Thermal Analysis of GaN Device on Diamond Substrate with High Thermal Conductivity

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This study investigated that the thermal resistance of a gallium nitride (GaN) device formed on a diamond substrate with high thermal conductivity. We experimentally confirmed that the thermal resistance of the GaN-on-diamond device was lowered by 45% and 70% compared with GaN-on-SiC and GaN-on-Si devices, respectively. By conducting steady-state thermal analysis considering the substrate thickness dependency, we found that only diamond was able to increase the reduction rate of the thermal resistance in case of thickening the substrate.

1. Introduction

As the detection distance of microwave radar has increased, the demand for high-output and highly efficient GaN high-frequency devices has grown. The main type of GaN high-frequency device used in industry is the GaN high electron mobility transistor formed on a semi-insulating silicon carbide substrate (GaN-on-SiC HEMT). However, its output density remains at about 10 W/mm owing to thermal limitations, and it is important to satisfy both high-reliability and high-output. To solve this problem, the concept of GaN-on-diamond thermal management design was recently proposed(1). Since the thermal conductivity of diamond is over 1,500 Wm^{-1}K^{-1} at room temperature, which is the highest among solid materials, it may be useful for controlling local high-temperature areas (hot spots) during high-output operation (Fig. 1). Although it is quite difficult to manufacture the GaN-on-diamond HEMT, several papers have reported actual verification and that the output density was three times the conventional value(2). In this feasibility study, the thermal characteristics of a commercially-available GaN-on-diamond substrate were evaluated, focusing on the material properties.

2. Device Structures and Experimental Setup

As shown in Fig. 2, the device was formed by the same process for the AlGaN/GaN epitaxial layer on various substrates (Si, SiC and diamond). The substrate thickness of Si, SiC and diamond was 625 μm, 325 μm and 130 μm. To correspond to the spatial resolution of the thermal evaluation system, a Van-der-Pauw structure that is a relatively large active area of 0.4 mm^2 was employed. In addition, the chip area is much larger than the active area, so that the effect of the heat conduction can be evaluated. We measured the maximum temperature when energized with direct current using infrared (IR) thermography. The surface was coated with black paint to compensate for the emissivity of the material.

3. Thermal Resistance by Using IR Thermography

Figure 3 shows the temperature increase, ΔT of the device for dissipated power density. Thermal resistivity ρ_{th}. is determined from a linear slope of this graph. Thermal resistivity of the GaN-on-diamond device was 0.21 mm^{2}K/W. The reduction was 70% for GaN-on-Si

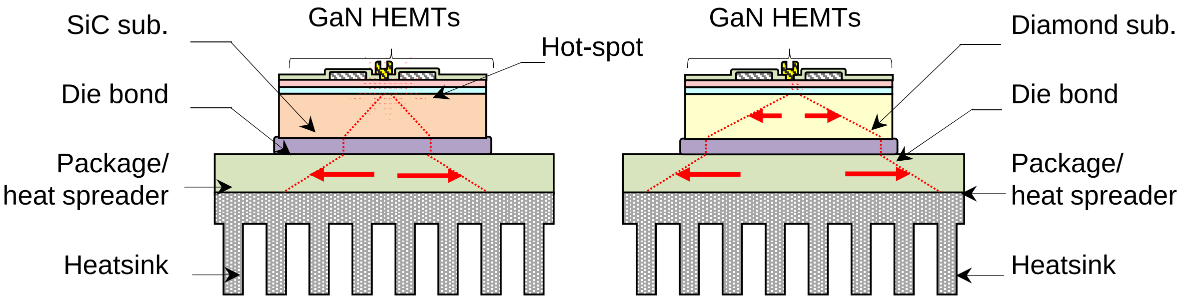

Fig. 1 Comparison of the effect of heat spread between conventional (GaN-on-SiC) and GaN-on-diamond device structure

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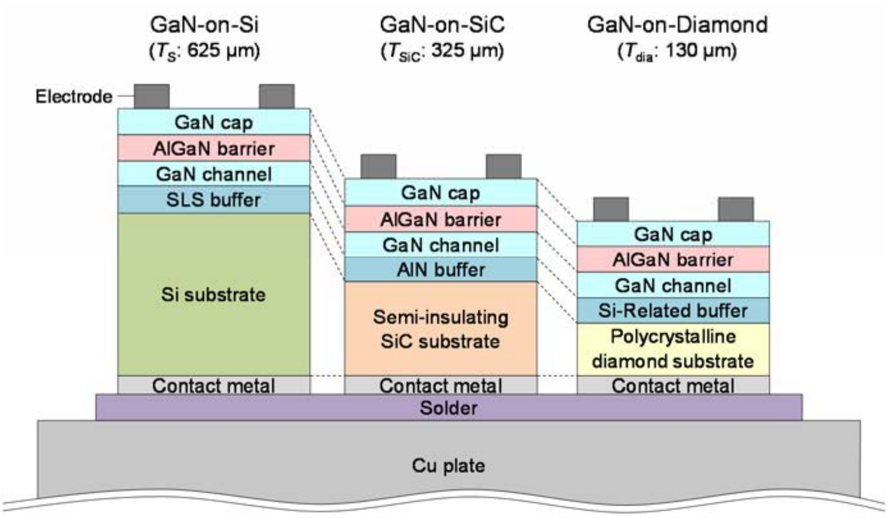

Fig. 2 Schematic cross section of fabricated GaN devices on various substrate for thermal evaluation

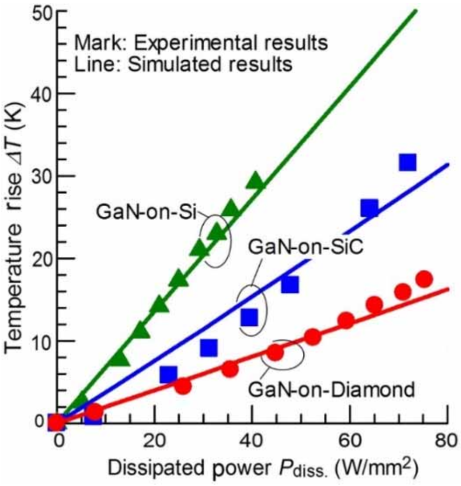

Fig. 3 Temperature rise versus dissipated power density

(0.71 mm^{2}K/W) and 45% for GaN-on-SiC (0.38 mm^{2}K/W). We demonstrated that the GaN-on-diamond has excellent thermal properties. However, it is noted that this result included the substrate thickness tolerance.

4. Thermal Analysis

Steady-state thermal analysis of the GaN-on-diamond structure was performed by using the numerical simulation for 3D finite element method. For the boundary conditions, the temperature at the back surface of the Cu plate was fixed and other outermost surfaces were vacuum-insulated.

Figure 4 shows the temperature distribution in the depth direction from the maximum thermal point at the dissipated power of 6 W. Figure 5 shows the thermal resistance of each layer structure calculated using the temperature difference. In the GaN-on-Si or the GaN-on-SiC, more than half of the total thermal resistance of the device is occupied by the thermal resistance of the substrate. In contrast, the substrate thermal resistance of GaN-on-diamond is limited to about 20% only, and the

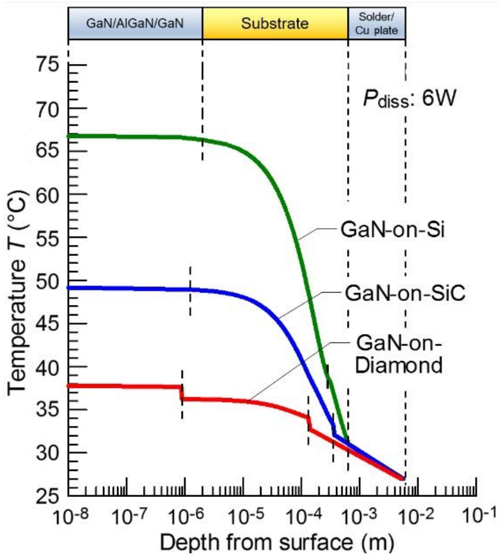

Fig. 4 Temperature distribution from the surface of the device in the depth direction at the dissipated power of 6 W

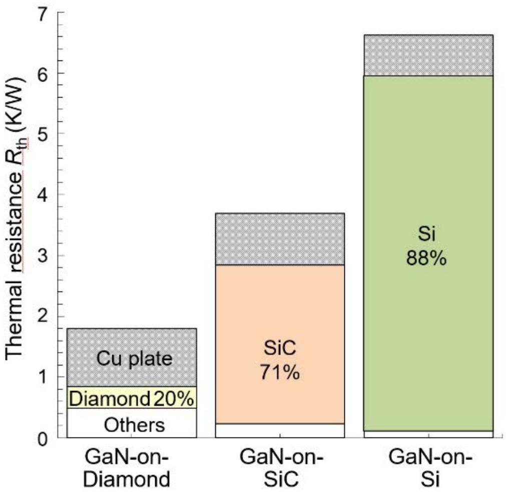

Fig. 5 Thermal resistivity and proportion of each layer structure of GaN devices

thermal resistance of the Cu plate is the largest. Thus, thermal analysis in the depth direction can be used to simply identify the rate-limiting factor of thermal resistance.

Since the substrate thickness of the GaN devices were not the same in this study, dependence of total thermal resistance on substrate thickness was calculated as depicted in Fig. 6.

It is expected that the thermal resistance is proportional to the heat transfer length, so that the total thermal resistance of the device for a thick substrate increase, regardless of the material. However, it actually increased for GaN-on-Si only; it stayed almost the same for GaN-on-SiC, and gradually reduced for GaN-on-diamond. Comparing the thermal resistance with a substrate of the same thickness for each, we found that the thermal management of GaN-on-diamond was more advantageous than the experiment result when the substrate thickness was 350 µm or more.

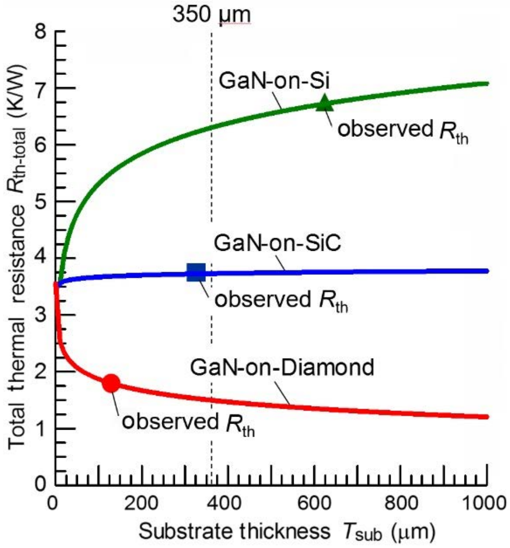

Fig. 6 Dependence of total thermal resistance on substrate thickness of GaN devices

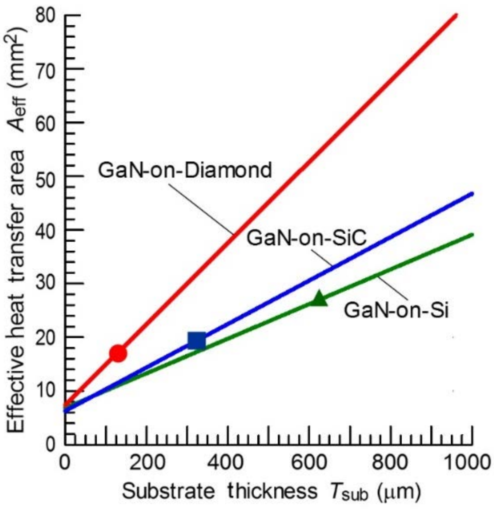

Fig. 7 Dependence of effective heat transfer area on substrate thickness of GaN devices

Figure 7 shows the effective heat transfer area A_{eff}. determined from following equation [1], where L_i, k_i and R_{th_i} are heat transfer length, thermal conductivity and thermal resistance, respectively.

$$A_{eff.} = \sum_{i=1}^{n} A_i = \sum_{i=1}^{n} \frac{L_i}{k_i R_{th-i}} \qquad [1]$$

The effective heat transfer area, A_{eff}. is defined as a total sum of a heat transfer area, A_i of each layer in the device. The difference of the rate of A_{eff}. increase for the substrate thickness only corresponds to the difference in the substrate materials. The highest rate of A_{eff}. increase in the GaN-on-diamond device suggests that a diamond has a superior heat spreading capacity. Therefore, we believe that the GaN device formed on thicker diamond exhibited thermal property advantageous. In addition, it is important to design a device geometry, chip area, and layer thickness for an optimum thermal management.

5. Conclusion

The thermal analysis of GaN-on-diamond substrate was performed by both experimental and simulation techniques. We confirmed that the GaN-on-diamond structure has more excellent thermal properties than GaN-on-Si or GaN-on-SiC which are the conventional substrate structures. Furthermore, we found that the total thermal resistance of the GaN-on-diamond decreased with increasing the substrate thickness due to the large effective heat transfer area. To optimize the thermal dissipation design, it is important to design the layer thickness, chip area and device layout according to the material type. This study may pave the way for the new development of GaN high-frequency devices.

6. Acknowledgement

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7. References

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