CENTRE D'INVESTIGACIÓ EN NANOCIÈNCIA I NANOTECNOLOGIA
CAMPUS UAB. BELLATERRA. BARCELONA

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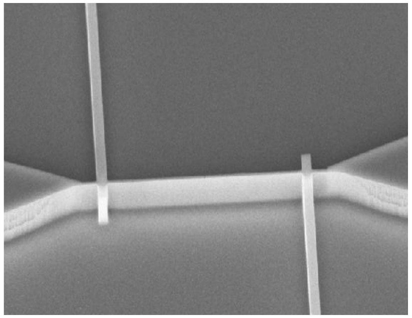

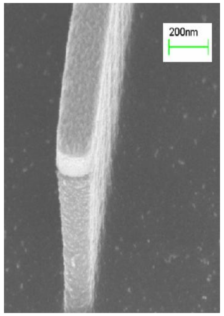

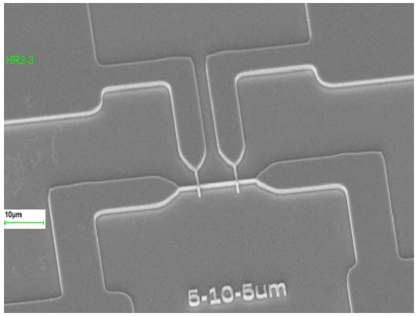

Effect of phonon confinement on heat dissipation in ridges

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ImagineNano, Bilbao, April 2011

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Outline

- **Phonon transport confinement effects**
- Measuring the temperature in ridge samples
- Thermal conductance of silicon ridges
- Conclusion/Perspectives

Phonon lengthscales

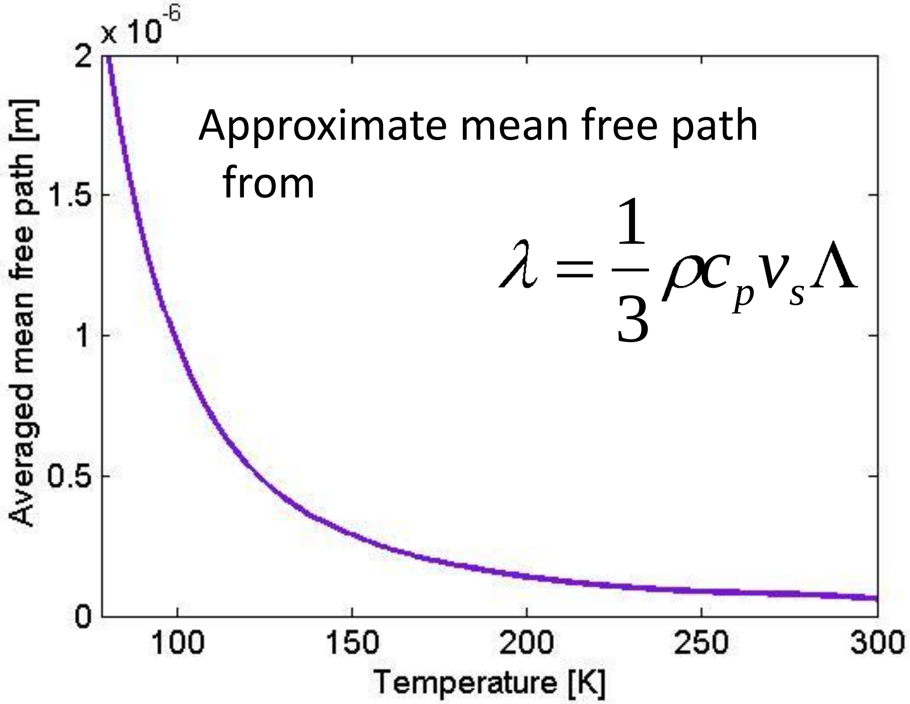
- Acoustic phonons are the main heat carriers in nonmetals

Thermal wavelengths

[~0 - 20] nm @RT

Mean free path (MFP)

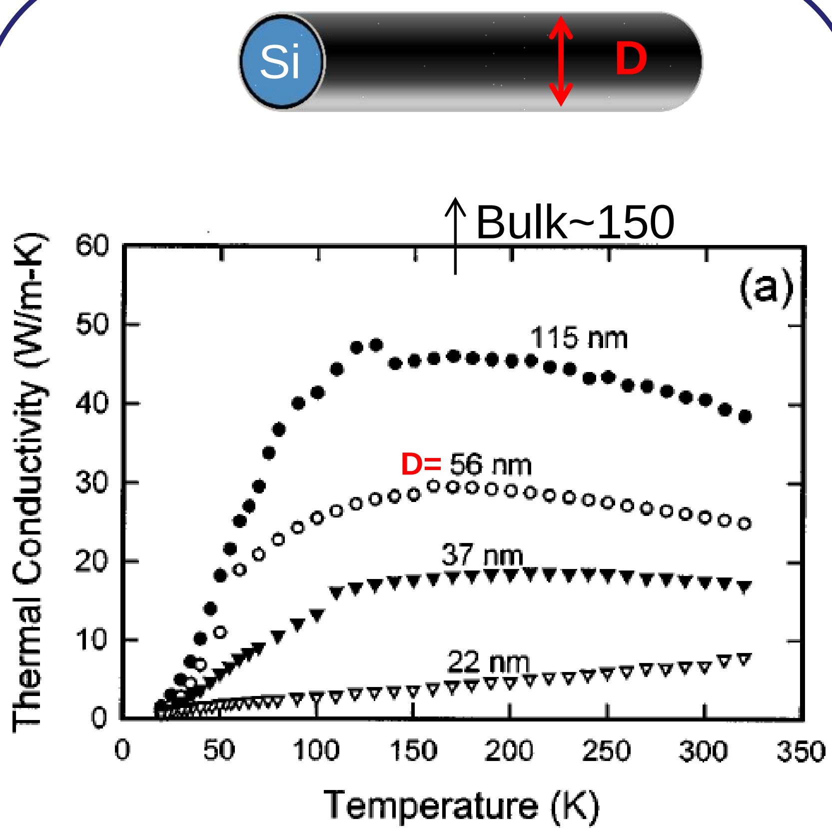
[10 – 500] nm =f(ω)



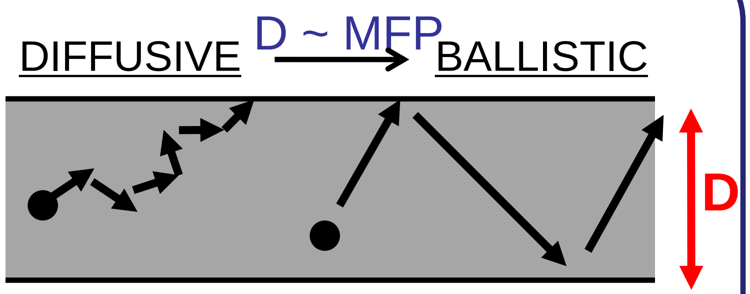
- Vary temperature to change the average MFP

Phonon transport confinement effects

Example: suspended nanowires



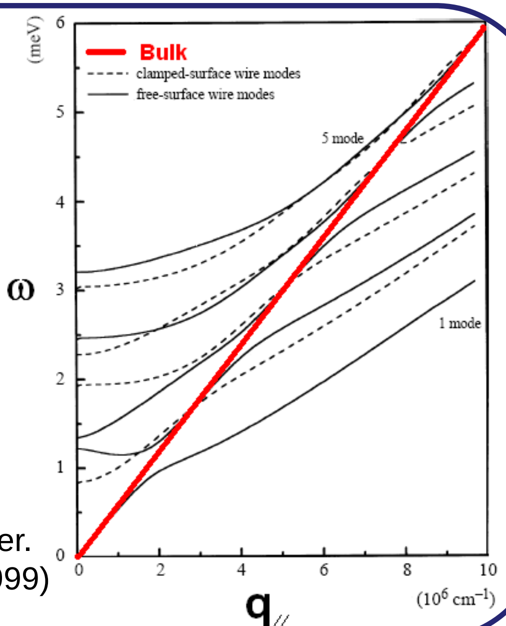
Li,…, Majumdar, Appl. Phys. Lett. 83, 2934 (2003)



Particle

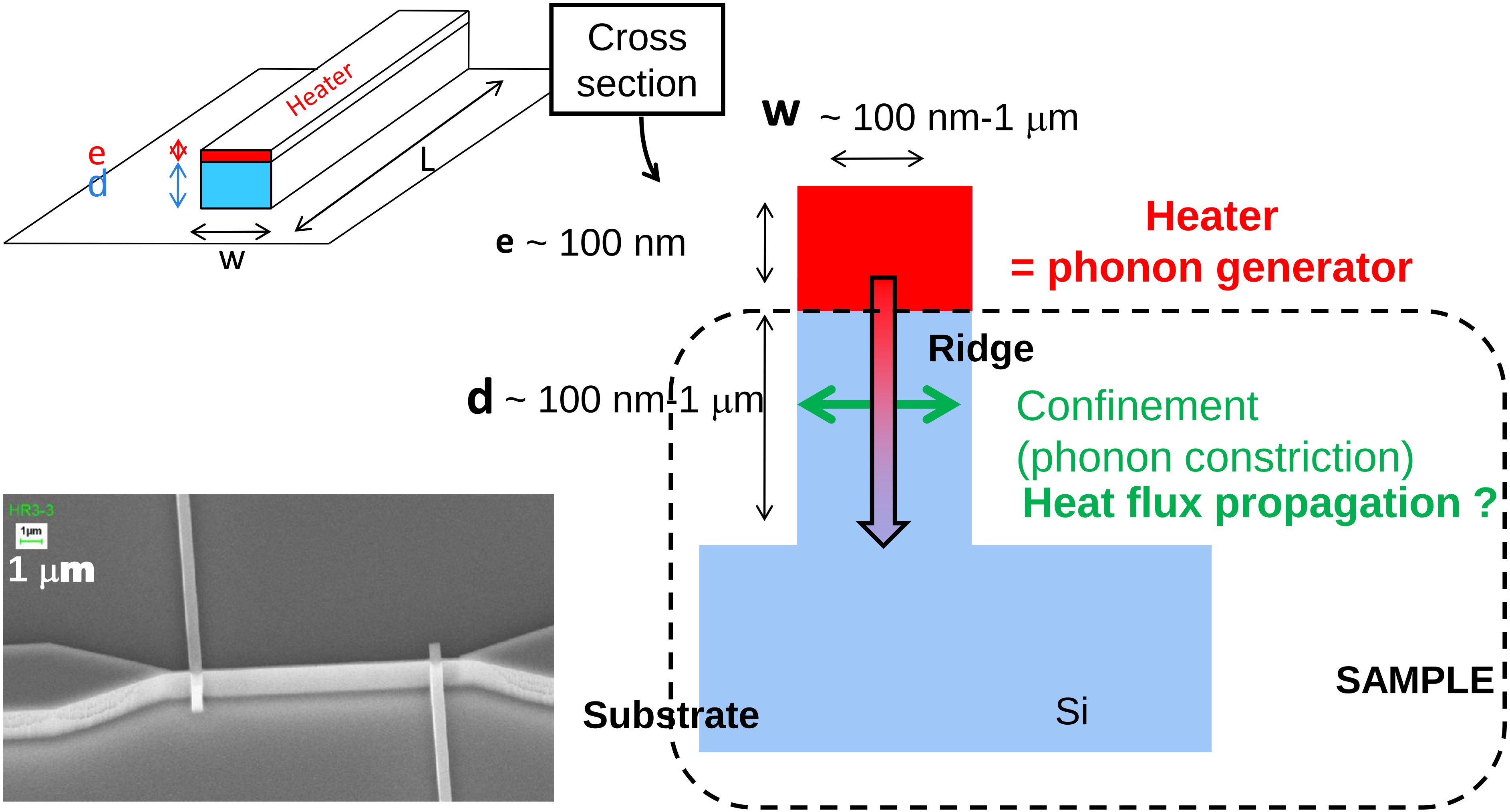
Wave ?

Change in dispersion relation



Balandin, J. Super. Micro 26, 181 (1999)

Supported nanostructures



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Wire temperature measurement

3ω method, Cahill, RSI (1990)

- $R(T) = R_0 (1 + \alpha \Delta T)$

Resistance depends on temperature

- $I = I_\omega \cos(\omega t)$

$\rightarrow P(t) = R\, I(t)^2 = \frac{1}{2} R_0(1 + \cos(2\omega t))$

$\rightarrow T(t) = T_0 + T_{DC} + T_{2\omega} \cos(2\omega t+\phi_{2\omega})$

Joule heating of the electric wire

$$U = RI = R_0[1 + \alpha(T_{DC} + T_{2\omega} \cos(2\omega t+\phi_{2\omega}))]\, I_\omega \cos(\omega t)$$
$$= R_0 I_\omega\, [(1+ \alpha T_{DC}) \cos(\omega t) + \tfrac{1}{2}\, \alpha T_{2\omega} \cos(\omega t-\phi_{2\omega}) + \tfrac{1}{2}\, \alpha T_{2\omega} \cos(3\omega t +\phi_{2\omega})\,]$$
$$= U_{1\omega} + \boxed{\tfrac{1}{2}\, \alpha R_0 I_\omega T_{2\omega} \cos(3\omega t+\phi_{2\omega})} \longrightarrow \boxed{\text{Lock-in detection}}$$

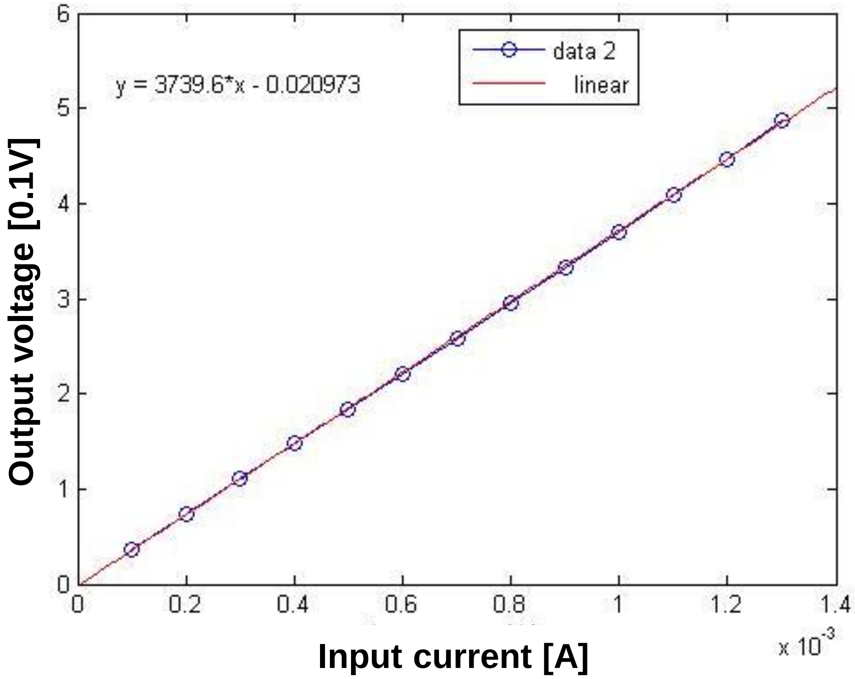
- Other possibility: Combining DC and AC current input

$I = I_0 + I_\omega \cos(\omega t) \longrightarrow \boxed{U_\omega = R_0\, I_\omega (1+ \alpha T_{DC}) \cos(\omega t)}$

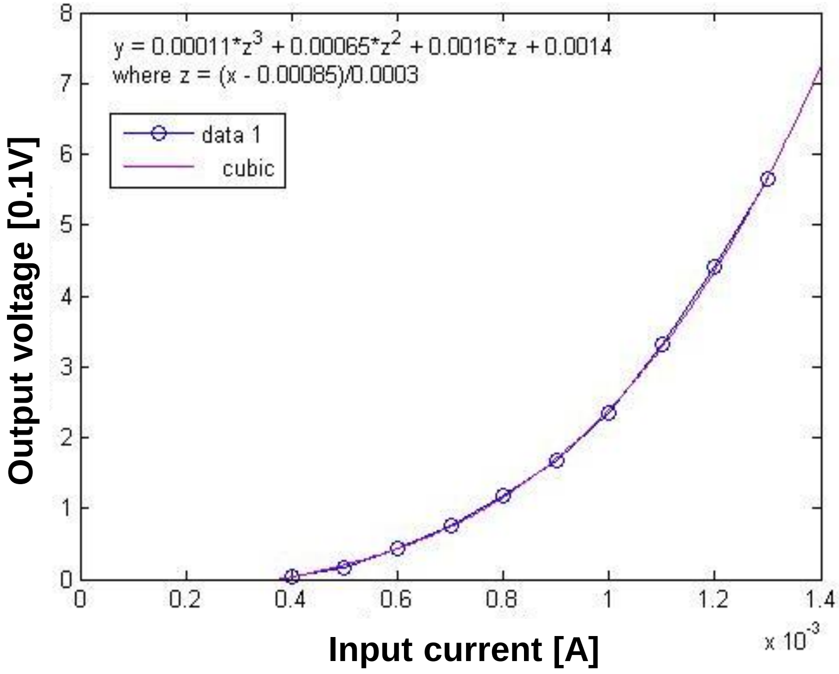
- Wire temperature = f (heat flux in the sample)

Wire temperature measurement

$V_{1\omega} = R_0 I \sim R_0$



$V_{3\omega} \sim I^3$



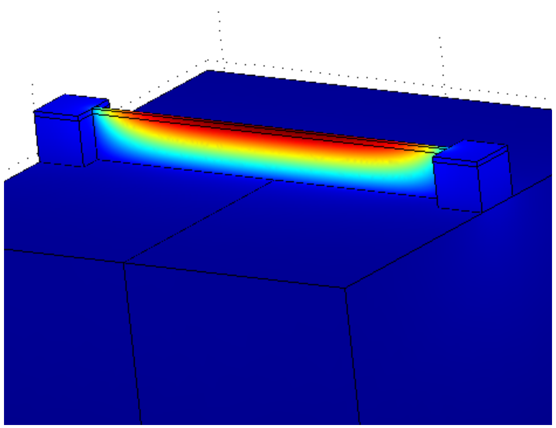
Calculation of the conductance G_{th}

- The conductance is obtained from

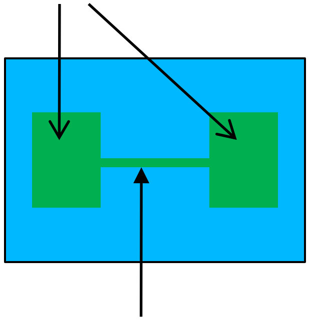
$$G_{th} = P/\Delta T$$
$$= F_{geometry}\ RI^2 / \Delta T$$

- $F_{geometry}$? take F = 1 as upper limit
- Pads are heat baths. T_{wire} is not constant along its length.

Temperature distribution



FEM simulation

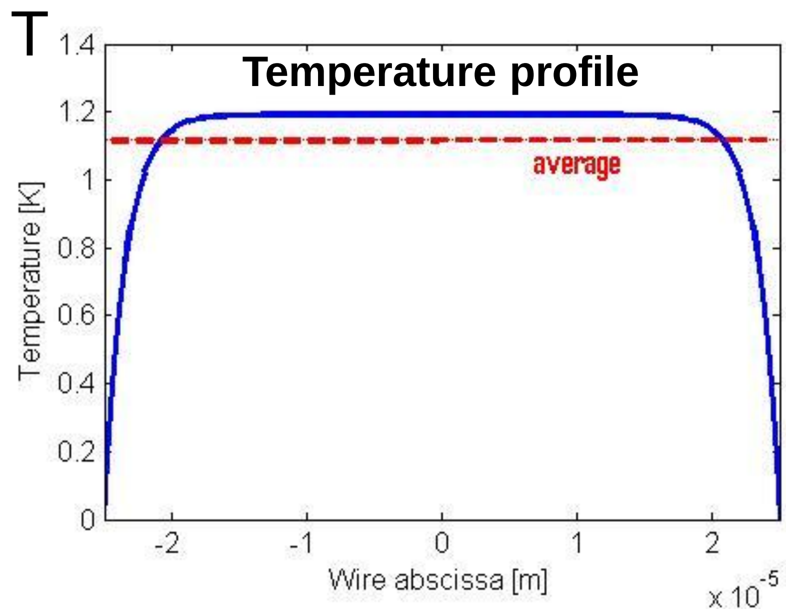


wire

$I_0 = 1.3\ 10^{-3}$ A

$g = 10^8\ WK^{-1}m^{-2}$

(f =12 Hz)



Analytical calculation

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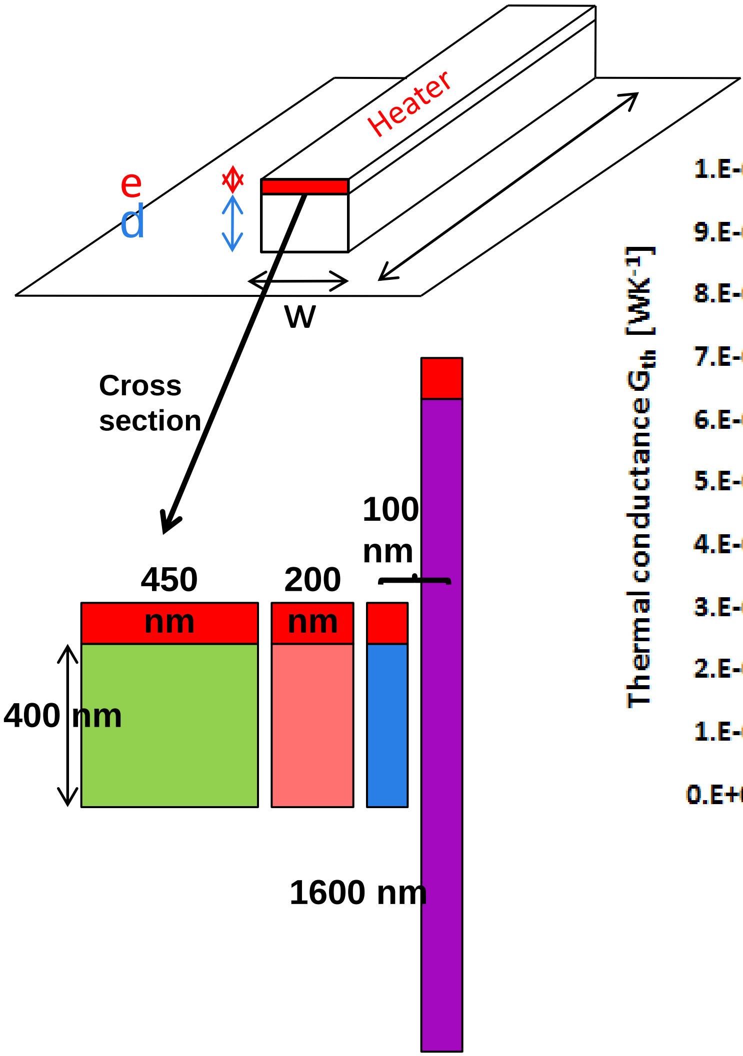
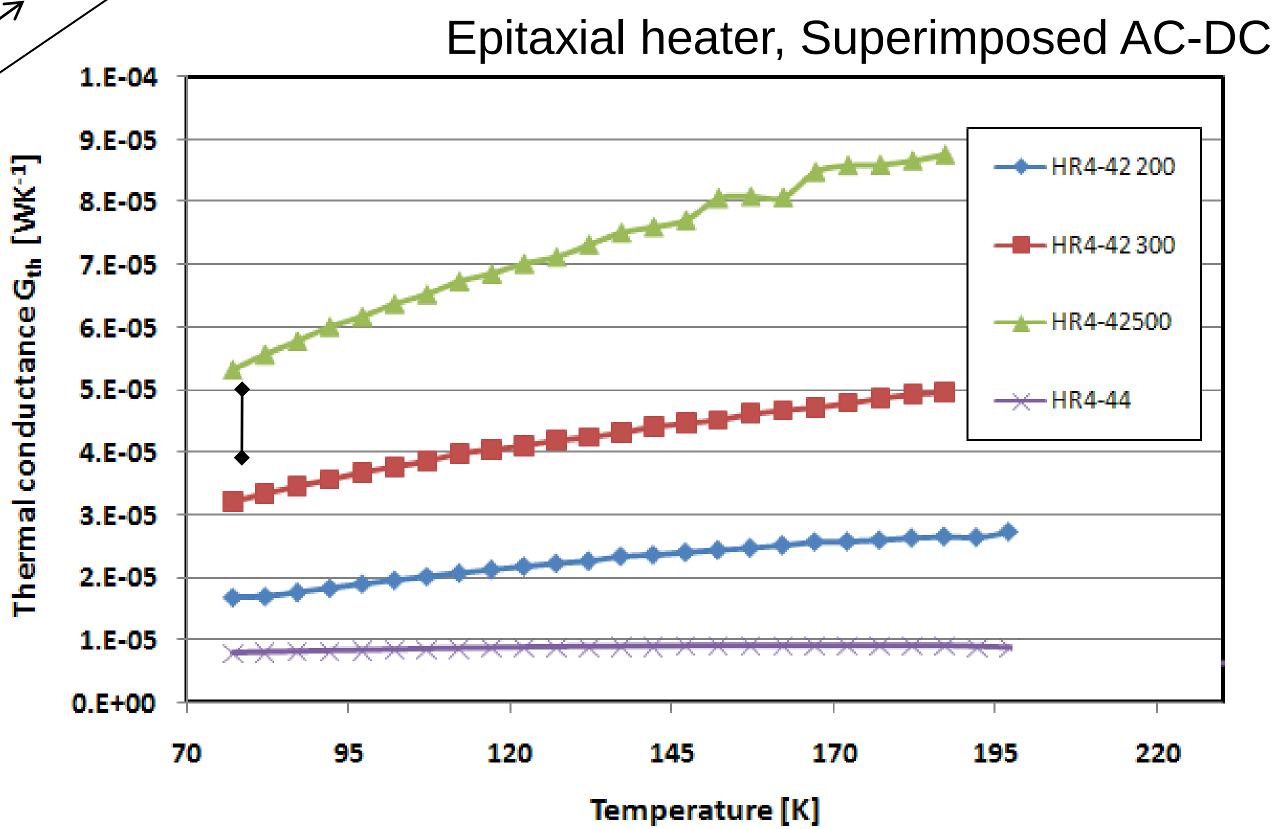
Thermal conductances of Si ridges



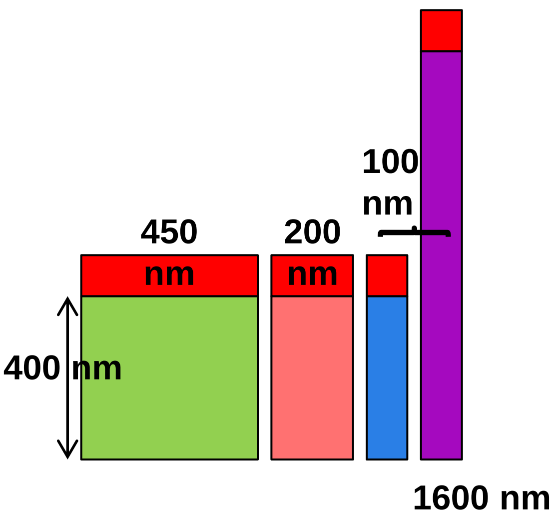


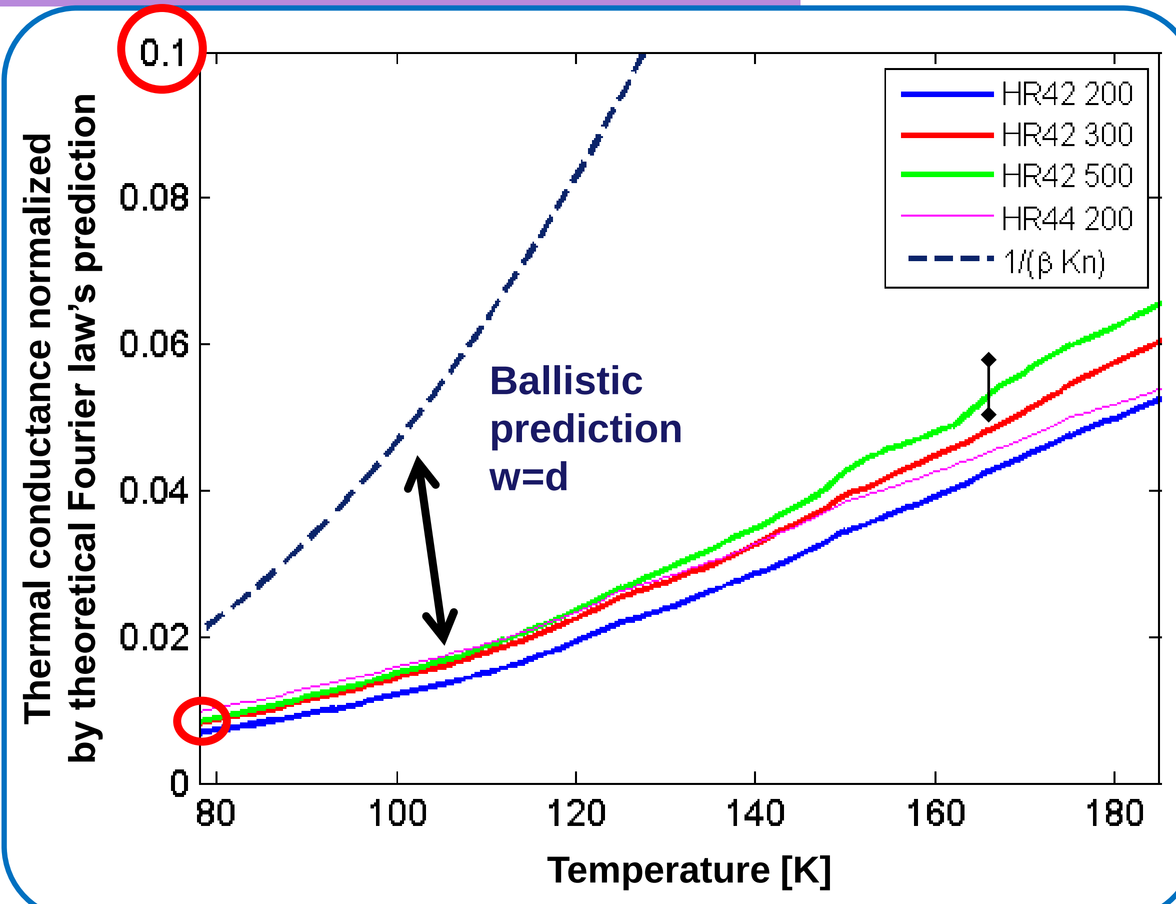
→ G appears to follow a w/d trend (Fourier ?)

Chapuis et al, Proceedings of THERMINIC 2010

Deviation from ballistic theory

	3	2	1	4
Ratio S(cavity)/ S(contact)	2.8	5	9	33





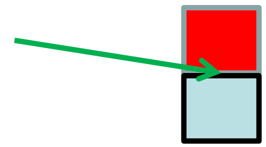
- Far below the Fourier prediction (<10%)
- Different from a pure ballistic prediction (<50%)

Chapuis et al, Proceedings of THERMINIC 2010

Thermal conductances of Si ridges

Why are there deviations from the ballistic theory

1) <u>Surface thermal resistance</u>



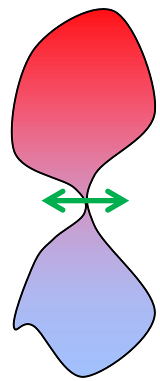
So far not observed with 3ω

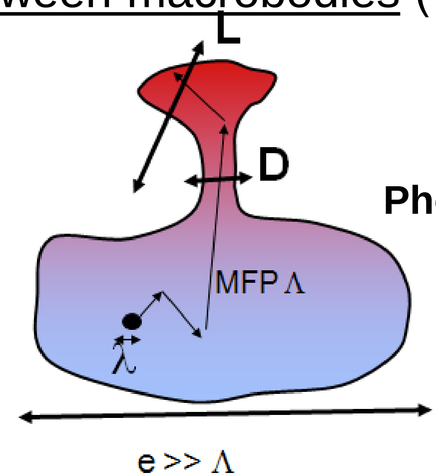
2) <u>Correction to theory of constrictions between macrobodies</u> (‘Nano’ correction)

Ballistic approach

Assumption : two heat baths

All phonons are supposed to be transmitted through the constriction





Phonon backscattering ?

No thermalization in the nanostructure ?

Fourier prediction

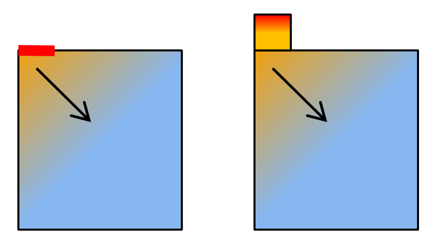
Ballistic deviation

$$R_{th} = R_{Fourier}(1+\beta Kn).C(W/BTE)\frac{1}{1-\gamma}$$

Wexler’s formula

BTE correction to Wexler (heat source case)

« Nano » correction to Wexler/BTE



Volz, JAP (2008)

Conclusion/Perspectives

- The thermal conductance of silicon ridges has been measured for ridges of thickness between 100-450 nm.
- Its temperature dependence (i.e. Knudsen number) was observed
- Compared to Fourier law a two orders of magnitude decrease was measured and ascribed to confinement
- At least one order of magnitude difference with the ballistic transport prediction

- Confirmation with other samples using the 3ω method
- Lower temperatures → interplay with strong wave effect
  Higher temperatures → larger range of Knudsen number
- Impact of roughness
- Refinement of the associated theory in progress

Chapuis et al, Proceedings of THERMINIC 2010

Thank you for your attention !

Questions ?