Roll-to-roll manufacturing of epi-GaN sheets on metal foil for LEDs and transistor devices

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Abstract

iBeam Materials has demonstrated a new technology to fabricate GaN devices directly on polycrystaline metal foil. This new technology is based on ion-beam crystal alignment to make templates for epitaxial GaN films on flexible metal foil. Thus far iBeam has demonstrated high-quality epi-GaN and GaN-based LEDs and HEMT devices on up to 4-inch scale. However, our approach will eliminate the traditional restrictions for manufacturing in wafers, allowing for scaled-up roll-to-roll processing and opening up possibilities for new classes of products in lighting, signage, displays and instrumentation. These products will be enabled by the ability to make large-area flexible sheets of GaN at low cost. In particular, sheets of LEDs produced by roll-to-roll manufacturing, will allow for large-area monolithic integration of LEDs and active transistor devices for display applications. MicroLED displays made on robust sheets of thin metal foil will enable super-bright, power-efficient, paper-thin and flexible displays.

INTRODUCTION

iBeam Materials is developing a revolutionary new technology to make large-area inexpensive sheets of GaN devices. This new technology is based on using ion-beam crystal alignment to fabricate substrates for epitaxial GaN films on flexible metal foil, that are lattice-matched, thermally very conductive and thermally matched to GaN. The ion beam assisted deposition (IBAD) technology comes from the field of high temperature superconductors (HTS), where manufacturing of epitaxial films for HTS wire is currently processed roll-to-roll on a kilometer scale. [1]

iBeam Materials have developed an IBAD texturing process for biaxially aligned films specific for GaN epitaxy. [2] Working with Sandia National Laboratories epitaxial GaN films were grown by the metal-organic chemical vapor deposition (MOCVD) process on the engineered flexible metal templates. Figure 1 below shows the schematic of the layer structure used for the template as well as our first InGaN LEDs fabricated on the metal foil. We start with a thin foil of a molybdenum alloy as the substrate. The substrate is smoothed by Chemical Solution Deposition of amorphous alumina. [3] Following that the IBAD process is used to create a single-crystal-like layer for epitaxial deposition of further layers.

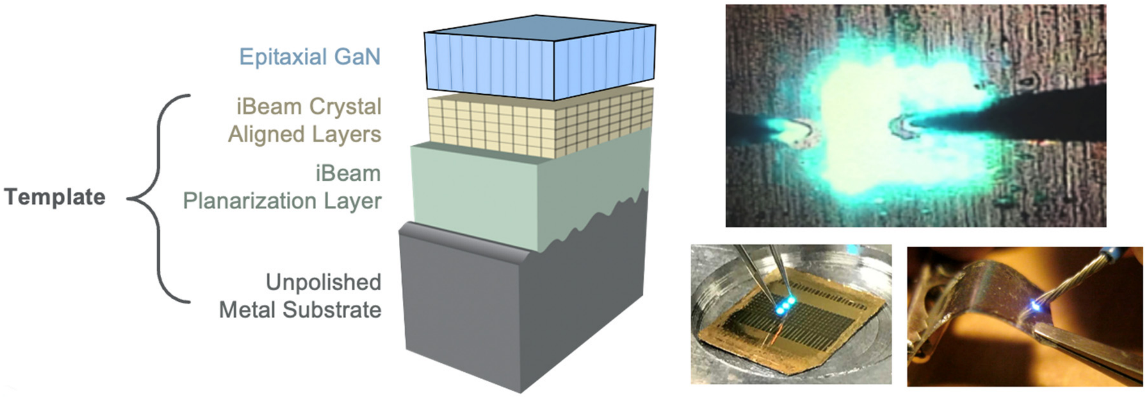

Figure 1. Schematic of the IBAD-based template layer structure used for growth of epi-GaN. On the right are pictures of GaN-based LEDs fabricated on metal foil.

EXPERIMENTAL

MOCVD was used to deposit epitaxial GaN on top of the IBAD template, see Figure 2. We have achieved GaN films of several microns in thickness on polycrystalline metal foils that have in-plane and out-of-plane alignment of less than 1° full-width half maximum FWHM and typical threading dislocation densities (TDD) of 4 – 8 x

$10^8/cm^2$, see also Figure 2. These TDD values are similar to those for GaN on sapphire.

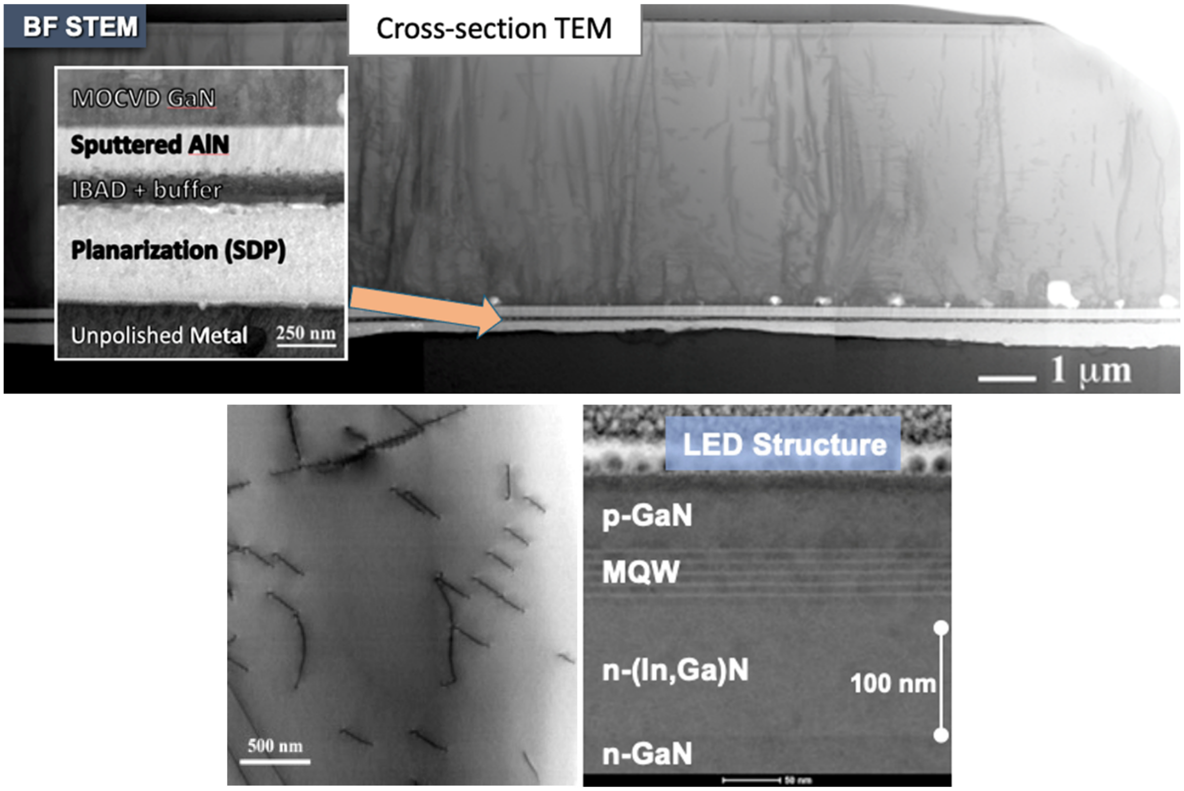

Figure 2. Transmission-electron microscope Cross section micrograph of a GaN device layer on metal, shown on top, plan-view TEM showing dislocations, bottom left, and cross-section detail with LED active layers on the right.

Epitaxial GaN films on IBAD/polycrystalline metal foil were used to deposit epitaxial multi-quantum well light emitting diode (LED) InGaN structures, see Figures 1 and 2, as well as GaN/AlGaN HEMT transistors. We have successfully fabricated LED devices and patterned microLED arrays. We observe photoluminescence intensities from the LED structures on metal foil of 70% compared to those fabricated on sapphire. These results are still early and not much was done yet to optimize light extraction. Based on the observed TDDs we expect to approach performance of LEDs on sapphire.

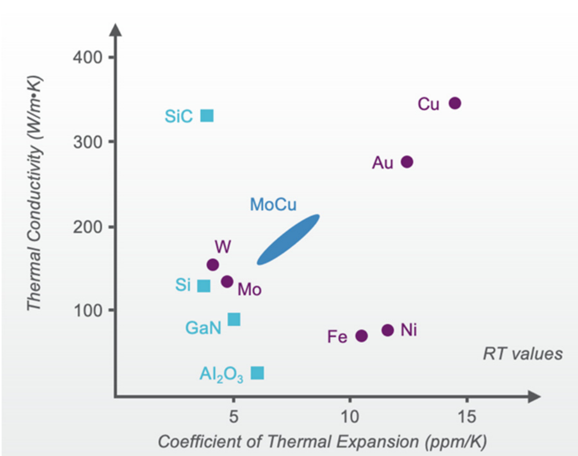

Figure 3. Thermal expansion and thermal conductivity (Room temperature values) of the various substrate materials. At 1000°C molybdenum is a 25 times better conductor than sapphire.

Discussion

The metal foil substrate offers several advantages compared to standard wafer substrates:

1) flexible and robust substrate material – *allowing for roll-to-roll* (R2R) deposition;

2) possibility of extremely large-area deposition – *scalable to 100s of meters* in deposition length, and the concomitant cost reduction;

3) thermally very well conducting, 25 times better than sapphire at deposition temperature, see Fig. 3 – yielding better LED wavelength uniformity; and

4) thermally matched to GaN – yielding less strain in the GaN material post deposition compared to sapphire substrates. The same IBAD paradigm can also be used to create large-area substrates for GaN on sheets of glass and ceramic materials, but without the flexibility and thermal advantages.

The IBAD deposition technology will enable new applications of GaN devices. One particular area of interest is in large-area monolithic integration of LEDs, as well as transistors, to make microLED displays; see Fig. 4. Instead of doing mass transfer of millions of microLEDs one could now concieve of large-area monolithic integration. This will also eliminate the traditional restrictions for the form factors of displays, redefining what devices look like based on the new types of digital information displays. These products will be further enhanced by the ability to make flexible sheets of LEDs at low cost as the technology matures. The sheets of GaN, produced by roll-to-roll manufacturing, will give an ultimate scale up to the epi GaN deposition. Based on our cost models we anticipate a 3-4x cost reduction with R2R scale up, and another 5x cost reduction by going to a hybrid HVPE/MOCVD process. Ultimately, in the long term, we believe an overall 100x cost reduction is possible.

Conclusions

We present a new paradigm for making GaN epitaxial sheets and devices. Instead of using traditional single-crystal wafer substrates for epitaxy, IBAD can enable other, esp. low-cost and large-area substrates to be used for growing GaN sheets, that will ultimately lead to new applications and with significantly lower costs for the devices.

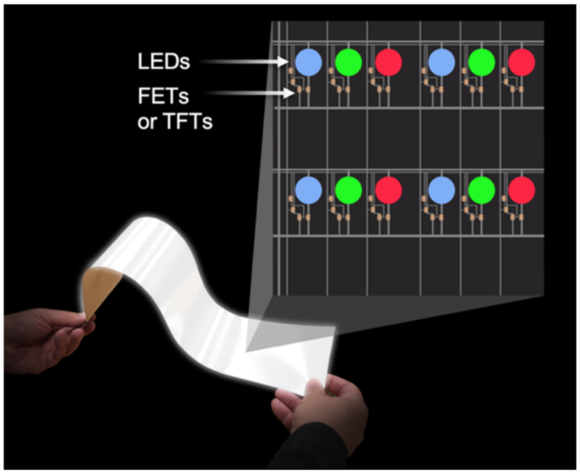

Figure 4. Schematic of monolithically integrated sheets of LEDs and transistor devices.

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Acronyms

LED: Light emitting diode; IBAD: ion beam assisted deposition; HTS: High-temperature superconductors; MOCVD: Metal-organic chemical vapor deposition; FWHM: Full-width half maxium; R2R: Roll-to-roll; HEMT: High-electron mobility transistor; TDD: Threading dislocation density.