Near-field thermal effects at mesoscopic scale

I.J. Maasilta

Nanoscience Center, Department of Physics, University of Jyväskylä, Finland

`maasilta@jyu.fi`

Outline:

sub-Kelvin to Kelvin temperature range

near-field heat transfer

- Simple theory
- Experimental design
- Preliminary data

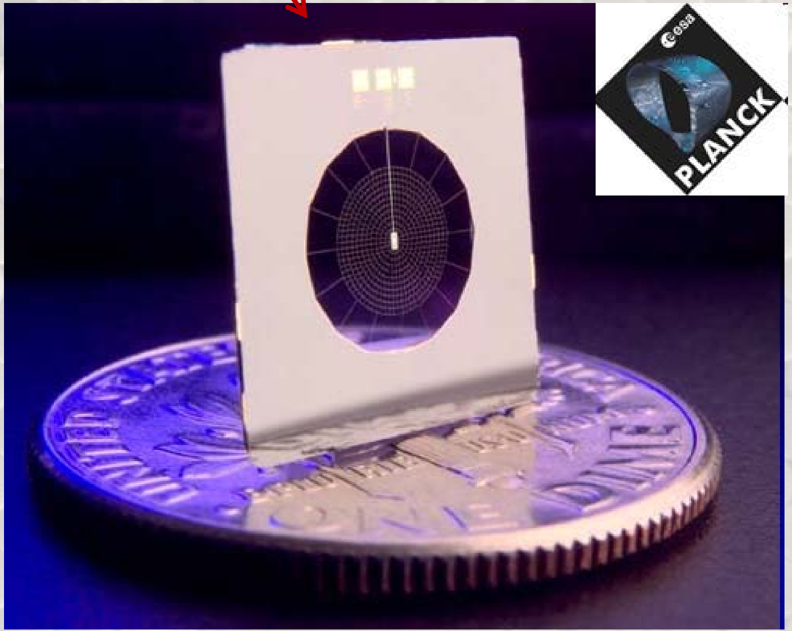
Why low temperatures?

- 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 ~ 0.1 K

Thermal Properties of Nanostructures

Examples of ultra-sensitive devices at low temperatures:

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



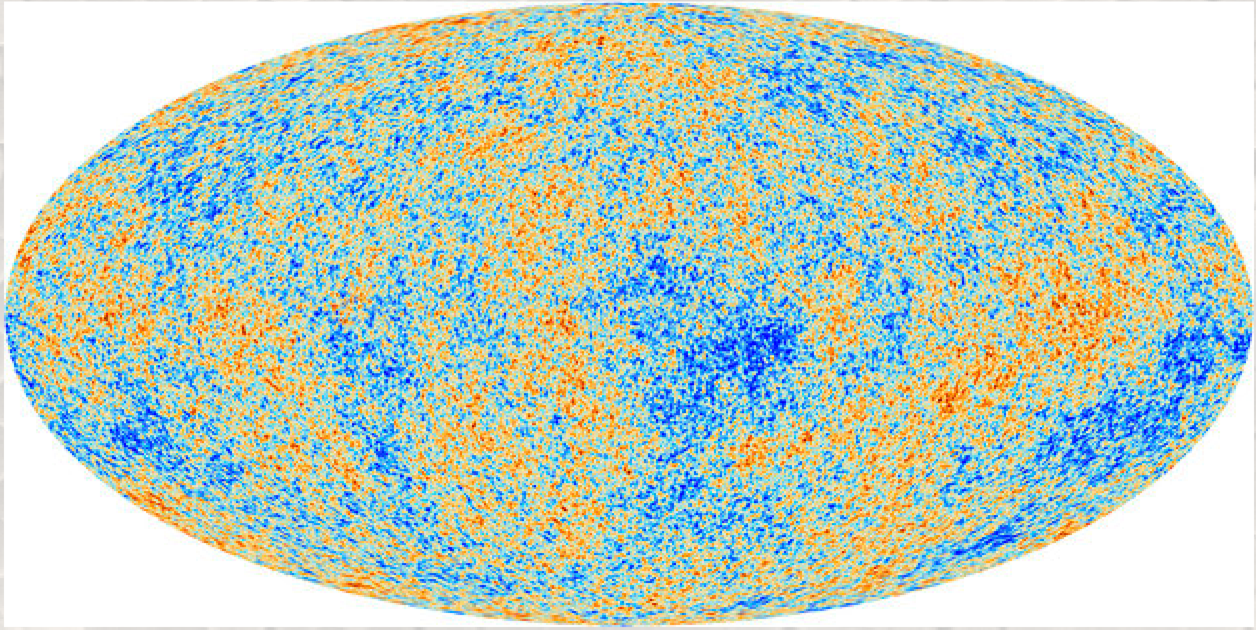
JPL built 0.1 K spider-web bolometer in Planck

G phonon ~ 100 pW/K , P ~ 2.5 pW

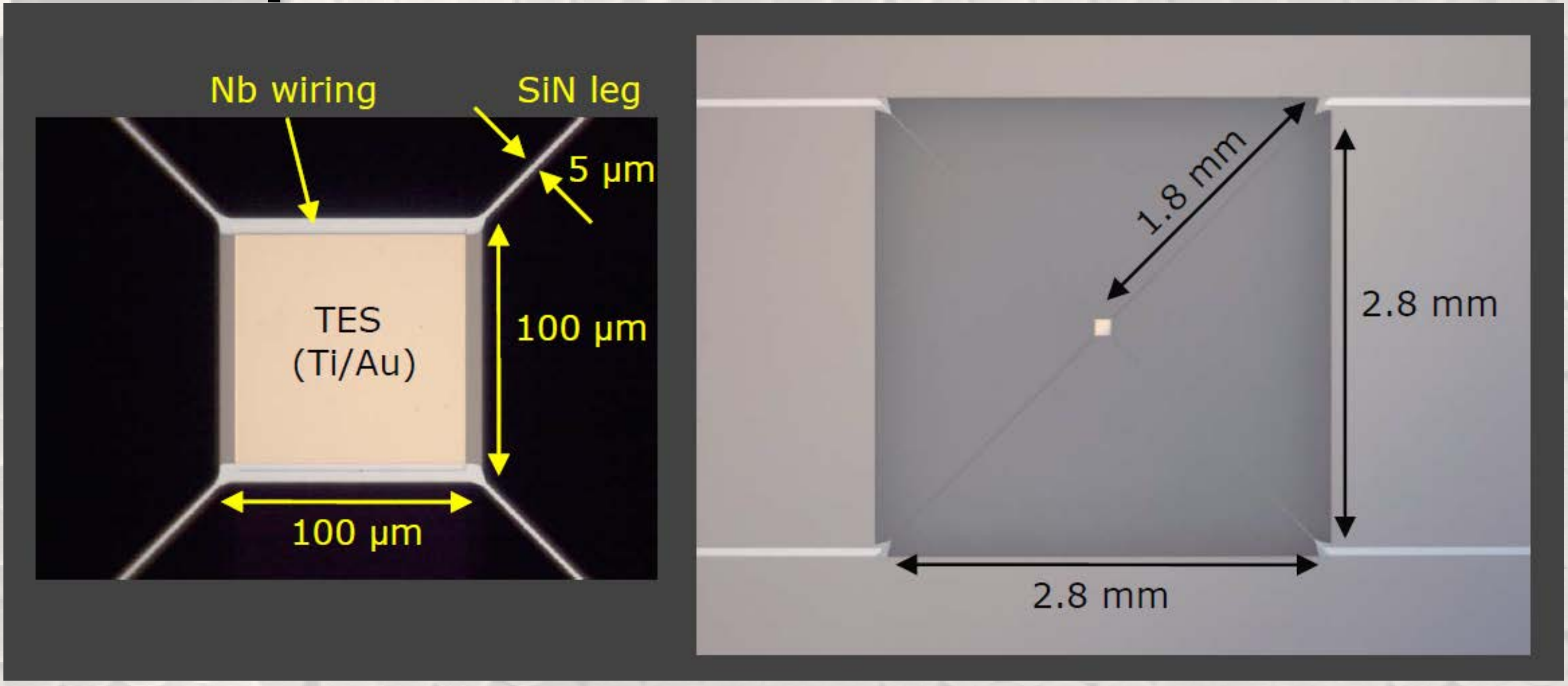
0.1 K TES X-ray detector array and SQUID readout, NIST+JYU

Without low-T detectors, no high-res CMB data !

Space is too HOT for the detectors (dilution refrigerator in space!)



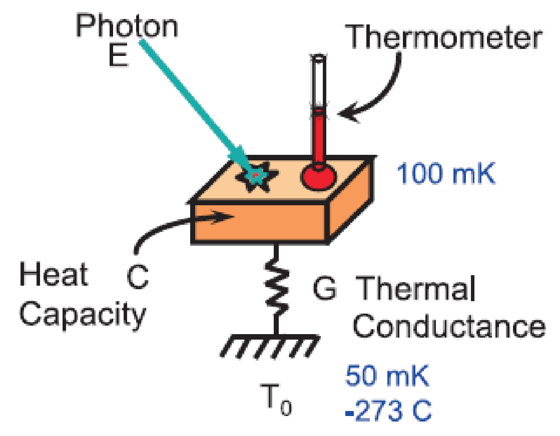
Example *real* devices in more detail



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

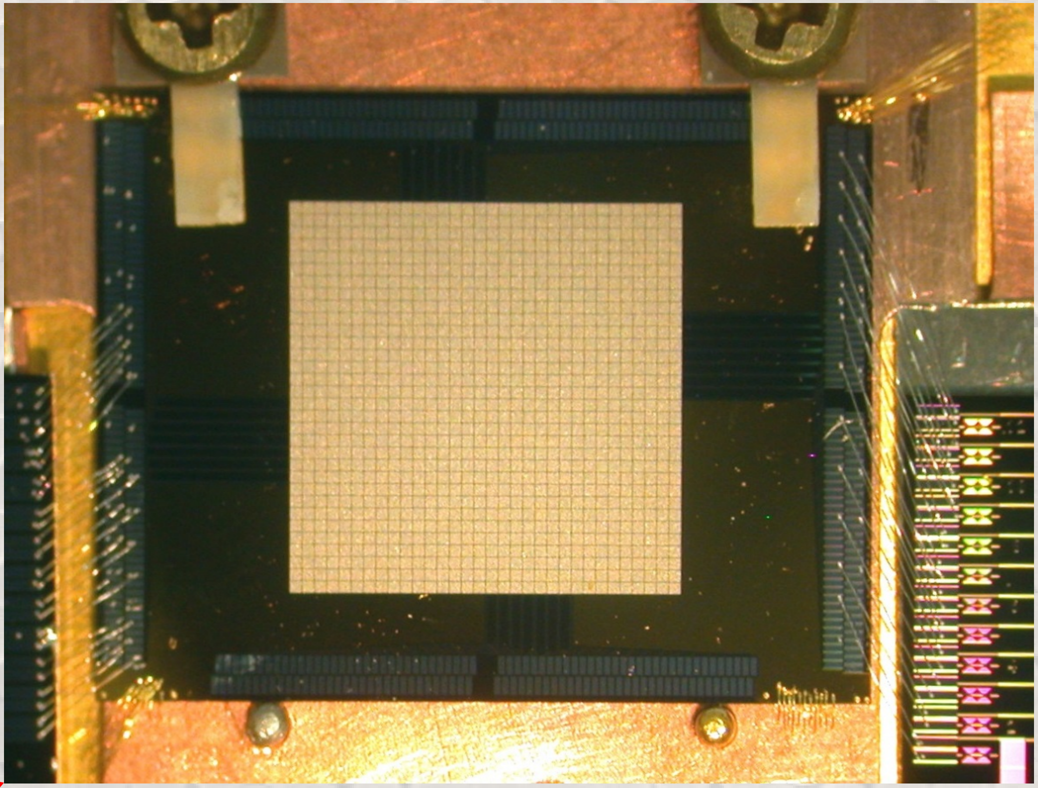
G ~ 0.1 pW/K , P ~ 3 fW

Example *real* devices in more detail 2:



G ~ 300 pW/K
P ~ 50-100 pW/pixel

Thermal cross-talk??



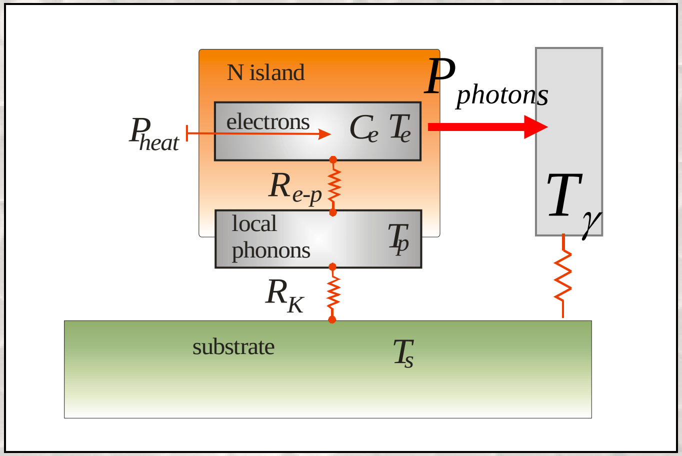
NASA Goddard 32 x 32 = 1024 pixel superconducting X-ray transition edge sensor array
Finnish 256 pixel array in progress (Jyväskylä+VTT)

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



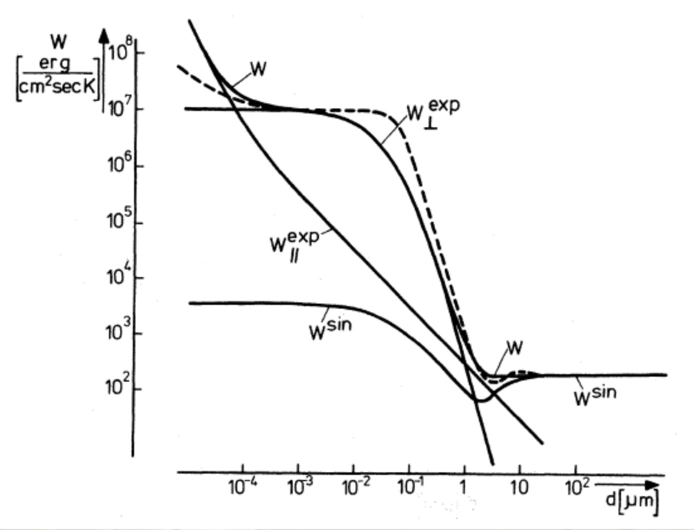
Thermal model for samples

- Electron-phonon interactions
- Phonon heat conductance
- Photon heat conductance

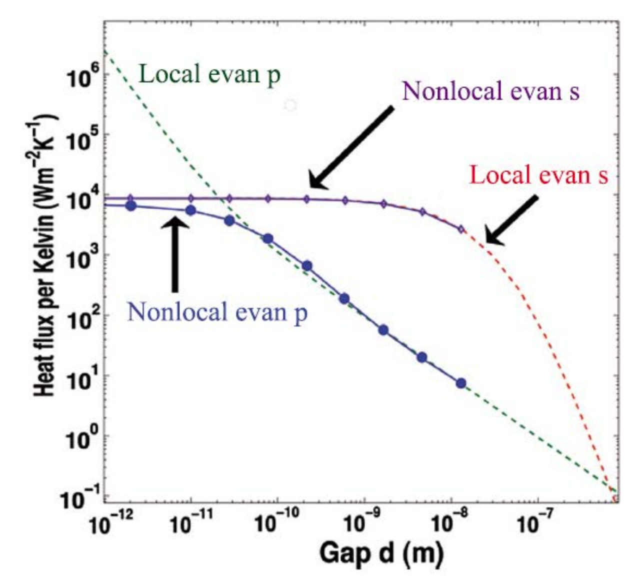
Low thermal conductance and cooling **increases bolometer performance** ($NEP \sim G^{1/2}T$)

How does near-field thermal transport depend on temperature in an ideal case (Drude metals, parallel planar surfaces)?

Most publications discuss only RT results



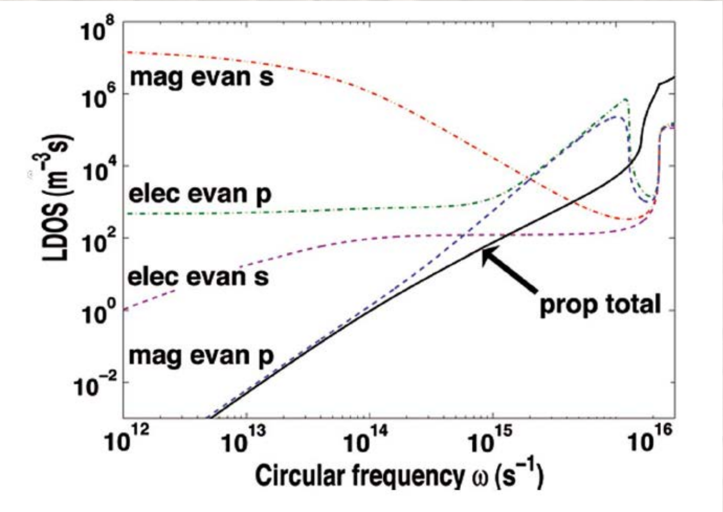
Polder and Van Hove, PRB 1971



Chapuis, Volz, Henkel, Joulain, Greffet, PRB 2008

Thermal Properties of Nanostructures

- 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



Thermal Properties of Nanostructures

Temperature acts as a low-pass filter, cutting off higher frequency components, cut-off frequency moves linearly up with T (Wien’s law)

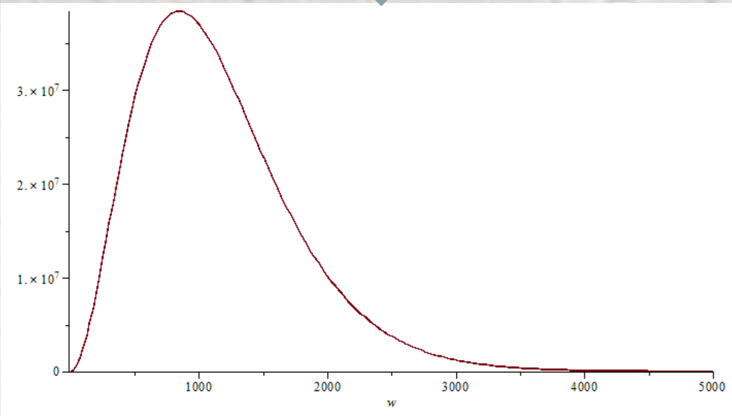
$$\phi = \int_{\omega=0}^{+\infty} d\omega [I_\omega^0(T_1) - I_\omega^0(T_2)]$$

$$\times \sum_{\alpha=s,p} \left[\int_0^{\omega/c} \frac{KdK}{\omega^2/c^2} \frac{(1-|r_{31}^\alpha|^2)(1-|r_{32}^\alpha|^2)}{|1-r_{31}^\alpha r_{32}^\alpha e^{2i\gamma_3 d}|^2} \right.$$

$$\left. + \int_{\omega/c}^{\infty} \frac{KdK}{\omega^2/c^2} \frac{4\,\mathrm{Im}(r_{31}^\alpha)\mathrm{Im}(r_{32}^\alpha)e^{-2\gamma_3'' d}}{|1-r_{31}^\alpha r_{32}^\alpha e^{-2\gamma_3'' d}|^2} \right],$$

Planck spectrum

$$I_\omega^0 = \frac{\omega^2}{4\pi^3 c^2} \frac{\hbar\omega}{(e^{\hbar\omega/k_B T} - 1)}$$



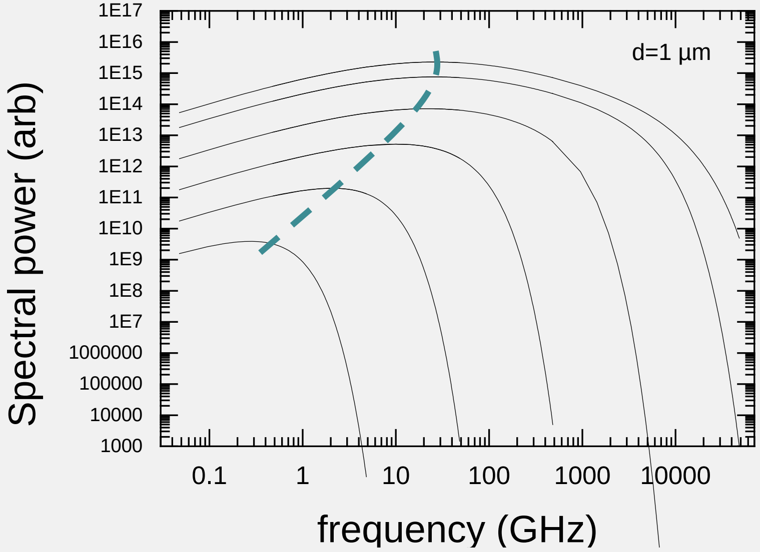
Thermal Properties of Nanostructures

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

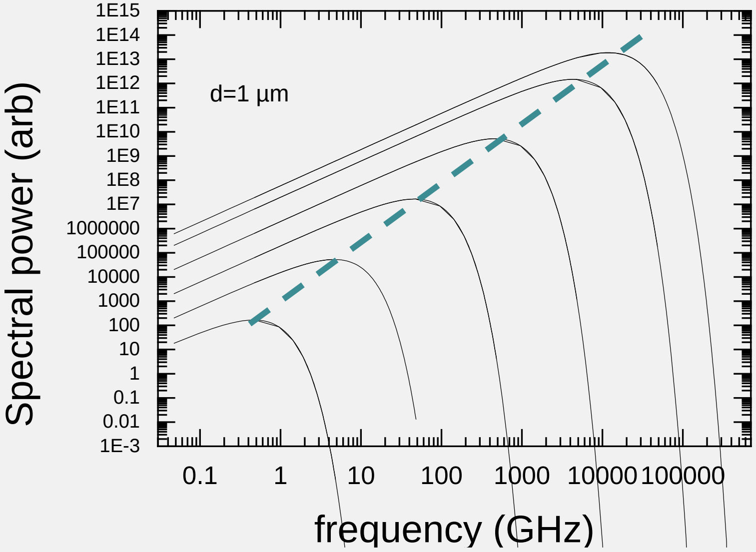
Power spectra are very different from Planckian for s-polarization (but close for p polarization)

T = 0.01 K- 300K

s polarization



p polarization

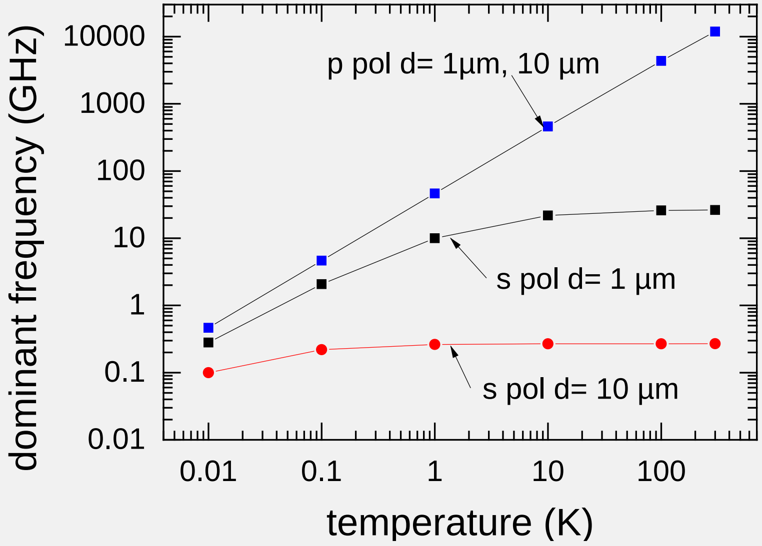


Dominant frequency does not scale linearly with T for s-polarization !
(3 orders of magnitude difference at RT)

Thermal Properties of Nanostructures

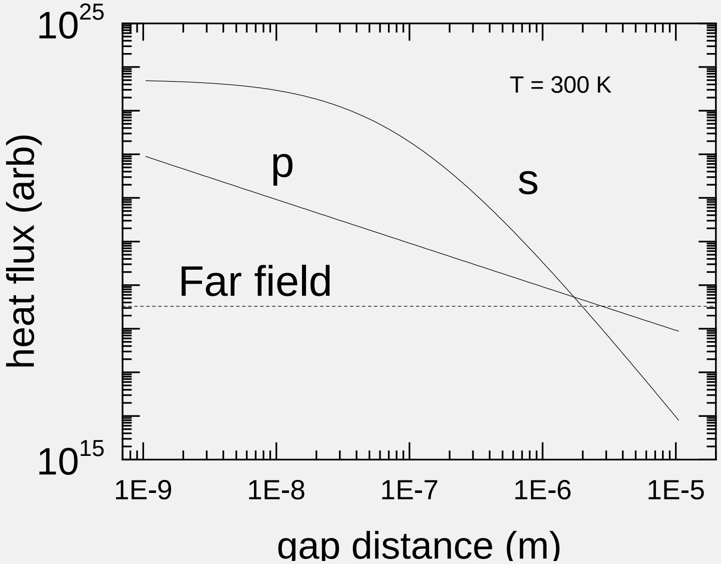
Position of dominant frequency for s-polarization also strongly dependent on gap distance

T = 0.01 K- 300K

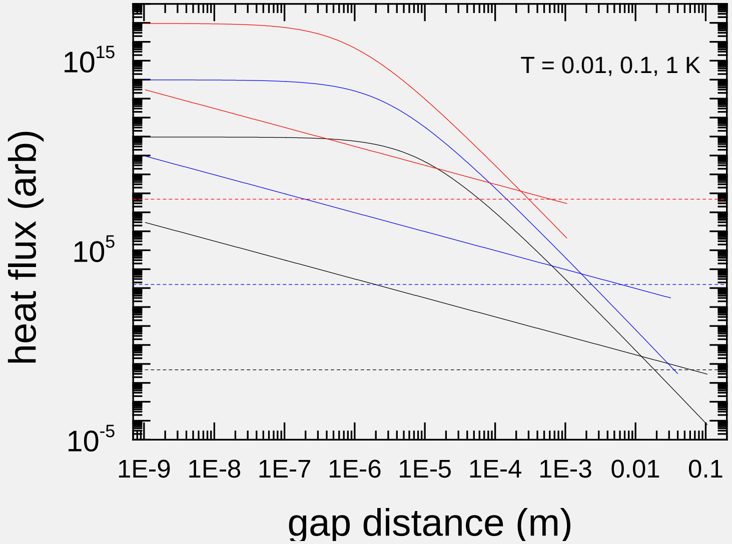


Thermal Properties of Nanostructures

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



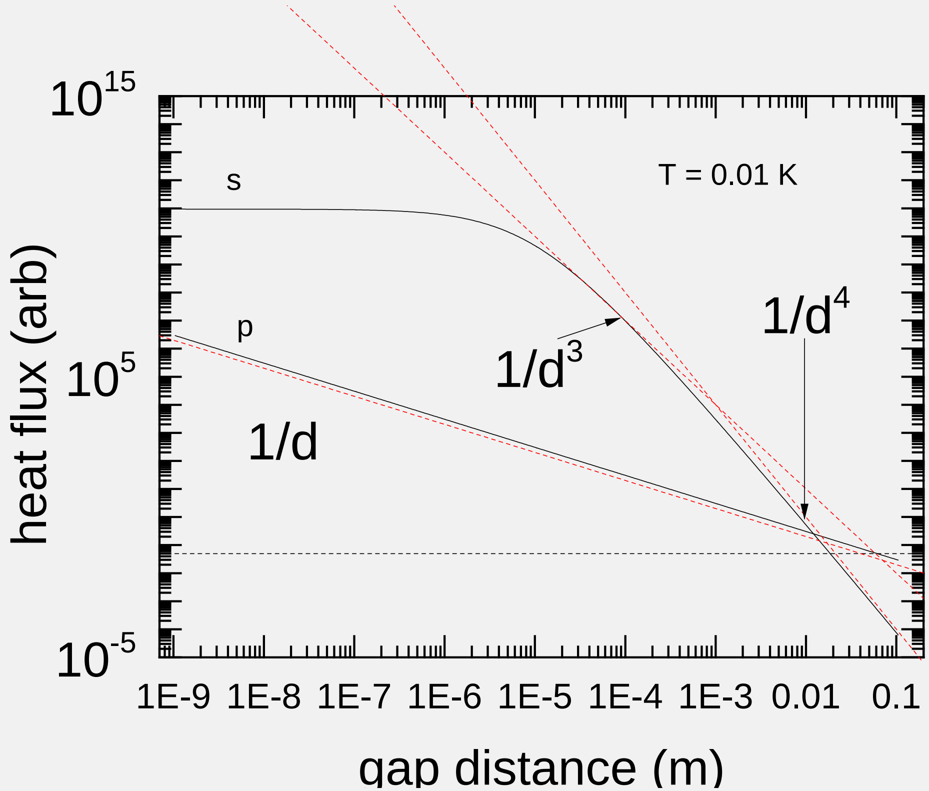
T= 0.01, 0.1, 1K



- Thermal near field starts at ~ 1 mm – 10 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 ~ 1 μm (0.01 K) – 100 nm (1K)
- Has a maximum power enhancement ~ 10^{12} (0.01 K) – 10^{9} (1 K)

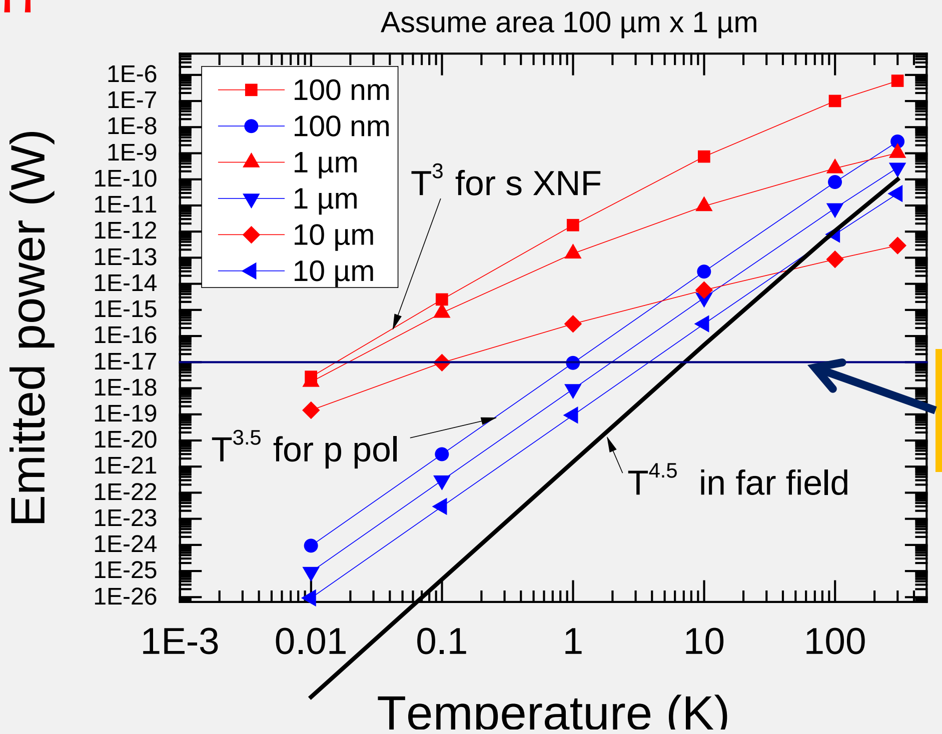
Thermal Properties of Nanostructures

- Distance dependence is not affected by temperature



Thermal Properties of Nanostructures

- Power enhancement is stronger because near field contribution dies out more slowly with T than the far-field contribution



Current neasurement limit
for our structures

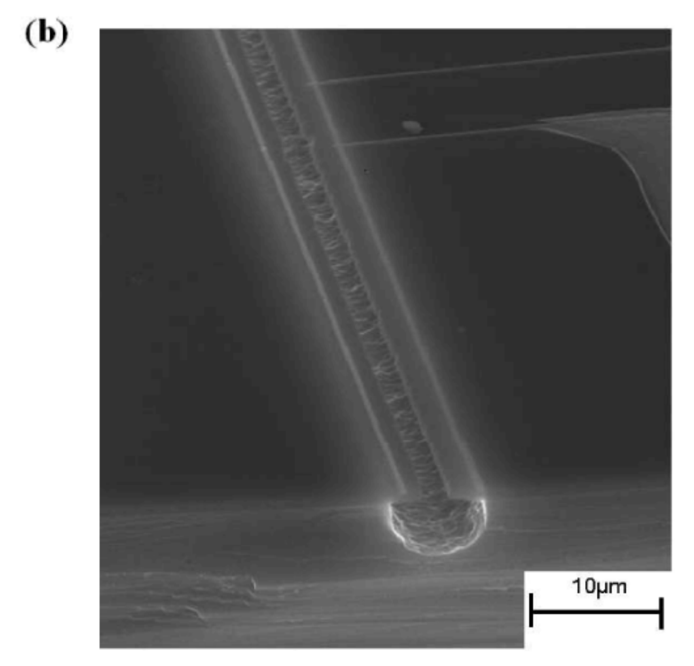
Near field heat transfer measurable at mesoscopic distances (up to ~10 µm) at cryogenic temperatures !

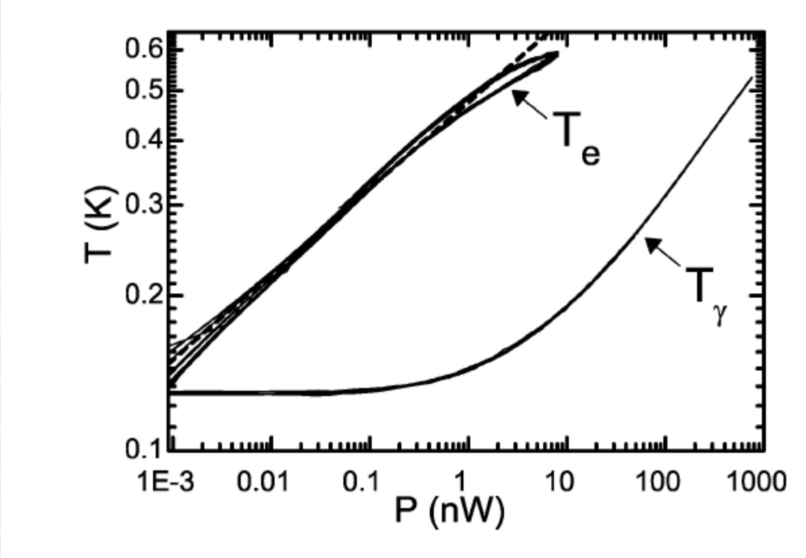
Thermal Properties of Nanostructures

sub-Kelvin to Kelvin temperature range
near-field heat transfer

- Experimental design
- Preliminary data

Early idea: etch a trench between two metallic wires



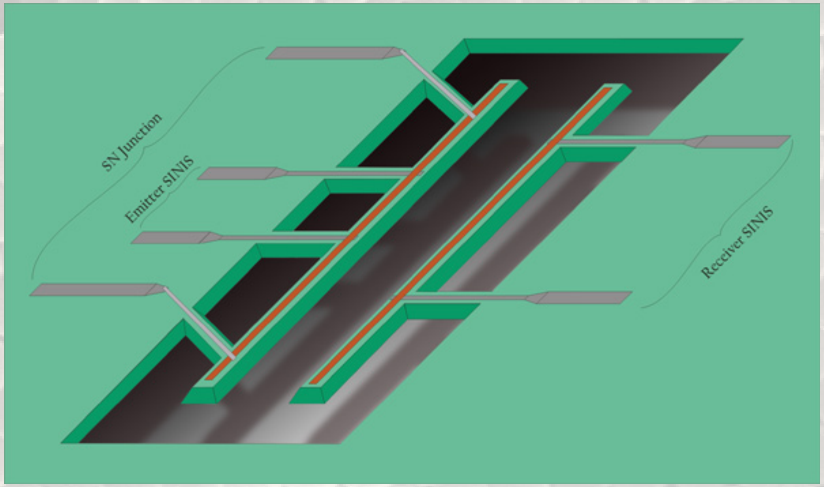


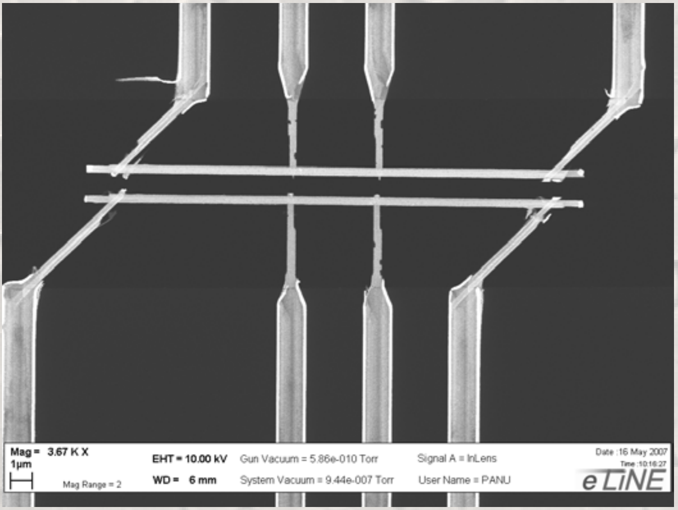
BUT: can we be sure that phonon conduction
Still doesn't dominate ??

P.J. Koppinen, J. T. Karvonen, L. J. Taskinen, I.J. Maasilta, *AIP Conf. Proc*. **850**, 1556 (2006)

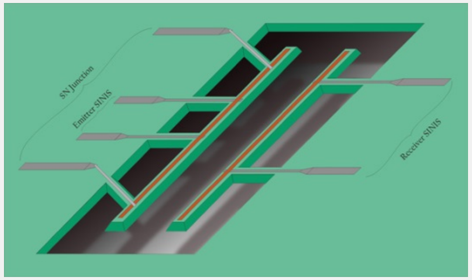
Thermal Properties of Nanostructures

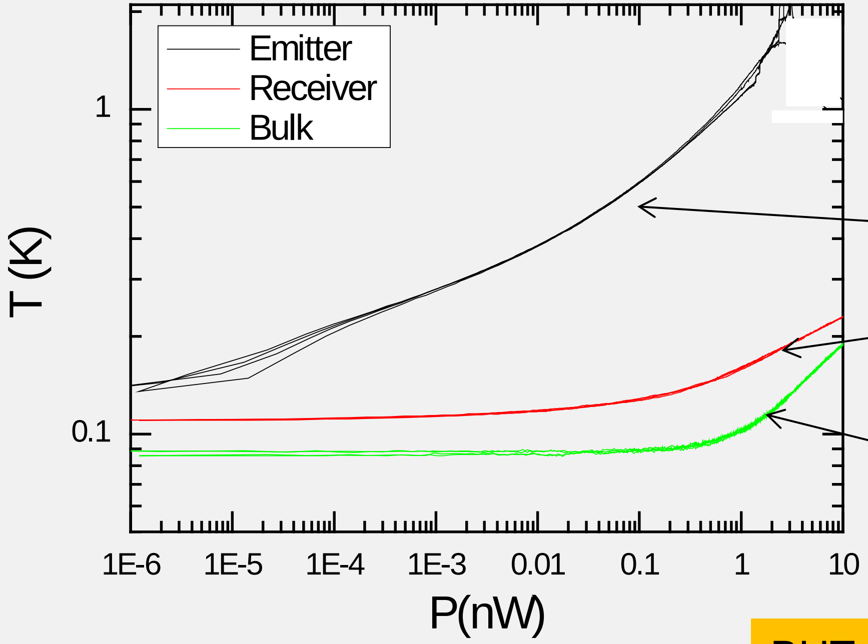
=> Move to suspended wire geometry to fully remove substrate between wires





Again clear heating signal in the receiver wire





Heated wire

Clear signal in the receiver wire

Much weaker signal in phonon thermometer

BUT: what is EMITTED NF power ?

P.J. Koppinen, T. J. Isotalo, I.J. Maasilta, *TRN 07, Les Houches* (2007)

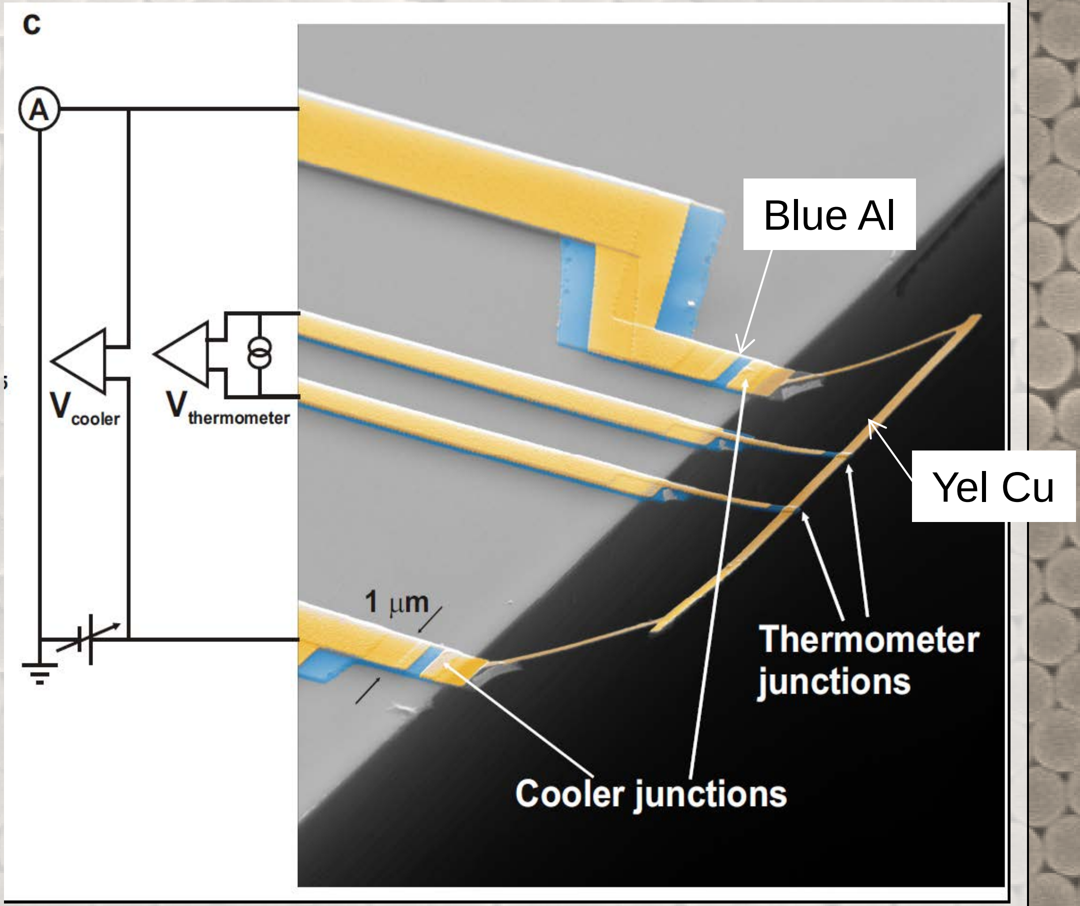
Typical device

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

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

nanowire length 10-20 μm,
thickness 60 nm and width 150-300 nm
4 supporting bridges length 5 μm,
thickness 60 nm and width 150 nm

P.J. Koppinen, I.J. Maasilta,
Phys. Rev. Lett. **102**, 165502 (2009)



Thermal Properties of Nanostructures

Background

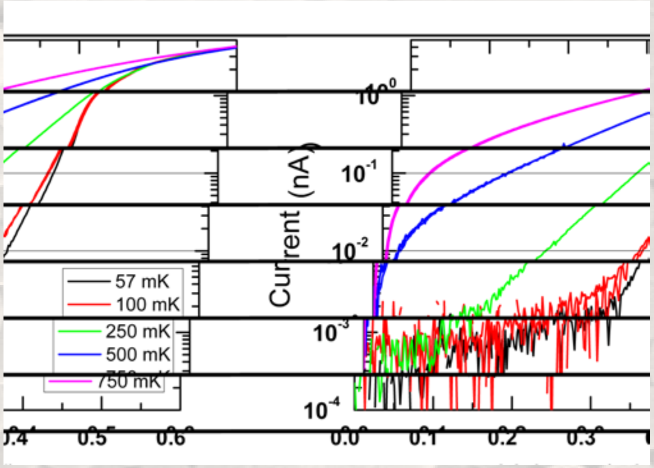
Tunnel junction thermometry

I-V characteristics non-linear with temperature

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

Independent of superconductor temperature

Resolution (~0.1 mK at 100 mK)

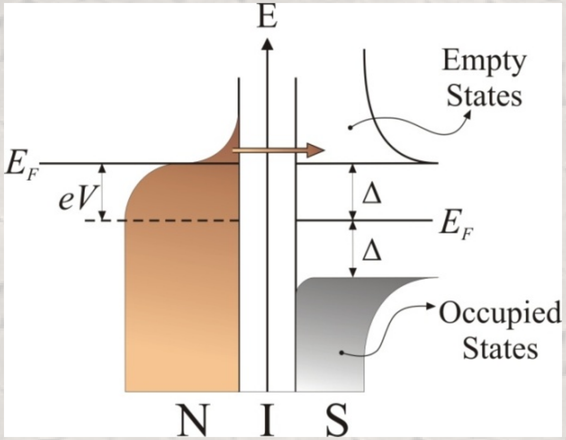


Tunnel junction cooling

Tunneling of “hot” electrons from Fermi tail

(bias voltage dependent, optimal at V ~Δ)

$$\dot{Q}_{cool} = \frac{1}{e^2R_T}\int_{-\infty}^{\infty}(E-eV)g_S(E)[f_N(E-eV,T_N)-f_S(E,T_S)]dE$$

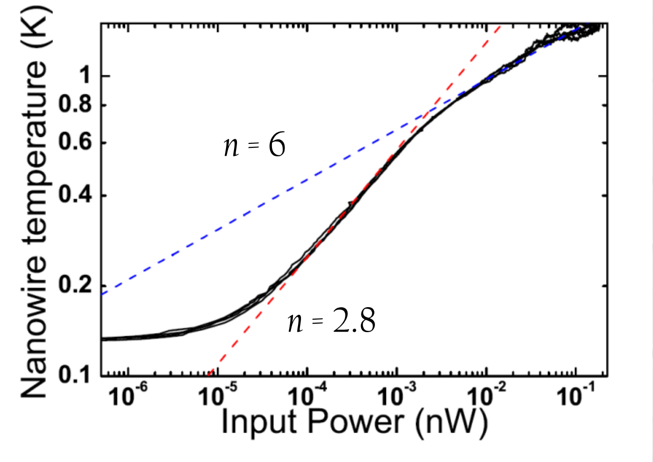


direct heating experiment without coolers

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

No T-gradients within wire =>

Heat flow dominated by the nanowire-bulk interface



$$\boxed{G = dP/dT = 0.4\ \text{pW/K at } 0.2\ \text{K } (0.1\ G_Q\ /\text{channel})}$$

Phonon emission power ~50 fW at 0.2 K

Extremely low G allows measurements of power *~ 10 aW resolution* with SINIS thermometry !

[1] C.M. Chang, M.R. Geller, *Phys. Rev. B* **71**, 125304 (2005)

Thermal Properties of Nanostructures

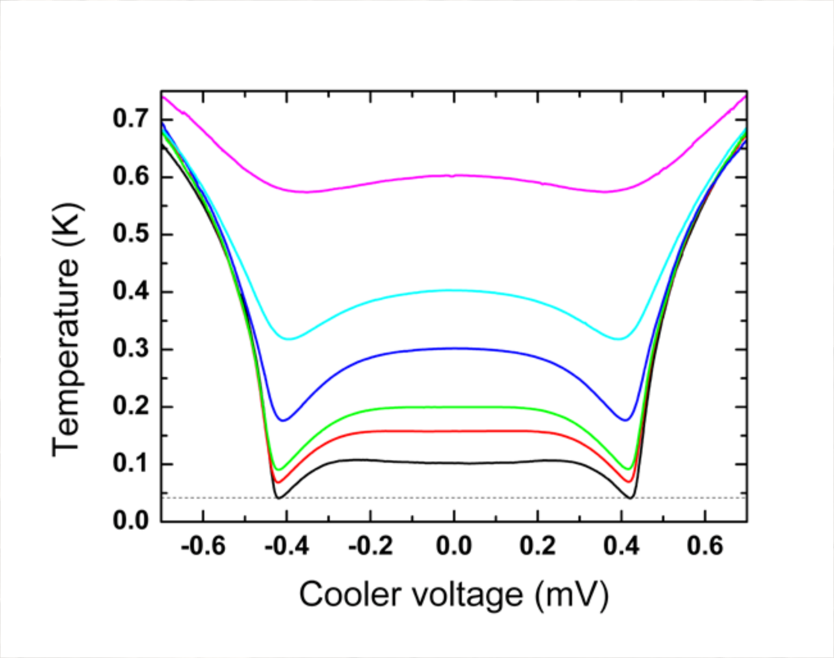
Cooling results and modeling

When refrigerator at 50 mK, nanowire

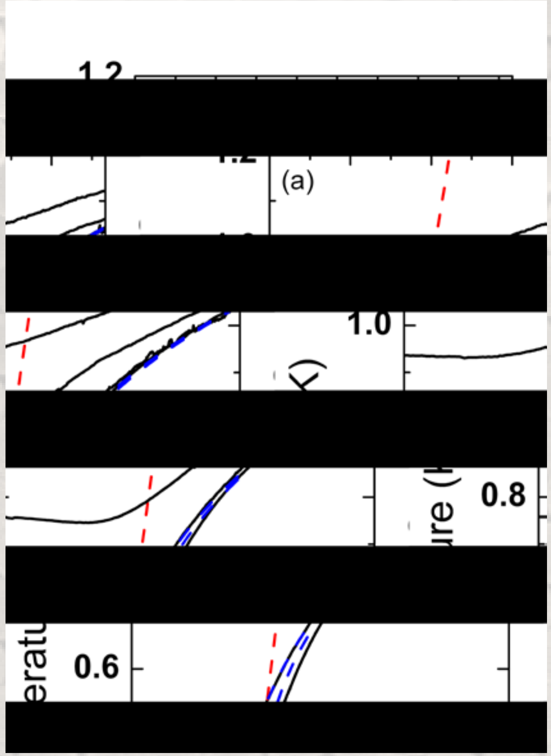
At 100 mK (noise heating), no cooling

At 42 mK with optimal cooling (< Tbath)

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)

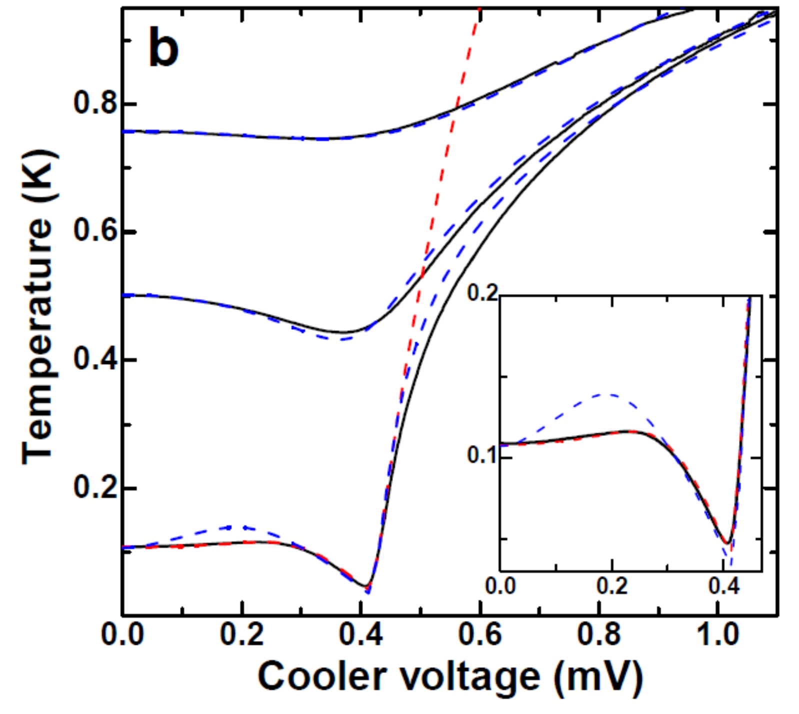


[redacted]

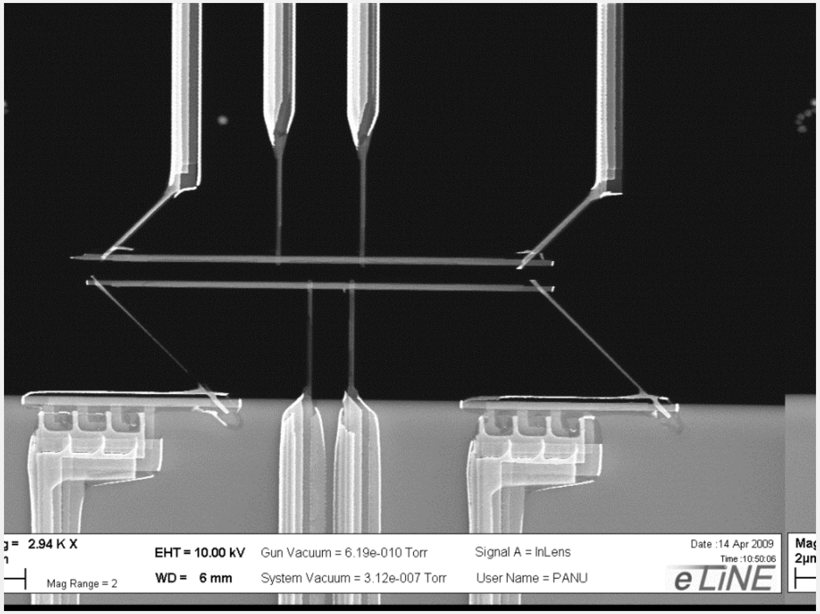
Thermal Properties of Nanostructures

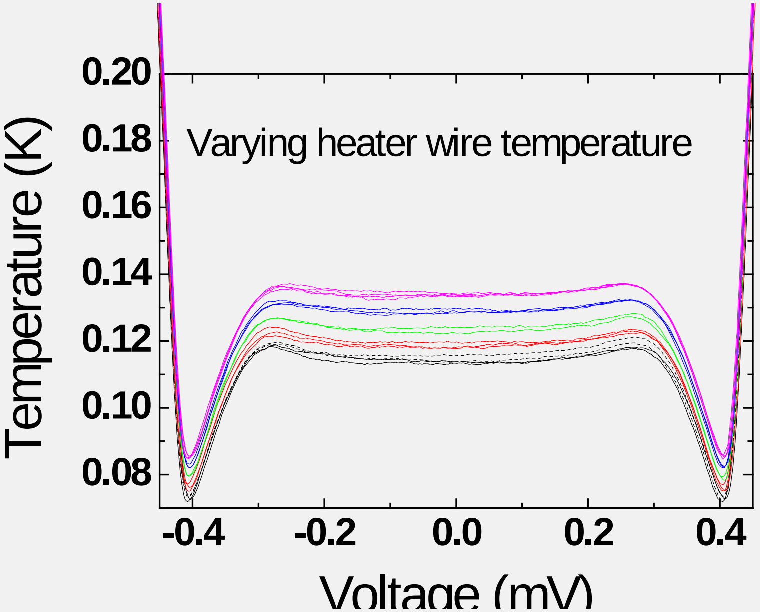
Cooling results and modeling

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)



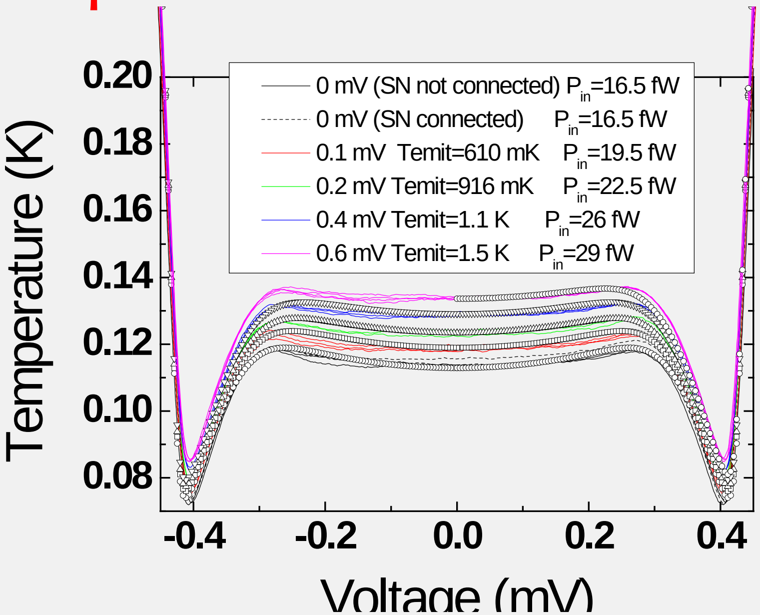


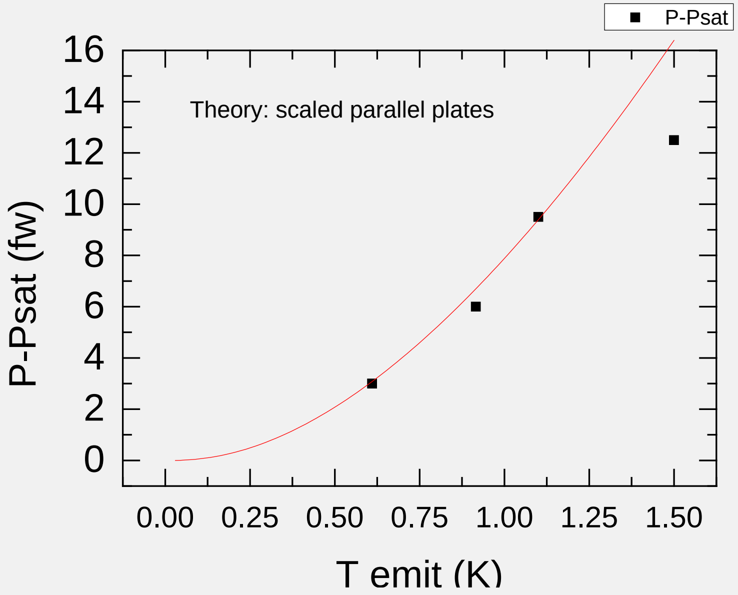
Manuscript in preparation

Thermal Properties of Nanostructures

Cooling results and modeling

The point: we can accurately fit the T vs V curve with a thermal model that includes external input power as a parameter.



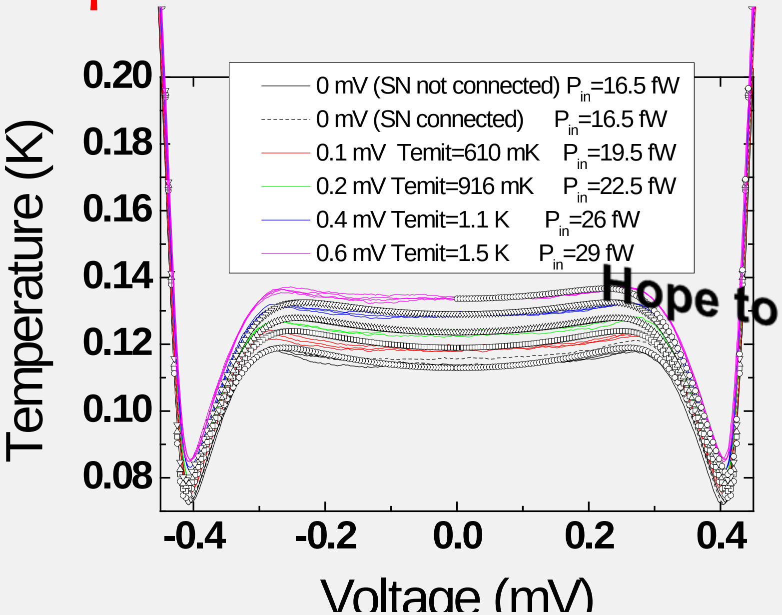


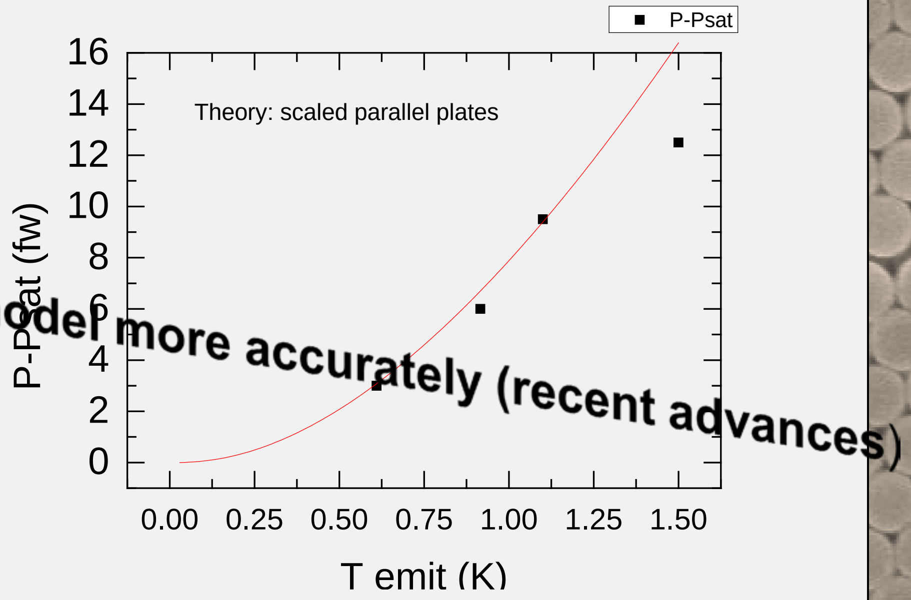
Ten times more power than what parallel plate model seems to predict, but approximately correct temperature dependence ?

Thermal Properties of Nanostructures

Cooling results and modeling

The point: we can accurately fit the T vs V curve with a thermal model that includes external input power as a parameter.





Hope to model more accurately (recent advances)

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

Thermal Properties of Nanostructures

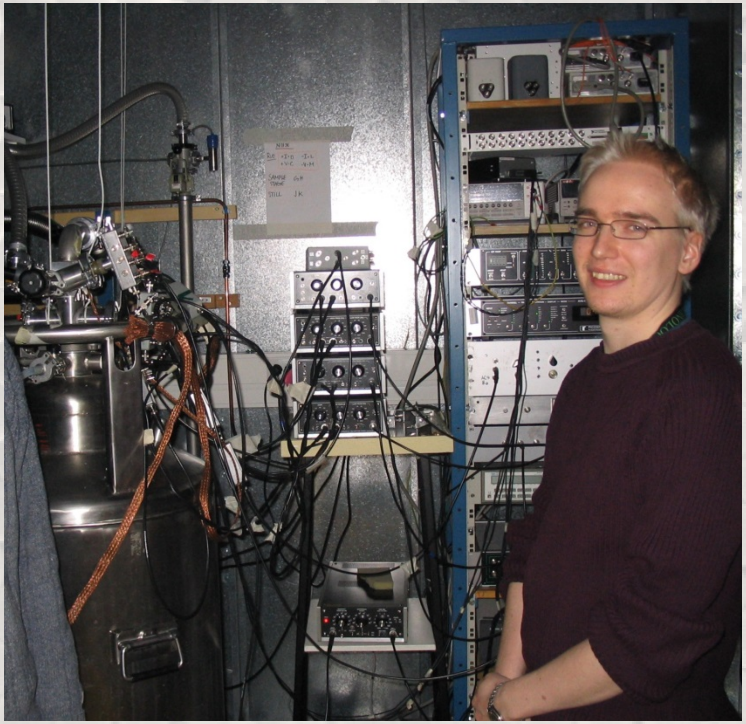
People who contributed

Current group members:

Dr. Saumyadip Chaudhuri

Tero Isotalo

Previous group member:



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