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Performance improvement of β-Ga_2O_3 SBD-based rectifier with embedded microchannels in ceramic substrate

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With the development of integrated circuits, there is a growing demand for higher power devices [1]. Gallium oxide (Ga_2O_3) holds promise for high power devices due to its wide bandgap and high breakdown electric field strength [2]. However, its low thermal conductivity induces severe self-heating effects, limiting its performance and reliability. Therefore, effective thermal management techniques are urgently needed for Ga_2O_3 devices.

Currently, research aimed at mitigating the self-heating effect of Ga_2O_3 devices primarily centers on passive cooling. Xu et al. [3] employed heterogeneous integration of Ga_2O_3 with SiC and Si to address its drawback of low thermal conductivity. Noh et al. [4] enhanced interfacial heat conduction by introducing an intermediate layer between Ga_2O_3 and substrate. Wang et al. [5] reduced the thermal resistance of Ga_2O_3 Schottky rectifiers through double-sided packaging. However, active cooling, which holds greater potential to reduce junction temperature, has not been reported to the best of our knowledge.

In this study, a β-Ga_2O_3 Schottky barrier diode (SBD)-based alternating-direct current (AC-DC) full-wave bridge rectifier with embedded microchannels in ceramic substrate has been realized. The impact of active embedded cooling on the thermal and electrical characteristics of the rectifier has been analyzed. Additionally, a finite element model has been employed to compare and analyze the thermal resistance composition of the active embedded cooling structure with the passive remote cooling structure.

Method and fabrication. Two physical structures and their thermal resistance compositions are depicted in Figures 1(a) and (b). In remote cooling, heat is transferred from the die to the heat sink and then dissipated through air convection. Conversely, embedded cooling involves heat transfer from the die to the microchannels, which is then dissipated through liquid convection. The thermal resistances enclosed by the red box in Figure 1(a), constituting 72.6%, represent potential areas for improvement in this study by integrating the substrate and microchannels into a unified structure, eliminating the necessity for intricate bonding procedures. Following optimization, the percentage decreases to only 20.2%. β-Ga_2O_3 SBDs are positioned above the microchannel with the highest flow rate, as determined by COMSOL Multiphysics analysis, to enhance Joule heat transfer.

The fabrication of β-Ga_2O_3 rectifier with embedded microchannels in the ceramic substrate includes developing the device, designing the substrate, and implementing the packaging procedures. Vertical β-Ga_2O_3 SBDs with a size of 1 mm×1 mm were prepared on (001) iso-epitaxial wafer consisting of a 650 μm substrate with a Sn doping concentration of 8×10^{18} cm^{-3} and a 10 μm epitaxial layer with a Si doping concentration of 3×10^{16} cm^{-3} (hydride vapor phase epitaxy, HVPE). Schottky barrier and ohmic contact were formed using Ni/Au (45 nm/400 nm) and Ti/Au (30 nm/200 nm) metal stacks, respectively. The turn-on voltage is 0.7 V, and the breakdown voltage is 300 V. The embedded ceramic substrate was fabricated via advanced additive manufacturing technology, comprising 95% Al_2O_3 and 5% SiO_2. It used for remote and embedded cooling shares identical external dimensions and fabrication processes, as shown in Figure 1(c), differing in the interior of the ceramic substrate whether solid or microchannels. Transfer the bridge rectifier circuit onto the polished ceramic substrate using processes including photolithography, sputtering, and electroplating. The β-Ga_2O_3 SBDs were soldered to it using gold-tin solder. Deionized water served as the coolant.

Results and discussion. To assess the pump power (P_{pump}) required by embedded cooling, both coolant flow rate and pressure drop (ΔP) were monitored and recorded. Figure 1(d) illustrates an increase in pressure drop from 13 mbar at 40 mL/min to 28 mbar at 80 mL/min. Only a pump power of 0.9 mW is required to achieve a flow rate of 40 mL/min. Utilizing embedded cooling, the DC output voltage (U_{out}) can increase from 19 to 49 V, and the output power can increase from 3.2 to 21.3 W, representing an approximately 6.6-fold increase at the same junction temperature (T_{j}) of 80°C, as depicted in Figures 1(e) and (f). With an increase in the coolant flow rate, the junction temperature tends to stabilize, as illustrated in Figure 1(f), attributed to the development of the thermal boundary layer [6]. It can be disrupted by enhancing the likelihood of turbulent flow, such as by incorporating ribs,

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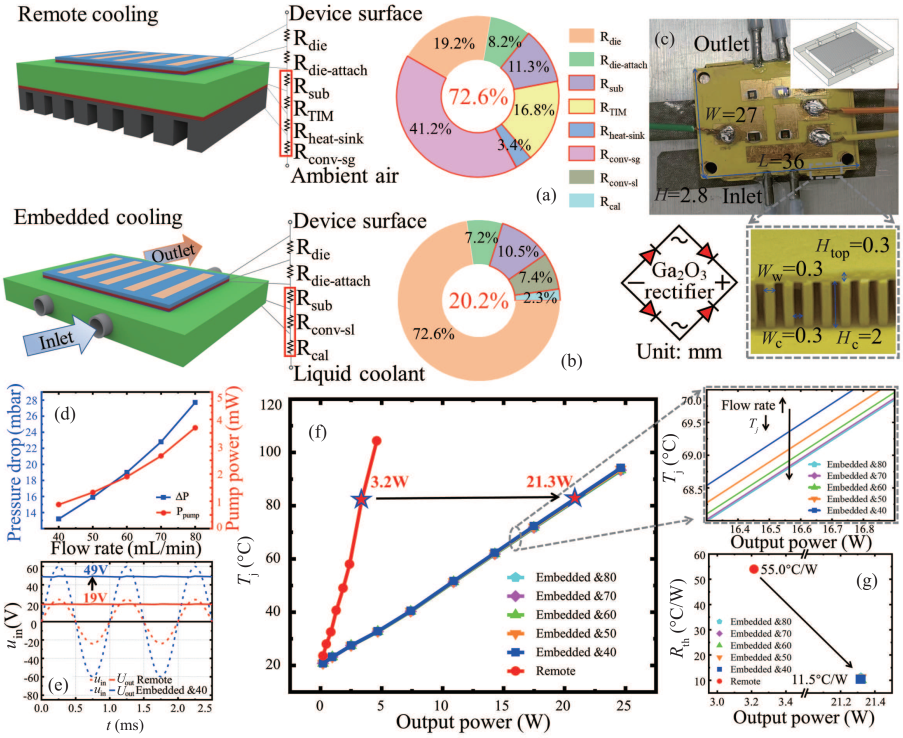

Figure 1 (Color online) (a) Remote cooling structure and its thermal resistance composition; (b) embedded cooling structure and its thermal resistance composition; (c) β-Ga_2O_3 rectifier with embedded microchannels in the ceramic substrate; (d) pressure drop and pump power versus flow rates; (e) rectification waveforms of β-Ga_2O_3 rectifier with embedded and remote cooling; (f) junction temperature versus output power under embedded cooling by different flow rates and remote cooling; (g) thermal resistance.

serrated flow paths, or utilizing jets. Thermal resistance ($R_{\rm th}$) decreases from 55.0 to 11.5°C/W, as shown in Figure 1(g).

Conclusion. This study proposed and fabricated a β-Ga_2O_3 SBD-based rectifier with embedded microchannels in a ceramic substrate for active cooling for the first time. Experimental results demonstrate that this technique can increase the output power from 3.2 to 21.3 W, consuming only 0.9 mW of pump power. The achievements in this work indicate that embedded cooling offers a powerful technique to suppress the thermal effects on Ga_2O_3 devices and circuits, thereby improving their electrical performance.

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