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High-Power GaN-on-Diamond HEMTs Fabricated by Surface-Activated Room-Temperature Bonding

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Abstract

GaN-on-Diamond high electron mobility transistors (GoD HEMTs) were fabricated by surface-activated room-temperature bonding. A film with GaN-HEMTs removed from a Si substrate was bonded to a crystalline diamond substrate. A cross-sectional transmission electron microscope (TEM) image showed that the interface was well-bonded without any voids. Measured drain current (I_d) -drain voltage (V_d) curves indicated GaN-HEMTs were successfully transferred on a diamond substrate and HEMT performance was improved due to effective heat dissipation via diamond with high thermal conductivity.

1. Introduction

GaN-based high electron mobility transistors (GaN HEMTs) are widely used for high-frequency and high-power applications thanks to superior material properties of GaN. In these applications, local heating in a channel region could cause deterioration of transistor-characteristics.

Using diamond as a substrate for GaN HEMTs (GaN-on-Diamond (GoD) HEMTs) is a promising solution to overcome this problem, since diamond has the highest thermal conductivity among natural materials.

Several attempts to fabricate GoD HEMTs have been reported so far [1-3]. In these reports, wafer-first process, which means HEMTs are fabricated after a GoD wafer is prepared, was employed. In the wafer-first process, a large GoD wafer bow prevents HEMTs fabrications. Meanwhile, device-first process, which means only GaN HEMTs layers are transferred from an original substrate to a diamond substrate, is much attractive since GaN HEMTs can be fabricated with well-established processes and structures.

In this presentation, large high-power GoD HEMTs consisting of multi-cells are reported. Surface-activated room-temperature bonding technology was employed to realize GoD HEMTs with device-first process.

2. Experimental

GaN HEMTs were prepared by conventional fabrication process on hetero-epitaxial AlGaN/GaN layers grown on a Si (111) substrate. A supporting wafer was temporarily attached on the GaN HEMTs with a Si substrate using resin-based adhesive. The Si substrate was completely removed using mechanical grinding and dry-etching process. The substrate-removed surface (i.e. the back-side of GaN HEMTs layers) was polished by chemical mechanical polishing (CMP) to make a flat and smooth surface.

A chemical-vapor-deposited crystalline diamond (CVD diamond) substrate with a size of 10 x 10 mm^2 was prepared. One surface was mechanically polished to be suitable for following bonding process.

The back-side-polished GaN-HEMTs layers attached on a supporting wafer was bonded to the mechanically-polished diamond wafer using surface-activated room-temperature bonding method [4]. In the bonding process, Si-based interface layer with few-nm-thickness was inserted to obtain sufficient bonding-strength. Finally, the temporarily-attached supporting wafer was removed from the surface of GaN-HEMTs.

A structure of bonded interface was observed using transmittance electron microscopy (TEM). Drain current (I_d) - drain voltage (V_d) curves of completed GoD HEMTs were measured using source measure unit (Keysight technology B1505A). Conventional GaN HEMTs having the same hetero-epitaxial layers on a Si (111) wafer (GoSi HEMTs) were also evaluated as a reference.

3. Results and discussions

Fig. 1(a) and (b) show photographs of a GoD HEMT, which is a part of a fabricated GoD HEMTs, in this study. Each picture corresponds to (a) a front-surface view and (b) a back-surface view of the fabricated device. As shown in the figures, a large GoD HEMT consisting of multi-cells (4 cells) was successfully transferred on a crystalline diamond substrate. Each cell in the GoD HEMT has multiple gate-fingers

(8 fingers in a unit-cell). Total gate-width of this device is 5.76 mm, which suggests that high-power operation can be expected.

Fig. 2(a) and (b) show cross-sectional TEM images of a fabricated GoD HEMT. The image taken with a wide range shown as Fig. 2(a) revealed that no voids were included near bonding interface. This result indicated that GaN HEMTs layers and a diamond substrate were well-bonded with smoothly polished surface. The image with a narrower range shown as Fig. 2(b) showed that a very thin interface layer with few-nm-thickness was formed between the bottom of GaN HEMTs layers and a diamond substrate. Thermal resistance between them could be suppressed compared to the device-structure reported in other studies [1, 3] since a thickness of the interface layer is significantly thinner.

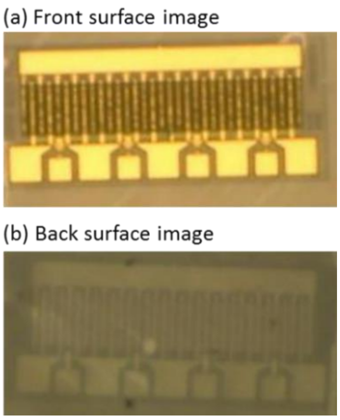

Fig. 1 Photographs of a fabricated GoD HEMT taken from (a) a front side of the HEMT and (b) a back side of the diamond substrate.

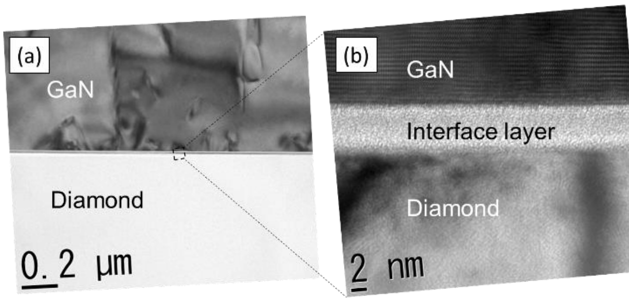

Fig. 2 Cross-sectional TEM images of a fabricated GoD HEMT observed with (a) a wider range and (b) a narrower range.

Fig. 3 shows I_d-V_d characteristics measured with a fabricated GoD HEMT at various gate voltages. In the figure, I_d-V_d curves measured with conventional GoSi HEMT were also shown as dashed lines. Drain currents obtained from GoSi HEMT were much lower than those obtained from GoD HEMT especially at higher drain voltage region. This result indicated that local heating near a channel region during transistor operation was drastically suppressed in a fabricated GoD HEMT structure.

From these results, we conclude that GaN HEMTs were successfully transferred on the diamond substrate without being damaged during thinning and bonding process.

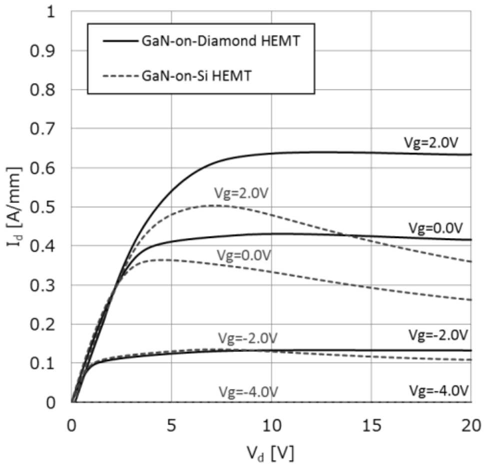

Fig. 3 Measured I_d-V_d characteristics of GoD HEMT (solid lines) and GoSi HEMT (dashed lines).

Conclusion

We successfully fabricated large GoD HEMTs with surface-activated room-temperature bonding technology. Bonding was operated without involving any voids at the interface. DC characteristics of a fabricated GoD HEMT showed that GaN HEMTs layers were successfully transferred on a diamond substrate from an original Si substrate. Moreover, HEMT performance was drastically improved due to effective heat dissipation of a diamond substrate.

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