invited Paper

Mechanically Transferred GaN-based Optical and Electronic Devices - A method for Lifting Thin-Film Devices from Substrates using Hexagonal BN -

Kazuhide Kumakura, Yasuyuki Kobayashi[a], Masanobu Hiroki, Toshiki Makimoto[b], Tetsuya Akasaka, and Hideki Yamamoto

NTT Basic Research Laboratories, NTT Corporation, Atsugi-shi, Kanagawa 243-0198, Japan, E-mail: kumakura.kazuhide@lab.ntt.co.jp,

GaN-based optical and electrical devices are attracted much attention in fields of solid state lighting, high-power and high-temperature electronics. If the thin-film devices can be easily set apart from their host substrates and transferred onto any other substrates, without any laser beam machining or chemical processing, they may have a wider field of application. Recently, we proposed the use of a hexagonal BN (h-BN) grown directly on a sapphire substrate as a release layer [1]. We have also demonstrated transfer of the GaN-based devices from the sapphire substrates to foreign materials, *e.g.*, metals or flexible sheets [1-3]. In this study, we fabricated light-emitting diodes (LEDs) and high electron mobility transistors (HEMTs) on the BN/sapphire substrates, and investigated their properties before and after the transfer to foreign materials.

We grew a single crystal h-BN layer (3 nm) on a c-plane sapphire substrate by metalorganic chemical vapor deposition. Source gases were triethylboron and ammonia. The orientation relationship between the substrate and the h-BN is $(0001)_{h\text{-}BN} \parallel (0001)_{sapphire}$, where the plane of boron and nitrogen bonded with sp^2 hybridization is parallel to the substrate surface. On the h-BN/sapphire substrate, we grew an InGaN/GaN LED structure, consisting of a 0.3-μm-thick Si-doped $Al_{0.1}Ga_{0.9}N$ layer, a 3-μm-thick Si-doped GaN layer, a 10-period InGaN/GaN multiquantum-well (MQW) structure, and a 0.1-μm-thick Mg-doped GaN layer. One period of the MQW structure consists of an 8.6-nm-thick GaN barrier layer and a 1.8-nm-thick $In_{0.15}Ga_{0.85}N$ well layer. We also grew a HEMT structure, consisting of a 0.3-μm-thick AlN layer, a 1.5-μm-thick GaN layer, and a 20-nm-thick $Al_{0.36}Ga_{0.64}N$ barrier layer.

After fabricating the LEDs by conventional photolithography, dry etching, and lift-off techniques, we mechanically released the LEDs from the substrate and formed an Al/Au electrode on the backside of them by e-beam evaporation. We subsequently put the LEDs on a foreign substrate via an adhesive sheet (an indium sheet). Finally, we heated whole the structure to a temperature (~ 170°C) sufficient to heat-seal the indium to the LEDs. Figure 1 shows the schematic illustration of the transferred LED. Figure 2 shows the photograph of blue-light electroluminescence from the transferred vertical-type LED. We confirmed that no degradation occurred during and after the transfer process. In a similar way, we also transferred an LED to a piece of Scotch tape, which was sealed by the other tape (Fig. 3). This very thin (< 0.1 mm) LED also emits blue-light under a forward bias condition.

We applied the same approach to a transfer of the HEMTs. After released from the substrate, an In metal was electroplated on the backside of the HEMTs, followed by a thermal fusion bonding to a copper plate (Fig. 4). We measured dc characteristics of the HEMTs before the release from the sapphire substrates and after the transfer to the copper plates. The transconductance was 80 mS/mm, and good pinch-off characteristics (Fig. 5) were obtained even for the transferred HEMT. No degradation due to the release and transfer process was observed in the I_D-V_{DS} and transfer characteristics.

Our newly developed method of mechanical release and transfer will open up avenues of fabricating novel devices, *e.g.*, thin flexible LEDs as well as improving the performance of high-power GaN-based transistors, which has been limited by self-heating effect.

[a] *present address: Hirosaki University, Japan*
[b] *present address: Waseda University, Japan*

References

[1] Y. Kobayashi, K. Kumakura, T. Akasaka, and T. Makimoto, "Layered boron nitride as a release layer for mechanical transfer of GaN-based devices," *Nature*, vol. 484, pp. 223-227, April 2012.

[2] T. Makimoto, K. Kumakura, Y. Kobayashi, T. Akasaka, and H. Yamamoto, "A vertical InGaN/GaN light-emitting diode fabricated on a flexible substrate by a mechanical transfer method using BN," *Appl. Phys. Exp.*, vol. 5, p. 072102, June 2012.

[3] M. Hiroki, K. Kumakura, Y. Kobayashi, T. Akasaka, H. Yamamoto, and T. Makimoto, "AlGaN/GaN HEMTs transferred from sapphire substrates to copper plates using layered BN as a release layer," *10th Int. Conf. on Nitride Semiconductors*, D3.01, Washington, D. C., August 2013.

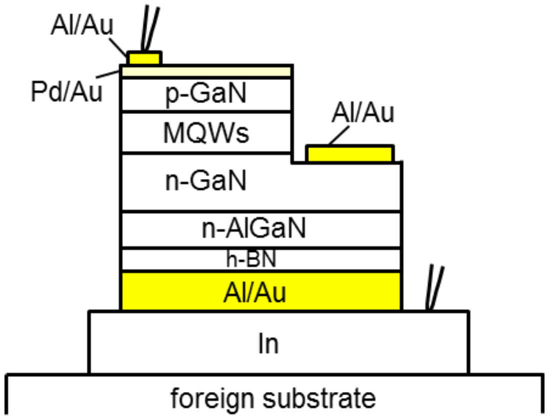

Figure 1. Schematic illustration of the transferred LED.

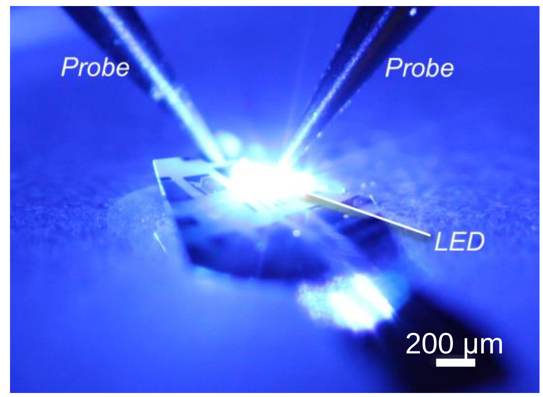

Figure 2. Photograph of blue-light electro-luminescence from the transferred vertical-type LED.

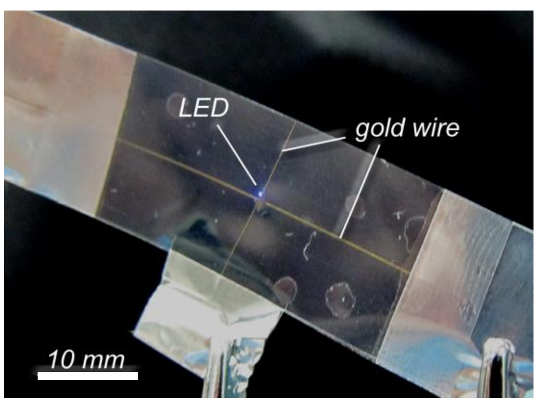

Figure 3. Photograph of the thin (< 0.1 mm) LED sandwiched by the commercially available adhesive tape.

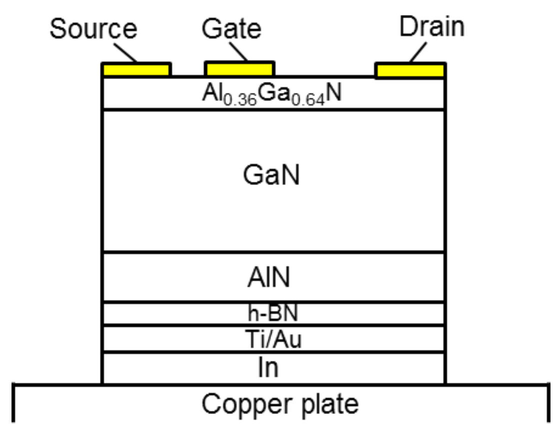

Figure 4. Schematic illustration of the transferred HEMT.

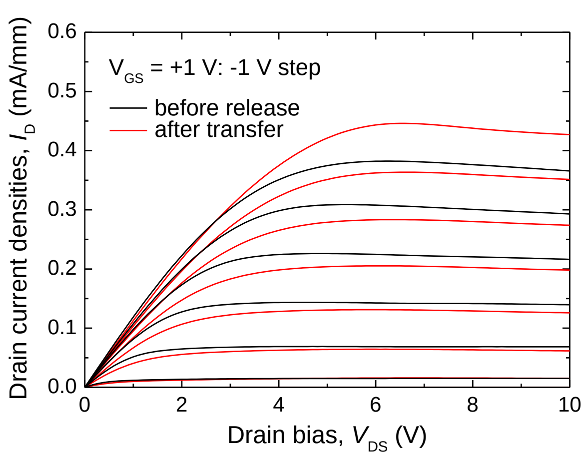

Figure 5. I_D-V_{DS} characteristics of the HEMT before release (black solid lines) and after transfer to the copper plate (red solid lines).