Comparison of Chemical and Laser Lift-off for the Transfer of InGaN-based p-i-n Junctions from Sapphire to Glass Substrates

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ABSTRACT

InGaN-based p-i-n structures were transferred from sapphire to soda-lime glass substrates using two approaches: (1) laser-lift-off (LLO) and thermo-metallic bonding and (2) chemical lift-off (LLO) by means sacrificial ZnO templates and direct wafer bonding. Both processes were found to function at RT and allow reclaim of the expensive single crystal substrate. Both approaches have also already been demonstrated to work for the wafer-scale transfer of III/V semiconductors. Compared with the industry-standard LLO, the CLO offers the added advantages of a lattice match to InGaN with higher indium contents, no need for an interfacial adhesive layer (which facilitates electrical, optical and thermal coupling), no damaged/contaminated GaN surface layer, simplified sapphire reclaim (GaN residue after LLO may complicate reclaim) and cost savings linked to elimination of the expensive LLO process.

Keywords: GaN, photovoltaic, LED, transfer, chemical lift-off, laser lift-off, wafer bonding, glass

1. INTRODUCTION

Gallium Nitride (GaN) is a direct wide bandgap material which can be engineered into the ultraviolet (UV) range through alloying with Aluminium (i.e. AlGaN) and into the visible range through alloying with Indium (i.e. InGaN) [1]. Since the development of p-type GaN in the 1990s [2,3] a huge range of AlInGaN-based p-n junction devices has emerged, including light emitting diodes (LEDs) [4], laser diodes, high power/frequency electronics, photodetectors and, more recently, third generation photovoltaics (PV) [5]. Commercial production of such devices usually employs alternative substrates (such as c-sapphire or 6H-SiC) because native GaN substrates with appropriate cost/quality/size are not currently available in industrial quantities. Such non-native substrates bring constraints, however, including significant crystal lattice mismatch, differences in thermal expansion coefficients, poor thermal/electrical conductivity, rigidity, limited size and high cost levels compared with competing materials systems. These constraints severely impact the cost/performance profile of the final devices.
Currently, therefore, there is considerable interest in the transfer of InGaN based junctions to alternative substrates. This could be, for instance, metal alloys for LEDs (so as to form vertical device structures with superior current distribution and thermal management [6]) or soda-lime glass substrates (so as to keep cost levels low).

This study contrasts the use of Laser Lift-Off (LLO) [7, 8] and Chemical Lift-Off (CLO) [9] for the transfer of InGaN based p-i-n junctions from c-sapphire to low-cost soda-lime glass substrates. Soda lime glass substrates are usually inaccessible for GaN-based devices because the elevated growth temperature required for high quality GaN growth (~1000ºC) melts the glass (Tg ~ 570 ºC [10]).

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2. EXPERIMENT

2.1 LLO and Thermo-metallic Wafer Bonding

GaN-based p-i-n structures were grown on commercial GaN-buffered c-sapphire substrates by Metal Organic Vapor Phase Epitaxy (MOVPE). Trimethylgallium (TMGa), Trimethylindium (TMIn) and ammonia (NH_3) were used as the Ga, In and N sources, respectively. SiH_4 (silane) and bis-cyclopentadienyl magnesium (Cp2Mg) were used for Si (n-type) doping and Mg (p-type) doping. H_2 was used as the carrier gas. Detailed growth conditions are given elsewhere [11]. Figure 1 shows a schematic of the p-i-n structure.

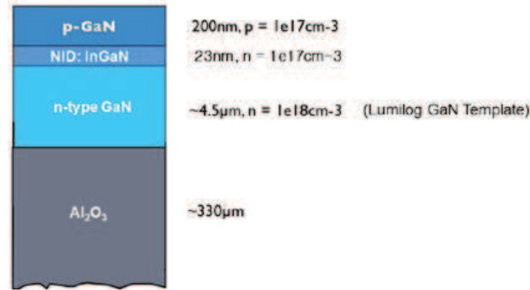

Figure 1. A schematic of the GaN p-i-n structure grown on c-sapphire substrate by MOVPE (NID = non-intentionally doped).

The GaN-based p-i-n structures were transferred onto optically-flat Corning microscope slides (soda-lime glass) via a process of thermo-metallic bonding to the glass with indium (using a hotplate) followed by LLO using a single pulse of a Coherent LPX krypton fluoride (KrF) excimer laser (248 nm) with a duration of 30 ns and a fluence of about 600 mJ/cm^2 [12].

2.2 CLO and Direct Wafer Bonding

InGaN p-i-n structures were grown by MOVPE on zinc oxide (ZnO)-coated c-sapphire substrates. ~46 nm of ZnO template was grown using pulsed laser deposition (PLD) from a 5N, sintered, ZnO target in molecular oxygen with the same KrF excimer laser, as described elsewhere [13]. Such ZnO layers offer a lattice match to InGaN with ~22 at% In [14] and thereby favorise the subsequent regrowth of high quality InGaN with elevated indium contents. The GaN p-i-n MOVPE growth procedure was modified from that described in section 2.1 (above) in order to avoid the dissociation of ZnO commonly observed during conventional GaN MOVPE [10]. This was achieved by introducing dimethylhydrazine (DMHY) as an N source and N_2 as a carrier gas, as described elsewhere [15, 16].
Figure 2 shows a schematic of the GaN p-i-n structure grown on the ZnO-coated c-sapphire substrate by MOVPE.

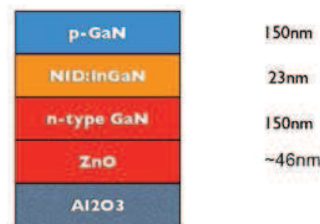

Figure 2. A schematic of the GaN p-i-n structure grown on the ZnO-coated c-sapphire substrate by MOVPE

The InGaN-based p-i-n structures were transferred onto optically-flat Corning microscope slides (soda-lime glass) via a process of CLO and direct fusion bonding which the authors developed and demonstrated recently for GaN thin films [9, 17] – see Figure 3. In this approach, the ZnO interlayer plays two roles. It acts first as a crystallographic template for GaN epitaxial growth and second as a sacrificial release layer, which is selectively chemically etched (in an acid or alkali) so as to separate the GaN from the sapphire substrate. A temporary “host” substrate is used to maintain the integrity of the GaN structure during the transfer process. After the dissolution of the sacrificial ZnO layer, the GaN p-i-n structure is transferred onto a glass substrate. This process is conducted at room temperature (RT), and consists of

applying a small compressive force so as to promote capillary action between the GaN and the glass. After drying, the host substrate is also removed by selective dissolution. Figure 3 shows a Transmission Electron Microscope (TEM) image of the GaN/glass interface following CLO from sapphire and direct wafer bonding to glass.

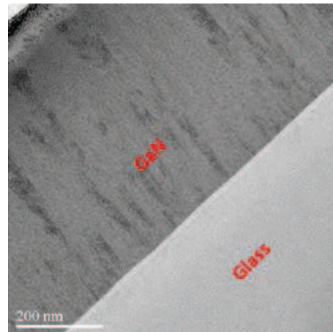

Figure 3. TEM cross-sectional image of GaN/substrate interface after CLO from sapphire and direct bonding to glass (acquired using Scanning TEM imaging of a focused ion beam cross-section in an aberration-corrected JEOL 2200 TEM).

The crystal structure of the GaN was preserved after the transfer and it can be seen from Figure 3 that such transfer gives an excellent GaN/glass bond/interface [17]. The thin interfacial layer apparent in the image is commonly observed in such a bonding approach and has been attributed to several possible causes including a surface oxide, a surface layer on the glass due to aging and contamination [17].

2.3 Characterisation

The laser-treated GaN surface was studied using backscattered-electron imaging in a Zeiss Supra 55 Scanning Electron Microscope (SEM). The overall crystalline nature of the materials was investigated using X-Ray Diffraction (XRD) measurements performed in a high resolution Panalytical X'pert Pro MRD system with Cu $K_{\alpha1}$ radiation.

3. RESULTS & DISCUSSION

3.1 LLO and Thermo-Metallic Bonding to Glass

Figure 4 shows a schematic of the process flow of thermo-metallic bonding to glass (with indium) and subsequent LLO of the sapphire substrate illustrated with photographs of the actual experiment.

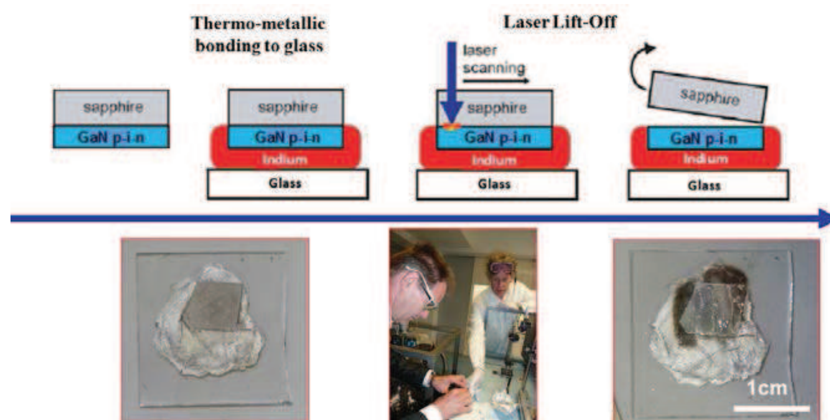

Figure 4. Process flow illustration and photographs of the actual thermo-metallic bonding and LLO from the sapphire substrate.

Figure 4 shows that samples of ~ 1cm x 1cm could be successfully lifted-off the sapphire and bonded to glass substrates. Figure 5 shows XRD 2 theta-omega scans before and after LLO.

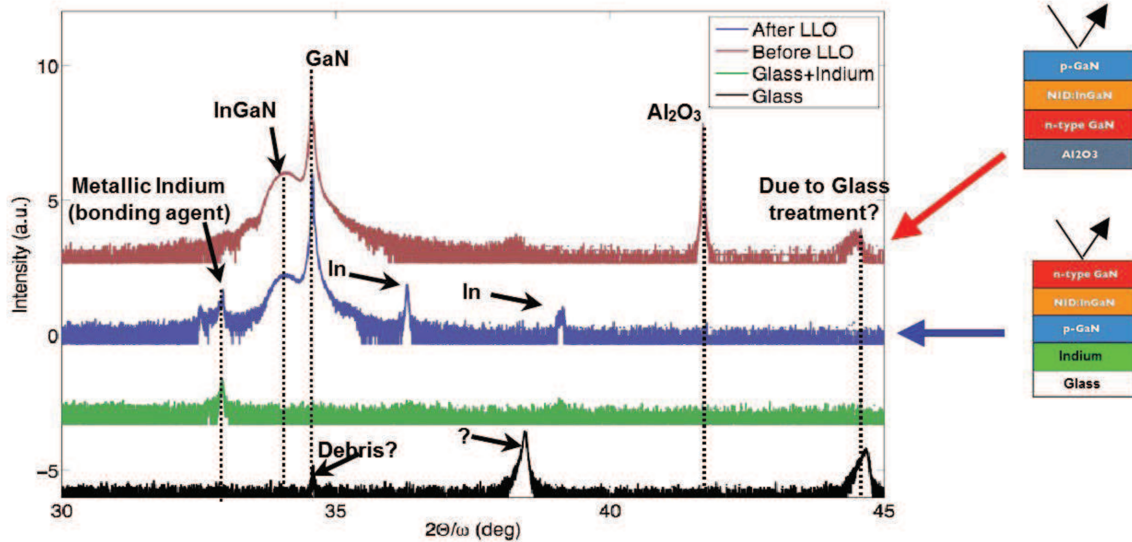

Figure 5. XRD 2 theta-omega scans for the GaN p-i-n/sapphire before and after LLO plus the scans for the glass substrate with and without indium (as references).

The 2 theta-omega scans reveal distinct wurtzite (0002) peaks for GaN and InGaN. The InGaN peak position corresponds to an indium content of about 9 at%. These peaks are clearly visible both before and after LLO and wafer bonding with no significant change in peak position or width. This indicates that there was successful transfer of the GaN p-i-n to glass without substantial degradation of the crystal quality.

Figure 6 shows an SEM image of the GaN back-surface (previously in contact with the sapphire substrate) after LLO.

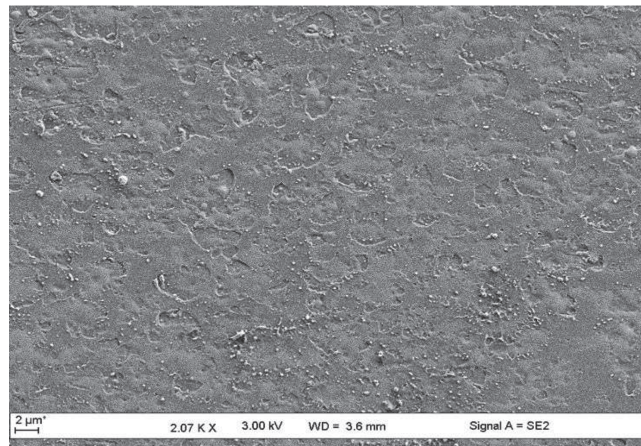

Figure 6. SEM image of the GaN back-surface (previously in contact with the sapphire substrate) after LLO.

The GaN surface shows roughening due to laser damage and some evidence of residues which are most probably metallic gallium droplets.

3.2 CLO and Direct Wafer Bonding

Figure 7 shows a schematic of the process flow plus corresponding photographs of the actual experiment for the GaN p-i-n CLO and direct wafer bonding.

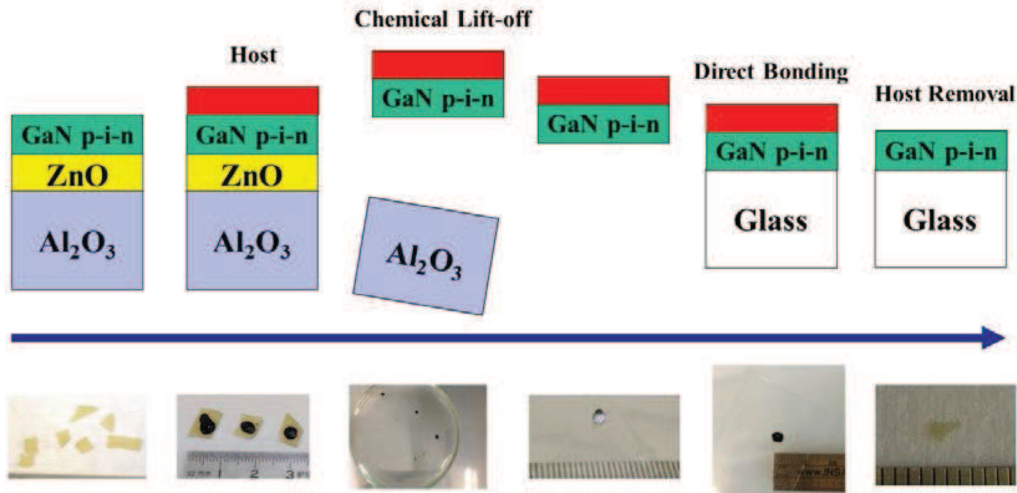

Figure 7. A schematic of the process flow plus corresponding photographs of the actual process for the GaN p-i-n CLO from sapphire and direct wafer bonding to glass.

The photographs in Figure 7 illustrate that a few mm^2 of GaN p-i-n was successfully transferred from sapphire to a glass substrate by CLO and direct wafer bonding.

4. CONCLUSIONS

It was shown that LLO and CLO-based approaches both work for the transfer of InGaN-based p-i-n junctions from sapphire to glass substrates. Table 1 shows a comparison of the pros and cons of the LLO and CLO processes described above.

	Thermo-metallic Bonding & LLO	Chemical Lift-off & Direct Wafer Bonding
RT Process	✓	✓
No Need for Adhesive Layer	✗	✓
GaN Undamaged	✗	✓
Substrate Reclaim	✓*	✓
Cost Level	✗†	✓
Wide Areas	Possible	Possible

* After removing Ga residue †Expensive/complex laser processing

Table 1. A table of the pros and cons of the LLO and CLO processes used to transfer GaN-based p-i-n junctions from sapphire to glass substrates.

Both processes function at RT, allow reclaim of the expensive single crystal substrate and have been demonstrated to offer the perspective of wafer-scale III/V semiconductor transfer [12, 18]. Compared with the industry standard LLO, however, the CLO with ZnO buffers offers the added advantages of an improved lattice match to InGaN with elevated indium contents (necessary for optimal (sweet spot) PV performance and for combating the drop-off generally observed

for green LED efficiency), no need for an interfacial adhesive layer (which facilitates electrical, optical and thermal coupling), no damaged GaN surface layer, simplified sapphire reclaim (GaN residue after LLO may complicate reclaim) and cost savings linked to elimination of the complex/expensive LLO processing.

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