

# Thermal transport in transistors based on GaN and novel 2D materials

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Acknowledgement: AFOSR, DARPA, ONR, AFRL

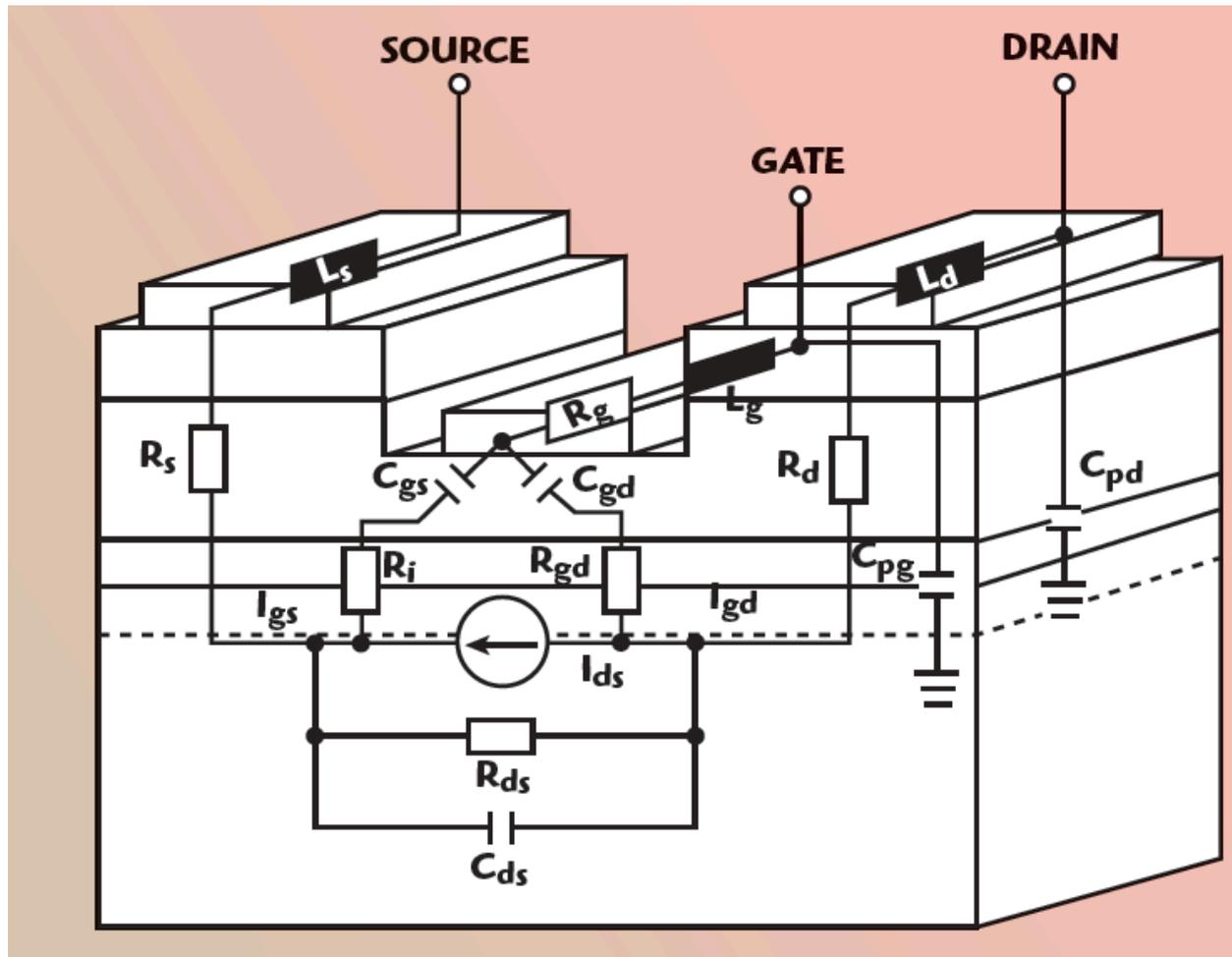
ARFTG, Honolulu, HI; June 9, 2017



Quantum Engineered Systems & Technology

# Motivation (Compact Models)

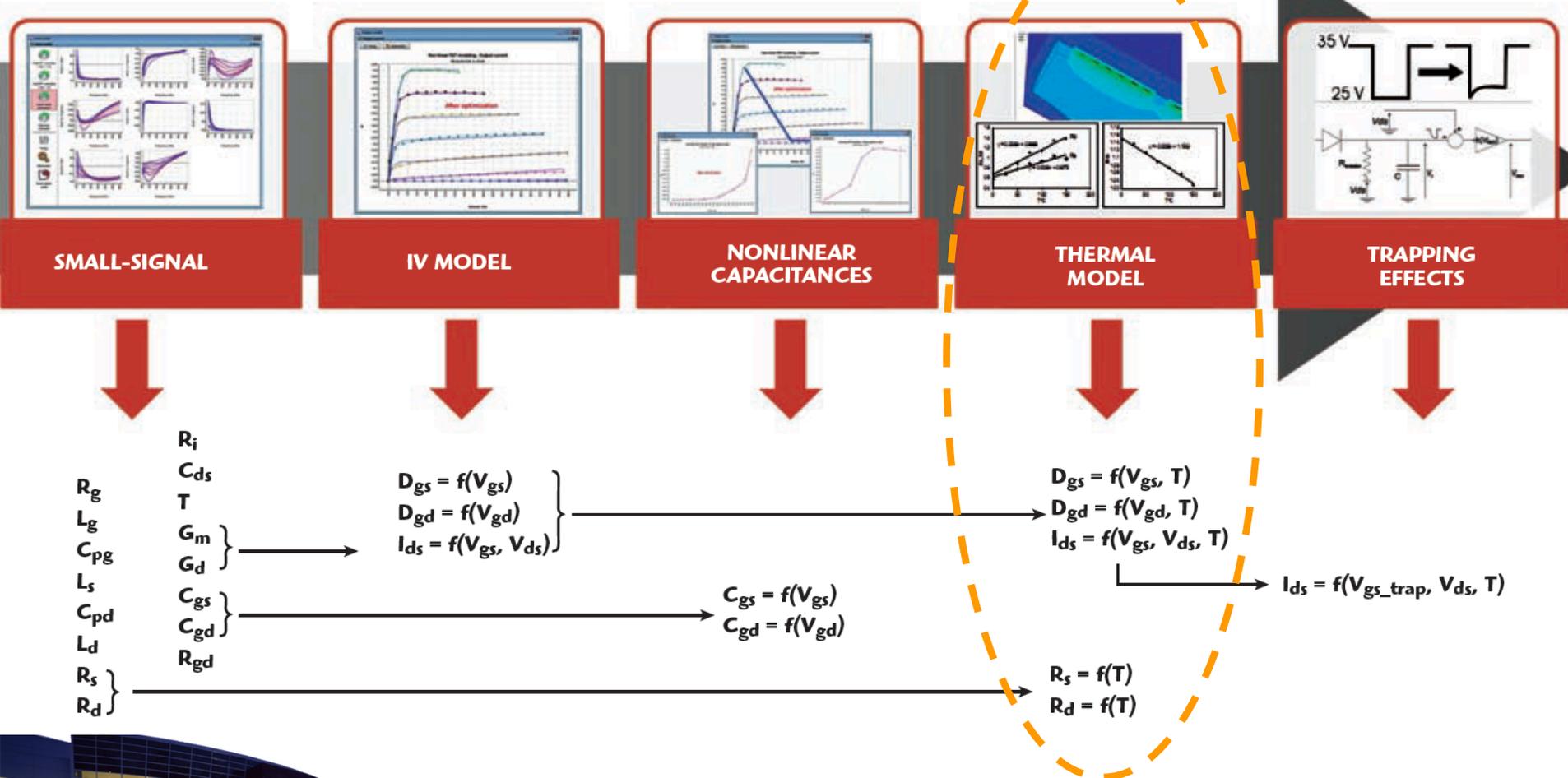
## Compact Transistor Models: The Roadmap to First-Pass Amplifier Design Success, Tony Gasseling, *Microwave Journal*, March 2012



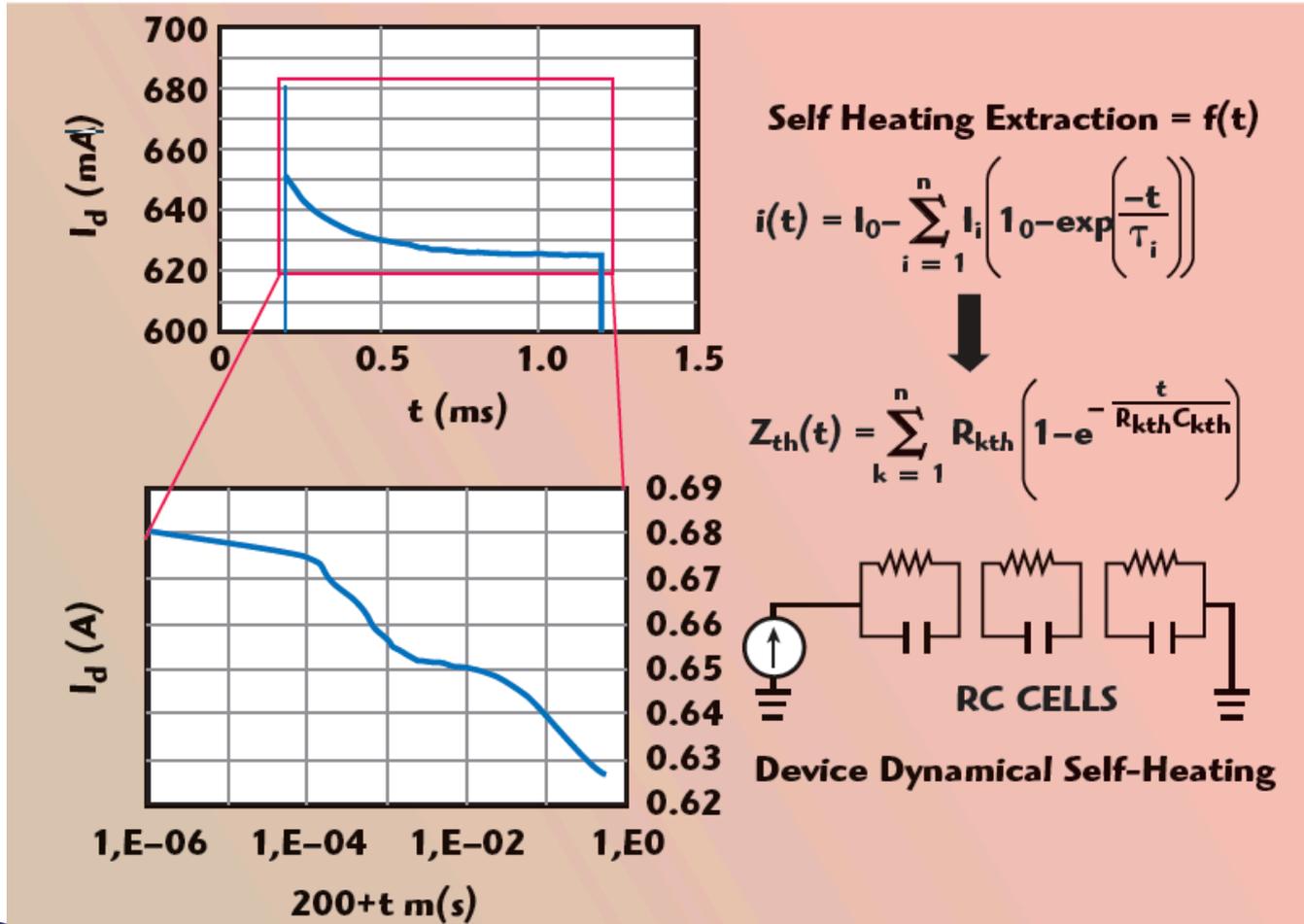
▲ Fig. 3 Compact FET model schematic.

# Motivation (Compact Models)

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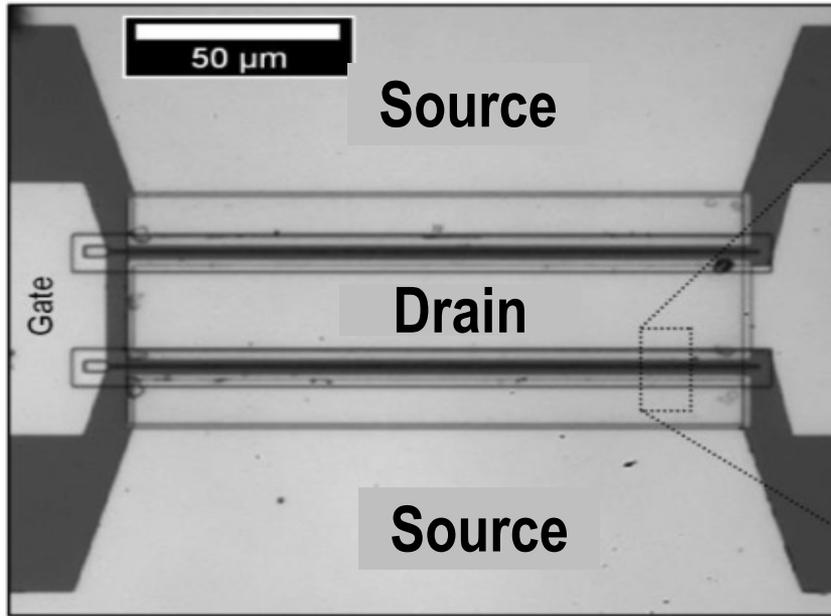
▲ Fig. 6 Thermal model extraction.

Method	Resolution			Imag- ing?	Notes
	x( $\mu\text{m}$ )	T (K)	t (sec)		
IR Thermography	3-10	0.02-1	1 $\mu$	Yes	Emissivity dependent
Lockin IR Thermography	3-10	10 $\mu$	NA	Yes	Need cycling
Liquid Crystal Thermography	2-5	0.5	100	Yes	Only near phase transition (aging issues)
Thermo-reflectance	0.3-0.5	0.08	800p-0.1 $\mu$	Yes	Need cycling
Micro Raman	0.5	1	10n	Scan	3D T-distribution

J. Christofferson, K. Maize, Y. Ezzahri, J. Shabani, X. Wang, and A. Shakouri, "[Microscale and Nanoscale Thermal Characterization Techniques](#)," J. Electronic Packaging, 130 (4) 041101, 2008



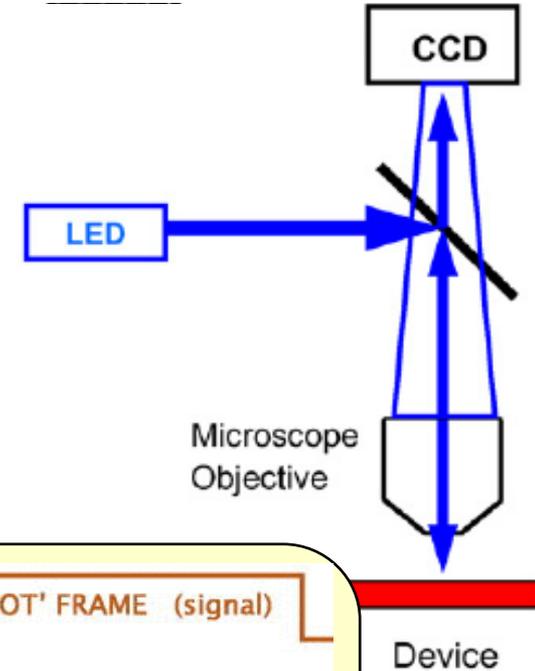
# Lock-in Thermoreflectance Imaging



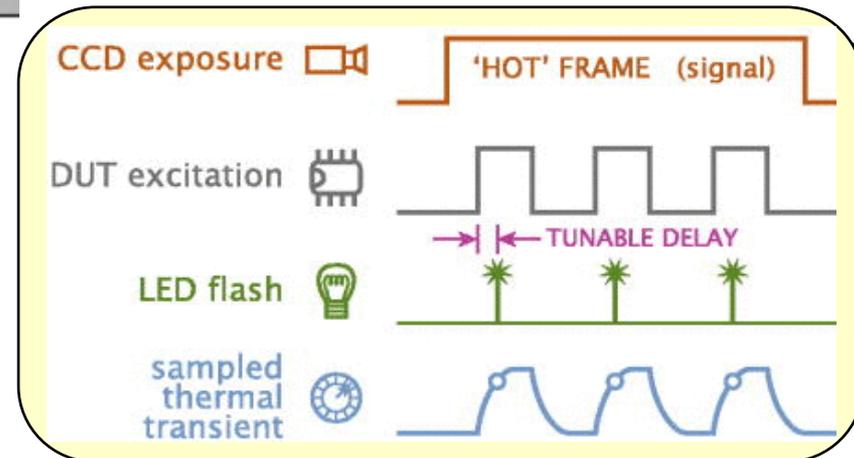
Optical  
Image of  
GaN HEMT

$$\frac{(\Delta R/R)}{\Delta T} \sim 10^{-4} / \text{C}$$

Mega Pixel Lock-in Camera

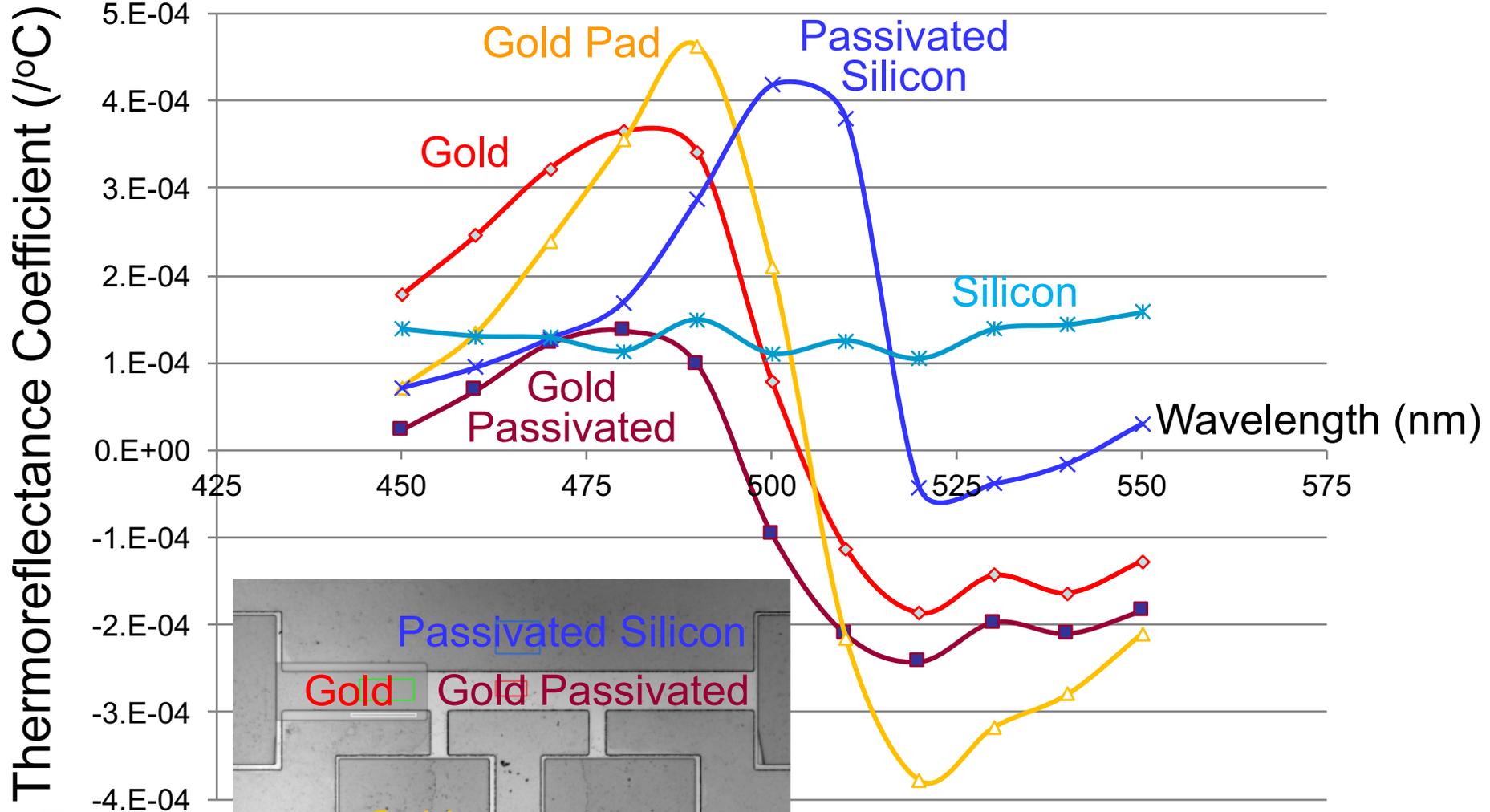


- Temp. resolution: **0.08°C**
- Spatial: **100's nm**
- Time: **100ns (800ps)**



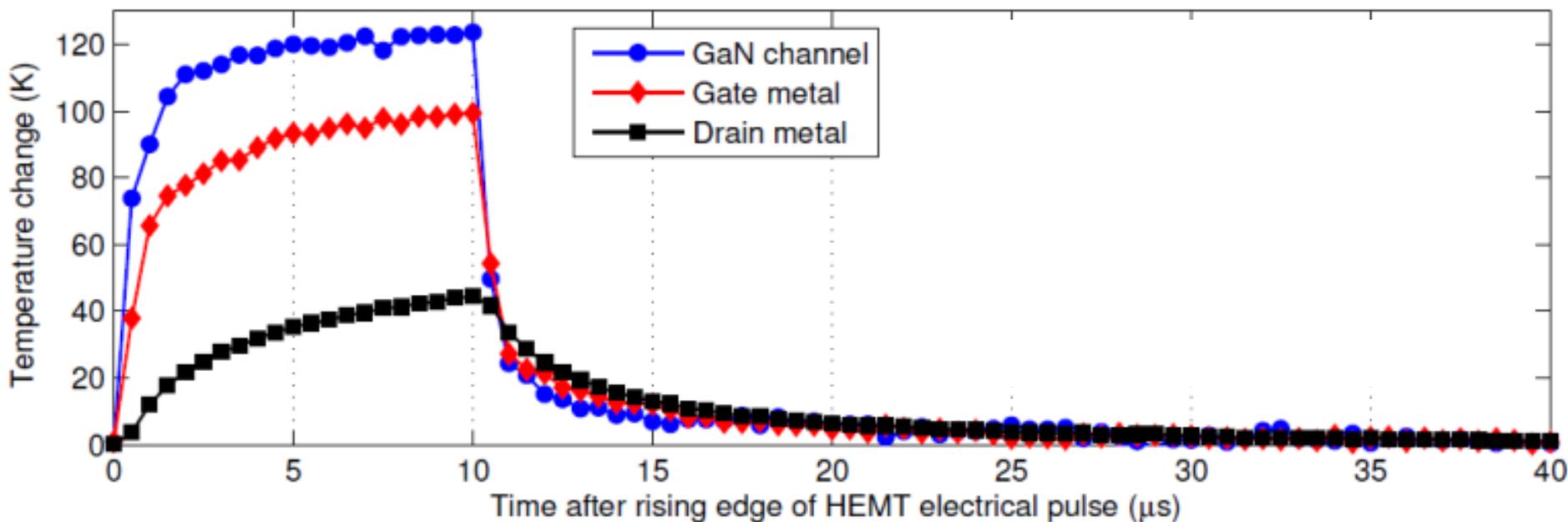
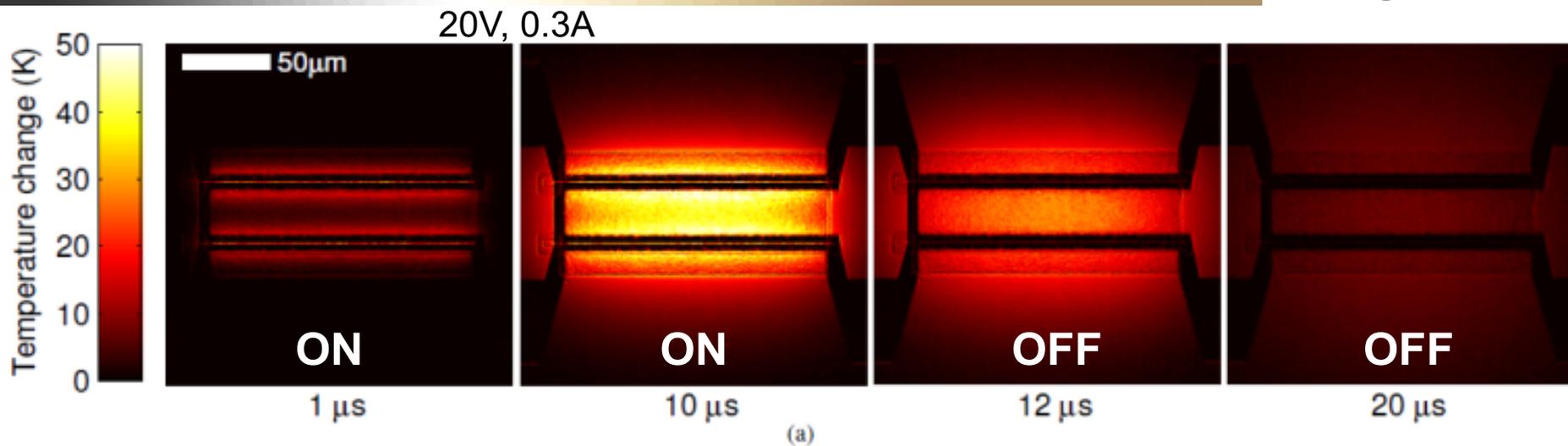
J. Christofferson, A. Shakouri, *Rev. of Scientific Instruments*, 2005  
K. Yazawa, A. Shakouri, *Electronics Cooling Magazine*, Vol. 3, p.10, March 2011

# Point-by-point Hyperspectral Thermoreflectance Coefficient Calibration



*Dustin Kendig, Microsanj*

# Heating in GaN Power Transistors



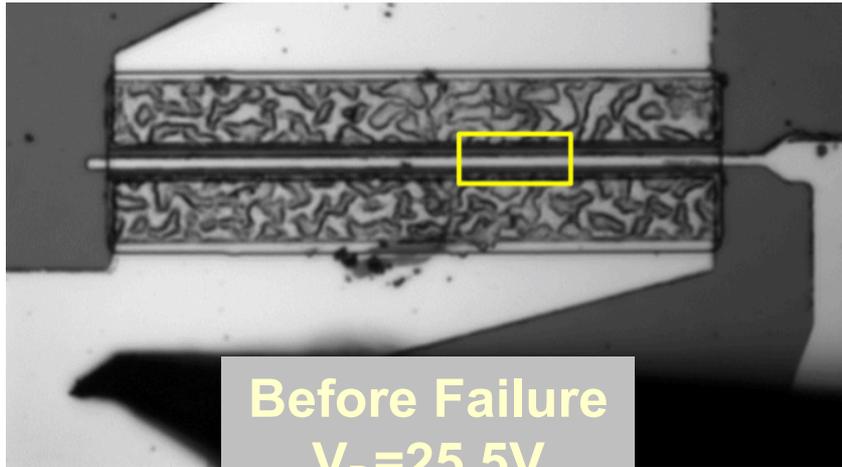
# GaN HEMT Breakdown Analysis

$L_{\text{Gate}}=2\mu\text{m}$ ,  $V_G=3\text{V}$

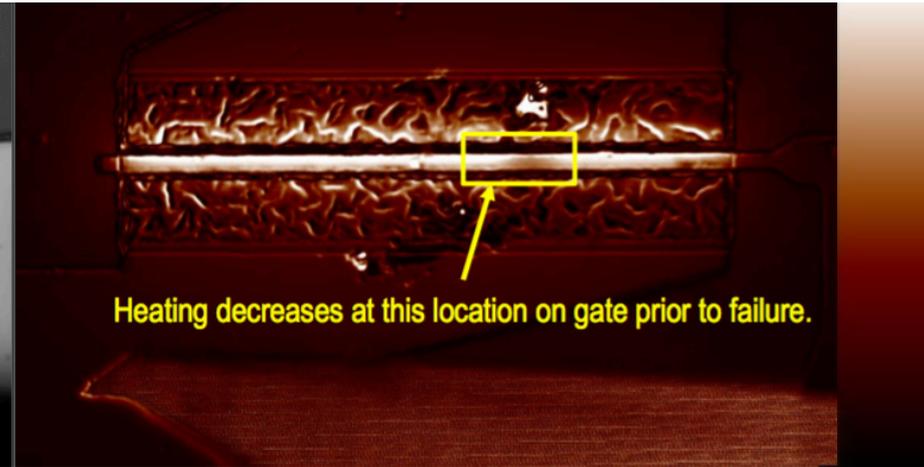
Optical Image

Thermal Image

141°C

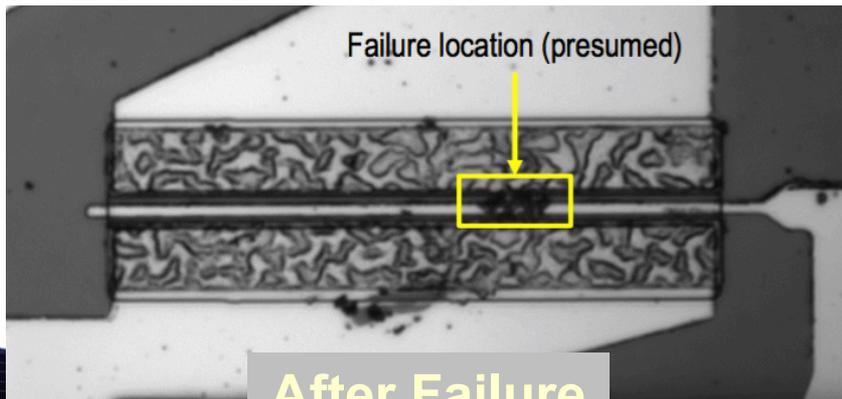


Before Failure  
 $V_D=25.5\text{V}$



Heating decreases at this location on gate prior to failure.

58°C

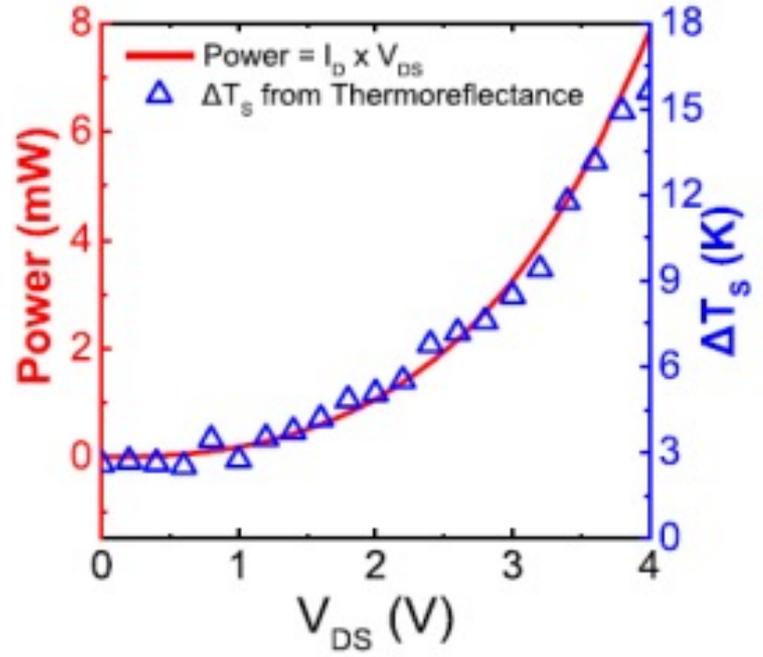
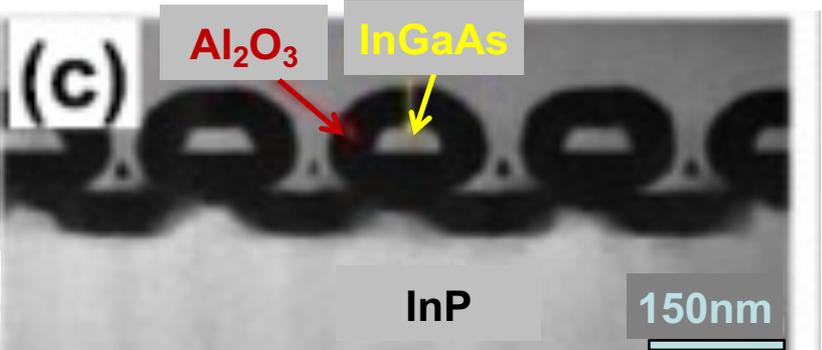
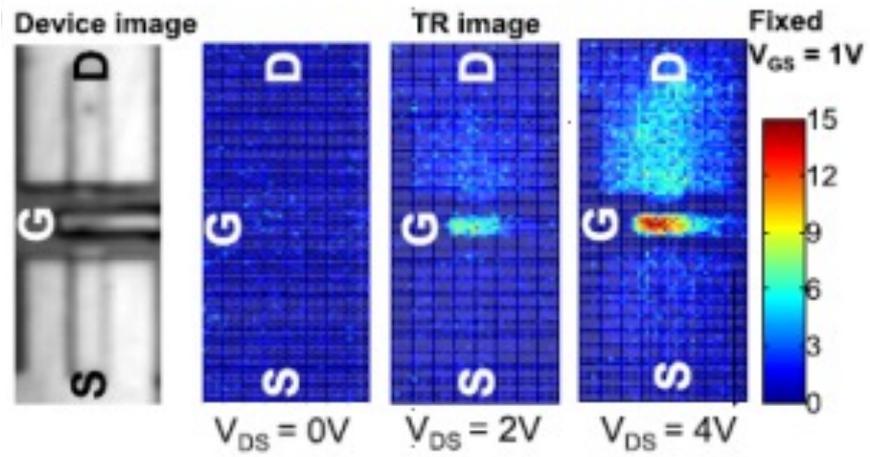
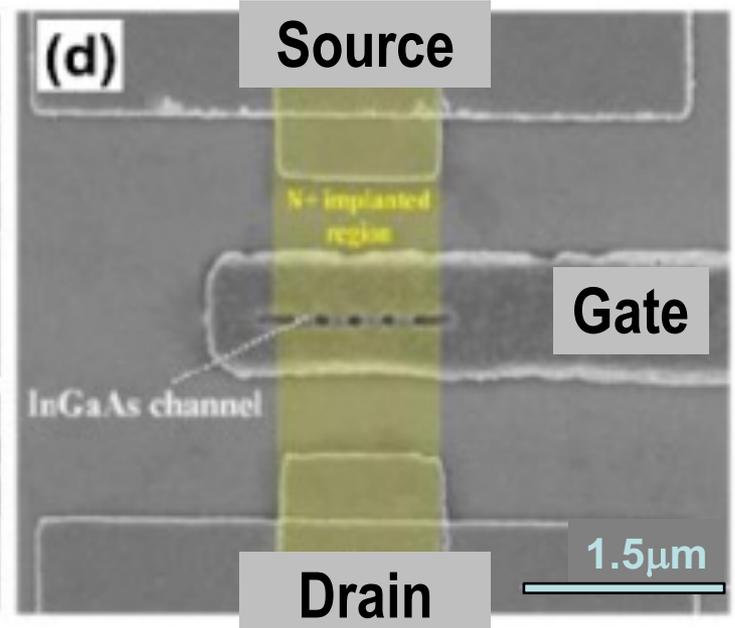


After Failure  
 $V_D=26\text{V}$

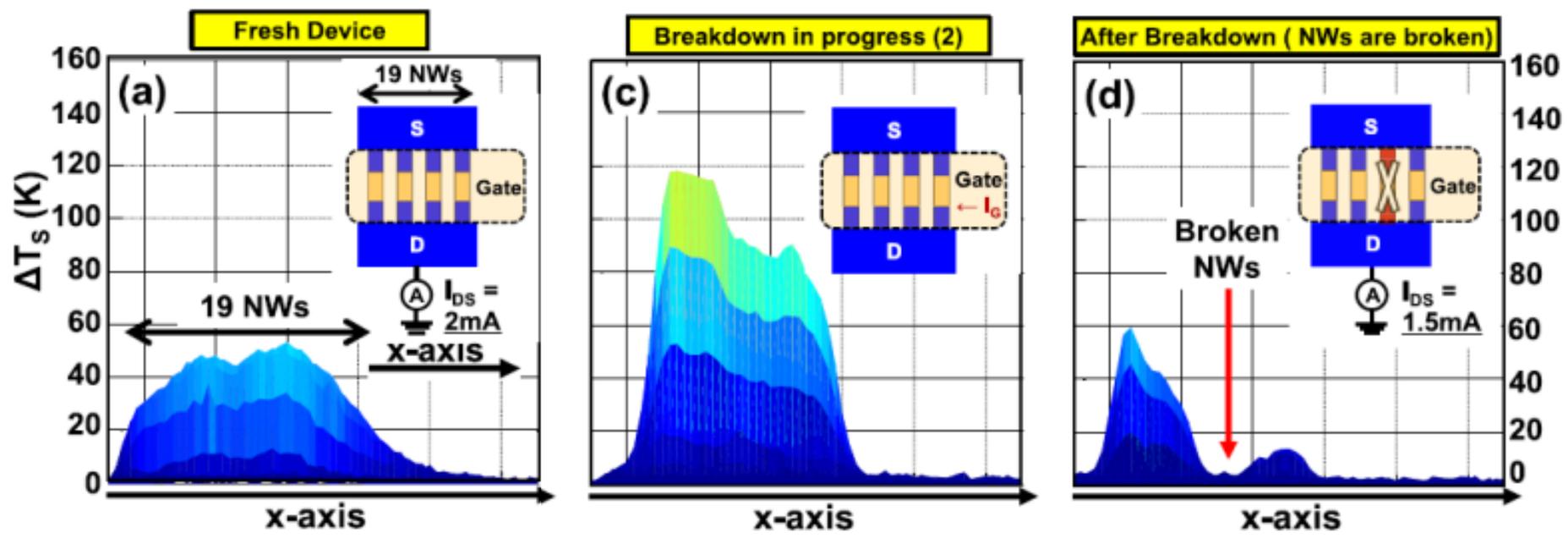


# Self Heating in Nanowire MOSFET

## InGaAs Gate-All-Around Multi Nanowire MOSFET



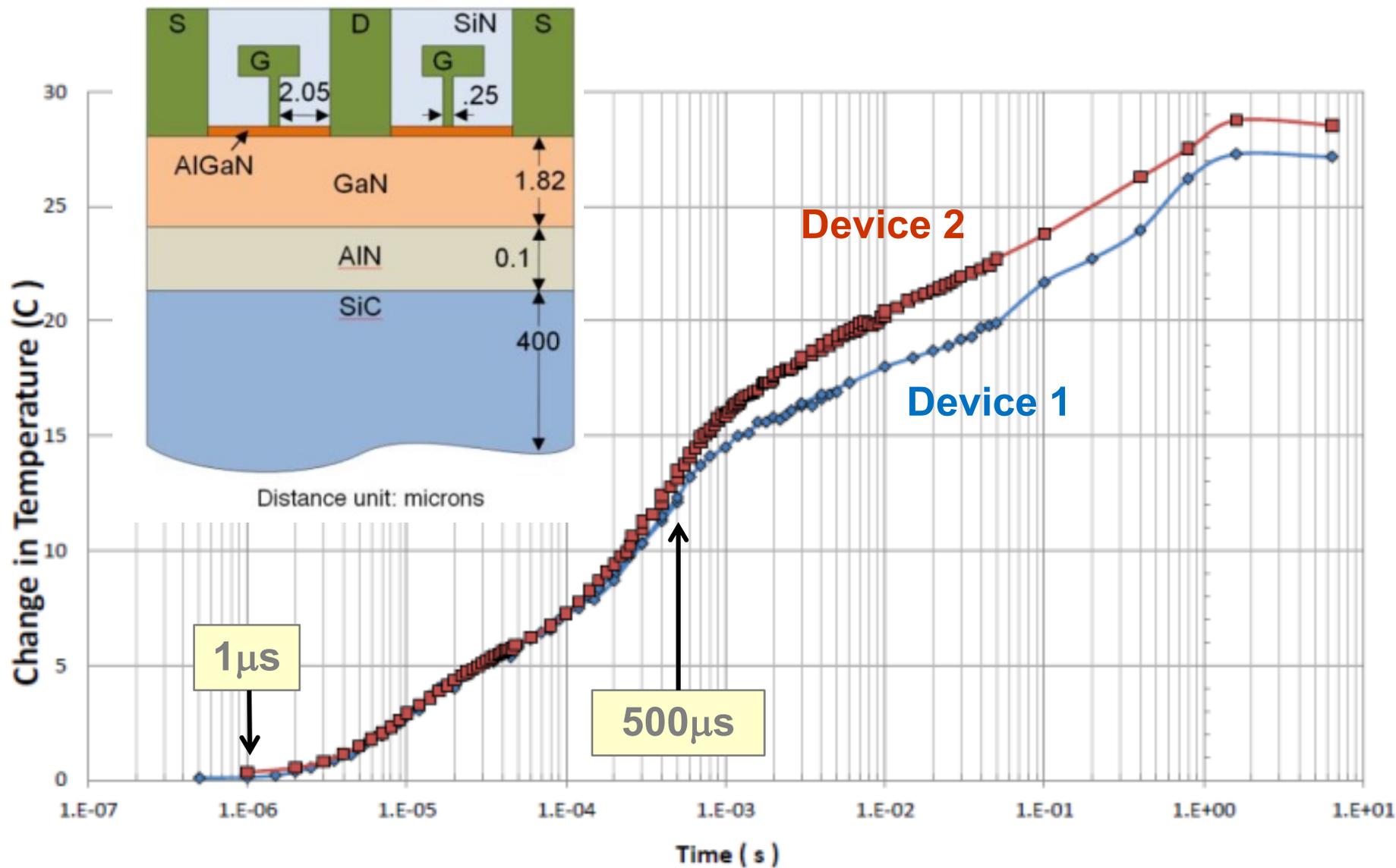
# Self heating in nanowire MOSFET

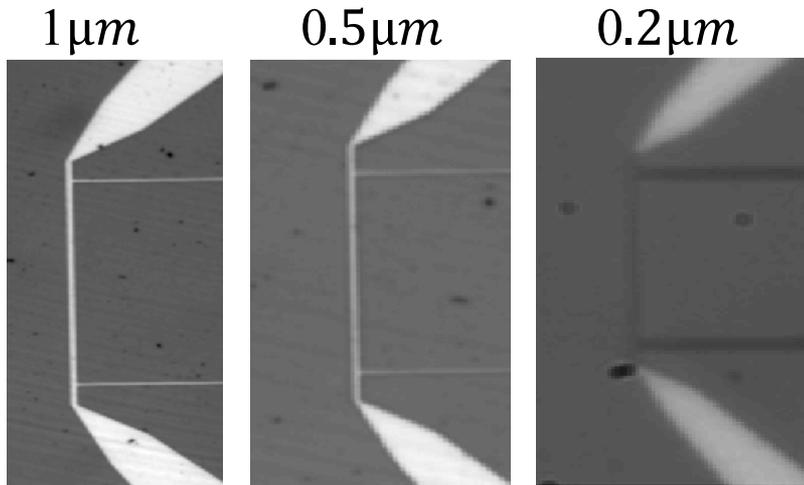


After stressing ( $V_{DS} = 2$  V,  $V_{GS} = 1$  V) Sample A (with 19 NWs) for a certain time, the channel region is suddenly heated due to the increased gate leakage (second image). Eventually, a fraction of the NWs is broken, and the remaining NWs settle the pre-BD temperature (right image). Correspondingly,  $I_{ON}$  is decreased from 2 mA at the beginning to 1.5 mA at the end. This clearly indicates that about one-fourth of the NWs are no longer functioning. Inset: schematic of BD of the NWs.

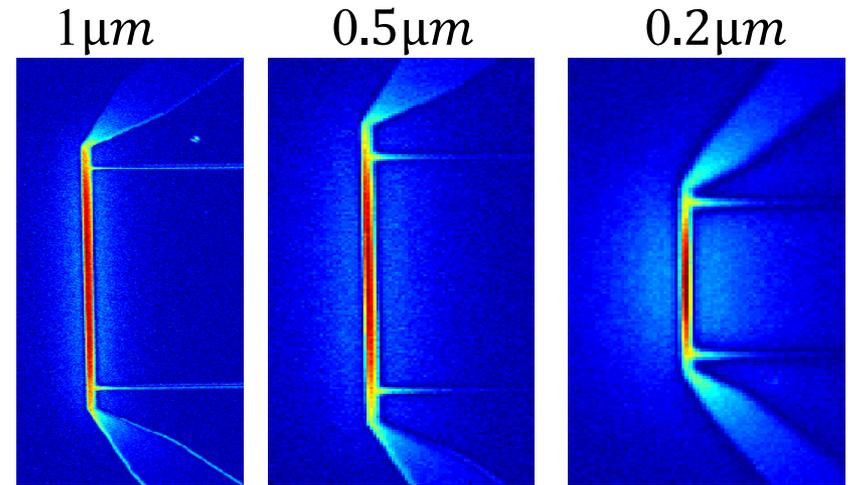


# 3D Thermal Mapping

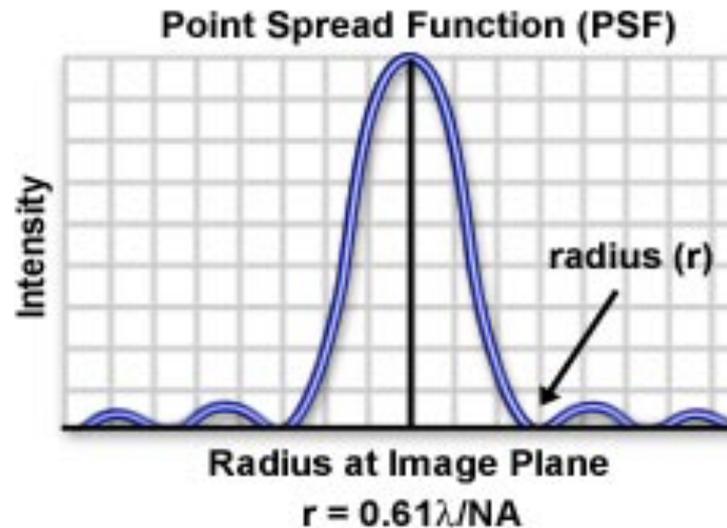




Optical Images

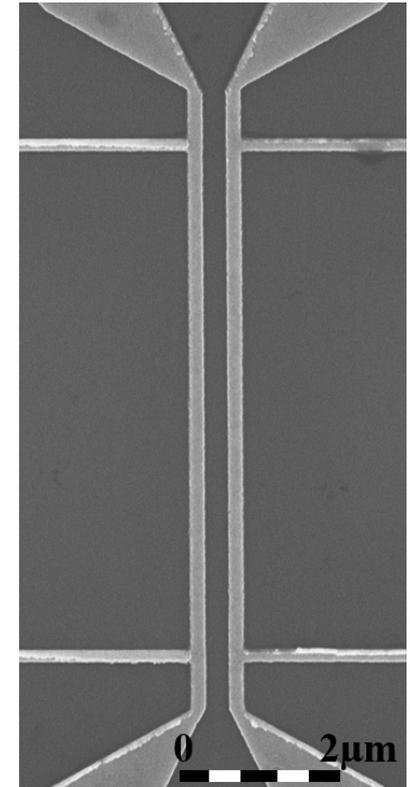
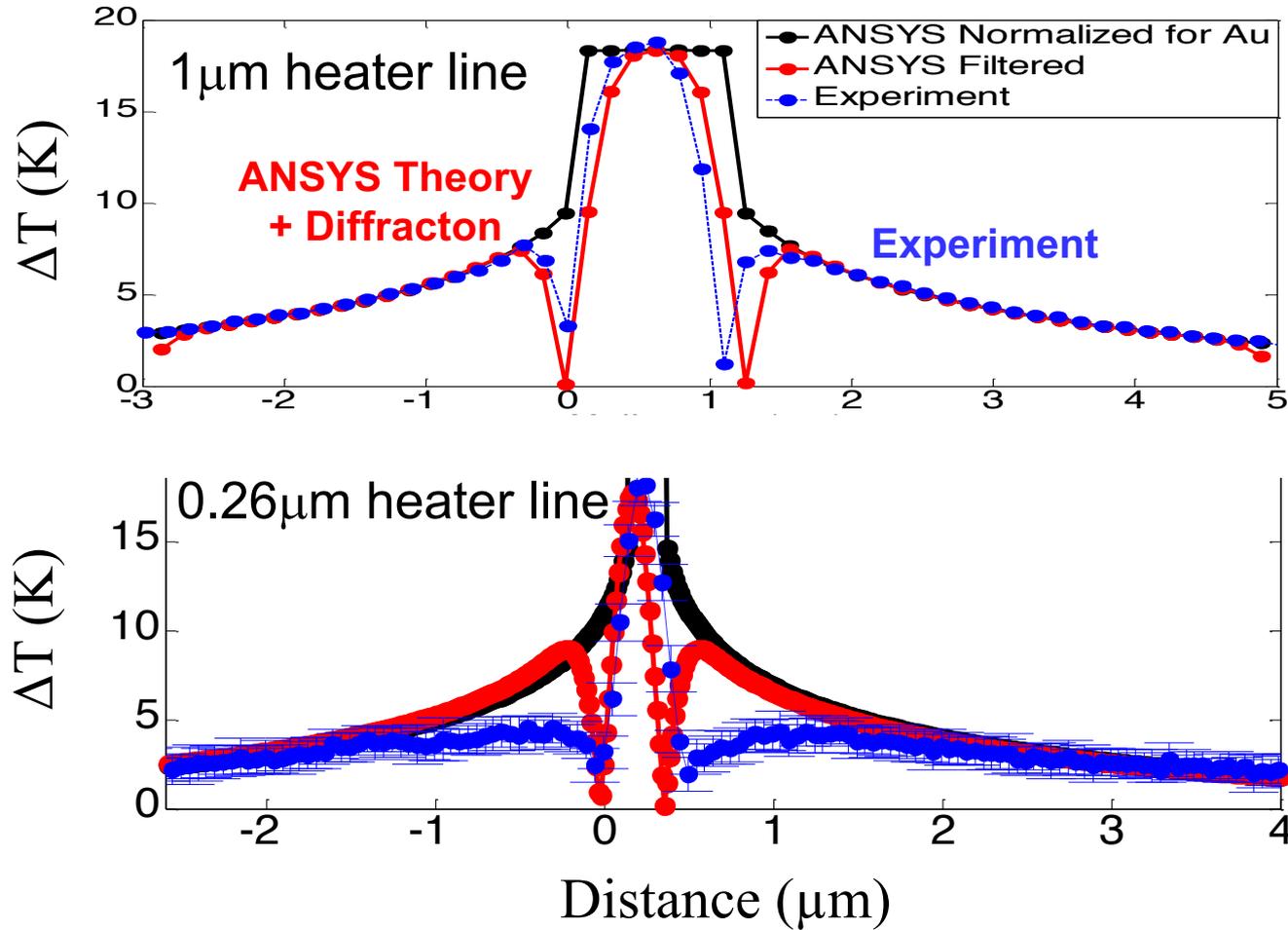


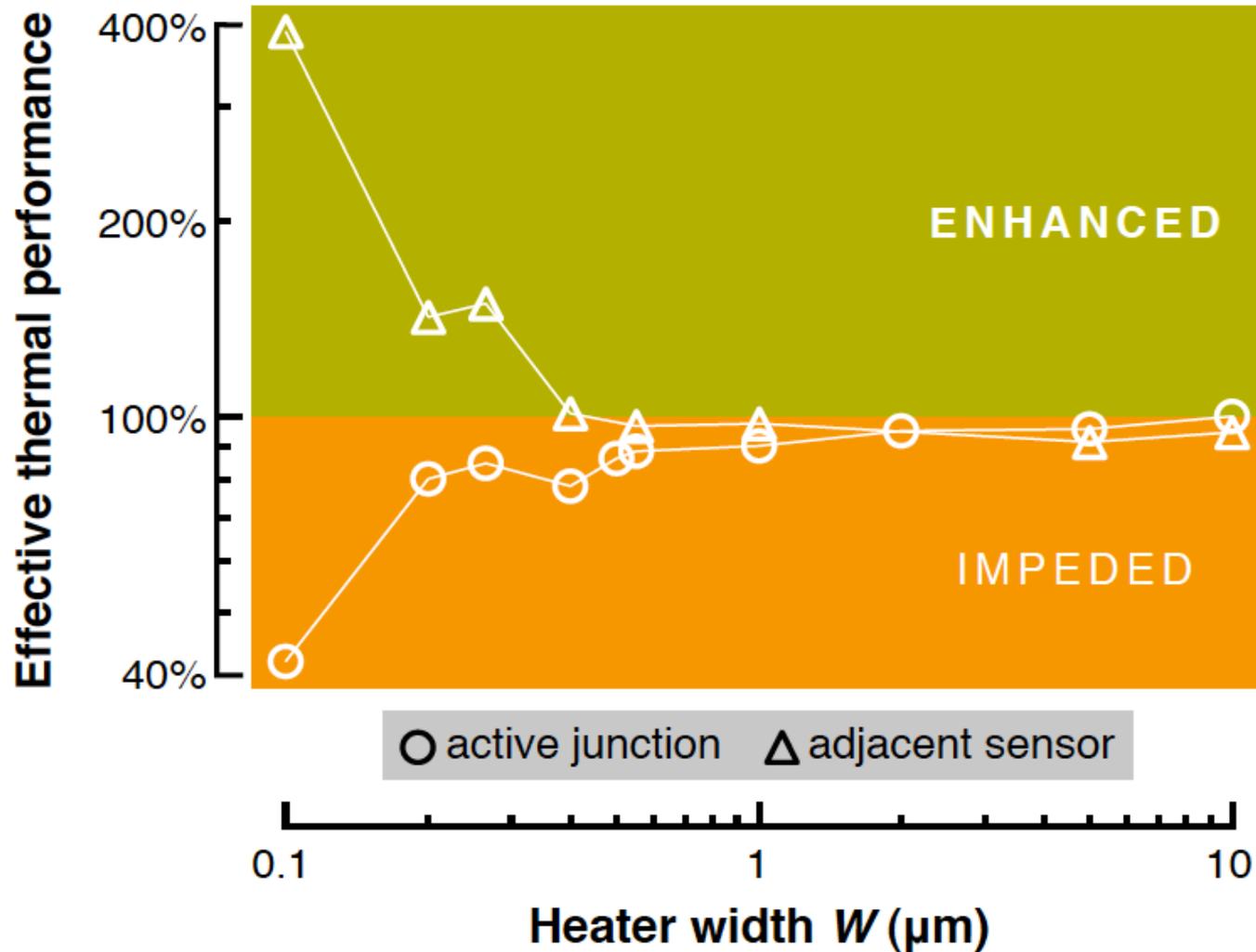
Thermal Images



<http://www.olympusmicro.com/primer/java/mtf/airydisksize/>





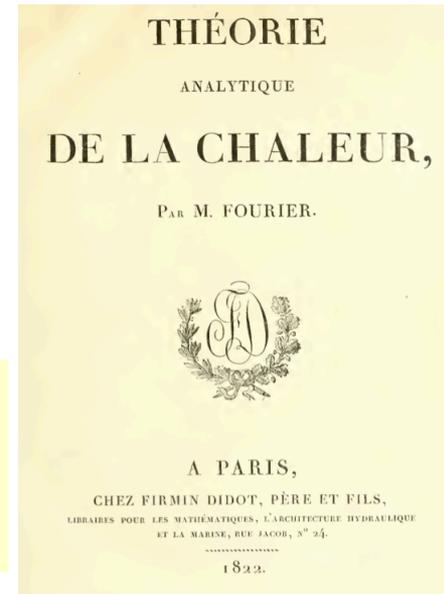


$$\partial T / \partial t = (k/C) \partial^2 T / \partial x^2$$

↙  
Thermal  
conductivity



Jean Baptiste  
Joseph  
Fourier, 1822

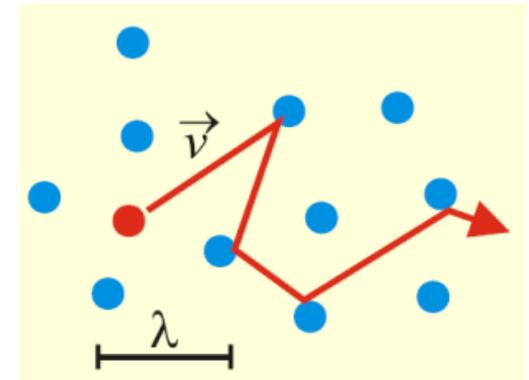


## Einstein's Brownian Motion (1905)

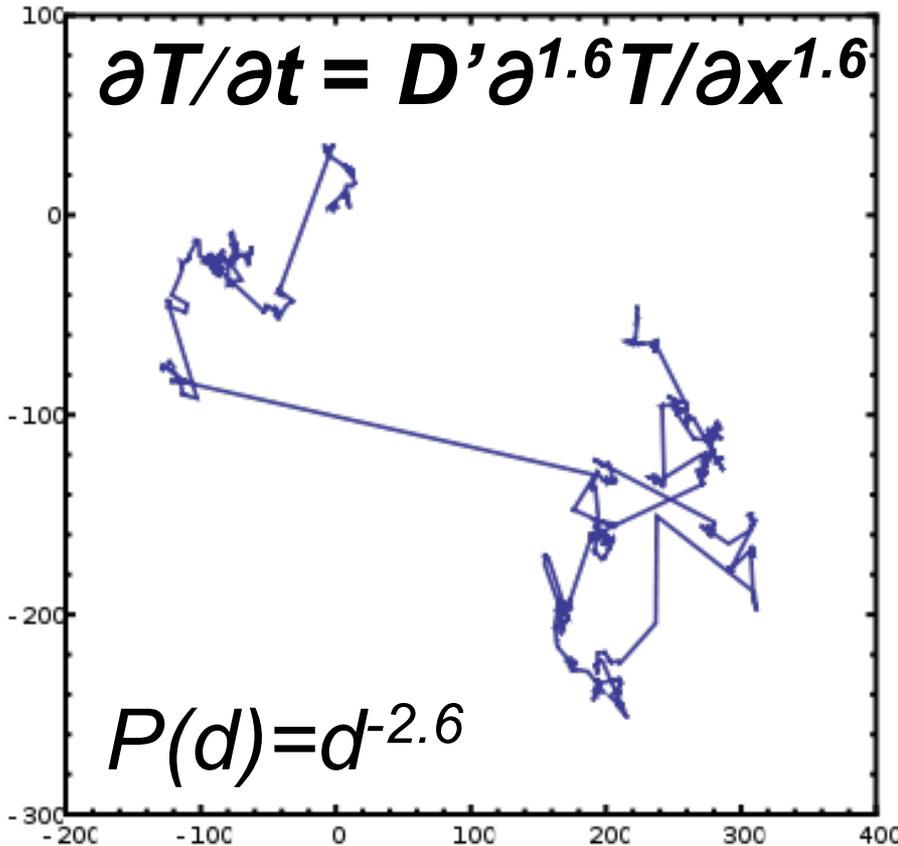
Mean-free-path/time  $\lambda, \tau$

$$k/C \sim \lambda^2 / \tau$$

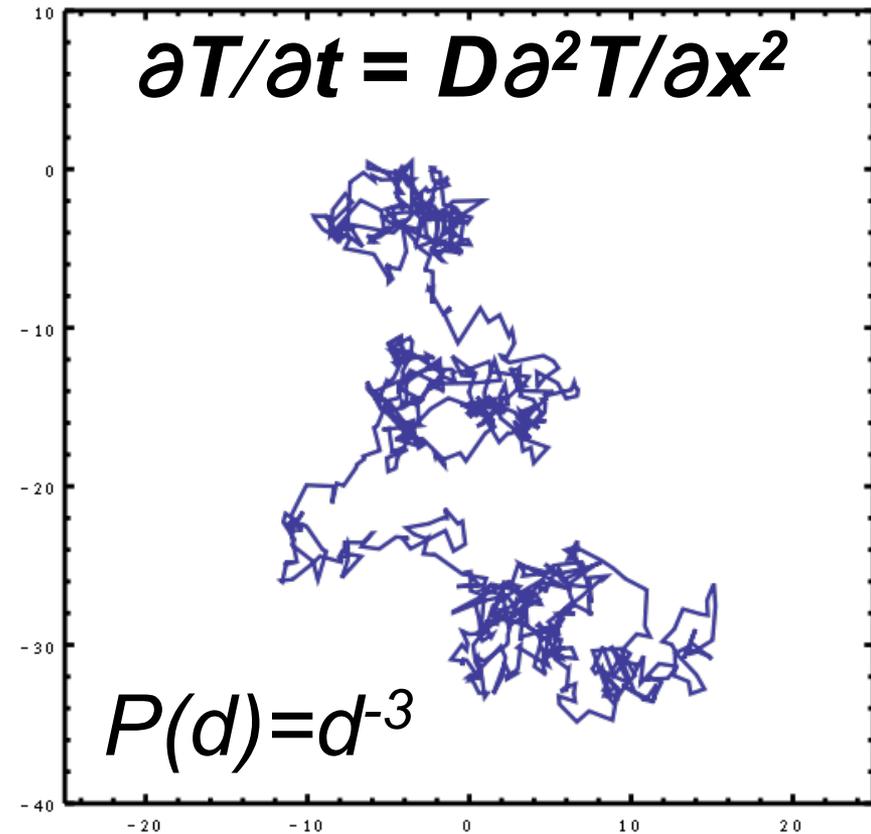
$$\langle x^2(t) \rangle \sim kt$$



**1000 steps, Lévy Flight**  
 $\alpha=1.6$



**1000 steps, Brownian Motion**



B. Vermeersch, et al., Superdiffusive heat conduction in semiconductor alloys, II. Truncated Levy formalism, Phys. Rev. B. 2015 (ArXiv)

- **High resolution transient thermal imaging**
  - Self heating in GaN, nanowires, membranes
    - Huge temperature gradients inside power devices
  - Pre-breakdown studies
  - 3D thermal mapping, Compact thermal models
- **New physics of heat transport at room T**  
( $T_{\text{gradient}}$  over  $<0.5\mu\text{m}$ )
  - Hydrodynamic effects (reduced cross-talk between neighboring transistor fingers)
  - Superdiffusion of heat (Levy random walk)