Influence of Phonon Ballistic Transport on Electrical Performance of GaN HEMTs

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1. Introduction
2. Methodologies
3. Results and Discussion
4. Conclusion

Non-Fourier Heat Conduction in GaN HEMTs

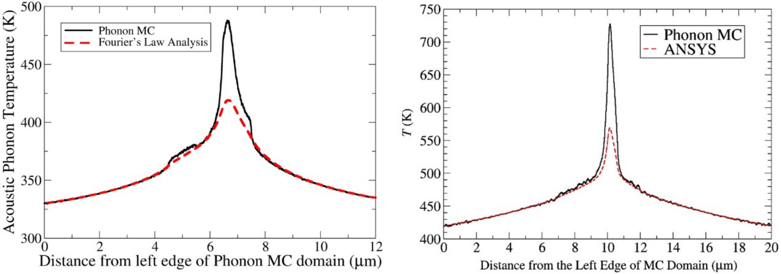

Figure 1: Comparison of channel temperature between phonon MC simulation and Fourier's law calculation[1,2].

Phonon ballistic transport can significantly increase the channel temperature.

[1] Q. Hao, H. Zhao, and Y. Xiao, "A hybrid simulation technique for electrothermal studies of two-dimensional GaN-on-SiC high electron mobility transistors," *Journal of Applied Physics*, vol. 121, no. 20, p. 204 501, 2017.

[2] Q. Hao, H. Zhao, Y. Xiao, *et al.*, "Electrothermal studies of GaN-based high electron mobility transistors with improved thermal designs," *International Journal of Heat and Mass Transfer*, vol. 116, pp. 496–506, 2018.

Phonon Transport Mechanism

Cross-plane ballistic effect: Phonon MFPs comparable with the thickness of GaN layer

Heat source-related ballistic effect: Phonon MFPs comparable with the width of heat generation area.

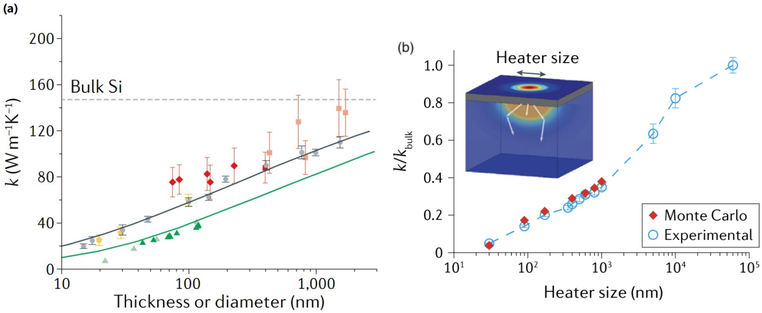

Figure 2: (a)Thermal conductivity versus film thickness or nanowire diameter. (b) Effective conductivity versus varying heater sizes[3].

[3] G. Chen, "Non-fourier phonon heat conduction at the microscale and nanoscale," *Nature Reviews Physics*, vol. 3, no. 8, pp. 555–569, 2021.

Bias-Dependent Phonon Transport

Cross-plane ballistic effect caused by phonon-boundary scattering is only controlled by film thickness.
Heat source-related ballistic effect is highly bias-dependent.

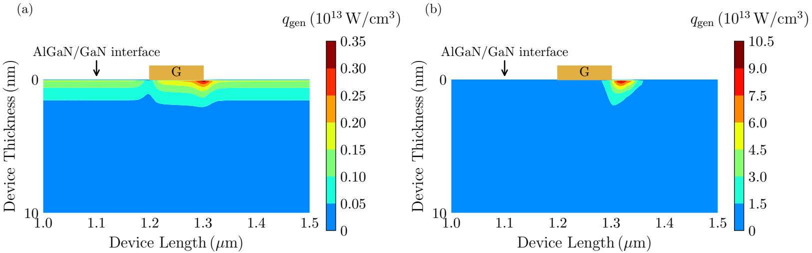

Figure 3: Heat source distributions at different biases with $P_{\text{diss}} = 5\,\text{W/mm}$, (a) $V_g = 2\,\text{V}$, $V_d = 3.8\,\text{V}$, (b) $V_g = -1\,\text{V}$, $V_d = 6.7\,\text{V}$[4].

[4] Y. Shen, X.-S. Chen, Y.-C. Hua, *et al.*, "Bias dependence of non-fourier heat spreading in gan hemts," *IEEE Transactions on Electron Devices*, vol. 70, no. 2, pp. 409–417, 2022.

Influence on Electrical Performance

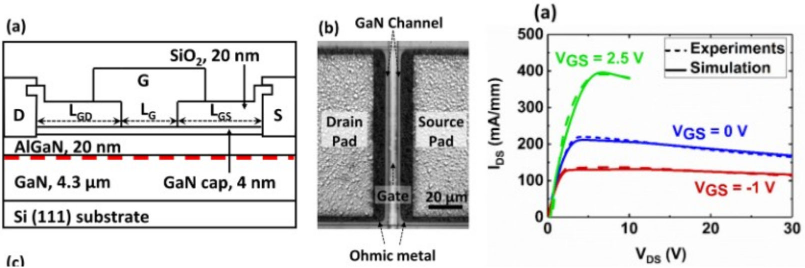

Figure 4: Left: Schematic cross-sectional view of the symetric AlGaN/GaN HEMT, $L_{\mathrm{G}} = 2\,\mu\mathrm{m}$, $L_{\mathrm{GS}} = L_{\mathrm{GD}} = 3\,\mu\mathrm{m}$. Right: Output characteristics of the AlGaN/GaN HEMT. Test data and simulation show excellent agreement.[5]

Electrothermal simulation is based on Fourier's law with film thermal conductivity.

[5] B. Chatterjee, C. Dundar, T. E. Beechem, *et al.*, "Nanoscale electro-thermal interactions in AlGaN/GaN high electron mobility transistors," *Journal of Applied Physics*, vol. 127, no. 4, p. 044 502, 2020.

Influence on Electrical Performance

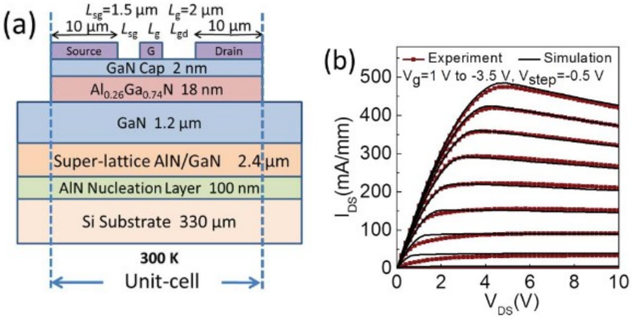

Figure 5: (a) Schematic of lateral AlGaN/GaN HEMT structures on Si substrates. (b) Comparison between simulation and experiment DC output characteristics of a single finger lateral HEMT[6].

The excellent agreement is geometry- and bias-independent.

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[6] Y. Zhang, M. Sun, Z. Liu, *et al.*, "Electrothermal simulation and thermal performance study of gan vertical and lateral power transistors," *IEEE transactions on electron devices*, vol. 60, no. 7, pp. 2224–2230, 2013.

This Work

Objective

- Try figuring out the influence of phonon ballistic effects on the electrical performance of GaN HEMTs.

Electrothermal TCAD simulation and Phonon Monte Carlo simulation are conducted to investigate self-heating in GaN HEMTs.

TCAD Simulation

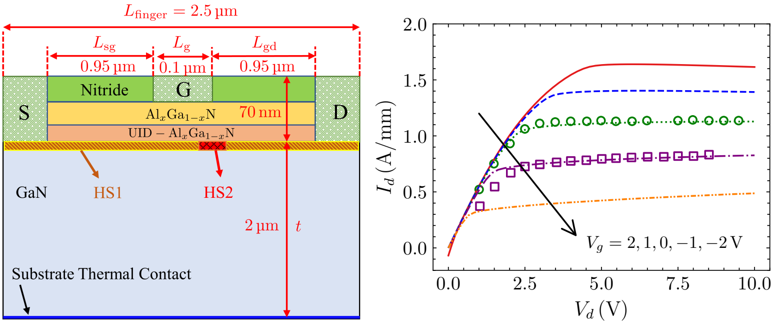

Figure 6: Left: Schematic of the GaN-on-SiC HEMT for TCAD simulation. Right: Output characteristics of the HEMT from -2 V to 2 V with an interval of 1 V extracted from TCAD simulations (lines) and experimental values (symbols).

Phonon Monte Carlo Simulation

- An isotropic sine-shaped phonon dispersion (Born-von Karman dispersion) is used for GaN and SiC,

$$\omega(k) = \omega_{\mathrm{m}} \sin\left(\pi k / 2k_{\mathrm{m}}\right)$$
$$k_{\mathrm{m}} = \left(\frac{6\pi^2 N}{V}\right)^{1/3}, \; a = \pi / k_{\mathrm{m}}, \; \omega_{\mathrm{m}} = 2v_{0g}/a$$

- Relaxation time is calculaed using Matthiessen's rule,

$$\tau^{-1} = \tau_{\mathrm{I}}^{-1} + \tau_{\mathrm{U}}^{-1} = A\omega^4 + B\omega^2 T \exp(-C/T)$$

- Diffuse mismatch model (DMM) is used for interfacial phonon transport,

$$T_{12}(\omega) = \frac{\sum_p v_{2,g,p}(\omega) D_{2,p}(\omega)}{\sum_p v_{1,g,p}(\omega) D_{1,p}(\omega) + \sum_p v_{2,g,p}(\omega) D_{2,p}(\omega)}$$

Phonon Dispersion and Relaxation time

Table 1: Fitted phonon dispersion and scattering parameters[7].

Parameter (Unit)	GaN	SiC
$k_0\,(1 \times 10^9\,\mathrm{m}^{-1})$	10.94	8.94
$\omega_m\,(1 \times 10^{13}\,\mathrm{rad/s})$	3.50	7.12
$a_D\,(\text{Å})$	2.87	3.51
$A\,(1 \times 10^{-45}\,\mathrm{s}^3)$	5.26	1.00
$B\,(1 \times 10^{-19}\,\mathrm{s/K})$	1.10	0.596
$C\,(\mathrm{K})$	200	235.0

[7] Q. Hao, H. Zhao, and Y. Xiao, "A hybrid simulation technique for electrothermal studies of two-dimensional GaN-on-SiC high electron mobility transistors," *Journal of Applied Physics*, vol. 121, no. 20, p. 204 501, 2017.

Phonon Dispersion and Relaxation time

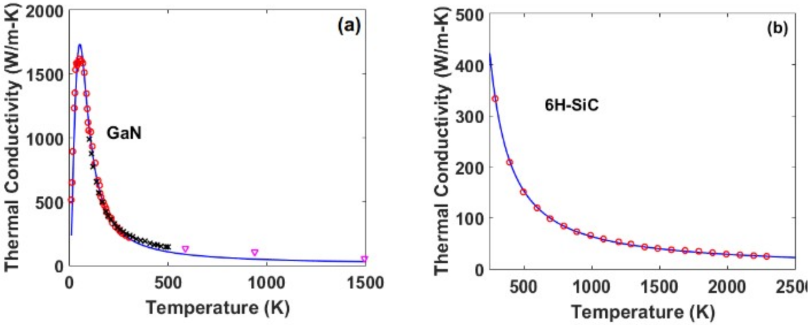

Figure 7: Thermal conductivity from model calculations (line), and from experiments (symbols)[8].

[8] Q. Hao, H. Zhao, and Y. Xiao, "Multi-length scale thermal simulations of GaN-on-SiC high electron mobility transistors," in *MultiscaleThermal Transport in Energy Systems*, Nova Science Publishers, 2016.

Channel Temperature Distribution

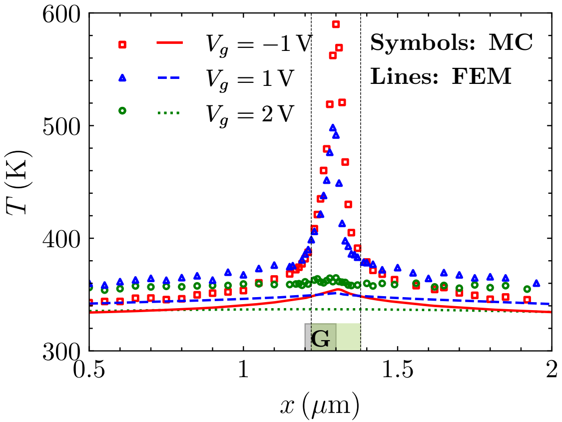

Figure 8: Comparison of channel temperature distributions predicted by MC simulation and FEM with k_{bulk} at different biases with $P_{\text{diss}} = 5\,\text{W/mm}$.

Two-Heat-Source Model[9]

$$\begin{cases} P_1 = I_d V_d, P_2 = 0, & V_d \leq V_{\mathrm{dsat}} \\ P_1 = I_d V_{\mathrm{dsat}}, P_2 = I_d \left(V_d - V_{\mathrm{dsat}} \right), & V_d > V_{\mathrm{dsat}} \end{cases}$$

$V_d \leq V_{\mathrm{dsat}}$: When the device is in the linear regime, all the heat is dissipated in HS1.
$V_d > V_{\mathrm{dsat}}$: As the channel is pinched-off and the device works in the saturation regime, the heat dissipated in HS1 stays the maximum, and excessive heat is only dissipated in HS2.

The heat source-related ballistic effect becomes noticeable when heat is dissipated in HS2.

[9] X. Chen, S. Boumaiza, and L. Wei, "Modeling bias dependence of self-heating in GaN HEMTs using two heat sources," *IEEE Transactions on Electron Devices*, vol. 67, no. 8, pp. 3082–3087, 2020.

Channel Temperature Reconstruction

We use size-dependent film thermal conductivity to reflect the cross-plane ballistic effect, and set a very low thermal conductivity in HS2 to reflect the impact of heat source size-induced ballistic effect.

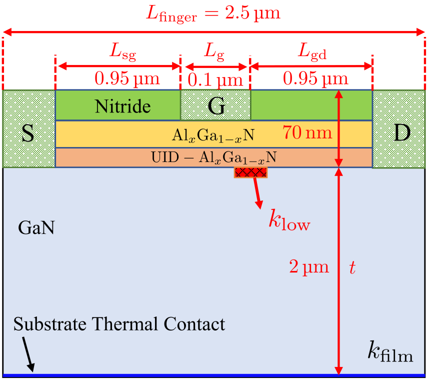

Figure 9: Schematic of channel temperature reconstruction.

Channel Temperature Reconstruction

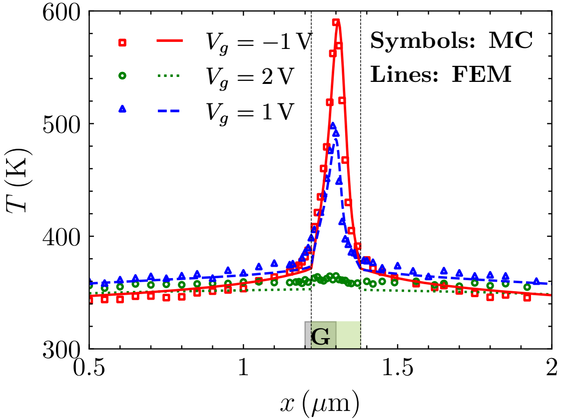

Figure 10: Comparison of channel temperature distributions predicted by MC simulation and FEM with k_{eff} at different biases with $P_{\text{diss}} = 5\,\text{W}/\text{mm}$.

Influence of Heat Source-Related Ballistic Effect

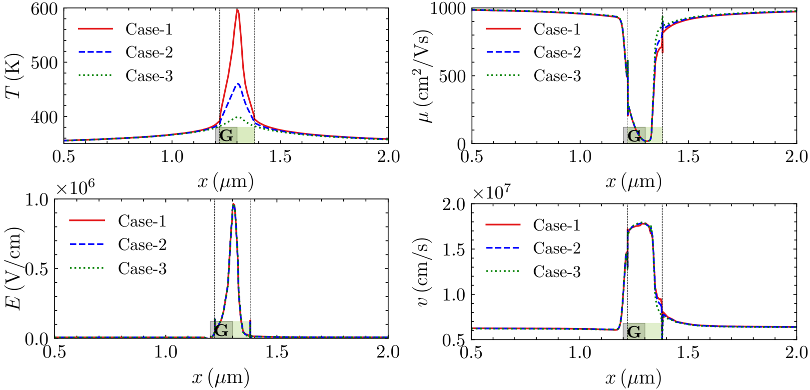

Figure 11: Channel temperature, electron velocity, electric field, and electron mobility distributions at $V_g = -1\,\text{V}$, $V_d = 6.7\,\text{V}$.

Device Output Characteristics

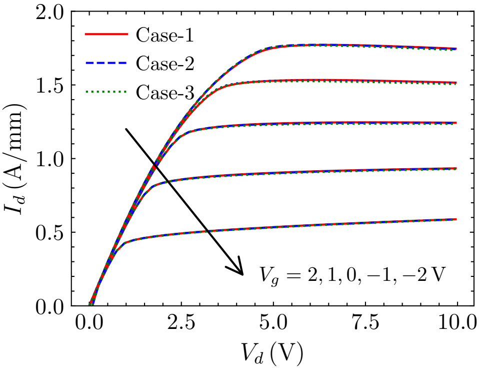

Figure 12: Output characteristics at different biases.

Phonon ballistic effect mainly exists in the high-field region, where the electron velocity is saturated.

Simulation of Longer Gate HEMT

$$L_g = 1\,\mu\text{m},\ L_{sg} = 1\,\mu\text{m},\ L_{gd} = 3\,\mu\text{m}$$

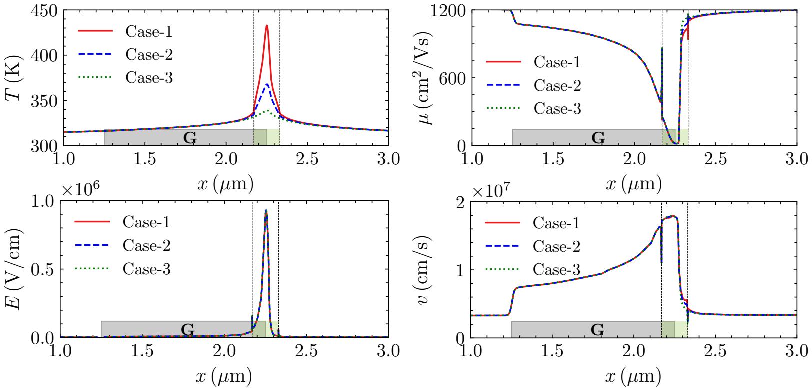

Figure 13: Channel temperature, electron velocity, electric field, and electron mobility distributions at $V_g = -1$ V, $V_d = 6.7$ V.

Device Output Characteristics

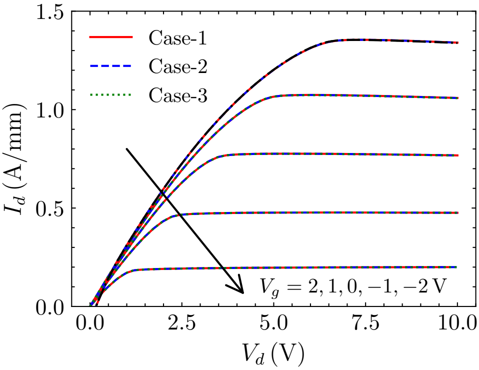

Figure 14: Output characteristics at different biases.

For a longer gate HEMT, the source side of gated channel is not saturated. However, the heat source is still concentrated at drain-side gate edge.

Influence of Cross-Plane Ballistic Effect

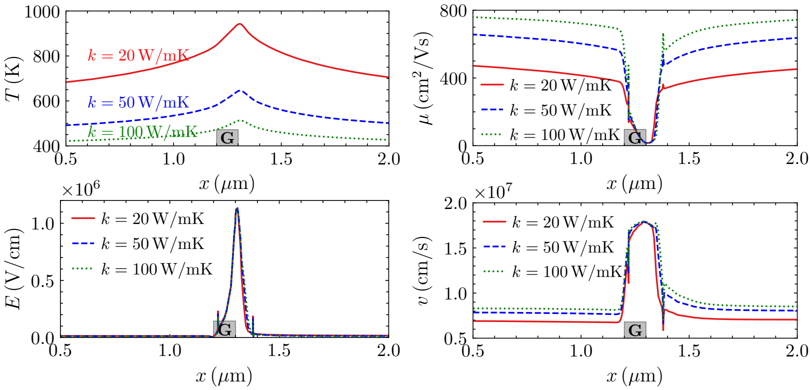

Figure 15: Channel temperature, electron velocity, electric field, and electron mobility distributions at $V_g = 0$ V, $V_d = 10$ V.

Device Output Characteristics

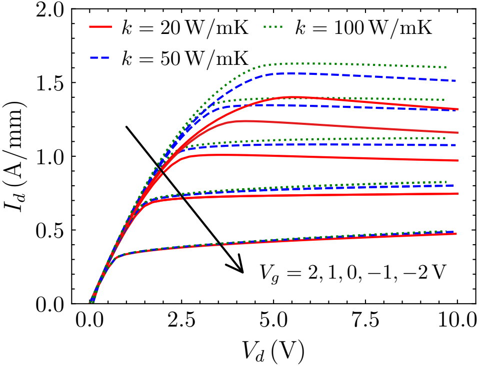

Figure 16: Output characteristics at different biases.

Equivalent Channel Temperature[10]

$$T_{\mathrm{eq}}\,(V_{\mathrm{GS}}, V_{\mathrm{DS}}) = T_{\text{uniform}}\,(V_{\mathrm{GS}}, V_{\mathrm{DS}})|_{@I_{\mathrm{DS},\ \text{self-heating}}} = I_{\mathrm{DS},\ \text{uniform}}$$

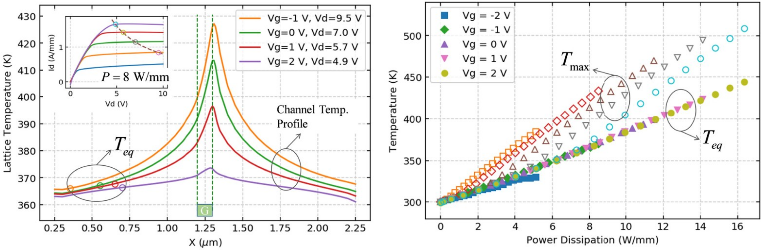

Figure 17: Left: channel temperature profiles at four different biases. Right: Equivalent channel temperature and maximum channel temperature versus the power dissipation.

All the conclusions remain reliable after considering phonon transport, no additional modifications are necessary.

[10] X. Chen, S. Boumaiza, and L. Wei, “Self-heating and equivalent channel temperature in short gate length GaN HEMTs,” *IEEE Transactions on Electron Devices*, vol. 66, no. 9, pp. 3748–3755, 2019.

Conclusion

We have investigated self-heating in GaN HEMTs by integrating TCAD and phonon MC simulations.

We have examined the influence of the phonon ballistic effect on electrical performance by setting a low local thermal conductivity in the high-field region and re-conducting electrothermal TCAD simulations.

Our findings reveal that, due to velocity saturation, the electrical performance is nearly unaffected by the heat source-induced ballistic effect. Instead, it is primarily governed by the film thickness-dependent cross-plane ballistic effect.

Thank You!