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Surface Activated Bonding of SiC/Diamond for Thermal Management of High-Output Power GaN HEMTs

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Abstract

In this study, we developed a surface activated bonding (SAB) method between SiC substrate and a single-crystal diamond heat spreader for thermal management of high-output power GaN-based high electron mobility transistors (HEMTs). A thin metallic film on the diamond improved the bonding strength of the SiC/diamond because formation of a damaged layer on the diamond surface was suppressed. This SAB process was applied to our high-output power InAlGaN/GaN HEMTs on diamond. It successfully reduced the thermal resistance of the devices and enabled their high-power operation.

1. Introduction

GaN-based HEMTs are suitable for microwave and millimeter-wave amplifiers with high-output power and high efficiency in long distance radio-wave applications, such as weather radars and wireless communication systems. To boost the range of these systems with small chip sizes, increasing the output power density is essential. Increasing the output power must be accompanied by a reduction in the thermal resistance to suppress the temperature rise during high power operation. Therefore, high-thermal-conductivity-diamond is a promising material for integrated heat spreaders for GaN HEMTs [1]. However, in conventional GaN-on-diamond, the GaN epitaxial layer is bonded on diamond through a dielectric bonding layer, such as amorphous SiN and a chemical vapor deposition (CVD)-diamond nucleation layer on SiN, which may have high thermal resistance [2,3]. Furthermore, we thought that a nucleation layer on a substrate should not be removed because the back-side buffer potential significantly affected device characteristics such as pinch-off and current collapse. Hence, we selected HEMTs with a SiC substrate /diamond-bonded heat spreader by SAB. SAB is a bonding technology at room temperature, which uses Ar beams for activation of the bonding surfaces [4]. SAB is a promising bonding method for achieving low interfacial thermal resistance since it does not need thick adhesive layers. In this study, SiC/diamond was successfully bonded by SAB. This bonding method was applied to high-output power GaN HEMTs.

2. Experimental

Semi-insulating SiC wafers and (100) single-crystal diamond substrates made by CVD were used as bonding materials. Each material was polished by chemical mechanical polishing (CMP) to obtain an extremely smooth surface for SAB. The SiC wafer (carbon face) and the diamond substrate were bonded to each other at room temperature by SAB. The SAB process flow is shown in Fig.1. In the SAB process, Ar fast atomic beams were used to activate both the SiC and the diamond surfaces. However, we had previously reported that Ar beams formed a low-density damaged layer on the diamond surface, which weakened bonding strength [5]. Therefore, thin metallic cover film was deposited on the diamond to protect the surface from Ar irradiation. In order to ensure the surface was smooth, the the thickness of the metallic cover was restricted to 10 nm or less.

A schematic cross-sectional view of our InAlGaN/GaN HEMT with SiC/diamond-bonded heat spreader is shown in Fig. 2 [6]. In order to increase the current density, we used an InAlGaN barrier layer, which allowed us to achieve high sheet carrier density without increasing tensile strain. Following device fabrication on the front side, the SiC substrate was thinned to 50 μm and the back-side surface was smoothed by CMP prior to diamond bonding by SAB.

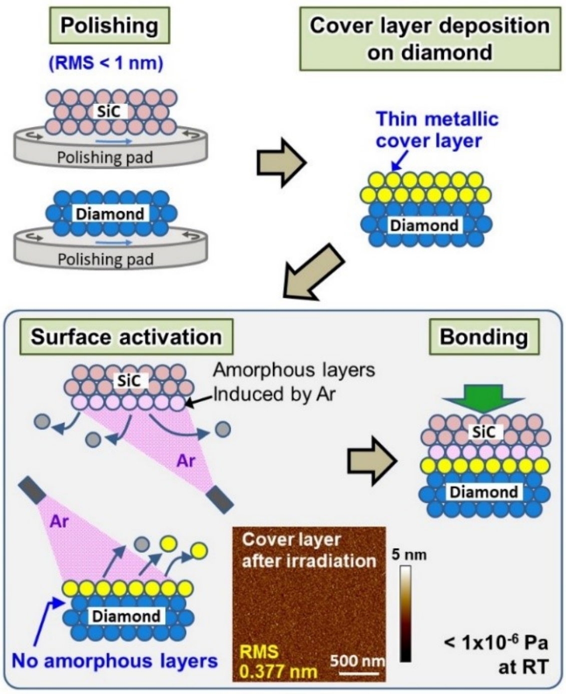

Fig. 1 Process flow diagram of SAB with cover layer on diamond for suppressing amorphous diamond

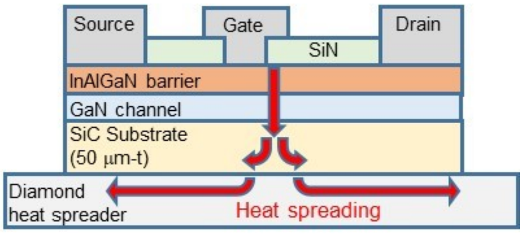

Fig. 2 Schematic cross-sectional view of InAlGaN/GaN HEMT on a SiC substrate bonded to a diamond heat spreader.

3. Results and discussions

SiC/diamond bonding

Fig. 3 shows cross-sectional TEM images of semi-insulating SiC wafer/diamond bonding by the SAB process with the cover layer [5]. There were no voids at the bonding interface and no amorphous layers on the diamond. Bonding strength was then improved by eliminating the damaged layer on the diamond surface. The interfacial thermal resistance of the SiC/diamond obtained by the SAB was 67 m^2K/GW, which was low enough for heat dissipation of the GaN-based devices. Moreover, a diamond was successfully bonded to a 50 µm thick SiC substrate for AlGaN/GaN HEMTs by the SAB process (Fig. 4).

InAlGaN HEMTs on diamond heat spreaders by the SAB

The SAB process in this study was applied to our high-output power InAlGaN/GaN HEMTs [6]. Fig. 5 shows the drain bias dependence of the saturated output power (Psat) at the S-band with pulse duty cycles of 1% and 10%. The saturated output power of the device without the diamond measured at 10% duty showed the maximum power at the drain bias of 90 V, and output power decreased when the drain bias was further increased over 90 V due to the influence of heat generation. On the other hand, in the device on the diamond, output power continued to increase by increasing the drain bias, and the saturated output power density improved from 14.8 W/mm to 19.8 W/mm at the 10% pulse condition. Moreover, under the 1% pulse duty, a high-output power density of 22.3 W/mm was obtained. These results showed that the SiC/diamond-bonded heat spreader successfully reduced the temperature rise of these devices, thus enabling their high-power operation.

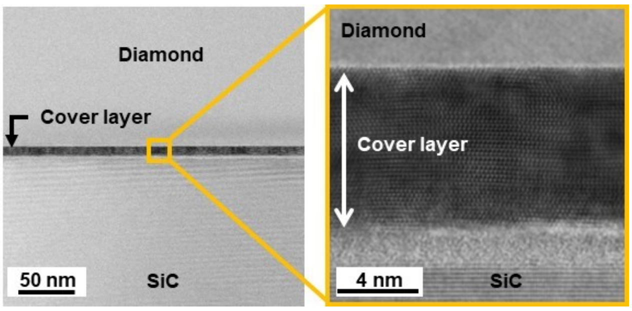

Fig.3 Cross-sectional TEM images of SiC/diamond bonding by the SAB process with the cover layer

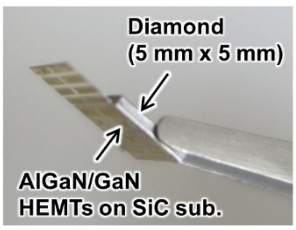

Fig.4 Photograph of AlGaN/GaN HEMTs on SiC substrate after bonding with diamond.

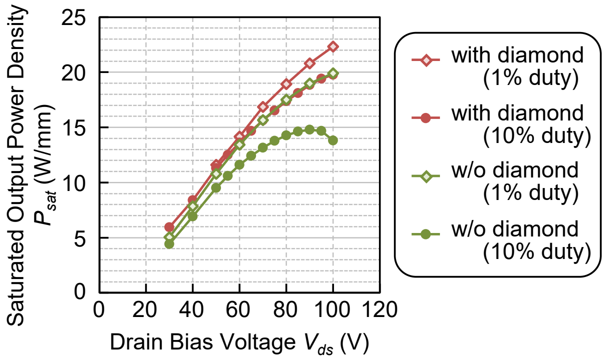

Fig. 5 Output power of InAlGaN/GaN HEMTs evaluated by load-pull measurement at the S-band. Total gate width was 1mm.

4. Conclusions

We developed a SiC/diamond bonding process by SAB. In the SAB, a thin metallic cover layer eliminated the formation of a damaged layer on the diamond surface and improved the bonding strength of the SiC/diamond. The interfacial thermal resistance of this bonding was sufficiently low of 67 m^2K/GW. Moreover, the SiC/diamond -bonding was applied to our high-output power InAlGaN/GaN HEMTs and enabled high-power operation of the devices. These results showed the excellent heat dissipation effect of the SiC/diamond-bonded heat spreader by SAB.

Acknowledgements

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