Substrate-transfer Technique Using h-BN for GaN-based High-power Transistors

Masanobu Hiroki, Kazuhide Kumakura, and Hideki Yamamoto

Abstract

We transferred AlGaN/GaN (aluminum gallium nitride/gallium nitride) high electron mobility transistors from a sapphire substrate to a material with high thermal conductivity using a substrate-transfer technique that involves the use of an h-BN (hexagonal boron nitride) release layer. We succeeded in suppressing the self-heating effect and obtained good power performance in direct current characteristics. The transfer technique can overcome thermal problems in power transistors.

Keywords: GaN, high-power transistors, epitaxial lift-off

1. Introduction

Gallium nitride (GaN) and its alloys are attractive materials for short-wavelength light-emitting devices and for high-power electronic devices due to their wide energy gap. Blue light-emitting diodes, blue-violet laser diodes, and high electron mobility transistors (HEMTs) have been widely used for room illumination, Blu-ray Disc* players, radio frequency amplifiers in Long Term Evolution mobile base stations, and in other applications. Other III-nitride semiconductor materials such as indium nitride (InN), aluminum nitride (AlN), boron nitride (BN), and their alloys are also attractive for new applications of III-nitride semiconductors. Indium nitride has a narrow bandgap (0.7 eV) and has been reported to have an electron mobility as high as 4400 cm^2/Vs [1]. Thus, InN and its alloys are attractive for infrared light-emitting devices and high-speed electronic devices. Aluminum nitride and BN have an extremely wide bandgap of around 6 eV, which enables the fabrication of ultraviolet-light-emitting devices and high-power transistors. We recently succeeded in growing high-quality single-crystal hexagonal boron nitride (h-BN) and found that it can be used as a release layer for nitride semiconductors [2, 3].

Epitaxial lift-off (ELO) and substrate-transfer techniques enable new ways to use semiconductor devices. These techniques have been used to fabricate a flexible GaAs (gallium arsenide)-based solar cell [4]. In addition, they help to reduce fabrication costs because we can reuse substrates. With III-nitride semiconductors, however, ELO from substrates is difficult because of their strong atomic bonding with the substrate as well as the lack of a suitable etchant for selective etching. We recently proposed using an h-BN release layer for ELO of III-nitride layers [3]. One of the benefits of the ELO and substrate-transfer techniques is the enhanced heat dissipation in GaN-based electrical devices. For HEMT on sapphire, the temperature rises significantly in operation with high current levels since a sapphire substrate widely used for the growth of GaN has low thermal conductivity (κ) of 40 W/m K. This self-heating degrades device performance and reliability. By transferring the devices to a material with high thermal conductivity, we can suppress the temperature rise in the active region of devices. This article describes the enhancement of

* Blu-ray Disc is a trademark of the Blu-ray Disc Association.

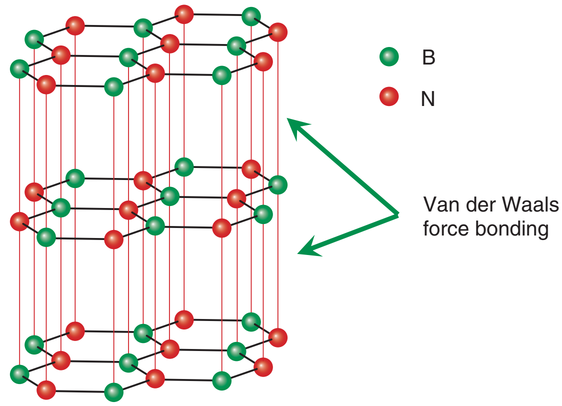


Fig. 1. Crystal structure of h-BN.

heat dissipation for aluminum gallium nitride/gallium nitride (AlGaN/GaN) HEMTs transferred to a copper plate with a thermal conductivity of 390 W/m K [5, 6].

2. Transfer technique for AlGaN/GaN HEMTs using h-BN ELO

First, we present our ELO technique based on the h-BN release layer. The crystal structure of h-BN is shown in **Fig. 1**. The h-BN crystal has a layered structure like graphite, and each layer is weakly bonded by van der Waals forces. Thus, the layers can be easily exfoliated. Moreover, single-crystal GaN layers can be grown on an AlN or AlGaN nucleation layer (NL) deposited on h-BN. Thus, the GaN layers can be released from sapphire substrates by mechanical forces.

The transfer process for AlGaN/GaN HEMT is illustrated in **Fig. 2**. First, the h-BN layer is grown on a C-plane sapphire substrate by metal organic vapor phase epitaxy (MOVPE). Next, a 100-nm-thick AlN NL is grown on the h-BN layer. Subsequently, an AlGaN/GaN heterostructure is grown by MOVPE at a temperature of 1000°C at a pressure of 300 Torr. These are the same as the conventional conditions for the direct growth on sapphire substrate. The heterostructure consists of a 3-μm-thick GaN buffer layer and 27-nm-thick AlGaN barrier layer. Two-dimensional electron gas (2DEG) with a 1×10^{13} cm^{-2} density is induced by a polarization charge at the AlGaN/GaN heterointerfaces, which forms a conductive path from the source to the drain.

AlGaN/GaN HEMTs were fabricated using conventional photolithography and lift-off techniques. The AlGaN barrier outside the active region was etched away by inductively coupled plasma etching to remove the 2DEG conductive channel for electrical isolation between devices (mesa isolation). We used electron-beam evaporation for metal deposition and rapid thermal annealing to form the ohmic contacts. The source/drain ohmic electrodes consisted of titanium (Ti; 15 nm)/ aluminum (Al; 80 nm)/ nickel (Ni; 30 nm)/gold (Au; 50 nm) annealed at 850°C for 30 s. The Schottky gate electrode was Ni (50 nm)/Au (100 nm). The gate length, source-drain spacing, and gate width were 1.5, 6, and 100 μm, respectively.

The next step in the process is to release AlGaN/GaN HEMTs from the sapphire substrate and transfer them to a copper plate. For that purpose, we first coated the sample surface with PMMA (polymethyl methacrylate) and adhered the sample to a glass plate. Then we mechanically released it from the sapphire substrate. For transfer to a copper plate, we used Au-Au thermocompression bonding [7]. We deposited Ti/Au on the back side surface of the HEMT, and we deposited Au on the copper plate. The two Au surfaces were brought into contact with each other, and then a pressure of approximately 20 MPa was applied at about 200°C. The cross-sectional transmission electron microscopy (TEM) image of the transferred HEMT is shown in **Fig. 3**. The TEM image reveals that the GaN layer strongly adhered to the copper layer at the Au-Au thermocompression interface.

3. Enhancement of heat dissipation of AlGaN/GaN HEMTs using substrate-transfer technique

Typical drain current (I_d)–drain bias (V_{ds})

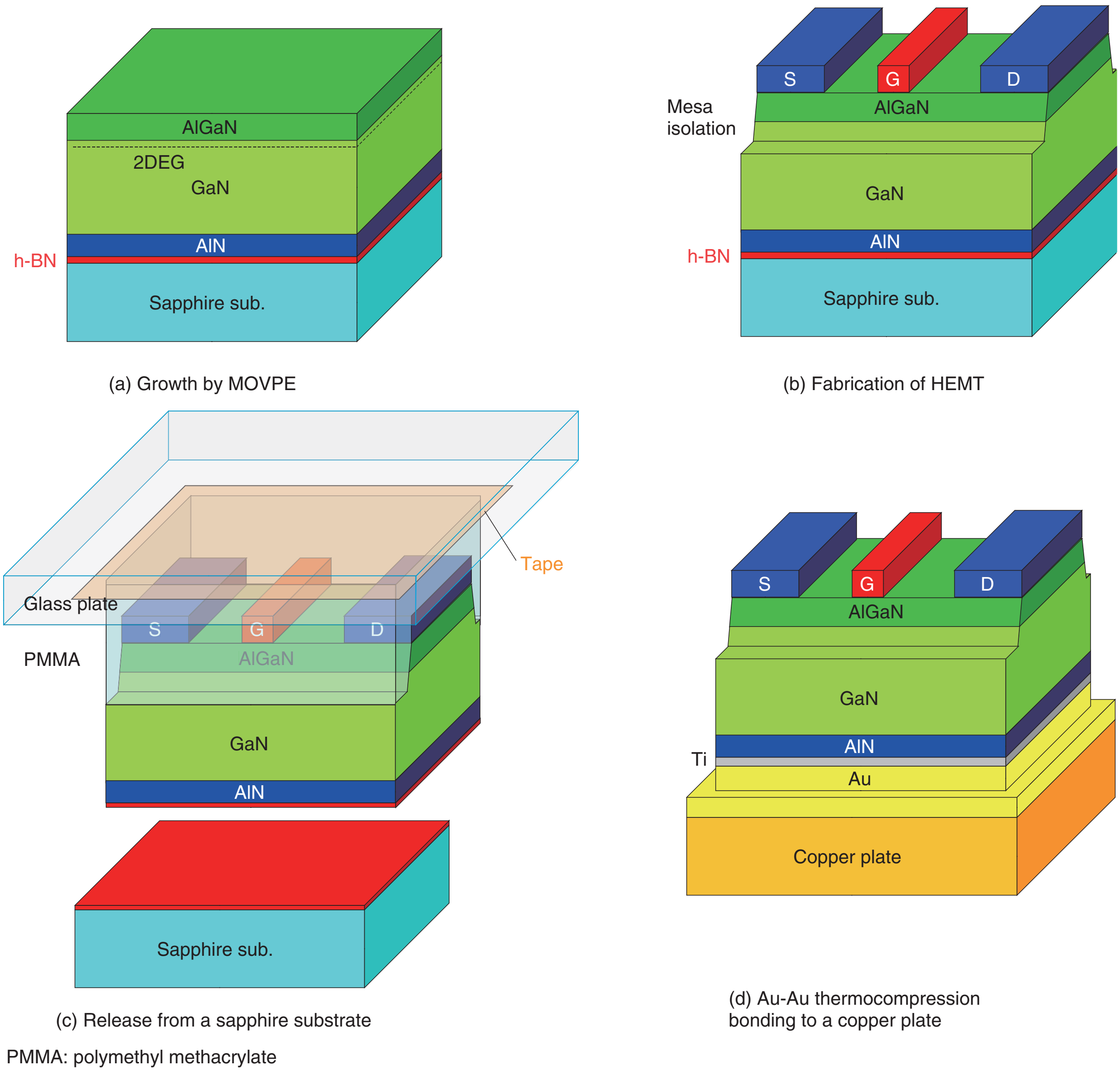
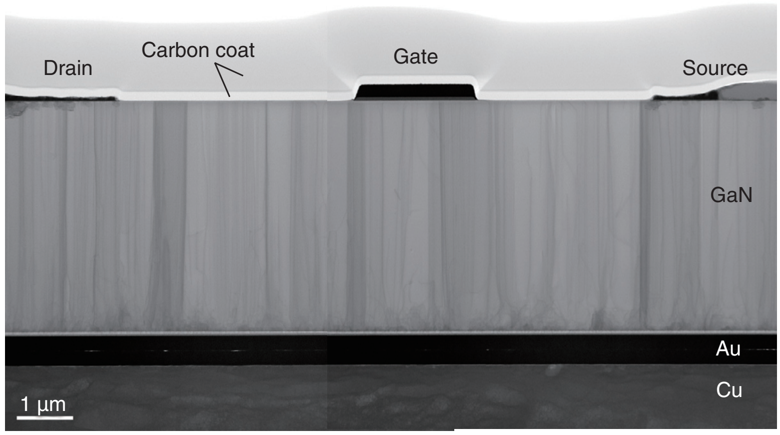


Fig. 2. Schematic views of h-BN ELO and transfer processes of AlGaN/GaN HEMT. (a) Growth of AlGaN/GaN heterostructures on AlN NL deposited on h-N/sapphire. (b) Fabrication of AlGaN/GaN HEMTs by conventional photolithography and lift-off technique. The labels S, G, and D indicate source, gate, and drain electrodes, respectively. (c) Mechanical ELO of the HEMTs from sapphire substrate. (d) Transfer of the HEMTs to a copper plate by Au-Au thermocompression bonding.

characteristics of the AlGaN/GaN HEMT before release from the substrate and after transfer to the copper plate are shown in **Fig. 4**. Good pinch-off and saturation characteristics were obtained even after the transfer, indicating that no degradation took place in the transfer process. The device performance significantly improved after transfer. The maximum I_d at a gate bias (V_{gs}) of 1 V significantly increased from 0.55 A/mm to 0.68 A/mm. Before release, a large reduction in I_d vs V_{ds} was observed in the saturation region at a large positive gate bias (V_{gs}). At V_{gs} = 1 V, the I_d decreased by 25% as the V_{ds} increased from 5 V to 20 V. In contrast, the decrement in I_d vs V_{ds} was as small as 3% for the transferred HEMT. The negative slope is commonly attributed to self-heating in the device operation [8]. The transfer from the sapphire to the copper plate improves the heat dissipation efficiency and thereby suppresses the decrease in



Cu: copper

Fig. 3. Cross-sectional TEM image of an AlGaN/GaN HEMT transferred to a copper plate by Au-Au thermocompression bonding. White and grey layers on the sample surface consist of carbon, which was coated for surface protection in TEM measurements. The difference in the colors is caused by the purity of carbon.

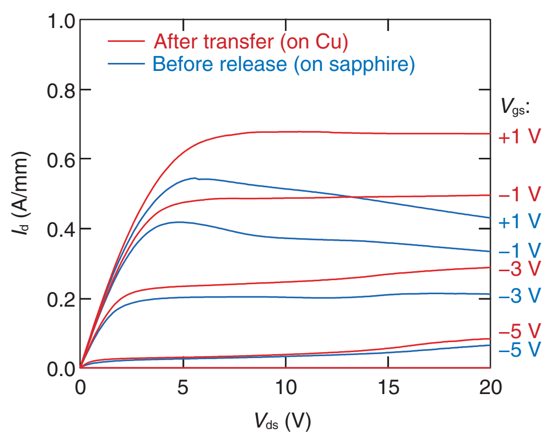


Fig. 4. I_d–V_{ds} characteristics of AlGaN/GaN HEMT before release and after transfer.

drain current under high-bias operation.

We also estimated the temperatures in the active region of HEMTs using micro-Raman spectroscopy. The temperatures of the devices can be estimated from the peak shift in the A_1 phonon mode [9, 10]. The temperature maps of an HEMT on a sapphire substrate and another HEMT transferred to copper are shown in **Fig. 5**. The highest temperature was observed at the center of the channel at the gate edge on the drain side. For the HEMT on sapphire (before its release), the temperature exceeded 200°C at a power dissipation (P) level of 0.68 W. In contrast, for the transferred HEMT, the temperature was only 110°C at P = 1.54 W. The channel temperature as a function of P in the HEMTs is plotted in **Fig. 6** before their release and after their transfer. The channel temperature is the average one in the center region of the channel at the gate edge on the drain side where the highest temperature was observed. A linear approximation revealed that the thermal resistances of the HEMTs before their release and after their transfer were 28 and 6.5°C mm/W, respectively, indicating a one-fourth reduction. The transfer to copper significantly improved the heat dissipation in the HEMTs.

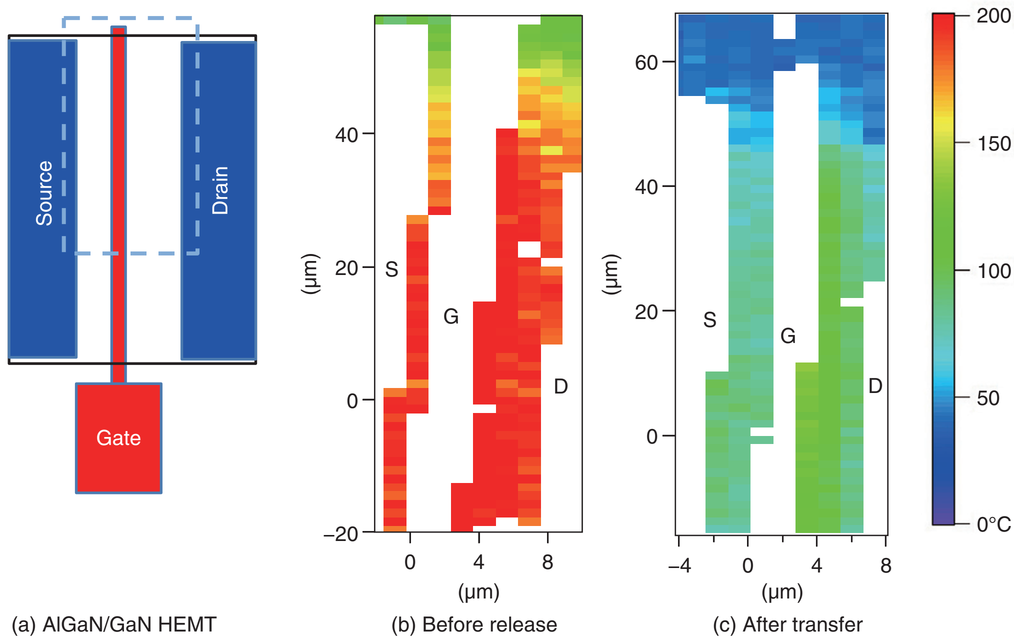


Fig. 5. (a) Schematic view of AlGaN/GaN HEMT. The dotted rectangle corresponds to the measurement area by micro-Raman spectroscopy. Temperature maps of (b) an HEMT on sapphire (before release) at a power dissipation of 0.68 W and (c) another HEMT transferred to a Cu plate at a power dissipation of 1.54 W. The white regions in each map represent the source, gate, and drain electrodes from left to right.

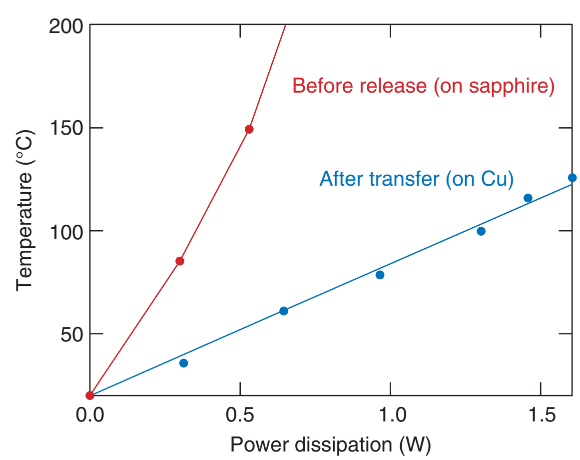


Fig. 6. Temperature at the gate edge on drain side as a function of power dissipation in HEMTs before release and after transfer.

4. Conclusion

We transferred AlGaN/GaN HEMTs from a sapphire substrate to a copper plate using the ELO technique with an h-BN release layer. The negative slope of I_d caused by the self-heating effect was reduced after the transfer. We also observed the temperatures in the active HEMTs using micro-Raman spectroscopy and found that the temperature rise was suppressed after the transfer to the copper plate. The temperature at $P = 1.54$ W was 110°C for the HEMT after transfer, whereas it exceeded 200°C at $P = 0.68$

W before the release. These results indicate that the transfer technique is effective for enhancing the heat dissipation in GaN-based devices.

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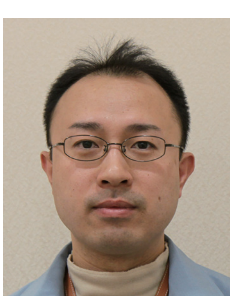

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