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Effect of diamond and graphene heat spreaders on characteristics of AlGaN/GaN HEMT

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Abstract

The impact of diamond and graphene heat spreading layers on the thermal and electrical characteristics of AlGaN/GaN high electron mobility transistors (HEMTs) has been investigated using numerical simulations in the hydrodynamic model. It is shown that the introduction of heat spreader significantly reduced maximum device temperature, increased the device lifetime, and improved current-voltage characteristics. The conditions under which the heat spreader works most effectively were found.

Keywords: heat spreader; high electron mobility transistor (HEMT); AlGaN; GaN; graphene; diamond

1. Introduction

The problem of self-heating in high electron mobility transistors (HEMTs) based on AlGaN/GaN is very important. Degradation of basic characteristics (drain current, generation frequency, gain, output power and device lifetime) in such devices is often a consequence of a channel temperature rise. Therefore, effective methods of heat removal are essential.

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Experimental and theoretical studies (Turin and Balandin (2006); Sarua et al. (2006)) have shown that the power dissipation in the GaN HEMT leads to the formation of the hot spots near the transistor channel, wherein the temperature is significantly higher than in other areas of the device. Overheating at these points causes degradation of the device properties, or even permanent damage. This problem can be solved by the introduction of a heat spreader (Wang et al. (2013)) near the hot spots. It removes heat directly from the hot spots.

In Ref. (Yan et al. (2012)) effect of graphene-graphite heat spreader has been studied using the heat equation. Hot spots were modeled as a heat source. Computer modeling the influence of diamond heat spreader on the thermal and electrical characteristics has been investigated in a thermodynamic model (Wang et al. (2013)), in which the drift-diffusion equations are solved self-consistently with the heat equation. It has been shown that diamond and graphene-graphite heat spreaders significantly reduce the maximum device temperature.

In this paper, we have studied in detail the effect of the diamond and graphene heat spreaders on the temperature and current-voltage characteristics of GaN HEMT using the numerical simulation in the hydrodynamic model. It is possible to optimize the structure and parameters of the heat spreaders.

Nomenclature

T_L	lattice temperature
T_e	electron temperature
I_d	drain current
V_d	drain voltage
T_m	maximum lattice temperature in HEMT without a heat spreader
T_{ms}	maximum lattice temperature in HEMT with a heat spreader

2. The model and numerical method

We consider a two-dimensional geometry of GaN HEMT, similar (Wang et al. (2013)). It is schematically shown in Fig. 1. The semiconductor structure includes a 5 μm thick substrate (as the substrate material used silicon carbide or sapphire), a 1.5 μm thick GaN buffer layer, a 20 nm thick $Al_{0.27}Ga_{0.73}N$ barrier layer and 50 nm thick Si_3N_4 passivation layer. The gate length is 0.5 μm, the distance between source and gate is 2.4μm and the distance between gate and drain is 9μm. The thermal conductivity of the materials at 300K are presented in Table 1, and its temperature dependence is taken as in (Wang et al. (2013)).

Table 1. The thermal conductivity of the materials at 300K.

Material	GaN	AlGaN	Si_3N_4	Substrate SiC/Al_2O_3	Diamond	Graphene-graphite
Thermal conductivity, $\frac{W}{cm \cdot K}$	1.3	1.765	0.2	3.7/0.3	10	20

The simulation was performed in the program Sentaurus TCAD from Synopsys in the hydrodynamic model using the finite element method.

3. Results

Fig. 2 shows the temperature distribution along the channel of the transistor without the heat spreader at different values of drain voltage. From this figure, it is possible to observe that the hot spot has a size of about one micrometer and it is located between the gate and drain near the gate edge. The hot spot appears only at high drain voltages (~10V), before the temperature in the channel is uniformly distributed.

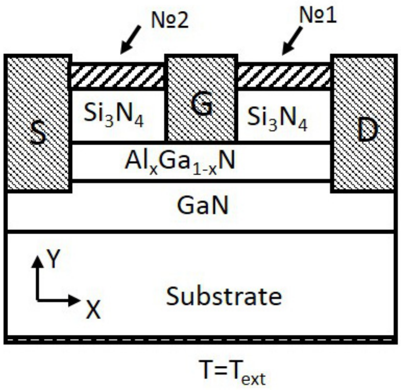

Fig. 1. AlGaN/GaN HEMT structure.

After we determine the position of the hot spots, the diamond heat spreader is placed in the area between the gate and drain (№1 in fig.1), in contrast to (Wang et al. (2013)), where it is additionally located between the gate and source (№2 in Fig. 1). Since diamond is an insulator, it can be done. We considered the thermal conductivity of diamond is equal to 10 W/(cm*K). The X size of the diamond heat spreader is the distance between the gate and drain, i.e. 9 μm. Fig. 3 shows (a) the lattice temperature, (b) the electron temperature distribution along the transistor channel in HEMT with (dash line) and without (solid line) the diamond heat spreader. The thickness of the heat spreader $L_{Spread} = 1 \mu m$, the drain voltage $V_d = 20V$. From fig. 3, it is possible to observe that the maximum electron and lattice temperatures are considerably reduced due to the heat spreader. It should be noted that the heat spreader reduces the maximum temperature and the temperature in the region below the transistor gate (which is indicated in the figures by vertical straight lines). This region plays an important role.

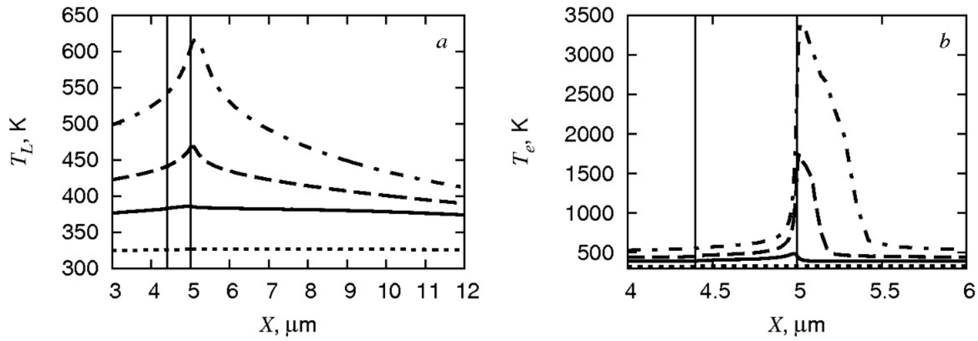

Fig. 2. The (a) lattice, (b) electron temperature in AlGaN/GaN HEMT without the diamond heat spreader as a function of the coordinate x along the device channel. The substrate material is Al_2O_3. $V_d = 4V$ (dotted line), $V_d = 8V$ (solid line), $V_d = 12V$ (dashed line), $V_d = 20V$ (dash dotted line). The gate voltage is zero.

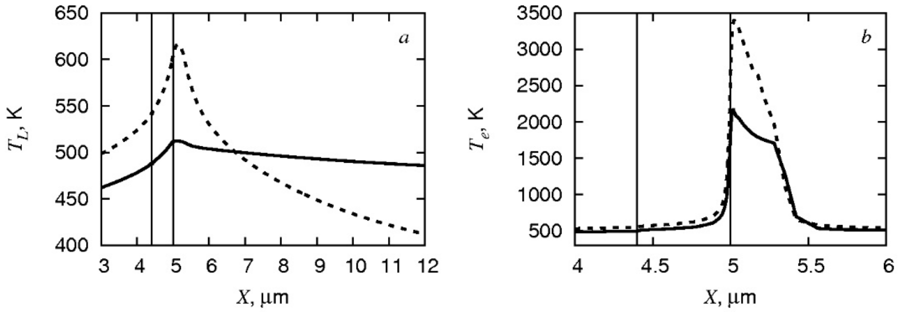

Fig. 3. The (a) lattice, (b) electron temperature in AlGaN/GaN HEMT with (solid) and without (dotted line) diamond heat spreader as a function of the coordinate x along the device channel. V_d = 20V. The substrate material is Al_2O_3. The gate voltage is zero.

Fig. 4 shows the dependence of the heat spreader efficiency

$$\eta_T = \frac{\Delta T_m}{T_m}, \Delta T_m = T_m - T_{ms} \quad (1)$$

as a function of the diamond heat spreader thickness L_{Spread} at different values of drain voltage and different substrate materials. Efficiency of the heat spreader has a maximum value at L_{Spread} = 0.25μm and at larger thicknesses practically unchanged. Also, note that the difference in the heat spreader efficiency for different substrates is small. However, the maximum temperature of the device in the case of using a substrate with low thermal conductivity (sapphire) is significantly higher than when using the high thermal conductive substrate (silicon carbide). Therefore, the value of ΔT_m is significantly higher for sapphire substrate, for example, at V_d= 40V and L_{Spread} = 10μm ΔT_m = 263K for sapphire and ΔT_m = 163K for silicon carbide.

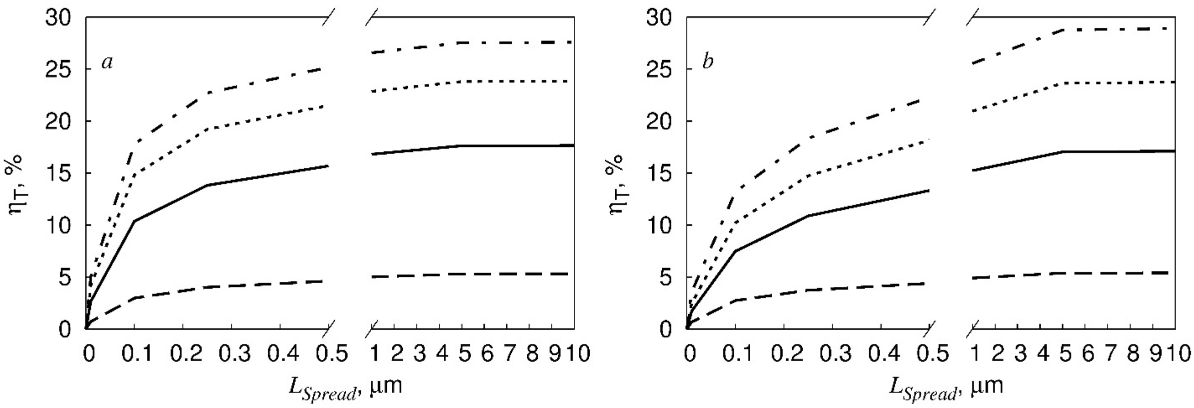

Fig. 4. The heat spreader efficiency as a function of the heat spreader thickness. The substrate material is (a) Al_2O_3, (b) SiC. V_d =10V (dashed line), V_d = 20V (solid line), V_d = 30V (dotted line), V_d = 40V (dash dotted line). The gate voltage is zero.

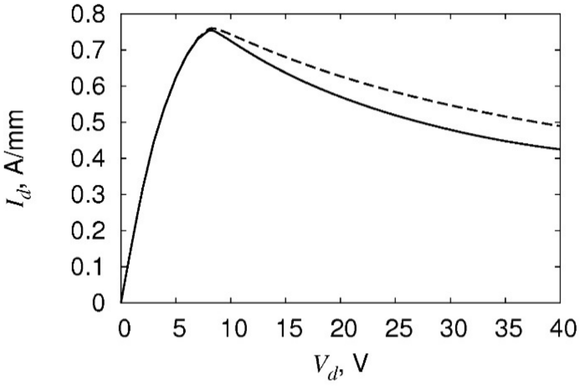

Fig. 5. Drain current as a function of drain voltage. The gate voltage is zero. The substrate material is Al_2O_3.

We have considered another configuration of the heat spreader, as in (Yan et al. (2012)). In this case, the heat spreader is composed of few layers of graphene (FLG) and placed on the drain contact. There is an additional heat sink located at the distance 10 μm from the drain contact. We investigated the influence of the FLG thickness on the maximum device temperature. We have shown that the influence of the FLG heat spreader can be neglected up to its thickness of about 10 nm.

4. Conclusion

We performed numerical simulation in hydrodynamic model to study the influence of diamond and graphene heat spreaders on AlGaN/GaN HEMT characteristics. It was shown that the hot spots in our HEMT structure (fig.1) is formed near the edge of the gate, and maximum electron and lattice temperature can be reduced significantly by introduction of the diamond heat spreader (№1 fig.1). In addition, it was shown that FLG heat spreader starts to work effectively only if it thickness is greater than 10nm.

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