Mesoscopic effects on the thermal conductance of silicon nanowires

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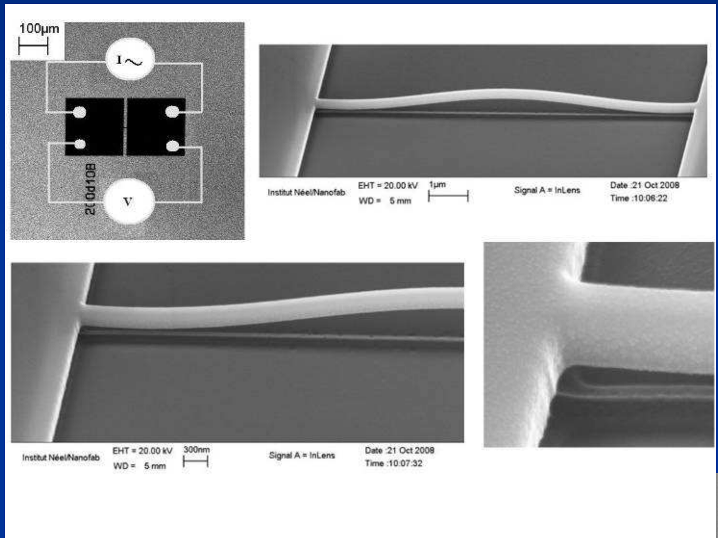

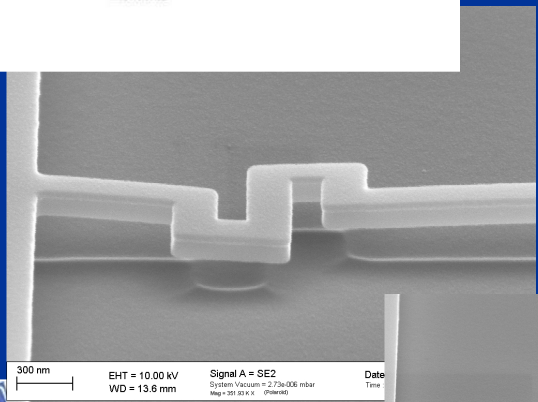

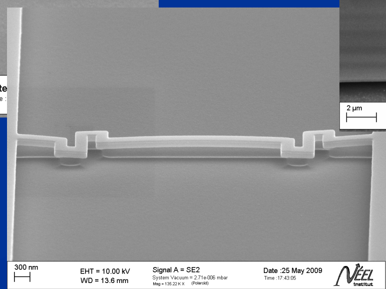

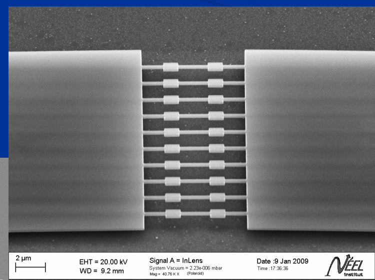

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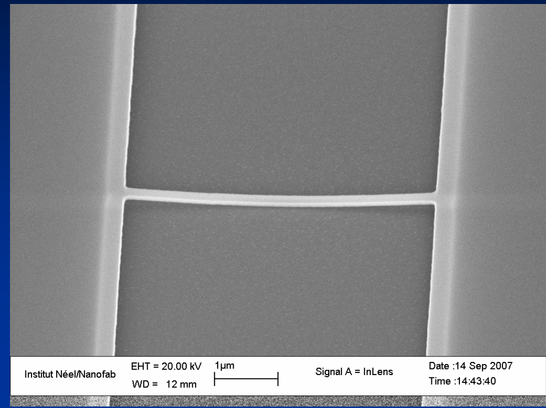
Low dimensionality

- Loss of the bulk behaviour (phonon transport, superconductivity, magnetism) competition between surface effect and volume.
- Characteristic length play a significant role (dominant phonon wave length, phase coherence length, etc…)
- Manipulation of phonons at the nanoscale
- Specific thermal behaviour at small length scale (quantification of the thermal conductance, definition of the temperature …)
- Development of new tools designed for the study of thermal event at the nanoscale: nanocalorimetry, thermal conductance
- Measurement of very small thermal signal, detection on mesoscopic systems of energy variation as small as Zepto (10^{-21}J) or YoctoJoule (10^{-23}J).

Outline

- Introduction
- Thermal conductance of silicon nanowire
  - Effect of the geometry on the phonon transport
  - 3ω method
  - Thermal conductance of nanowire: Casimir limit
- Blocking the phonon transport in silicon nanowire
- Some perspective: transmission coefficient, phononic crystals
- Conclusions and perspectives

Thermal transport at mesoscopic scale and cryogenic temperatures



•1- λ_T<<d, Casimir theory (Casimir model): the thermal transport is only limited by the boundary scattering limiting the mean free path

•2- λ_T~d intermediate regime:

- •Important characteristic length: the dominant phonons wave length λ_T
- •Roughness of the nanowire surface

$$\lambda_T \approx \frac{\theta_{Debye} a}{T} \approx \frac{h v_s}{2.82 k_B T}$$

At 1K, λ_T ~0.1µm
At 0.1K λ_T~1µm

3- λ_T>>d at very low temperature the thermal conductance becomes independent of the materials and the geometry (quantum regime)

•ballistic transport, only 4 acoustic modes of vibration thermally activated

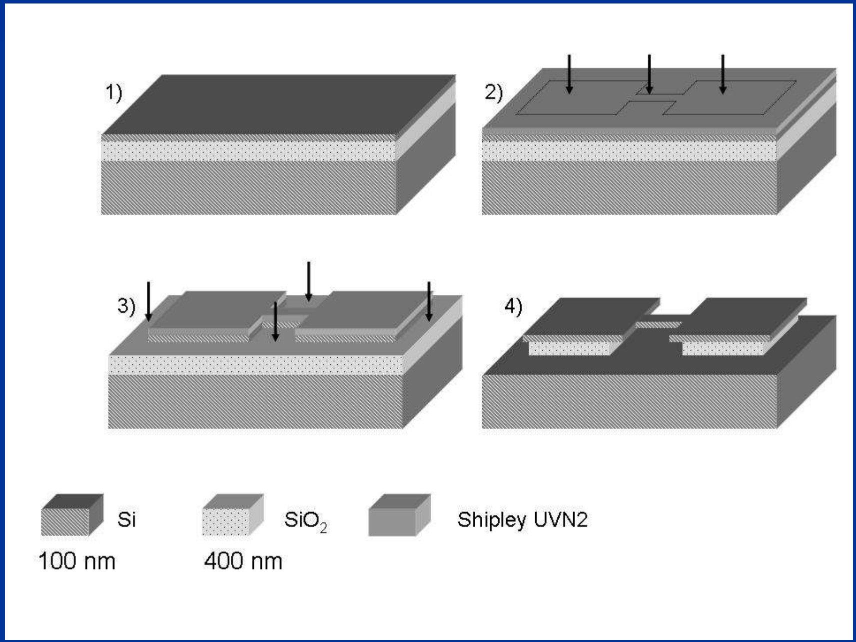
- •The thermal conductance is equal to n*kQ* (where n is the number of channels)

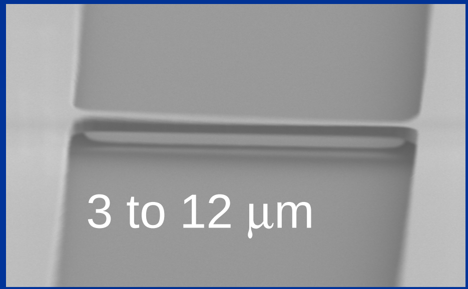
$$k_Q = \frac{\pi^2 k_B^2 T}{3h}$$

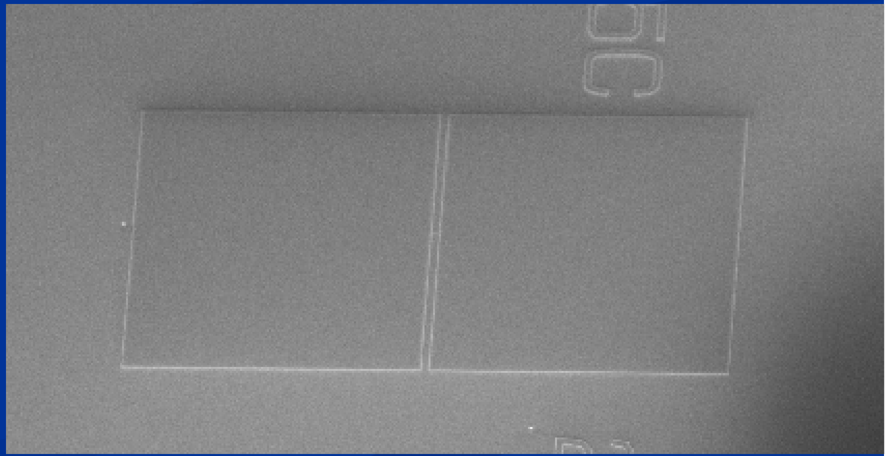
Ziman, *Electrons and Phonons*,

Sample fabrication

- The fabrication of **monolithic** silicon nanowires are realized by e-beam lithography at the LETI on SOI substrate, or by ourselves with Nanofab.
- Numerous different wires can be built from 50 to 400 nm of cross-section of 100 nm and 200 nm thick, and of length 3 to 12 μm.
- A NbN transducer is deposited on top: thin film 50 nm thick.







3ω Method

In the NbN layer, an alternative courant is delivered : $I_0\sin(wt)$

The thermal balance of the nanowire is given by the Fourier equation :

$$\rho C_P \frac{\partial}{\partial t} T(x,t) - k \frac{\partial^2}{\partial x^2} T(x,t) = \frac{I_0^2 \sin^2(wt)}{LS} [R + (\frac{dR}{dT})_{T_0} (\Delta T(x,t))]$$

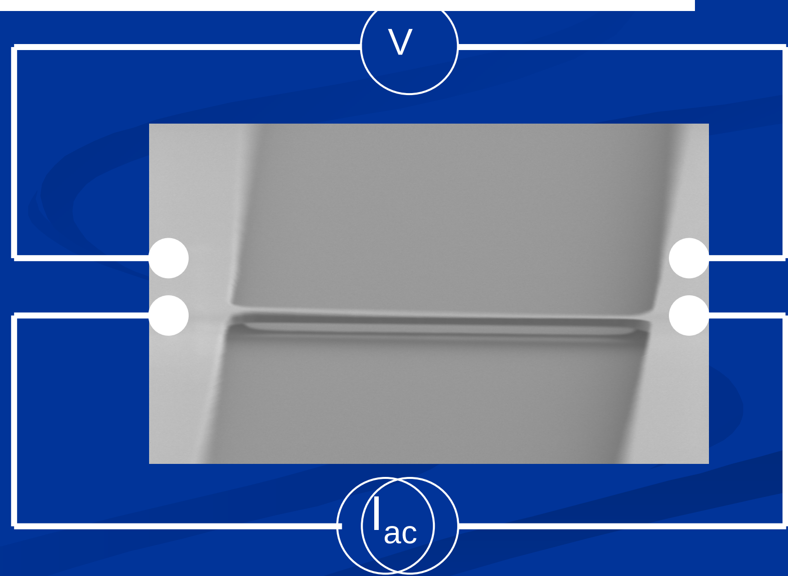
❒ : mass density of the nanowire

C_P : specific heat

k : thermal conductivity

R : electrical resistance

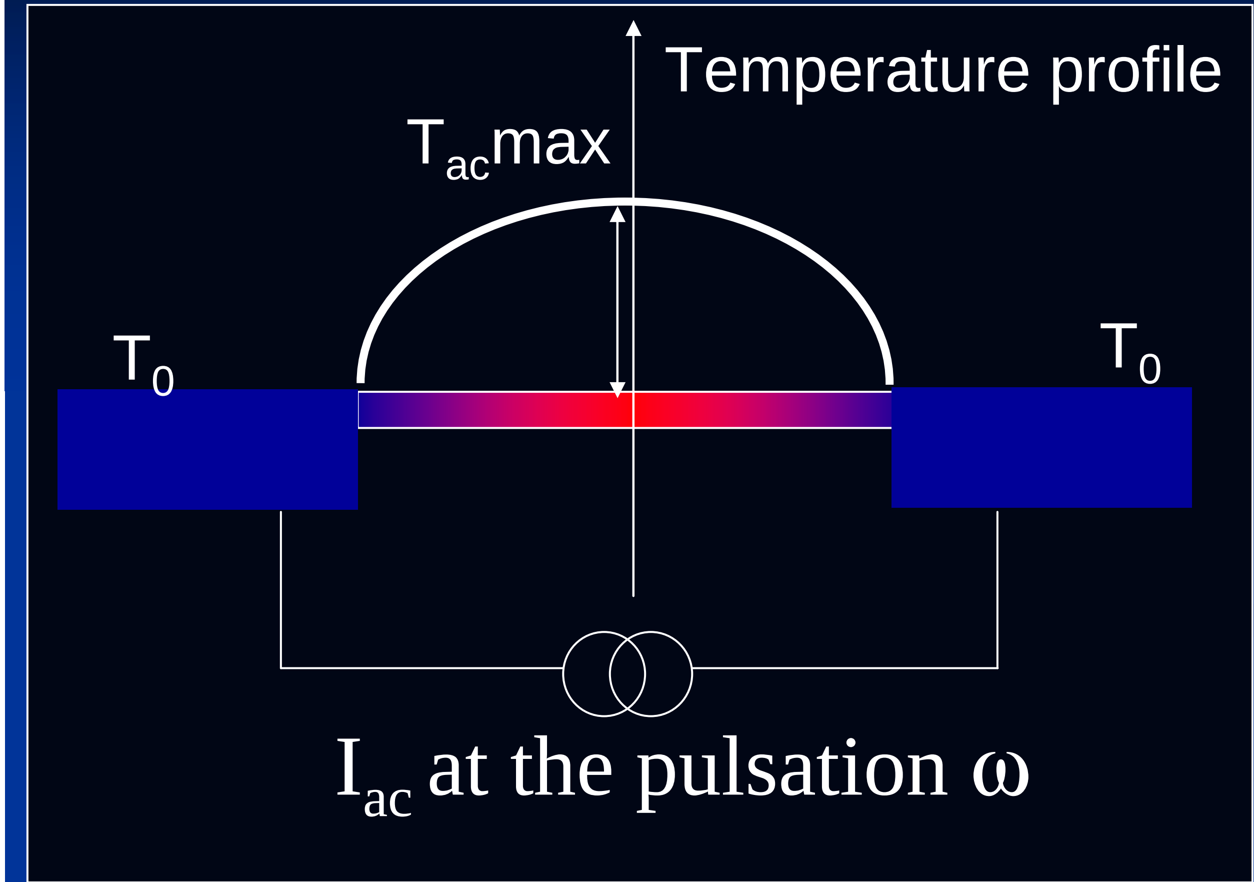
L and S : length and section of the nanowire



Cahill, *Rev. Sci. Instrum.* **61**, 802 (1990)

The 3ω method – Lu, Yi, Zhang, *Rev. Sci. Instrum.* **72**, 2996 (2001)

3ω Method



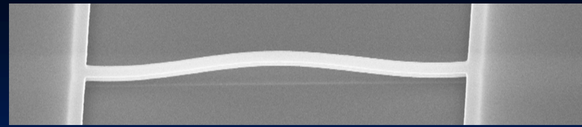
- $I_{ac} \sim 1\omega$
- $T_{ac} \sim I^2 \sim 2\omega$
- $R \sim T \sim 2\omega$
- $V_{3\omega} \sim I_{ac}R \sim 3\omega$

$$K = \frac{4 I_0^3 R^2 \alpha}{\pi^4 V_{3\omega}}$$

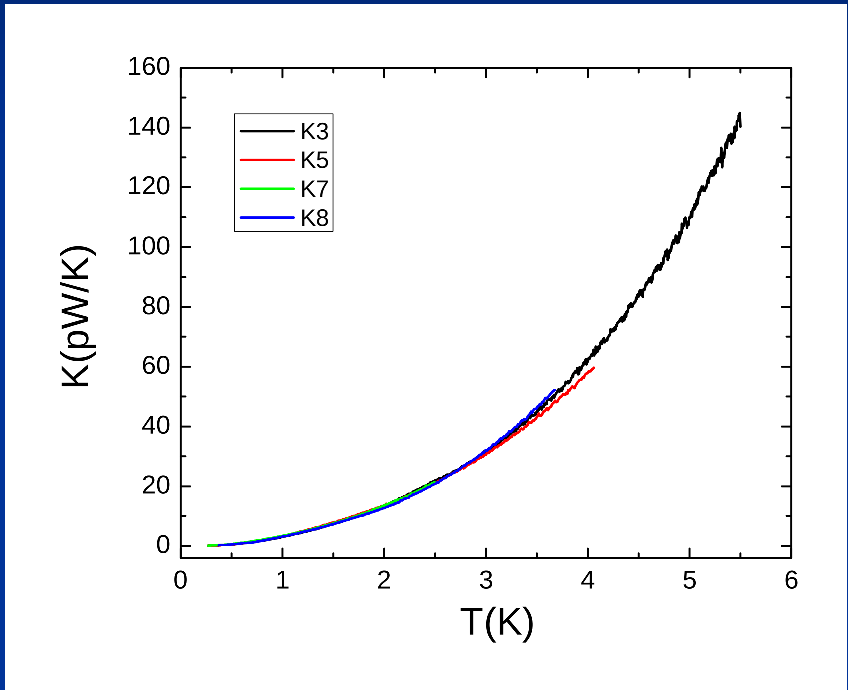
$K_{NbN} << K_{Si}$

O. Bourgeois, Th. Fournier, and J. Chaussy, *Measurements of the thermal conductance of silicon nanowires at low temperature*, J. Appl. Phys. **101**, 016104 (2007)

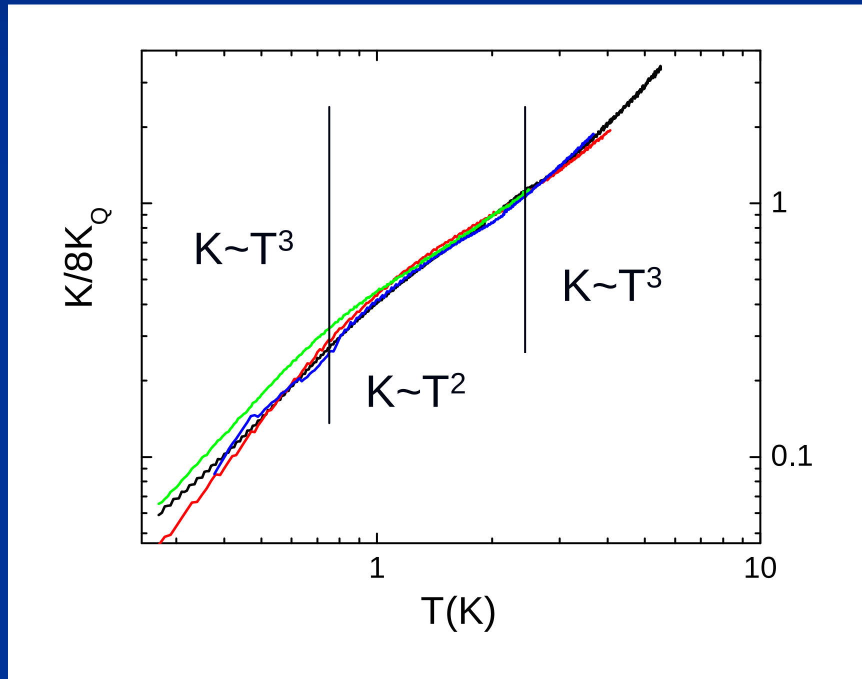
Measurement Method : the 3ω method



$$K_Q = \frac{\pi^2 k_B^2 T}{3h}$$



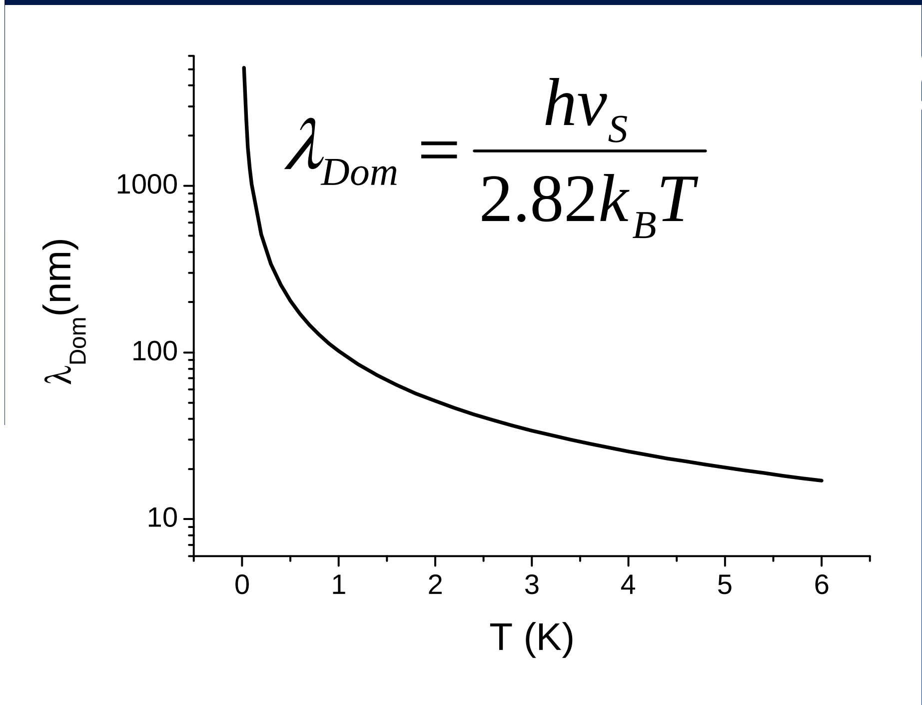
Thermal conductance for 4 identical samples



Thermal conductance normalized by 8 quanta of conductance

J.-S. Heron, T. Fournier, N. Mingo and O. Bourgeois, *Mesoscopic surface effects on the phonon transport in silicon nanowire*, Nano Letters **9**, 1861 (2009).

T>4K



High temperatures, dominant phonon wave length largely inferior to the roughness average of the surface (η_0~4 nm): diffusive reflection

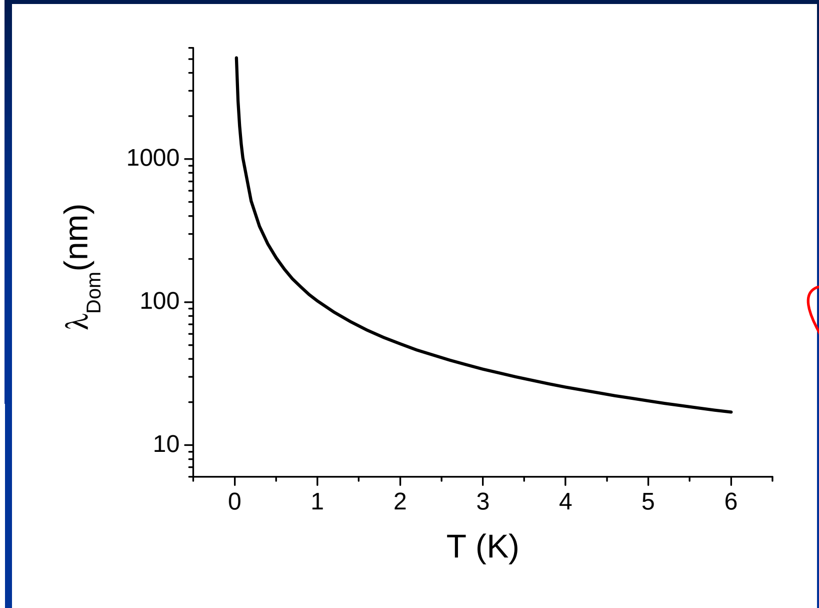
Evolution of the dominant phonon wave length

For the high temperatures: bulk behavior, Casimir diffusive transport

$$K \sim \Lambda_{Cas} T^3 \text{ with } \Lambda_{Cas} = 150 \text{ nm}$$

T~3K

$\lambda_{Dom} \sim 4\eta_0$



Evolution of the dominant phonon wavelength

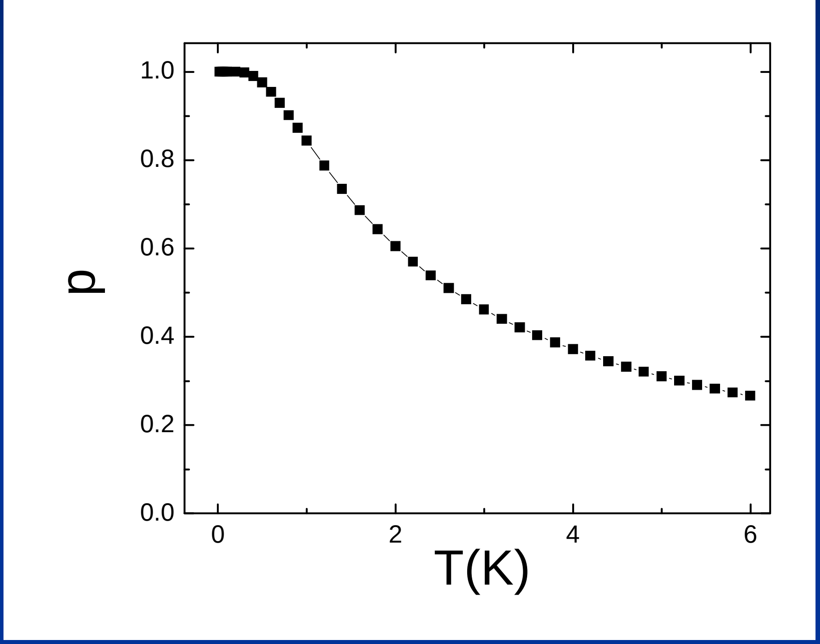
Diffusive and ballistic reflections

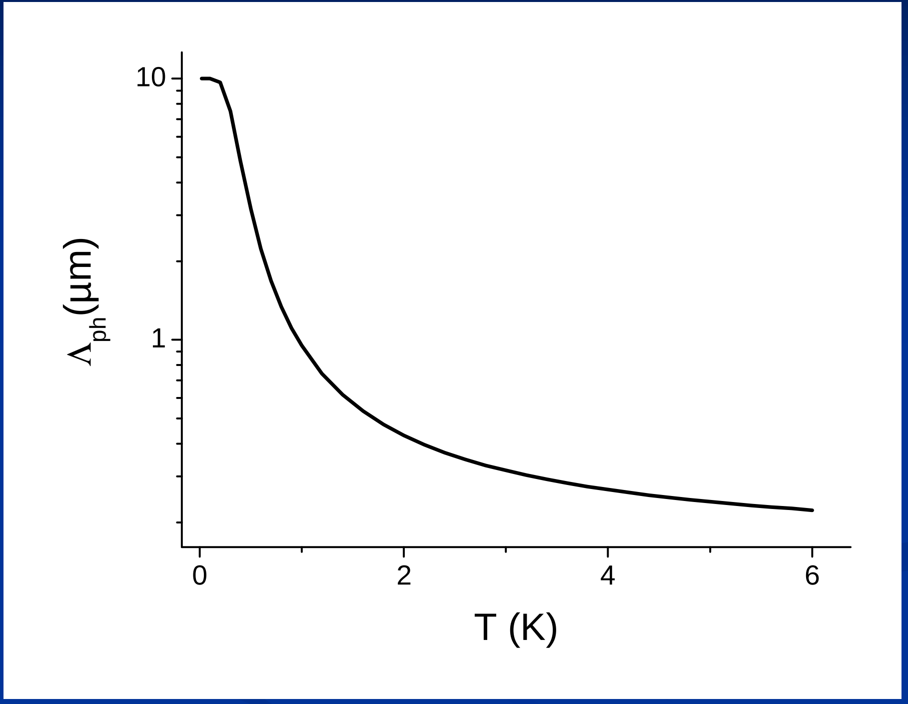
The apparition of ballistic reflection implies an increase of the mean free path

J.-S. Heron, T. Fournier, N. Mingo and O. Bourgeois, *Mesoscopic surface effects on the phonon transport in silicon nanowire*, Nano Letters **9**, 1861 (2009).

$$\Lambda_{eff} = \frac{1+p}{1-p}\Lambda_{Cas}$$

$$\Lambda_{ph}^{-1} = \Lambda_{eff}^{-1} + L^{-1}$$

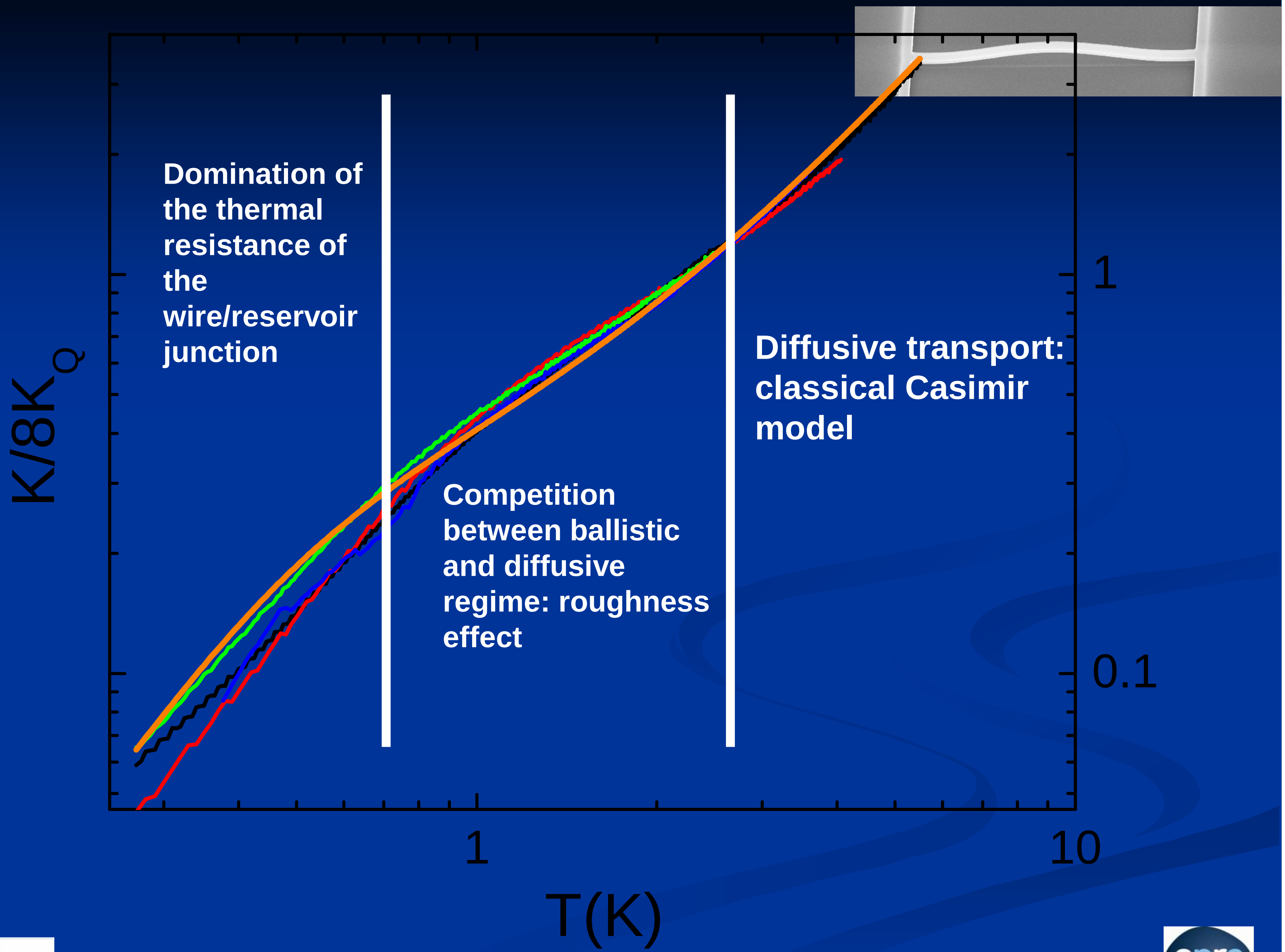




Evolution of the probability to have a specular reflection and consequence on the mean free path .

$$K \sim \Lambda_{ph}(T)T^3 \sim T^2$$

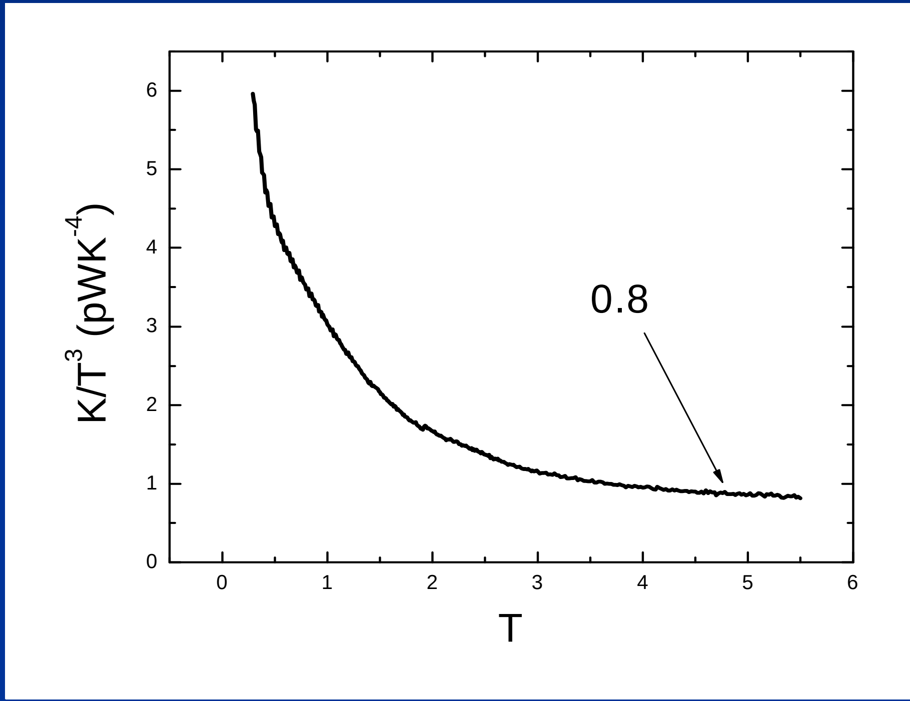
J.-S. Heron, T. Fournier, N. Mingo and O. Bourgeois, Nano Letters **9**, 1861 (2009).

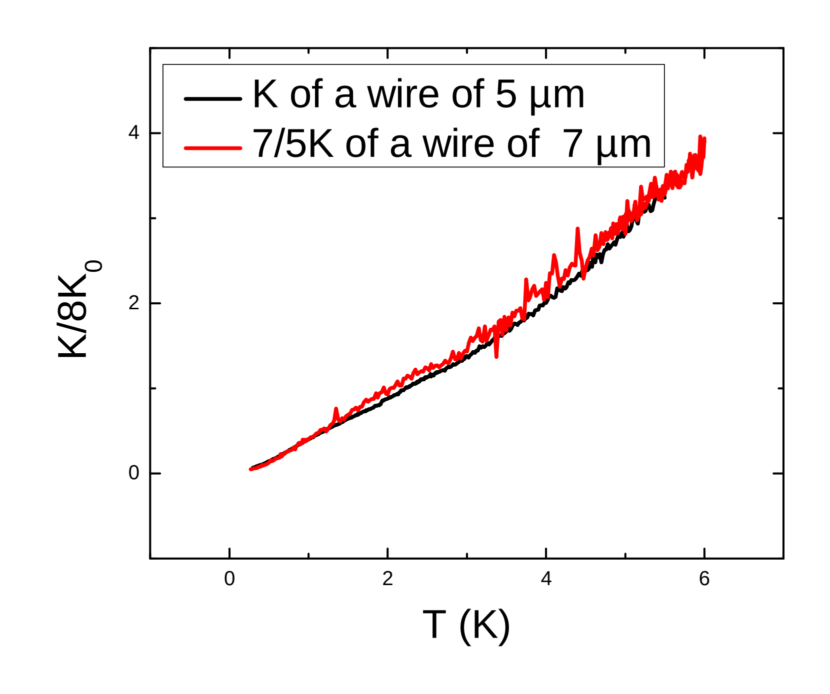


η_0=4 nm and speed of sound v_s=9000m/s

Identical nanowires (diff. length)

Above 2 K, no problem : Casimir regime and T^3 law : $K = aT^3$

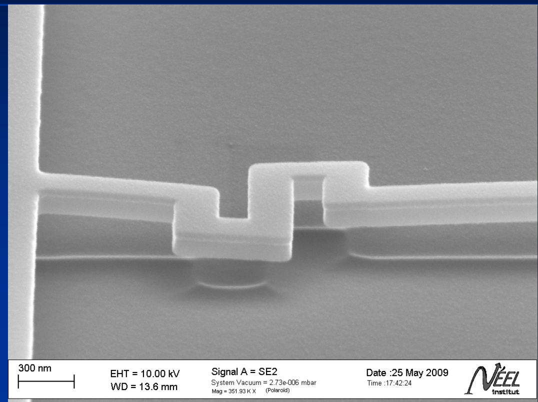


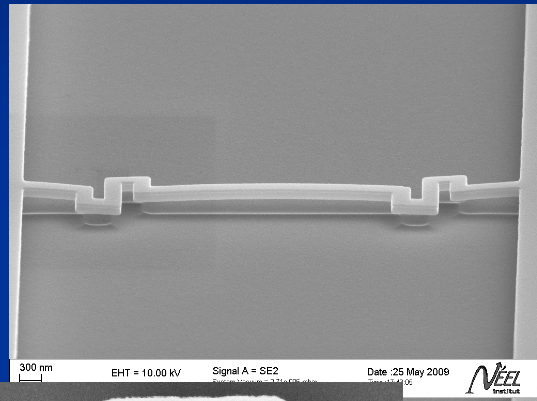


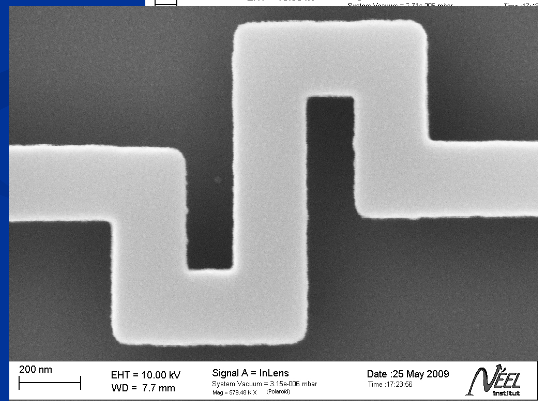
J.-S. Heron, T. Fournier and O. Bourgeois, *Surface effect on the phonon transport of silicon nanowire*, Journal of Physics: Conference Series **92**, 012088 (2007).

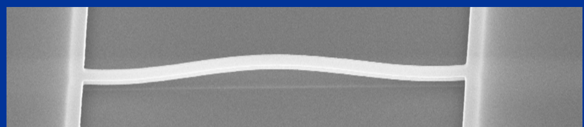
Blocking the phonon transport in nanowire

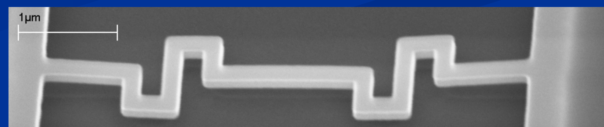
- double bent nanostructure smaller than the mean free path
- Compare the thermal conductance measurement to a straight nanowire





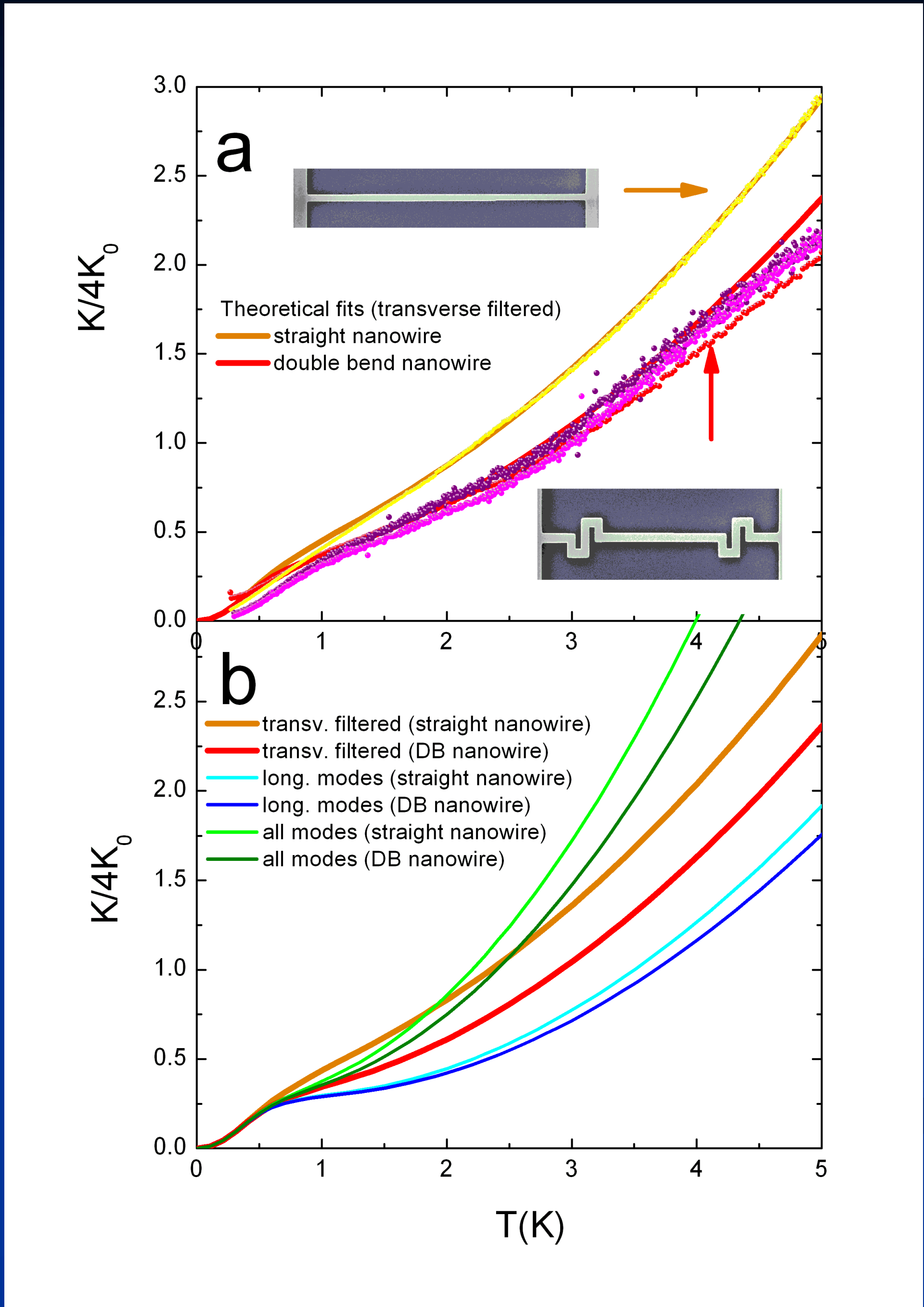




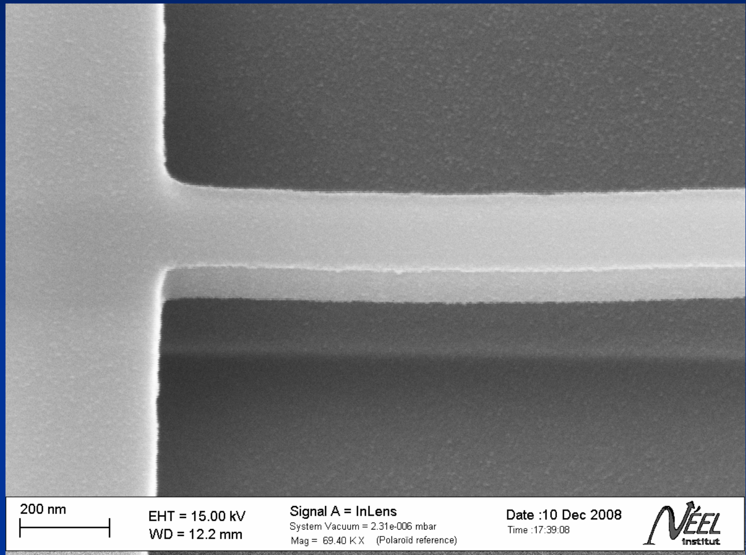


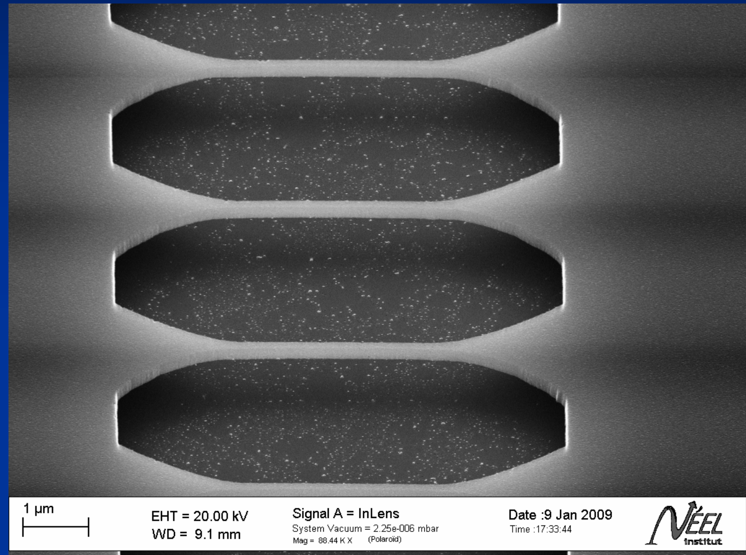
Strong perturbation of the phonon transport

- Model: transverse phonon are preferentially scattered at the surface than long. phonon
- Normal speed of sound 5000m/s
- Transmission coefficient at low temperature



Thermal resistance of the wire/reservoir junction at very low temperature



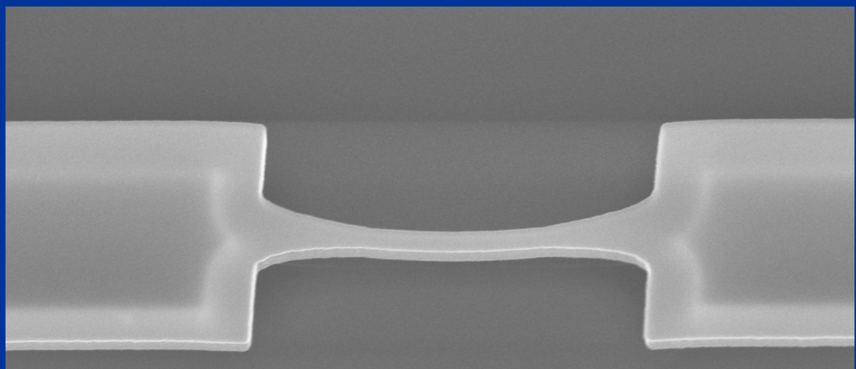


The mismatch between the density of states of the phonons of the 2D reservoir and the 1D wire implies an important thermal resistance which becomes dominant below 0.5K, with a cubic temperature dependence

Chalopin, Y;Gillet, J.-N.; Volz, S. Phys. Rev. B **77**, 233309 (2008).

Transmission coefficients and geometry

- Effect of the connection between the nanowire and the heat bath: transmission coefficients < 1 decreases the measured conductance.
- Specific geometries can modify the conductance:

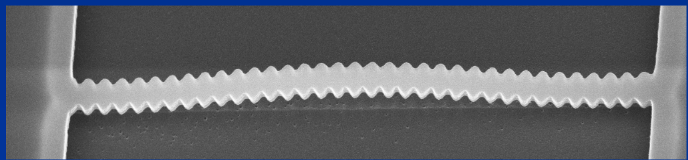


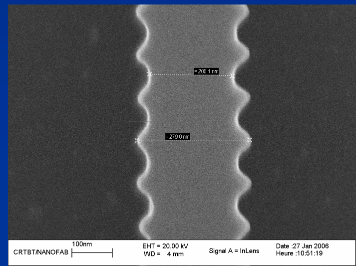
In profiled wire, we expect the improvement of the transmission coefficient, better contact between heat bath and nanowire (Tanaka *et al.*, PRB **71**, 2005)

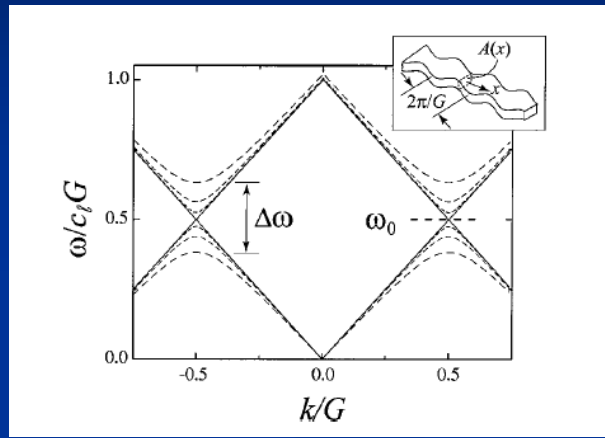
Rego and Kirszenov, PRL 1998

Phononic crystals

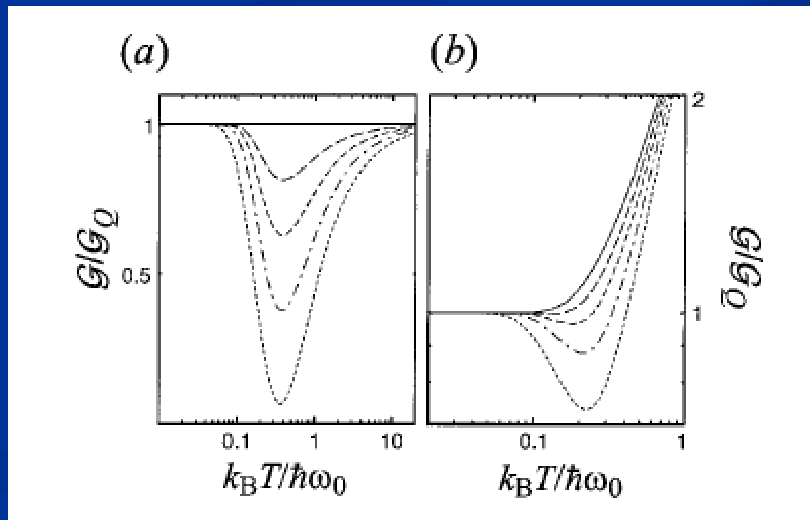
Specific geometries can modify the conductance:







With sinusoidal profile, opening of a GAP in the dispersion relation for the acoustic phonons, so the conductance exhibit a minimum at a well defined temperature (λ_D=modulation)



From Thermal conductance of nanostructured phononic crystals, Cleland et al., PRB 2001

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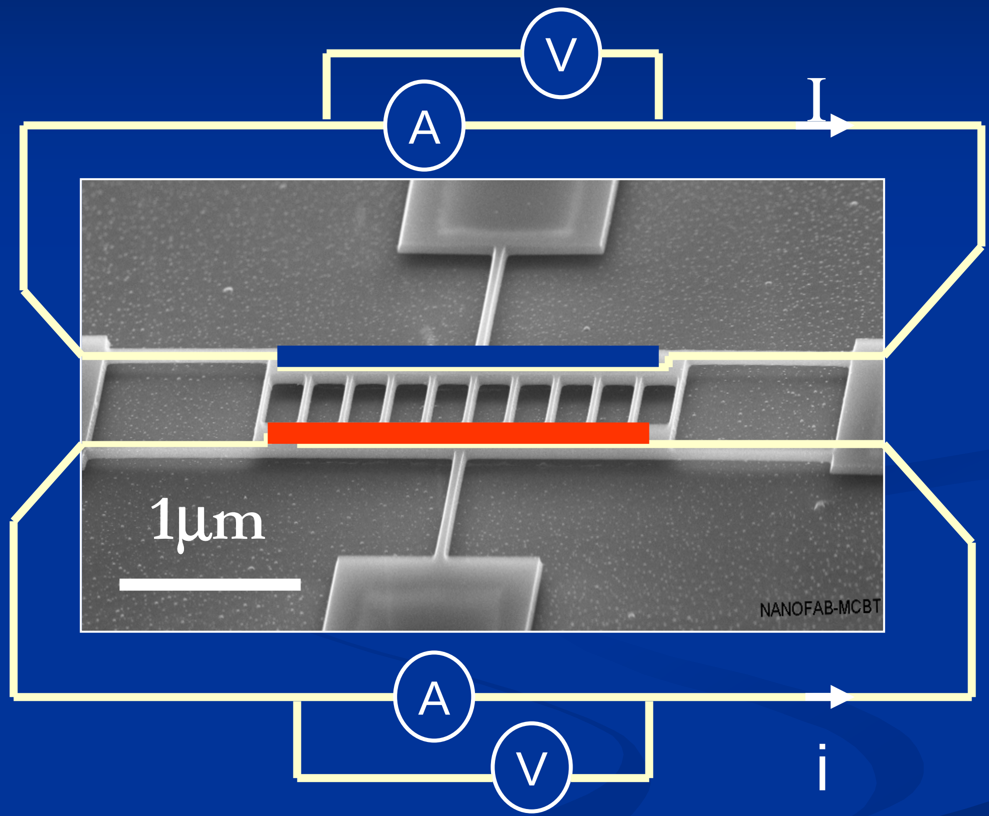
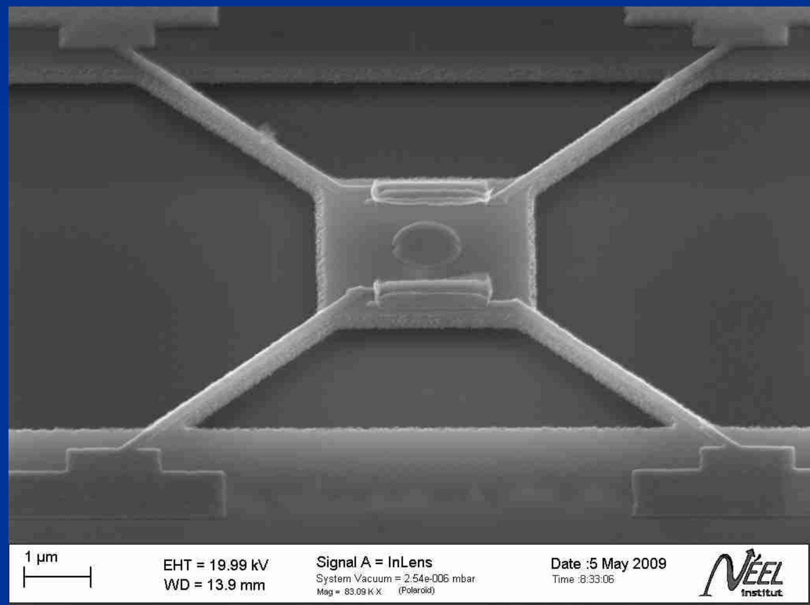
Perspectives with new devices

- Objectives: no materials on top of the nanowires
- Two separated transducers (A and B)
- The nanowires are not perturbed by a top layer like in the 3w method
- same kind of device for single nano-object calorimetry
- Temperature largely below 1K (dilution fridge)
- New materials: silicon nitride



Zeptojoule calorimetry: towards the measurement of single meso objects

- Submicron suspended silicon membrane sensor
- Thermometer and heater (by ebeam litho)
- SOI: thickness of the membrane 200nm
- Single mesoscopic object
- $C=10^{-20}/10^{-21} J/K$
- Sensitivity of 1% à 0.1% near one k_B (10^{-23} J/K)



conclusions

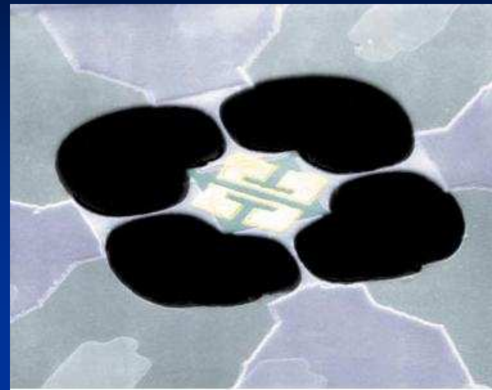
- The observation of the Casimir regime validates our experimental method.
- Strong effect of the roughness as compare to the dominant phonon wave length (break down of the Casimir regime)
- Phonons can be blocked by angles in nanowires.
- Thermal conductance can be reduced by up to 40% at low temperature
- Orientation towards the nanothermoelectricity

Remerciements

- Pôles techniques de l'Institut Néel
  - Capteurs Thermiques et Calorimétrie (J.-L. Garden, E. André, P. Lachkar)
  - NanoFab (Th. Fournier, Th. Crozes, C. Lemonias, B. Fernandez)
  - Mécanique et Cryogénie (P. Brosse-Maron)
  - Electronique (O. Exchaw, J-L. Mocelin, M. Grollier)
- Etudiants
- Florian Ong (Thèse soutenue en oct 2007)
- Jean-Savin Heron (Thèse soutenue en oct 2009)
- Christophe Blanc (M2R)
- Collaborations
  - Thierry Fournier
  - Philippe Gandit (dilution)
  - Natalio Mingo (Liten-CEA)
  - Stephan Dilhaire
  - LETI (S. Bécu, T. Ernst)
- Equipe soutenue par: Région, IPMC, Europe FP7, ANR

Equipe de Roukes au Caltech

- Calorimétrie par relaxation, pulse de chaleur créé: ΔT=100mK.
- Résolution: 10^{-4}
- Sensibilité: $5x10^{-19}$ J/K
- Sensibilité/μm^2: 100 k_B.



Thermal conductivity of nanowire (Roukes Nature 2000)

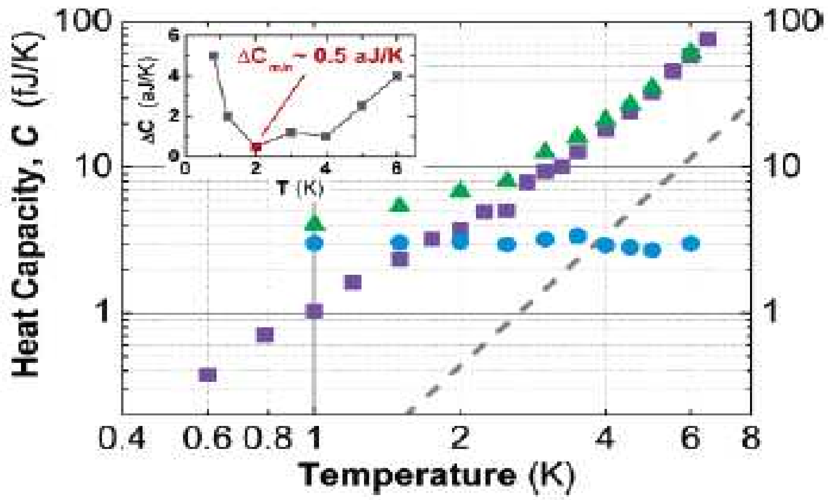
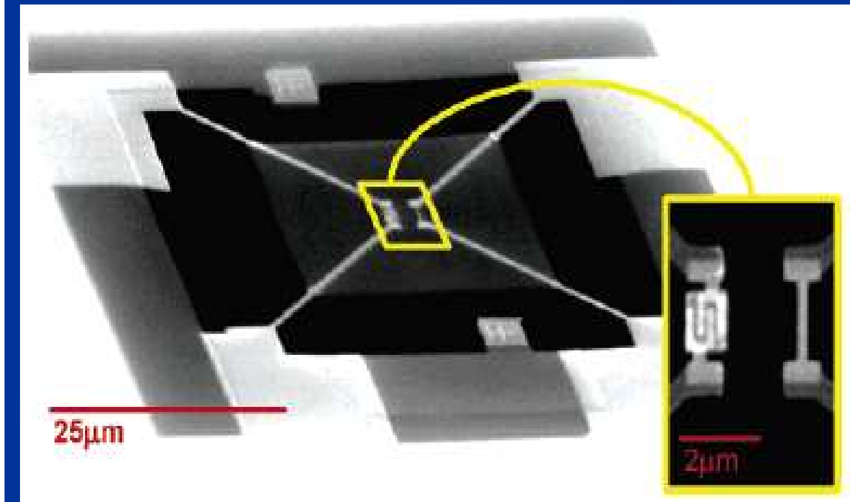


Figure 4. The heat capacity of the calorimeter (violet), the heat capacity of calorimeter with adsorbed He gas film (green), and the heat capacity of the He gas film (blue). The He gas coverage is ~0.16 monolayer over the device. The dashed gray line represents the estimated Debye phonon heat capacity of the calorimeter. Inset: Measurement resolution attained at various temperatures by the calorimeter for 5 s averaging time. Highest resolution, $\Delta C \sim$ 0.5 aJ/K (~36000k_B), is attained at 2 K in these experiments.



Fon et al., NanoLetters 2005

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