Fabrication of GaN LED's by Wafer bonding and Lift-off techniques: A Review

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Abstract- Fabrication of high brightness GaN Vertical Light Emitting diodes (VLED) by various wafer bonding and lift-off techniques are reviewed. Among the wafer bonding techniques the proven to be optimum technique for the fabrication of GaN VLED is metal bonding technique. This includes diffusion bonding, eutectic bonding and transient liquid phase bonding. These wafer bonding techniques are reviewed in detail along with Adhesive bonding technique which is a low temperature wafer bonding technique. Lift-off techniques for the fabrication of GaN VLED are reviewed which includes laser lift-off technique, Chemical lift-off technique, Ion-induced lift-off technique and Thermal stress induced lift-off technique. The mechanism of each lift-off technique is discussed. Enhancements in Optical property due to different wafer bonding techniques are tabulated. A summary of various wafer bonding technique along with various lift-off techniques which are applicable for the fabrication of high brightness GaN VLED's along with the process complexity is tabulated. Also and disadvantages of various lift-off techniques are reviewed.

Keywords – Vertical Light emitting diodes, Non-native substrates, Wafer bonding techniques and Lift-off techniques

I. INTRODUCTION

Gallium nitride (GaN) is a III/V direct bandgap semiconductor commonly used in bright light-emitting diodes (LED) since the last decade. GaN LED's produce all three primary colors as monochromatic light and are now commercially used for traffic signal lamps, where the ability to emit bright monochromatic light is a desired feature. They are also used in full-color displays, backlighting in liquid-crystal displays, miniprojectors and in strings of holiday lights etc. Fabrication of majority of GaN LED is traditionally by the growth of GaN LED structure on non-native substrates like C-plane sapphire and 6H silicon carbide due to the high cost of gallium nitride (GaN) substrates. Use of mentioned non-native substrates are detrimental to the light output performance of the high brightness GaN based vertical Light Emitting Diode (VLED) in many ways. The threading dislocations generated in the GaN epitaxial film to accommodate the large mismatch between the film and the sapphire substrate and the difference in thermal expansion coefficients of the epitaxial film and the substrate are the most important detrimental factors1. Also sapphire substrate inherently is a poor conductor of the heat generated in the device and is an electrical insulator though it is transparent to the generated light in the active region of the GaN VLED. Thus the use of sapphire substrates complicates the processing steps where in, it requires to etch away a portion of substrate for deposition or electroplating of contact electrodes for external ohmic contact. GaN substrates on the other hand provide an alternative to have multi-step nucleation processes, allowing for elimination of interlayer, eliminate processing steps and improve device yield and reliability. William Sam Wong et.al in 1990 was successful in fabricating GaN LED by laser lift-off separation of sapphire substrate from GaN LED structure. With the separation of sapphire substrate from GaN LED structure various merits are realized such as increased luminous intensity, reduction in operating voltage, durability of LED due to the increased thermal and electrical conductivity etc.

In addition, the drawbacks of non-native substrates especially of the sapphire substrates has been circumvented by many techniques like epitaxial lateral overgrowth 2, 3, wafer bonding with lift-off techniques4- 6 and surface roughening in collaboration with wafer bonding and lift-off 7-9 etc. Vertical Light Emitting diodes(VLED) 10 , as shown in Figure 1 has overcome the drawbacks such as current crowding due to series resistance and top electrode coverage in Lateral light emitting diodes(LLED). Fabrication of thin-film GaN VLED's bonded to Si substrate by Au-Sn eutectic bonding and by Removal of sapphire substrate by mechanical grinding and chemical mechanical polishing (CMP) was studied by Shengjun et.al11, 12. Mechanical grinding has drawbacks like scratches as in Fig. 2, generation of thermal and mechanical stress during wafer thinning and bonding. Scratches formed by mechanical thinning process are removed by the CMP process. However, compared with thermal and chemical approaches, mechanical release is, in principle an uncomplicated technique requiring neither chemical treatments nor additional equipment for the transfer. However, damage, limited size of the released GaN and limited throughput in mechanical releases have remained serious issues.

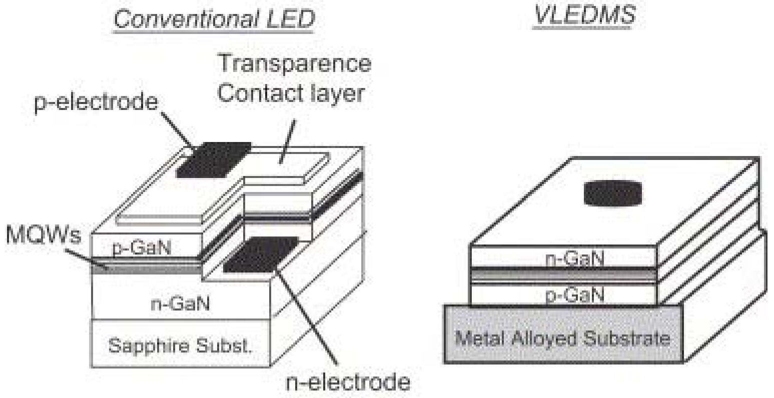

Fig 1. The Schematic diagram and comparison of GaN LED's on sapphire substrate and GaN VLEDMS. Ref [10]

William Sam Wong et.al fabricated GaN LED bonded to high conductive Si substrate by Pd-In metal bonding and laser lift-off technique[13-17, 69]. With this technique they were able to achieve high melting point at the bonded interface, high thermal conductivity and high electrical conductivity at the substrate. GaN exfoliation induced by H implantation was first reported by Kucheyev et al., [23]and the mechanism in H-ion induced GaN thin layer splitting was studied by O.Moutanabbir et.al, [24-26]. This process has significant drawbacks for fabrication of GaN based VLED structures like lattice distortion due to ion-implantation which damages the crystal structure and the MQW which is very close to the top surface.

Laser lift-off technique mentioned above is an expensive and complex technique for fabricating LEDs. It is necessary to carefully control the laser parameters to protect from damaging the GaN epilayer and producing LEDs with high current leakage. However these defaults can be evaded by considering chemical lift-off technique. Jun-Seok Ha et.al.,[27] has fabricated GaN VLED by selectively etching CrN buffer layer used for growing GaN VLED structure. Yu Zhang et.al.,[28] presented a new scheme in splitting and lifting-off GaN using a nanoporous (NP) GaN medium by a simple and robust electrochemical (EC) etching process. This procedure can be considered an implementation of the 'smart-cut' principle using nanoscale wet etching and is compatible with wafer-level scaling-up. Ray-Hua Horng et.al.,[29] successfully transferred thin film GaN LED Epi-Structure to the Cu Substrate by Chemical Lift-Off technology by increasing the interface strain between the substrate layer and the epilayer. The bonding process followed by the removal of sapphire substrate by any one means like mechanical and/or CMP means of lift-off, laser lift-off, and chemical lift-off creates an enhanced output performance GaN VLED. The wafer bonding and lift-off technique thus paves way for high brightness GaN VLED where high current injection is required. In this paper we review and discuss various aspects of wafer bonding and lift-off technique for GaN VLED.

II. PROCESS STEPS

The fabrication of GaN VLED's by wafer bonding and Lift-off process has few basic steps: (*i*) growth of GaN layer by HVPE, MOVPE or MOCVD. Alternately there can be a buffer layer as an intermediate layer between sapphire and GaN epilayers.(*ii*) Contacting the GaN LED structure with adhesive or by metal layers to the conductive substrates like Si or Cu.(*iii*) Finally, lift-off of GaN substrate from sapphire can be done by many means like: (*a*) by laser lift-off technique (*b*) by chemical lift-off technique (*c*) by thermal stress due to difference in co-efficient of thermal expansion and mechanical lift-off technique (*d*) by ion-cut method for separation of thin film substrates for LED devices. The process flow of wafer bonding and lift-off technique is shown in flowchart 1.

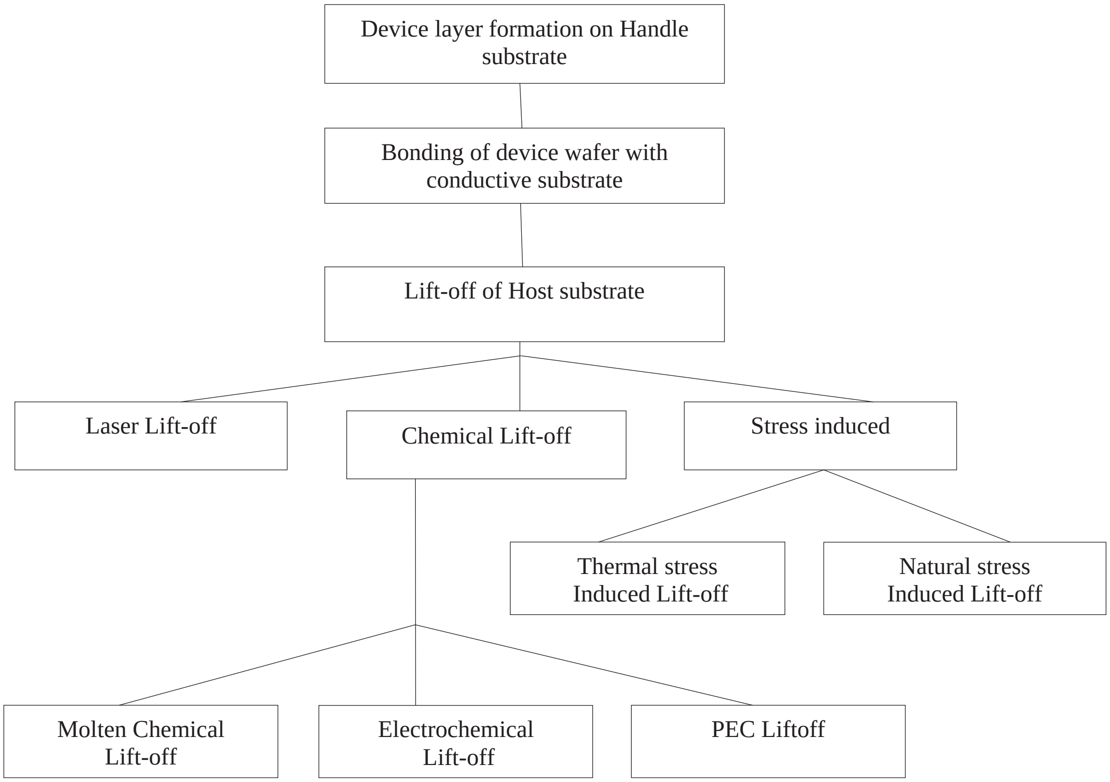

Fig 1. Flowchart of process steps in fabrication of GaN VLED's

III. BONDING METHODS FOR GaN VLED's

In GaN VLEDs, the bonding layer is multifunctional. It acts as electrical contact to the p-GaN, therefore conductivity needs to be high to reduce ohmic losses. In addition, the bonding layer transfers wasted heat from the LED to the heat sink. From a material standpoint, many eutectic metal systems (e.g. Au: Sn)[61] or diffusion solders (e.g. Au: In) fulfil these requirements. However, each presents different processing requirements. The chosen metal system determines the bonding temperature. Because the sapphire substrate and the carrier substrates have quite different coefficients of thermal expansion, a metal system with low bonding temperature will keep strain at a more manageable level. The selection of these layers is beyond the scope of this article, but typically metal layers such as platinum, aluminium and gold combinations of these materials are used.

Regarding GaN on Si, direct bonding by atomic rearrangement is likely to be difficult chiefly due to difficulty in heteroepitaxial growth. Also, for the Si (001) surface, on which Si devices are fabricated generally, the mismatch in crystalline structure with hexagonal GaN obstructs the direct bonding. A solution to avoid these issues is a metal-mediated low-temperature bonding technique. Wafer bonding technique thus has been used to replace thick epitaxial growth of films and to bond dissimilar materials. The choice of bonding method depends on whether the bond is to be permanent or temporary, and electrically conductive or insulating[44, 45].

IV. METAL BONDING APPROACH

Diffusion Bonding:

The metal bonding approach is the only one that is applicable to high-brightness LEDs, due to the requirement for low thermal resistance. This is not the only benefit of this type of bond it can also increase the luminous efficiency of the device. diffusion bonding[46-49] of two metals happens when two metals are pressed together under applied force and heat which enables atoms to migrate from lattice site to lattice site “stitching” the interface together. Diffusion processes require intimate contact between the surfaces since the atoms move by lattice vibration. Wen-Jie Liu[46] et.al., has used low temperature fusion bonding technique for the fabrication of high brightness GaN VLED. By various trial experiments the optimized bonding temperature was observed and GaN VLED was fabricated with Sn as the fusion bonding layer between GaN and Si substrate. As compared with conventional GaN-based LEDs, the vertical LEDs revealed improved forward current–voltage characteristic especially, the reverse current of the vertical LEDs was as low as 39 nA at the reverse bias of 10 V. In the mean time, vertical LEDs showed an increase in light output of about 127% at 200 mA, and no saturation was observed as the driving current increased to 500 mA. Further measurement revealed that vertical LEDs had a much lower junction temperature. These results indicate that the Sn fusion bonding technique is an effective way for fabrication of high-power GaN-based LEDs. Metal bonding technique in GaN VLED enhances the reflected light inside the VLED. Various teams[47-58] have worked for the enhancement of reflection in GaN VLED by incorporating reflective mirror metal layer along with bonding metal layer in GaN VLED. SUN Yuanping et.al[59]., achieved metal mediated bonding of GaAs/GaN with Si substrate using Ni-Au-In-Au-Pt-Ti as the multiple metal layer between GaN and Si. The bonding process completed by annealing the axially pressed system at 230$^{\cdot}$C for 15 mins.The GaAs handle substrate was then removed with etching solution of NH_4OH : H_20_2=1 : 10 for 2 h.

Table I summarizes various intermediate bonding materials and their bonding temperature for metal/eutectic bonding technique used in GaN LED layer transfer from sapphire to Si substrate.

Intermediate bond layer between GaN and Si	***Temperature***	***Reflectivity***	***Luminance intensity at 20mA compared to conventional LED***	***Operating Junction temperature***	***Reference***
NiO–Au–Ag	500$^{\cdot}$C	92% @ 470nm	21.6%	low	[51]
Sn	250$^{\cdot}$C		127% @ 200mA	55$^{\cdot}$C @ 200mA	[46]
ITO-Al-Au	500$^{\cdot}$C	92% @470nm	6 times more	87.C	[52]
Cu-Sn-Ag	150$^{\cdot}$C		82.2% @ 350mA	low	[54]
Ag-Au	150$^{\cdot}$C	90% @470nm	165mcd@350mA	low	[50]
Ni-Au-Si	500$^{\cdot}$C		204 mcd	low	[63]
Pd-Au	500$^{\cdot}$C		130 mcd	low	[57]

Table 1. Few results of metal bonding technique in fabrication of GaN VLED’s

Eutectic Bonding:

A eutectic alloy is sometimes called a “solder” however, this is not necessary the correct metallurgical term. A eutectic alloy is a two component alloy that undergoes a direct solid to liquid phase temperature at a specific composition and temperature[44]. In Figure 2, we can see the eutectic phase diagram of Au-Sn alloy. Tao Zhou et.al., has proposed that Au-Sn solder alloy is best for optoelectronic devices due to their physical properties[42].Some advantages of this eutectic alloy is that the soldering temperature is 20 ~ 30·C above its melting point (300·C ~310·C). Because the alloy is eutectic, minimal superheat is needed for the wetting and flowing in the soldering process. It also freezes quickly resulting in a shorter soldering cycle. The alloy has high yield strength at ambient temperature, and even at assembly temperatures of 250-260 ·C, it is still strong enough to maintain hermeticity. The alloy allows for fluxless soldering due to the minimal surface oxidation of the high content of Au (80 wt. %). If used in a vacuum or under a forming gas (N2/H2-mixture), soldering can be achieved without the use of a chemical flux.

Tian Peng Fei et.al., [61,62] in their research has found that Au/Sn bonding in VSLEDs can relax the stress in GaN. They observed as in Fig. 4, in the two phases existing in Au/Sn (δ phase, ζ phase) Vertical distribution of the δ phase and ζ phase with proper voids in the Au/Sn bonding layer showed the best bonding quality. Good bonding quality led to little shift of the E2-high mode of Raman spectra peak in GaN after laser lift off (LLO). It also caused more light extraction and forward bias reduction to 2.9 V at 20 mA.

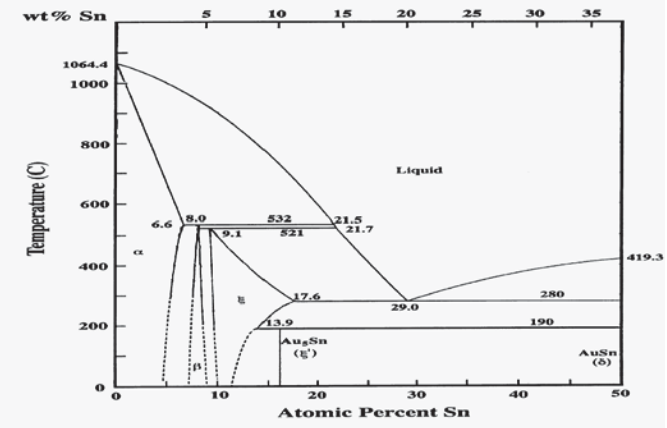

Fig 3. Au-Sn binary phase diagram.(Au rich side).Ref [61]

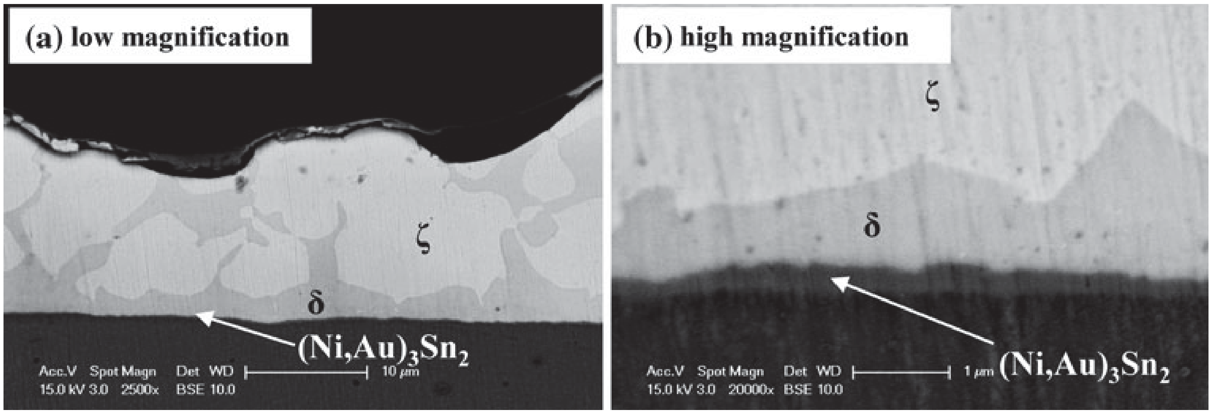

Fig 4. Cross-sectional SEM images of the Au–Sn/Ni/Kovar interface reflowed at 300 .C for 60 secs. Ref [68]

Transient liquid phase bonding:

For InGaN LEDs, however, surface roughness and defect density are considerably larger and eutectic or transient liquid phase bonding is preferred. W.S.Wong et.al[13]., as in Fig. 5 demonstrated transfer of light emitting diodes (LEDs) off their original sapphire substrate onto a new silicon wafer using transient liquid-phase Pd-In bonding to attach the wafers and laser lift-off to separate the sapphire substrate from the GaN lateral epitaxial overgrowth (LEOs). The liquid melt formed during the bond process allows the embedding of interfacial particles in the melt without creating defects. Good wetting is achieved even on very rough surfaces, which are typical for

InGaN-based LEDs. This contributes to enhanced device yield and performance. For high-brightness LED manufacturing process flows, the material should be kept below the bonding temperatures for the most usual eutectic alloys (300$^{.}$C – 400$^{.}$C). In such situations an alternative process can be used – diffusion soldering or transient liquid phase (TLP) bonding, which results in an inter-metallic compound bonding layer. This technique uses one thin metal layer typically 1-10 μm thick – which inter-diffuses with its bonding partner during a thermal process to yield an intermetallic compound layer with a re-melting temperature higher than the bonding temperature. Cu-Sn and Au-Sn are the most popular TLP systems[13-16, 44].

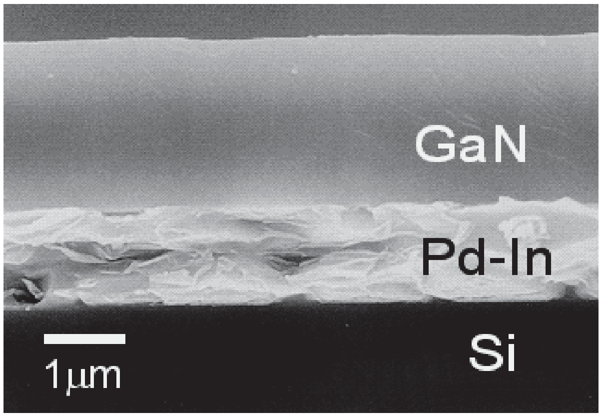

Figure 5. Cross sectional SEM micrograph of a transferred GaN film onto a Si substrate. Pd-In metal bilayers were used as bonding material which formed the compound Pd-In after the low-temperature bonding process. Ref [13]

V. ADHESIVE BONDING APPROACH

The attachment between adhesive and substrate may occur either by mechanical means, in which the adhesive works its way into small pores of the substrate, or by one of several chemical mechanisms. The strength of adhesion depends on many factors, including the means by which it occurs. In some cases, an actual chemical bond occurs between adhesive and substrate. In others, electrostatic forces, as in static electricity, hold the substrates together. A third mechanism involves the Van der Waals forces that develop between molecules. A fourth means involves the moisture-aided diffusion of the glue into the substrate, followed by hardening[64, 65]. Applicators of different adhesives are designed according to the adhesive being used and the size of the area to which the adhesive will be applied. The adhesive is applied to either one or both of the materials being bonded. The pieces are aligned and pressure is added to aid in adhesion and rid the bond of air bubbles[66]. Figure 6 is a cross-section SEM image depicting GaN and Si adhesive bonding.

Many epoxies and related polymeric adhesives are suitable as permanent bonding materials. Candidate materials include 2-part epoxies, polyimide, benzocyclobutene (BCB) and UV-curable photopolymers such as SU-8. *Seung Hyun Lee et.al.,*[67] have made an empirical study on adhesive bonding materials for GaN LEDs which resulted in SU-8 with thermal release tape as the best one for strong adhesion to withstand the laser beam for lift-off of sapphire wafer. The bonding configuration does not permit significant evolution of vapor during the final curing process, and air can be trapped if the bonding is not performed in vacuum. All of these factors demand that considerable effort be devoted to developing an optimal bonding process for a particular application[44]. Figure 7 depicts the SU-8, Thermal release tape with laser lift-off technique.

With a summary to bonding techniques in fabrication of GaN VLED's the various lift-off techniques will be discussed which is applicable along with above mentioned wafer bonding techniques for fabrication of GaN VLED's. By lift-off we mean the separation of sapphire substrate from the LED structure. The following section is a review of many lift-off techniques proposed for removal of sapphire substrate from GaN VLED structure.

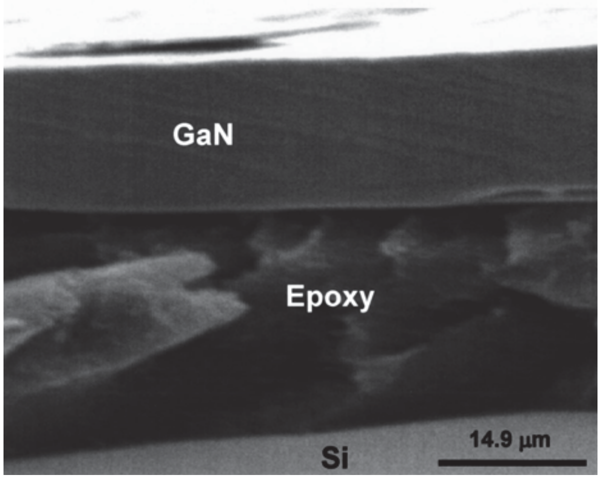

Figure 6. Typical cross-sectional image of GaN/Si with epoxy bonding.Ref [64]

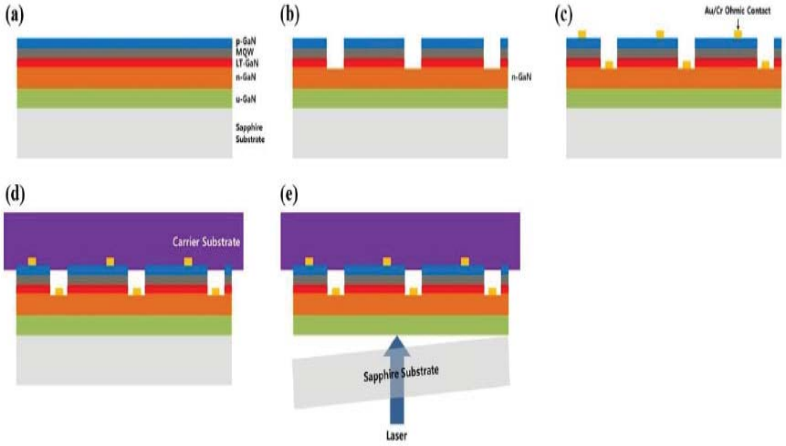

Figure 7. Schematic diagram of SU-8 and thermal release tape with LLO technique. Ref [67]

VI. DEVICE LAYER SEPARATION - LIFT-OFF TECHNIQUES

Laser lift-off technique:

The high-power ultraviolet pulsed laser is irradiated to the interfacial GaN from the backside of the sapphire substrate, while not absorbed in sapphire. At a sufficiently high power these processes cause thermal decomposition of GaN by selective heating up. Figure 8 shows the thermal decomposition of GaN and separation of sapphire substrate taken from the W.S.Wong et.al[13] teams work.

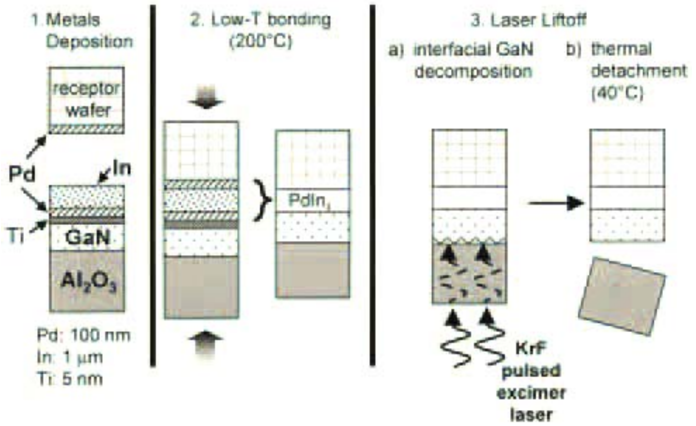

Figure 8. Process flow for liftoff and transfer of GaN from sapphire onto Si. Ref [16]

Physical mechanism of LLO technique:

The chemical reaction taking place at the interface can be expressed by[17]

$$2GaN\ (s) \rightarrow 2Ga\ (l) + N2\ (g)$$

Figure 9 depicts the laser lift-off process.

LLO results from laser-induced thermal decomposition of GaN, a process by which optical energy is transferred to the material, exciting a large number of electrons, which, in turn, transfer energy to the lattice (electron–phonon interactions). One photon can excite an electron across the band gap of GaN with a maximum excess energy of 1.6 eV due to the much higher laser photons. As a result, the electronic subsystem goes out of the equilibrium and becomes highly unstable. Mainly, the excited electrons with excess energy equilibrate through electron–electron scattering shortly. After self-thermalization, the heated electron gas begins to transfer its energy to the lattice and externally thermalizes with the lattice through electron–phonon (mainly LO phonons) interactions over a picoseconds timescale. Thermalization leads to many collisions between the electrons and phonons due to the large energy difference between the excess energy of electrons and phonons (such as E1(LO) 92 meV and E1(LO) 91 meV for GaN).At a sufficiently high power these processes cause thermal decomposition.

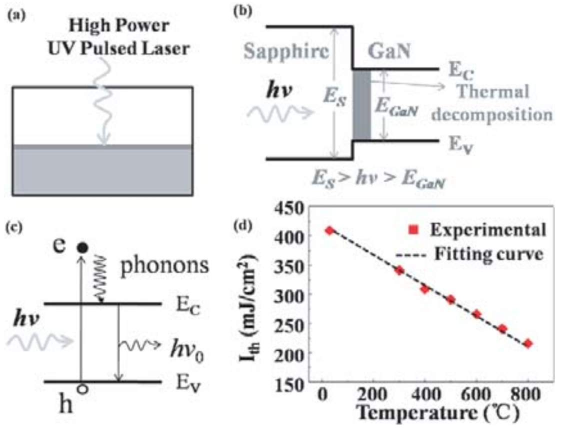

Figure 9. Schematic diagram of the physical mechanism of LLO technique. Ref [17]

Comparative study of Krf excimer laser and YAG laser lift-off:

Y.S Wu et.al[18,19], have done a comparative study on the influence of YAG laser[20] and Krf pulsed excimer laser[21] at the interface of GaN and sapphire substrate. In the observation it was found, under a reverse bias of −5 V, the leakage current of CV-LED was only 0.05 nA. However, the leakage current of YAG-LED was $1.65x10^3$ nA, which was 10000 times higher than that of the KrF-LED (0.17 nA). TEM images of LEDs showed that the screw dislocation density of YAG-LED was much higher than that of KrF-LED. GaN had different absorption depth for YAG laser compared to Krf pulsed excimer laser which was the cause for different dislocation densities in GaN thin film.

Advantages and disadvantages of Laser lift-off technique:

Compared to a process that requires ion implantation, laser-based processes are relatively rapid and do not require irradiation through the material that will comprise the active region of the device. Compared to sacrificial layer methods, laser-based layer transfer processes are faster and generally do not require prolonged exposure to liquid etchants that might attack metallization or dielectrics applied prior to the layer transfer step[44]. The disadvantages of laser transfer processes include the requirement that the substrate be a window to the incident laser light. Laser-based processes are also sensitive to the homogeneity of the beam and to the condition of the entrance surface. Perhaps most challenging are the mechanical, thermal and optical issues related to pulse overlap and pulse edge effects. Many of the problems related to laser stability and cost of ownership have been diminished in recent years due to technological improvements in pulsed laser systems. Energy of the laser beam is not easy to spread averagely and will then cause different decomposition rate and heat accumulation. Hard to precisely control the heat transfer and decomposition at the GaN/substrate interface. Due to thermal shock the quality of the GaN layer decreased. Besides these the most the laser lift-off process cause significant reverse leakage current in the device along with reduced yield during the process. Additionally, metallic Ga remains on the surface of the GaN epilayer after laser irradiation. These residual Ga droplets are detrimental to the device performance and should be removed using chemical etchants such as HCl

Chemical Liftoff technique:

The notable drawbacks in Laser lift-off method and ion-implantation method can be countered by Chemical lift-off technique (CLO)[27-33] in which the epilayers are selectively etched from the substrate without damaging the epilayers' structural and electrical properties. This can be can be carried out in many ways as following:

(i) anisotropic etching of buffer layer or sacrificial layer[34-38] (CrN,Ga_2O_3 and AlInN) embedded epitaxially in the structure *(ii)* photo electrochemical[41] etching.*(iii)* Electrochemical[28] etching of substrate to produce porous weakened sub layer. Figure 10 shown below is example of anisotropic etching of sacrificial layer and etching of sub layer to create porous layer.

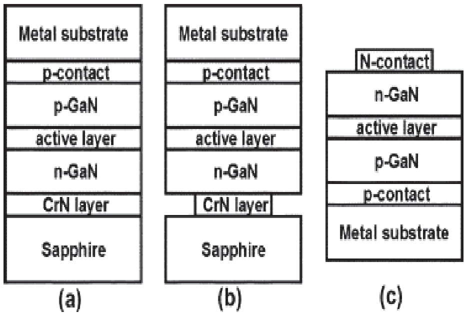

Figure 10. Schematic diagram to show the chemical lift-off of GaN LED by sacrificial etching of CrN buffer layer. [27]

Physical mechanism of CLO[31] technique*:*

The wet etching of semiconductors involves oxidation of the semiconductor surface and subsequent dissolution of the resulting oxides. Oxidation requires holes that can be supplied either chemically or via an electrochemical circuit. By distinguishing the etching mechanisms, wet etching of semiconductors can generally be divided into two categories, namely electrochemical etching (including anodic etching, electroless etching, and photo electrochemical[70-72] (PEC) etching), and chemical etching including conventional etching in aqueous etchants and defect-selective etching in molten (i.e. fused) salts. In anodic etching, the semiconductor and an inert electrode are attached to the positive and negative terminals of a direct voltage source, respectively. Both electrodes are put inside an electrolyte, e.g. aqueous potassium hydroxide (KOH). The semiconductor is oxidized by removal of bonding electrons (injecting holes) from the surface bonds via an external voltage source. The resulting oxides subsequently dissolve into the electrolyte. For electroless etching, neither an external voltage nor electrical contact to the samples is required. The oxidation of the semiconductor is driven by the potential of an oxidizing agent in the electrolyte, which depletes valence-band electrons in the semiconductor, and thus, supplying holes. Chemical etching has a completely different etching mechanism compared to the electrochemical etching processes, in that no free carriers or electrolyte are involved, thus, the etching process is not affected by an external potential. The reactive molecules from the etchant break the bonds at the semiconductor surface and form oxides that are subsequently dissolved in the etchant.

Jun-Seok Ha et al., [27] have worked with CrN as buffer layer which etches out the GaN LED from the sapphire substrate selectively by chemical solution. In Table II, the summary of various sacrificial layers used for lift-off of GaN thin film is tabulated below. The work showed very good current–voltage performance with low series resistance of 0.65 ohm and low operated voltage of 3.11 V at 350 mA. Also, this device could be operated at a much higher injection forward current (1118 mA at 3.70 V) by thermally conductive metal substrate which enabled the high current operation with excellent heat dissipation. Yu Zhang et al.,[28] have successfully combined the electrochemical etching with adhesive bonding for the fabrication of vertical GaN LED's. This is a process to slice and separate GaN epilayers for LED's which effectively eliminates use of sacrificial buffer layer and the laser lift-off layer which damages the GaN device layer. The nanoporous(NP) GaN serves dual purposes of supporting subsequent overgrowth of LED structures while undergoing, during growth, shape transformation into a largely voided morphology. It is shown that this voided region decreases the lateral fracture resistance and enables large-area separation of the LED structures after appropriate wafer bonding. The separated LED layers are shown to have comparable material quality before and after the liftoff process. Blue emitting GaN LEDs are transferred to silicon substrates with vertical configuration by this unique process.

Ray-Hua Horng et al, [29] has separated GaN thin film with Cu substrate from sapphire substrate by increasing the interface strain between sapphire and the GaN epilayers by means of hydrofluoric acid. This method had no damage to the GaN film as compared to the laser lift-off technique. Chieh Hsieh et al.,[33] have proved enhanced luminance in GaN VLED by photoelectrochemical etching of the GaN LED epilayer and found that the output intensity of the VLED is higher than that of the lateral LED(LLED) (by 47% at 95 mA in injection current). Slight current leakage can be seen in the VLED. The device resistance of VLED is 20% less than Lateral light emitting diode (LLED).

Sacrificial buffer layer	***Etching solution***	***Lift-off method***	***Reference***
BN		Mechanical release	[36]
GaN		Thermal release	[43]
CrN	di-ammonium cerium (IV) nitrate with perchloric acid	CLO	[27]
Ga_2O_3	Hydrofluoric acid	CLO	[37]
ZnO	0.1M HCl	CLO	[34,35]
AlN	Hot KOH,5min	CLO, adhesive tape	[38]

Table II. GaN VLED lift-off by removal of sacrificial buffer layer from sapphire by mechanical and chemical lift-off

Advantages and Disadvantages of CLO technique:

In addition to highlighting the various authors work and the advantages in it ,Yu Zhang et al[28] in his effort to separate large area free standing GaN thin film by applying electrochemical etching has compared electrochemical etching with selective etching of sacrificial layers like AlN and CrN and has found that the selective etching resulted in the effective separation of sub-millimetre scale membrane formation when electrochemical etching with nanoporous layer formation could separate GaN thin film as thin as 0.5 um to few microns while preserving the crystallinity of GaN layers. The disadvantages of CLO technique can be discussed as: Requirement of the movement of etchant towards the wafer surface, reaction at surface and the removal of the reactant products. These all could be a rate limiting steps in CLO technique.

Ion implanted lift-off technique:

The ion induced lift-off technique is another method for separating the thin film from the non-conductive substrate. K. V. Srikrishnan[22] separated Si thin film from bulk substrate by H-ion induced lift-off technique. This technique was applied to separate GaN thin film from the bulk substrate by S. O. Kucheyev et al, O. Moutanabbir et al. This process helps to transfer bulk quality sub-micrometer-thin layers onto a foreign material which has any epitaxial relationship with the substrate. The mechanism of splitting the GaN thin film from the substrate is studied by O.Moutanabbir et al, However, detailed investigations of the underlying physics of ion slicing of GaN are still in their infancy.

Physical mechanism of ion-implantation lift-off technique26:

As a first step, light energetic ions (hydrogen and/or helium) are implanted into free standing GaN (fs-GaN) donor wafer at the optimal fluence. After implantation, the implanted wafer is bonded to a handle wafer. During annealing at intermediate temperatures (500°C), the interaction of the implanted species with the produced radiation damage acts as an atomic scalpel, creating extended internal surfaces. This leads to the splitting of a thin layer with a thickness equivalent to the implantation depth. Therefore, it is possible to tune the thickness of the transferred layer by adjusting the energy of the implanted species. However, layer splitting can only take place if the bonded interface between the donor and handle is sufficiently stable. The process of splitting the thin GaN layer is shown in Fig. 12.

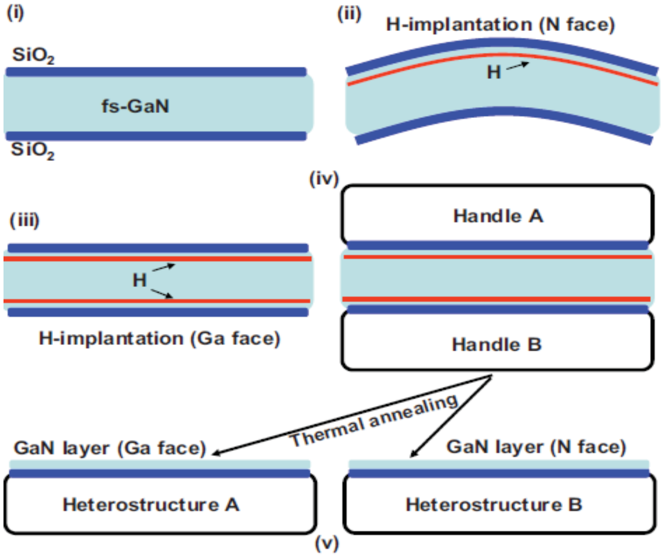

Figure 12. Schematic diagram of separation of GaN thin film by H-ion impalantation technique. Ref [26]

Advantages and Disadvantages of ion induced lift-off technique:

Thinning of one of the bonded wafers down to a thickness between about 10 nm to some micrometers is possible. The split wafers can be reused. When H-ion is implanted with boron the annealing temperature is very much reduced. This method offers high degree of uniformity, homogeneity, low cost as added advantages. When mentioning disadvantages, the epitaxy layers are heated to vaporize ions to provide pressure for separating. The ion implantation process will destroy the crystal structure of the epitaxial layer, and the defect density which influences the device performance and the material quality will also be increased. With this type of the method, it is not possible to fabricate vertical GaN LED’s because the multi quantum well (MQW) of this kind LED is placed on top layer where the lift-off takes place and hence is affected during the ion-induced splitting method. Thus it is not pursed for the fabrication of GaN LED’s.

Thermal stress induced Lift-off technique:

In thermal stress induced separation of GaN thin film structures, the lattice constant mis-match of the substrate and the epitaxial layer and the difference in co-efficient of thermal expansion between them are effectively made use to fulfil the objective of separation[39-43]. Separation in the interface arises due to the biaxial compressive strain in GaN and the tensile strain in the Sapphire substrate.

Physical mechanism of Thermal stress induced lift-off:

After HVPE growth when sample is brought down to room temperature, separation occurs between sapphire substrate and GaN epilayer due to differences in the thermal expansion coefficient between the two materials. Specifically, the average in-plane thermal expansion coefficient is in the temperature range 300–1000K for sapphire which is greater than that of GaN, causing the sapphire to contract at a faster rate than GaN upon cooling. However, the sapphire is mechanically constrained by the GaN epi-layer, and therefore held at a length that is elongated compared to the length it would have achieved had it not been constrained. This results in a tensile stress in the sapphire substrate. The stress analysis of the GaN layer follows analogous logic. GaN would like to contract at a certain rate but is coerced to contract faster than normal under action of the sapphire substrate. The final length of the GaN layer is shorter than it would be had the layer contracted independently and is thus under compressive-stress. The expression for thin film stress:

$$\sigma f = (\alpha s - \alpha f)\Delta T / [\frac{1-\nu f}{d f E f} + ((1 - \nu s / d s E s)](d f)$$

Such stresses can be quantified utilizing the Stoney Equation, which expresses the thermal stress in the film as a function of fundamental parameters of the film and substrate. The epitaxial film stress (σ_f) depends on the thermal expansion coefficients (a), Poisson’s ratios (n), Young’s moduli (E), thickness (d), and the temperature change (DT). The subscripts ‘‘f’’ and ‘‘s’’ denote values for the film and substrate. The separation of GaN from sapphire substrate due to thermal stress is depicted in Fig. 13

Adrian D. Williams et al[40]., proposed natural stress-induced separation of a GaN layer from a sapphire substrate. They suggested that the separation occurred via a LT-GaN buffer layer during the cooling process after the HVPE growth. This is achieved in a single HVPE reactor without any special processing before or after the growth procedure, which drastically streamlines the fabrication process.

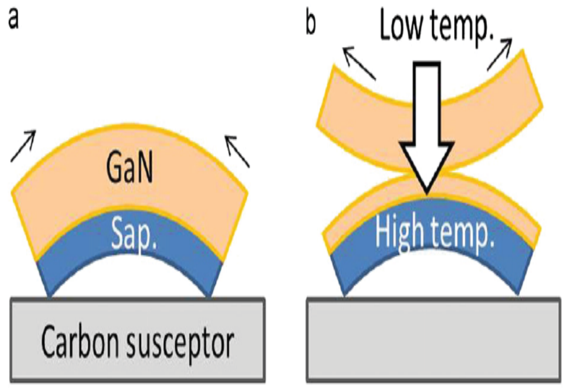

Figure 13. Separation of GaN thin film from the sapphire substrate by natural stress induced separation. Ref [40]

Advantages and Disadvantages of Thermal stress induced lift-off technique:

This technique eliminates ex-situ processing of the substrate by simplifying the fabrication process compared with LLO and CLO technique. Also allows for higher carrier mobilities, increased radiative efficiency due to substrate homogeneity, longer device lifetime and lower leakage current. In addition, this technique does not require the additional deposition of buffer layer like sacrificial buffer layer as in CLO technique. Compared with other lift-off techniques this technique makes it possible for the effective streamlining of the fabrication process for GaN VLED’s with native substrate. Though the fabrication of high quality GaN thin films having higher carrier concentration and Hall mobility values has been reported by Shuji Nakamura and thin film GaN substrates by Adrain D.Williams et al, Moustakas et al and Yamane et al., as per review there has been no results for the fabrication of GaN VLED by this technique.

V. FUTURE PERSPECTIVES

As mentioned in the laser lift-off (LLO) technique, the lift-off process by thermal decomposition at the sapphire and GaN interface has many after effects like damage of GaN layer, increased threading dislocation and increased reverse bias leakage which is due to the increased damage in GaN layer. The damage to GaN layer occurs when N_2 evolves from the GaN surface and finds a path for effusion from the device.

$$2GaN\,(s) \rightarrow 2Ga\,(l) + N2\,(g)$$

By patterning the sapphire substrate a channel is established for the N_2 effusion and damage to GaN can be reduced. In this way improvement can be done for the reduced reverse bias leakage.

In the discussion for chemical lift-off technique the main cause for the reduced rate of reaction between the etchant and the intermediate layer is identified as the reduced thickness of the intermediate buffer layer between the sapphire substrate and the GaN VLED structure. If the thickness of the intermediate layer is increased to few micrometers an optimum channel width can be established for the movement of etchant to the reaction site and the removal of reacted product away from the reaction surface, thus efficiently increasing the rate of reaction between the etchant and the intermediate layer. When undoped GaN layer which is included in the VLED structure is used as the sacrificial layer for the lift-off between the sapphire substrate and the vertical LED structure, the use of buffer layer as sacrificial layer can be eliminated.

In study about thermal stress induced lift-off technique it was found to be more efficient than other processes since this process enables the streamlining of in-situ fabrication process. But then it requires further research and data about the quality of the fabricated LED structure.

VI. CONCLUSION

A detailed study of several bonding techniques along with lift-off techniques for the fabrication of high brightness GaN VLED is done. Table III gives a summarized review of various wafer bonding techniques with lift-off techniques for the fabrication of GaN VLED. The various wafer bonding and lift-off techniques that circumvent the inadequacy of sapphire substrate like poor thermal conductivity and poor electrical conductivity to fabricate high brightness GaN VLED is discussed elaborately. This vast exploitation of the wafer bonding and lift-off technique has increased the luminance intensity output of the GaN VLED by improving the reflectivity in all direction. Also has improved GaN VLED’s lifetime by increased thermal conductivity with added electrical conductivity and enhanced optical properties. It is observed from study ,when the optimized wafer bonding process along with choice lift-off techniques and surface texturing techniques as highlighted in this paper are availed it ultimately results in an enhanced light extraction efficiency and external quantum efficiency of the device. GaN VLED’s fabricated by wafer bonding and Lift-off techniques show excellent electrical performance with film properties comparable to bulk material. The efficiency of this procedure is confirmed by the operation of GaN VLED when transferred to p-type Si substrate or Cu substrate. It is seen from review, when substrates of low thermal conductivity and low electrical conductivity are transferred to other metallic conductors there can be seen a significant reduction in series resistance, operating voltage and operating temperature of the device. This in turn makes it possible for the high light output efficiency and life time of the device. Thus the wafer bonding with Lift-off technique for the fabrication of GaN VLED also brings promise to expand solid-state lighting to general lighting.

GaN Led method of Bonding and bonding temperature			***Method of Lift-off from Host Substrate***	***Process Complexity***	***Comments***	***Reference***
HVPE			Natural Stress induced Lift-off	Low	The samples grown on a low temperature GaN buffer naturally delaminate from the sapphire substrate post-growth over the entire thickness range studied.	[39,40,42,43]
HVPE			Thermal stress concentration	Low	Stress will strain the atomic bonds between the sapphire and the GaN and facilitate the TSEE process.	[41]
Metal Bonding	Pd-In	200°C	Laser Lift-off	Low	Low-temperature transient liquid-phase Pd-In wafer-bonding process was employed to form a thermally and electrically conductive interface between the transferred GaN and the "receptor" substrate.	[13-18]
	Au and Si Eutectic bond GaN LED to Si	Low temperature ~ 400°C	Laser Lift-off	High	The high performance LED was achieved due to the strong guided-light scattering efficiency while employing double diffuse surfaces	[63]
	Ag-Au,Ag-Al diffusion bonding	Low temperature ~150°C	Mechanical Lift-off	Low	The low bonding temperature allowed GaN LED sapphire wafer to be easily bonded to Si without any serious warp.	[50,48]
	GaN LED bonded by Pt/Au/Ti to Si	Temperature ~ 550°C	Mechanical Lift-off	High	Sapphire etched vertical electrode nitride semiconductor (SEVENS) LED having a conducting Si receptor and reflector metal light-output power increased linearly with increasing junction current.	[30]
	GaN LED deposited with Ni/Ag/Au bonded to Au deposited Si	Temperature ~ 200°C	photoelectrochemical LO	Low	The output intensity of the VLED is higher than that of the LLED (by ~47% at 95 mA in injection current)	[51]
	GaN-Cu	Temperature ~ 500°C	Chemical Lift off	Low	It was found that Cu-substrate LEDs could be operated in a much higher injection forward current, 800 mA, which was eight times higher than that used in GaAs-substrate LEDs.	[4]
	Cu/Sn/Ag Bonding	Temperature ~ 150°C	Laser Lift-off	Low	The inverted pyramidal pattern has an equivalent function with the surface roughening process, which can greatly enhance the light extraction efficiency	[54,55]
Glue Bonding	BCB (C_8H_6) bonding layer between GaN and Si	Temperature ~ 200°C for 60 min	YAG Laser Lift off	Low	Light from the vertical InGaN LED device to be improved such that a single electrode could be used and the light could be reflected downward using a mirror and rougher n-GaN surface.	[8]

Table III. Summarized report on several wafer bonding technique along with lift-off techniques for fabrication of GaN VLED's.

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