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Thermal simulation of high power GaN-on-diamond substrates for HEMT applications

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ABSTRACT

A three-dimensional thermal simulation for analysis of heat dissipation of AlGaN/GaN HEMT with diamond substrates is presented by the finite element method. The model accounts for the nonlinear thermal conductivities of GaN and diamond materials by employing Kirchhoff's transformation with the aim to improve calculation accuracy. In addition, the geometric parameters of AlGaN barrier, heat sources, and interfacial thermal resistance are considered and treated appropriately in our numerical analysis. We investigate the temperature distribution and heat spreading paths of the intra-chip, and those results indicate that the thickness of epitaxial layers and interfacial thermal resistance have certain influence on the magnitude of the junction temperature, especially interfacial thermal resistance of which the effect is as high as 19 K per 10 m^2 K/GW due to the capacity of horizontal and vertical heat spreading in the near-junction region. The analytical heat dissipation is necessary for providing helpful insight into the dominant factors in the formation of highly localized hotspots in the near-junction region.
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1. Introduction

GaN-based high electron mobility transistors (HEMTs) are extremely promising for RF power electronic applications; however, they are affected by self-heating. Self-heating leads to increased junction temperature which not only reduces the electron mobility and saturation velocity, but also decreases the median time to failure of power devices. Moreover, the potential for junction temperature-related degradation is more critical, given the high power density involved [1,2].The self-heating effect has been a critical limitation for practical applications of HEMTs. To reduce junction temperature, several approaches have been proposed to effectively manage the heat produced [1–7]. The obvious solution is to use low thermal resistivity substrates material with high thermal conductivities immediately adjacent to the hot spot of the chip to minimize the temperature increase. Thus, GaN-on-diamond technology has been developed to reduce thermal resistance of near-junction region of GaN HEMTs, owing to the unique properties of diamond, such as the highest thermal conductivity and high electrical insulation [4–10]. However, thorough understanding of thermal transport in the near-junction region, including AlGaN barrier, GaN buffer, the diamond substrates and as well as the GaN/diamond interfacial layers, have not been well addressed [8–16], which are desirable for optimal implementation of GaN-on-diamond. This underscores the need for a reliable temperature estimation method.

Here, we want to characterize the impacts of diamond heat substrates on the junction temperature characterization of GaN HEMTs through a theoretical model based on finite element analysis. This model takes into account structure factors of the near-junction region, including details of AlGaN barrier, GaN buffer and diamond substrates layers, and interfacial thermal resistance (R) of GaN/diamond, and so on which is challenging [8–16]. In addition, the model accounts for the nonlinear thermal conductivity of GaN and diamond substrates materials by employing Kirchhoff's transformation with the aim to improve calculation accuracy, which has been reported in many previous studies [1,2,12,17].

In this letter, the relationships between junction temperature and geometric parameters of GaN-on-diamond substrates are analyzed using the finite element method which was implemented in a commercial simulation software (COMSOL). In Section 2, the simulation details are described, such as the geometry of a typical multi-fingers GaN and analytical equations for the temperature-dependent thermal conductivities of the materials. The numerical results and discussion in Section 3 focus on illustrating the heat spreading effect and optimizing its structural design. Finally, some conclusions are presented in Section 4.

2. Simulation details

To understand the effort of thermal transport of near-junction regions by the diamond substrates, the near-junction region of the GaN-chip is designed as shown in Fig. 1(a), and includes an AlGaN barrier layer, a GaN buffer layer, an interface of a GaN/diamond, and a diamond substrates layer, the calculation model for the actual power module in which a GaN chip was soldered to a CuMo heatsink with an AuSn joint

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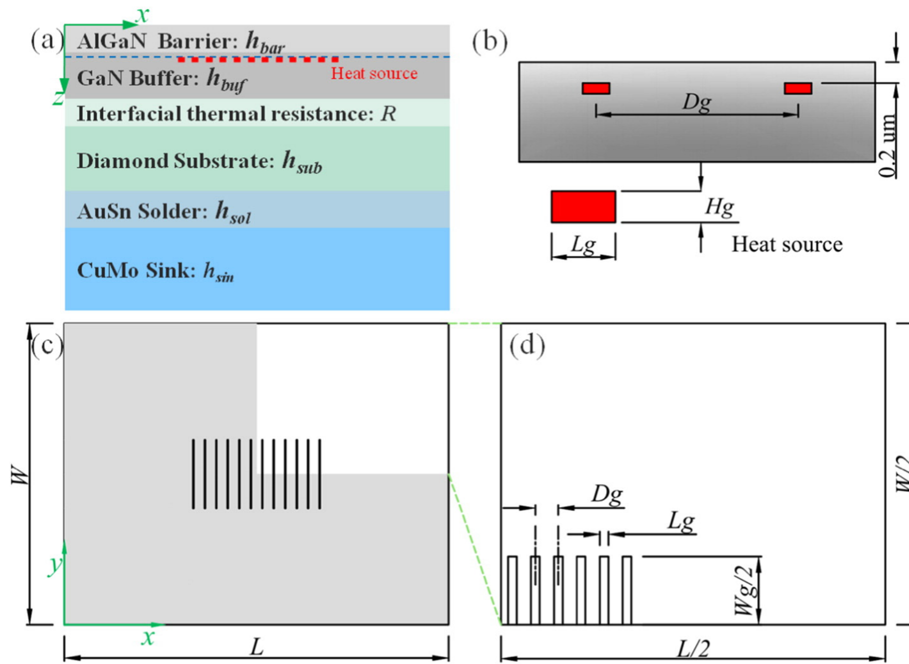

Fig. 1. (a) schematic of cross section, (b) the heat source, (c) top, and (d) the actual quarter module views of multi-fingers AlGaN/GaN HEMTs.

layer [8–11,15–18]. To avoid the effect of overall heat dissipation capacity affected by the macro size of the device, the sizes of the GaN chip are design fixed structure as Fig. 1(c and d) and Table 1, the length and width of chip are the *L* and *W*, and the transistor is made up of 12 gate fingers with a 120 μm width and 20 μm pitch spacing. A simple numerical module shown in Fig. 1 is used for the calculation model to investigate the thermal properties by varying the structural parameters shown in Table 1.

For accurate simulations, the temperature-dependent thermal conductivities (κ(T)) of chip materials are introduced into the model. AlGaN, GaN, and diamond materials have been considered with nonlinear thermal conductivities by employing Kirchhoff's transformation and are modeled as

$$\kappa(T) = \kappa_0 \left(\frac{T}{T_0}\right)^{\alpha}$$

where κ_0 is the thermal conductivity at $T_0 = 300$ K and α is the power law coefficient. Model parameters for temperature ranges are provided in Table 2 [1,12,17]. The interface of GaN/diamond is a thick AlN nucleation layer with 20 nm thickness that involves intricate resistance mechanisms, including defects, dislocations, and interfacial disorders; these mechanisms seriously damage thermal property and are often impossible to separate experimentally. Moreover, this thick transition layer is polycrystalline, and the thermal conductivity is an isotropic nucleation material. Therefore, the heat spreading capacity of this transition layer is represented as a single effective interface thermal resistance (*R*) in our model [6,12,17,18].

The calculations are carried out by the three-dimensional finite element method with COMSOL multiphysics under conditions identical to those in a previous paper. The heat sources, whose cross section of the model is illustrated in Fig. 1(b), represent the constant heat flux generated by dissipated power directly under the gate fingers, and gate/drain/source metallization is omitted due to the small structural complexity effect [8–14,16–21]. The heatsink thickness is placed by means of the infinite element domain model because of the millimeter level size. Moreover, boundary conditions are assumed that the bottom of the substrates is an isothermal surface plane with a constant temperature of 293.15 K, and other external surfaces are applied to natural convection. Due to their structural symmetry, only a quarter of the device shown in Fig. 1(d) is simulated [16–22].

3. Numerical results and discussion

In this section, the effects of the epitaxial layer structure on the thermal performance of GaN-on-diamond substrates for HEMTs are examined in detail based on the structure in Fig. 1 and parameters in Table 1, with some results and discussions to illustrate its applicability for thermal management.

Table 1
Geometrical parameters of the AlGaN/GaN HEMTs.

	Definition	Value		Definition	Value
L	Length of structure	670 μm	h_{bar}	AlGaN barrier thickness	22 nm
W	Width of structure	530 μm	h_{buf}	GaN buffer thickness	0.9–2.1 μm
Lg	Heat source length	120 μm	h_{sub}	Diamond substrate thickness	70–130 μm
Wg	Heat source width	0.5 μm	h_{sol}	AuSn solder thickness	20 μm
Hg	Heat source thickness	0.2 μm	h_{sin}	CuMo heatsink thickness	4.0 mm
Dg	Gate-gate pitch spacing	20 μm	*R*	Interfacial thermal resistance	0–60 m^2 K/GW

Table 2
Thermal parameters used in the simulation.

Material	Thermal conductivity *k* (W/m·K)	Heat capacitance *c* (J/kg·K)	Mass density *ρ* (kg/m^3)
AlGaN	$25 * (T/300)^{-1.44}$	490	6070
GaN	$150 * (T/300)^{-1.42}$	490	6150
Diamond	$1185 * (T/300)^{-0.55}$ (in plane) $1480 * (T/300)^{-0.55}$ (through plane)	520	3515
AuSn	57	128	14,700
CuMo	167	134	9900

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