Bias Dependence of Non-Fourier Heat Conduction in GaN HEMTs

Yang Shen

Department of Engineering Mechanics, School of Aerospace Engineering,
Tsinghua University

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Overview

- Self-heating in GaN HEMTs can cause reliability issues and degrade the device performance. Being the result of Joule heating, self-heating is highly bias dependent.
- Previous studies on self-heating are mainly based on Fourier's law of heat conduction, the non-Fourier effects have not been studied quantitatively.
- We reexamined the bias dependence of self-heating in GaN HEMTs by TCAD and hybrid Monte Carlo-diffusion simulations, and developed a semi-empirical thermal resistance model which can take the bias dependence and phonon transport into account.

1. Introduction
   - Self-Heating in GaN HEMTs
   - Bias Dependence of Self-Heating
   - Phonon Ballistic Transport in GaN HEMTs
2. Device Structure and Simulation Details
3. Results and Discussion
4. Remaining Work
5. Program Development

Thermal Issues in GaN HEMTs

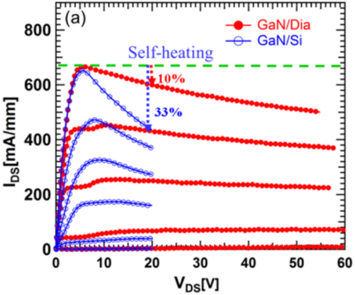

Figure 1: $I_{\mathrm{DS}} - V_{\mathrm{DS}}$ of GaN/Dia and GaN/Si HEMTs [3].

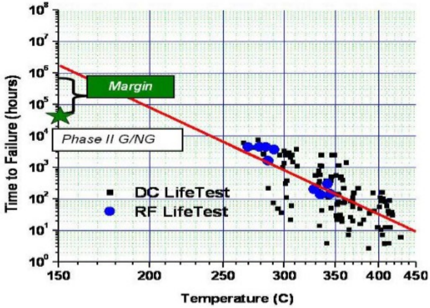

Figure 2: Mean time to failure (MTTF) for TriQuint GaN PAs [4].

The significant overheating within the devices largely degrades the electrical performance and shortens the device lifetime.

[1] K. Ranjan, S. Arulkumaran, G. Ng, *et al.*, “Investigation of self-heating effect on dc and rf performances in algan/gan hemts on cvd-diamond,” *IEEE Journal of the Electron Devices Society*, vol. 7, pp. 1264–1269, 2019.

[2] M. Rosker, C. Bozada, H. Dietrich, *et al.*, “The darpa wide band gap semiconductors for rf applications (wbgs-rf) program: Phase ii results,” *CS ManTech*, vol. 1, pp. 1–4, 2009.

Bias Dependence of Self-Heating

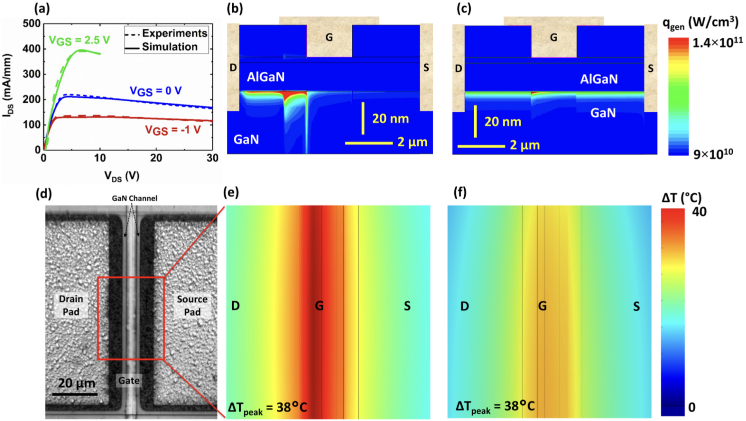

Figure 3: Bias dependent results for channel conditions with $V_{\mathrm{GS}} = -1\,\mathrm{V}$ and $V_{\mathrm{GS}} = 2.5\,\mathrm{V}$, respectively[3], $P_{\mathrm{diss}} = 250\,\mathrm{mW}$.

[3] 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.

Two Heat Source Model[4]

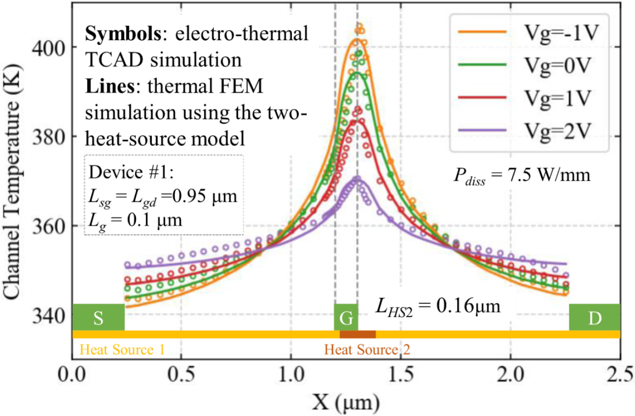

Figure 4: Temperature profiles across the channel at $P_{\text{diss}} = 7.5\,\text{W}/\text{mm}$ and the four different biases.

[4] 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.

Phonon Ballistic Transport

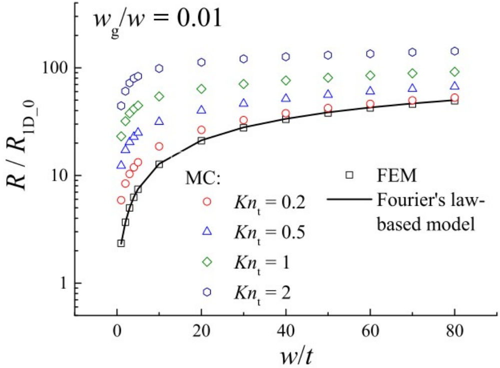

Figure 5: Dimensionless total thermal resistance as a function of w/t, with $w_g/w = 0.005$ and 0.01[5].

Phonon Ballistic Transport can significantly increase the thermal resistance.

[5] Y.-C. Hua, H.-L. Li, and B.-Y. Cao, "Thermal spreading resistance in ballistic-diffusive regime for gan hemts," *IEEE Transactions on Electron Devices*, vol. 66, no. 8, pp. 3296–3301, 2019.

This Work

Motivation

- Reexamine the self-heating effects in GaN HEMTs with the consideraton of phonon ballistic transport.

This Work

- TCAD and hybrid Monte Carlo-diffusion simulations were conducted to study the self-heating effects in GaN HEMTs, the two-heat-source model was improved to take the ballistic effects into consideration.

Device Structure[6]

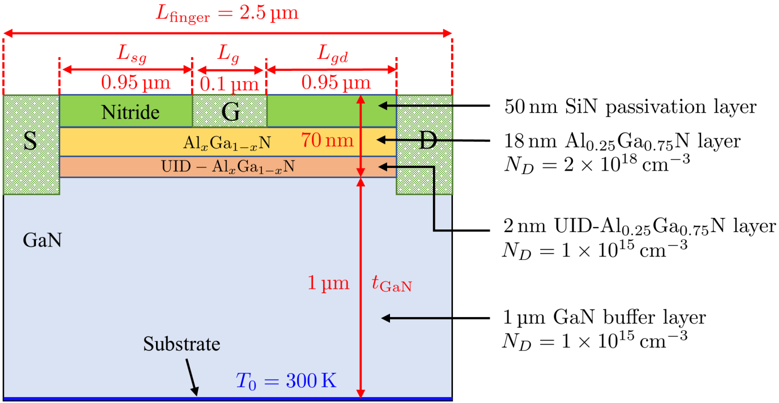

Figure 6: Schematic of GaN HEMT. The geometries are not drawn to scale.

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[6] 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.

Output Characteristics

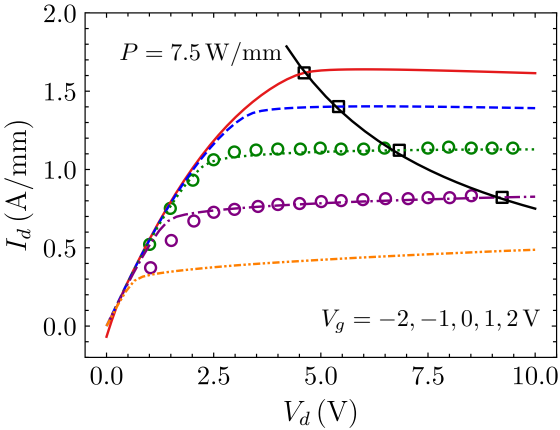
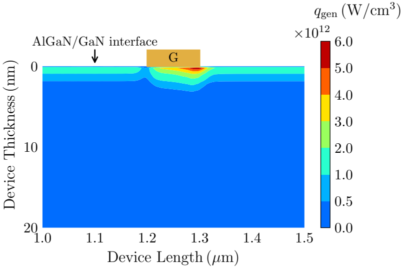


Figure 7: Output characteristics of the HEMT under V_g from $-2\,\mathrm{V}$ to $2\,\mathrm{V}$ with an interval of $1\,\mathrm{V}$.

Bias-Dependent Heat Generation



(a) $V_g = 2\,\text{V}$, $V_d = 4.5\,\text{V}$ (b) $V_g = -1\,\text{V}$, $V_d = 9.5\,\text{V}$

Figure 8: The total power dissipation level for the two bias condions, $P = 7.5\,\text{W/mm}$.

Phonon Monte Carlo Simulation

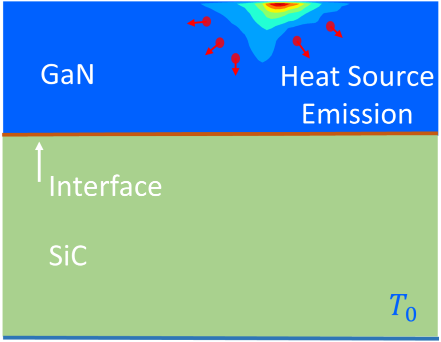


Figure 9: Schematic diagram of the simulated GaN HEMT, the Juole heating profile calculated by TCAD is imported to MC simulations as heat source.

Phonon Dispersion

- An isotropic sine-shaped phonon dispersion (Born-von Karman dispersion) is used.
- Longitudinal and transverse branches are not differentiated.

$$\omega(k) = \omega_{\max} \sin\left(\pi k / 2k_m\right)$$

$$k_m = \left(\frac{6\pi^2 N}{V}\right)^{1/3}, \; a = \pi / k_m, \; \omega_m = 2v_{0g}/a$$

Relaxation time

Matthiessen's rule:

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

Thermal conductivity fitting:

$$\mathscr{L}(A, B, C) = \sum \left\| \frac{1}{3} \sum_p \int_0^{\omega_m} C_\omega v_\omega l_\omega \mathrm{d}\omega - k_{exp} \right\|^2$$

$$C(\omega, p) = \hbar\omega D(\omega, p) \frac{\partial f^{BE}}{\partial T} = \hbar\omega \frac{\kappa^2}{2\pi^2 \left|v_g\right|} \frac{\hbar\omega e^{\frac{\hbar\omega}{Tk_B}}}{T^2 k_B \left(e^{\frac{\hbar\omega}{Tk_B}} - 1\right)^2}$$

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

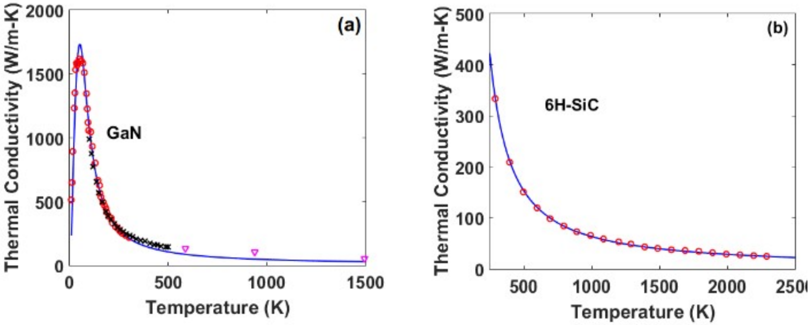


Figure 10: Thermal conductivity from model calculations (line), and from experiments (symbols)[8].

[8] Q. Hao, H. Zhao, Y. Xiao, *et al.*, "Multi-length scale thermal simulations of gan-on-sic high electron mobility transistors," in *Multiscale Thermal Transport in Energy Systems*, Nova Science Publishers, 2016.

Interface Phonon Transport

Based on diffuse mismatch model (DMM), phonons are diffusively transmitted or reflected by an interface.

The frequency-dependent phonon transmissivity from material 1 to 2 is given as

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

The thermal boundary resistance (TBR) can be further calculated by

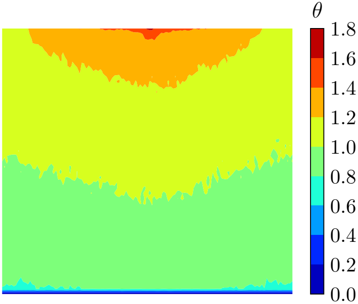
$$R = \frac{4}{\int T_{12} C_1(\omega) v_1(\omega) d\omega}$$

Validation of MC Code

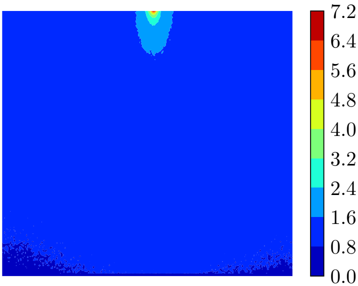
Table 2: TBR of GaN/SiC predicted by DMM and MC simulations (Unit: m^2K/GW)

DMM	Heat flux heating		Temperature difference heating	
	GaN emission	SiC emission	GaN emission	SiC emission
23.20	19.23	20.30	19.06	18.16

MC Simulations at Different Bias



(a) $V_g = 2\,\text{V}$, $V_d = 4.5\,\text{V}$



(b) $V_g = -1\,\text{V}$, $V_d = 9.5\,\text{V}$

Figure 11: Dimensionless temperature distribution predicted by MC simulations.

Remaining Work

- Figure out the simulation size dependence of the results, ensuring the validity of the simulation.
- Develop automated and parametric analysis process.
- Carry out TCAD simulations with different gate lengths.
- Investigate the hybrid algorithm with phonon dispersion considered, *e.g.* the selection of the size of different sections.
- Current work and previous work are all based on small temperature difference approximation, thus the thermal resistance model is power independent. detailed analysis and necessary model corrections have to be done in the future, *e.g.* importing $f(P)$ to the model.

Python-based 2D Ray-tracing Phonon MC Code

```
.
├── .git
├── docs
├── examples
├── shengmc
│   ├── __init__.py
│   ├── dispersion.py
│   ├── geometry.py
│   ├── mc.py
│   ├── phonon.py
│   ├── run.py
│   └── statistics.py
└── setup.py
```

Figure 12: Directory tree of shengmc.

shengmc

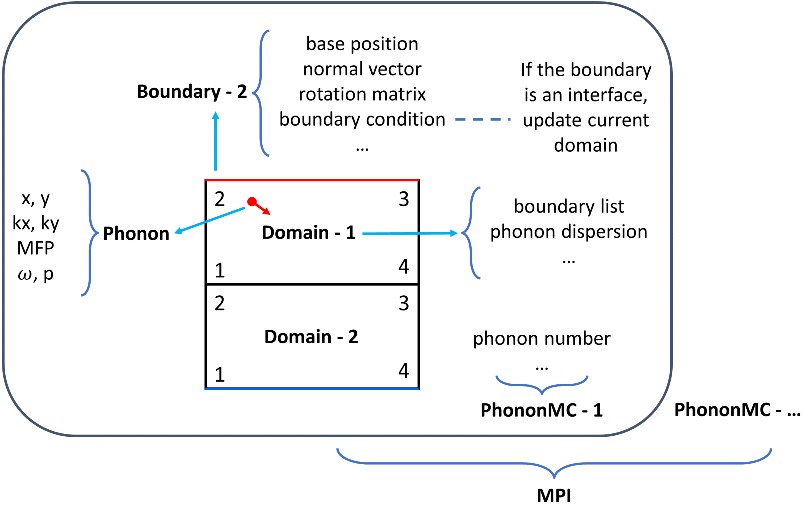


Figure 13: Schematic diagram of shengmc.

Inclined Interface

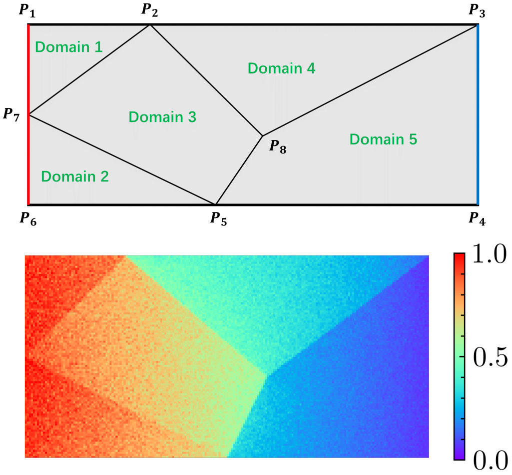


Figure 14: Simulation of a tangram like system.

Multiple Interfaces With Phonon Dispersion

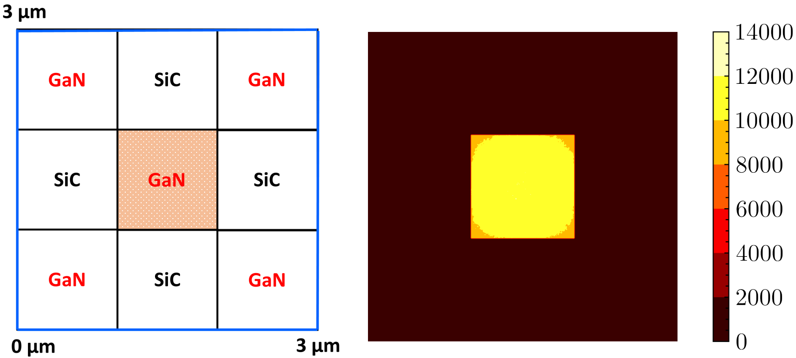


Figure 15: Simulation of a grid like system.

Non-uniform Heat Source

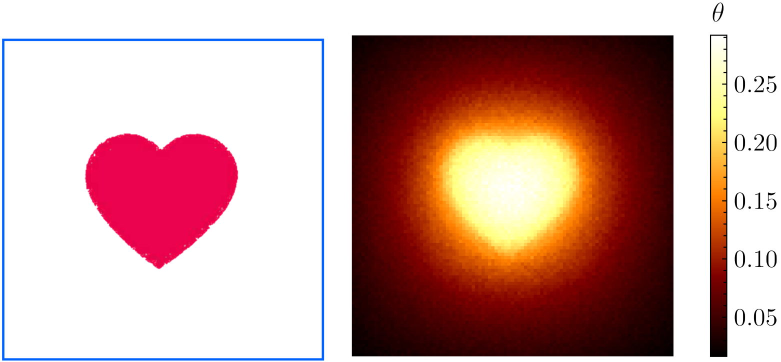


Figure 16: Simulation of a system with non-uniform heat source.

Internal Hole

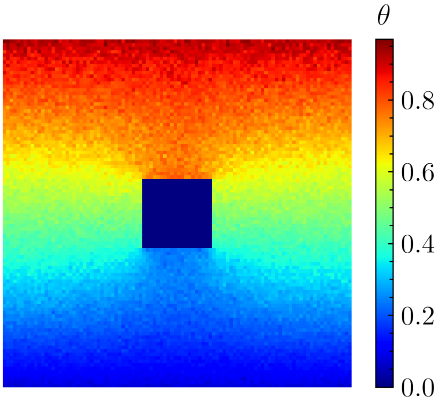


Figure 17: Simulation of a system with an internal hole.

Prospective Features

- Support the cross-scale module for device level simulations.

Thank You!