Influence of the Diamond Layer on the Electrical Characteristics of AlGaN/GaN High-Electron-Mobility Transistors *

Xue-Feng Zheng(郑雪峰)[1**], Ao-Chen Wang(王奥琛)[1], Xiao-Hui Hou(侯晓慧)[2], Ying-Zhe Wang(王颖哲)[1], Hao-Yu Wen(文浩宇)[1], Chong Wang(王冲)[1], Yang Lu(卢阳)[1], Wei Mao(毛维)[1], Xiao-Hua Ma(马晓华)[1], Yue Hao(郝跃)[1]

[1]*Key Laboratory of Wide Bandgap Semiconductor Materials and Devices, School of Microelectronics, Xidian University, Xi'an 710071*

[2]*School of Computer Science and Technology, Xidian University, Xi'an 710071*

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The thermal management is an important issue for AlGaN/GaN high-electron-mobility transistors (HEMTs). In this work, the influence of the diamond layer on the electrical characteristics of AlGaN/GaN HEMTs is investigated by simulation. The results show that the lattice temperature can be effectively decreased by utilizing the diamond layer. With increasing the drain bias, the diamond layer plays a more significant role for lattice temperature reduction. It is also observed that the diamond layer can induce a negative shift of threshold voltage and an increase of transconductance. Furthermore, the influence of the diamond layer thickness on the frequency characteristics is investigated as well. By utilizing the 10-μm-thickness diamond layer in this work, the cutoff frequency $f_{\rm T}$ and maximum oscillation frequency $f_{\rm max}$ can be increased by 29% and 47%, respectively. These results demonstrate that the diamond layer is an effective technique for lattice temperature reduction and the study can provide valuable information for HEMTs in high-power and high-frequency applications.

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Due to the advanced material properties, AlGaN/GaN high electron mobility transistors (HEMTs) are considered to be promising candidates for high-voltage and high-power applications.[1–3] Within these areas, the channel temperature is much higher than that in conventional devices, which can cause significant device performance degradation, such as drain current, operation frequency, gain, and output power.[4,5] Meanwhile, it also affects the long-term reliability of HEMTs. Therefore, the thermal management is becoming an important issue that needs to be solved for AlGaN/GaN HEMTs.

In previous works, it was demonstrated that the highest temperature in GaN-based HEMTs occurs near the device channel, which is commonly referred as the hot spot.[6,7] Then, hot spots play an important role in thermal management. In recent years, the diamond layer is proposed to solve this problem, which is selectively deposited on the surface of the device and is referred to as the diamond heat spreader. Experimental data have shown that the thermal conductivity of chemical vapor deposited (CVD) polycrystalline diamond can even reach up to 2000 W/m·K,[8] which is much higher than most of the materials before. Therefore, a great deal of attention has been paid to eliminating the hot spots in HEMTs recently. In 2011, Anderson *et al.* firstly observed that the temperature in AlGaN/GaN HEMTs can be reduced with the aid of a diamond heat spreader.[9] Utilizing the simulation technique, Wang *et al.* studied the effect of the diamond heat spreader on the temperature and output characteristics.[10] Although preliminary works have been carried out, the effect of the diamond heat spreader on the frequency characteristics of AlGaN/GaN HEMTs is still missing to the best of our knowledge.

The aim of this work is to gain insights into the influence of the diamond layer on device performance in AlGaN/GaN HEMTs. Based on the hydrodynamic model, the dependence of lattice temperature and electrical characteristics on the diamond layer are analyzed. Moreover, the effect of the diamond layer thickness on the frequency characteristics is studied.

A typical AlGaN/GaN HEMT structure with a diamond layer as shown Fig. 1(a), is used for simulation in this work. The epitaxial structure is grown on a SiC substrate, including a 1.5-μm-thick GaN buffer layer and a 20-nm-thick $Al_{0.27}Ga_{0.73}N$ barrier layer. A 50 nm Si_3N_4 layer is used for surface passivation and a 1 μm diamond layer is deposited on it sequentially. The gate length $L_{\rm g}$, the source-to-gate distance $L_{\rm gs}$ and the drain-to-gate distance $L_{\rm gd}$ are 0.6 μm, 1 μm, and 2.4 μm, respectively. For comparison, an identical AlGaN/GaN HEMT without the diamond layer is also used in this work, as shown in Fig. 1(b).

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**Corresponding author. Email: xfzheng@mail.xidian.edu.cn

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The simulation is performed by the commercial Sentaurus TCAD simulator with the hydrodynamic model, which considers the energy transfer of the carrier and is suitable for short-channel devices compared with the drift-diffusion and thermodynamic models.[11] The thermal conductivity of the materials used in this work is presented in Table 1.[10]

Table 1. The thermal conductivity of the materials used in this work.

Material	SiC	GaN	AlGaN	Si_3N_4	Diamond
Thermal conductivity ($W{\cdot}cm^{-1}{\cdot}K^{-1}$)	$4.55\times(300/T)$	$1.3\times(300/T)^{1.4}$	$1.765\times(300/T)^{1.4}$	0.2	10

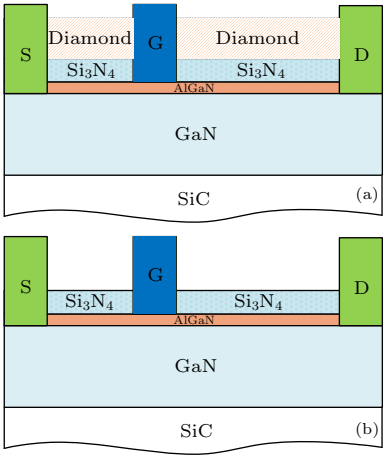

Fig. 1. Cross-section schematic illustration of AlGaN/GaN HEMTs (a) with and (b) without the diamond layer.

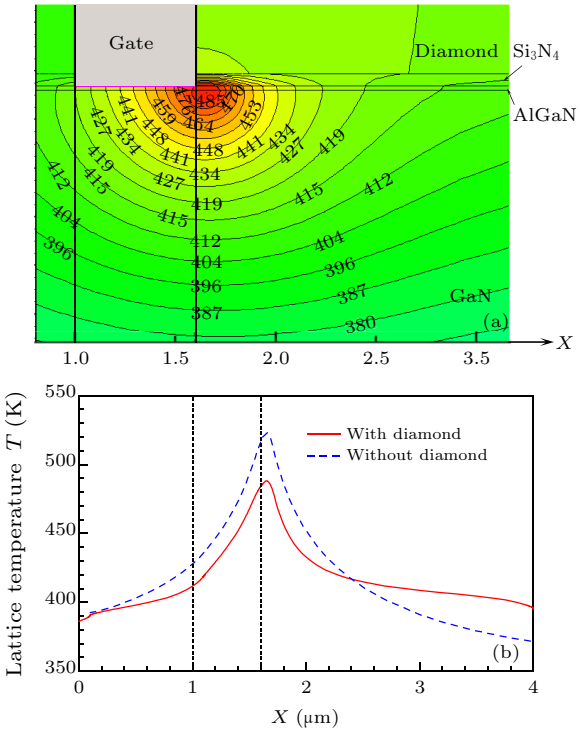

Fig. 2. (a) The lattice temperature distribution simulated by Sentaurus TCAD with the hydrodynamic model in AlGaN/GaN HEMT with the diamond layer, and (b) the influence of the diamond layer on temperature in AlGaN/GaN HEMTs. During simulation, the drain bias V_{ds} and the diamond layer thickness are 20 V and 1 μm, respectively. Here X indicates the distance from the source electrode.

To evaluate the influence of the diamond layer on device performance, the lattice temperatures of AlGaN/GaN HEMT are simulated firstly in this work. During simulation, the thermal boundary condition of the diamond layer is set as an adiabatic condition. In this work, all temperature results are extracted from the location that is 1 nm below the AlGaN/GaN interface, which is in the 2DEG channel. During simulation, the drain bias V_{ds} and the thickness of the diamond layer $t_{diamond}$ are set as 20 V and 1 μm, respectively. The lattice temperature distribution in AlGaN/GaN HEMT with the diamond layer is shown in Fig. 2(a). To gain a quantitative analysis, the temperature along the channel in HEMTs with and without the diamond layer are compared in Fig. 2(b), respectively. It is clearly observed that the peak lattice temperature can be reduced from 523 K to 488 K with the aid of the diamond layer, indicating that the diamond layer has a significant influence on the lattice temperature reduction in HEMTs. The result is consistent with that observed in AlGaN/GaN HEMTs with a sapphire substrate.[12] Moreover, it also obviously presents that the highest temperature occurs at the gate edge near the drain, which is consistent with the results that were observed by the electroluminescence spectrum and referred to as hot spots.[13]

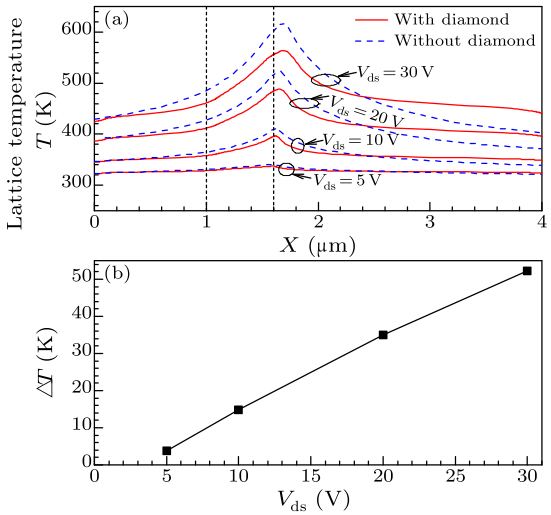

Fig. 3. (a) The lattice temperature distribution along the channel in AlGaN/GaN HEMTs with and without the diamond layer under different drain biases. (b) The peak lattice temperature shift ΔT versus the drain bias V_{ds}. The thickness of the diamond layer is 1 μm. The drain biases are 5 V, 10 V, 20 V and 30 V, respectively.

It is known that the lattice temperature is strongly

dependent on the power dissipation, which is generally related to the drain bias in AlGaN/GaN HEMTs. To study it, the temperature distribution under different drain biases is simulated, which is shown in Fig. 3(a). It is noted that the reduction of peak temperature is also severely affected by the drain bias. Figure 3(b) shows the peak lattice temperature shift ΔT between HEMTs with and without the diamond layer under different drain biases. When the drain bias is as low as 5 V, the peak temperature shift is negligible. This is because the power dissipation is insignificant under a low drain bias, which will not cause an obvious lattice temperature increasing. Accordingly, the application of the diamond layer is not critical for the device. When the drain bias increases to 30 V, the temperature shift can even reach up to 52 K, indicating the good heat dissipation effect of the diamond layer. This is because the power dissipation is much higher under the high drain bias, and can cause severe self-heating effect accordingly. Generally, the higher drain bias will induce a higher lattice temperature, i.e., the temperature difference between the channel and ambient is larger, and more heat can be conducted to the ambient via diamond layer. Thus the lattice temperature in the channel can be decreased obviously. We can conclude that the diamond layer is a very effective technique for HEMTs in high-power applications.

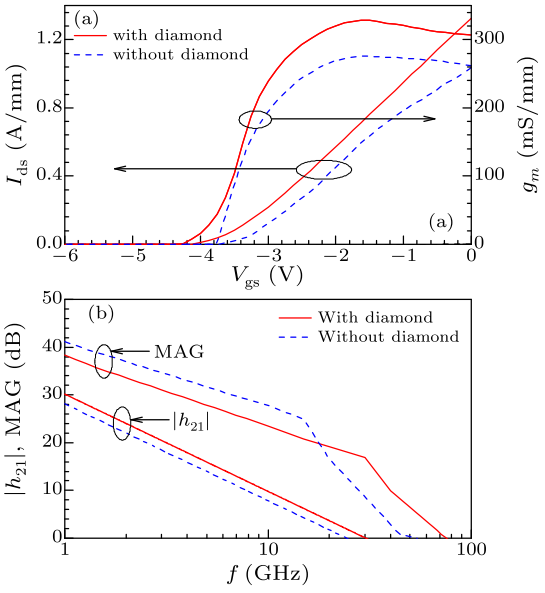

Fig. 4. (a) The transfer characteristic curves, and (b) the current gain and maximum available gain versus frequency curve for AlGaN/GaN HEMTs with and without the diamond layer. The thickness of the diamond layer is 1 μm and the drain bias is 30 V.

Figure 4(a) shows the influence of the diamond layer on the dc characteristics of AlGaN/GaN HEMTs. In comparison with the conventional HEMT, the threshold voltage of the HEMT with the diamond layer has an evident negative shift. It is claimed that the stress induced by the diamond layer can cause the increase of the two-dimensional electron gas (2DEG) density under the gate electrode.[14,15] Then a more negative gate bias is required to deplete it. The changes of the negative shift of the threshold voltage and the increasing drain current are consistent with the results in the previous works.[14–16] Meanwhile, it is also observed that the transconductance increases with the aid of the diamond layer. It can be attributed to the increasing channel electron mobility under the lower lattice temperature with the aid of the diamond layer.

In addition to the dc characteristics, the frequency characteristic is more attractive due to the application of AlGaN/GaN HEMTs in high-frequency areas. However, the influence of the diamond layer on the frequency characteristic has not been studied to the best of our knowledge. Figure 4(b) presents the curves of current gain and maximum available gain versus frequency for HEMTs with and without the diamond layer. The drain bias here is 30 V, which meets the requirement for GaN-based HEMTs. As shown in Fig. 4(b), the cutoff frequencies f_T for AlGaN/GaN HEMTs with and without the diamond layer are 30.3 GHz and 24.4 GHz, respectively. The maximum oscillation frequencies f_{max} for AlGaN/GaN HEMTs with and without the diamond layer are 75.3 GHz and 53.6 GHz. It is indicated that the utilization of the diamond layer can effectively improve the frequency performance of GaN HEMTs.

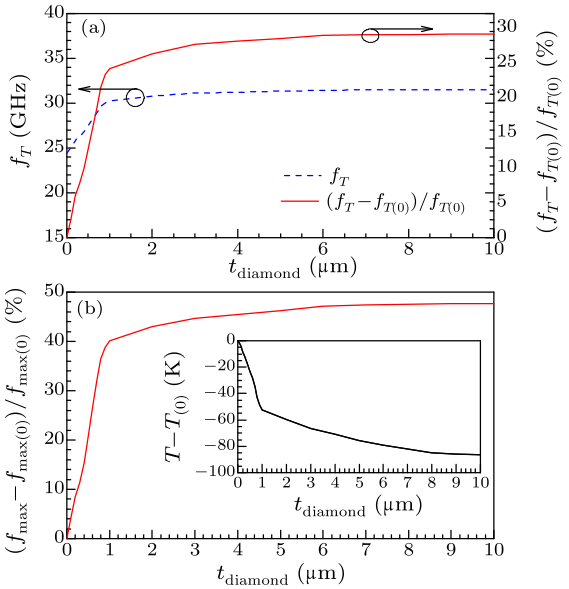

Fig. 5. The impact of the diamond layer thickness $t_{diamond}$ on (a) the cutoff frequency characteristic, and (b) the maximum oscillation frequency characteristic in AlGaN/GaN HEMTs. The inset gives the change of lattice temperature versus the diamond layer thickness. The drain bias is 30 V. Here $f_{T(0)}$, $f_{max(0)}$ and $T_{(0)}$ represent the cutoff frequency, maximum oscillation frequency and lattice temperature for HEMTs without the diamond layer.

It is known that the thickness of the diamond layer has an effect on the heat dissipation, which will affect

the lattice temperature in the channel accordingly. To study it, the impact of the diamond layer thickness on the frequency characteristics of HEMTs are investigated in this work, which is not studied in previous works. Figure 5(a) gives the curves of cutoff frequency f_{T} versus the diamond layer thickness t_{diamond} in AlGaN/GaN HEMTs under the drain bias of 30 V. In comparison with the HEMT without the diamond layer, f_{T} can be improved from 24.4 GHz to 31.5 GHz when the diamond layer is up to 10 μm, indicating a 29% increase. It is also observed that f_{T} increases rapidly within 1 μm, while it becomes saturated gradually when t_{diamond} is larger than 1 μm. It corresponds to the trend of lattice temperature with increasing the diamond layer thickness, which is given in the inset of Fig. 5(b). It is known that more heat can be absorbed and dissipated to the diamond surface via the thicker diamond layer. Therefore, we can observe that the diamond layer plays a significant role in lattice temperature reduction firstly. However, when the diamond layer is thick enough, it will decrease the heat conduct efficiency. Then we can observe that the temperature becomes saturated. Figure 5(b) gives the relationship between the maximum oscillation frequency f_{max} and t_{diamond}. With the diamond layer getting thicker, f_{max} can be increased by 25.5 GHz when t_{diamond} reaches 10 μm, indicating a 47% increase compared to that in HEMT without the diamond layer. According to the above results, we can conclude that the diamond layer is an effective technique to improve the device high-frequency performance.

In conclusion, the effect of the diamond layer on the electrical characteristics of AlGaN/GaN HEMTs has been investigated by means of simulation. It is shown that the lattice temperature can be effectively decreased by utilizing the diamond layer. Moreover, the diamond layer plays a significant role under the higher drain bias. Using the diamond layer, the threshold voltage has a negative shift and the transconductance increases. The influence of the diamond layer thickness on the frequency characteristics is investigated as well. Utilizing the 10-μm-thickness diamond layer, the cutoff frequency f_{T} and the maximum frequency f_{max} can be increased by 29% and 47%, respectively. These results can provide valuable information of the performance enhancement and reliability improvement of AlGaN/GaN HEMTs.

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