sup>19</sup> In our experiment, a standard photolithography-based process has been applied while contact with liquids was limited and no



**Figure 2.** (a) HR-XRD  $2\theta - \omega$  scan of the grown MQW structure (blue curve) with simulation (red curve); the inset shows the RSM. (b) Wavelength distribution of photoluminescence mapping performed at room temperature.



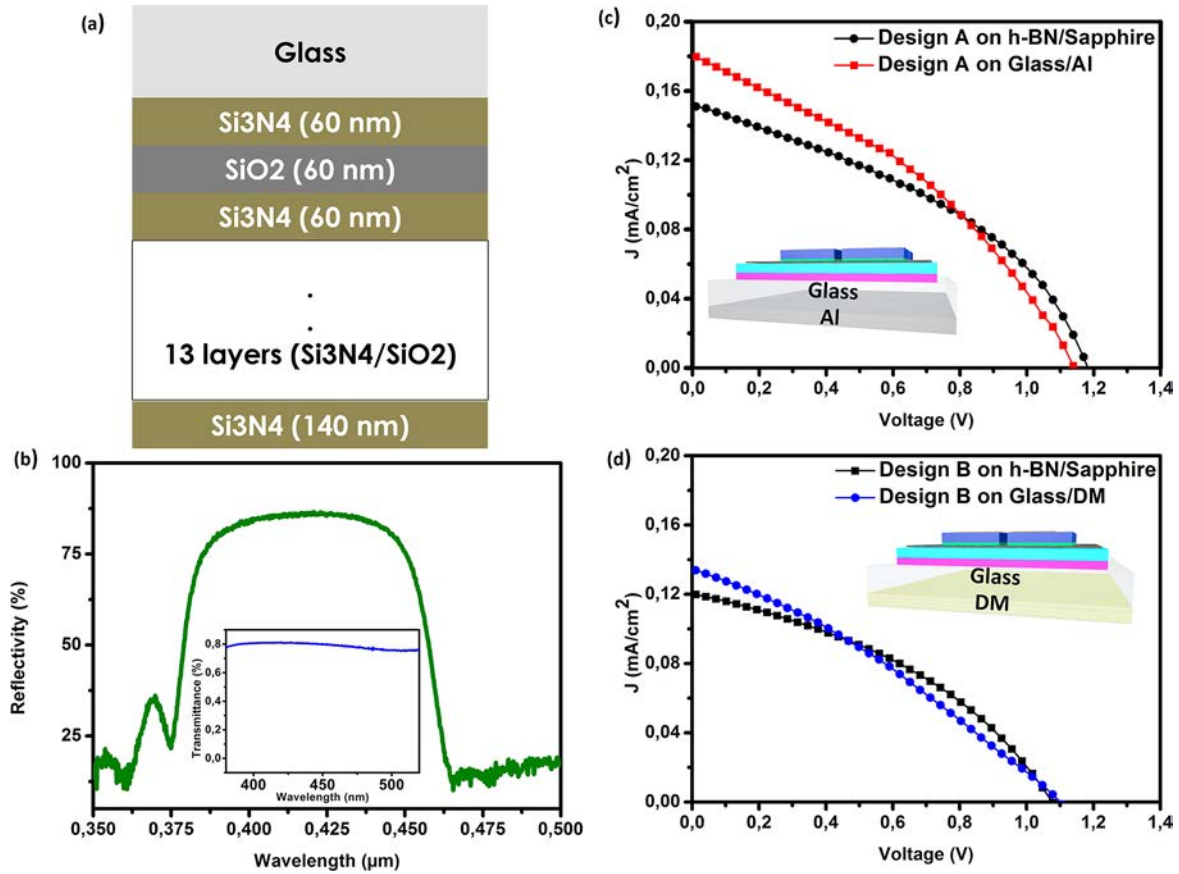
**Figure 3.** (a) Photograph of the fabricated solar cells on 2 in. h-BN/sapphire. (b) Optical microscopy image of a  $\sim 1 \text{ mm}^2$  solar cell with design A. (c) Dark  $I$ - $V$  curves of devices with design A in different locations on the wafer and their corresponding illuminated  $J$ - $V$  curves under AM 1.5 condition in (d). Inset in (d) shows the illuminated  $J$ - $V$  under a concentrated light source emitting at 440 nm.



**Figure 4.** (a) TEM image of the grown structure after release from sapphire. (b) Dark IV curves of the same device before and after its transfer to a glass substrate. Inset in (b) is an optical microscope image of a solar cell device after its transfer on a glass substrate.

ultrasonic cleaning was used. After fabrication, dark and illuminated  $I$ - $V$  measurements were performed. The results for a set of devices having the same design and located at different positions on the wafer are presented in this paper. The dark  $I$ - $V$  curves, shown in Figure 3c, demonstrate good process uniformity at the wafer scale. Figure 3d exhibits the  $J$ - $V$  curves under AM 1.5 conditions. Extracted efficiency, fill factor, open circuit voltage, and short circuit current density

are, respectively, equal to 0.08%, 39.5, 1.17 V, and 0.17 mA/cm<sup>2</sup>. These performances are comparable with a similar reported InGaN solar cell grown on sapphire.<sup>4</sup> To compare the experimental results to models, we have simulated the fabricated solar cell using commercially available SILVACO-Atlas software. Considering 35% of p-contact coverage, the simulation with AM 1.5 illumination condition results in an efficiency, a fill factor, an open circuit voltage, and a short



**Figure 5.** (a) Schematic of the deposited DM on glass. (b) FTIR measurements for the deposited DM on glass. (c, d) are  $J$ - $V$  curves under AM 1.5 illumination condition of respectively the same solar cell with design A before and after its transfer to a glass with Al back reflector and the same solar cell with design B before and after its transfer to a glass with a dielectric mirror. Inset in (b) shows the transmittance of the polyurethane-based resin.

circuit current density equal to 0.14%, 37.2, 2.28 V, and 0.17 mA/cm<sup>2</sup>, respectively. The difference with the measured  $V_{oc}$  is mainly attributed to the barrier height from the p-contact. It is known that the formation of good ohmic contacts on p-doped GaN layers is difficult compared to on n-doped layers.<sup>20</sup> PV measurements using a lamp emitting at 440 nm with a power density around 140 mW/cm<sup>2</sup> have been performed on several devices. They result in short circuit current densities  $J_{sc}$  of more than 40 mA/cm<sup>2</sup> and higher  $V_{oc}$  around 1.6 V as compared to the results under AM 1.5 condition, as shown in the inset of Figure 3d. These increased performances under high irradiance confirm the suitability of the InGaN solar cells for high concentrated photovoltaic (HCPV) applications.

After processing, the devices were easily transferred to a glass slab with a backside reflector by means of water dissolvable tape, as illustrated in Figure 1a. The devices were bonded to the final substrate using a polyurethane-based resin and the tape was removed in water without leaving residues. The transmittance of the resin is shown in the inset of Figure 5b. The transfer method does not require any harsh chemicals or processing, and it is favorable for cost reduction since the growth substrate can be reused for future material depositions.

During the transfer process, device structures remained completely intact and free from damage due to the gentle lift-off and transfer method. This is confirmed by the transmission electron microscopy (TEM) image in Figure 4a, which shows the preservation of the MQW structure. Figure 4d exhibits similar dark IV curves of a device (shown in the inset of Figure

4d) before and after its release. This further confirms that no degradation has been induced from the transfer process.

Two solar cell designs, shown in Figure 1b, were tested under AM 1.5 illumination conditions before and after their transfer. In Figure 5c, we present the results for design A. In this case, the backside reflector is simply a 100 nm thick layer of Al that has around 90% reflectivity for the entire visible spectrum. This transfer resulted in a 20% increase in the  $J_{sc}$  since more light can be absorbed by the solar cell from the reflected photons. For a 4-terminal tandem device with an InGaN-based solar cell on top, it is not possible to use an aluminum back reflector since it reflects the long-wavelength incident light. Hence, we designed a DM to selectively reflect wavelengths that can be absorbed by the InGaN cell and to transmit longer wavelengths. Fourier-transform infrared spectroscopy (FTIR) measurements on the deposited DM give reflectivity around 85% within the InGaN cell absorption spectrum and less than 20% for the higher wavelengths, as shown in Figure 5b. Solar cells with design B were transferred to a glass on which we deposited the designed DM. In this case, the reflected light has resulted in a  $J_{sc}$  increase by 12%, as shown in Figure 5d. The  $V_{oc}$  remained almost unchanged for both cases, which indicates the preservation of the grown solar cell structure after the transfer process. Simulations have been performed considering a back-side reflector with 85% reflectivity. The results predict a 30% increase in the  $J_{sc}$ .

In summary, this paper demonstrates an unprecedented growth and fabrication of InGaN solar cells using a 2 in. h-BN/

sapphire wafer. The devices exhibit PV performances comparable to similar solar cells grown on sapphire. An easy, nontoxic and low-cost liftoff process was used to separate the devices from the growth wafer without cracks. After their release, thin-film solar cells are bonded on glass with a backside reflector. This transfer offers a new technological degree of freedom that allowed an increase in the  $J_{sc}$  up to 20% when placed on a back-side reflector. The results presented here provide viable routes to the development of advanced InGaN-based solar cells that can lead to a significant improvement in the efficiency and a cost reduction for both terrestrial and space photovoltaic applications.

## METHODS

The growth was performed in an Aixtron MOVPE CCS  $3 \times 2''$  system on a (0001) sapphire substrate. Triethylboron (TEB), trimethylgallium/triethylgallium (TMGa/TEG), trimethylindium (TMIn), trimethylaluminum (TMAI), and ammonia ( $\text{NH}_3$ ) were used as B, Ga, In, Al, and N sources, respectively. Silane ( $\text{SiH}_4$ ) and  $\text{Cp}_2\text{Mg}$  were used as n-type and p-type doping sources. First, a h-BN layer (3 nm) was grown on the sapphire substrate at 1300 °C. Then, an intermediate Si-doped AlGaIn layer (300 nm) with an Al mole fraction of 14% was grown at 1100 °C. The InGaIn-based solar cell structure consists of a Si-doped GaN layer (0.5  $\mu\text{m}$ ), 5 periods of InGaIn/GaN multiquantum wells (MQWs), and a Mg-doped GaN layer (0.3  $\mu\text{m}$ ). The electron and hole carrier concentrations in the Si- and Mg-doped GaN layers are  $5 \times 10^{18} \text{ cm}^{-3}$  and  $1 \times 10^{17} \text{ cm}^{-3}$ , respectively. The MQW structure consists of a 12 nm thick GaN barrier layer and a 2.5 nm thick InGaIn quantum well layer. High resolution X-ray diffraction (HR-XRD) scans were performed in a Panalytical X'pert Pro MRD system with Cu  $K\alpha$  radiation in triple axis mode and emission properties were studied by photoluminescence (PL) mapping at room temperature.

For the fabrication of the solar cells, a standard photolithography-based process was employed. First, mesa etching isolation was achieved by inductively coupled plasma with  $\text{BCl}_3/\text{Cl}_2/\text{Ar}$  chemistry. Ti/Al/Ni/Au, Ni/Au, and another Ti/Al/Ni/Au stacks was used for the n-contact, the p-contact, and the bus bars, respectively. All the metal layers have been deposited by thermal evaporation. N-Contact annealing was carried out at 850 °C for 30 s under  $\text{N}_2$ . The p-contact was annealed at 600 °C for 60s under an  $\text{O}_2/\text{N}_2$  atmosphere. Dark  $I$ - $V$ s were measured by an automated probe station and the photovoltaic results were obtained using an Oriol Sol3A solar simulator.

We have used SILVACO-Atlas for our simulations. SILVACO-Atlas is a finite-volume physical based simulation tool, which solves the three equations: Poisson equation, continuity equations, and transport equations at each node. details about the used physical model can be found in ref 4.

The transfer of the devices to the final substrates is performed in two steps. First, we release the devices from the h-BN/sapphire by means of a commercially available water-dissolvable tape. Then the devices are bonded to the final substrate using a polyurethane resin. The resin is cured at 60 °C for 4 h than the tape is easily removed by rinsing in water.

The dielectric mirror (DM) was deposited on a glass substrate by plasma-enhanced chemical vapor deposition (PECVD). It consists of 13 alternating layers of SiN (60

nm)/ $\text{SiO}_2$  (60 nm) and a final 140 nm SiN layer. FTIR measurements were performed to check the DM reflectivity.

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### Notes

The authors declare no competing financial interest.

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