Project Report
LSP-288

Low-Defect III-N Devices By Remote Epitaxial GaN: FY19 Advanced Materials and Processes Line-Supported Program

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1. LOW-DEFECT III-N DEVICES BY REMOTE EPITAXIAL GaN, PROGRAM STATUS

Gallium nitride (GaN) is an important semiconductor, not just for visible-to-UV light emitters but also for high-power, high-voltage and high-frequency electronics. Much of the challenge in realizing a manufacturable process for GaN devices, particularly those requiring a low-defect density, is mitigating the unfavorable trade between substrate cost and suitability. Low-defect GaN substrates are commercially available but are expensive and still limited to a maximum of 100 mm diameter. Having the ability to separate the expensive GaN substrate from low-defect device layers, (nondestructively to both) would be an enabling technology for III-N devices. The goal of this program was to investigate using remote-epitaxy of GaN (RE-GaN) utilizing a thin graphene (or similar) layer to enable fracture and separation of the film at this interface due to the weakened bond strength due to graphitic layer.

Our previous work on RE-GaN illustrated two specific process limitations that the current effort hoped to address. The first was the limited area and quality of the transferred graphene layer and the second was the observed instability of this layer at high temperature, particularly in the presence of ammonia, as used in MOCVD growth. The former issue was addressed by replacing the exfoliated graphene with *in-situ* grown amorphous BN layers and the latter was mitigated by depositing a thin MBE-grown GaN layer first on the amorphous BN layer by RE. Done properly, these “engineering-layers” would have an encapsulated BN layer to provide a means of separation after a thick MOCVD device epilayer growth was performed.

The major technical objectives of this project were to: (1) optimize graphene transfer for adherence and monolayer control; (2) develop low dislocation density template using remote epitaxy GaN (RE-GaN) and subsequent MOCVD regrowth; and (3) demonstrate an active device structure on an MOCVD regrown template and evaluate the device performance.

In the first quarter, the growth and exfoliation of RE-GaN using transferred graphene was achieved. However, a high background n-type doping in the RE-GaN in the range of 1018 cm-3 to 1019 cm-3 was observed. This prohibited its utilization in device applications. It was suspected that the auto-doping resulted from polymer residue on the surface after the graphene transfer to GaN substrate surface. Residue

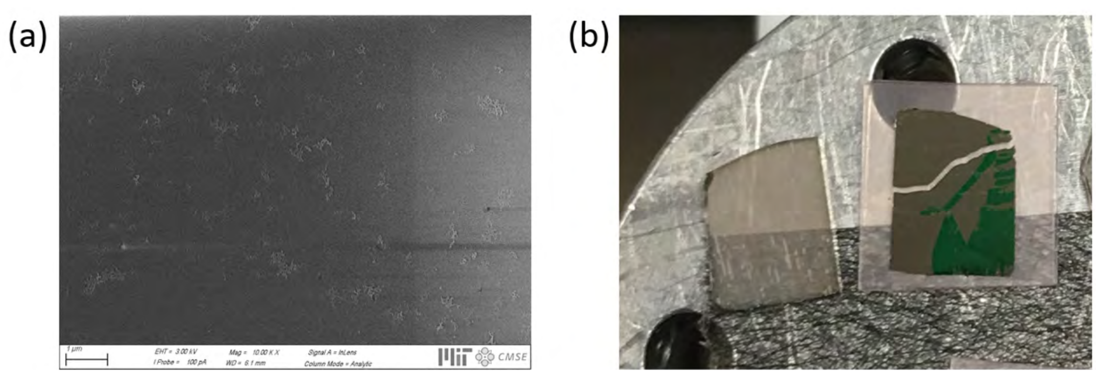

Figure 1 Challenges related to RE-GaN using graphene as an interlayer. (a) SEM image of graphene transferred on SiO2 showing polymer residues. (b) Photograph of RE-GaN exfoliation with exfoliated area limited by graphene size.

was visible under SEM as shown in Figure 1a. Additionally, the area of the RE-GaN growth was limited by the available size of the graphene transferred, which is typically ~1x1 cm2 as shown in Figure 1b. The repeatability and uniformity of the process was also fundamentally limited by the ex-situ transfer that introduced uncertainty from handling. Therefore, in the second quarter an investigation in using in-situ large-area deposition of amorphous boron nitride (a-BN) as the 2D interlayer for RE-GaN was started. The structural, electrical and optical material quality of RE-GaN on such films was characterized and a specular surface with AFM roughness less than 1 nm (see Figure 2a) was achieved. The epitaxial RE-GaN crystallographically aligned with the substrate across the a-BN interlayer (see Figure 2b), with dislocation density of high 108 to 109 cm-2 - close to but slightly higher than that of its substrate (low 108 cm-2), as determined by etched pit counting (see Figure 2c). Maximum electron mobility of RE-GaN is measured to be 325 cm2V-1s-1 (not shown here). Additionally, the cathodoluminescence of RE-GaN shows reduced defect-related yellow luminescence in comparison to a MOCVD GaN substrate as shown in Figure 2d. In

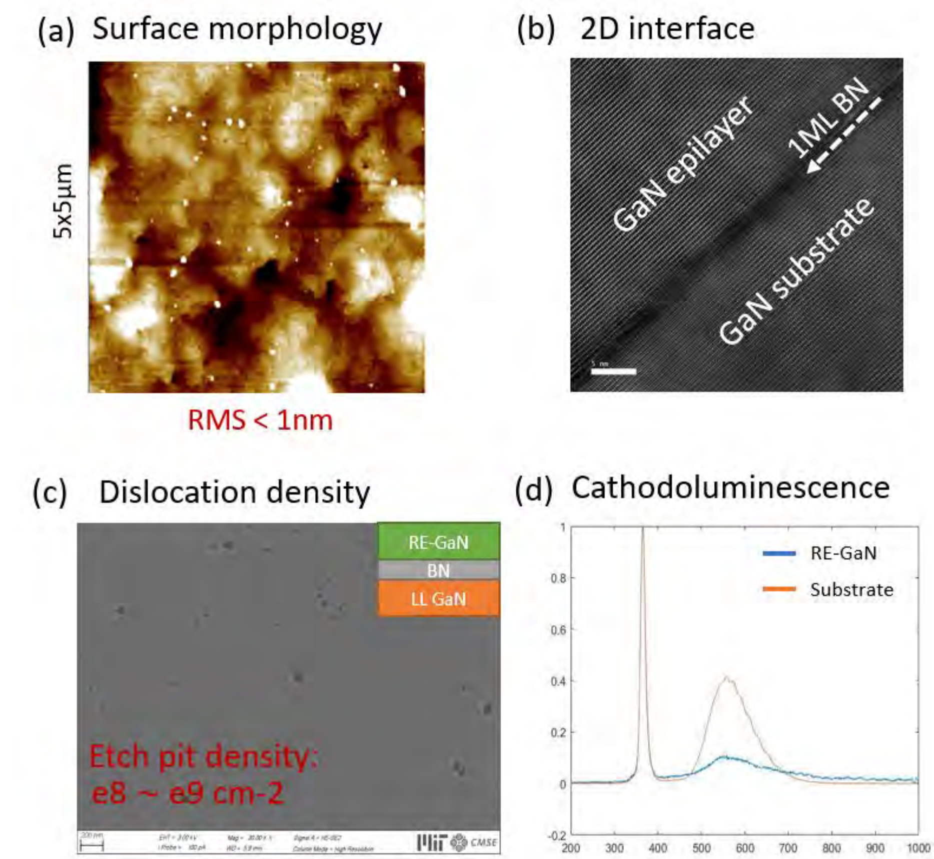

Figure 2 Material characterization of RE-GaN using amorphous BN as an interlayer. (a) AFM image of RE-GaN showing atomically flat surface morphology. (b) Cross-sectional TEM shows BN interlayer buried between RE-GaN and substrate, with atomic alignment across the BN layer. (c) Etched pit counting of RE-GaN shows dislocation density at the range of 108 to 109 cm-2. (d) Cathodoluminescence of RE-GaN show reduced defect related yellow luminescent peak intensity compared to that of bare substrate.

summary, the material quality of RE-GaN template is on par to that of RE-GaN on graphene, while the background doping is reduced to 10^{15} cm^{-3}, which is adequate for further development for active devices. In addition, the growth of RE-GaN on a-BN is scalable to large diameters as a result of the in-situ 2D material coating process. Figure 3a shows a photograph of RE-GaN over a 2-inch diameter wafer. The exfoliation of RE-GaN is edge to edge for the piece cleaved from the 2-inch wafer (see Figure 3b). We also demonstrated the pristine GaN substrate surface being recovered after the exfoliation, evidenced by the step features of MOCVD GaN (see Figure 3c).

Figure 3 Wafer-scale RE-GaN and exfoliation up to 2-inch in diameter with substrate reusable. (a) Photograph of 2-inch RE-GaN with in-situ 2D material interlayer. The dark spots are due to indium mounting at the back of the wafer. (b) Photograph of 100% exfoliation yield from edge to edge for pieces cleaved from the 2-inch RE-GaN template. (c) AFM image of substrate after exfoliation showing preservation of step surface morphology of the MOCVD GaN substrate.

In the third quarter, MOCVD regrowth on an MBE-grown RE-GaN template was developed and demonstrated exfoliation. A MOCVD GaN buffer layer of 3 µm thickness was grown on the MBE RE-GaN template and a specular growth surface was achieved, as shown by SEM (see Figure 4b). However, inverse pyramidal pits developed at the MBE/MOCVD growth interface (see Figure 4b), which were not observed for the RE-GaN template (see Figure 4a). The pit density is on the order of 10^8 cm^{-2} to 10^9 cm^{-2}, correlating with the dislocation density of the RE-GaN template. We suspect the origin of the pits are threading dislocations propagating from the RE-GaN template but surface contamination at the regrown interface is also possible as the pits aggregate and form clusters.

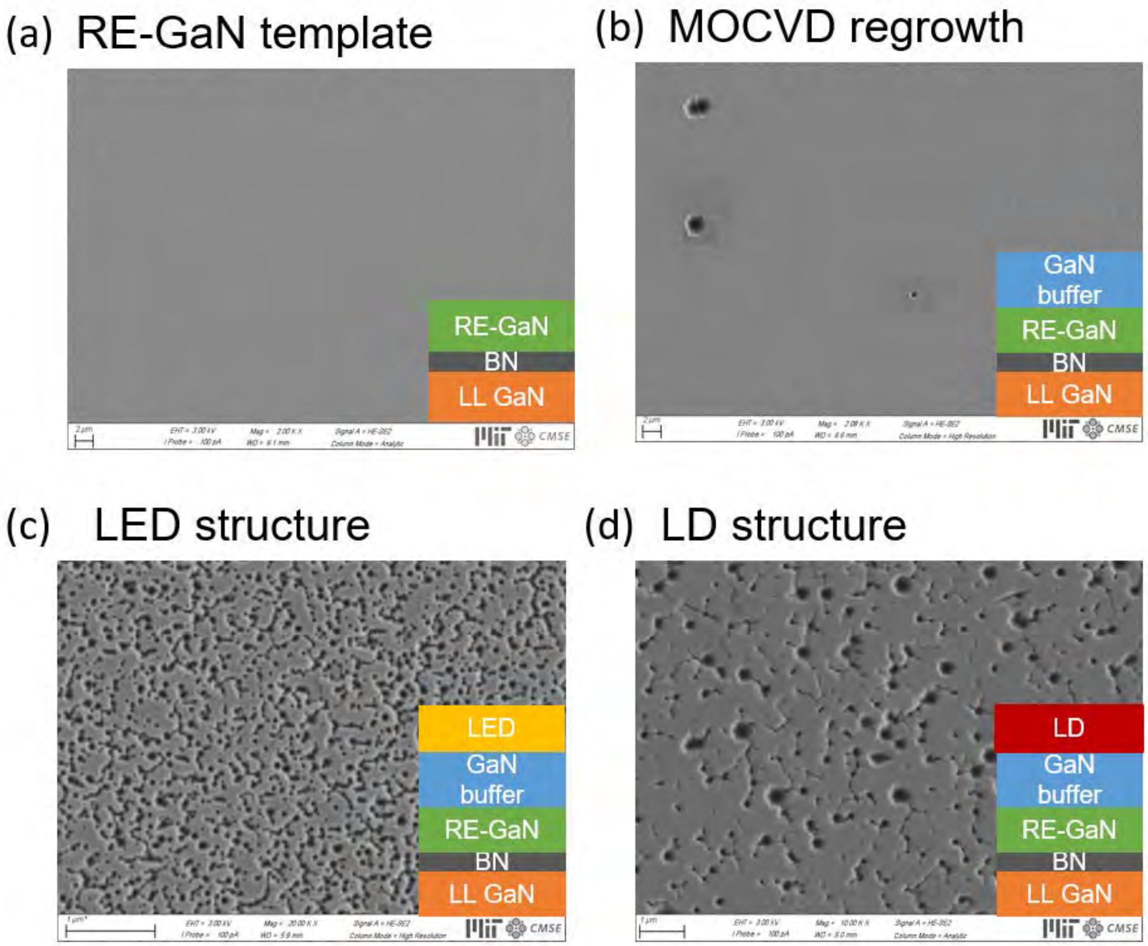

Figure 4 SEM images showing the surface morphology of (a) RE-GaN template, (b) MOCVD homoepitaxial regrown on RE-GaN template, (c) LED structure on MOCVD regrown buffer, and (d) LD structure on MOCVD regrown buffer. Pits on the surface may be related to varied conditions at the regrown surface.

In the fourth quarter, active device structures such as LED and LD have been grown on top of the MOCVD buffer layer on RE-GaN templates. However, dense pits are uniformly distributed across the top surface of the device layer (see Figures 4c and 4d), not seen either from the RE-GaN template and the MOCVD regrown layer in previous samples (see Figures 4a and 4b). The excessive pit generation severely affects the optical response of the LED and LD structure, and reduced photoluminescence is observed in comparison to the same device grown on more conventional GaN-on-sapphire substrates. Theses pits may originate from the surface treatment before the MOCVD regrowth or variability in the RE-GaN templates. An investigation is in progress to find out the cause of these defects.

Nevertheless, the exfoliation yield of MOCVD regrowth on RE-GaN has been enhanced from 20% up to 100% over the duration of the project (see Figure 5a). An examination of the surface of samples exfoliated after MOCVD regrowth reveals a relationship between the interfacial roughening and increased process temperature and/or time. To simulate the MOCVD regrowth thermal environment an MBE-grown RE-GaN layer was annealed in a tube furnace at 900 °C and 1000 °C respectively, and it was observed the interface was partially damaged at 1000 °C annealing for 2 hrs, but was intact at 900 °C for 2 hrs or at 1000 °C for 1 hr (see Figure 5b). This suggests the elevated temperatures in MOCVD regrowth environment may degrade the interface between the RE-GaN and GaN substrate, and this may also cause damage to the 2D material layer. Therefore, a reduced MOCVD growth temperature process was developed, employed, and 100% exfoliation yield was achieved (see Figure 5a). Further interfacial stability could be achieved by instead using AlN substrates, which can endure higher processing temperature.

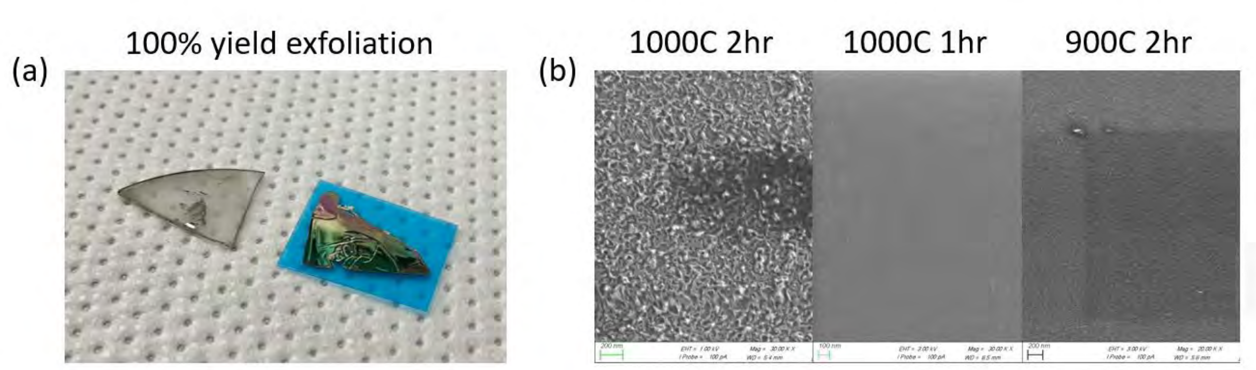

Figure 5 Exfoliation test of (a) RE-GaN after MOCVD regrown showing 100% yield for cleave pieces, and (b) RE-GaN after annealing at elevated temperature to simulate the interface damage in MOCVD regrown environment.

To date, relatively high quality RE-GaN templates have been developed in terms of structural, electrical and optical characteristics, on a 2-inch wafer scale. Successful MOCVD regrowth of epitaxial layers have been achieved on RE-GaN, although pyramidal defects occur which could be linked to surface treatment before the regrowth. Active device structures such as LED and LD on top of the MOCVD regrown buffer show excessive defects and severely affected the device performance. The origin of these defects is under investigation. Nevertheless, 100% exfoliation yield with improved 2D layers and reduced MOCVD growth temperatures was achieved, after studying the 2D interfacial thermal damage in the RE-GaN in a MOCVD growth environment.

Programmatically, we suffered some delays in this effort due to a 3-month delay in funding and several months at the end of the fiscal year where the MOCVD reactor had some other program efforts that required dedication to 200 mm GaN-on-Si growth. However, we are continuing this RE-GaN work and hope to reduce the surface roughness/pits sufficient to demonstrate devices on RE-GaN and transfer the process to bulk GaN to further reduce the density of dislocation in the device layers.