Heterogeneous Integration of Gallium Nitride HEMTs with Single Crystal Diamond Substrates via Micro-transfer Printing for Thermal Management

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ABSTRACT

Gallium nitride high electron mobility transistors (HEMTs) were micro-transfer printed onto Si, SiC, and diamond substrates using an X-Celeprint tool. A NbN sacrificial layer was used to release the as-fabricated devices from the growth substrate. The stress state of the GaN films on the growth substrate and after micro-transfer printing was characterized using Raman spectroscopy. The GaN films of the transfer printed HEMTs exhibited reduced tensile stress with respect to the as-grown GaN film. Subsequently, the device thermal performance of the transferred HEMTs was assessed using thermoreflectance thermal imaging. The temperature rise of the gate electrode as a function of power density was quantified to determine the device-level thermal resistance of the transferred HEMTs. The transfer-printed GaN HEMTs on the Si, SiC, and diamond substrates were measured to have thermal resistances of 10.6, 6.7, and 4.0 mm·K/W, respectively. Compared to the GaN-on-Si HEMT, the GaN-on-diamond HEMT demonstrated a 62% reduction in thermal resistance.

INTRODUCTION

Gallium nitride (GaN)-based devices have been researched for over two decades due to (i) the wide bandgap of GaN (3.4 eV) which allows for higher voltage, higher power, and higher temperature operation and (ii) the ability to form a high mobility (>2000 $cm^2V^{-1}s^{-1}$) 2DEG channel using $Al_xGa_{1-x}N$/GaN heterostructures. While GaN-based devices have been commercialized, thermal management has been an area of much attention over the last decade and continues to be so in order to optimize device performance and improve device reliability and lifetime. Recently, micro-transfer printing has been demonstrated as an effective method for heterogeneous integration of GaN-based devices with high thermal conductivity substrates which has the potential to reduce device-level thermal resistance without sacrificing electrical performance [1].

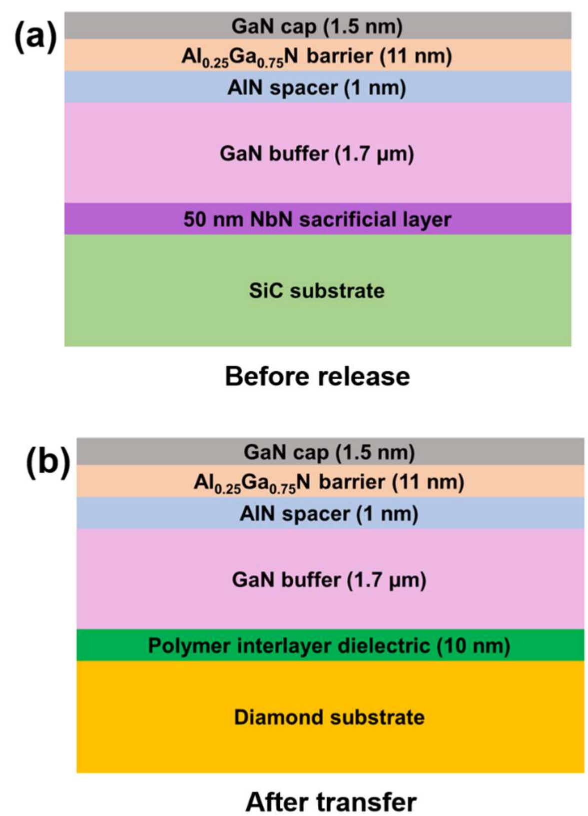

Fig. 1. Cross-sectional schematic of the material stack (a) before release and (b) after transfer. In (b) only the diamond substrate is shown, however, devices were also transferred onto Si and SiC substrates.

EXPERIMENTAL

Gallium nitride high electron mobility transistors (HEMTs) were first fabricated on a SiC substrate in preparation for micro-transfer printing onto Si, SiC, and single crystal diamond substrates (Fig. 1a). First, a NbN sacrificial layer was grown on the SiC substrate via molecular beam epitaxy (MBE) followed by metal-organic chemical vapor deposition (MOCVD) growth of a 1.7 µm thick GaN buffer layer. Subsequently, a 1 nm thick AlN spacer, 11 nm thick $Al_{0.25}Ga_{0.75}N$ barrier layer, and 1.5 nm thick GaN cap were grown via MOCVD to form the two-dimensional electron gas (2DEG) channel at the top of the 1.7 µm thick GaN layer. Following HEMT fabrication, a Cl_2 etch was used to isolate device structures and expose the NbN sacrificial layer. XeF_2 etching was then used to remove the sacrificial layer, and micro-transfer printing from the SiC substrate onto the Si, SiC, and diamond substrates was performed using an X-Celeprint tool (Fig. 1b). Before micro-transfer printing, a 10 nm polymer interlayer dielectric (ILD) was spun on the surface of the diamond substrate as an adhesion layer. Electrical characterization was performed using a Keithley 4200SCS semiconductor parameter analyzer. The stress state of the HEMTs on the growth substrate (NbN sacrificial layer on SiC substrate) and after transfer-printing was assessed using a Thermo Scientific DXR3xi Raman spectrometer with 532 nm excitation and a 100X objective. A laser power of 1 mW was used to prevent laser heating of the Si substrate. Thermal performance was assessed using a TMX Scientific T°Imager thermoreflectance thermal imaging system with a 530 nm LED and a 100X objective. The base temperature of the samples was maintained at 20 °C during thermal measurements.

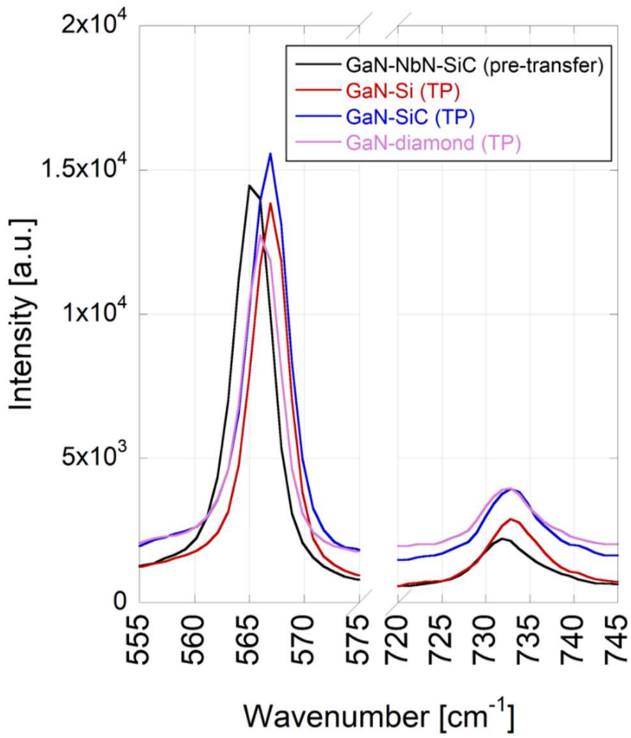

Fig. 2. Raman spectra of the E_2 (high) (left) and A_1 (LO) (right) modes of the reference GaN HEMT on the NbN-SiC substrate (before transfer) and the GaN HEMTs transfer printed (TP) onto Si, SiC, and diamond substrates.

Results and Discussion

First, Raman spectroscopy was performed to measure the change in stress state due to release of the HEMT structures from the NbN interlayer/SiC growth substrate and subsequent transfer to the Si, SiC, and diamond substrates. Since the peak position of the characteristic Raman peaks shift with film stress, they can be used to assess relative changes in the stress states of the films. For Raman measurements of GaN, the E_2 (high) and A_1 (LO) phonons modes have prominent peaks in the Raman spectra around 568 cm^{-1} and 735 cm^{-1}, respectively. As shown in Fig. 2, all transfer-printed GaN films showed an increase in the Raman peak position of both the E_2 (high) and A_1 (LO) modes with respect to the reference as-grown GaN film on the NbN sacrificial layer/SiC growth substrate. The increase in the Raman peak position of the transfer printed GaN films demonstrates reduced tensile stress with respect to the reference film. Furthermore, Choi et al. reported the stress-free peak position of the E_2 (high) mode of GaN to be 568.15 ± 0.13 cm^{-1} [2], indicating that the stress state of the transfer printed GaN films shifted towards a stress-free state.

Fig. 3 shows DC output and transfer characteristics of the micro-transfer printed GaN-on-diamond HEMT. The device exhibited an ON/OFF ratio of $>10^3$, and at V_{GS}=2V, $I_{DS,max}$ was 345 mA/mm. At V_{GS}=2V and V_{DS}=10V, the device was operating with a power density of ~3.5 W/mm. Typically, power densities of this magnitude result in self-heating that is significant enough that it results in a reduction of the saturation drain current [3]; however, the GaN-on-diamond HEMT maintained a constant I_{DS}. As such, the effectiveness of the heterogeneous integration with the diamond substrate on the device electrothermal performance can already be observed. Subsequently, thermal imaging of the transferred HEMTs was performed using thermoreflectance thermal imaging. Fig. 3c shows a representative 2D thermal map of the GaN-on-diamond HEMT operating at a power density of 10.2 W/mm (V_{GS}=2V, V_{DS}=30V) with a peak temperature rise on the gate electrode of 44 K.

To compare the thermal performance of the GaN HEMTs transferred to Si, SiC, and diamond substrates, the peak temperature rise on the gate electrode as a function of power density (V_{GS}=2V) was measured. The peak temperature rises of the transferred HEMTs are shown in Fig. 4. The device-level thermal resistance of the HEMTs can then be extracted from the slope of the linear fits in Fig. 4. For the GaN HEMTs transferred onto Si, SiC, and diamond substrates, the device-level thermal resistances were found to be 10.6, 6.7, 4.0 mm·K/W, respectively. As expected, the device-level thermal resistance decreased as the thermal conductivity of the substrates increased from Si (lowest thermal conductivity) to diamond (highest thermal conductivity). With respect to the HEMTs transferred to Si and SiC substrates, a 62% and 40% reduction in device-level thermal resistance was observed as compared to the GaN HEMT transferred onto the diamond substrate.

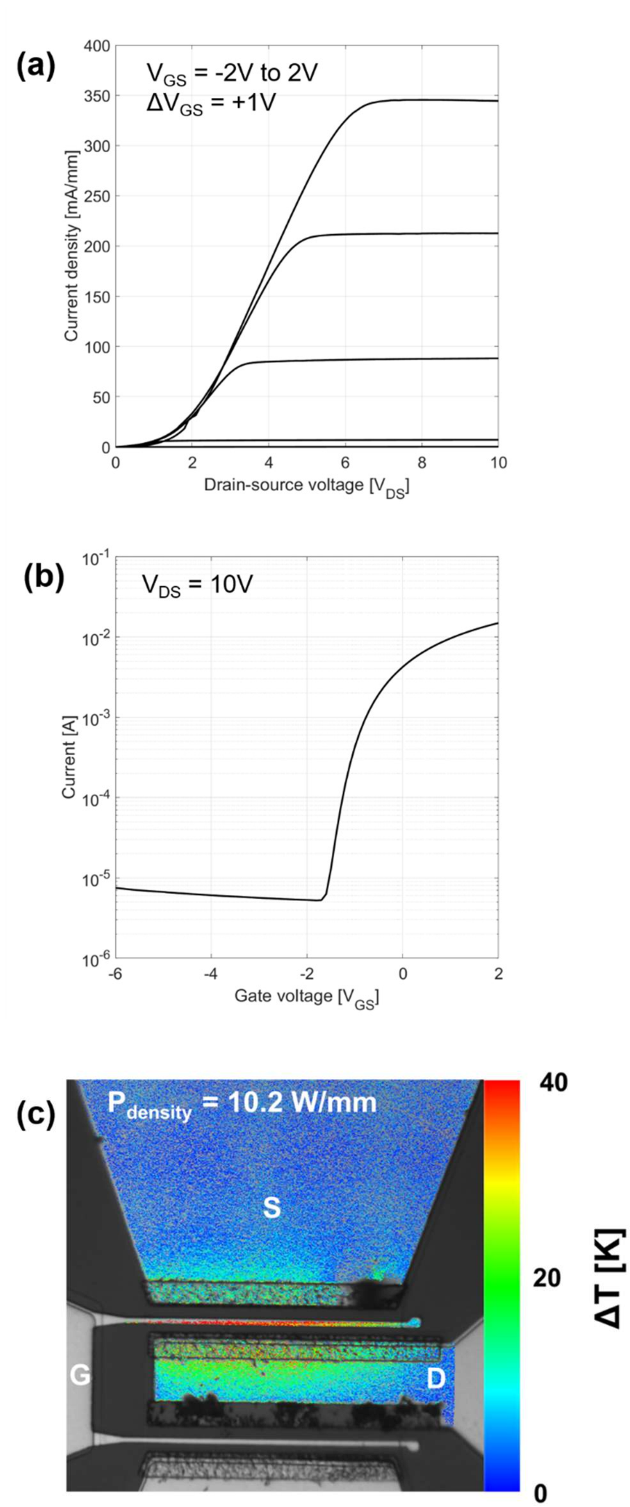

Fig. 3. (a) DC output and (b) DC transfer characteristics of the GaN HEMT micro-transfer printed on the diamond substrate. (c) 2D thermal map of the GaN HEMT micro-transfer printed on the diamond substrate operating at a power density of 10.2 W/mm (V_{GS} = 2V, V_{DS} = 30V).

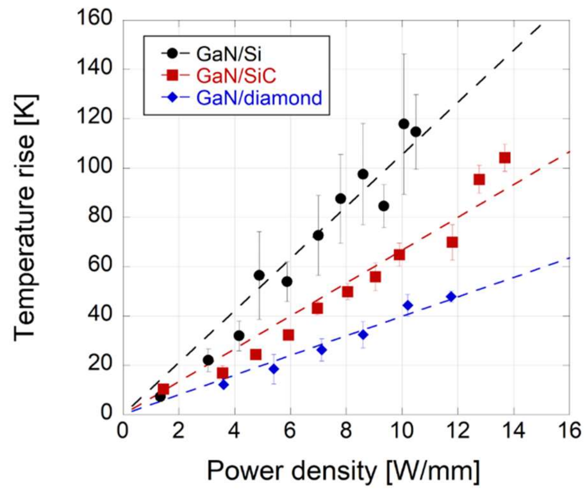

Fig. 4. Temperature rise on the gate electrode as a function of power density (V_{GS} = 2V) for the GaN HEMTs micro-transfer printed onto Si, SiC, and diamond substrates.

Conclusions

In conclusion, HEMT structures were fabricated on GaN films grown on NbN sacrificial layers on SiC substrates via MOCVD. The HEMTs were then micro-transfer printed onto Si, SiC, and diamond substrates using an X-Celeprint tool. The stress state of the GaN films was qualitatively assessed using Raman spectroscopy. It was observed that following micro-transfer printing of the HEMTs, the stress state of the GaN films became less tensile and relaxed towards a stress-free state with respect to the as-grown GaN film. Subsequently, the thermal performance of the transferred HEMTs was assessed. The peak temperature rise of the gate electrode was measured as a function of power density (V_{GS} = 2V) to quantify the device-level thermal resistance and found to be 10.6, 6.7, and 4.0 mm·K/W for the GaN HEMTs transferred onto Si, SiC, and diamond substrates, respectively. Accordingly, a 62% and 40% reduction in thermal resistance was realized for GaN HEMTs transferred to diamond as compared to Si and SiC substrates, respectively. This work also has significance for devices based on ultra-wide bandgap semiconductors with low thermal conductivity, such as Ga_2O_3. Since thermal obstacles severely limit device performance for these technologies, micro-transfer printing of devices onto high thermal conductivity diamond substrates is very relevant for future work.

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