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Progress and Prospects of III-Nitride Optoelectronic Devices adopting Lift-Off Processes

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Lift-off processes have been developed as the enabling technology to free the epitaxial III-Nitride thin film from a conventional growth substrate such as sapphire and Silicon, in order to realize a variety of novel device designs and structures not otherwise possible. An epitaxial lift-off (ELO) process can be adopted to transfer the entire film to an arbitrary foreign substrate to achieve various functions, including enhancement of device performance, improvement of thermal management and to enable flexibility amongst others. On the other hand, partial ELO techniques, whereby only a portion of the thin-film is detached from the substrate, can be employed to realize unconventional device structures or geometries, such as apertured, pivoted, and flexible devices, which may be exploited for various photonic structures or optical cavities. This paper reviews the development of different lift-off strategies and processes for III-Nitride materials and devices, followed by a perspective on the future directions of this technology.

I. INTRODUCTION

Due to their excellent optical and electronic properties, III-Nitride-based devices are now widely used and are essential to our everyday lives, with a global market estimated to reach USD 24.9 billion by 2026[1]. From light sources and TVs to chargers, more and more devices and appliances are adopting and incorporating III-Nitride technologies such as light-emitting diodes (LEDs), laser diodes (LDs), and high-electron-mobility transistors (HEMTs).

The success of III-Nitride devices relies on the epitaxial growth of crystalline materials on selected substrates such as sapphire[2,3], silicon (Si)[4,5], and silicon carbide (SiC)[6] by metalorganic vapor phase epitaxy (MOVPE) or molecular beam epitaxy (MBE). Bulk GaN substrate grown by hydride vapor phase epitaxy (HVPE)[7] is also a popular choice due to its low dislocation density. But with a 2-inch *c*-plane bulk GaN substrate currently priced at above 1000 USD, it is much more expensive than heteroepitaxial GaN based on Silicon or Sapphire substrates that only cost a small fraction for a 6-inch substrate, typically less than 5% that of the bulk GaN substrate price. Generally speaking, to obtain a usable III-Nitride film, the thicknesses of various layers in the epitaxial structure must be large enough to mitigate dislocations[8,9]. This can be achieved with the help of interlayers[10], but it may be difficult to attain an ideal strain state[11–13] due to thermal mismatch and lattice mismatch. This strain adversely affects the piezoelectric polarization field, thus giving rise to the Quantum Confined Stark Effect (QCSE)[14,15] together with the spontaneous polarization field inherent in the wurtzite crystal structure of III-Nitride materials.

However, the use of such substrates during epitaxial growth also poses a great limitation to the device structure. Epitaxial lift-off (ELO) technology has thus been developed for the separation of high-quality III-Nitride films from their respective substrates to realize various novel device designs, as illustrated in Fig. 1, which are especially important for optoelectronic devices. An ELO process would allow transfer of the film to a foreign substrate to enhance functionality[16,17], improve the efficiency[18,19], and/or provides a platform for integrating various III-Nitride device components[20]. While an ELO process typically refers to lift-off process involving the entire film, development of partial ELO, on the other hand, allows unique device geometries, including apertured, pivoted, and flexible film structures formed by selective area backside etching, partial chemical lift-off, and selective area laser lift-off (LLO) processes, respectively. These structures have their own advantages and applications in various devices and systems such as laser diodes and transistors, which will be discussed later. There are also cases where partial ELO would be favorable over complete ELO, especially when various components and devices are integrated.

In this article, we give an overview of III-Nitride optoelectronic devices involving various lift-off processes. Section II discusses thin film devices based on ELO process. Sections III, IV and V describe apertured, pivoted, and flexible devices based on partial ELO processes, respectively. Finally, Section VI gives a brief perspective on the current status of III-Nitride optoelectronic devices involving lift-off processes.

II. THIN FILM DEVICES

To form a thin film structure, an ELO process can be employed to lift off a GaN film, which is then transferred to a foreign substrate. Although GaN films are generally brittle and susceptible to cracks, several lift-off approaches have been demonstrated with little degradation in performance. Such methods include laser lift-off (LLO), chemical lift-off, and spalling, with all three of the techniques proven to be useful in large-area ELO. To aid transfer of the film to another substrate, the wafer is first bonded to the target substrate with adhesive or a metal layer before the ELO process. The target substrate then acts as a support for the fragile film during or after the ELO process.

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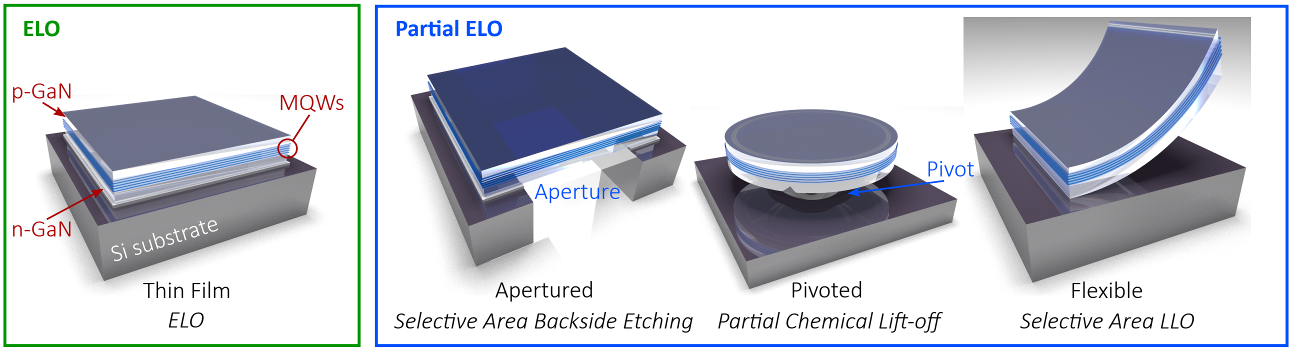

FIG. 1. Schematic diagram of structures enabled by various lift-off processes.

A. Epitaxial Lift-off (ELO)

1. *Laser Lift-off (LLO)*

The use of the LLO process for GaN films was first demonstrated by Kelly *et al.* using a 355 nm Q-switched Nd:YAG laser with an energy density of 15 - 31 mJ/cm^{2}and a pulse duration of 6 ns[23]. Using a similar approach, they later demonstrated LLO of an almost 2-inch HVPE-GaN from a sapphire substrate using the same 355 nm Q-switched laser with an energy density of 0.3 J/cm^{2}and a pulse duration of 5 ns[24]. W. S. Wong *et al.* developed an LLO process for GaN films using a 248 nm KrF Excimer laser with an energy density of 0.4 - 0.6 J/cm^{2}and a pulse duration of 38 ns[25]. They later applied this technique to demonstrate the first LLO-based thin film InGaN LED with the same 248 nm KrF laser and similar parameters, with an energy density of 0.6 J/cm^{2}and a pulse duration of 38 ns[26].

As shown in the schematic diagrams in Fig. 2(i), the LLO process uses a laser beam at a wavelength typically below the absorption edge of GaN to illuminate the substrate/film interface and induce laser ablation through thermal decomposition. Typically, the laser beam is illuminated through the backside to minimize any damage caused by the laser beam travel path. As such, the LLO process is normally only applied to films with transparent substrates, such as Sapphire and bulk GaN substrates, that are polished smooth on the backside. Material to be ablated, such as GaN in this case, with bandgap energy lower than the laser will readily absorb the laser energy, as illustrated by the band diagram in Fig. 2(ii). When the energy density of the laser pulse increases above the ablation thresh-

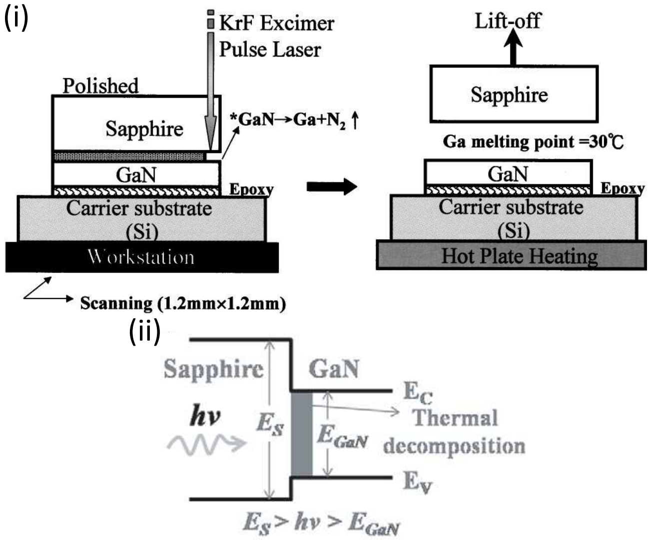

FIG. 2. (i) Schematic diagrams (Reprinted with permission from Chu *et al.*, J. Appl. Phys. 95, 3916 (2004). ©2004 AIP Publishing) and (ii) band diagram (Reprinted with permission from Su *et al.*, J. Phys. D: Appl. Phys. 46, 205103 (2013). ©2013 IOP Publishing.) of the LLO process.

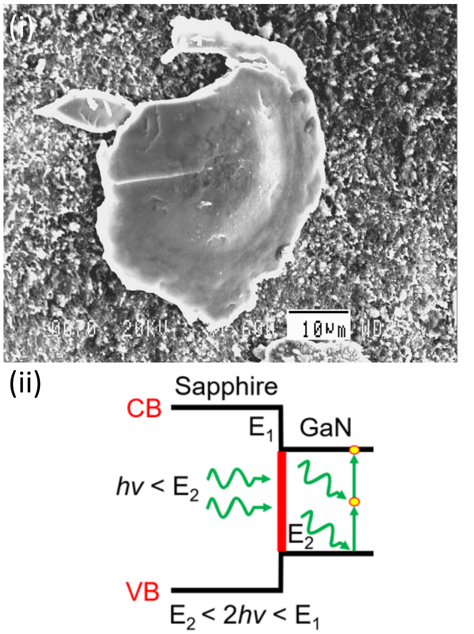

FIG. 3. (i) SEM image of a GaN crystal lift-off by a pulsed 532 nm laser. Reprinted with permission from Ho *et al.*, Mater. Chem. Phys. 81, 99 (2003). ©2003 Elsevier; and (ii) the band diagram of the LLO process using a femtosecond laser. Reprinted with permission from Yulianto *et al.*, ACS Appl. Electron. Mater. 3, 778 (2021). ©2021 American Chemical Society.

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old, typically in the range of 0.1 - 0.6 J/cm^2 [29–32], GaN will decompose into nitrogen gas and Ga droplets[21,22]:

$$2\,\mathrm{GaN}_{(s)} \longrightarrow 2\,\mathrm{Ga}_{(l)} + \mathrm{N}_{2(g)} \tag{1}$$

Following decomposition, the Ga droplets on the film can be removed together with the substrate by heating above the melting point of Ga at 30°C[25]. Any Ga or Ga oxide residues on the ablated surface can be further cleaned by dilute acid such as HCl or H_2SO_4/H_2O_2[21].

The laser utilized used for lift-off will needs to have an higher energy higher than that of the absorption edge of the material to be ablated. In the case of lift-off, the ablation typically occurs at the interface of the substrate and GaN, thus the laser wavelength is usually chosen to be shorter than the absorption edge of GaN at around 365 nm (3.4 eV[33]). In addition, care has to be taken to make sure any ablation damage is confined to near the interface. Typically, a pulsed laser with a pulse duration of at most a nanosecond is used to reduce damage caused by heat dissipation. Some common lasers used in the LLO process include pulsed Excimer ArF laser at 193 nm[34,35], Excimer KrF laser at 248 nm[25,26,36–40], XeCl laser at 308 nm[41] and Nd:YAG Q-switched laser at 266 nm[42] and 355 nm[23,24,43].

To lift-off an entire film that is normally larger than the size of a typical laser spot, the laser beam needs to scan through the entire area during the LLO process. There are typically two strategies: the step-and-repeat method and the line scan method[44]. For the step-and-repeat method which is also the most commonly used method, the laser spot is focused to attain appropriate energy density that is above the ablation threshold. The spot then scans along one direction, one row at a time, until the entire area is covered. For the line scan method, the two axes of the laser beam are independently shaped, often by using a cylindrical lens in combination with a slit mask, forming a homogeneous laser line beam. Usually only a single pass of scan is needed for a laser line beam to cover an entire wafer. As such, the line scan method is beneficial to large area lift-off, despite a more complex system and the requirement of a laser with much higher laser pulse energy. Successful demonstrations of line beam LLO to separate GaN film from sapphire substrate have been reported by R. Delmdahl *et al*.[45,46].

H. P. Ho *et al*. demonstrated a method using a pulsed 532 nm Nd:YAG laser with energy lower than the bandgap, with an energy density of >12.4 mJ/cm^{2}and a pulse duration of 10 ns. In this approach, the laser beam is absorbed by free carriers in the conduction band, and the energy is transferred to the lattices via electron-phonon scattering[43]. Unfortunately, the longer wavelength results in a deeper penetration, which can induce cracking over the film. As such, only GaN crystal of 50 μm in diameter is demonstrated in this study, as shown in Fig. 3(i). Moreover, part of the GaN melted by the laser was transformed into a cubic phase[27]. Meanwhile, D. Iida *et al*. demonstrated an LLO technique for bulk GaN substrate, even though LLO based on free-carrier absorption seems to be impractical. The developed LLO method used a pulsed 532 nm Nd:YAG laser to selectively ablate an InGaN layer inserted during growth. In the AlGaN-based UV-A LED, a sacrificial layer of $In_{0.15}Ga_{0.85}N$/GaN superlattices in between the n-GaN layer was ablated by a 532 nm laser, with an energy lower than GaN material but higher than InGaN. With an energy density of 0.125 J/cm^{2}while the pulse duration was not reported, laser ablation occurred via thermal decomposition of the InGaN layer to form an In droplet layer, resulting in an increased EL intensity by 1.7-fold after LLO[47].

Since the development of ultrashort pulse laser technology in the 1990s[48–50], femtosecond lasers have been widely adopted in micromachining[51], including the LLO process. Laser pulses with only femtosecond pulse width introduce less heat than conventional pulsed laser with nanosecond pulse width. Laser pulses with only femtosecond pulse width introduce less heat compared to a conventional pulsed laser with nanosecond pulse width. In addition, a laser with longer wavelength will also minimize damage on non-targeted areas, as only photons near the focus point of the fs-laser pulse undergo two-photon absorption for ablation, as illustrated by the band diagram in Fig. 3(ii). For example, N. Yulianto *et al*. demonstrated an LLO process using a 520 nm femtosecond laser, with a pulse energy of 5.5 - 9.7 μJ, an energy density of 2.6 - 4.4 J/cm^{2}and a pulse duration of 350 fs, to fabricate a flexible thin film LED, as shown in Fig.. 6(iii)[28]. Another LLO process for bulk GaN substrate was demonstrated by V. Voronenkov *et al*., which utilized a “slicing” technique that does not require a special release layer. In this approach, They focused a low energy 1030 nm femtosecond laser beam, with a pulse energy of >0.2 μJ (energy density not reported) and a pulse duration of 350 fs, at 6 μm beneath the sample surface utilizing a 100× oil immersion objective with an immersion oil having a refractive index of $n = 1.518$. Only GaN was decomposed near the focus spot where the nonlinear breakdown threshold was exceeded[52].

2. *Chemical Lift-Off (CLO)*

Various chemical etching methods have also been introduced to achieve substrate removal. Typically, the sample is submerged in a dilute acid solution or a KOH solution (sometimes assisted with a bias voltage and/or illumination) to dissolve a selected layer in the epitaxial structure to release the film from the substrate. A special case is Si substrate that can be preferentially etched away by an HF/HNO_3 solution without damaging or roughening the GaN layer[56]. In most cases, a sacrificial layer is incorporated into the epitaxial structure during growth, which is then chemically etched for lift-off.

In chemical lift-off process with only chemicals, a zinc oxide (ZnO) layer can be incorporated in the epitaxial structure. The ZnO can then be readily dissolved in a dilute HCl solution to release the film[57]. In chemical lift-off process involving electrochemical etching, an Si-doped GaN layer can be removed with oxalic acid, nitric acid, or HF acid[58–60] upon application of a bias voltage. As demonstrated in Fig. 4(i), the acid will etch the n-doped layer to form a nanoporous layer, while leaving the p-GaN and MQWs intact[54]. The nanoporous etching technique leads to the subsequent development of porous GaN photonic structures such as porous distributed

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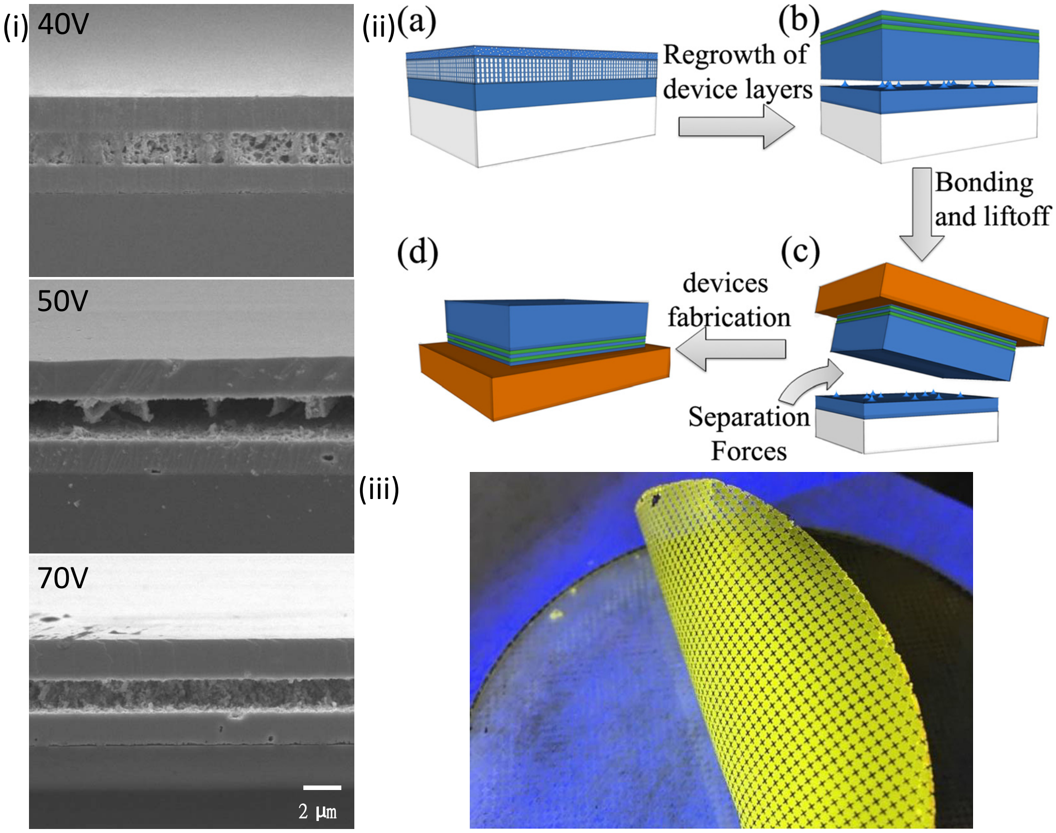

FIG. 4. (i) Schematic diagram depicting the PEC chemical lift-off process, with overgrowth on top of an n-GaN layer before PEC-etching. Reprinted with permission from Zhang, Leung, and Han, Appl. Phys. Lett. 100, 181908 (2012). ©2012 AIP Publishing (ii) Cross-sectional SEM images showing n-GaN layer electrochemically etched in oxalic acid under different bias voltages. Reprinted with permission from Park *et al.*, Appl. Phys. Lett. 94, 221907 (2009). ©2009 AIP Publishing; (iii) A photo showing wafer-scale GaN thin film lift-off from a 4-inch sapphire substrate. Reprinted with permission from Youtsey *et al.*, physica status solidi (b) 254, 1600774 (2017). ©2017 John Wiley and Sons.

Bragg reflectors (DBR)[61–63]. To break off the nanoporous GaN layer, external pressure is applied during processes such as wafer bonding to release the LED structure bonded to the target substrate[53], as shown in the process flow in Fig. 4(ii). In chemical lift-off process involving photoelectrochemical (PEC) etching, several methods can be applied. In PEC etching of InGaN, the sample is etched by submerging in a KOH solution and illuminated with a Hg-arc lamp[64]. By tuning the wavelength of the illumination source, the InGaN sacrificial layer in the epitaxial structure can be preferentially etched to achieve GaN film lift-off[65]. To achieve lift-off at the wafer-scale, trenches are first fabricated by a photoenhanced vertical wet etch in a KOH solution through a patterned metal mask applied by electroplating. The trenches help the KOH solution reach the InGaN sacrificial layer for subsequent lateral PEC etching. Successful wafer-scale ELO of a 4-inch wafer by such approach is illustrated in Fig. 4(iii).[55] Instead of an InGaN layer, a sacrificial MQW layer can also be used for PEC etching. After the MQW on bulk GaN sample is submerged in KOH, the sacrificial MQW is illuminated and excited by an LED source at 405 nm, which causes electron-hole pairs to be photogenerated to assist in the etching[66].

3. Spalling

Spalling was initially proposed by M. Tanielian *et al.*, who demonstrated spontaneous peeling of Si and GaAs layers from their corresponding substrates[67]. The conventional process of spalling involves separation of the film by introducting cracks/fractures that propagate in an in-plane direction. While typical cracks would have propagated through the entire thickness of the film and/or substrate, the deposition of a tensile-strained stressor layer would cause the fracture will first propagate downward before travelling in the in-plane direction, leading to peeling of the film. The mechanisms of the crack propagation during the spalling process can be determined by the three fracture modes: mode I (open stress), mode II (shear stress) and mode III (out-of-plane shear stress). The equilibrium crack depth is at a position/thickness where mode II stress becomes zero. At this depth, the crack kink angle will become zero[68], which means that the crack will propagate parallel to the film, resulting in spalling of the film.

a. Controlled Spalling To improve the control of cracking during spalling, S. W. Bedell *et al.*has introduced a "controlled spalling" process that initiates and controls crack propagation by the application of external force through the implementation of a handle layer[69]. The team has applied the technology for GaN based wafers and devices. For instance, they have demonstrated ELO of an entire 2-inch vertical LED structure via spalling, although the parasitic resistance increases as a result[70]. Controlled spalling of an entire 4-inch InGaN based LED structure from a sapphire substrate[71] and entire 2-inch GaN film from bulk GaN substrate[72] are then subsequently demonstrated.

b. Self spalling Spalling can also be achieved naturally by incorporating a Ti mask during growth. The Ti mask is first grown on an MOCVD-grown GaN/sapphire template before HVPE growth, as demonstrated by M. Amilusik *et al.*. The wafer-scale self-lift-off then occurs naturally during the cool-down process after growth, although the quality of the film depends on a nitridation process[73]. Similarly, V. V. Voronenkov *et al.*demonstrated that self spalling can occur by deposition of a GaN film with a thickness of larger than 2800 μm by incorporating a carbon buffer layer before HVPE growth[74].

c. Mechanical release by 2D materials A novel technique to achieve ELO is the incorporation of a thin layer of 2D materials during growth, which can be later released mechanically by breaking the Van der Waal's forces. The unique properties of the 2D materials enable an ELO process with high smoothness. As reported by K. Chung *et al.*, a graphene layer was coated with ZnO to promote nucleation of GaN for subsequent epitaxial growth of the LED structure. Due to the nature of the graphene layer, the epitaxial structure could then be lifted off mechanically, as illustrated in Fig. 5(i)[75]. Y. Kobayashi *et al.*, also demonstrated lift-off of a sapphire substrate incorporating a 3-nm thick hexagonal Boron Nitride (h-BN) layer, which did not impact the crystal quality during growth of subsequent epitaxial structure. The h-BN layer could then be released upon the application of a mechanical force[76]. Photos of the lift-off of a device with a h-BN release layer are shown in Fig. 5(ii) and (iii). E. W. Blanton *et al.*also incorporated a BN release layer in the MOCVD-grown film while using a controlled spalling process for ELO from sapphire substrate with sub-nanometer roughness[77].

B. Wafer Bonding

The ELO process can be used to transfer GaN-based thin film devices to other foreign substrates, allowing new functionalities[78,79], improved performance[19,80,81] and even cost savings by recycling expensive bulk GaN substrates[82]. Typically, the sample is first bonded to another substrate for support before proceeding to the ELO process.

There are two main ways of bonding the thin film to a foreign substrate, adhesive or eutectic bonding. Although earlier studies mainly used plain adhesives to bond to other substrates[23,26], for practical purposes, later studies used a metallic layer[37,86,87] and conductive glue[88,89] to facilitate electrical contact. There is also a report on the bonding of LEDs to a flexible polyimide substrate via a pre-coated metallic Au/Cr layer by S. H. Lee *et al.*[16]. Plain adhesive are mainly used in cases where temporary bonding is needed during "double-flipping"[37], for fabrication of free-standing membranes[26], or for bonding the epitaxial structure to flexible substrates[89–91]. Direct wafer bonding using a surface activated bonding approach has also been demonstrated. F. Mu *et al.* reported a GaN surface smoothed by chemical-mechanical polishing (CMP), followed by surface activation by ion beam bombardment on both sides to facilitate the formation of covalent bonds during bonding at room temperature under ultra-high vacuum (UHV)[92].

Although there are numerous types of substrates, they can be mainly classified into four categories: metallic substrates, Si substrates, flexible substrates, and free-standing thin films (i.e., no substrate). Metallic substrates, such as Ni or Cu, are usually chosen for their good electric and thermal conductivity[19,21,37,86,87]. Thin films can usually be adhered to a metal substrate via electroplating to a thickness of about 30 – 50 μm for Ni and 70 – 100 μm for Cu[19,86,87,94–96]. As the metallic substrate is in thermal contact, it naturally acts to transfer heat from the thin film device, resulting in better heat dissipation and improved device performance[96].

On the other hand, silicon is a cost-effective substrate for thin film devices and has an advantage of higher thermal conductivity compared with sapphire. Moreover, a silicon substrate allows heterogeneous integration with silicon electronics. Although one can grow GaN directly on top of a silicon substrate[97], the bonding process usually involves deposition of a metal layer to bond the thin film and the Si substrate. Use of the metal layer improves the current spreading capabilities of now flipped p-GaN layer, and allows fabrication of a backside contact for vertical devices[18,19,43,81,86–88,98–102], as well as provide a reflecting surface for enhancing light output[86–88,103].

Given the recent trends in flexible devices, novel applications, and advancement in flexible electronics, there is growing interest in transferring devices to flexible substrates[104]. Besides devices on flexible adhesive tape, which also doubles as a way to release the film[54,90], other common flexible substrates include polyethylene terephthalate (PET)[17,58,59,89,91] and polyimide film[16].

As for the free standing thin films, this can be easily achieved by removing all supporting substrates[26]. However, for practical applications, a selected area of the epitaxial structure can be lifted off, such that only part of the thin film is suspended in the air with the sides supported by the substrate[78,105].

C. Applications

1. LEDs

One of the initial motivations for thin film III-Nitride devices is the performance increase of thin film LEDs over conventional LEDs. By transferring thin film LED to another substrate, several areas can be improved such as efficiency, addition of a reflective metal layer to the foreign substrate, bonding to a substrate with better thermal conductivity, and removal of the light-absorbing u-GaN layer.

As demonstrated by W. S. Wong *et al.*, an LED adhesively

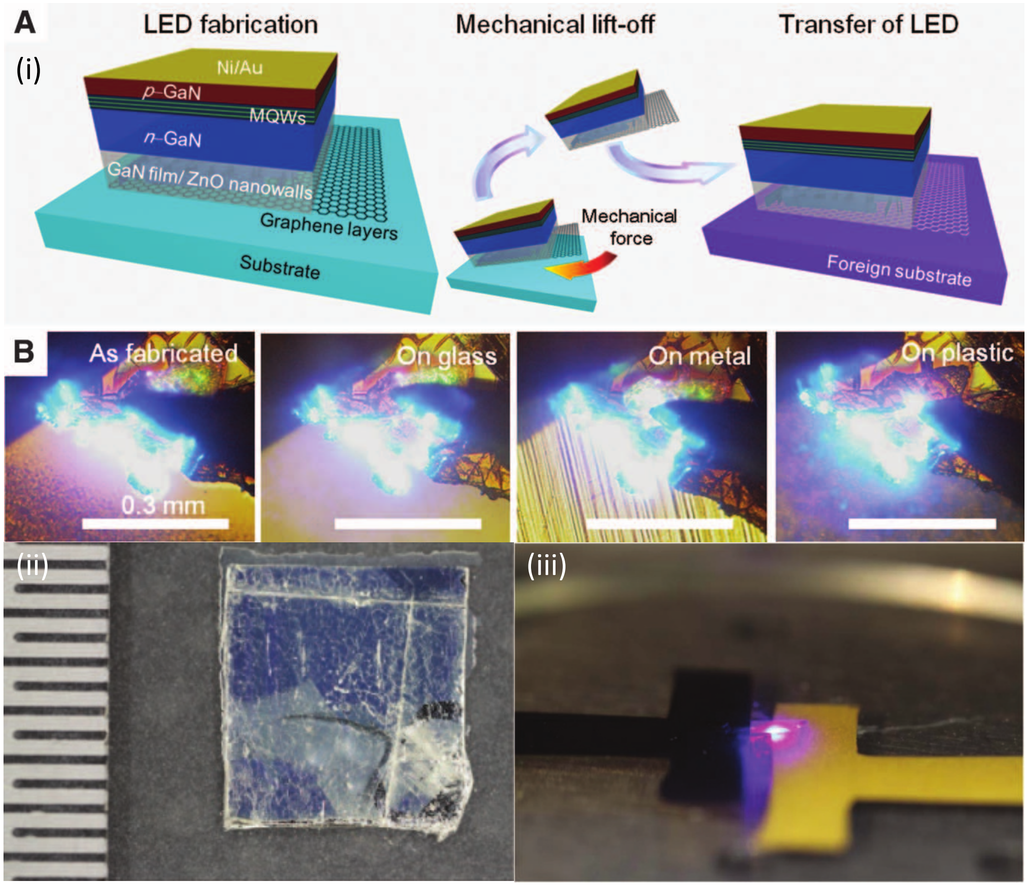

FIG. 5. (i) (A) Schematic diagram illustrating the growth and mechanical lift-off process using graphene layers; and (B) light emission from corresponding thin film devices on different substrates. Reprinted with permission from Chung, Lee, and Yi, Science 330, 655 (2010). ©2010 The American Association for the Advancement of Science; (ii) Photo of a transferred MQW structure on an indium sheet after mechanical lift-off involving a h-BN layer, and (iii) the photo shows the corresponding device under electroluminescence. Reprinted with permission from Kobayashi *et al.*, Nature 484, 223 (2012). ©2012 Springer Nature.

bonded to an Si substrate after LLO (248 nm, 0.6 J/cm^2, 38 ns) may exhibit a small decrease in output power[26]. Conversely, B. S. Tan *et al.* attached a thin film vertical LED to a Cu substrate via silver epoxy, which showed a 28% increase in light output due to better heat conduction and reflective silver epoxy, following a LLO process using a 248 nm laser with an energy density of 0.6 J/cm^{2}and a pulse duration of 23 ns[106]. By removing the u-GaN layer after the LLO process (248 nm laser, 0.6 J/cm^2, 25 ns) and bonding to a Cu substrate, C. -F. Chu *et al.* was able to demonstrate significantly enhanced light output by about 2.2-fold (4 times increased light output over 1.8 times increased emission area).[21]. There was little to no increase in light output power when not removing the u-GaN[26,106] and even when using a less damaging femtosecond laser[28], which suggests that the u-GaN layer substantially impedes light output. Indeed, the base of the u-GaN layer near where the nucleation layer situates has a much higher defect density[8,9], which may be a source of light absorption. A study by H. T. Chen *et al.* compared device performance between a conventional LED and a thin film LED with the u-GaN layer removed by a LLO process using a 266 nm laser. The study showed increase in light output by 39% , a 3-fold increase in luminous efficacy, and reduced thermal resistance by 35.3%[42].

To further enhance the light output, n-GaN layer, which is on the top side, can be roughened[18,103]. T. Fujii *et al.* demonstrated a four-fold increase in the EL intensity using a texturized n-GaN layer in a vertical LED with a cone-shaped surface through PEC etching in KOH solution[107]. Besides roughening, other studies have fabricated a photonic crystal on the n-GaN layer of a vertical LED. Y. F. Cheung *et al.* fabricated a nanopillar array using nanosphere lithography with nanospheres of 500 nm diameter. The photonic crystal served as a means for light extraction, which enhanced light output by 42%[108]. Using a similar approach, K. H. Li *et al.* fabricated a hexagonal micro-mesh on the n-GaN surface of a thin film LED, which enhanced light extraction efficiency by a factor of >100%[109]. However, a study of a photonic crystal structure fabricated on the n-GaN layer by A. David *et al.* showed that the photonic modes were strongest with a thin device, as shown in Fig. 6(ii), but the efficiency was severely limited by metal absorption of the contacting substrate[84]. Indeed, H. K. Cho *et al.* demonstrated only a 76% improvement in a thin film photonic crystal LED[95] compared to a 3-fold enhance-

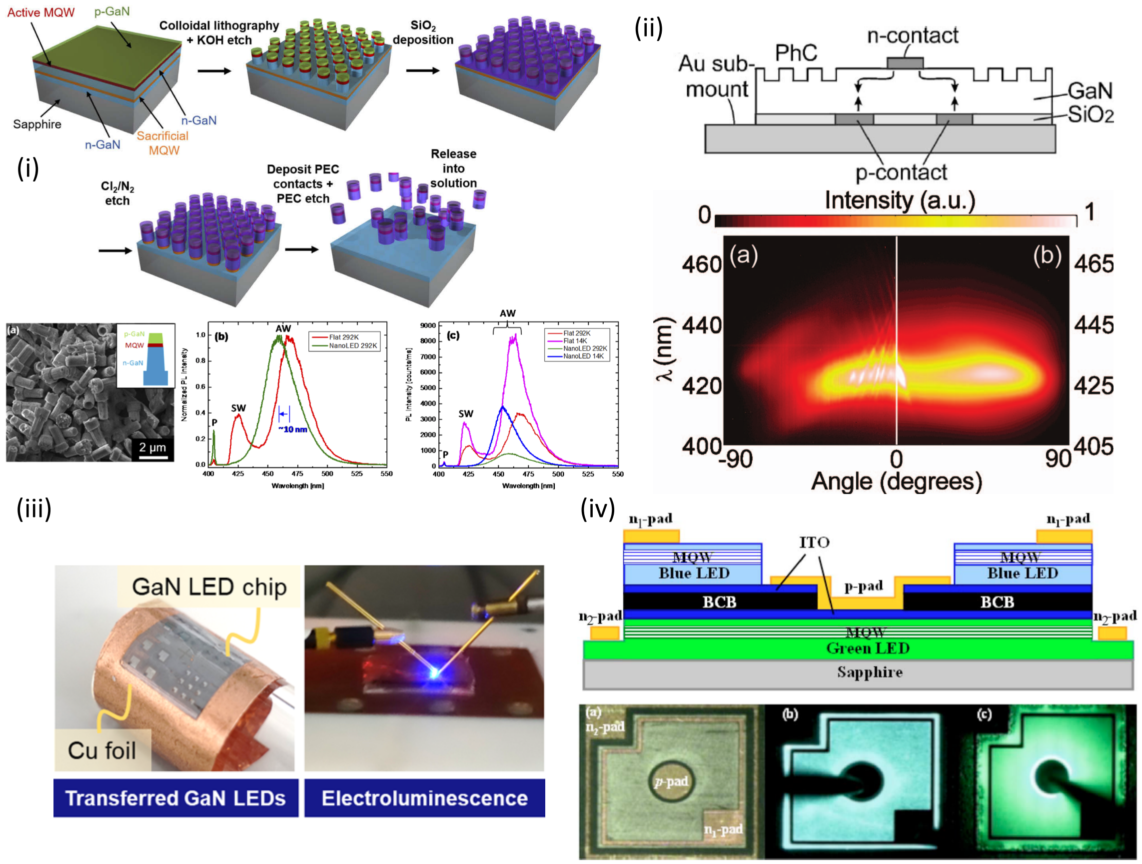

FIG. 6. (i) Schematic diagram of the process flow, and SEM image and PL spectra of a submicron-LED after ELO. Reproduced with permission from Chan *et al.*, Opt. Express 28, 35038 (2020). ©2020 The Optical Society. (ii) Schematic diagram and angle-resolved spectra of a photonic crystal LLO-LED. Reprinted with permission from David *et al.*, Appl. Phys. Lett. 88, 133514 (2006). ©2006 AIP Publishing; (iii) GaN LED transferred to a Cu foil by LLO utilizing a femtosecond laser. Reprinted with permission from Yulianto *et al.*, ACS Appl. Electron. Mater. 3, 778 (2021). ©2021 American Chemical Society; (iv) Schematic diagram and optical micrographs of a dichromatic LED formed by bonding a thin film of blue-emitting LEDs to an as-grown green LED. Reprinted with permission from Lee *et al.*, Appl. Phys. Lett. 90, 161115 (2007). ©2007 AIP Publishing.

ment in PL with a photonic bandgap structure fabricated on top of a conventional LED[110].

Although vertical LEDs can have increased performance compared to conventional LEDs, the huge decline in the cost of LEDs over the years[111] limits the application of these high brightness but expensive thin film LEDs. However, ELO thin film LEDs may find their place in the growing display market. There have been demonstrations of flexible LEDs fabricated by transferring thin film LEDs onto flexible substrates like PET[17,58,59,89,91] and polyimide film[16,112], which may find applications in flexible displays. The recent demonstration of an ELO process for sub-micron LEDs by L. Chan *et al.*[83], as shown in Fig. 6(i), may also facilitate the development of microLED displays that utilize a “mass transfer” approach[113]. Moreover, Y. J. Lee *et al.* also utilized ELO to assemble a dichromatic LED comprised of stacks of blue and green thin film LEDs, as demonstrated in Fig. 6(iv)[85], which can potentially be utilized to realize a stacked microLED display, as proposed by H. W. Choi[114,115].

2. *Lasers*

a. Edge-emitting laser diodes Given the success and increased performance of numerous vertical thin film LEDs as described in the previous section, there has been increasing research into thin film vertical laser diodes. W. S. Wong *et al.* initially investigated an InGaN laser diode with a light output of less than 12 mW. This laser diode was bonded to a copper substrate via an Indium layer through a LLO process using a 308 nm XeCL laser with an energy density of 0.5 J/cm^2 and a pulse duration of 20 ns[23], but there was little performance gain[37]. This experiment was repeated by M. Kneissl *et al.* using a laser diode with a similar configuration (308 nm laser, 0.5 J/cm^2, 20 ns) bonded to the copper substrate, but they observed an almost 10-fold increase in light output with a output power of 50 mW[36]. These studies suggest that improving the thermal performance of the thin film configuration could help to improve device performance, even with the same laser.

b. Vertical-cavity surface-emitting laser (VCSELs) A vertical-cavity surface-emitting laser (VCSEL) can also be realized by ELO. R. Martin *et al.* demonstrated a dielectric DBR

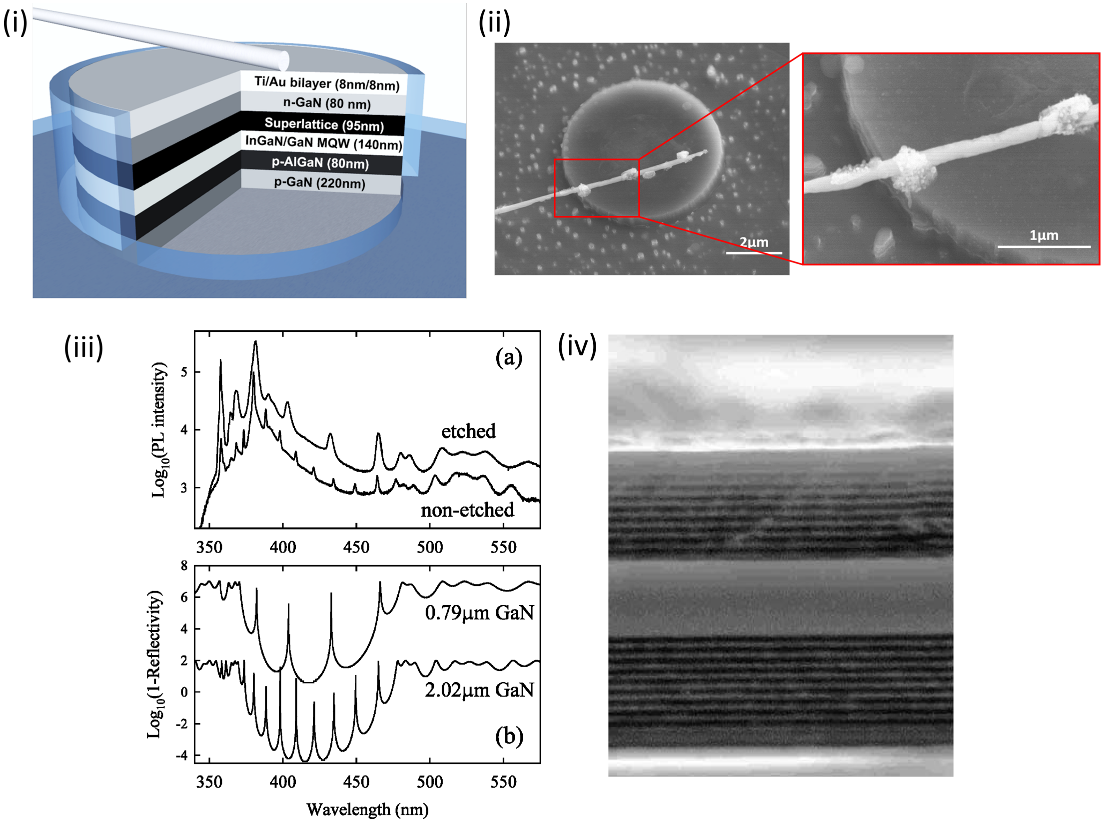

FIG. 7. (i) Schematic diagram and (ii) SEM images of an electrically injected thin film microdisk. Reprinted with permission from Li *et al.*, Appl. Phys. Lett. 119, 101106 (2021). ©2021 AIP Publishing; (iii) PL spectra and (iv) TEM images showing the cavity and pairs of DBRs of a thin film VCSEL. Reprinted with permission from Martin *et al.*, Mater. Sci. Eng. B 93, 98 (2002). ©2002 Elsevier.

by first depositing SiO_2/ZrO_2 on a typical LED structure using e-beam deposition and then bonding to an Si substrate. After performing the LLO process (248 nm laser, 0.6 J/cm^2, 38 ns) the cavity length was tailored by an ICP etchback step before the deposition of a second DBR to form the VCSEL cavity[79], as demonstrated in Fig. 7(ii). In this configuration, a Fabry-Pérot resonance can be observed between the top and bottom surface[116]. The ability to tailor the vertical confinement has led to the development of thin film microdisk laser technologies, in which the overlap between the field mode and quantum well contributes to an improvement of the Q factor and threshold of the lasing mode[93,117]. Flexible microdisk lasers have also been demonstrated on a polydimethylsiloxane (PDMS) substrate with emission peak tunable by bending[118].

c. Microdisk laser The ELO process can also allow the wafer to be transferred to a reflective substrate to improve optical confinement of the microdisk microcavity. Moreover, optical absorption can also be suppressed by removing the u-GaN layer after the ELO process, as the wafer is mounted with its bottom side up. A previous study reported a Q factor of 770 with a microdisk diameter of 6.6µm on a ceramic substrate with silver epoxy coating[119]. By replacing the silver epoxy coating with an Ni (5 nm)/Ag (150 nm) coating deposited via electron beam evaporation, the Q factor was further boosted to 1673 using a similar microdisk with a diameter of 7µm[120]. To achieve electrical injection, a Ti/Au contact was deposited on the thin film sample before the fabrication of microdisk. A silver nanowire is then used for wire bonding[93], as shown in Fig. 7(i). To further improve the performance, the microdisk was transferred to a copper substrate by electroplating before the ELO process. The improved thermal performance enabled lasing in the microdisk during electrical injection[121]. In addition to these advantages, using a thin platform with reflective substrate allows the fabrication of a waveguide, which can coupled the whispering gallery modes (WGMs) from the microdisk to realize unidirectional emission, or to connect to a photonic system for further optical signal manipulation[117].

3. *Electronics*

While the discussion focuses on optoelectronic devices, we will also briefly touch on the topic of high-electron-mobility transistors (HEMTs) for comprehensiveness. The ELO processes allows the high power devices to be moved to a foreign substrate for much improved thermal management, as well as for different device designs with the N-polar surface. In particular, N-polar HEMTs have advantages of strong back-carrier, low-resistivity ohmic contacts and improved scalability over Ga-polar HEMTs[122]. While typically achieved through growth by MBE and sometimes by MOCVD, the ELO process offers an alternative approach to expose the N-

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polar surface for fabrication of N-polar HEMT. This is first demonstrated by J. W. Chung *et al.*, who removed the Si(111) substrate by DRIE with SF_6 plasma and fabricated an N-polar HEMT with performance comparable to state-of-the-art Ga-polar HEMT[123]. K. K. Ryu *et al.*later demonstrated ELO of an entire 4-inch wafer and fabricated N-polar HEMTs on it[124]. Nevertheless, N-polar grown wafer seems to be in favor for the fabrication of such devices, as there is no follow-up work on the topic since then, to the best of our knowledge.

On the other hand, the improvement in performance for conventional Ga-polar HEMTs after substrate transfer is not so obvious, except for diamond substrate. Some studies reported none or even some degradation of performance[125,126], although H. Ji *et al.* demonstrated an increase in performance by transferring from a sapphire substrate to Si via an LLO process with a 355 nm Nd:YAG laser[127]. With an extremely high thermal conductivity of about 2000 W/m-k, diamond would be a promising choice as a substrate which could serve as an excellent heat spreader for GaN electronics[128], such as phased arrays for electronic attack, solid-state power amplifier, high power tube replacement, and wideband communications[129].

The first demonstration of AlGaN/GaN HEMTs operation on diamond substrate was reported by G. H. Jessen *et al.*. The HEMT epilayers were initially MOCVD-grown on a Si substrate before atomically bonded to the diamond substrate[130]. The bonding process should be performed at a low temperature to suppress the mismatch of the thermal expansion coefficients between GaN and diamond[131]. T. Liu *et al.*later demonstrated transfer of an entire 3-inch HEMT devices onto a diamond substrate with 80% yield[132]. F. Mu *et al.*have further optimized the bonding process by making use of a modified surface-activated-bonding (SAB) method that enables bonding at room temperature[133]. J. Liang *et al.*has further investigated the GaN/diamond heterointerface using the SAB method, and observed a decreasing intermediate layer with increasing annealing temperature as amorphous carbon are turned into diamond during annealing[134].

Another way to attach a diamond substrate to the HEMT structure after lift-off would be chemical vapour deposition (CVD). This basically involves the deposition of a dielectric diamond seeding layer on the HEMT epilayers after removal of the initial Si substrate by chemical lift-off and the AlGaN transition layer by etching. The diamond substrate can thus be grown on the bottom surface with CVD[135,136]. A 30% lower thermal resistance (than GaN-on-SiC)[135] and a 40% reduction in peak channel temperature[136] have been reported. The key parameter in optimizing the thermal resistance would be the thickness of the dielectric diamond seeding layer[137,138].

In addition, there have been various demonstrations of thin film HEMTs transferred to flexible tapes with little change in performance[80,139].

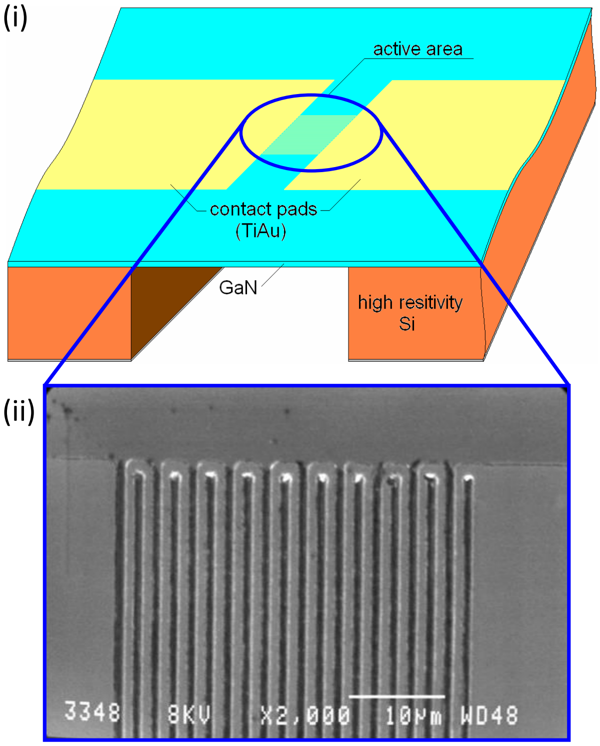

FIG. 8. (i) Schematic diagram showing GaN membrane with selective lift-off from an Si substrate via selective area backside etching, and (ii) an SEM image showing the lift-off part. Reproduced with permission from Muller *et al.*, Proc. SPIE 6415, 65 (2006). ©2006 Society of Photo-Optical Instrumentation Engineers.

III. APERTURED DEVICES

A. Selective-Area Backside Etching

Apertured devices can be fabricated by employing selective area backside etching. The backside of the substrate is dry etched before lift-off of the GaN film from the selected area. This is typically achieved by a combination of CMP followed by masked dry etching, usually on an Si substrate. It is difficult to etch through a thick substrate by dry etching alone, therefore the substrate can be lapped to thin it down for subsequent dry etching. This approach prevents excessive plasma damage due to prolonged etching time. Subsequently, the area to be lifted off can be defined by a metal mask fabricated via a photolithography process for dry etching, as illustrated in Fig. 8(i) and (ii)[78]. A similar technique can be used to lift off the whole film without the masking step by either dry etching[139] or wet etching[80].

B. Application

One major application of apertured devices would be to attain suspended devices for optical confinement. For instance, a suspended waveguide could be fabricated by a partial chemical lift-off process. Wet etching with HF/HNO_3

solvent can be employed to selectively remove the Si underneath the waveguide to form a suspended waveguide, which is possible because a waveguide is much thinner than a normal optoelectronic device fabricated on an Si substrate. A GaN/Air interface can replace the original GaN/Si interface of the waveguide to provide improved optical confinement and lower optical loss. To this end, a transmission of pseudorandom binary sequence (PRBS) at rates of 250 MB/s has been demonstrated[140].

IV. PIVOTED DEVICES

A. Partial Chemical Lift-Off

Pivoted devices can be formed by a partical chemical lift-off process by wet etching the substrate and removing the substrate from the edge of a microstructure. This is typically used for GaN on an Si wafer, where wet etching of the substrate is feasible. A microstructure such as a micropillar or microdisk is initially fabricated by dry etching, followed by preferential wet etching of the Si substrate in HF/HNO_3 solvent. The Si substrate underneath the microstructure is partially etched away, resulting in a microstructure supported solely by a pivot, with the bottom area of the surrounding GaN microstructure suspended in the air. This approach, usually known as "undercut", is commonly used to fabricate a microdisk optical cavity[120,141–144]. Undercutting allows the GaN microdisk to be optically isolated from the Si substrate, which improves the optical confinement[56]. Fabrication of a suspended waveguide using this approach has been previously reported[140]. In addition, a pivoted ELO microdisk device fabricated by the deposition of an oxide layer before the wafer bonding and ELO process has also been reported. The oxide layer, which is at the bottom after transferring the film to a second substrate, can be undercut to form the pivot by a partial chemical lift-off process with HF acid[145]. Y. Mei *et al.* utilized the geometry to realize an electrically injected microdisk with WGM emission[121].

B. Application

A high optical confinement is essential to attain a microdisk microcavity with a high quality factor. Nevertheless, one of the constraints in the fabrication of a microdisk is the interface between the film and substrate. The situation is particularly severe for GaN films, as the conventional substrates of GaN (e.g., sapphire, Si, or bulk GaN) do not constitute an interface that facilitates optical confinement. Transparent substrates like sapphire or GaN cause the optical mode to leak out of the GaN microdisk, reducing the optical confinement and quantum well overlap, whereas substrates such as Si cause additional optical losses due to absorption. To alleviate the optical loss, researchers have tried to either undercut the device to allow the circumference of the microdisk, where the WGMs are located, to be suspended in the air, or by a complete ELO process that transfers the device to a foreign substrate that facilitates optical confinement.

Notably, a partial lift-off would be a more convenient and versatile way to attain high optical confinement. As mentioned above, undercutting via a partial chemical lift-off approach could be utilized to partially remove the part of the substrate beneath the circumference of the microdisk, thus leaving only a pivot supporting at the center of the microdisk. As the bottom surface of the GaN film is now in contact with air, as shown in Fig. 9(i), the larger refractive index contrast would lead to high optical confinement, enabling a high quality factor optical cavity[141,142,146]. This approach has been demonstrated for a microdisk with a large diameter of $20\mu m$, but also works for a small diameter down to $2\mu m$[143]. It was observed that the biaxial tensile strain in GaN on an Si wafer was relaxed as the microdisk was partially lifted off from the substrate, with the extent of relaxation dependent on the size of Si pivot, as shown by a blue-shift in the micro-Raman spectra and a reduction in peak shift in the near-field PL (nf-PL) spectra measured with a Scanning Near-field Optical Spectroscopy (SNOS)[147]. Moreover, hemispherical microcavities, as a variant of a microdisk, have also been reported. Using a similar fabrication approach, a microdome geometry was attained by including SF_6 gas during ICP etch with a silica microsphere to simultaneously etch the microsphere mask with the GaN-based LED film below. A further wet etch was used to undercut the film from the Si substrate, leaving a pivoted hemispherical microcavity with a Q factor of over 500[144], as illustrated in Fig. 9(ii).

V. FLEXIBLE DEVICES

A. Selective-Area Laser Lift-Off

Flexible devices can be formed by a selective area LLO process. K. H. Li *et al.* demonstrated a selective area LLO process by covering a selected area and irradiating only a part of the film by a laser beam from a 266 nm Nd:YAG laser during the LLO process, resulting in partial lift-off of LED arrays with the LEDs suspended in the air and contacts still attached to the substrate[105].

B. Applications

The selective area LLO process can allow the fabrication of flexible LED arrays for display applications. By applying LLO on only one side of a long strip of thin film LED arrays, the thermal and lattice mismatch strain causes the film to curl up when it is separated from the substrate by the lift-off process. The result is that one side of the film is suspended in air due to curling up, while the other side is still attached to the substrate[105], which improves light extraction, as shown in Fig. 10. This configuration also demonstrates the potential use of flexible GaN LEDs in flexible displays and other photonic applications. In fact, the same strategy can be used to fabricate bendable waveguides for the transmission of signals between

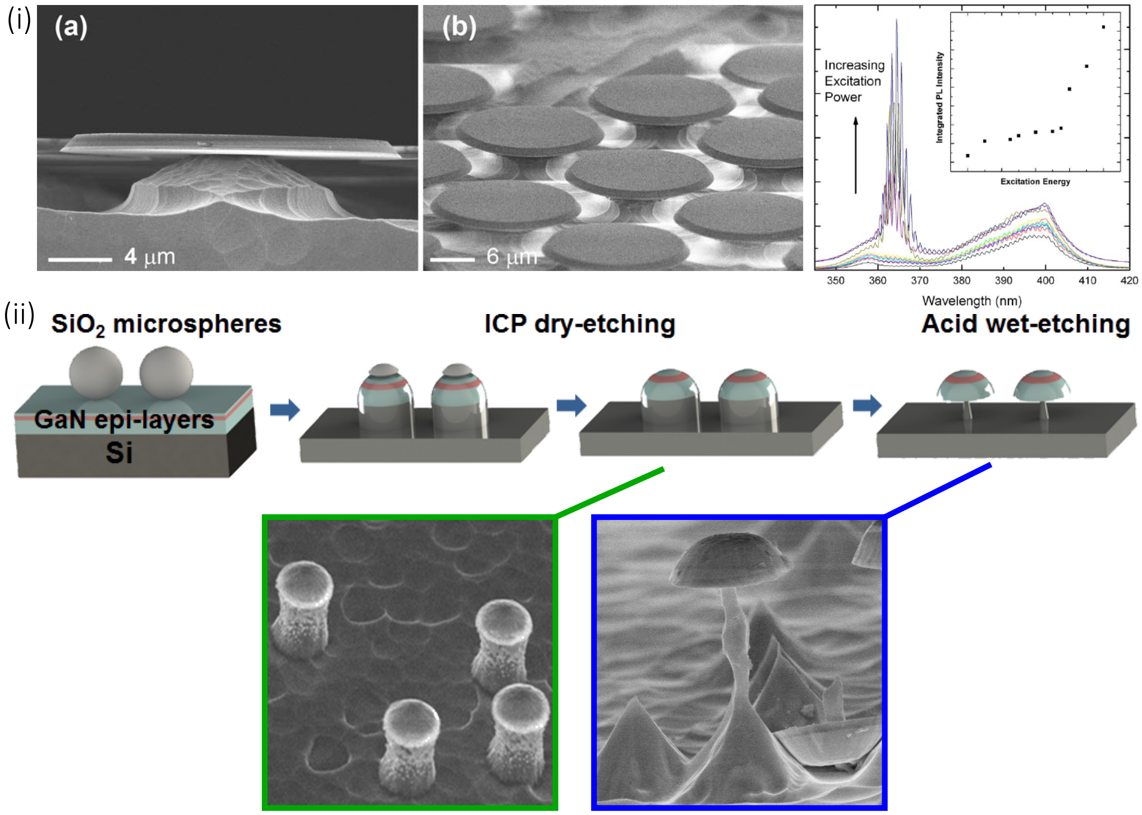

FIG. 9. (i) SEM images and corresponding PL lasing spectra of a pivoted microdisk. Reprinted with permission from Choi *et al.*, Appl. Phys. Lett. 89, 211101 (2006). ©2007 AIP Publishing; (ii) schematic diagram and SEM images showing the fabrication process and the resultant geometry of pivoted hemispherical microcavities. Reprinted with permission from Zhang *et al.*, Appl. Phys. Lett. 108, 031110 (2016). ©2016 AIP Publishing.

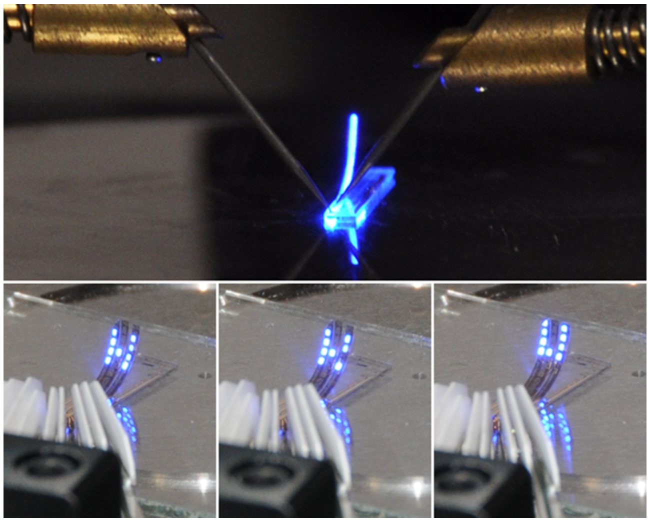

FIG. 10. A flexible LED suspended in air after partial LLO. Reprinted with permission from Cheung, Li, and Choi, ACS Appl. Mater. Interfaces 8, 21440 (2016). ©2016 American Chemical Society.

an LED and a photodetector on different wafers. To this end, a transmission rate of 250 Mb/s with an opening in the eye diagram has been demonstrated.[148]

VI. DISCUSSIONS AND PERSPECTIVE

A. ELO

In addition to device-specific requirements that result in restricted device performance after the ELO or partial ELO processes, there are other factors that can limit performance. One major limiting factors is the roughness of the surface after lift-off. With the exception of LEDs that require a rough surface to enhance light extraction[103,154,155], a smooth surface is usually preferable for device fabrication, especially in the case of laser diodes where a low surface roughness is crucial for mode confinement to attain a high quality factor[100,116,156]. In Fig. 11, we compared the root mean square (RMS) roughness of the surface after lift-off without any further treatments in studies on LLO[21,28,149,150], PEC[64,83] and mechanical release[76]. The roughness of conventional controlled spalling is not included in the comparison as the resulting roughness is typically very high (>100 nm)[70,72]. The RMS roughness of LLO and PEC surfaces were generally in the ranges of 11-68 nm and 2-112 nm, respectively, respectively, and the one reported value for mechanical release process was 0.95 nm. This suggest

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that LLO produces relatively consistent surface morphology, whereas PEC can result in varying roughness depending on the specific reactions and chemicals used, assuming all other parameters during ELO are optimized. Moreover, the use of a femtosecond pulse laser does not seem to lower the roughness of the LLO process, with a reported RMS roughness of 50 nm[28]. Notably, a very smooth surface with an RMS roughness of 1.2 nm after LLO has also been reported[103]. Another study using PEC produced much smoother surfaces than LLO, which was needed for optical confinement in the microdisk cavity[56]. Nevertheless, samples can be polished to smoothness over a small area after ELO[65].

Besides the roughness issues, another major concern is film damage caused by the ELO or partial ELO process. Due to the nature of the approaches, CLO, self spalling, and mechanical release approaches used in ELO, as well as partial chemical lift-off approaches used in partial ELO produce little damage to the film. This is especially useful in preserving the material quality of the film grown on bulk GaN substrates with low dislocation densities, which is crucial in realizing electronic devices such as vertical field-effect transistors (FETs)[157,158], high-voltage diodes[159] and heterojunction bipolar transistors (HBTs)[160]. This may be an interesting direction for electronic devices involving lift-off processes, given that there is little or no reports of such devices fabricated through lift-off processes yet. After all, lift-off of electronic devices would help in re-using of expensive bulk GaN substrates. The situation is more complex for optoelectronic devices, however, as the improvement over IQE is limited with decreasing dislocation density[161], due to the involvement of point defects as nonradiative recombination centers in the material[162].

On the other hand, methods involving laser and ion etching such as LLO, selective area LLO, and selective area backside etching can cause additional damage to the film. For the selective area backside etching approach, plasma-induced damage occurs during ICP etching[163]. Although the surface damage can be usually removed by wet etching with KOH solution[164,165], the roughness may increase as wet etching on GaN is sensitive to crystal orientation. For the LLO and selective area LLO approaches, the damage is caused by the laser ablation. After LLO with a nanosecond pulsed laser, GaN surface damage can be observed as stacking faults and twinnings induced near the 50-nm region right beneath the ablated surface[149,151], as illustrated in Fig. 12(i). Moreover, a series of "half loops" formed by dislocations caused by laser-induced shock waves[151] can be seen in Fig. 12(ii) and (iii) within the 200-nm region beneath the interface. These shock waves not only travel inside the film, but also propagate laterally[22], as demonstrated in Fig. 12(v). Moreover, vapor pressure due to nitrogen flux during GaN decomposition induces stress in the film, which are subsequently relieved by the formation of fractures and cracks[41], as illustrated in Fig. 12(iv). These stresses can be suppressed by optimizing the laser beam spot and energy density[22,41].

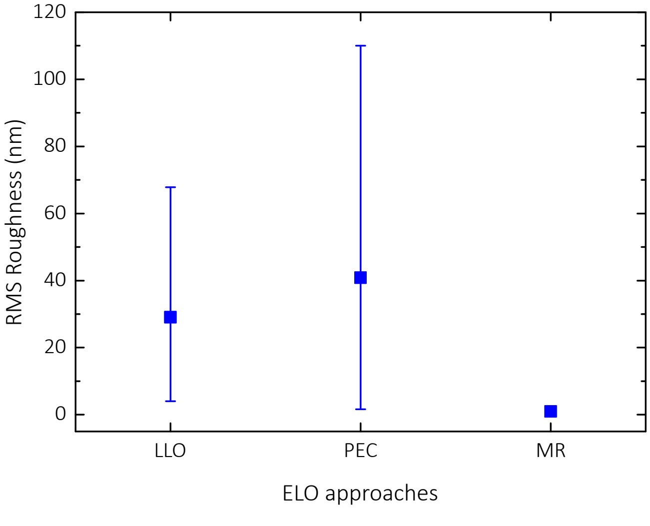

FIG. 11. Plot of RMS roughness of different ELO approaches from previous studies, including LLO[21,28,149,150], PEC[56,64,83], and mechanical release[76].

As discovered by H. Aoshima *et al.*, these defects can be a problem when using the LLO process with films flip chip-bonded to another substrate with the metallic bump technique. Additional epoxy underfill can be utilized to support the film and avoid chipping, as illustrated in Fig. 13(i)[152]. M. Chen *et al.* made use of this phenomenon to demonstrate an "auto-split" LLO technique. Only selected areas of the film were electroplated with Ni for bonding to a foreign Si substrate, whereas regions outside these areas fractured and crumbled away during the LLO process, which can save the ICP step for electrical isolation and mesa definition, as shown in Fig. 13(ii)[98].

There is one controversial study by M. H. Doan *et al.* that showed the laser beam can damage the MQWs several micrometers beneath the ablated surface during the LLO process[99]. The authors provided much evidence such as increased cone-shaped defects when etching from the ablated surface (N-polar side) compared to from top (Ga-polar side); spectral blue-shift after LLO; and changes in CL and TEM image contrast, although most of these can be explained in other contexts. For instance, the N-polar side forms much more defects during wet etching compared to the Ga-polar side[166], which could contribute to the difference in cone-shaped defects when etching from the N-polar side. Moreover, the spectral blue-shift could be attributed to a change in the strain state of the film after lift-off[105]. In addition, the image contrasts were compared without any other quantitative analysis, which weakens the evidence that the MQWs are damaged during LLO. Considering that only the 200-nm region near the ablated surface is damaged, this damaged region can easily be removed by dry etching. Nevertheless, a u-GaN layer next to the ablated surface is usually used to improve efficiency after LLO[18,21,86,93].

Notably, one special case is the use of LLO on a patterned sapphire substrate (PSS). T. -M. Chang *et al.* found that the laser energy density required for LLO on PSS was about 30% higher compared to a planar sapphire substrate[153]. Given the higher energy density and the refracting and diffracting effect of the PSS pattern, the induced damage is likely to be higher on PSS. Moreover, residues of α-Al_2O_3 at the base of

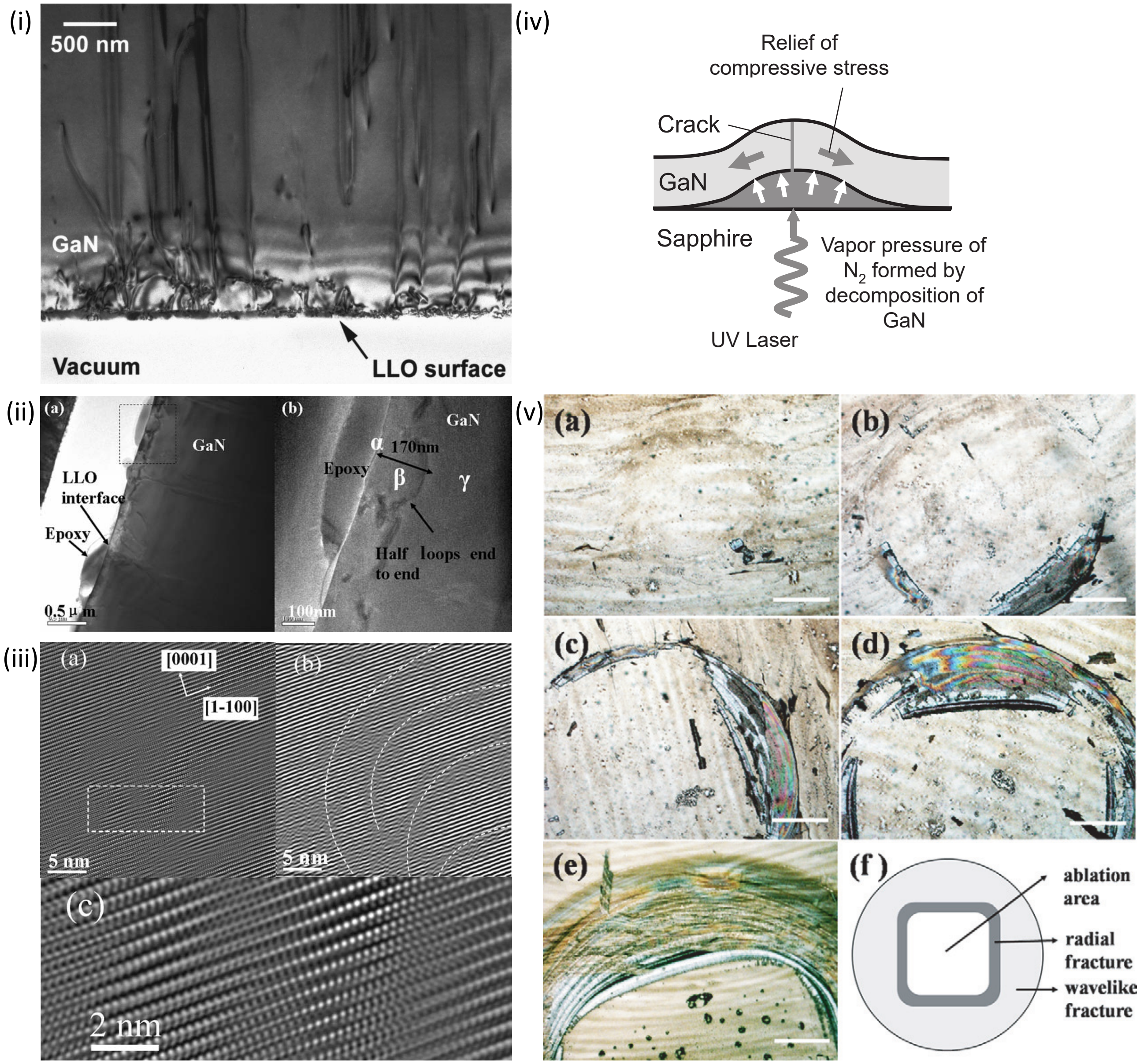

FIG. 12. Bright-field TEM images showing (i) defects and (ii) clusters of half loops near the LLO surface (Reprinted with permission from Stach *et al.*, Appl. Phys. Lett. 77, 1819 (2000). ©2000 AIP Publishing); (iii) HRTEM images showing lattice damage caused by shock waves (Reprinted with permission from Chen *et al.*, Appl. Phys. Lett. 91, 121114 (2007). ©2007 AIP Publishing); (iv) Schematic diagram showing cracks caused by N_2 vapor pressure. Reprinted with permission from Ueda, Ishida, and Yuri, Jpn. J. Appl. Phys. 50, 041001 (2011). ©2011 IOP Publishing; (v) Optical micrographs showing laser-induced damage along the lateral direction. Reprinted with permission from Su *et al.*, J. Phys. D Appl. Phys. 46, 205103 (2013). ©2013 IOP Publishing.

the PSS's inverted cone pattern were also observed, as illustrated in Fig. 13(iii).

While the issues on roughness, defects and damages due to ELO processes are most commonly discussed in research papers, there are much less reported investigations into improving the processing speed, accuracy, stability and repeatability of ELO processes, which are crucial in realizing successful commercialization of devices adopting lift-off processes. Moreover, with the damage and defects incurred during ELO processes, as well as weaker bonding that binds the film and foreign substrate, thin films attained through ELO processes are often believed to have a lower reliability. However, there is also a lack of reliability study on the devices adopting ELO processes as compared to conventional devices. In addition to these typical lift-off parameters and issues that are usually only optimized by the industry instead of in a lab environment, one important criteria to consider for ELO processes would be the ability to perform lift-off on a wafer scale. At the moment, the most promising approach to wafer-scale ELO would be chemical lift-off and controlled spalling. These ELO

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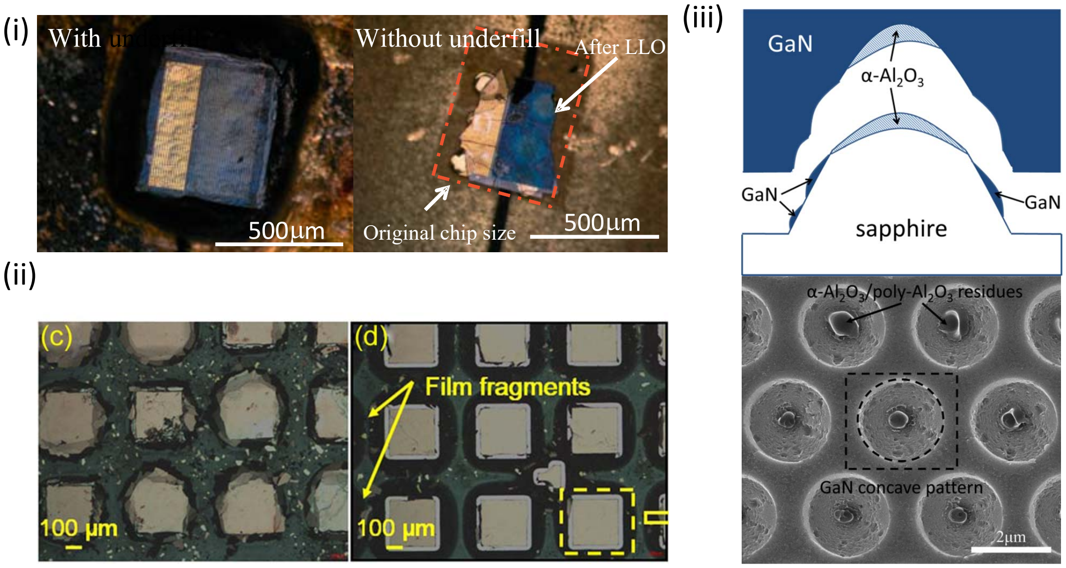

FIG. 13. (i) SEM image of GaN crystal lift-off by a pulsed 532 nm laser. Reprinted with permission from Aoshima *et al.*, physica status solidi c 9, 753 (2012). ©2012 John Wiley and Sons; (ii) Optical micrographs showing the results of “auto-splitting” at a laser energy density of (c) 550 mJ/cm^{2}and (d) 650 mJ/cm^2. Reproduced with permission from Chen *et al.*, IEEE Photonics J. 5, 8400407 (2013). ©2013, IEEE. (iii) Schematic diagram and SEM image showing α-Al$_2$O$_3$ residue after LLO of a patterned sapphire substrate. Reprinted under the terms of the CC BY license from Chang *et al.*, ECS J. Solid State Sci. Technol. 4, R20 (2015).

approaches have been demonstrated to lift-off a 4-inch wafer successfully[55,71,124]. That said, one main reason why there are less studies on wafer-scale ELO of wafers with diameters of 4 inch or above is due to the limitation of epitaxial growth technology. Unfortunately, epitaxial growth of GaN wafers of 4 inch or above is still technically challenging and costly, unlike the more mature material systems such as GaAs or InP.

B. Devices

Looking at the studies on ELO of III-Nitride over the years, it is obvious that there has been a decline in the development of vertical LEDs utilizing the ELO process, probably due to a global decline in the cost of LEDs. However, these technologies may find a new lease of life in the form of microLEDs or flexible display technologies with ELO processes playing an integral role. On the other hand, ELO processes have an inherent advantage in the fabrication of laser diodes, as the cavity thickness can be tailored via etching without compromising the internal quantum efficiency (IQE) of the MQWs, which would deteriorate if the grown film thickness is reduced. Laser structures such as VCSELs and microdisks with critical requirements on cavity vertical thickness will thus benefit from ELO processes. The ELO process also benefits HEMTs with better thermal dissipation brought about by the use of substrates with high thermal conductivity, such as diamond substrates.

Current injection to devices adopting ELO/partial ELO processes may be trivial or challenging depending on the type of interlayer used for wafer bonding. In most cases, the interlayer is a metallic layer that serves concurrently as an ohmic contact and as an optical reflector, with a target of achieving low contact resistance and high reflectivity. As mentioned in Section II B and Section II C 2, Ni/Ag metal layers have been demonstrated to serve these purposes well. Nevertheless, higher reflectivity is desired for thin-film optical cavities, which call for better reflectors such as DBRs to improve optical confinement[79]. Nevertheless, DBRs typically comprise of non-electrically-conducting dielectric materials, posing a challenge to achieve electrical injection. Recent developments on conductive DBRs such as a porous GaN DBR structures may offer a solution to this challenge. An n+-GaN layer can become porous when etched under a controlled electrochemical etching process, thus reducing the layer’s effective refractive index. By growing alternating layers of n+-GaN and n-GaN layers, a porous GaN/GaN conductive DBR can be formed[63]. There are also conductive DBRs implemented with conductive oxides subjected to an electrical breakdown process[167,168], as well as the porous ITO DBR[169], although care must be taken to incorporate these DBRs into the wafer bonding process.

N-polar devices enabled by ELO processes is another topic of interest. While the ELO process exposes the high conductivity n-GaN layer on which ohmic contacts can be formed readily without plasma damage effects and with good current spreading properties, fabrication of devices on the N-polar surface can be challenging. The reversed crystal orientation causes a different reaction chemistry during etching, thus forming vastly different post-etch morphology as compared to Ga-polar surfaces. For instance, etching on N-polar surface is more inclined to form hexagonal pyramids[170]. As such, more in-depth studies to understand the change in etch behavior would be beneficial. Nevertheless, this provides an

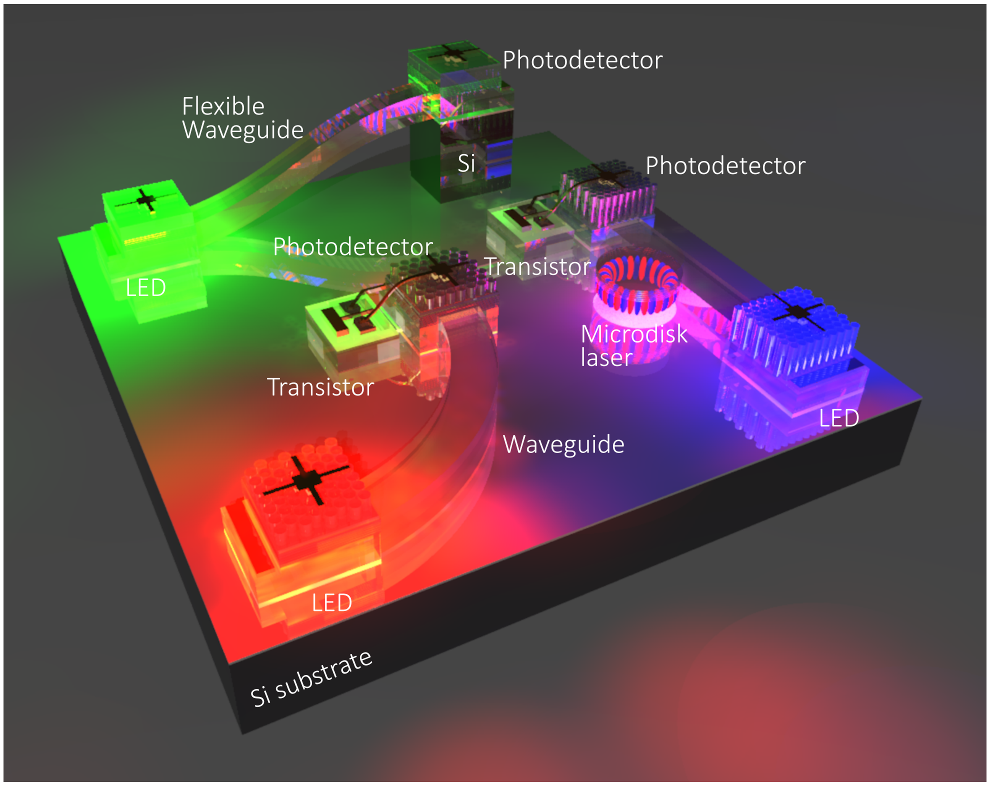

FIG. 14. 3D schematic diagram of a GaN-based photonic system with components monolithically integrated.

opportunity to develop N-polar devices through a device processing approach instead of the usual approach of growing on c-plane substrates with nitridation. There were reports on N-polar HEMTs fabricated using such methods[123,124], although there are limited follow-up works.

Apart from developing specific devices based on ELO or partial ELO processes, the substrate-removed film serves as a versatile platform for the integration of different types of devices to build functional integrated systems. The thickness-controllable thin film retains the epitaxial quality of the as-grown thick film, while offering high optical confinement that could not have been achieved on the original substrate. As such, the platform supports the development and integration of photonic components such as microdisk lasers, VCSELs and waveguides that make good use of the optical confinement to form optical microcavity devices that constitute the components of an photonic integrated circuit or system. The system can be further expanded to include electronic devices, forming electronic-photonic integrated systems through the monolithic integration of BJTs[171] or MOSFETs[172] that can be fabricated onto the thin-film platform. Additional devices and circuits such as HEMTs[80] and CMOS chips[173] can be integrated heterogeneously by flip-chip bonding as necessary. The illustration in Fig. 14 demonstrate our vision of how optoelectronic, photonic and electronic components can be integrated harmoniously onto the common thin-film platform, harnessing the full potentials of GaN technology.

VII. CONCLUSION

This paper summarizes the progress of lift-off processes and the various III-Nitride optoelectronic devices derived from the process. Given the amount of studies reported, LLO and PEC processes are the most popular approaches for ELO. Nevertheless, novel lift-off techniques such as mechanical release with 2D materials are attracting attention due to the smooth surface after the ELO process. The PEC and spalling processes are most promising for large-area epitaxial lift-off, with successful demonstrations on ELO of 4-inch wafers. Yet, further progress on large-area lift off might be hindered by the development of epitaxial growth technology on large-area wafers. A bigger concern from the device performance aspects would be the roughness, defects and damages caused by the ELO processes, in addition to the current injection issues. There is also a lack of reliability study of devices adopting ELO processes which could raise concerns over device longevity and performance. With the continuing global price drop of LEDs, ELO technology is expected to be applied mainly to LDs and novel GaN devices such as flexible devices and integrated photonic systems.

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Kong SAR (Project A_HKU703/17)

DATA AVAILABILITY

The data that supports the findings of this study are available within the article.

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