Migration Enhanced Metalorganic Chemical Vapor Deposition of AlN/GaN/InN based heterostructures

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Abstract

We applied a new Migration Enhanced Metalorganic Chemical Vapor Deposition (MEMOCVD™) epitaxial technique for growing AlN/GaN/InN epitaxial films and heterostructure layers on 2", 3" and 4" substrates. The growth of the AlN/GaN/InN layers was carried out using controlled precursor pulsed flows to achieve accurate thickness control over large area substrates. This technique bridges the gap between molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD). The Al composition in AlGaN barrier layer of AlGaN/GaN high electron mobility transistor (HEMT) structures varied less than 3% over 3" and 4" wafers. For AlGaN/GaN HEMTs, the sheet resistance of 463 ohm/sq has been achieved over a 4" diameter wafer grown on sapphire. The MEMOCVD technique ensures an improved material quality resulting in a better device performance. This technology should also find applications for nitride photonic devices, such as deep ultraviolet light emitting diodes, ultraviolet lasers, and solar blind ultraviolet photodetectors.

INTRODUCTION

To date, most work on GaN-based high power microwave transistors has been done using two competing approaches for growth of III-Nitride transistor structures: MOCVD and MBE. Although MBE has a proven track record in commercialization of GaAs and InP electronic devices, so far there is no clear proof of the viability of this technology for commercial III-Nitride transistor development. Both MOCVD and MBE techniques have their advantages and disadvantages in the growth of AlInGaN-based epilayers.

The MOCVD growth of AlGaN/GaN heterostructures requires much higher temperatures than MBE. Typical MOCVD growth temperatures for high quality GaN and AlGaN epitaxial layers are well above 900 ^{o}C. Such high temperatures impose fundamental limits on the abruptness of the deposited heterointerfaces, which directly impacts transport properties of the two-dimensional electron gas at the AlGaN/GaN heterointerface. In addition, it is much more difficult to incorporate significant amount of indium and to control uniformity of epitaxial wafers at high temperatures, especially for wafers grown on larger diameter substrates.

MBE uses significantly lower temperatures than MOCVD, typically below 700 ^{o}C. The lower temperature and uniform growth enable the deposition of very high quality heterostructures with abrupt heterointerfaces. However, GaN buffer layers grown at these temperatures are conducting, which make them unsuitable for high frequency device applications. Therefore, MOCVD grown semi-insulating GaN templates are widely used in MBE deposition of AlGaN/GaN heterostructures. This approach however requires transfer of wafers/templates from MOCVD reactor to MBE reactor, which inevitably results in the surface contamination;

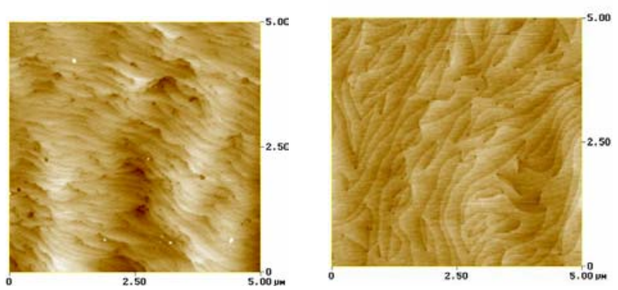
Our preliminary studies of AlInGaN deposition using a migration enhanced metalorganic chemical vapor deposition (MEMOCVD™) indicate that the deposition temperature can be significantly reduced (by more than 150 ^{0}C) without compromising the material quality[1]. In the MEMOCVD™, the duration and waveforms of precursor pulses are optimized, and the pulses might overlap allowing for a continuum of growth techniques. Using this new technique, we achieved a better mobility of pre-cursor species on the surface and thus, a better atomic incorporation and improved surface coverage. Moreover, our initial data on the AlGaN layer growth showed that, at the same growth temperature, the thickness uniformity across the wafer is better for the MEMOCVD deposition. The development of a hybrid AlGaN/GaN growth technology using MOCVD and MEMOCVD would combine the advantages of both high and low temperature deposition in a single growth chamber.

EXPERIMENTAL

In our growth procedure, the deposition of AlN buffer layer on sapphire and SiC was carried out using MEMOCVD. Trimethyl Aluminum (TMAl), Trimethyl gallium (TMGa), Trimethyl Indium (TMIn) and ammonia (NH_3) were used as precursors for Al, Ga, In and N, respectively. The buffer layer deposition was followed by the deposition of the 1.5-3.0μm thick semi-insulating GaN layer using a conventional MOCVD method. An undoped AlGaN barrier layer (Al% - 24-27%) was capped over GaN template for AlGaN/GaN HEMT structures. During the AlN growth, the duration of TMAl and NH_3 pulse was set for 6 seconds each. However, there is an overlap of both precursors' flow pulses for 2 seconds. The sequential flow can be described as Al, AlN and N. The total numbers of pulses adjusted for different thickness of buffer layer. The epilayers were characterized using X-ray diffraction (XRD), atomic force microscopy (AFM), Photoluminescence (PL), light-induced grating (LITG) technique for non-destructive determination of carrier lifetime, and Sheet resistance mapping.

RESULTS AND DISCUSSION

Figure 1 compares the atomic force images of GaN grown with conventional MOCVD and MEMOCVD AlN buffer layers over 5 x 5 μm^2. Both the surfaces show step morphology growth with steps termination at the tip of threading dislocations. The density of surface pits are 2 orders of magnitude lower for the MEMOCVD buffer layer sample compared with the conventional MOCVD buffer layer. The root mean square roughness of MOCVD grown layer is 5 Å whereas for MEMOCVD AlN buffer layer sample, the rms roughness is 1.7 Å over 1x1μm^2.



(a) (b)

Fig. 1. Atomic force microscopic images of GaN layers grown with (a) conventional buffer layer and (b) MEMOCVD buffer layer.

Figure 2 shows results of the carrier lifetime measurement for GaN layers grown on sapphire substrate with different buffer layer conditions. The measurement was carried out using nondestructive light induced transient grating technique. The extracted lifetime in GaN grown on sapphire using conventional MOCVD-grown AlN buffer is around 40-60ps. However, for MEMOCVD AlN buffer layer samples, the carrier lifetime is more than 350ps. This increase in carrier lifetime demonstrates the improvement in the quality of the MEMOCVD grown epitaxial layers.

Figures 3a and b show the sheet resistance mapping of AlGaN /GaN HEMT structures grown on three (3") inch SiC and sapphire substrate, respectively. The average sheet resistances for these heterostructures are 360 ohm/sq and 340 ohm/sq for SiC and sapphire substrates, respectively. These values correspond to the electron mobility exceeding 1600cm^2/V.s with the sheet carrier density above 1.2x10^{13} /cm^2. The thickness uniformity is less than 5% and the sheet resistance standard deviation over 3" wafer is less than 4%.

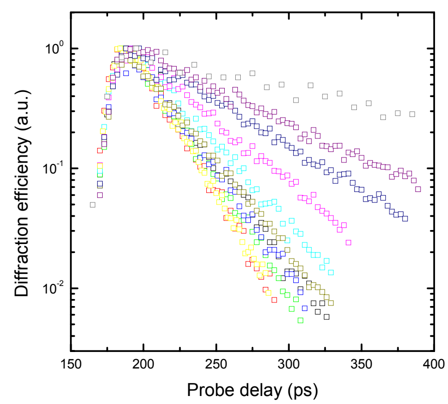


Fig. 2. Decay of light-induced grating in GaN layers with different carrier lifetimes.

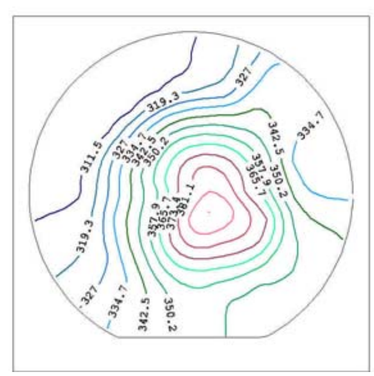


Fig. 3(a). Sheet resistance mapping of AlGaN/GaN HEMT on 3" semi-insulating silicon carbide substrate

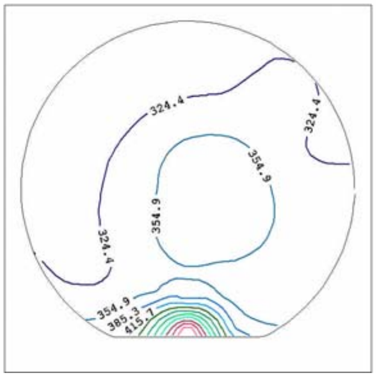


Fig. 3(b). Sheet resistance mapping of AlGaN/GaN HEMT on 3” sapphire substrate.

We have also demonstrated the AlGaN/GaN HEMT on 4” diameter sapphire substrate. First, the MEMOCVD AlN buffer layer was grown followed by the deposition of a 1.3 micron GaN layer. Finally, the structure was capped with the 250Å undoped AlGaN barrier layer (Al composition is 24-25%). Figure 4 shows the sheet resistance mapping for the HEMT structures on 4” diameter sapphire substrate. The average sheet resistance is 463ohm/sq. with standard deviation less than 5% with 8mm edge exclusion. The Al% composition variation is less than 3% over the whole 4” wafer. It is only possible to uniform composition and thickness due to MEMOCVD™ growth mode.

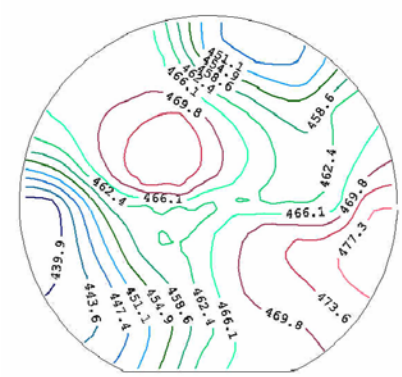


Fig.4. Sheet resistance mapping of AlGaN/GaN HEMT on 4” sapphire substrate with 8mm edge exclusion.

Figure 5 shows the photoluminescence spectra for GaN layer measured using excimer laser (peak wavelength at 193nm). The PL intensity from center to edge of the wafer is very uniform with full width half maxima less than 5nm over 4 inch diameter. The band edge emission peak is a few orders of magnitude stronger than deep level peak, which also indicats a high quality of the grown layers.

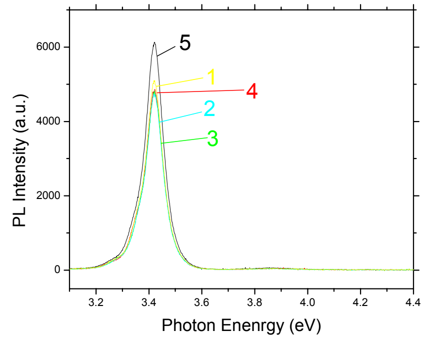


Fig. 5. Photoluminescence spectra of AlGaN/GaN layers grown on 4” diameter sapphire wafer (#1-5 corresponds to center (1) to edge (5) with 10mm spacing between each measurement)

CONCLUSIONS

High quality GaN layers have been grown using migration enhanced metalorganic chemical vapor deposition method. The MEMOCVD growth allowed us to achieve sharp interfaces and superlattices and excellent uniformity across the wafers. This technique combines advantages of the molecular beam epitaxy and metalorganic chemical vapor deposition methods. The demonstrated improvement in the carrier life time of GaN layers and a better uniformity over large area substrates makes the MEMOCVD technique viable for nitride optoelectronic devices such as ultraviolet light emitting diodes, ultraviolet lasers, high electron mobility transistors and solar blind UV photodetectors.

REFERENCES

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ACRONYMS

MEMOCVD: Migration Enhanced Metalorganic Chemical Vapor Deposition

MBE: Molecular Beam Epitaxy

MOCVD: Metalorganic chemical vapor deposition

HEMT: High electron mobility transistor