Thermal Analysis of GaN-HEMT/SiC on Diamond by Surface Activated Bonding

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Abstract

We analyzed GaN-HEMT/SiC on diamond by surface activated bonding (SAB) using thermal simulation. In GaN/SiC/diamond structures, the heat transfer mechanism changes at a SiC/diamond interface thermal resistance of 400 m^2K/GW. At less than 400 m^2K/GW, the total thermal resistance decreased as SiC thickness decreased. This indicates that it is effective to transmit the heat to diamond as fast as possible and spread the heat in the diamond. The interface thermal resistance of SiC/single-crystal diamond by SAB was found to be 67 m^2K/GW. Consequently, the GaN/SiC/diamond structures enabled us to reduce the total thermal resistance by more than 30%, compared to the conventional GaN/SiC structure. In addition, we simulated the cost-reduced diamond-bonded structure.

INTRODUCTION

GaN high electron mobility transistors (GaN-HEMTs) have high output power and efficiency for long-distance radio wave applications such as base stations, weather radars, and millimeter-wave wireless backhaul. To further expand the reachable distance, a greater increase of output power leads to the enhancement of the self-heating of GaN-HEMTs. Therefore, GaN-on-diamond is very attractive for thermal management for high-power GaN-HEMTs [1]. However, in conventional GaN-on-diamond, the GaN epitaxial layer was bonded on diamond through a dielectric bonding layer such as amorphous SiN [2,3] and a CVD-diamond nucleation layer on SiN [4,5] which may become thermally resistant. In addition, the change of the backside buffer potential determined by a nucleation layer on a substrate may significantly affect the device characteristics such as pinch-off and current collapse. Therefore, we selected GaN-HEMT/SiC on a single-crystal diamond by surface activated bonding (SAB). SAB is the bonding technology in which surfaces of different materials are cleaned in a vacuum by an argon (Ar) beam and bonded at room temperature (RT). This can bond materials that have different coefficients of thermal expansion. Therefore, SAB enables us to bond SiC to diamond without an extra bonding layer at RT. Furthermore, the device performance is expected to remain stable due to the remaining SiC.

In this study, we analyzed GaN-HEMT/SiC on single-crystal diamond by SAB using thermal simulation. We evaluated the SiC/diamond interface thermal resistance dependence of the total thermal resistance against the thickness of the remaining SiC substrate. In addition, we simulated the cost-reduced diamond-bonded structure which uses a poly-crystalline diamond with the lower thermal conductivity and the heterogeneous integration for GaN MMIC high power amplifiers (PAs).

OUR GAN-HEMT/SIC ON DIAMOND BY SAB

Fig. 1 shows a schematic of our GaN-HEMT/SiC on diamond by SAB. With SAB, the Ar beams are used to remove impurities on both SiC and diamond surfaces. However, a low-density damaged layer formed on the diamond, as shown in Fig. 2(a), which weakens bonding strength. Therefore, we developed a technique that protects the diamond surface with an extremely thin metallic film before it is exposed to the Ar beam. In order to ensure the surface is planar, the metallic film is held to a thickness of 10 nm or less. Then, the RMS roughness of the metallic film after Ar beam exposure was 0.377 nm, which was sufficiently smooth for SAB. Although the metallic layer still slightly remained at the bonding interface as shown in Fig. 2 (b), the bonding strength was improved by eliminating the damaged layer. Details of SiC/diamond SAB were reported elsewhere [6]. Fig. 3 shows a single-crystal diamond bonded at RT to a 50-µm thick SiC substrate for GaN-HEMT.

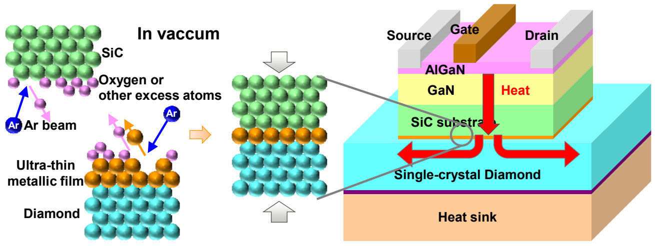

Fig. 1. Schematic our GaN-HEMT/SiC/diamond structure by SAB.

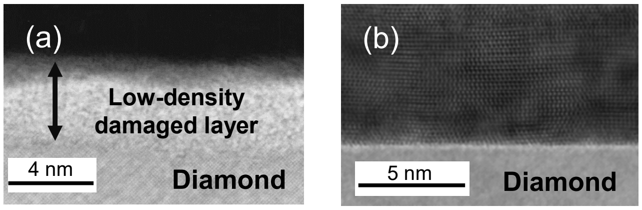

Fig. 2. Diamond cross section after Ar beam exposure; (a) bared surface and (b) ultrathin metal-deposited.

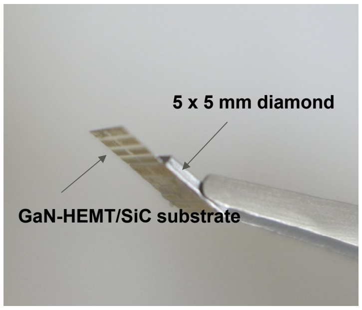

Fig. 3. A GaN-HEMT/SiC substrate with diamond bonded using this technology.

THERMAL ANALYSIS OF GAN-HEMT/SIC ON DIAMOND

We used Mentor Graphics FloTHERM for thermal simulation. Fig. 4 shows the simulated GaN/100-µm SiC conventional structure (a) and GaN/SiC/diamond structure (b). The thicknesses of GaN, AuSn, diamond and CuW are 2, 25, 300, 1000 µm, respectively. The thickness of the remaining SiC substrate was varied from 10 to 100 µm. The GaN/SiC chip size is 1 x 6 mm. The size of the diamond and CuW is 10 x 10 mm. The power of a heat source with a size of 0.5 µm x 0.3 mm x 0.1 µm was 2 W. 96 heat sources were placed in the GaN layer spaced 50 µm apart. Table I shows the thermal parameters used for this simulation. The total thermal resistance was determined by dividing the temperature deference between the maximum temperature and CuW temperature by the power dissipation (192W).

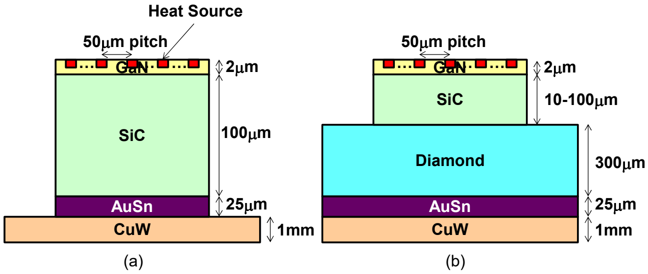

Fig. 4. Simulated device structures; (a) conventional GaN/SiC structure and (b) GaN/SiC/diamond structure.

Table I. Thermal parameters used for thermal simulation.

Parameters	GaN	SiC	Diamond	AuSn	CuW
Thermal conductivity (W/mK)	88	420	1000 1500 2000	57	200
Interface thermal resistance (m^{2}K/GW)	N/A	16	10～500	N/A	N/A

*Interface thermal resistances were set at the interface of GaN/SiC and SiC/diamond.

Fig. 5 shows the SiC thickness comparison of the SiC/diamond interface thermal resistance dependence of the total thermal resistance of the structure (b). Then, the thermal conductivity of diamond is 2000 W/mK. The total thermal resistance of the conventional structure (a) was 1.53 K/W, which is shown as a black dotted line. As a result, the structure (b) enables us to further reduce the total thermal resistance compared to the structure (a). The interface thermal resistance of SiC/single-crystal diamond by SAB was found to be 67 m^{2}K/GW [3]. Therefore, the total thermal resistance can be reduced by more than 30%, compared to the conventional structure.

However, when the SiC/diamond interface thermal resistance is lower than 400 m^{2}K/GW, the total thermal resistance decreases as SiC thickness decreases. This indicates that it is effective to transmit the heat to the diamond as fast as possible and spread the heat in the diamond. On the contrary, when the SiC/diamond interface thermal resistance is higher than 400 m^{2}K/W, the total thermal resistance increases as SiC thickness decreases. This suggests that it is effective to spread the heat in SiC before transmitting it to the diamond. It is necessary to change the design of the thermal management in the SiC/diamond interface thermal resistance.

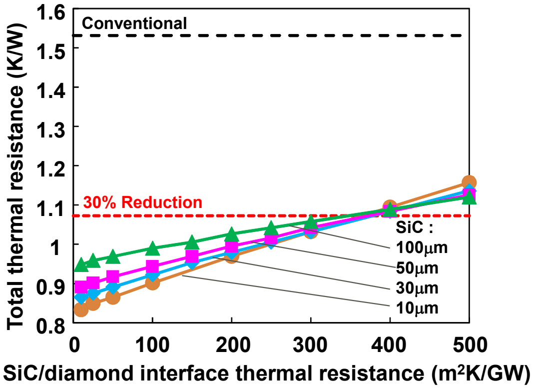

Fig. 5. SiC thickness comparison for SiC/diamond interface thermal resistance dependence of the total thermal resistance of the structure (b) using diamond with a thermal conductivity of 2000 W/mK.

Fig. 6 shows the simulated comparison of heat in 200-W class GaN-HEMT PAs using this measured parameter. In this case, the SiC thickness was fixed to be 50 µm. It is understood that heat spreads more clearly in a diamond-bonded structure than the conventional structure. Consequently, this technology would significantly reduce thermal resistance of 200W-class devices to 61%, which is equivalent to an 80°C reduction in surface temperature. Therefore, this technology enables us to further increase the output power of GaN-HEMT PAs.

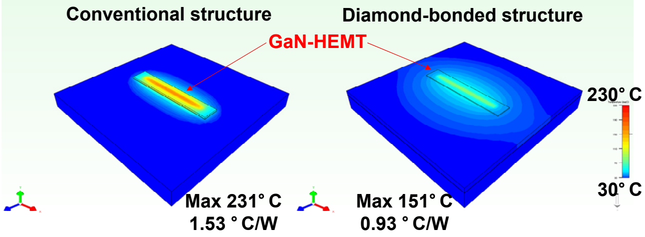

Fig. 6. Simulated comparison of heat in 200W-class GaN-HEMT PAs.

COST-REDUCED DIAMOND-BONDED STRUCTURE

The diamond-bonded structure is very effective for cooling GaN-HEMT PAs. However, the single-crystal diamond which is commercially available is very small (less than 10 x 10 mm) and too expensive. So, we simulated the cost-reduced diamond-bonded structure which uses a poly-crystalline diamond with lower thermal conductivity and heterogeneous integration. A poly-crystalline diamond wafer with a larger size (~4inch) and lower cost (~1/10) can be fabricated compared to a single-crystal diamond. Furthermore, we reported the heterogeneous integration of microwave GaN-HEMT PAs with Si matching circuits to reduce production costs [7].

Fig. 7 shows a diamond thermal conductivity comparison for 30-µm SiC/diamond interface thermal resistance dependence of the total thermal resistance of the structure (b) shown in Fig. 4. When the SiC/diamond interface thermal resistance is less than 100 m^2K/GW, the total thermal resistance will be reduced by 30% more than the conventional structure (a) even if using poly-crystalline diamond with a thermal conductivity of 1000 W/mK. Meanwhile, it may be difficult to flatten the surface of poly-crystalline diamond involving various grains.

Fig. 8 shows the simulated heterogeneous integrated PAs consisting of a GaN/100-µm SiC chip (c) or a GaN/10-µm SiC/90-µm diamond chip (d) and Si matching circuits. Table II shows the additional thermal parameters used for this simulation. The interface thermal resistance of SiC/diamond was set to 70 m^2K/GW. The GaN chip size is the same as the size of the underlying SiC and diamond. The size of heterogeneous integrated PAs is fixed to 6 x 6 mm. The thicknesses of GaN, Si, AuSn and CuW are 2, 100, 25, 1000 µm, respectively. The mold materials are placed between the GaN chip and Si matching circuits, spaced 50-µm apart. The size of CuW is 10 x 10 mm. The heat sources are the same as above.

Fig. 9 shows a GaN chip width dependence of total thermal resistance in simulated heterogeneous integrated GaN PAs. Consequently, in the heterogeneous integrated PAs, the diamond-bonded structure enables us to decrease the total thermal resistance compared to the GaN/SiC structure. The total thermal resistance decreased as the GaN chip width increased up to 3 mm in the diamond-bonded structure. This suggests that the heat at least spreads here, in the diamond. Here, to obtain a thermal resistance of 1.22 K/W, it is necessary that the GaN chip widths are more than 3 and 1.3 mm for the diamond with a thermal conductivity of 1000 and 2000 W/mK, respectively. Then, if the high thermal conductivity diamond is half the cost of the lower one, the use of the higher one would enable us to decrease the production cost. To balance the cost with the cooling efficiency for GaN-HEMT PAs, it is necessary to optimize the size and thermal conductivity of the diamond heat spreader.

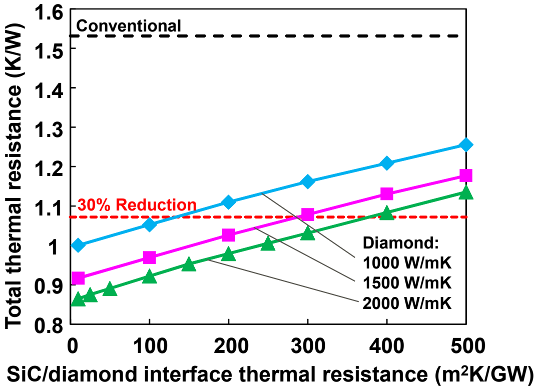

Fig. 7. Diamond thermal conductivity comparison of 30-µm SiC/diamond interface thermal resistance dependence of the total thermal resistance of the structure (b).

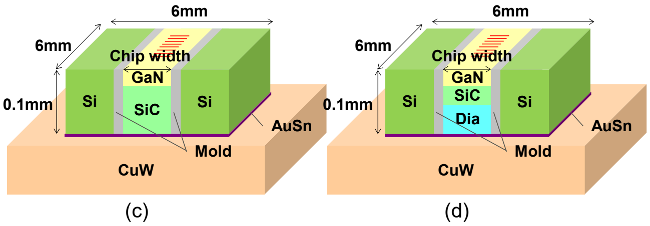

Fig. 8. Simulated heterogeneous integrated PAs consisting of a GaN/100-µm SiC chip (c) or a GaN/10-µm SiC/90-µm single-crystal diamond chip (d) and Si matching circuits.

Table II. Additional thermal parameters used for simulation.

Parameters	Si	Mold
Thermal conductivity (W/mK)	149	0.2

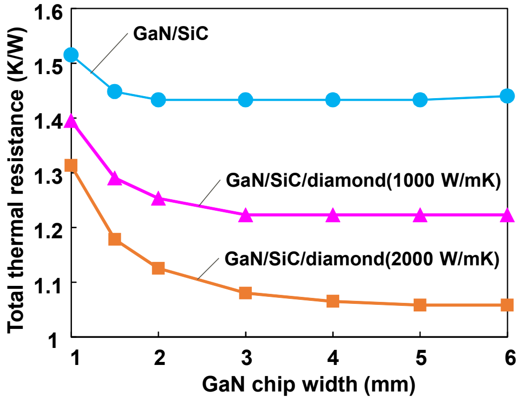

Fig. 9. GaN chip width dependence of total thermal resistance in simulated heterogeneous integrated GaN PAs.

CONCLUSIONS

The authors reported on the thermal analysis of GaN-HEMT/SiC on diamond by SAB. As a result, this technology enables us to reduce the total thermal resistance by more than 30%, compared to the conventional structure, which has the feasibility to further increase the output power of GaN-HEMT PAs. In addition, we simulated the cost-reduced diamond-bonded structure that uses the poly-crystalline diamond and the heterogeneous integration for GaN MMIC PAs. Consequently, to balance the cost with the cooling efficiency for GaN-HEMT PAs, it is necessary to optimize the size and thermal conductivity of the diamond heat spreader.

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ACRONYMS

SAB: Surface Activated Bonding
HEMT: High Electron Mobility Transistor
PA: Power Amplifier
MMIC: Monolithic Microwave Integrated Circuit