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Novel Scalable Transfer Approach for Discrete III-Nitride Devices Using Wafer-Scale Patterned h-BN/Sapphire Substrate for Pick-and-Place Applications

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The mechanical release of III-nitride devices using h-BN is a promising approach for heterogeneous integration. Upscaling this technology for industrial level requires solutions that allow a simple pick-and-place technique of selected devices for integration while preserving device performance. An advance that satisfies both of these requirements is demonstrated in this work. It is based on a lateral control of the h-BN quality, using patterned sapphire with a SiO_2 mask, to achieve localized van der Waals epitaxy of high-quality GaN based device structures. After process fabrication, the devices can be individually picked and placed on a foreign substrate without the need for a dicing step. In addition, this approach could reduce delamination of h-BN on large diameter substrates because each h-BN region is smaller, with independent device structures. Discrete InGaN LEDs on h-BN are grown and fabricated on 2 in. patterned sapphire using a SiO_2 mask. A set of devices are selectively released and transferred to flexible aluminum tape. The transferred LEDs exhibit blue light emission around 435 nm. The approach presented here is scalable on any wafer size, can be applied to other types of nitride-based devices, and can be compatible with commercial pick-and-place handlers for mass production.

With the electronics industry entering an era of acceleration and disruption, the role of heterogeneous integration will prove very important in response to the driving forces of several emerging fields like IoT, smart mobile, and intelligent automotive. One approach to heterogeneous integration is the transfer of epilayers from their native growth substrate to a dissimilar receiving substrate.[1] A range of epitaxial layer separation approaches have been developed including laser liftoff[2,3] and chemical liftoff which dissolves a sacrificial layer.[4,5] Van der Waals epitaxy of III-nitrides on graphene and device transfer on foreign substrates were demonstrated.[6] However, for a manufacturing setting, this latter technique would require significant capital expenses since graphene templates have to be prefabricated in a separate step.[7] More recently, the use of 2D h-BN as a mechanical release layer has been demonstrated to be a promising liftoff technique for the hybrid integration of III-nitride devices.[8–10] H-BN is a III-nitride material which exhibits a 2D structure when grown as monolayers of nanometer thicknesses,[11] similar to graphene. It is particularly compatible with growth of wurtzite III-N devices in a single epitaxial run. The h-BN based liftoff technique offers several advantages including 1) very rapid process, 2) no costly excimer laser is needed, 3) no laser damage, resulting in smooth separated surfaces,[12] and 4) no need for time consuming and hazardous chemical treatments. Moreover, chemically inert and mechanically stable at elevated temperatures, h-BN leaves no constraints on growth conditions of subsequent epilayers above when compared to other growth and liftoff processes.[13] In order for this h-BN based liftoff technique to reach industrial maturity, innovative solutions are needed to facilitate mass production while preserving devices performance. Our proposed approach consists of a localized van der Waals epitaxy of high-quality GaN based device structures on 3 nm thick h-BN grown on SiO_2 patterned sapphire substrates. The growth wafer surface is subdivided into delimited areas chosen for device locations. This enables a separation of the device structures as grown and would facilitate device-by-device pick-and-place without the need for a dicing step. In addition, a limited growth surface facilitates the epitaxial growth of h-BN and device structures on large wafers which is always critical since delamination may occur

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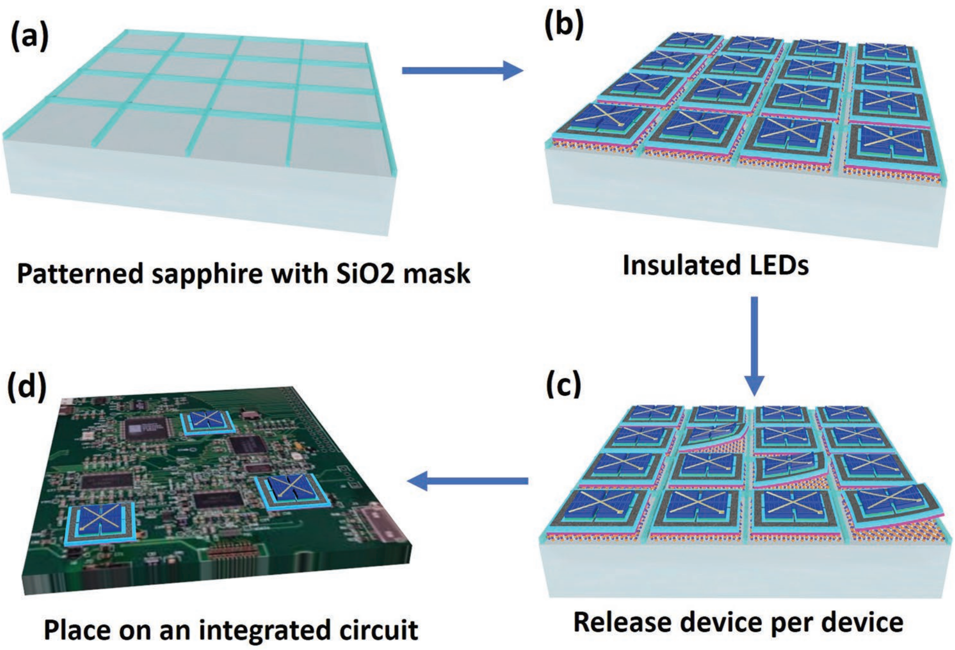

Figure 1. a) A large-surface sapphire wafer patterned into small areas using a SiO_2 grid. b) Insulated grown and fabricated devices on h-BN. c) The devices can be released from the sapphire one by one and d) placed on an integrated circuit.

sporadically at any step of growth.[14,15] With this approach, h-BN and device structures can be grown in any metal-organic chemical vapor deposition growth chamber size.

In this work, we demonstrate the first localized van der Waals epitaxy and fabrication of InGaN-based LEDs on 2D h-BN using dielectric patterns on sapphire substrates. The 2 in. diameter wafer surface is subdivided into small areas ranging from 1 mm^2 to 1 cm^2 by a mean of a SiO_2 grid, as illustrated in **Figure 1**a. After growth of a 3 nm h-BN layer, the InGaN-based LEDs are then selectively grown. Figure 1b shows a schematic of

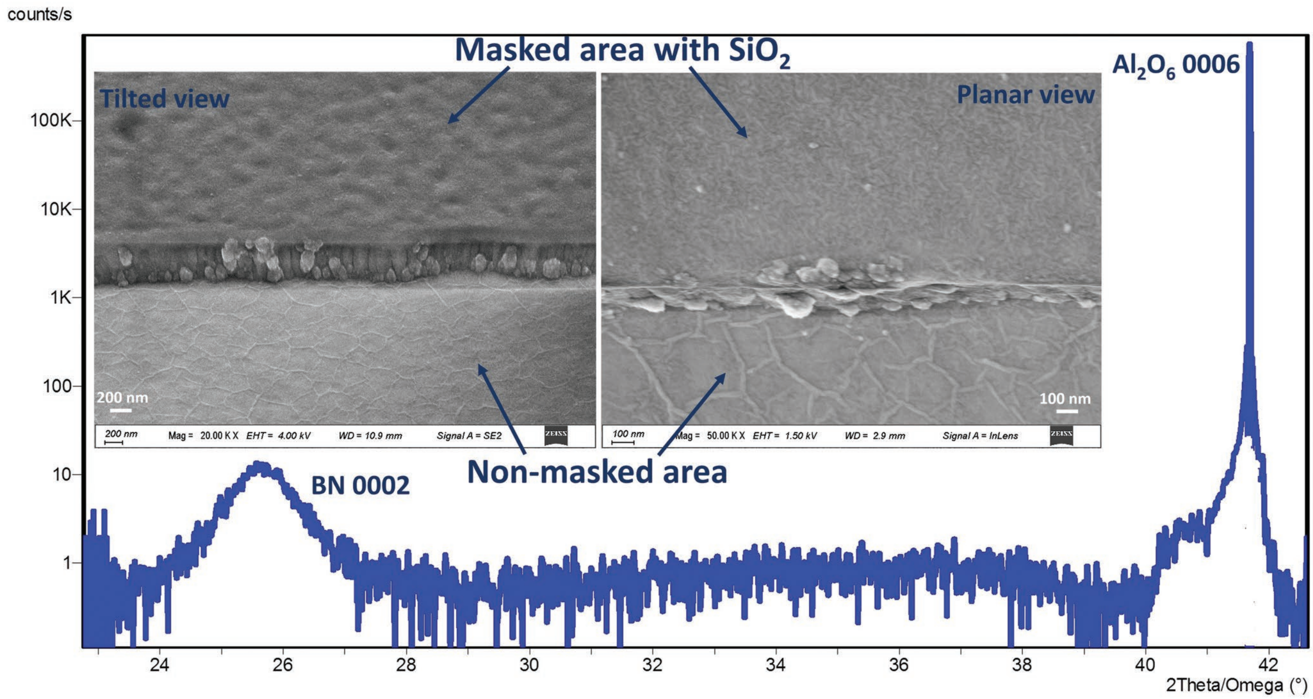

Figure 2. High-resolution triple axis $2\theta - \omega$ scan of the 20 nm thick h-BN layer grown on a patterned sapphire performed on the nonmasked area; left and right inset show a 45° tilted SEM image of the 20 nm h-BN layer grown on a patterned sapphire using a SiO_2 mask, and a planar SEM image, respectively.

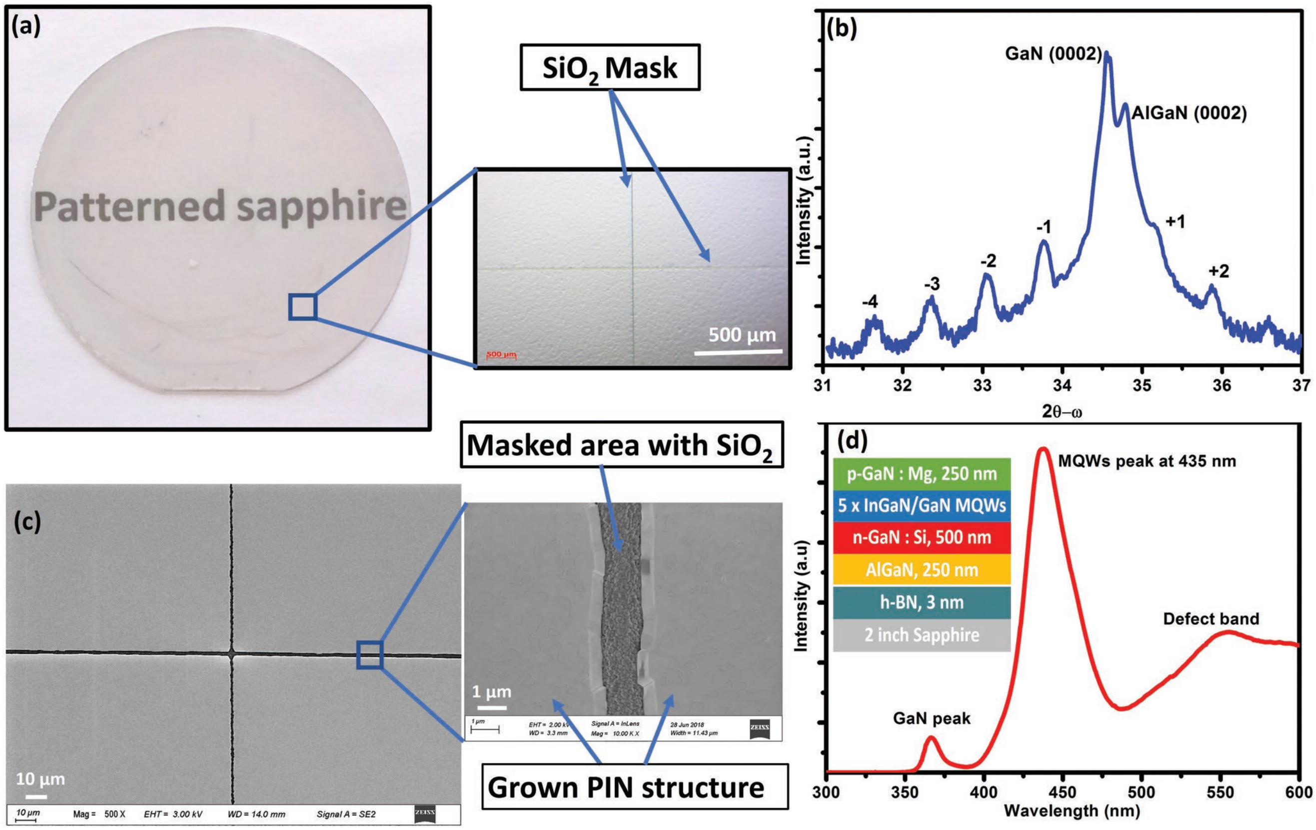

Figure 3. a) As-grown LED structure on 2 in. patterned sapphire with a SiO_2 mask, inset: optical microscope image showing separated growth areas. b) High resolution X-ray diffraction $2\theta - \omega$ scans of the grown structure on the patterned sapphire. c) SEM images of the locally grown LEDs structure on the patterned sapphire. d) CL spectrum recorded at room temperature under excitation of 5 keV, the inset shows the grown structure.

several devices separated by the SiO_2 grid. After fabrication, the devices can be released individually and placed on a specific carrier position in an integrated circuit for example, as illustrated in Figure 1c,d. This work proposes an innovative commercializable heterogeneous integration method for III-nitride devices.

Since h-BN is a key layer for the transfer method, we first investigated its growth using a patterned wafer. A SiO_2 mask has been fabricated on a sapphire substrate and then we have performed the growth of 20 nm h-BN. As shown in **Figure 2**, high resolution X-ray diffraction (HR-XRD) scans, performed in the nonmasked areas, give a clear symmetric diffraction peak located at 25.8° that relates to hexagonal boron nitride (0 0 0 2) crystal planes. The quality of the localized h-BN on sapphire is similar to the one on unpatterned substrate as can be seen by the wrinkles in the left inset scanning electron microscope (SEM) images of Figure 2 which are characteristic of the 2D layered h-BN. The h-BN growth is very localized with no visible connection between the BN layers on the mask and on the sapphire surface, as confirmed by the tilted SEM image showing the mask sidewall with isolated BN crystallites. On the SiO_2, randomly oriented BN has been grown showing a radical difference in quality between BN on dielectric SiO_2 and on sapphire substrates.

After studying the growth of the h-BN layer using patterned sapphire, we have performed a series of runs to grow InGaN-based LEDs using h-BN/patterned sapphire substrates. The LED structure, shown in the inset of **Figure 3**d, consists of five InGaN/GaN quantum wells sandwiched between 0.5 µm n-GaN and 0.25 µm p-GaN layers. This structure is grown on 3 nm h-BN using a 250 nm $Al_{0.14}Ga_{0.86}N$ nucleation layer. The SEM images in Figure 3c show the selective growth of the LED structure in regions where layered h-BN is deposited, avoiding the growth on randomly oriented BN on SiO_2. The inset zoom-in image shows very sharp side walls of the LEDs structure in each side of the mask which is required to guarantee the separation between the devices after process fabrication. To avoid the coalescence of the ≈1 µm thick grown structure due to the lateral growth, the SiO_2 mask thickness was chosen to be 400 nm. The high-resolution X-ray diffraction $2\theta - \omega$ scan around the (002) of the grown structure on the patterned sapphire is shown in Figure 3b. The scan clearly delineates the InGaN satellite peaks up to the fourth order as well as the peaks from the GaN and $Al_{0.14}Ga_{0.86}N$ layers. Optical characteristics of the multiquantum well (MQW) structure have been investigated, as shown in Figure 3d. Depth resolved cathodoluminescence (CL) spectrum for the MQW structure are recorded at room temperature with an electron beam excitation energy of 5 keV. A MQW emission peak around 435 nm has been obtained which corresponds to 14% In content in the quantum wells. These series of characterizations demonstrate the ability to selectively grow InGaN-based structures on a van der Waals surface with good quality using a 2 in. patterned sapphire wafer.

Several LEDs with various chip designs and sizes were fabricated using a 2 in. grown sample, as shown in **Figure 4**b. Figure 4a shows a set of eight devices with a 1 mm^2 area and

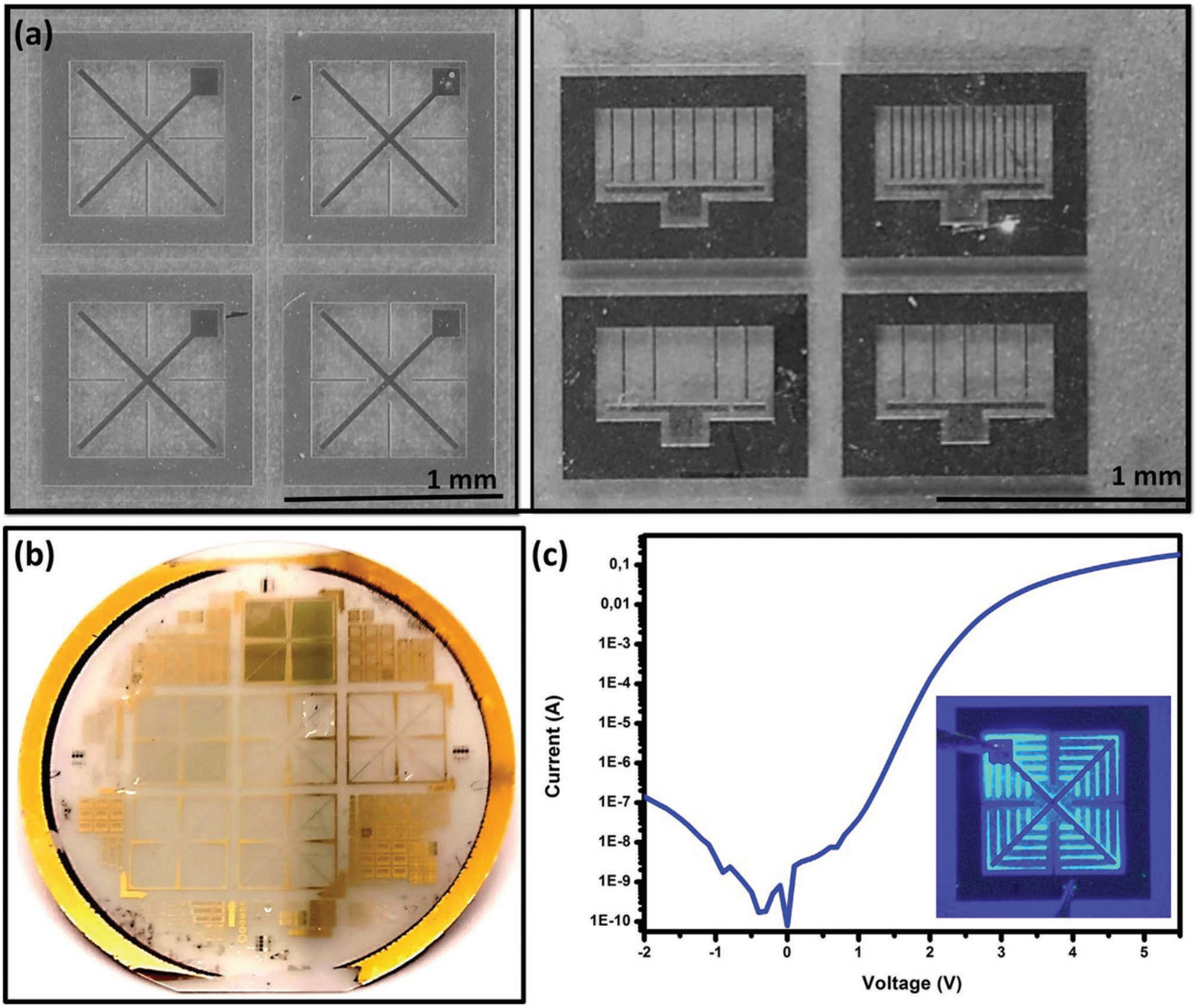

Figure 4. a) Optical microscope images of eight devices with 1 mm^2 area and different designs; separated by the SiO_2 mask (white lines around the devices) and ready for pick-and-place. b) Photo of the wafer-scale processed discrete LEDs. c) *I–V* characteristic of a fabricated device emitting blue light shown in the inset.

different designs that are insulated by the SiO_2 mask. 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.[15] In our experiment, a standard photolithography-based process has been applied while contact with liquids was limited and no ultrasonic cleaning was used. After fabrication, *I–V* measurements were performed as shown in Figure 4c with an inset exhibiting blue light emission from a LED device.

Thanks to the patterning with the SiO_2 mask, the fabricated devices are already physically insulated from each other. The discrete LEDs can be released and transferred individually without the need for a dicing step. In this work, a selected set of devices has been released by means of a water-dissolvable tape and transferred to a flexible aluminum tape. The tape is attached to a carrier for the release. Then, once the device is placed on the final substrate, the tape is simply removed by dissolving it in water for around 1 min. The pick-and-place capability is demonstrated in **Figure 5**a where we clearly see that some devices have been lifted off from sapphire leaving their locations empty while other LEDs were kept on the growth wafer.

During the transfer process, device structures remained completely intact and free from cracks and metallic contact damage. This crack-free transfer has been achieved primarily thanks to the optimized vertical liftoff of the devices, as shown in Figure 5b. A setup has been adapted to only enable a vertical movement during the device release step and avoid peeling off which induces strains on the surface and therefore cracks. **Figure 6**a,b shows an LED after its release from the growth wafer and its transfer to an aluminum tape, respectively. *I–V* measurements for a same LED were performed before and after its transfer to confirm the preservation of the device functionality, as shown in Figure 6c with an inset exhibiting blue

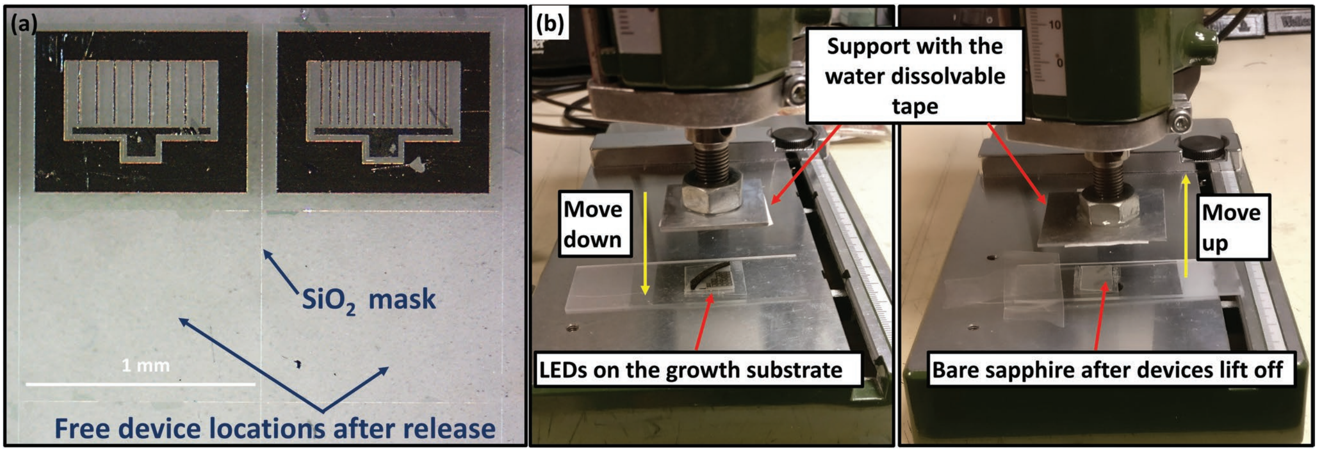

Figure 5. a) Optical microscope image showing empty locations of two lifted off LEDs and two other LEDs kept on the patterned sapphire. b) Photographs showing the vertical liftoff process to avoid cracks formation.

light emission from the device on the aluminum tape. In this work, the LEDs have been placed on the flexible final substrate with the p-side on top which is appropriate for this type of application. We should note that the proposed pick-and-place process could be adapted for other application like displays where the LEDs need to be placed up-side down in contact with an IC driver. For this case, one more transfer step after devices release is needed and can be easily implemented.

In summary, this work demonstrates a wafer-level mass manufacturable approach for the heterogeneous integration of III-nitride devices using 2D h-BN, which is robust and facilitate a simple device-level pick-and-place. The key step in the proposed solution is the patterning of the sapphire wafer to laterally control the h-BN quality and separate the device locations. Discrete blue LEDs have been fabricated on 2 in. patterned sapphire wafer with a SiO_2 mask. Subsequently, a set of devices have been mechanically released from the growth substrate thanks to the 2D layered h-BN and transferred on a flexible aluminum tape without damage. The results presented here provide viable routes to the development of advanced III-nitride based integrated devices at industrial scale.

Experimental Section

The SiO_2 was fabricated by a photolithography-based process. First, a 400 nm SiO_2 layer was deposited by plasma-enhanced chemical vapor deposition (PECVD) on a 2 in. sapphire wafer. Then, the patterns were defined by photolithography. Finally, the SiO_2 was etched by HF to open the device locations.

The growth was performed in an Aixtron MOVPE CCS 3 × 2 in. system on a (0001) patterned sapphire substrate. Triethylboron (TEB), trimethylgallium/triethylgallium (TMGa/TEG), trimethylindium (TMIn), trimethylaluminum (TMAl), and Ammonia (NH3) were used as B, Ga, In, Al, and N sources, respectively. Silane (SiH_4) and Cp_2Mg was used as n-type and p-type doping sources. First, an h-BN layer (3 nm) was grown on the sapphire substrate at 1300 °C. Then, an intermediate AlGaN layer (250 nm) with an Al mole fraction of 14% was grown at

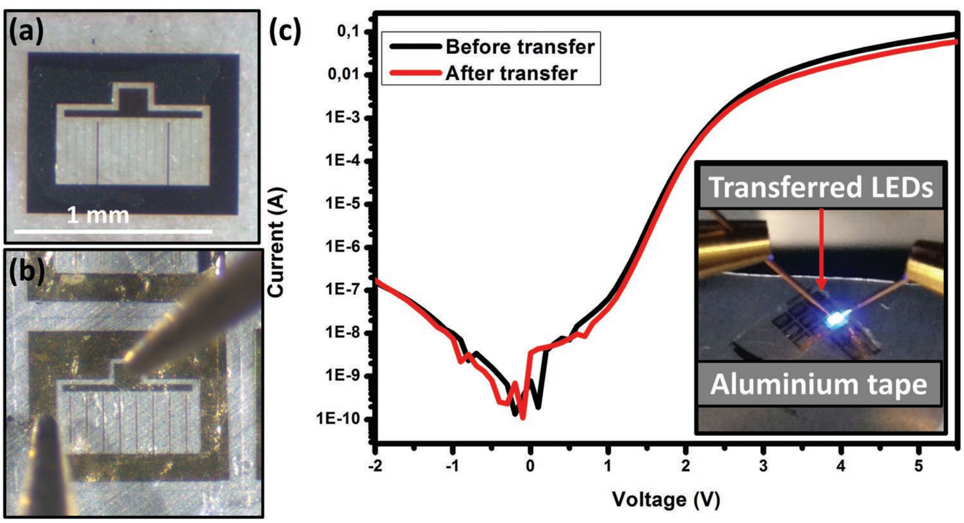

Figure 6. a) Microscope image from the back side of an LED on a water dissolvable tape after release. b) Microscope image of an LED after its crack-free transfer on a flexible aluminum tape. c) *I–V* characteristics of a same device before (black curve) and after its transfer (red curve) with its blue light emission shown in the inset.

1100 °C. The InGaN-based solar cell structure consisted of a Si-doped GaN layer (0.5 µm), 5-periods of InGaN/GaN multiquantum wells, and a Mg-doped GaN layer (0.25 µm). The MQW structure consisted of a 12 nm thick GaN barrier layer and a 2.5 nm thick InGaN quantum well layer. High resolution X-ray diffraction scans were performed in a Panalytical X'pert Pro MRD system with Cu Kα radiation in triple axis mode and emission properties were studied by cathodoluminescence at room temperature.

For the fabrication of the LEDs, a standard photolithography-based process was employed. First, mesa etching isolation was achieved by inductively coupled plasma with BCl_3/Cl_2/Ar chemistry. Ti/Al/Ni/Au, Ni/Au, and another Ti/Al/Ni/Au stack were used for the n-contact, the p-contact, and the pads, respectively. All the metal layers were deposited by thermal evaporation. N-contact annealing was carried out at 850 °C for 30 s under N_2; the p-contact was annealed at 600 °C for 60 s under an O_2/N_2 atmosphere. Dark *I–V*s were measured by an automated probe station. Resist development, resist stripping, and metal liftoff step were performed with gentle agitation of the liquids to limit the delamination risk.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

h-BN, heterogeneous integration, III-nitrides, pick-and-place

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