Near-field thermal effects at mesoscopic scale

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Thermal Properties of Nanostructures

Outline:

**sub-Kelvin to Kelvin** temperature range
near-field heat transfer
  - Simple theory
  - Experimental design
  - Preliminary data

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Thermal Properties of Nanostructures

Why low temperatures?

- Can access extreme near field conditions more easily, as dominant thermal wavelengths are 2-3 orders of magnitude larger.
- Possible relevance in low-temperature detector applications, where typical operating temperatures are $\sim 0.1$ K.
Examples of ultra-sensitive devices at low temperatures:

Spider-web bolometers, force/mass NEMS detectors, transition edge sensors

JPL built 0.1 K spider-web bolometer in Planck

G phonon $\sim 100$ pW/K, $P \sim 2.5$ pW

0.1 K TES X-ray detector array and SQUID readout, NIST+JYU

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Without low-T detectors, no high-res CMB data!
Space is too HOT for the detectors (dilution refrigerator in space!)
Example *real* devices in more detail

SRON FIR bolometer for future astronomy mission (SPICA) suspended SiN beams requirement

\[ G \sim 0.1 \text{ pW/K} , \quad P \sim 3 \text{ fW} \]
Example real devices in more detail 2:

G \sim 300 \text{ pW/K} \\
P \sim 50-100 \text{ pW/pixel}

Thermal cross-talk??

NASA Goddard 32 x 32 = 1024 pixel superconducting X-ray transition edge sensor array 
Finnish 256 pixel array in progress (Jyväskylä+VTT)
Thermal Properties of Nanostructures

Motivation

=> Need to understand and control thermal conductance in nanoscale

For bolometers, if thermal conductance is low, small heat loads lead to large temperature increase => more sensitivity

Low thermal conductance and cooling increases bolometer performance

(NEP \sim G^{1/2}T)
How does near-field thermal transport depend on temperature in an ideal case (Drude metals, parallel planar surfaces)?

Most publications discuss only RT results.

Polder and Van Hove, PRB 1971
Chapuis, Volz, Henkel, Joulain, Greffet, PRB 2008
For a typical Drude metal (Au,Cu,Al...) at RT:

- Thermal near field starts at ~ few µm
- Is dominated by s (TE)-polarized evanescent waves, with magnetic fields dominating
- Reaches saturation at distance ~ 1 nm
- Has a maximum power enhancement ~ $10^5$
Temperature acts as a low-pass filter, cutting off higher frequency components, cut-off frequency moves linearly up with $T$ (Wien’s law)

\[ \phi = \int_{\omega=0}^{+\infty} d\omega [I^0_\omega(T_1) - I^0_\omega(T_2)] \]

\[ \times \sum_{\alpha=s,p} \left[ \int_0^{\omega/c} \frac{KdK}{\omega^2/c^2} \frac{(1 - |r_{31}\alpha|^2)(1 - |r_{32}\alpha|^2)}{|1 - r_{31}\alpha r_{32}\alpha e^{2i\gamma_3d}|^2} \right. \]

\[ \left. + \int_{\omega/c}^{\infty} \frac{KdK}{\omega^2/c^2} \frac{4 \text{Im}(r_{31}\alpha) \text{Im}(r_{32}\alpha)e^{-2\gamma''_3d}}{|1 - r_{31}\alpha r_{32}\alpha e^{-2\gamma''_3d}|^2} \right], \]

Planck spectrum

\[ I^0_\omega = \frac{\omega^2}{4\pi^3c^2} \frac{\hbar \omega}{\left(e^{\hbar \omega/k_BT} - 1\right)} \]
Thermal Properties of Nanostructures

Example calculations for Drude Cu with a measured low-T mean free path:

Power spectra are very different from Planckian for s-polarization (but close for p polarization)

Dominant frequency does not scale linearly with $T$ for s-polarization!
(3 orders of magnitude difference at RT)
Position of dominant frequency for s-polarization also strongly dependent on gap distance

T = 0.01 K - 300K
Example calculations for Drude Cu with a measured low-T mean free path:

- Thermal near field starts at $\sim 1 \text{ mm} - 10 \text{ cm}$ distance
- Is still dominated by $s$ polarized evanescent waves, but a window of $p$-dominance appears at low $T$ when power first starts increasing
- Reaches saturation at distance $\sim 1 \mu\text{m} (0.01 \text{ K}) - 100 \text{ nm} (1 \text{ K})$
- Has a maximum power enhancement $\sim 10^{12} (0.01 \text{ K}) - 10^{9} (1 \text{ K})$
• Distance dependence is not affected by temperature

![Graph showing heat flux vs gap distance with power laws](image)
• Power enhancement is stronger because near field contribution dies out more slowly with $T$ than the far-field contribution

Near field heat transfer measurable at mesoscopic distances (up to $\sim 10 \, \mu m$) at cryogenic temperatures!
sub-Kelvin to Kelvin temperature range
near-field heat transfer

• Experimental design
• Preliminary data
Early idea: etch a trench between two metallic wires

BUT: can we be sure that phonon conduction still doesn't dominate??

=> Move to suspended wire geometry to fully remove substrate between wires
Thermal Properties of Nanostructures

Again clear heating signal in the receiver wire

![Graph showing thermal properties of nanostructures.](image)

- Emitter
- Receiver
- Bulk

- Heated wire
- Clear signal in the receiver wire
- Much weaker signal in phonon thermometer

BUT: what is EMITTED NF power?


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Low $G$ (phonon thermal conductance) due to nanoscale suspended beams

- SINIS (Superconductor-Insulator Normal metal) tunnel junction thermometry $< 1$K
- SINIS tunnel junction coolers

- Nanowire length 10-20 $\mu$m, thickness 60 nm and width 150-300 nm
- 4 supporting bridges length 5 $\mu$m, thickness 60 nm and width 150 nm

Tunnel junction thermometry

I-V characteristics non-linear with temperature

\[ I(V) = \frac{1}{eR_T} \int_\Delta^\infty \frac{|E|}{\sqrt{E^2 - \Delta^2}} [f(E - eV, T_e) - f(E + eV, T_e)]dE \]

Independent of superconductor temperature

Resolution (~0.1 mK at 100 mK)

Tunnel junction cooling

Tunneling of “hot” electrons from Fermi tail
(bias voltage dependent, optimal at \( V \sim \Delta \))

\[ \dot{Q}_{cool} = \frac{1}{e^2 R_T} \int_{-\infty}^{\infty} (E - eV)g_S(E)[f_N(E - eV, T_N) - f_S(E, T_S)]dE \]
direct heating experiment without coolers

\( n = 2.8 \) consistent with 1D-2D interface scattering \([1]\)

No T-gradients within wire => Heat flow dominated by the nanowire-bulk interface

\[ G = \frac{dP}{dT} = 0.4 \text{ pW/K at } 0.2 \text{ K} \quad (0.1 \text{ GQ/channel}) \]

Phonon emission power \( \sim 50 \text{ fW at } 0.2 \text{ K} \)

Extremely low \( G \) allows measurements of power \( \sim 10 \text{ aW resolution} \) with SINIS thermometry!

Thermal Properties of Nanostructures

Cooling results and modeling

When refrigerator at 50 mK, nanowire
At 100 mK (noise heating), no cooling
At 42 mK with optimal cooling (< T_{bath})

limited by superconductor material (Al)

For phonon heat flow \( P \sim T^n \) (\( G \sim T^{n-1} \)),
Data agrees with transition from \( n=2.8 \) (red) to \( n=6 \) (blue)
The point: we can accurately fit the T vs V curve with a thermal model that includes external input power as a parameter.
Preliminary data with a suspended cooler as a receiver (gap ~ 1 µm)
The point: we can accurately fit the $T$ vs $V$ curve with a thermal model that includes external input power as a parameter.

Ten times more power than what parallel plate model seems to predict, but approximately correct temperature dependence?
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Ten times more power than what parallel plate model seems to predict, but approximately correct temperature dependence?
Conclusions:

- Near field thermal radiation can be in a relevant power scale compared with the most sensitive bolometric LT detectors.
- At cryogenic temperatures, near field thermal radiation observable up to distances ~ 10 μm, currently.
- More detailed experiments are in progress and will be finished in the near future.
Current group members:  Previous group member:

Dr. Saumyadip Chaudhuri  
Tero Isotalo  

Dr. Panu Koppinen  
(now at VTT Micronova, Espoo)