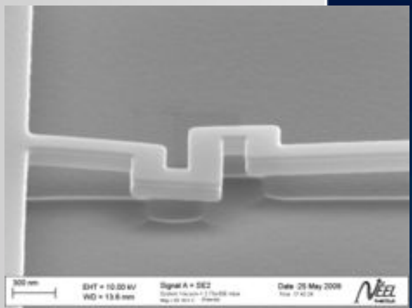
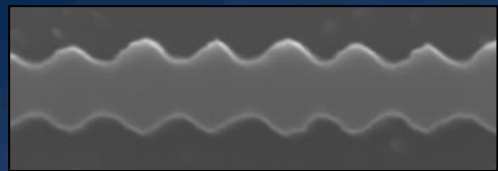
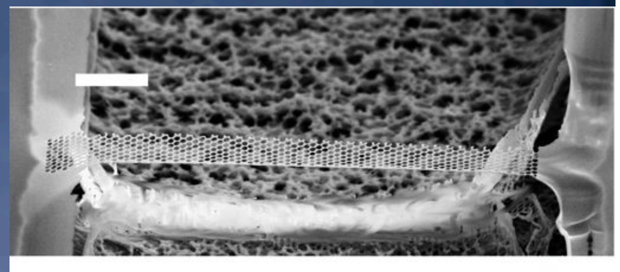
PHONONS AND THERMAL PHYSICS AT THE MICRO AND NANOSCALE

Olivier Bourgeois
Institut Néel







Séminaire Collège de France Mardi 19 Novembre 2013

OUTLINE

- Introduction: motivations, nanophononics
- Part 1: History of phonons and thermal measurements
  - Phonons
  - Thermal conductance, transport of phonon at the nanoscale, mean free path
  - Micro-nano and low temperature
- Part 2: Measurement of thermal transport in Si nanowire
  - Si Nanowire: Casimir Ziman model
  - Transmission coefficient
  - Ballistic transport
- Part 3Manipulation of heat and thermoelectricity
  - Phonon blocking
  - Corrugated nanowire: strong reduction of mean free path
  - Application to nanothermoeletricity
- Perspectives and Conclusive remarks

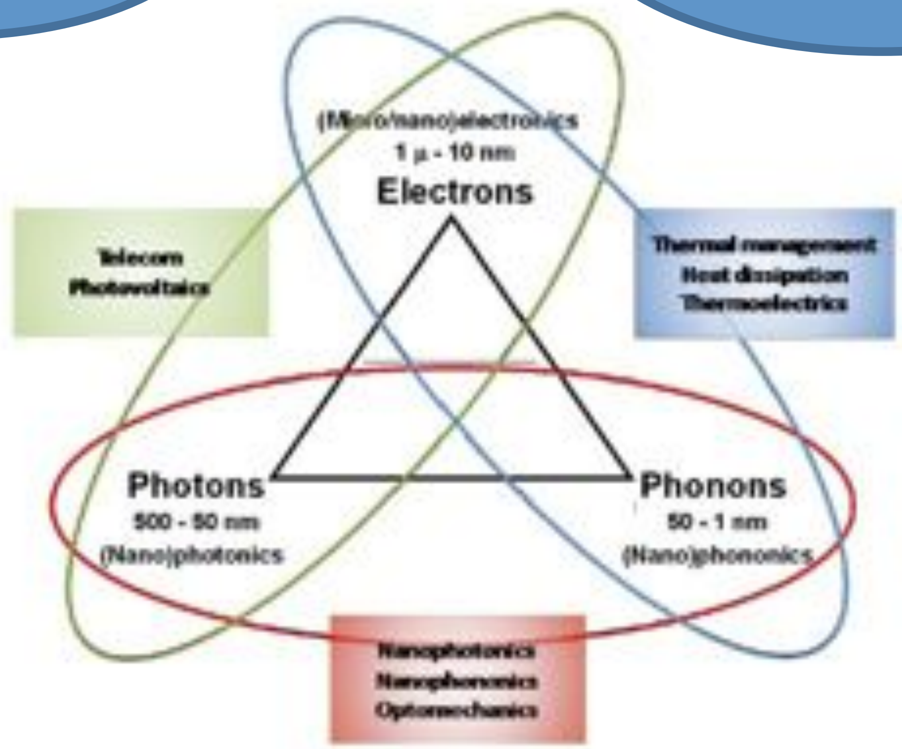
OBJECTIVES, MOTIVATIONS

Heat storage

(Specific heat)

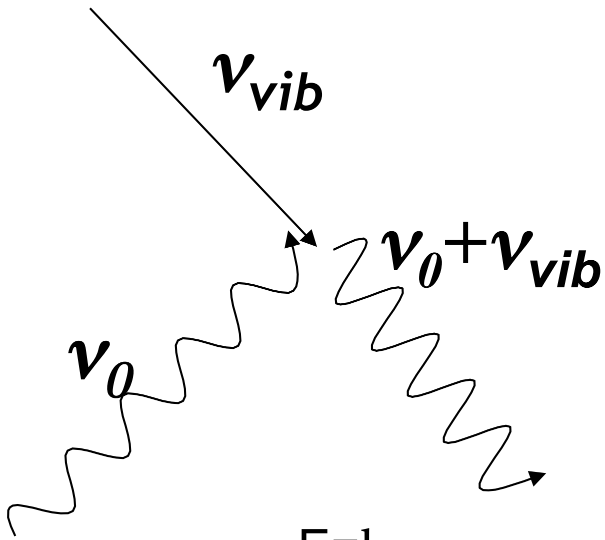
Heat transport

(Thermal conductivity)



WHERE DOES THE PHONON COMES FROM ?

- Debye and Einstein theory of specific heat of solids
- Mandelshtam and Raman 1928
- Igor Tamm “sound quanta” or “heat quanta” 1930
- Yakov Frenkel proposes the name “phonon” from ancient greek φωνη (voice) 1932
- Quantification of vibrational modes
- Photon interaction with solids (Brillouin scattering, Raman scattering)



E=hν

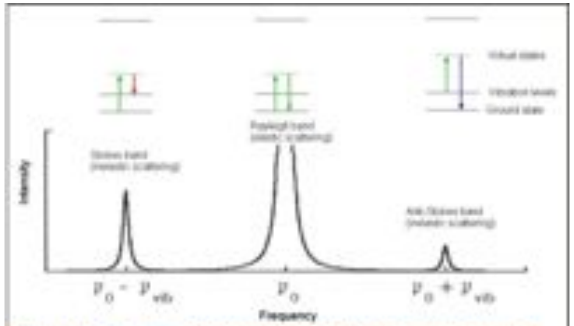
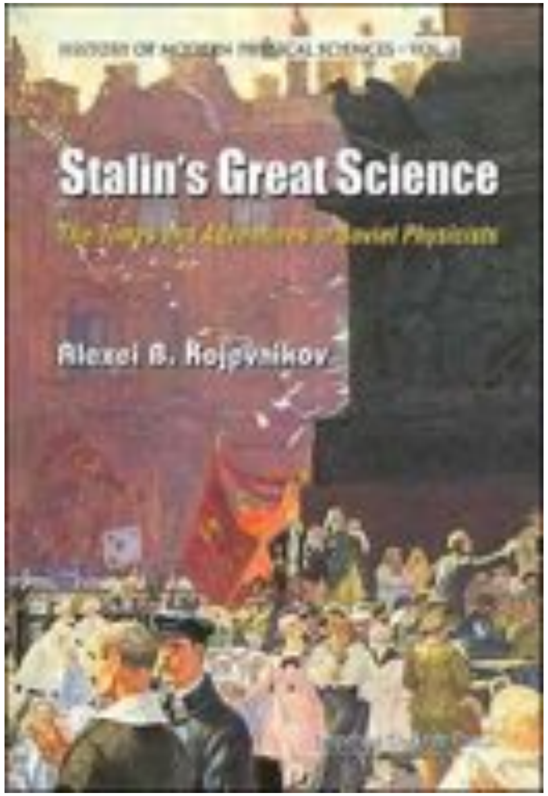


Fig. 4.1.2: Spectrum of photon transition from elemental ground level to virtual states.

© Mascaros et al., in: "Handbook on the Use of Lasers in Conservation and Conservation Science", 2008.

Igor Tamm



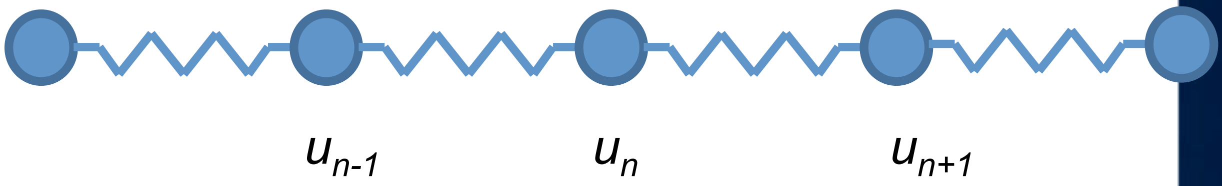
PHONON : LINEAR CHAIN

- Linear monoatomic chain
- Periodic conditions: Born-von Karman
- Quantization of the vibrational modes
- Dispersion relation
- Group velocity

$$v = \frac{\partial \omega}{\partial k}$$

- Elementary excitation: phonon

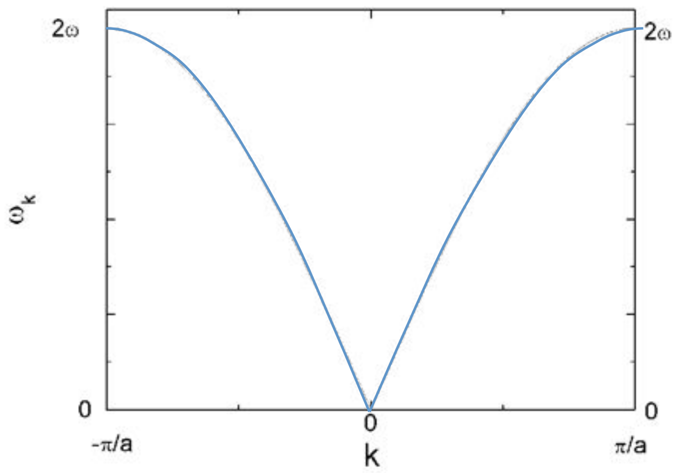
$$E = \left(n_q + 1/2\right)\hbar\omega$$



$$m\frac{d^2u_n}{dt^2} = K(2(u_{n+1} - u_n) + (u_n - u_{n-1}))$$

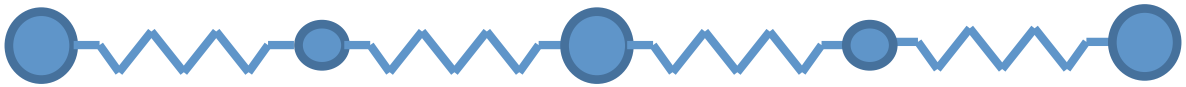
$$u_n = \exp(i(kna - \omega t))$$

$$\omega = \sqrt{\frac{K}{am}}\left|\sin\left(\frac{ka}{2}\right)\right|$$

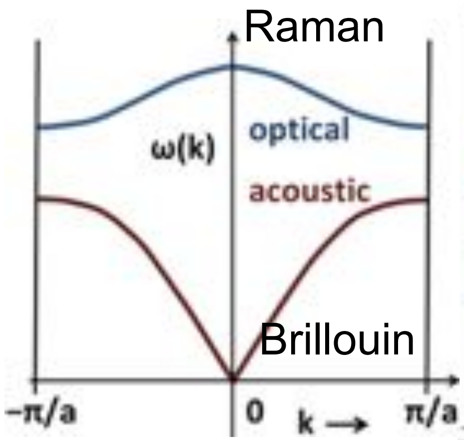


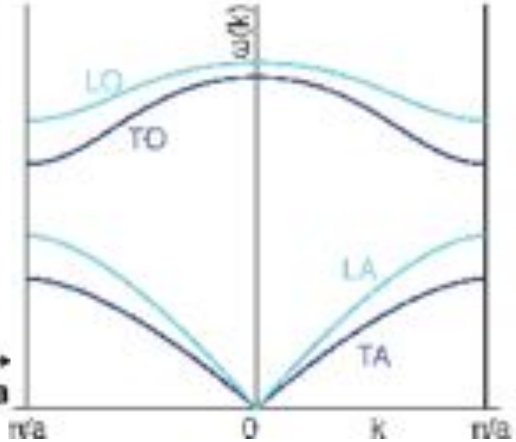
PHONONS AND LOW DIMENSIONS

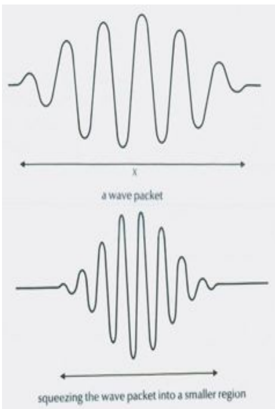
- Diatomic chain



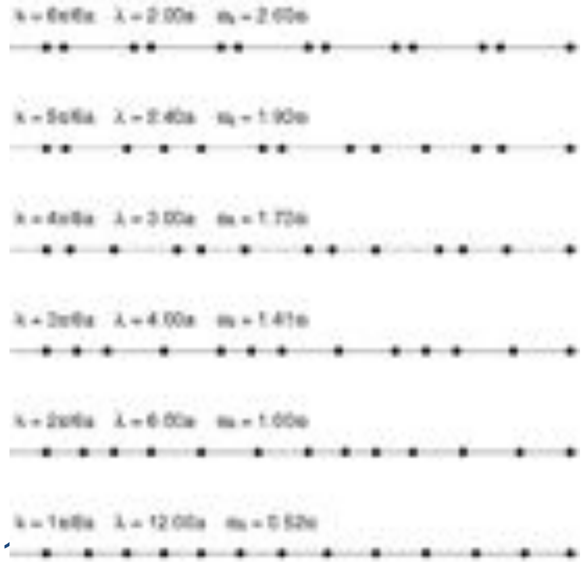
- Acoustic and optical modes
- Spatial extension of a phonon ?
- Phonon=Wave packet
- Propagating modes TA and LA (related to v)







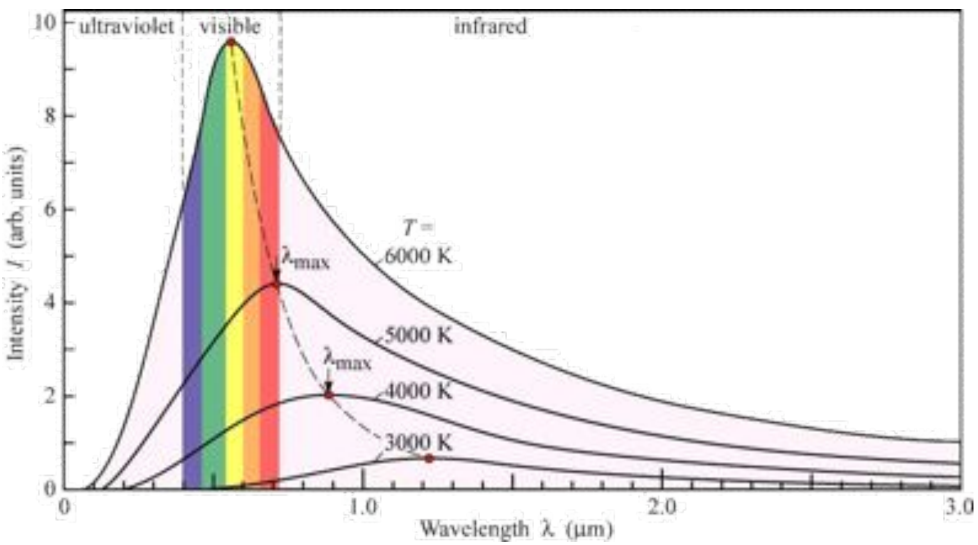
$$v = \frac{\partial \omega}{\partial k}$$



PHONON IDENTITY CARD

- Boson (Bose-Einstein distribution)
- Number of phonons not conserved
- Quasi-particle
- At low temperature : only large wave length phonon are excited (low energy)
- No optical phonon (only acoustic modes)
- Planck black body radiation (for infinitely rough surfaces)

$$n_q = \frac{1}{\exp\left(\frac{\hbar\omega}{k_B T}\right) - 1}$$



High temperature

$$n_q \approx \frac{k_B T}{\hbar\omega}$$

Low temperature

$$n_q \approx \exp\left(-\frac{\hbar\omega}{k_B T}\right)$$

$$\lambda_{Dom} = \frac{h v_S}{4.25 k_B T}$$

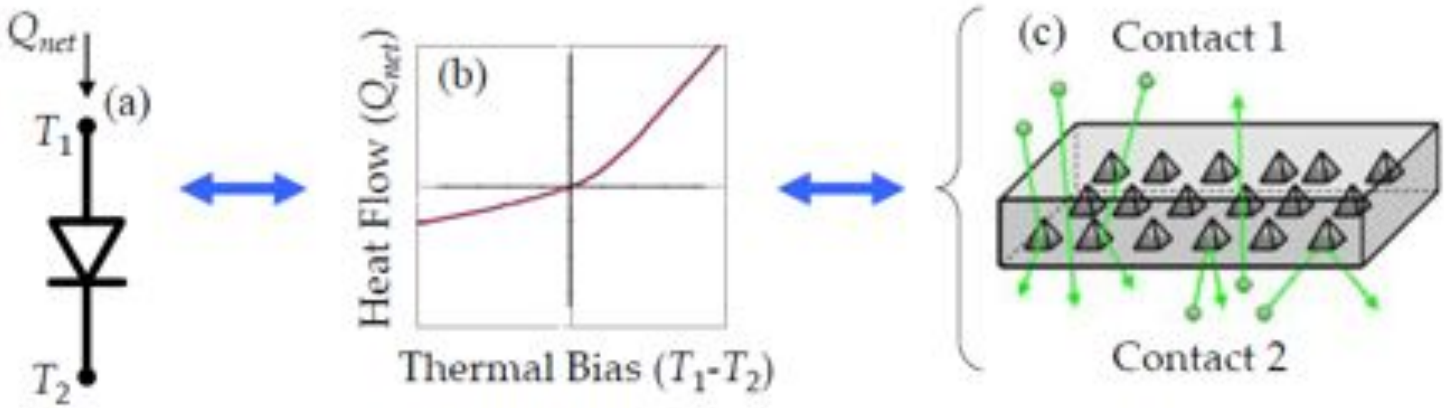
AT LOW TEMPERATURE

Two kind of heat carriers **(radiation neglected)**

Electrons		Phonons
Λ_{e-}~nm	•Mean free path	Λ_{ph}~mm
λ_F~0.1nm	•Relevant wave length	λ_{ph}~100nm
$L\varphi$~10µm	•Coherence length	Not coherent
T	•Temperature dependence (K, C)	T^3
diffusive	•Transport	ballistic
fermions	•statistic	bosons

HEAT MANIPULATION IN THE BALLISTIC REGIME

- Landauer model for heat transfer
- Universal quantum of thermal conductance
- Thermal rectification (Chris Dames review Proceedings of HT2009, page 1, 88488 (2009))
- Thermal insulation (phonon trapping, phonon blocking etc…)



Implications: thermalization, nanothermoelectricity

- Ballistic phonon->no local temperature
- ~~Thermal conductivity~~ ->thermal conductance (driven by the size of the systems)
- Play with the phonons: phonon focusing, phonon blocking etc..
- Application to thermoelectricity: phonon scattering at the nanoscale with clusters, nanoparticles, superlattice etc…

$$ZT = \frac{S^2 T\sigma}{\left(k_{elec} + k_{ph}\right)}$$

$$\eta_{\max} = \eta_c \frac{\sqrt{ZT+1}-1}{\sqrt{ZT+1}+1}$$

A PAGE OF HISTORY…

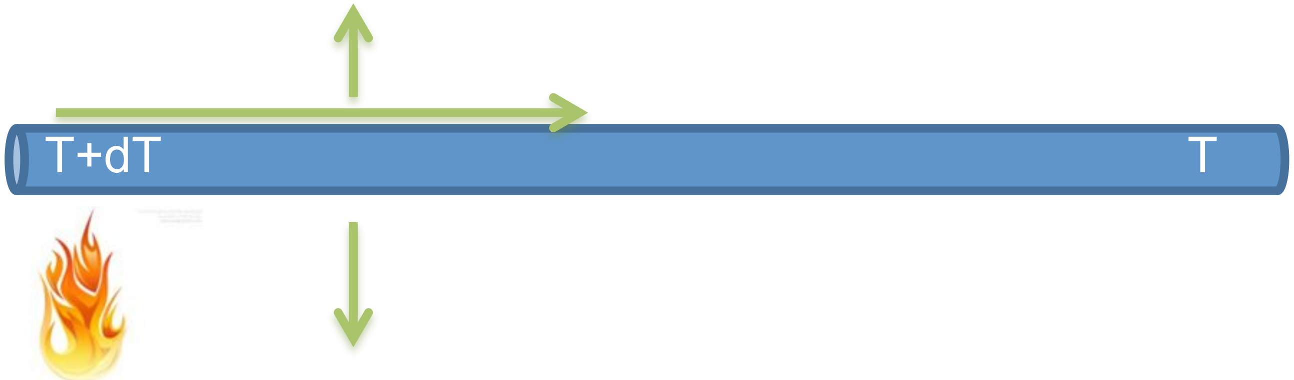
HISTORY OF THERMAL CONDUCTIVITY MEASUREMENTS I

- Early days : Guillaume Amontons (1663–1705): heat flow along the temperature gradient

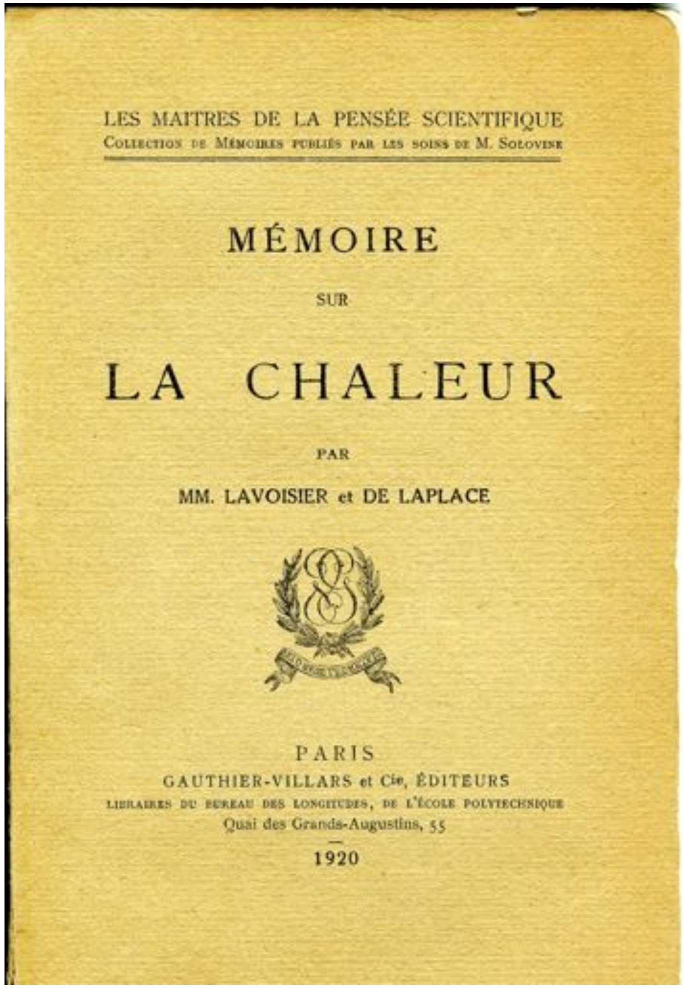
- Heat, matter and temperature: Latent heat,
  Joseph Black (1728-1799)

- First measurements: Jean-Henri Lambert (1728–77) published in 1779 : convection, geometry

Joseph Black



FIRST STUDIES ON HEAT…1780



"Les Physiciens sont partagés sur la nature de la chaleur"

Nouveaux concepts : chaleur libre, capacité de chaleur, chaleur spécifique

"Plusieurs d'entre eux la regarde comme un fluide répandu dans la nature"…

"D'autres physiciens pensent que la chaleur n'est que le résultat des mouvements insensibles des molécules de la matière."

Lavoisier et Laplace (Mémoire sur la chaleur 1780).

SPECIFIC HEAT MEASUREMENTS

Pierre Simon de Laplace

Antoine Laurent Lavoisier

- Treatise on calorimetry published in 1782
- First experiment of heat capacity
- Ice calorimeter (temperature reference)

L (latent heat ice/ water at T = 0°C)

= 334 J/g ≈ 80 cal/g

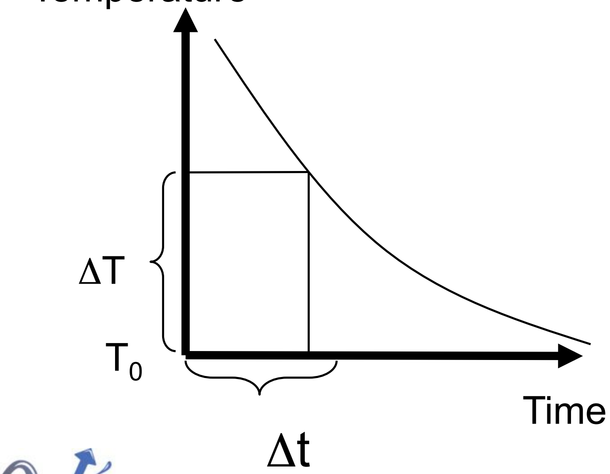
L (latent heat water/ water vapour at T = 100 °C) = 2260 J/g ≈ 539 cal/g

HISTORY OF THERMAL CONDUCTIVITY MEASUREMENTS II

- Benjamin Franklin (1706-1790) compared thermal conductivity of different metals
- Jan Ingen-Housz (1730-1799)
- Count Rumford (1753-1814) insulating materials
- Joseph Fourier (1768-1830)

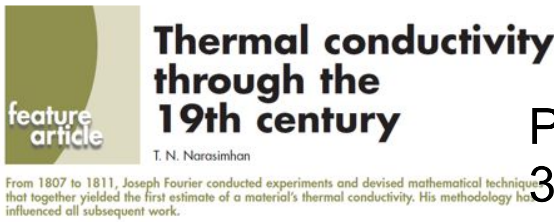
2 experiments: steady state (K,h), transient (C,h>>K)

Joseph Fourier



$$\tau = \frac{C}{K}$$

Time dependent experiments:


feature article

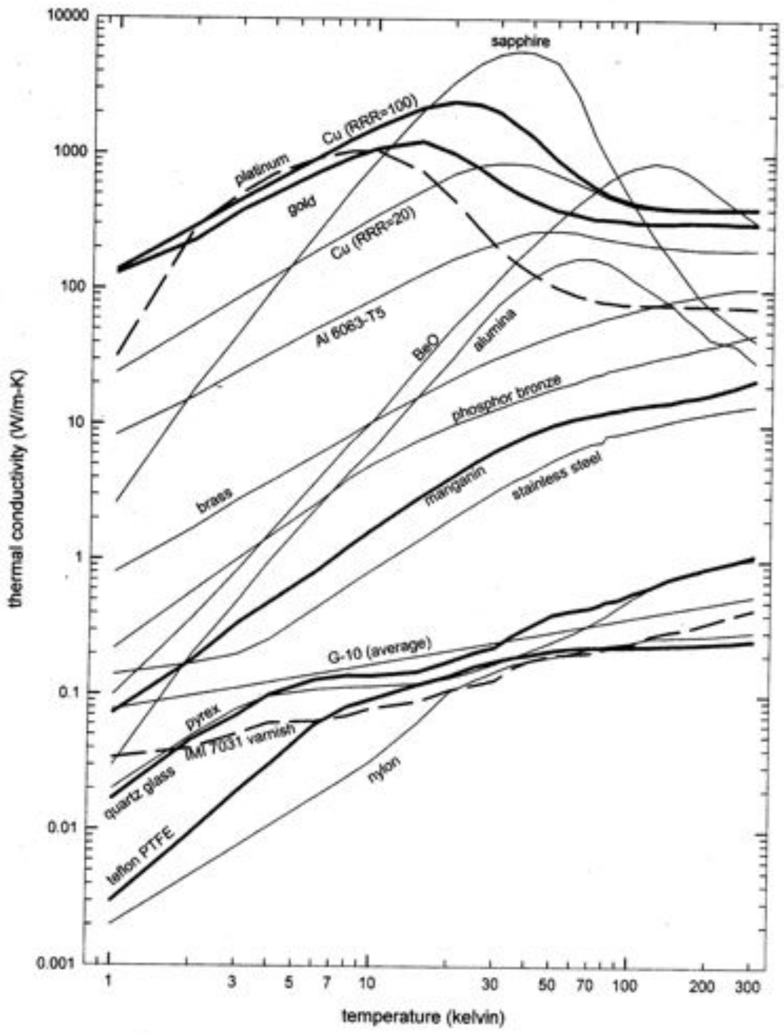
Thermal conductivity through the 19th century

T. N. Narasimhan

From 1807 to 1811, Joseph Fourier conducted experiments and devised mathematical techniques that together yielded the first estimate of a material's thermal conductivity. His methodology has influenced all subsequent work.

Physics Today **63**, 36 (2010)

TEMPERATURE BEHAVIOR OF THE THERMAL CONDUCTIVITY



Electrical

Thermal

Copper
6×10^7 S/m

Germanium
3 S/m

Glass 10^{-12} S/m

Teflon 10^{-25} S/m

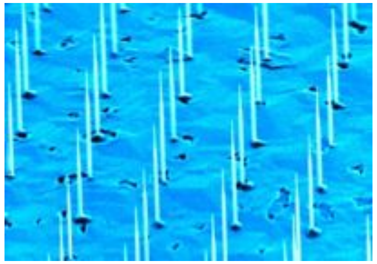
At 300K

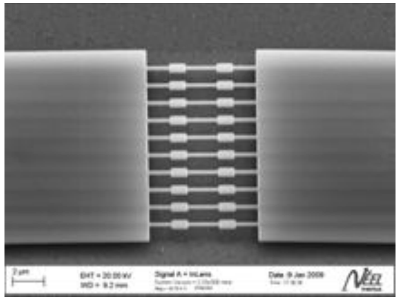
Diamond, graphen
10^3 W/mK

10^{-1} W/mK
Polysteren, glass

MEASUREMENT OF THERMAL CONDUCTANCE

“MICRO-NANO” PROBLEMATIC


AsGa nanowires (LPN, Marcoussis)


Si nanowires with phonon cavities (Institut Néel, Grenoble)

- Loss of the bulk behavior, competition between surface and volume.
- Relevant characteristic lengths (dominant phonon wave length, mean free path, thermal length, etc…)
- Specific thermal behavior at small length scale (universal thermal conductance, definition of temperature …)
- Systems under study need to be thermally isolated : membrane, suspended structure (nanowire, graphene sheet, sensitive sensors)
- Development of new experimental tools using nanotechnology adapted to very small thermal signals and adapted to very small mass samples of the order of zepto (10^{-21}J) or yoctoJoule (10^{-23}J).

SIGNAL TREATMENT/MEASURE USING TEMPERATURE MODULATION

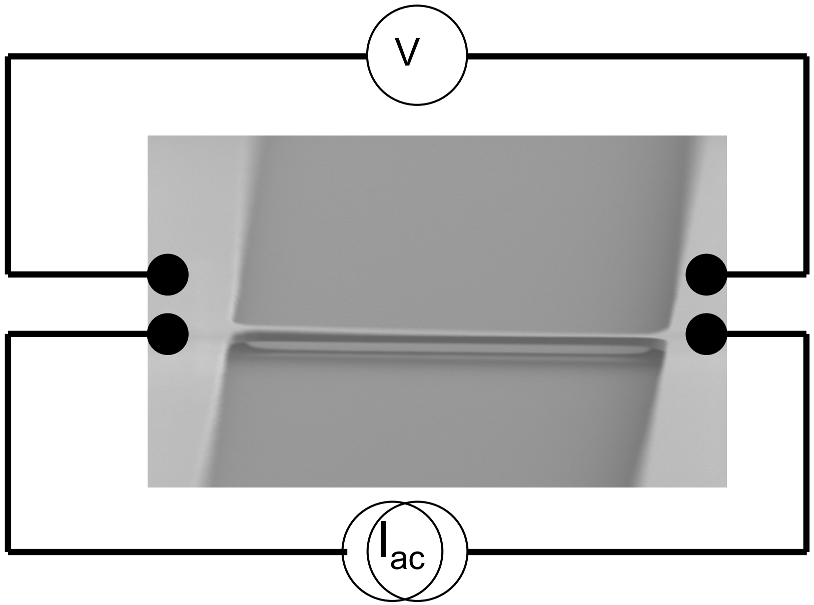
- Focus on electrical based measurement
- Problems related to measurement using continuous signal
- Preamplification of the signal before measurement
- AC thermal measurements: proposed since 1910/1911 by O. Corbino
- Measure by lock-in amplifier
- Differential geometry

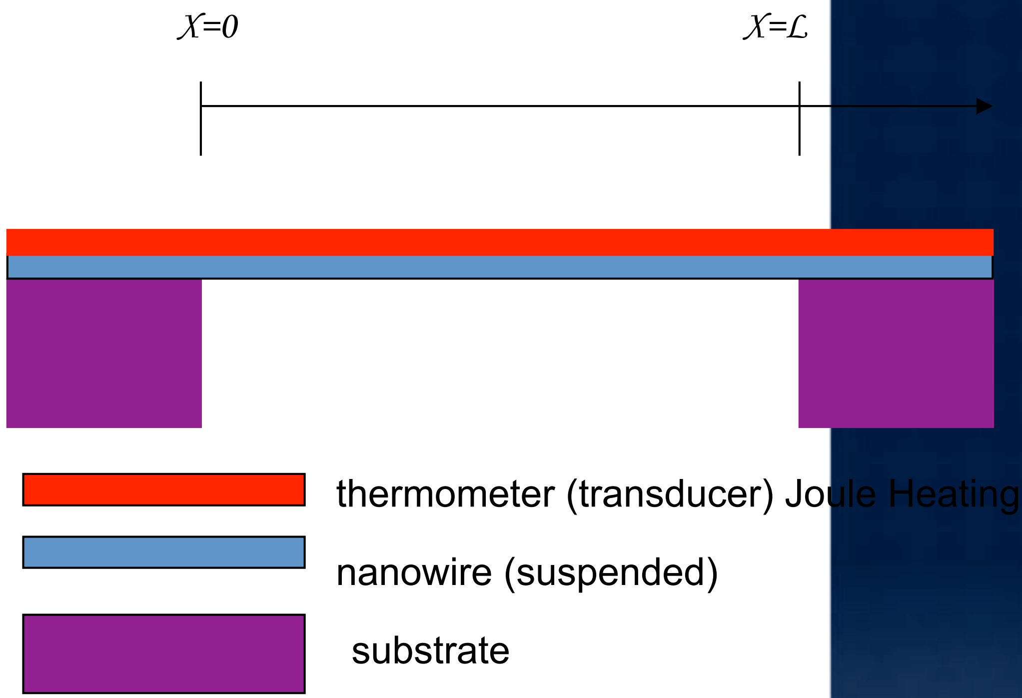
Orso Mario Corbino (1876-1937)

O.M. Corbino, Phys. Z. **11**, 413 (1910), *ibid.* **12**, 292 (1911)

3 OMEGA METHOD MEASURE IN PLANE (LONGITUDINAL)

- Proposed par Lu et coll.
- Adapted for suspended nanowires
- Limit at low frequency

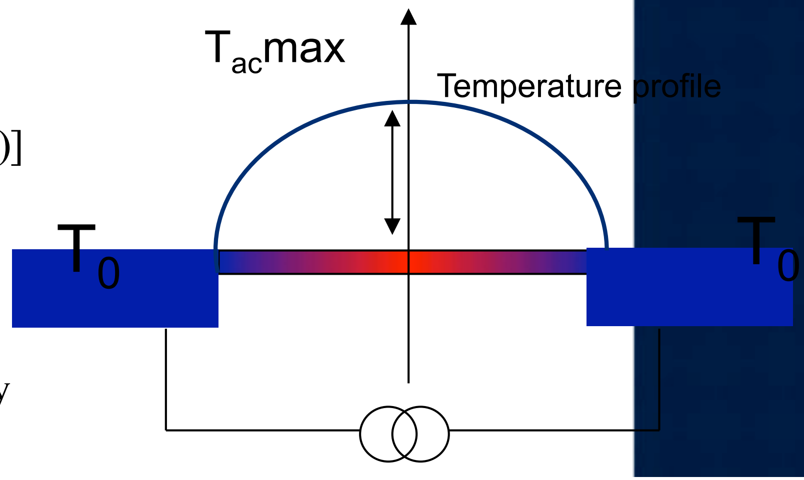


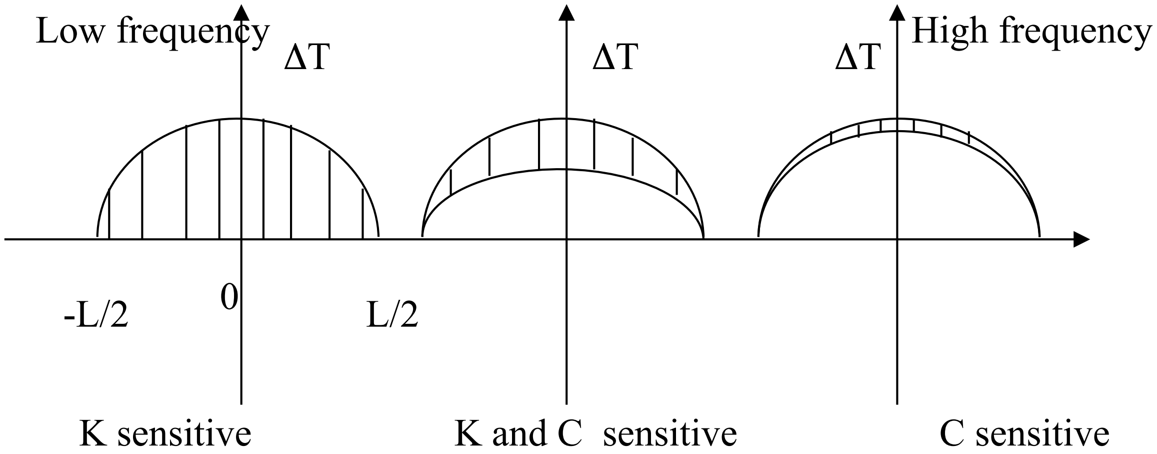


Lu L, Yi W and Zhang DL 2001 *Rev. Sci. Instrum.* **72** 2996

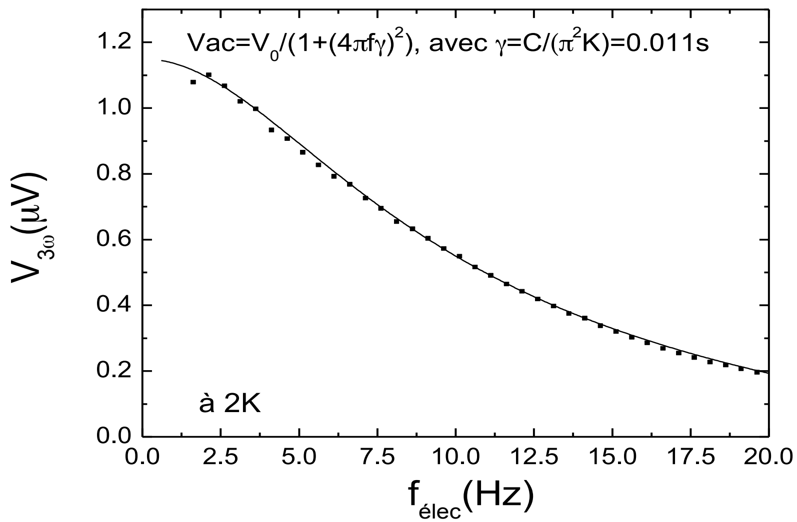
PRINCIPLE OF THE MEASUREMENT

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





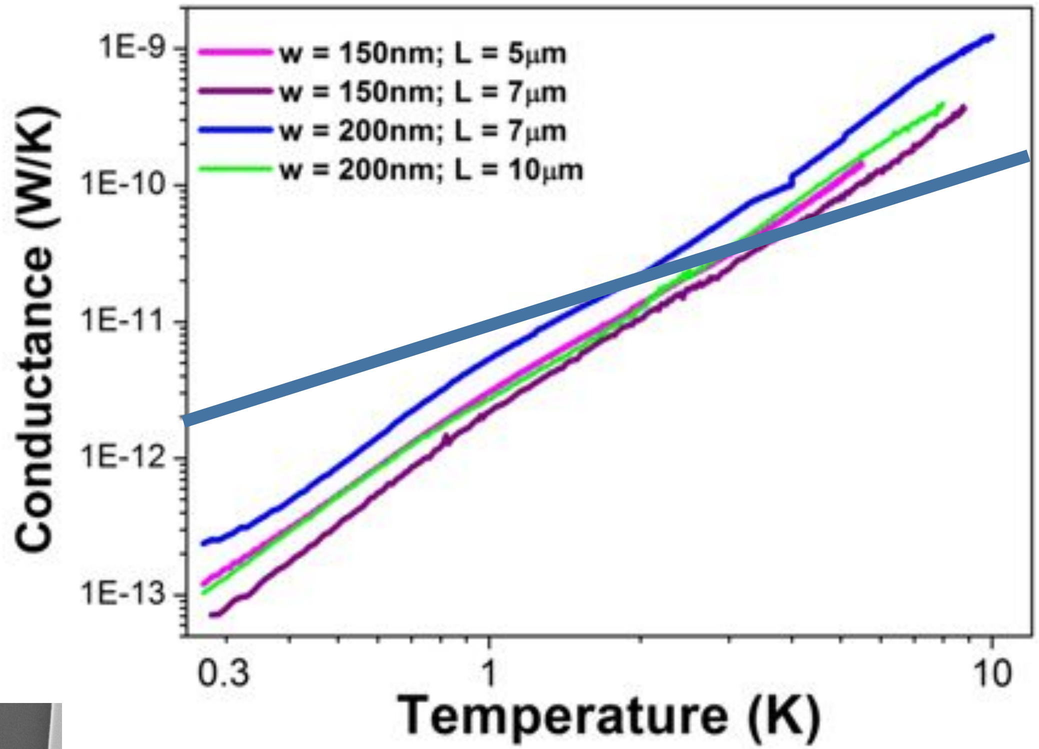
$$V_{3\omega} = \frac{4I_0^3R^2\alpha}{\pi^4K(\sqrt{1+(2\omega\gamma)^2})} \Rightarrow K = \frac{4I_0^3R^2\alpha}{\pi^4V_{3\omega}}$$

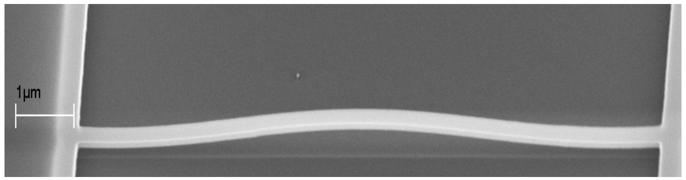


O. B, Th. Fournier and J. Chaussy, J. Appl. Phys, **101**, 016104 (2007)

THERMAL CONDUCTANCE OF SILICON NANOWIRES

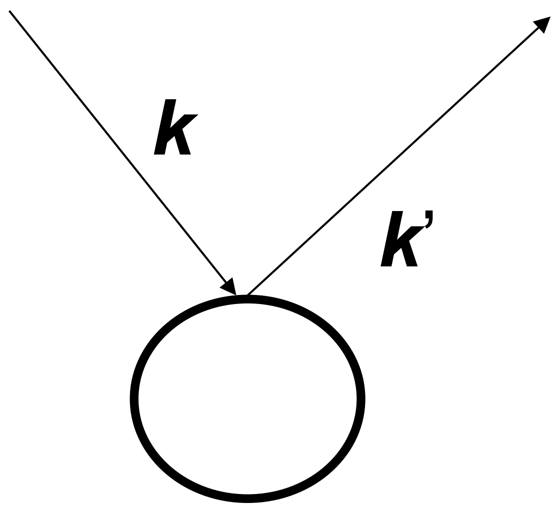
- Measurement between 0.3K and 10K
- Power law in temperature (T^2 and T^3)
- Different geometries
- 4 channels for heat transfer





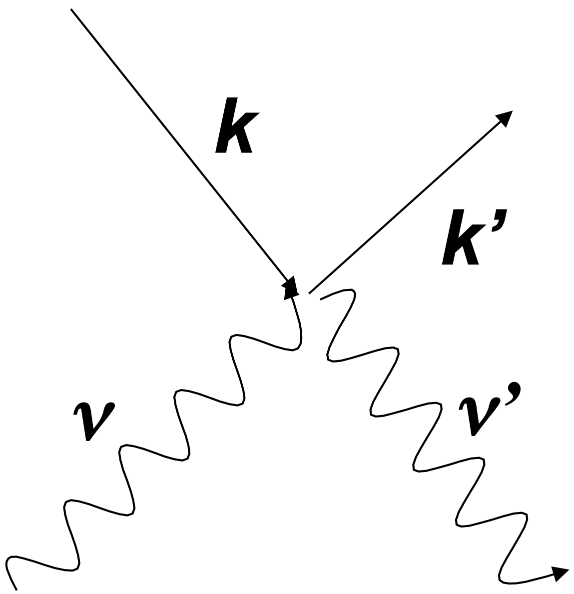
THERMAL TRANSPORT AT LOW TEMPERATURE AND SMALL LENGTH SCALE

MEAN FREE PATH: ELASTIC VERSUS INELASTIC



Phonon elastic scattering (impurity)

$$|k| = |k'|$$



Inelastic scattering

$$|k| \neq |k'| \quad \text{and} \quad |\upsilon| \neq |\upsilon'|$$

DIFFERENT SCATTERING PROCESSES

- Scattering on dislocation (static imperfection)
- Anharmonic scattering (three phonons, Umklapp processes)
- Electron-phonon interaction (doped semiconductor)
- Boundary scattering (finite size effect)

$$\frac{\partial f}{\partial t} + \frac{d\vec{r}}{dt}.\vec{\nabla} f + \frac{d\vec{p}}{dt}.\vec{\nabla} f = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

$$\left(\frac{\partial f}{\partial t}\right)_{coll} = -\frac{f - f_0}{\tau}$$

Mathiessen rule:

$$\tau^{-1} = \sum_{i=1}^{n} \tau_i^{-1}$$

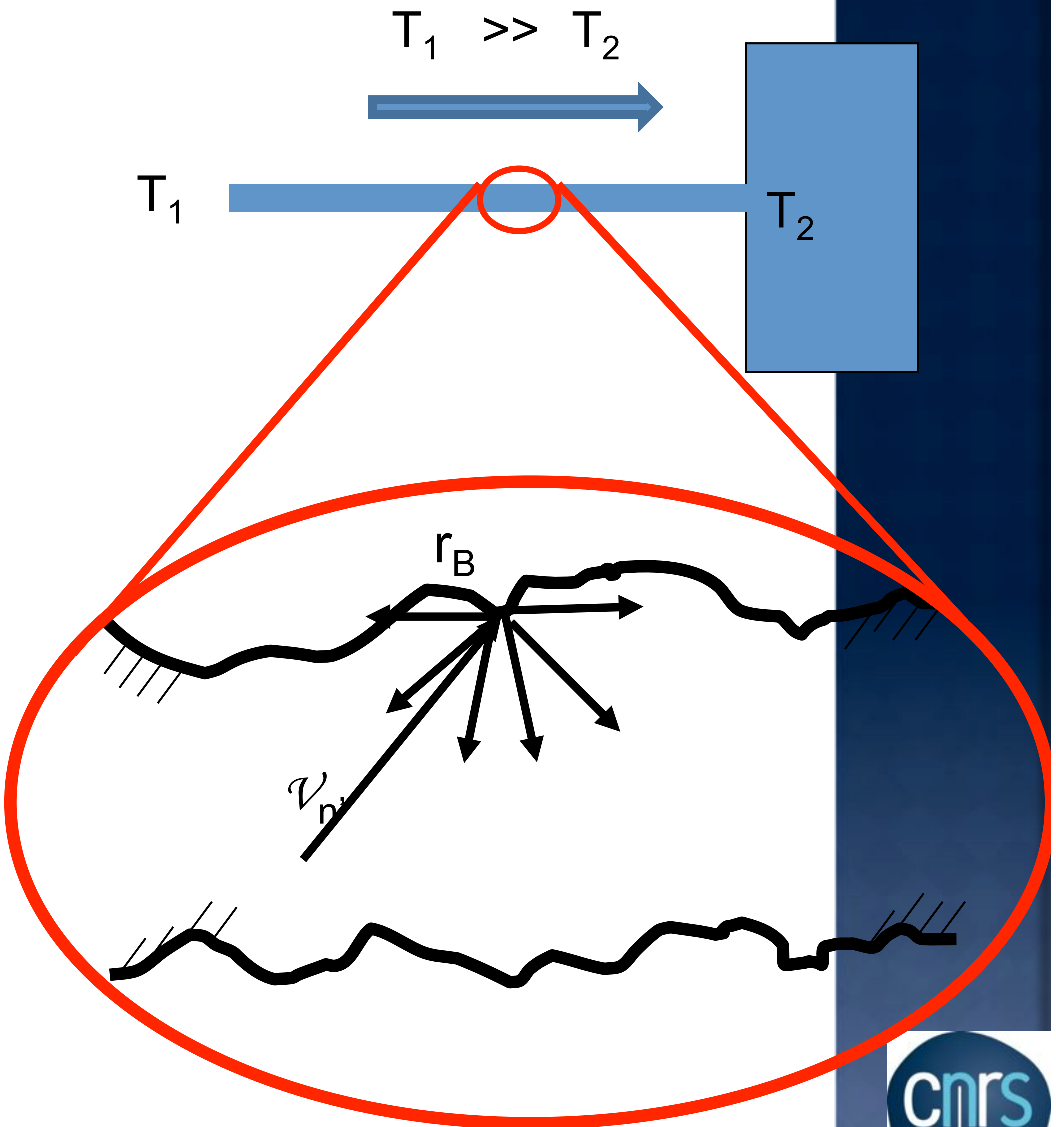
$$\Lambda_{ph} = v_{ph} \tau_{scatt}$$

FINITE SIZE EFFECT: CASIMIR THEORY FOR PHONON TRANSPORT

- Mean free path Λ_{ph}
- Λ_{Cas}=D (Diameter of the nanowire)
- Boundary scattering: black body radiation for phonons
- Expression for K(T)
- Still diffusive
- Comment on the specific heat (kinetic equation)

$$K(T) = 3.2 \times 10^3 \left(\frac{2\pi^2 k_B^4}{5\hbar^3 v_s^3}\right)^{(2/3)} \frac{S\Lambda_{Cas}}{L} T^3$$

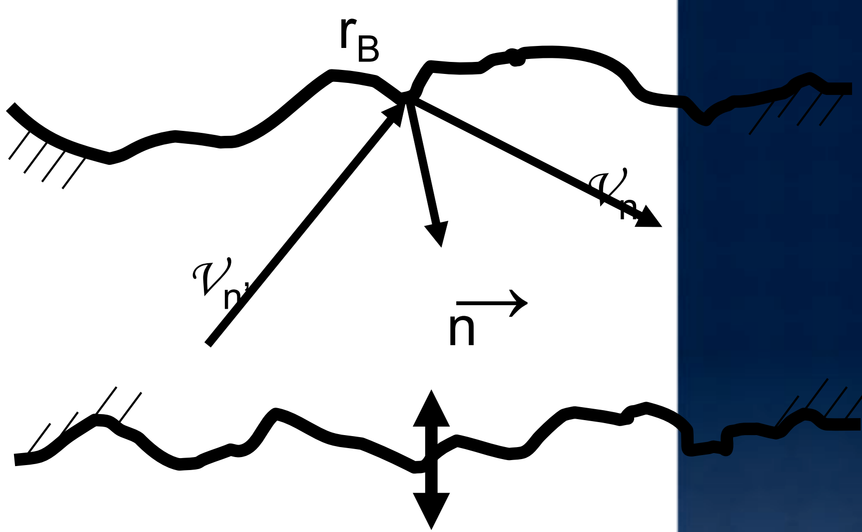
Breakdown of the concept of thermal conductivity



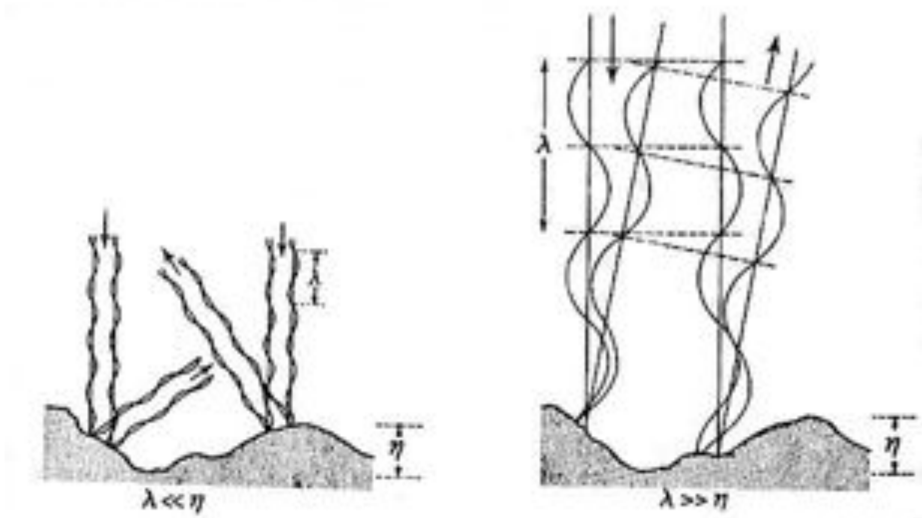
CASIMIR THEORY AND BEYOND

- At low temperature, the dominant phonon wave length is increasing:
- Probability of specular reflection $p(\lambda_{dom})$ depending on λ_{dom} (phenomenological parameter)
- $p(\lambda_{dom})=0$ (perfectly rough surface) $\lambda_{dom} << \eta_0$ Casimir model
- $p(\lambda_{dom})=1$ (perfectly smooth surface) $\lambda_{dom} >> \eta_0$

$$\lambda_{Dom} = \frac{h v_S}{4.25 k_B T}$$



η_0 is the root mean square of the asperity



J.M. Ziman *Electrons and phonons* (Clarendon Press, Oxford, 2001)

CASIMIR THEORY AND BEYOND : THE ZIMAN MODEL

- Ziman-Casimir model

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

where *p* probability of specular reflection

If *p*=0 transport is diffusive (Casimir), if *p*=1 ballistic transport

$$p(\lambda) = \int P(\eta) e^{\frac{-16\pi^3\eta^2}{\lambda_{dom}^2}} d\eta$$

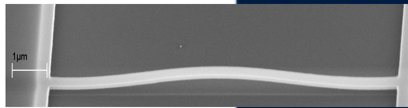
Probability distribution of asperity

$$P(\eta) = \frac{1}{\eta_0} e^{-\eta/\eta_0}$$

$$K(T) = 1.35 \times 10^{-5} \left(\frac{2 - e^{-4\pi\lambda_{dom}(T)/\eta_0}}{e^{-4\pi\lambda_{dom}(T)/\eta_0}} \right) \Lambda_{Cas} T^3$$

Ziman model of phonon transport: ballistic contribution

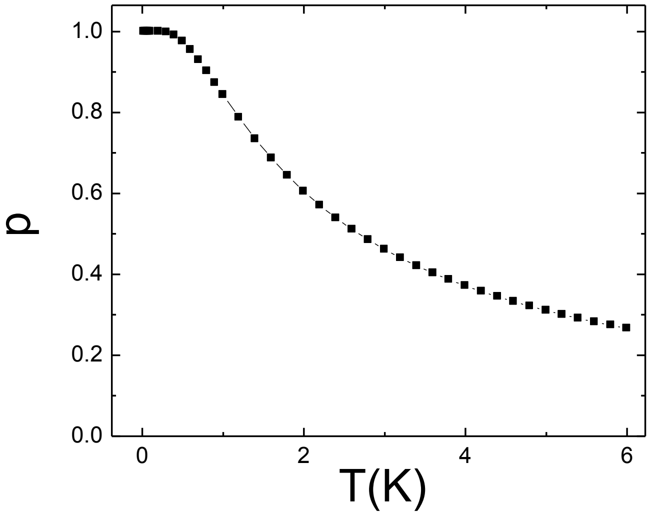
$$K = 3.2\times10^{-3}\left(\frac{2\pi^2 k_B^4}{5\hbar^3 v_s^3}\right)^{2/3}\frac{S\Lambda_{eff}}{L}T^3$$

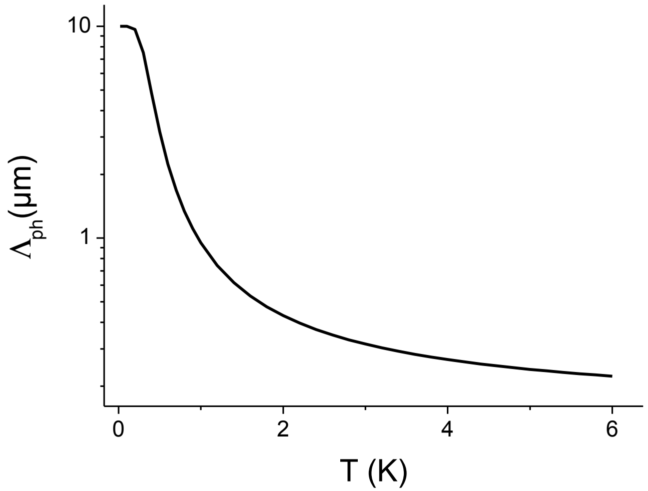


$$\lambda_{Dom} = \frac{hv_S}{4.25k_BT}$$

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

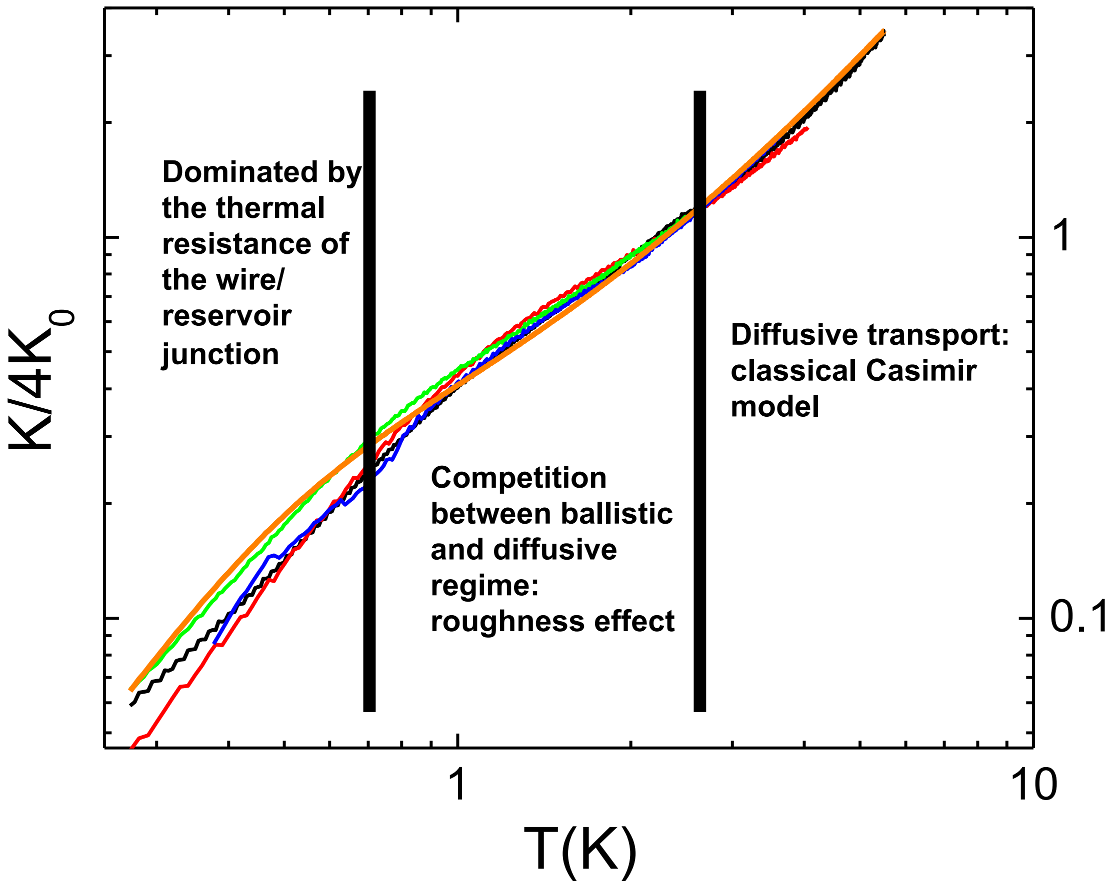
$$\Lambda_{ph}^{-1} = \Lambda_{eff}^{-1} + L^{-1}$$

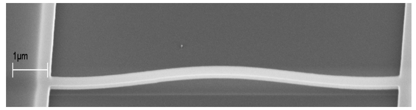




J.-S. Heron, T. Fournier, N. Mingo and O. Bourgeois, Nano Letters **9**, 1861 (2009).

Evidence of contribution from ballistic phonons





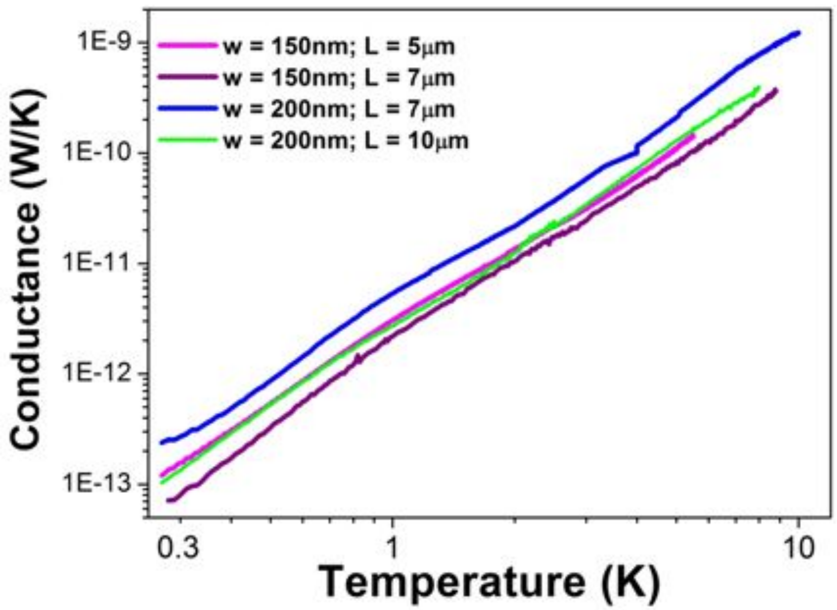
Fitting parameter:

- Roughness h=4nm
- Speed of sound 9000m/s
- Contribution of the contact (Chang, C.; Geller, M. *Phys. Rev. B* **2005**, *71*, 125304.)

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

NORMALIZATION OF THE THERMAL CONDUCTANCE

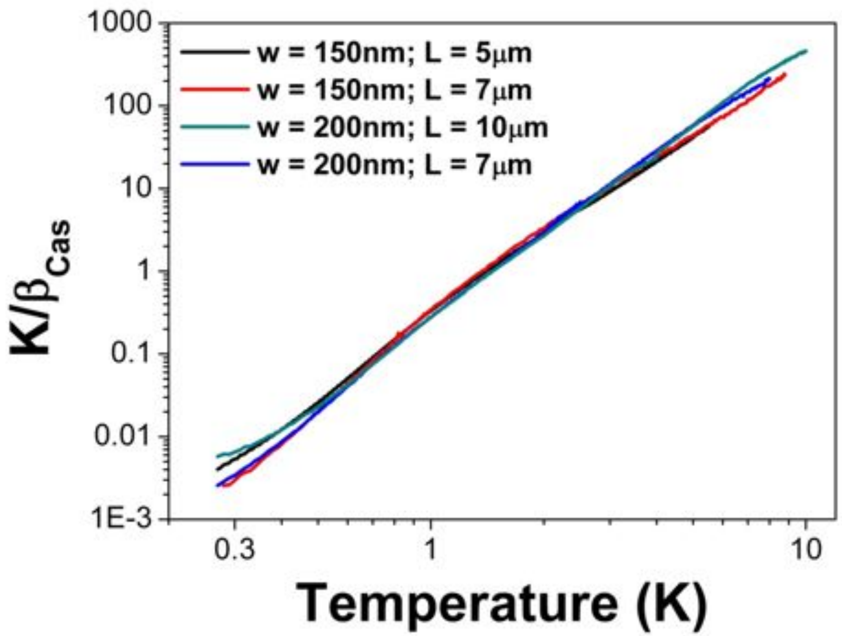
Four different nanowires, different section and different length



$$K = 3.2 \times 10^{-3} \left(\frac{2\pi^2 k_B^4}{5\hbar^3 v_s^3} \right)^{2/3} \frac{S\Lambda_{eff}}{L} T^3 = \beta_{Zim} T^3$$

NORMALIZATION OF THE THERMAL CONDUCTANCE

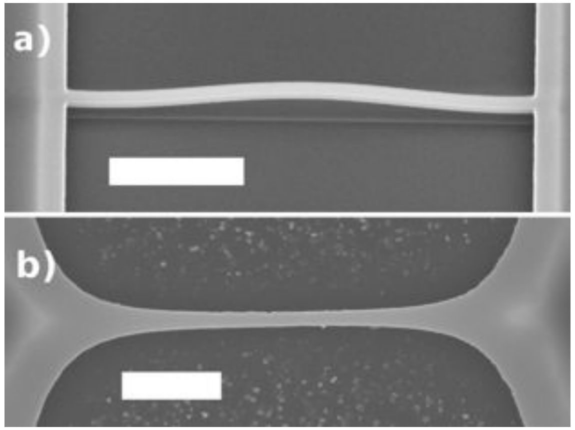
Four different nanowires, different section and different length

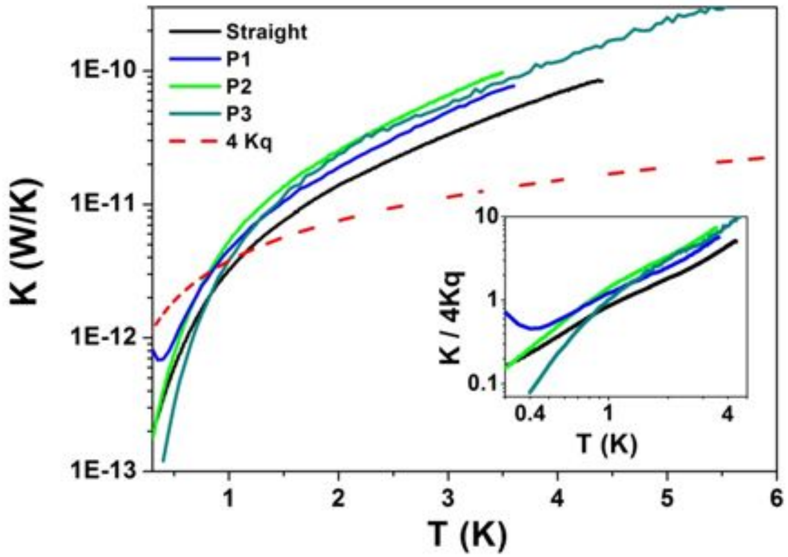


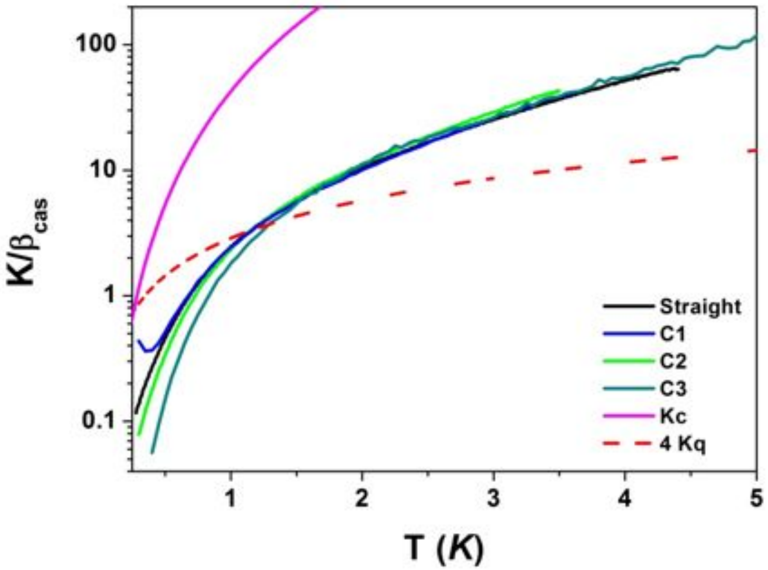
$$K = 3.2 \times 10^{-3} \left(\frac{2\pi^2 k_B^4}{5\hbar^3 v_s^3} \right)^{2/3} \frac{S\Lambda_{eff}}{L} T^3 = \beta_{Zim} T^3$$

CONTRIBUTION OF THE CONTACTS

- Profiled contact
- Identical normalization
- Optimal acoustic adaptation: catenoidal shape
- Above 1K, transmission coefficient T~1

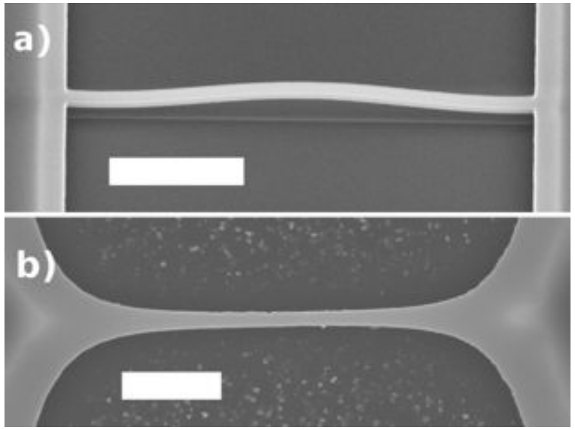


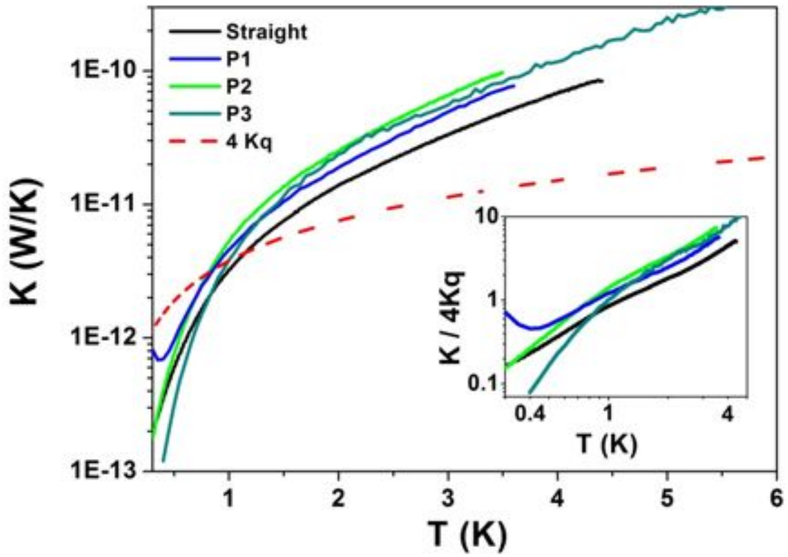


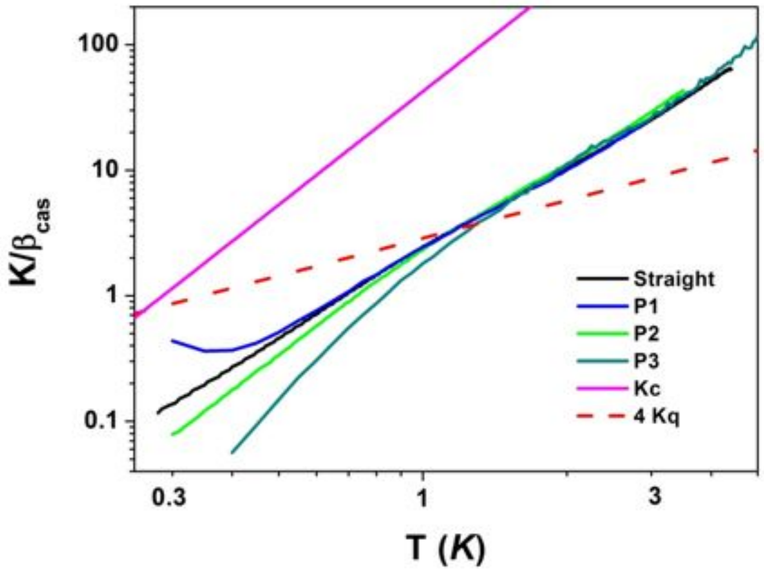


CONTRIBUTION OF THE CONTACTS

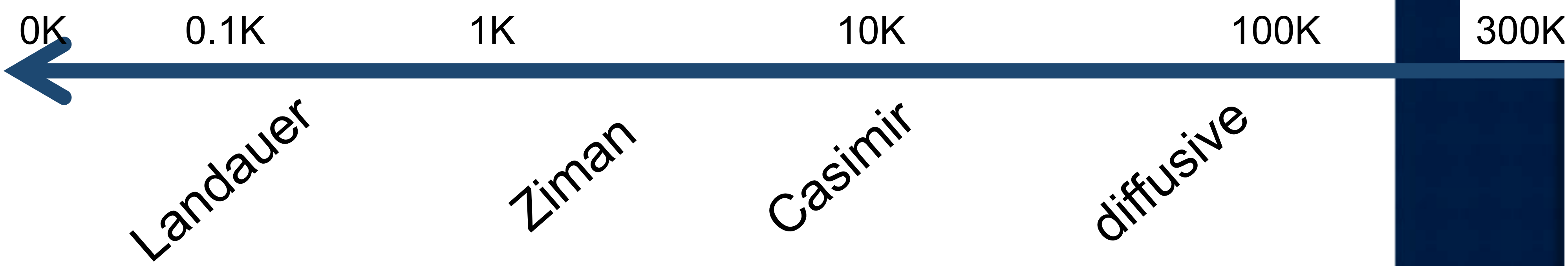
- Profiled contact
- Identical normalization
- Optimal acoustic adaptation: catenoidal shape
- Above 1K, transmission coefficient T~1







PHONON TRANSPORT : SPECIFICITY OF LOW TEMPERATURE

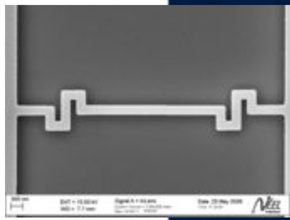


Silicon nanowire of diameter: 100nm

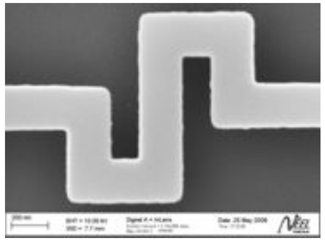
$\lambda_{dom}(T) < \Lambda_{ph}(T) < L$	Diffusive regime	Maxwell Boltzmann :	$k = \frac{C v_s \Lambda_{ph}}{3}$
$\lambda_{dom}(T) < L \sim \Lambda_{Cas} < \Lambda_{ph\text{-}bulk}(T)$	Casimir regime	Casimir model	$K_{Cas} = \beta \Lambda_{Cas} T^3$
$\lambda_{dom}(T) \sim L < \Lambda_{Ziman}(T)$	Ziman regime	Ziman model	$\Lambda_{Ziman} = \frac{1+p}{1-p} \Lambda_{Cas}$
$L < \lambda_{dom}(T) < \Lambda_{ph}(T)$	Ballistic regime	Landauer :	$T = \frac{1}{1 + \Lambda_{eff} / L}$

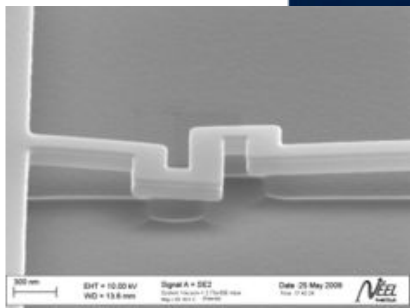
MANIPULATION OF HEAT TRANSPORT AT THE NANOSCALE

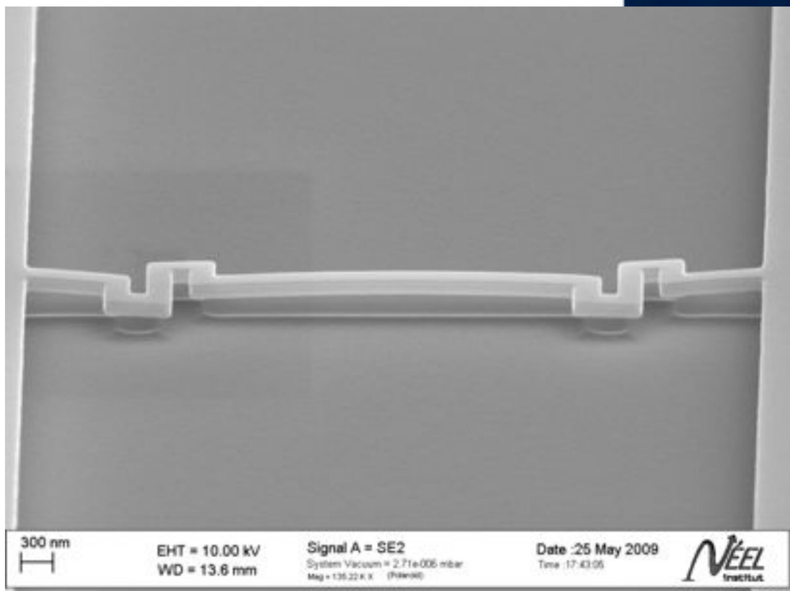
BLOCKING PHONONS AT THE NANOSCALE



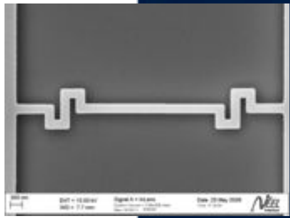
- Introducing of a serpentine nanostructure in the suspended nanowire (5µm long)
- Length scale 200nm
- Blocking only the ballistic phonons
- Reduce the thermal conductance



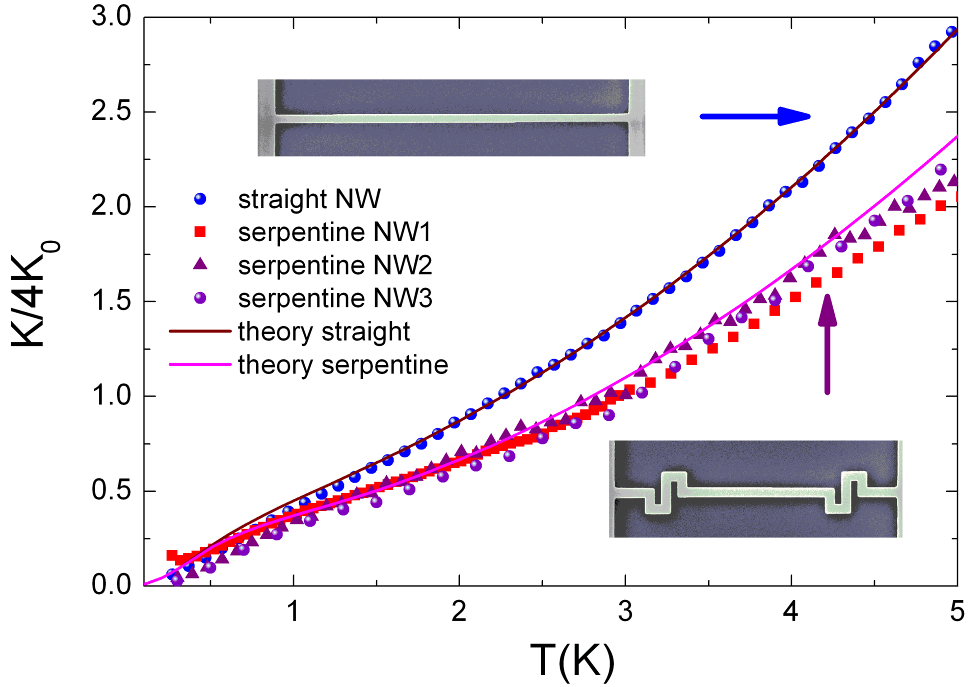




STRONG REDUCTION OF THERMAL CONDUCTANCE



- Reduction of up to 40% of the thermal conductance
- Model this system by transmission function analysis
- Very good agreement between the model and the data
- Concerning ballistic phonons the reduction is of the order of 80%

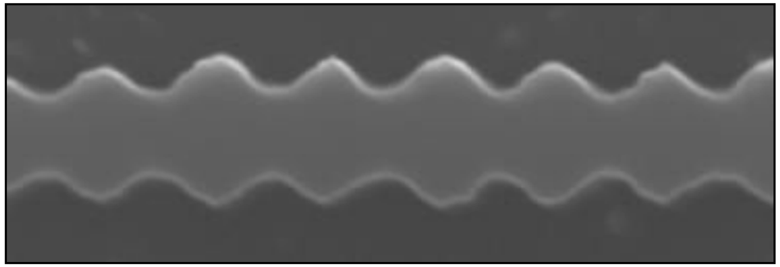


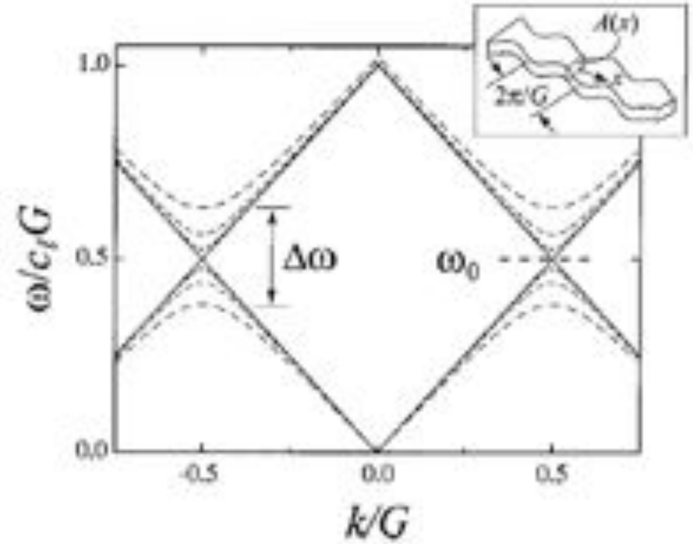
http://www.youtube.com/watch?feature=player_embedded&v=v91i1AlUwLw

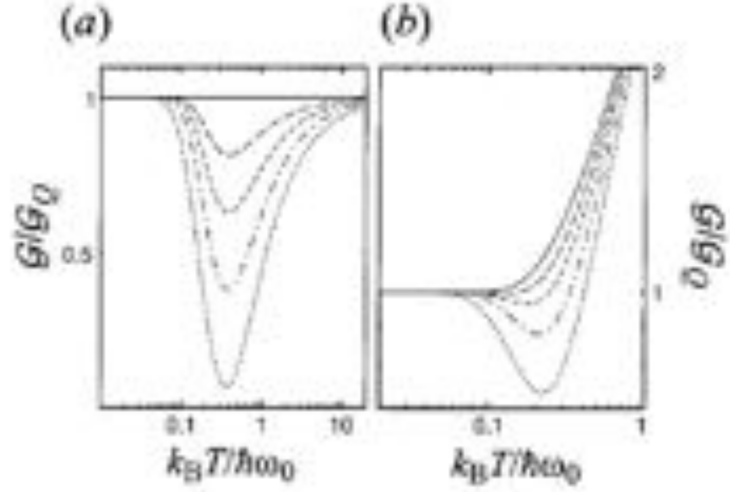
J-S. Heron, C. Bera, T. Fournier, N. Mingo, and O. Bourgeois, *Blocking phonons via nanoscale geometrical design*, Phys Rev B **82, 155458** (2010)

PHONONIC CRYSTAL

- Intoducing periodic modulations
- Phononic crystal geometry
- Major effect when the periodicity of the phononic crystal corresponds to the dominant phonon wave length
- For Si: λ_{dom}=60nm at 1K

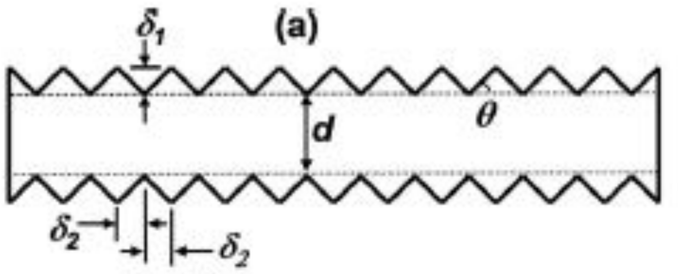


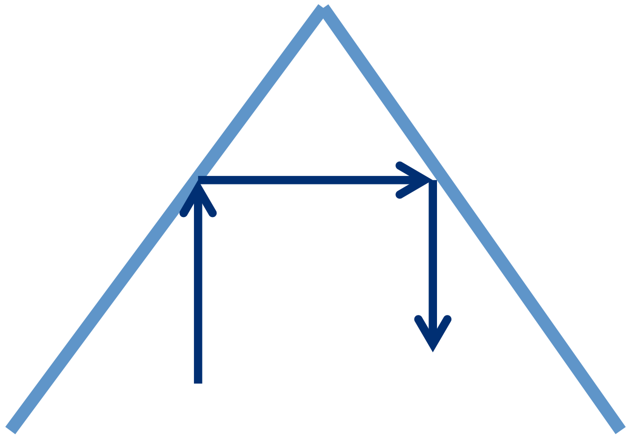




Cleland *et al.*, P. R. B, **64**, 172301 (2001)

OVERVIEW: EXPECTED EFFECT OF CORRUGATED SURFACES OF A NANOWIRE





- Multiple scattering
- Backscattering in sawtooth nanowire
- Reduction of the mean free path

Phonon backscattering and thermal conductivity suppression in sawtooth nanowires

APPLIED PHYSICS LETTERS 93, 083112 (2008)

Arden L. Moore,[1] Sanjoy K. Saha,[2] Ravi S. Prasher,[2,3,a)] and Li Shi[4,a)]

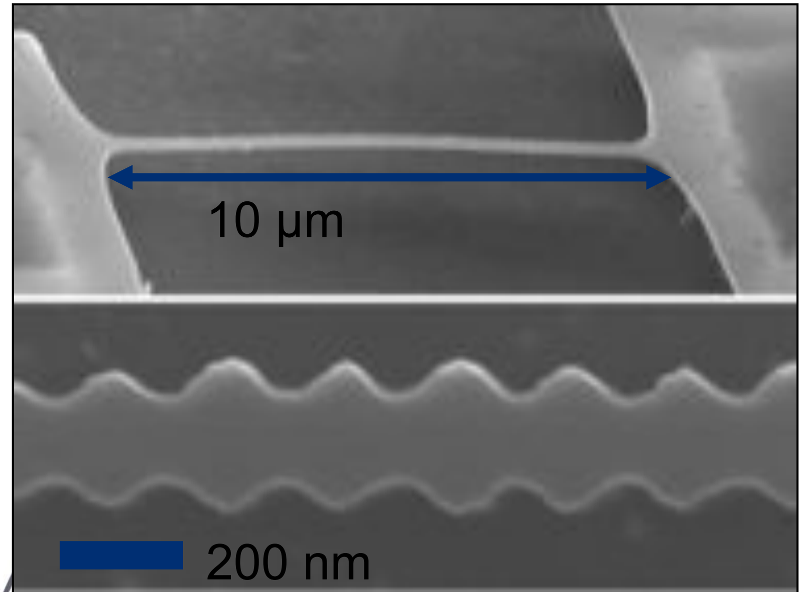
Tunable superlattice in-plane thermal conductivity based on asperity sharpness at interfaces: Beyond Ziman's model of specularity

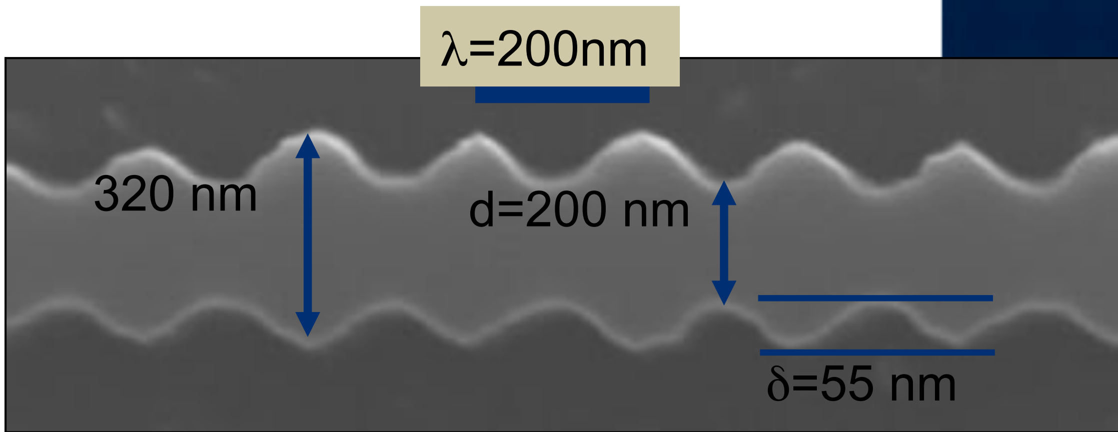
Ali Rajabpour,[1,2] S. M. Vaez Allaei,[1,3,a)] Yann Chalopin,[4] Farshad Kowsary,[1] and Sebastian Volz[4,5,a)]

JOURNAL OF APPLIED PHYSICS 110, 113529 (2011)

SAMPLES: MONOCRYSTALLINE SILICON NANOWIRE

- Samples made by ebeam lithography
- λ_{dom}=60nm at 1K in silicon very close to the periodicity of the modulation of roughness
- Comparison to smooth nanowire



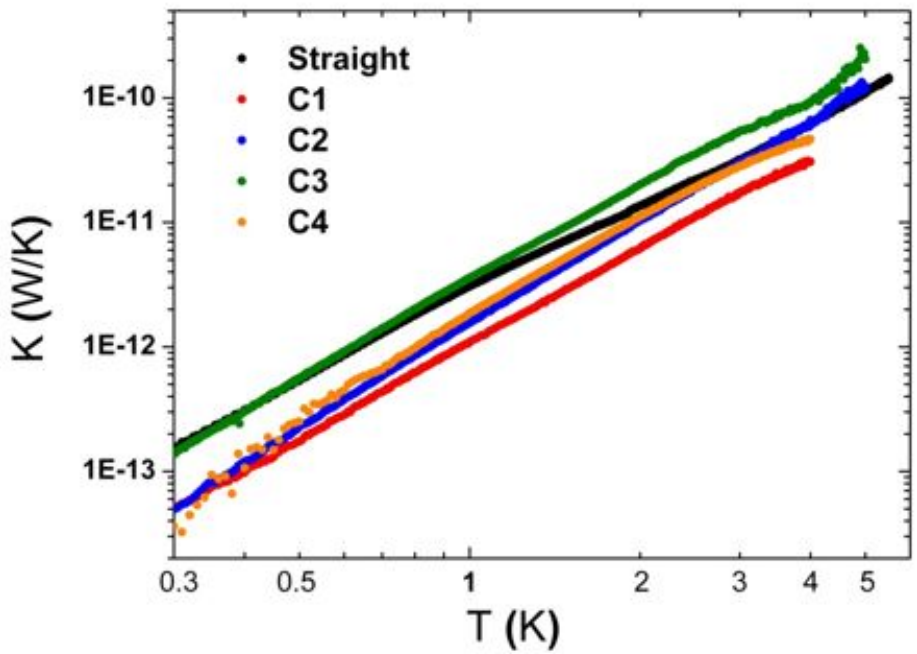


THERMAL CONDUCTANCE MEASUREMENTS: CASIMIR-ZIMAN SCENARIO

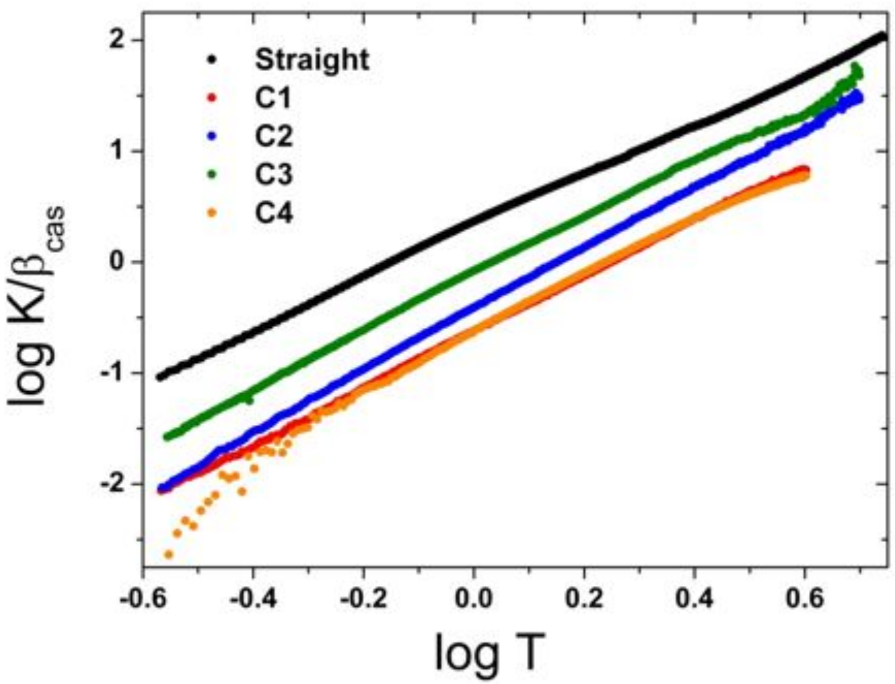
$$K(T) = 3.2\times10^3\left(\frac{2\pi^2 k_B^4}{5\hbar^3 v_s^3}\right)\frac{S\Lambda_{Cas}}{L}T^3$$

$$K(T) = 3.2\times10^3\left(\frac{2\pi^2 k_B^4}{5\hbar^3 v_s^3}\right)\frac{S\Lambda}{L}T^\beta$$

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

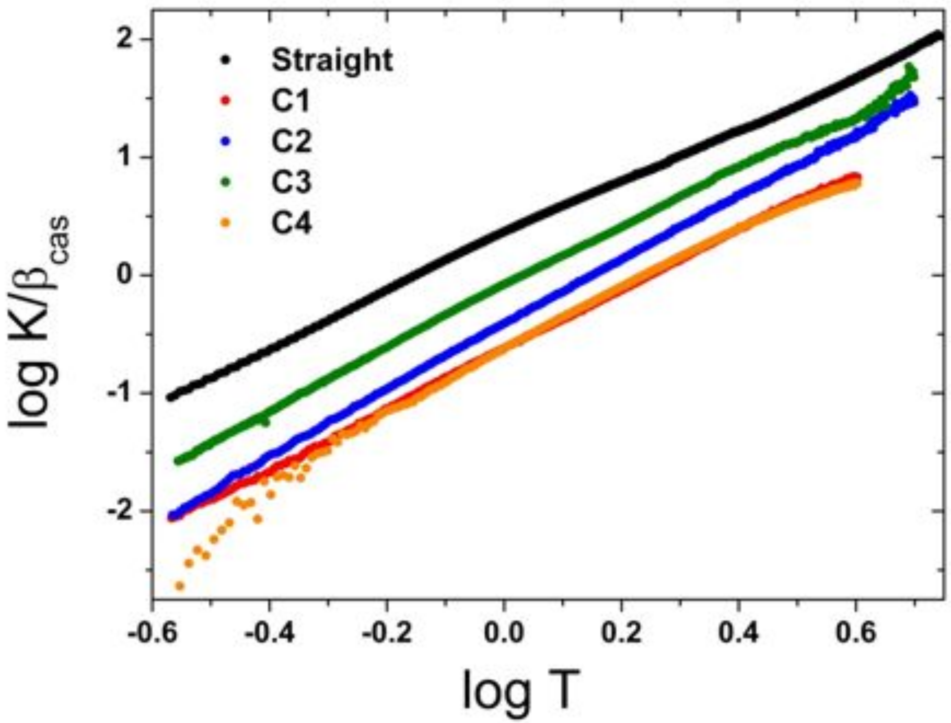


THERMAL CONDUCTANCE AND MONTE-CARLO SIMULATIONS



- Smooth nanowire have large mean free path
- Comparable temperature power law (β=2.6)
- Mean free path strongly reduced by regular corrugated surfaces
- Comparison to smooth nanowire

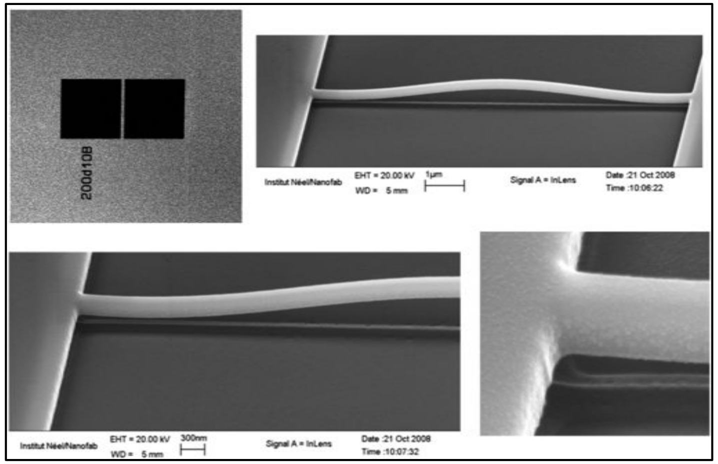
THERMAL CONDUCTANCE

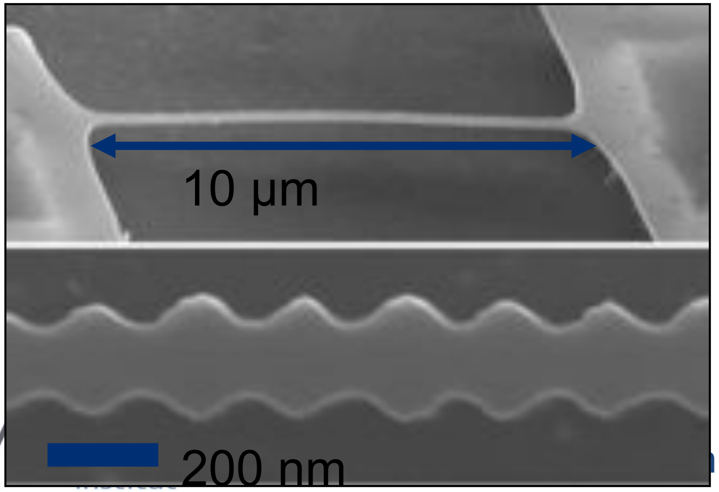


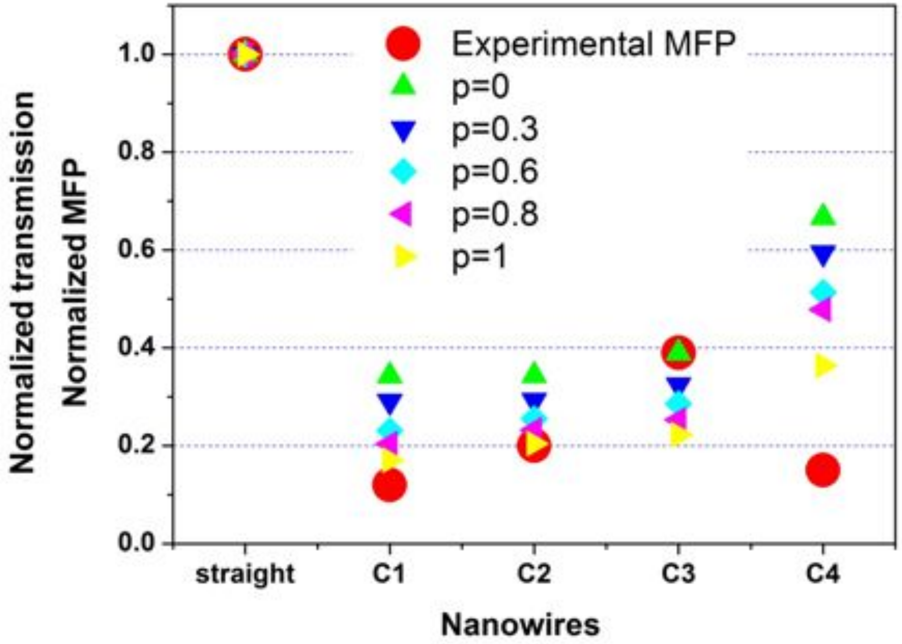
- Presence of backscattering
- Phonon trapped in the Si tooth

Sample	L (μm)	$w_{min}(nm)$	$w_{max}(nm)$	period (nm)	MFP (nm)	Normalized MFP	b	p
straight	5	200	200	0	454	1	2.27	0.60
C1	4.4	130	250	200	57	0.13	2.52	-0.32
C2	5	140	245	200	90	0.2	2.74	-0.10
C3	5	160	260	200	178	0.39	2.54	0.22
C4	4.4	230	250	50	70	0.15	2.6	-0.27

THERMAL CONDUCTANCE AND MONTE-CARLO SIMULATIONS: RAY TRACING



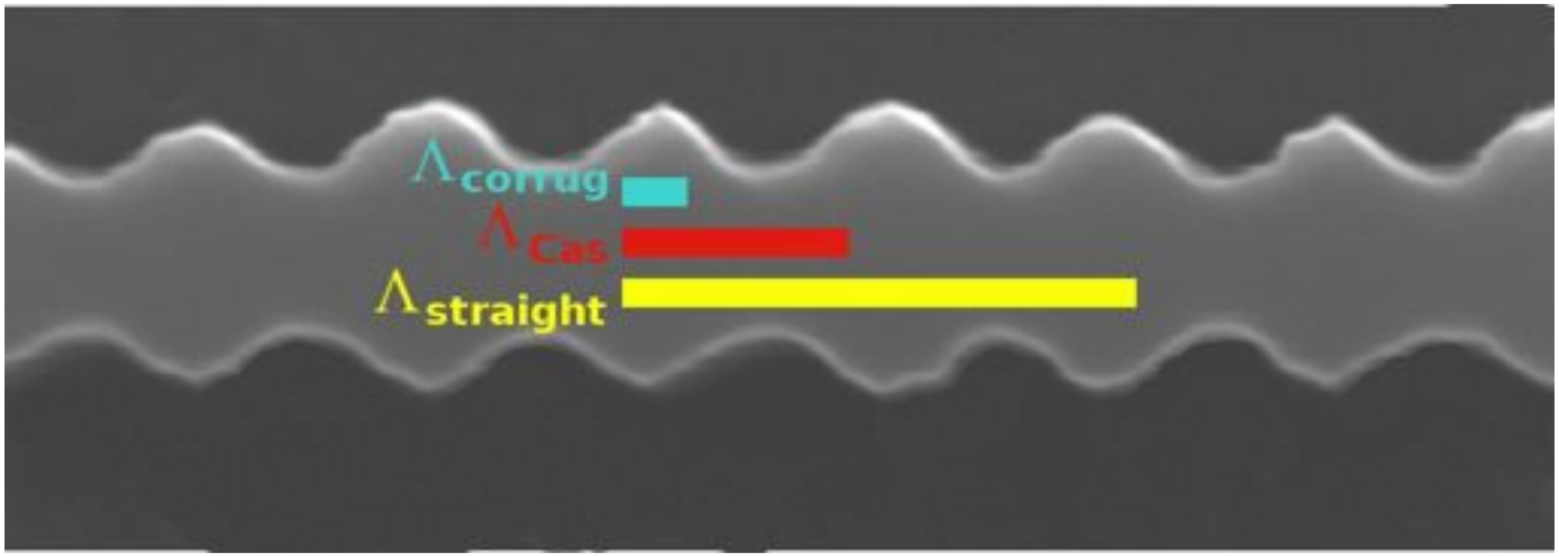




Ali Rajabpour, S. Volz

Conclusions: below the Casimir limit

- Strong backscattering effect of the corrugation (negative parameter p)
- The corrugation acts like a trap for the phonons
- Factor of 9 in the mean free path between smooth and corrugated wires



C. Blanc, A. Rajabpour, S. Volz, T. Fournier, and O. Bourgeois, *Phonon Heat Conduction in Corrugated Silicon Nanowires Below the Casimir Limit*, Appl. Phys. Lett. **103**, 043109 (2013).

APPLICATION TO THERMOELECTRICITY AND PERSPECTIVES

Implications: thermalization, nanothermoelectricity

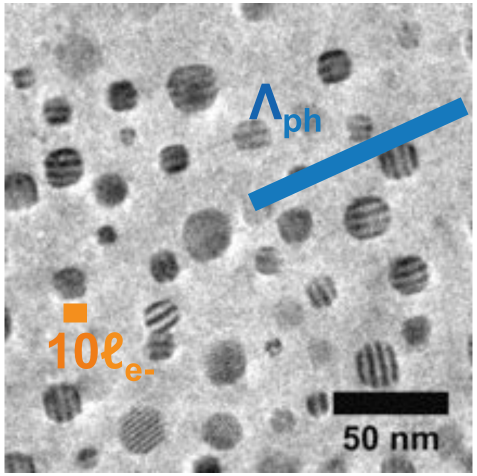
- Ballistic phonon->no local temperature
- ~~Thermal conductivity~~ ->thermal conductance (driven by the size of the systems)
- Play with the phonons: phonon focusing, phonon blocking etc..
- Application to thermoelectricity: phonon scattering at the nanoscale with clusters, nanoparticles, superlattice etc…

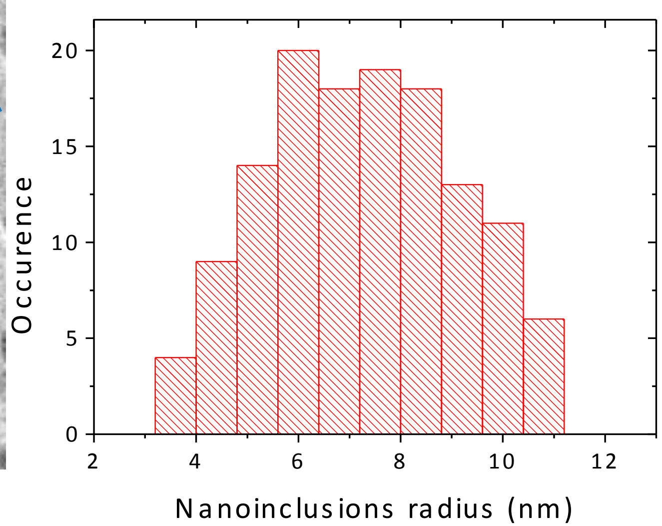
$$ZT = \frac{S^2 T\sigma}{\left(k_{elec} + k_{ph}\right)}$$

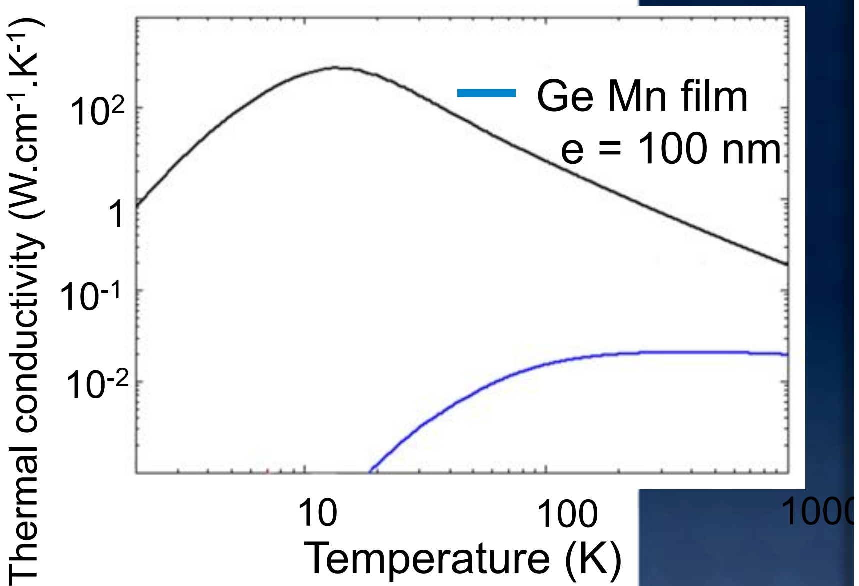
$$\eta_{\max} = \eta_c \frac{\sqrt{ZT+1} - 1}{\sqrt{ZT+1} + 1}$$

RELATION TO NANOTHERMOELECTRICITY

- GeMn inclusions in Ge matrix (single crystal)
- Broad distribution of scatterers
- Much higher ZT as compared to regular semiconductor
- Collaboration ARC Energy with CETHIL (Séverine Gomes)
- EU collaboration MERGING CEA INAC (André Barski), ICN (Barcelone), VTT (Helsinki), Max Planck I. (Mainz))





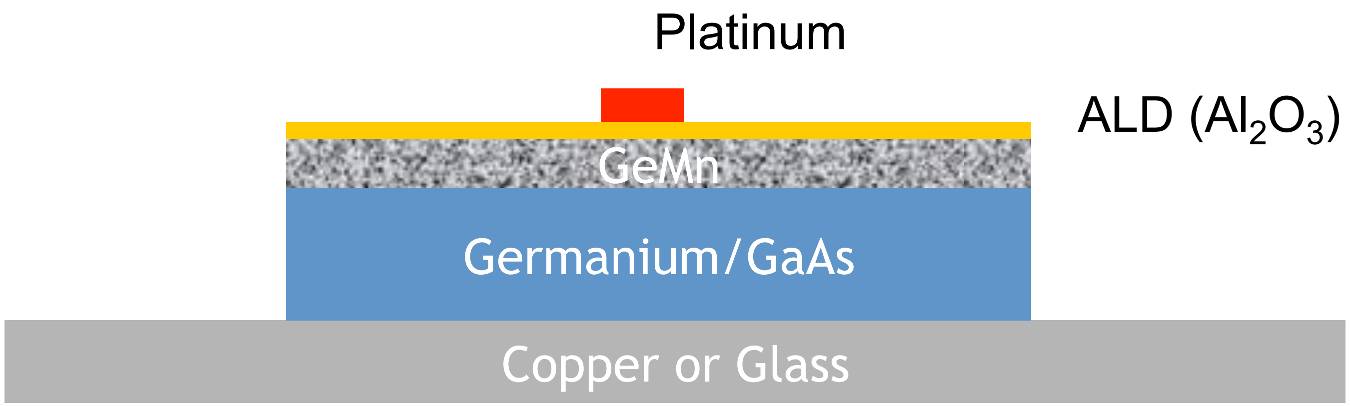


merging

Thesis Yanqing Liu (ARC Energy project)

3Ω METHOD HEAT TRANSPORT PERPENDICULAR TO THE PLANE (RADIAL)

- Heater=thermometer=Platinum (no NbN)
- Thermal conductance measurement at low frequency (Cahill RSI 1990)
- Application to multilayers



$$\Delta T = \frac{P}{\pi\, l\, k_0}\left[\frac{1}{2}\ln\frac{D}{r^2\omega} + \ln 2 - 0.5772 - \frac{i\,\pi}{4}\right] + \frac{P\, t_1}{2\, l\, b\, k_1}$$

Yanqing Liu (Thesis) and Dimitri Tainoff (Post-doc)

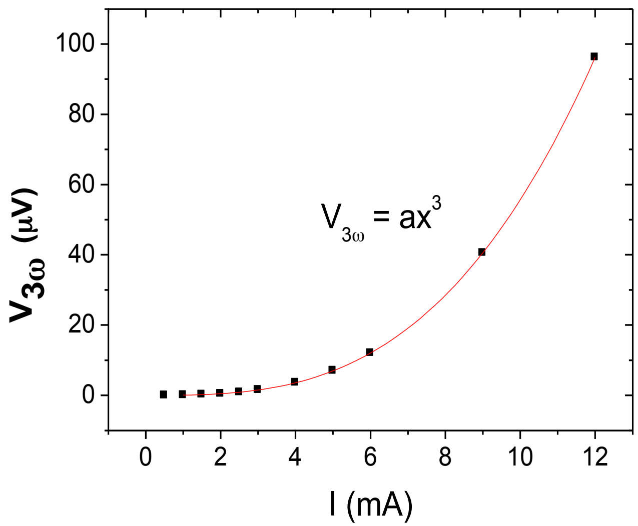
D. G. Cahill, Rev. Sci. Instrum. **61**, 802 (1990)

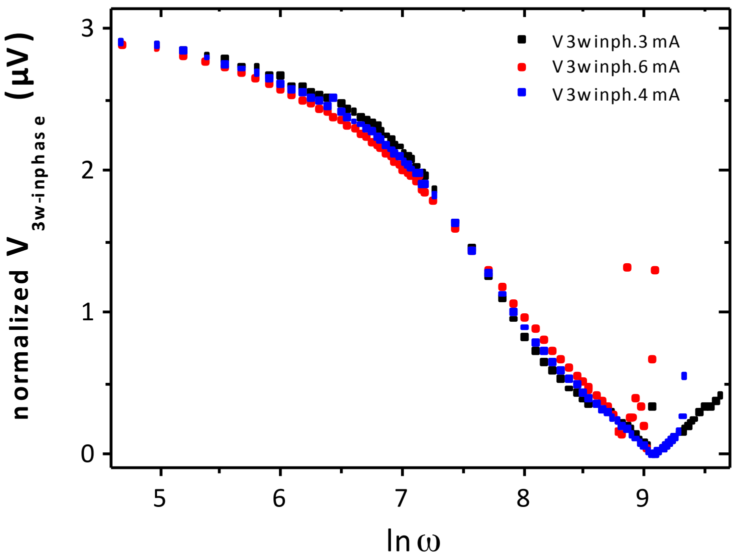
J.-Y. Duquesne, Phys. Rev. B. **79**, 153304 (2009)

FIRST THERMAL MEASUREMENT ON GERMANIUM

$$k = -\frac{\alpha \cdot R^2 \cdot I^3}{2\sqrt{2} \cdot \pi \cdot l}\left(\frac{dV_{3\omega inph.}}{d\ln\omega}\right)^{-1} \qquad \lambda_{th} = \sqrt{\frac{D}{\pi \cdot f}}$$

K_{Ge}=44 W/mK



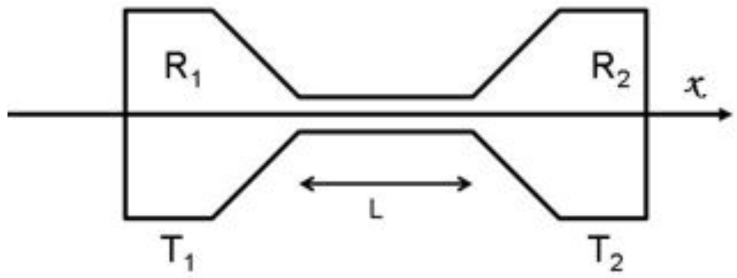


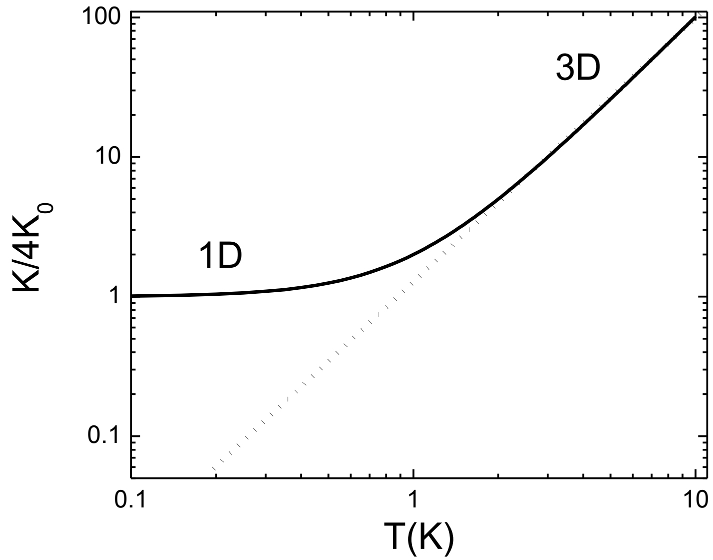
LIMIT AT LOW DIMENSIONS AND LOW TEMPERATURE: UNIVERSAL THERMAL CONDUCTANCE

- Λ>>d
- λ_{dom}>>d
- 4 acoustic phonon modes

$$K_0 = \frac{4\pi^2 k_B^2 T}{3h}$$

- Conduction channel (Similar to the Landauer model of electrical conductance)
- Not dependant on the materials
- Valid whatever the heat carrier statistic
- Pendry, Maynard: flow of entropy or information





J.B. Pendry, J. Phys. **16**, 2161 (1983)

R. Maynard and E. Akkermans, Phys. Rev. B **32**, 5440 (1985)

L.G.C. Rego and G. Kirczenow, Phys. Rev. Lett. **81** 232 (1998)

CONCLUSIVE COMMENTS

- Heat nano-engineering at small length scale
- K: 3ω method, hot wire, thermal gradient
- Single crystals: serpentine and corrugation
- Amorphous materials
- Breakdown of the concept of thermal conductivity (MFP larger than the size of the system)
- Quantum regime: universal behavior of K (dom. phonon wavelength is bigger than the size of the system)

Phononics 2013

2nd International Conference on Phononic Crystals/Metamaterials, Phonon Transport & Optomechanics

June 2 - June 7
Sharm El-Sheikh, Egypt

- Phononics conference every two years
- 2015 Phononics in Paris

- 2017 Phononics in China (Changsha)

- Creation of The Phononics Society (2013)

- Nanofab(rication), Electronic, mechanical facilities, Pole Capteur
- Christophe Blanc, Hossein Ftouni, Yanqing Liu, (Jean-Savin Heron)
- Kunal Lulla, Dimitri Tainoff
- Séverine Gomes, Sebastian Volz, Natalio Mingo
- TPS, UBT etc…
- Financial supports from Région Rhones Alpes (ARC Energy), Agence Nationale de la Recherche, European Union (FP7) MERGING

THANKS FOR YOUR ATTENTION