Manufacturable processes and performance characteristics of few-layer hexagonal boron nitride-based templates on sapphire

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Keywords: MOCVD, hexagonal boron nitride, hBN, HEMT

Abstract:

In this paper we demonstrate growth and film transfer of h-BN template grown films on c-plane sapphire. Growth and characterization results are reported for template layers of hBN and GaN on hBN. Films deposited by MOCVD on c-plane sapphire demonstrate structural and electrical characteristics needed for use with HEMT device structures. We routinely produce h-BN, AlN/h-BN, and GaN/hBN templates used as starting materials for HEMT, optical (LED/detector), and piezoelectric (oscillator/filter) devices on wafers as large as 100mm. The few monolayer h-BN films are typically 2nm (+/-10%) thick across a 100mm wafer. GaN templates grown on hBN exhibit thickness uniformity of 3% across 100mm for 2µm thick films while AlN templates show uniformities of +/-5%.

We demonstrate exfoliation of device layers by separation of the hBN layers near the hBN/sapphire interface.

INTRODUCTION:

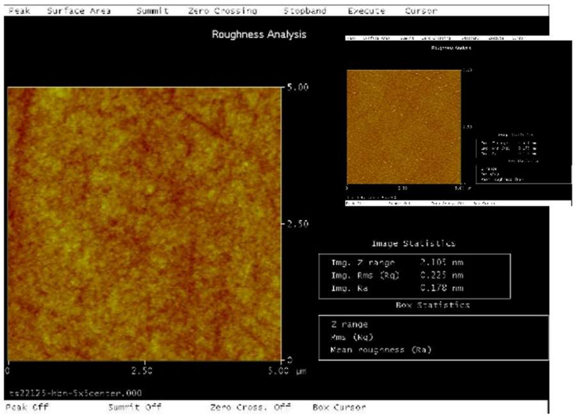
Like its well-studied relative - graphene, hexagonal boron nitride (h-BN) has emerged as an interesting two-dimensional material for a variety of applications.[1-5] The structural characteristics of hBN are like graphene in that it forms and is most stable in a hexagonal bonding configuration with strong bonds with neighboring in-plane atoms, but relatively weak van der Waals bonding with out of plane atoms. Owing to the similar physical structure to graphene, few monolayer hBN is routinely exfoliated from substrate materials in a manner similar to graphene. Exfoliation of films grown on hBN allows for the heterogeneous integration of devices based on a wide band gap and ultra-wideband gap semiconductors with circuits or devices on Silicon or other compound semiconductors. Because of the unique physical and electrical characteristics of h-BN, it has emerged as a starting material for growth templates for III-nitride materials on sapphire substrates. The weak in-plane bonding configuration has allowed for the demonstration of thin film exfoliation processes for the transfer of films and devices to alternate substrates. Transfer to flexible substrates has been considered for applications like wearable electronics, while transfer to more thermally conductive substrates is being considered for better thermal management in high power RF and energy conversion applications.[2] Transfer to optically transparent substrates allows for unique optical devices such as multi-wavelength detectors grown with different processes and integration after processing.

EXPERIMENTAL:

The h-BN films are grown in a close-coupled showerhead reactor capable of 6-2” wafers and up to 1-6” wafer. Films are grown at near 1200ºC using TEB and NH_3 precursors on c-plane sapphire starting materials. The h-BN films are characterized by AFM, Raman, and Xray reflectivity (XRR). RMS roughness as measured by AFM is typically 0.1-0.2 nm for films near 2nm in thickness as measured by XRR. Growth conditions are established to produce a self-limiting growth mode allowing for relatively tight control over film thickness and morphology. Growth conditions for the III-nitride template materials are typical for growth of those materials using TMAl and TMGa precursors. Films are characterized by AFM, XRD, Raman spectroscopy, and electrical conductivity. Rocking curves give typical FWHM of 0.1deg to 0.2deg and 0.2deg to 0.3 deg for the (002) and (102) reflections, respectively.

RESULTS:

Figure 1 shows a typical AFM scan for hBN films grown in this work. Surface roughness shown is R_q=0.225 nm for the 4-inch sample shown across a 5umx5um area.



Img. Z range 2.105 nm
Img. Rms (Rq) 0.225 nm
Img. Ra 0.178 nm

Figure 1. typical AFM scan on 4-inch hBN films with Rq=0.225nm. Inset shows typical surface for 2-inch wafers.

Interestingly, 2-inch samples routinely show improved AFM roughness with R_q as low as 0.15 nm as shown in the inset. The features of the scans shown are characteristic of high-quality films grown.

Figure 2 shows an x-ray reflectivity (XRR) spectrum used to determine thickness for hBN films for GaN template growth. Angular position of the sharp valley in the XRR spectrum is a result of diffraction of the beam reflected from the top and bottom surfaces of the hBN film and is used to determine thickness. The inset shows simulated thickness versus valley position from models used for the thickness estimate. XRR is measured at various locations on the wafers. The valley positions for the curves in Figure 2 indicate film thickness uniformity to within tenths of angstroms.

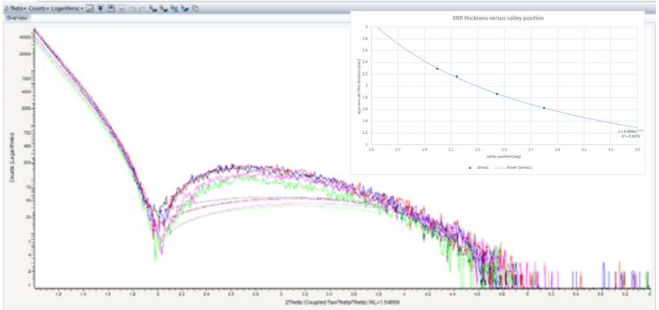
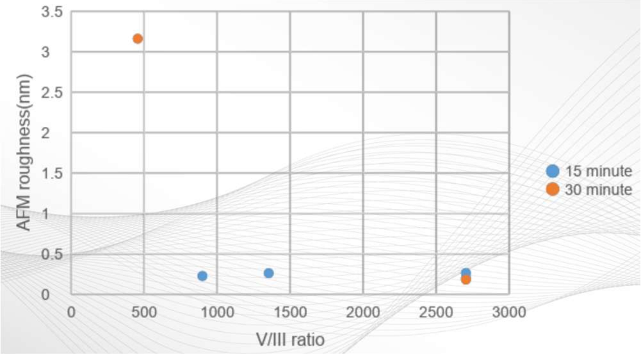
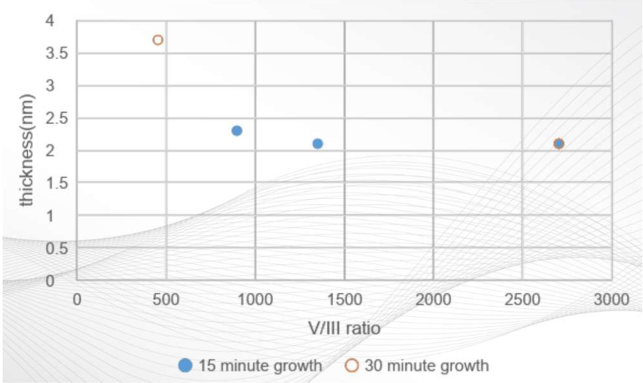


Figure 2. XRR data for a typical hBN film at various points across the wafer. Valley position is used to determine thickness.



(a)



(b)

Figure 3. Dependence of surface roughness (a) and film thickness (b) on growth parameters for hBN films

Figure 3 shows plots of surface roughness and thickness as a function of growth conditions. Film roughness and thickness are dependent on growth conditions, with ammonia and TEB flow having the most controllable effect on film quality. Surface roughness is independent of V/III ratio for high ammonia or low TEB flow while lower ratio produces rougher films on the atomic scale. The increased surface roughness is characteristic of increased nucleation with higher TEB/NH3 ratio at the wafer surface during growth. At the same time film thickness increases at reduced V/III ratio as shown in Figure 3b. With increased nucleation at low V/III ratio, layer growth can continue leading to thicker films. Higher V/III produces a self-limited growth mode such that after the initial nucleation roughness is smoothed, the film growth slows due to lack of available nucleation sites. These results are consistent with those published previously. [6] Consistently reproducible hBN film characteristics are well controlled once the process is tuned.

High quality GaN films are routinely grown on the hBN films for production of subsequent device layers and as a handle layer for film exfoliation. The GaN films are grown at conditions typical of GaN on sapphire. An AlN nucleation layer is first deposited on the hBN surface followed by GaN roughening, recovery, and a thicker, high quality buffer layer. Figure 4 shows an AFM scan and XRD spectra for typical GaN films deposited in this project.

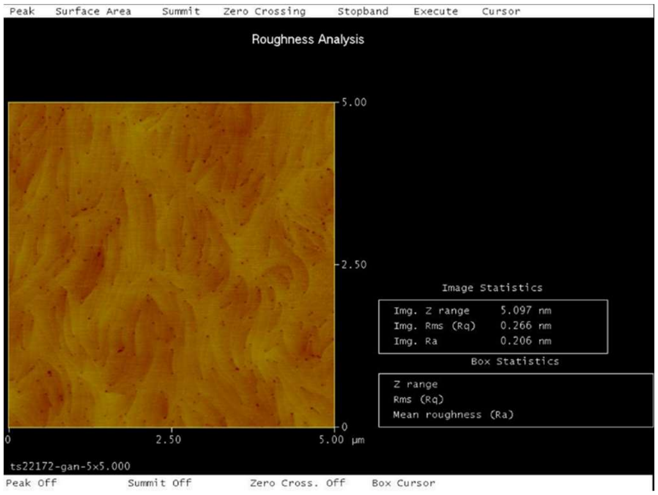


Image Statistics

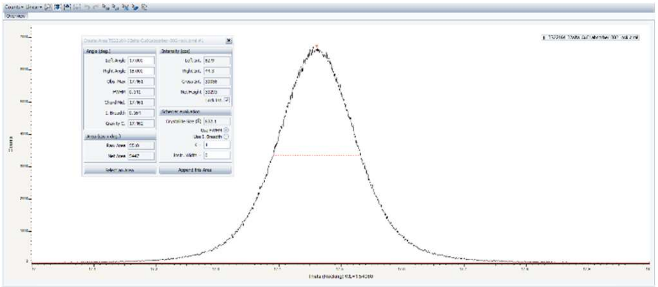
Img. Z range 5.097 nm
Img. Rms (Rq) 0.266 nm
Img. Ra 0.206 nm

Box Statistics

Z range
Rms (Rq)
Mean roughness (Ra)

ts22172-gan-5x5.000

(a)

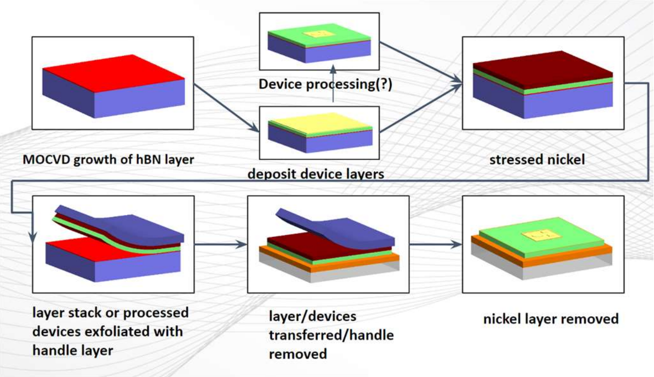


(b)

Figure 4. 5umx5um AFM scan(a) and XRD spectrum(b) for high quality GaN films grown on hBN template layers on sapphire.

Typical measured surface roughness (R_q) is in the 0.2-0.4nm range. The films grown are within the range specified for subsequent device layer applications.
XRD data is shown in figure 4b showing linewidths of FWHM ~500asec. The linewidths are consistent with material quality expectations for HEMT structures for customer applications.

Finally, film exfoliation experiments were conducted to characterize the use of hBN for film transfer to alternate substrates. Nickel stressor layers were sputter deposited at a variety of places throughout the film deposition process to perform liftoff experiments and to develop process control for production. The nickel is deposited with a slight tensile stress as a way to locally stress the GaN and help with the separation of the hBN film. The nickel layer is followed by attaching thermal release tape as a carrier layer for the exfoliated films. Experiments were performed on wafers of different diameters. Figure 5 shows a sketch of the exfoliation process and an example of a film that was lifted from a 4-inch substrate.



(a)

(b)

Figure 5. Demonstration of the process (a) and results (b) of Ni assisted exfoliation of 4-inch films

The films generally lift completely except for a small edge exclusion where the GaN/hBN films are either of lower quality or have experienced slight spontaneous peeling during post growth handling. The films can be lifted with minimal cracking. The best films to date have 3 to 4 cracks across a full 4-inch wafer. Once reattached to the new substrate, it is expected that any yield loss will be small due to the cracking. In addition, improved process development should result in full transfer of 4-inch to 6-inch films with minimal added defects during transfer.

SUMMARY:

We have demonstrated the initial stages of the technology transfer of films grown on hBN/sapphire and successful hBN assisted exfoliation of large area films for transfer to alternate substrates. The films deposited and exfoliated demonstrate quality consistent with that needed for HEMT device fabrication.

ACKNOWLEDGEMENTS:

The authors would like to thank the support of the Air Force Research Lab (AFRL) for both characterization and financial support. This work is funded by an AFRL SBIR grant: DoD SBIR D2P2 – AF221-DCS01

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ACRONYMS

hBN: hexagonal Boron Nitride
HEMT: High Electron Mobility Transistor
GaN: Gallium Nitride
XRD: X-ray Diffraction
AFM: Atomic Force Microscopy
XRR: X-ray Reflectivity
MOCVD: Metal-Organic Chemical Vapor Deposition