High-Field, Thermal & Energy Properties of 2D Devices & Layers

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**Device (Transistor) Scaling**

- **Problem:** 20th century transistors "carved" out of 3D materials (Si) → surface roughness restricts mobility, band gap, scaling of dimensions

  \[ L_G \sim \left( \frac{t_{ox}}{t_{ch}} \right)^{1/2} \]

- **Solution:** 21st century transistors with atomically thin 1D and 2D materials (<1 nm) can re-enable \( L_G \) scaling
High-Field Transport in Suspended Graphene

Suspended graphene allows us to study intrinsic coupled electrical-thermal properties

Simulation: Ambipolar + Poisson + Heating

models “GFETTool” and “S2DS” available on http://nanoHUB.org

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ONLINE SIMULATION AND MORE FOR NANO TECHNOLOGY

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E. Pop
Transport at Graphene Grain Boundaries

**Goal:** Understanding nanometer scale graphene transport, heating and reliability
- Measured heating at graphene grain boundaries (GB)
- Deduced grain boundary resistance; Collaboration with ORNL

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High-Field Transport in MoS\(_2\)

- Negative differential conductance (NDC) at high-field in MoS\(_2\)
- Simulations suggest combination of:
  - Self-heating and \(\mu(T) \sim T^{-2}\)
  - Intervalley scattering (K to Q valley)
- Results shed light on band structure
Some Recent Results on Monolayer CVD MoS$_2$

- Growth of monolayer MoS$_2$ by CVD on PTAS/SiO$_2$/Si
- Effective mobility ($\mu_{\text{eff}}$) comparable to exfoliated material

Good current achieved (~275 µA/µm) in 80 nm device, but contact resistance remains dominant

Summary of Challenges in 2D Devices

- Contact Resistance ($R_C$):
- Interfaces:
- Material Quality:
- +Variability!
A Few Words on Thermal 2D Work

- **Large in-plane** thermal conductivity of graphene, BN (>500 W/m/K)
- **Ultra-low cross-plane** thermal conductivity of layered WSe₂ (<0.1 W/m/K)
  - Lower than plastics and comparable to air
- Huge thermal anisotropy in all layered 2D materials (>10-100x)
- MRS Bulletin review with AFRL:


- **Large thermopower** in TMDs (S ~ 0.5 mV/K) → Thermoelectrics?

Ballistic Phonons in Graphene Ribbons

First measurement of quasi-ballistic heat flow in graphene near room temperature

First measurement of phonon edge scattering in graphene nanoribbons

Maximum heat flow also limited by edge scattering.

But, “short” graphene devices reach up to ~35% of theoretical ballistic thermal limit at room T.
Looking Ahead: Future Opportunities

collab: E. Reed, K. Goodson, K. Saraswat, H.-S.P. Wong, Y. Cui

Could we:
– Exploit **anisotropy** for routing heat? (thermal diode)
– Separate thermal and electrical flow? (thermal transistor)
– Design electronics with **built-in thermoelectric cooling**?
– Achieve transparent heat spreaders and flexible thermoelectrics?

![Diagram of thermal switching](image1)

**Thermal Switching**

A. Sood, F. Xiong, [...], E. Pop, Spring MRS (2015)
Summary

- **Goals**: understand 2D materials and devices for analog (e.g. graphene) and digital (e.g. MoS$_2$) electronics
- High-field transport experiment & models
- Insights into band structure, grains, power dissipation
- Unique 2D thermal properties

**Next:**
- Quasi-ballistic transport evaluation
- Role of contact geometry
- Exploit heterostructures, thermal anisotropy, thermoelectric properties

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