METAmatériaux acoustiques et transport thermique

22 janvier 2016

Jean-François Robillard

GT4 : Domaines émergents

Journée de lancement du GDR META - Paris

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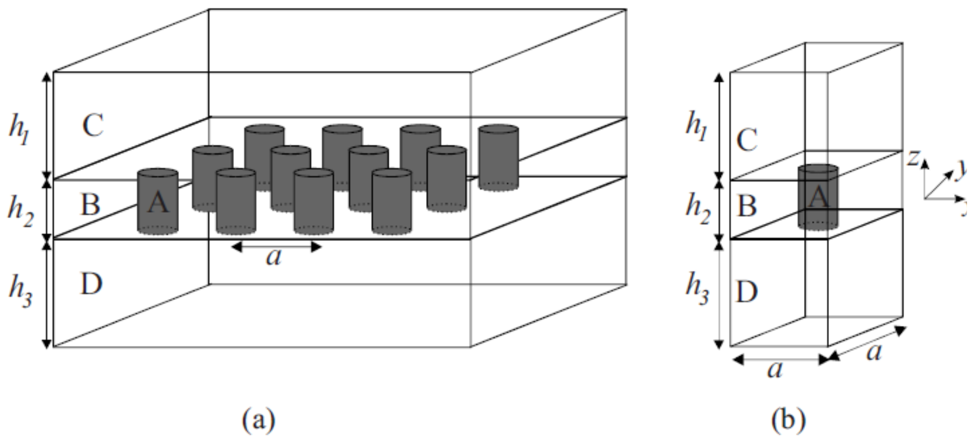
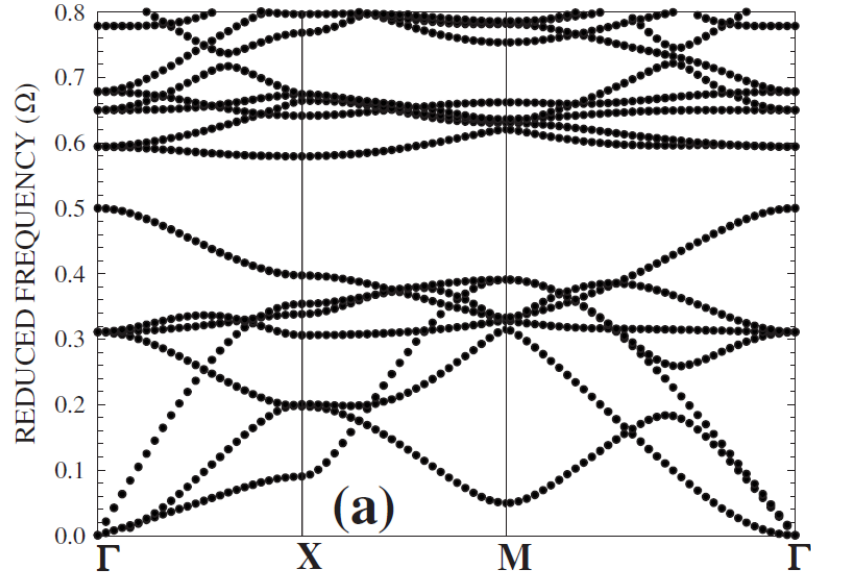
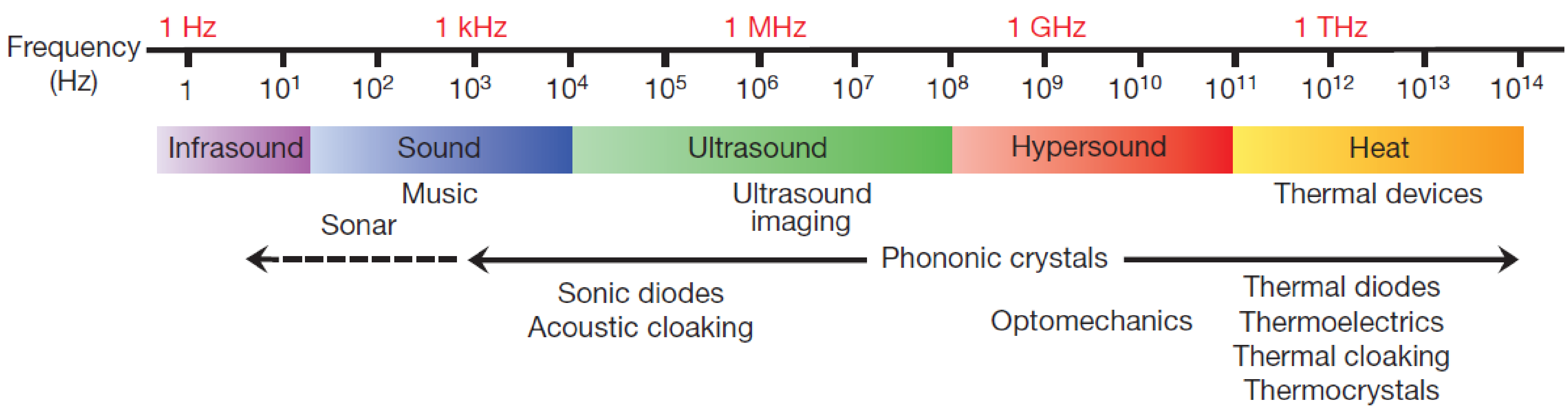
cnrs Université de Lille 1 Sciences et Technologies Université de Valenciennes et du Hainaut-Cambrésis ISEN école d'ingénieurs RENATECH



J. O. Vasseur et al., *Phys. Rev. B* **77**, 085415 (2008)





M. Maldovan, *Nature* **503**, 211 (2013)

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Outline

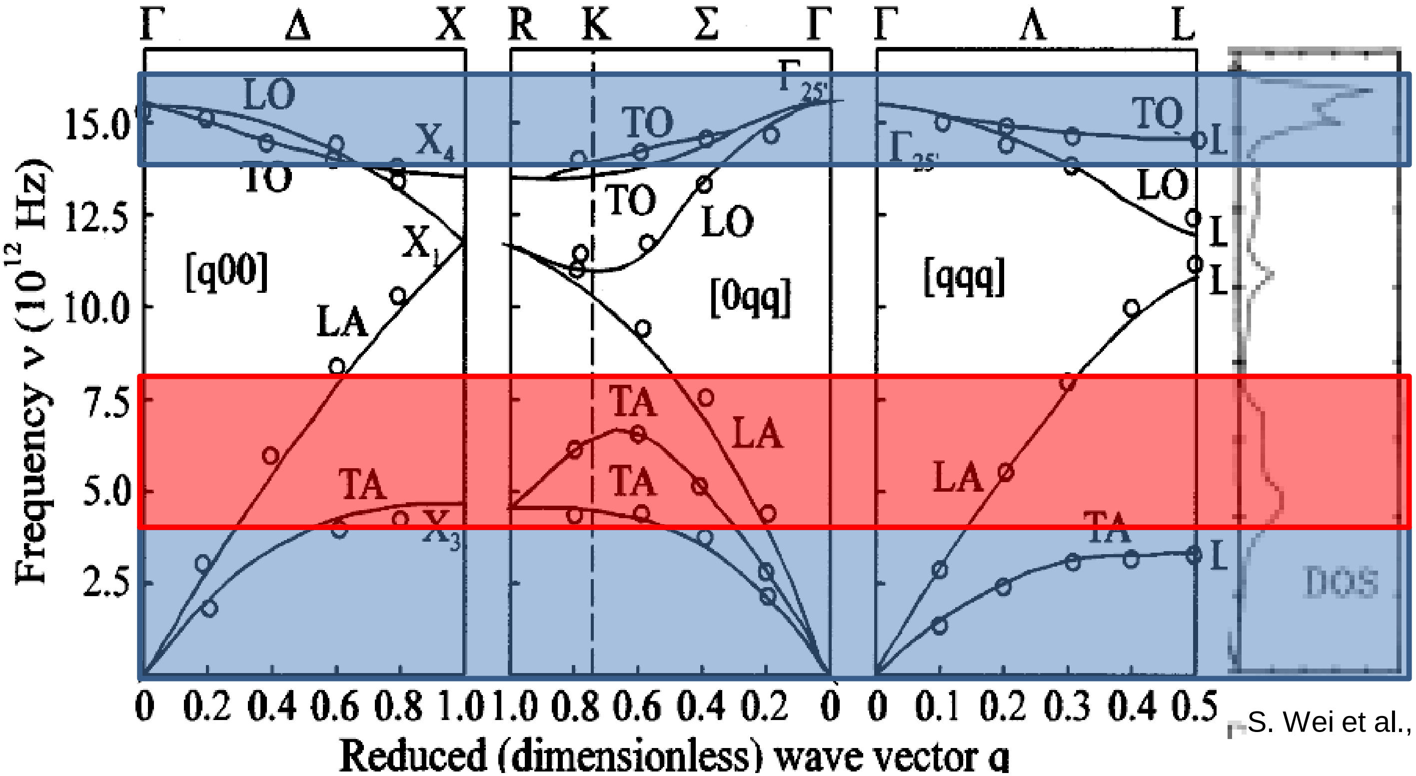
Principles/Fundamental questions

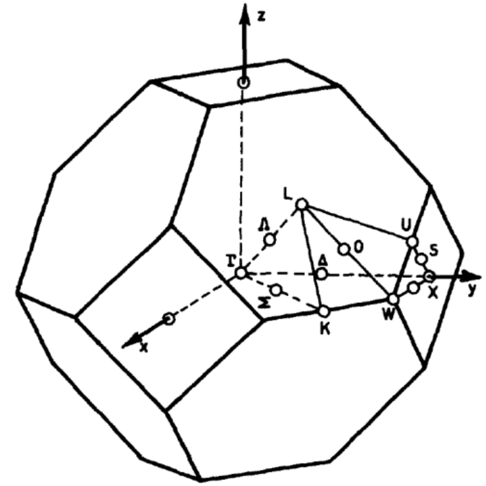
Challenges and state-of-the-art

- Modeling
- Fabrication
- Characterization

Panorama

Potential applications…





S. Wei et al., *Phys. Rev. B* **50,** 2221 (1994)

$$\kappa = \frac{1}{(2\pi)^3} \sum_{\lambda} \int C_{ph}(\vec{k},\lambda)(\vec{v}_g(\vec{k},\lambda)\cdot\hat{l})^2 \tau(\vec{k},\lambda) d\vec{k}$$

$$= \int g(E) C_{ph}(E,T) v^2(E) \tau(E,T) dE$$

$$C_{ph}(k,\lambda) = k_B \left(\frac{\hbar\omega(k,\lambda)}{k_B T}\right)^2 \frac{\exp(\hbar\omega(k,\lambda)/k_B T)}{[\exp(\hbar\omega(k,\lambda)/k_B T) - 1]^2}$$

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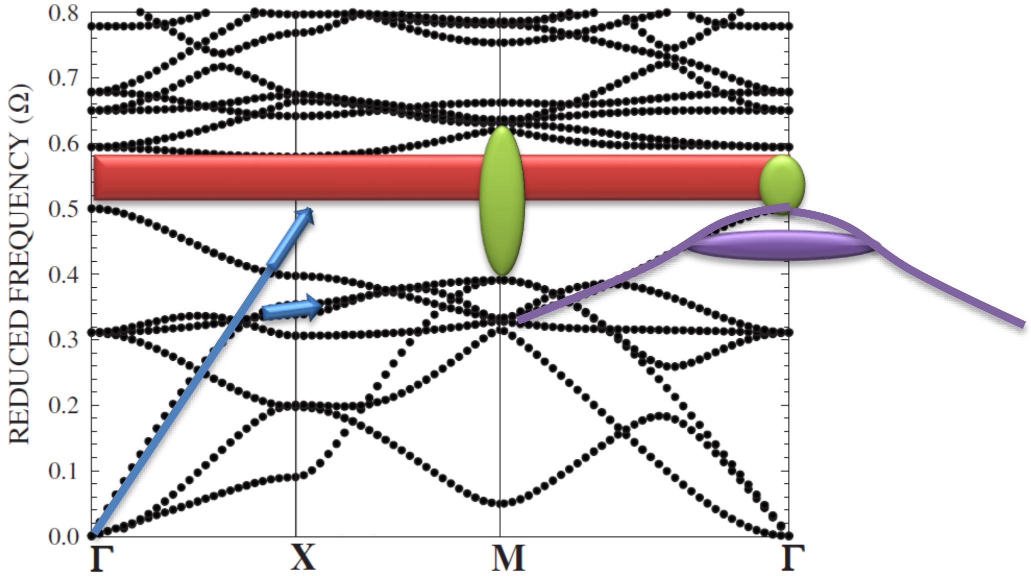
$$\Omega = \frac{\omega}{\omega_0}, \omega_0 = \frac{2\pi c_L}{a}$$



J. O. Vasseur et al., *Phys. Rev. B* **77**, 085415 (2008)

Bande interdite
Réduction de vitesse de groupe
Anisotropie induite
Réfraction négative

Typiquement premier gap à $\frac{\omega_0}{2}$

Exemple Si, v~8500 m/s, $\frac{\omega_0}{2} = 5THz$

a=10.6 nm
Echelle nanométrique…

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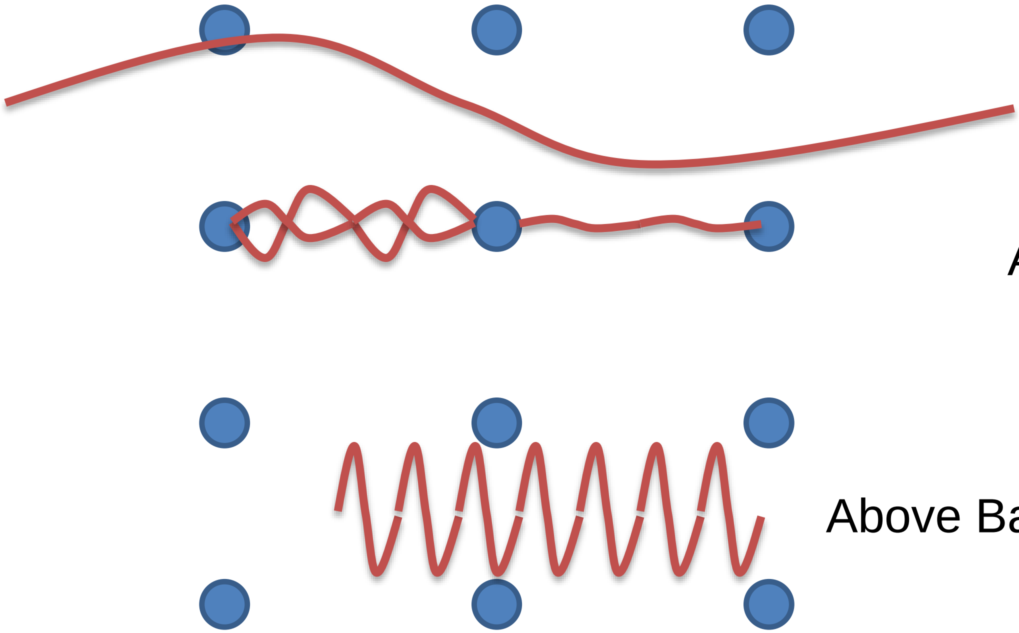
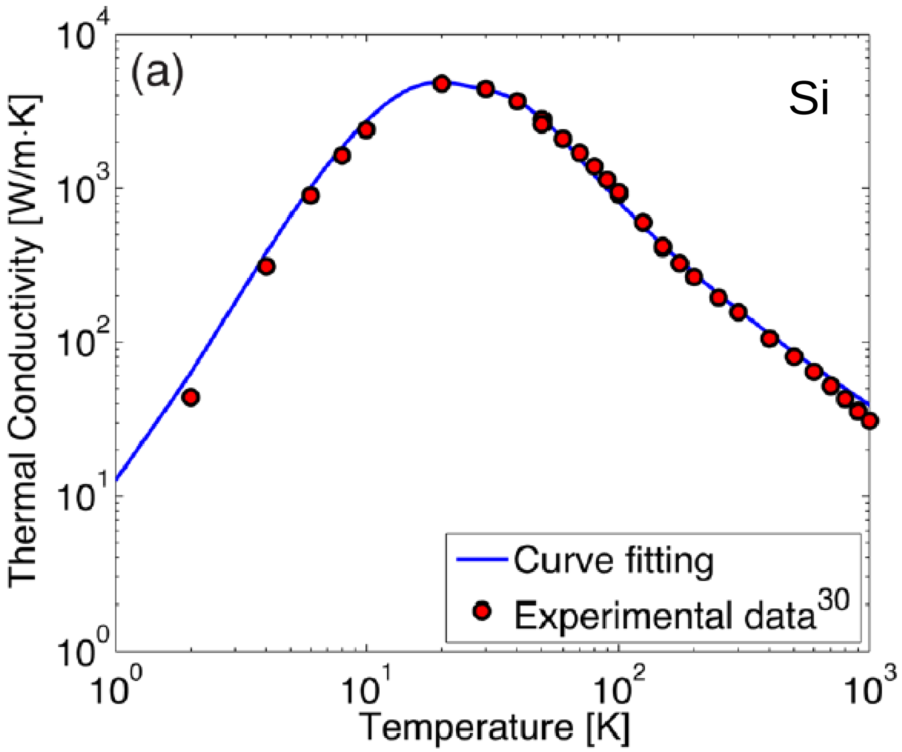
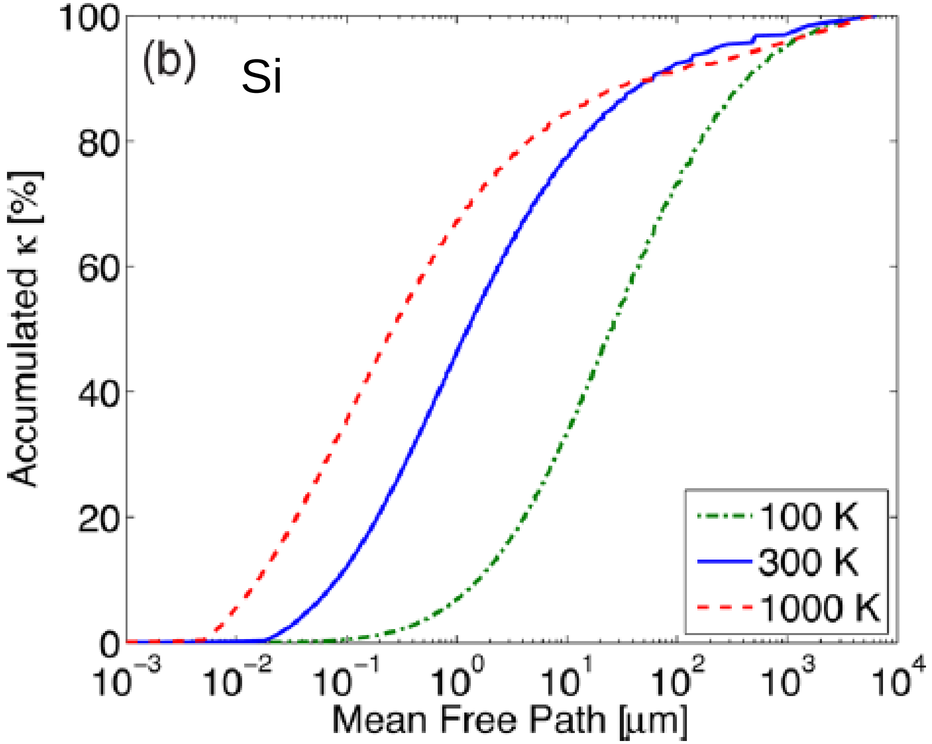
Bragg scattering is an interference process
Coherence is required



In order to observe Bragg effects, coherence length must be at least a few "a_{PC}"
-> This is naturraly the case for low-ω narrow band sources
-> But thermal phonons have a wide spectrum -> short coherence length

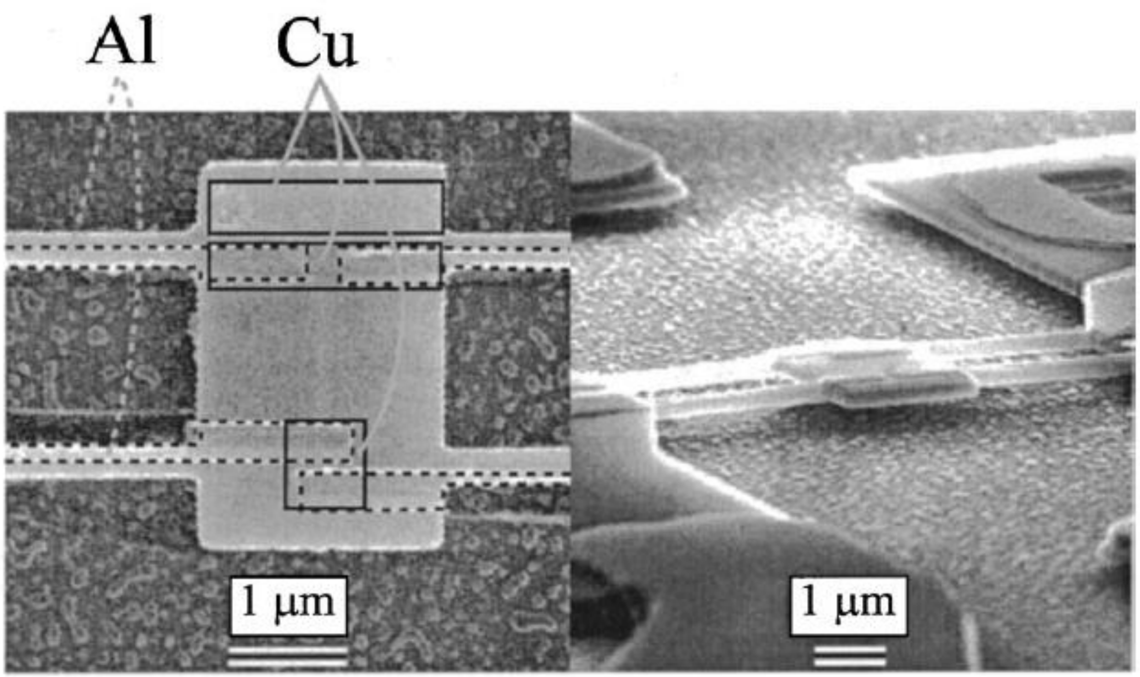


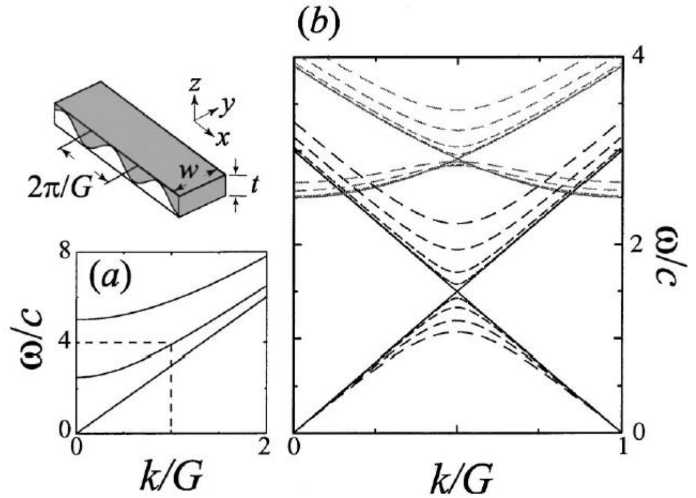


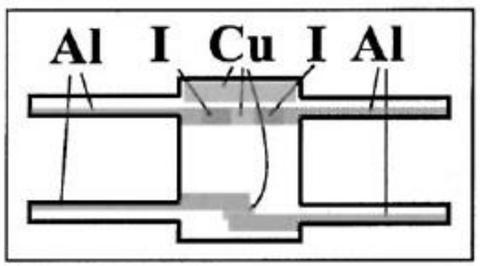
Ordres de grandeurs
Longueur d'onde λ~1 à 5 nm
Longueur de cohérence ~ quelques λ
Libre parcours moyen Λ ~ 100 nm à qqes µm

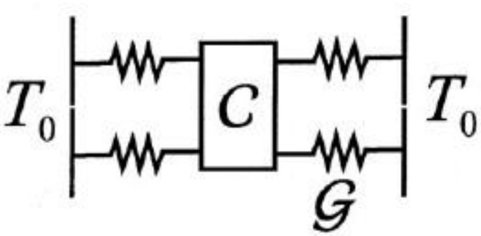
Deux possibilités :
- Taille véritablement nano
- **Basses températures**

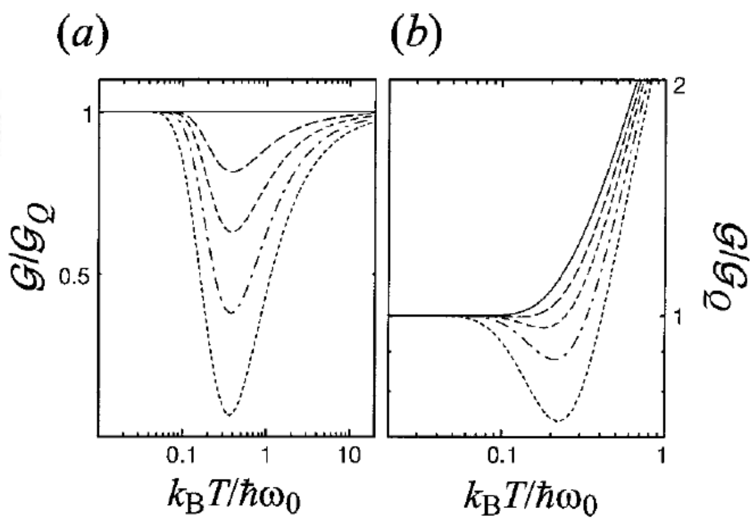
Dechaumphai et al., J. Appl. Phys. **111**, 073508 (2012)



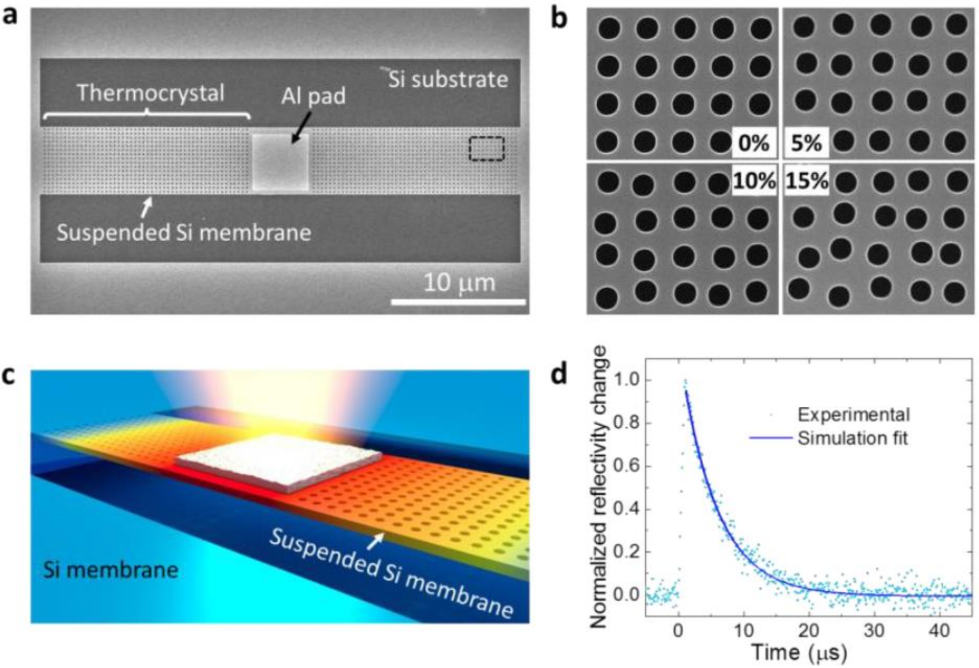


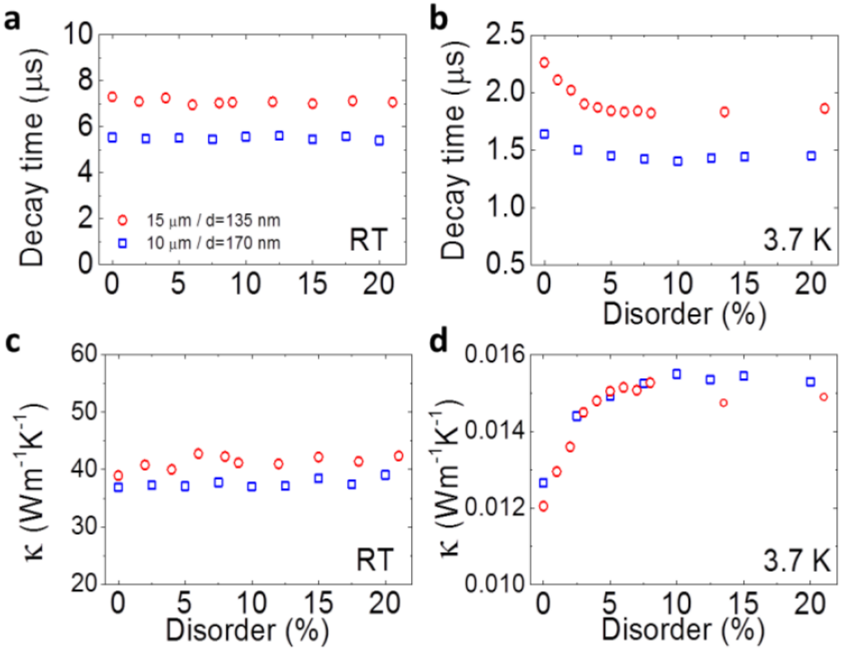






A. N. Cleland et al., *Phys. Rev. B* **64**, 172301 (2001)





Silicon
Low T vs high T
Time-Resolved Thermo Reflectance

J. Maire et al., *in press* (2016)
M. Nomura group, Univ. Tokyo

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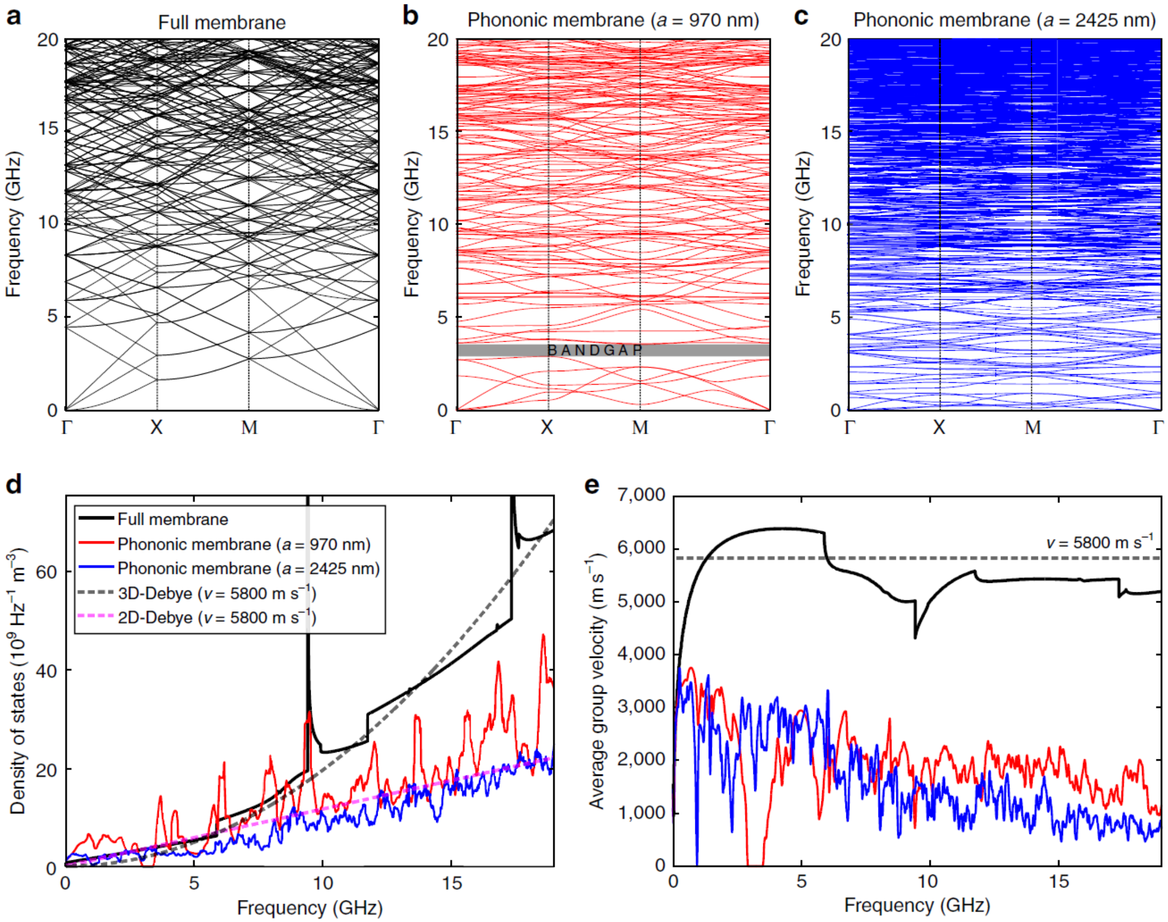
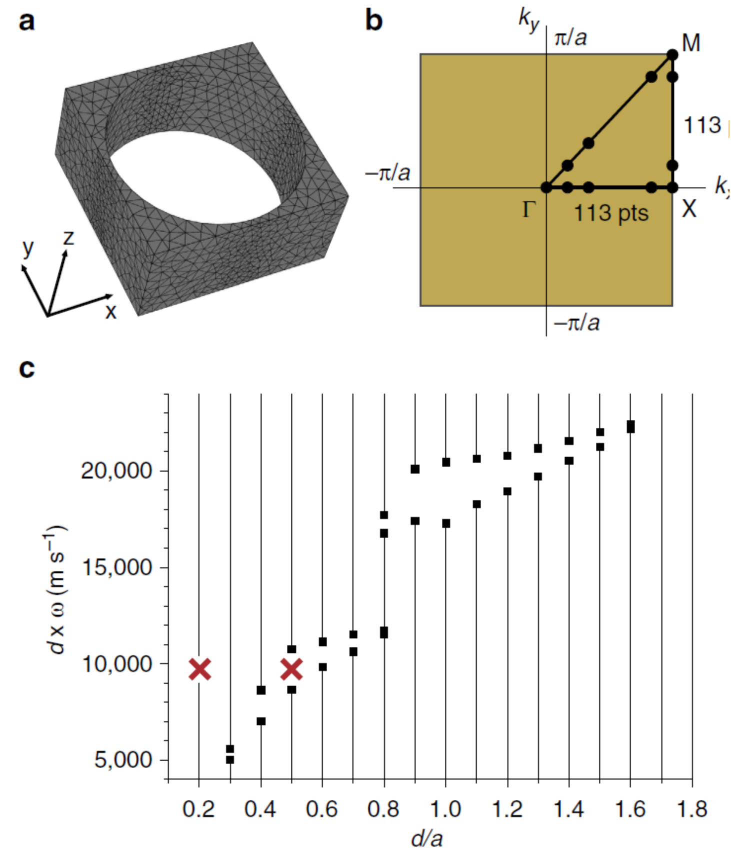
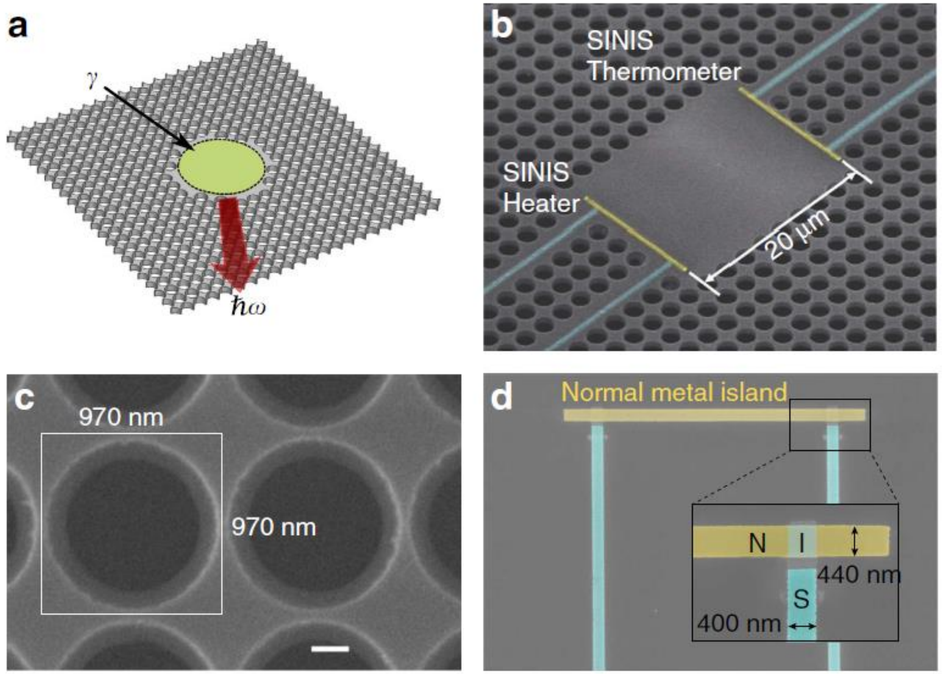
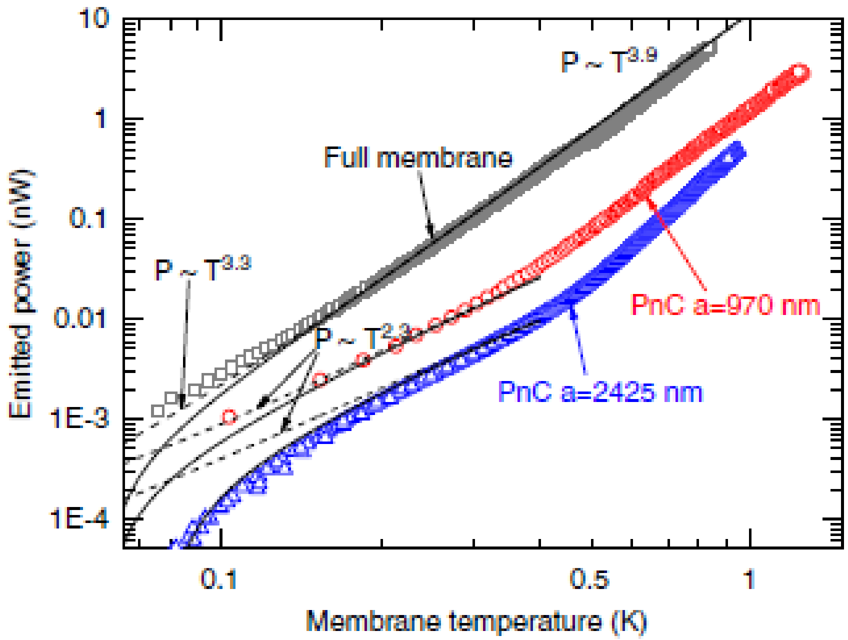




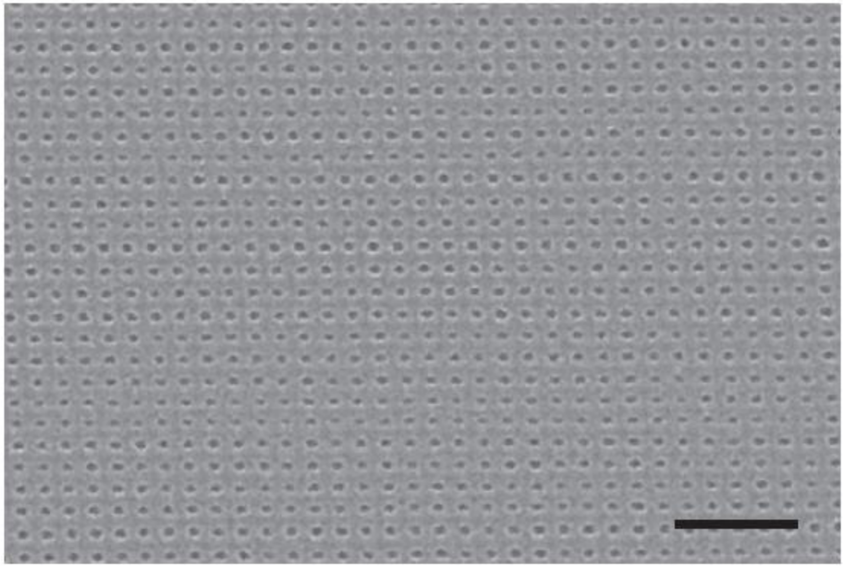
N. Zen et al., *Nature Communications* **5**, 3435 (2014)

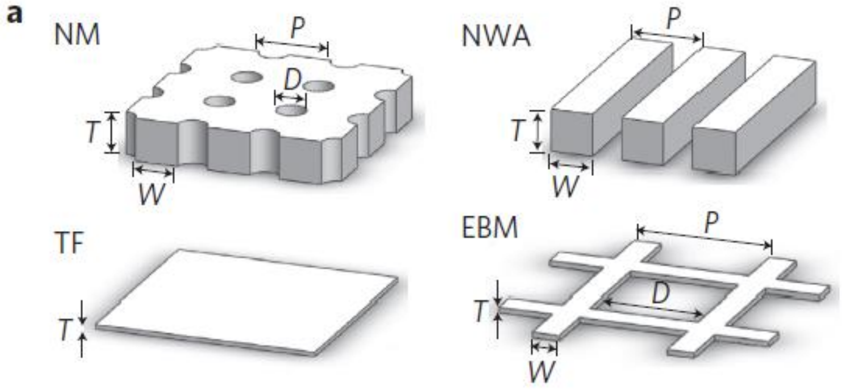




Silicon Nitride
Ultra-low T <1K
Large pitch (µm)
Conventional lithography/etching
Bolometer

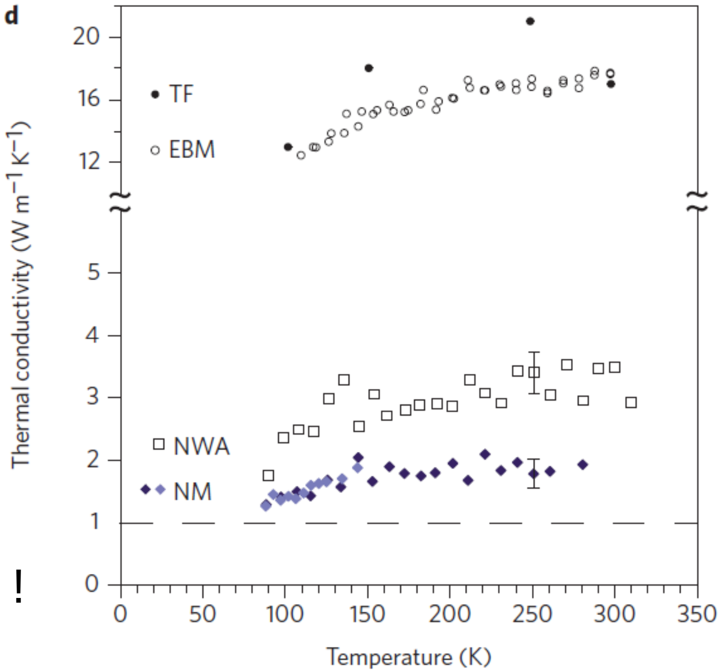
N. Zen et al., *Nature Communications* **5**, 3435 (2014)





Pitch 40 nm
Room temperature
Silicium
Metal mask – ebeam lithography
Electrothermal - 3ω

Conductivité du massif
150 W/m/K / Rapport 100 !



J.-K. Yu et al., *Nature Nanotechnology* **5**, 718 (2010)

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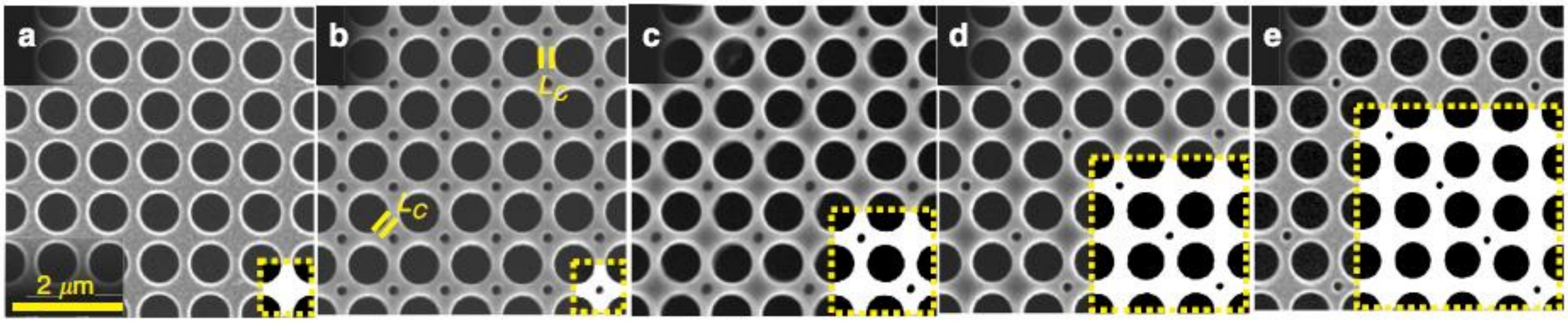
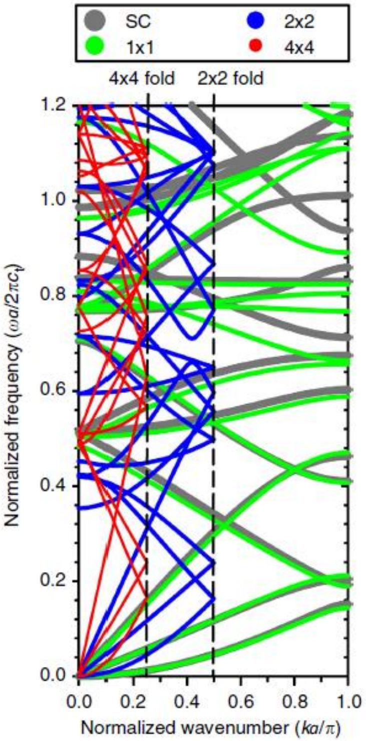


Figure 1 | SEM image of the fabricated PnC structures. All samples were fabricated to have a periodicity $a = 1{,}100$ nm, thickness $t = 366$ nm and a chosen critical dimension $L_c = 250$ nm. Highlighted in white is the unit cell of each supercell lattice: (**a**) SC, (**b**) 1 × 1, (**c**) 2 × 2, (**d**) 3 × 3 and (**e**) 4 × 4.

Silicium
Température ambiante
Pitch µm
Electro-thermique



S. Alaie et al., *Nature Communications* **6**, 7228 (2015)

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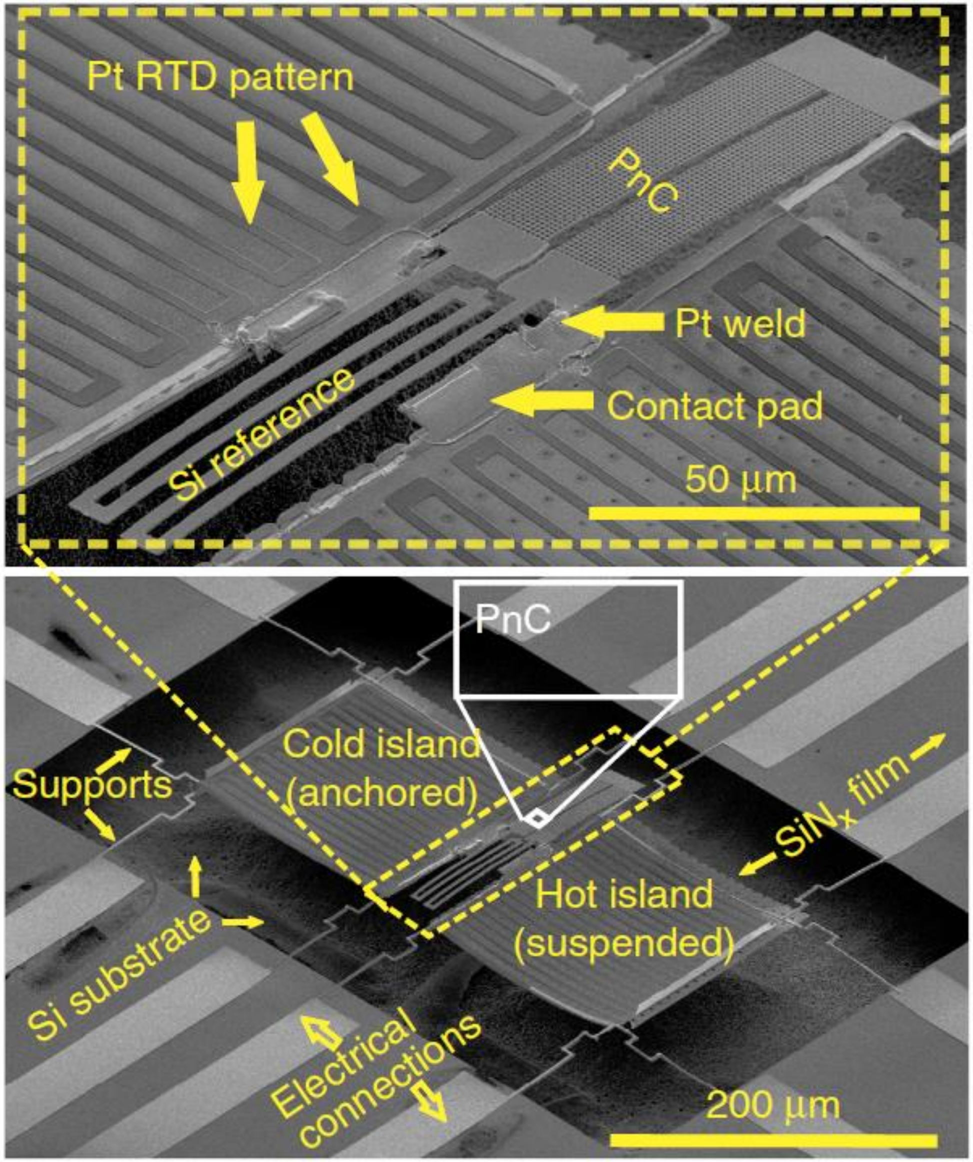
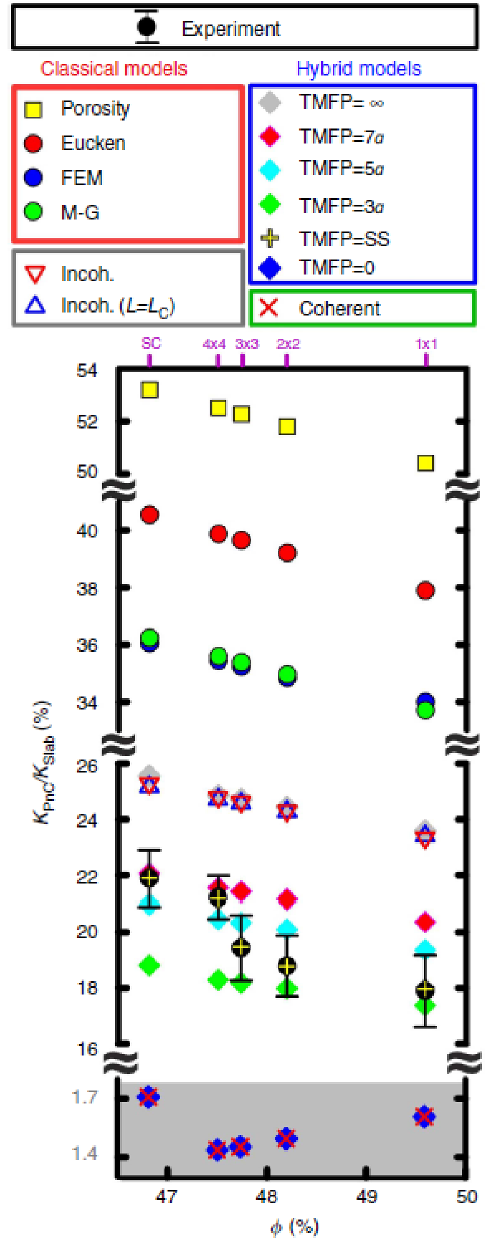


S. Alaie et al., *Nature Communications* **6**, 7228 (2015)



Cohérence à température ambiante ?

Equipes ayant (modélisé+réalisé+caractérisé)
des matériaux nano-phononiques (thermocristaux)

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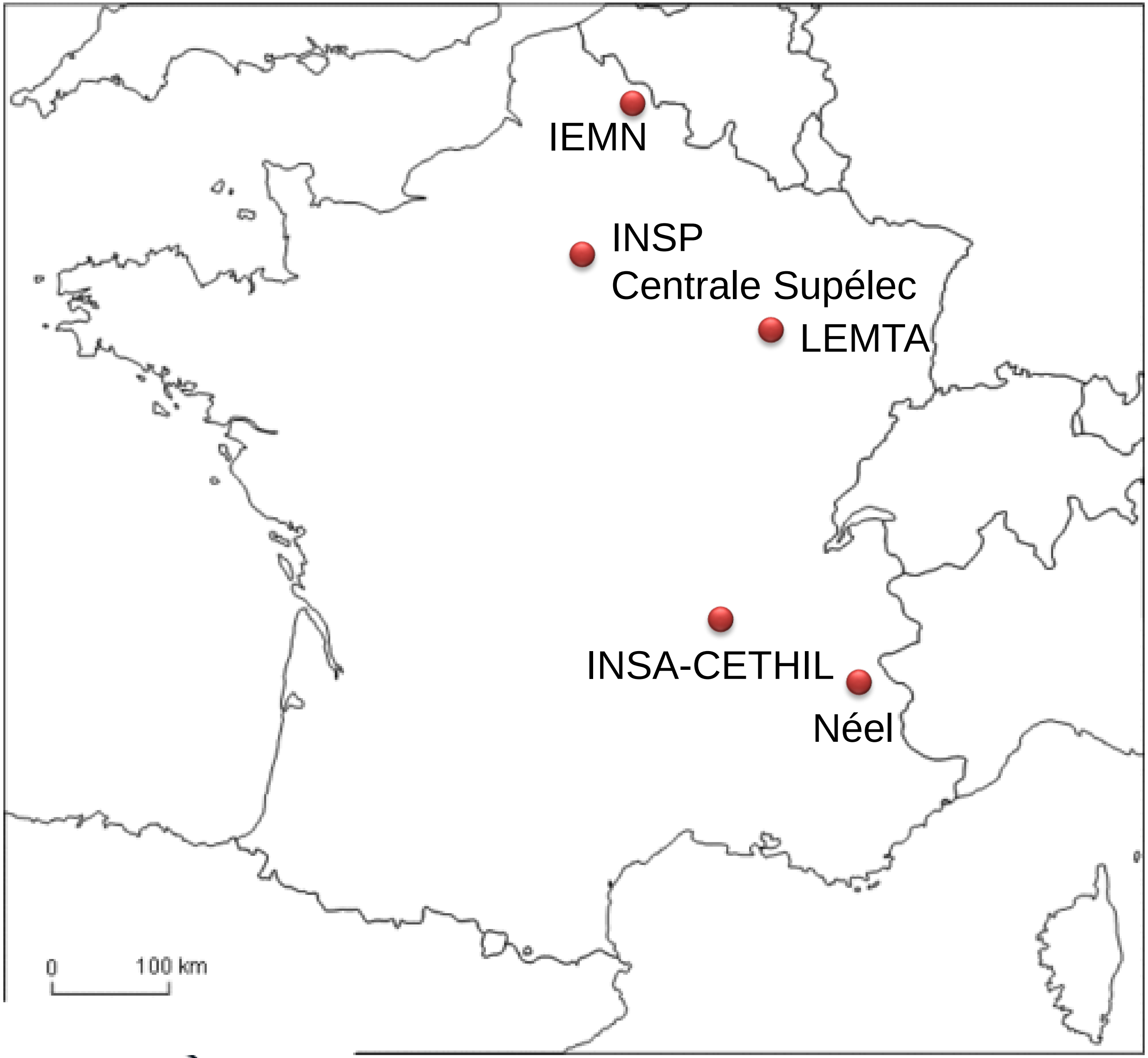

Panorama
non-exhaustif

Compétences françaises en :
- Modélisation
- Fabrication,
- Mesure thermique

Electronics
Microelectronics
Nanotechnology

~500 people

250 Profs/Researchers/Staff
250 PostDoc/PhD students

Villeneuve d’Ascq

Lille

- **1600 square meters clean room devoted to micro and nanotechnology**
- **Staff: 26 Ing/Tech**
- **Equipment: about 20 M€**

Micro and Nano Fabrication clean-room

Near field microscopy platform

HF Characterization facilities

Telecom-EMC platform

RENATECH
French national nanofabrication network

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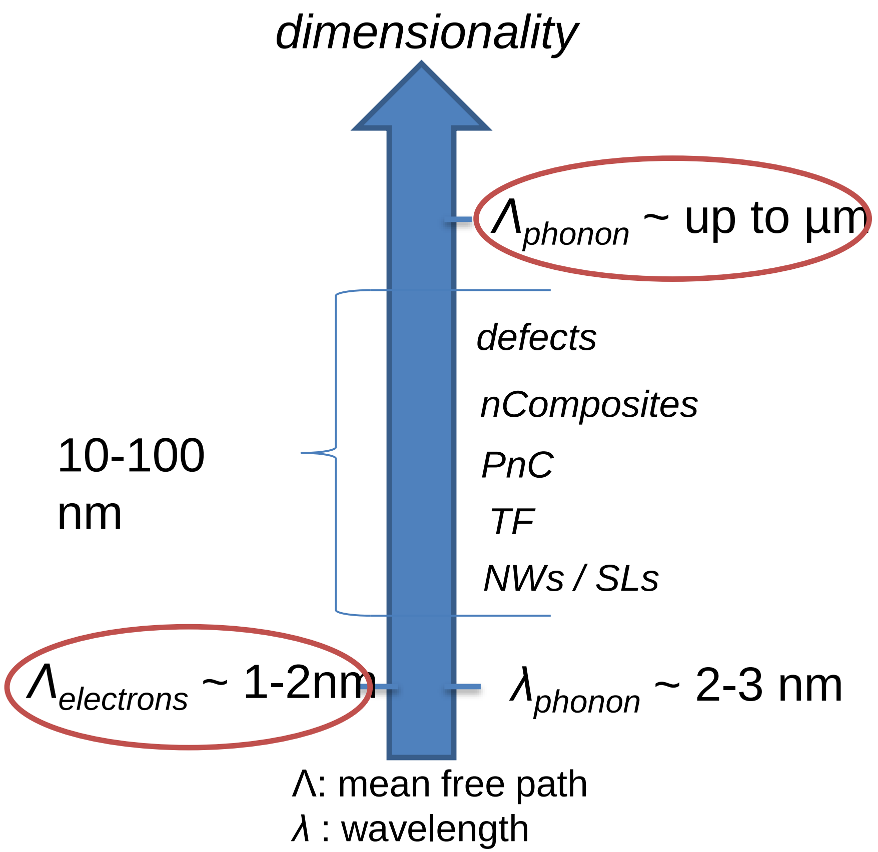
Can we make a thermoelectric material out of silicon ?

Phononic Engineering

	Si	Bi_2Te_3
S (µV.K^{-1})	~ 250	~200
κ (W.m^{-1}.K^{-1})	149	1.4
σ (Ω^{-1}cm^{-1})	$2.3*10^4$ (doping 10^{19})	10^5
κ_e(W.m^{-1}.K^{-1})	0.165 (doping 10^{19})	0.23
ZT (@300K)	~0.0001	1.1

Contribution phonons :
95% to 99% (depends on doping)

$$zT = \frac{S^2\sigma}{\kappa_{el} + \kappa_{ph}} T \longrightarrow 4$$



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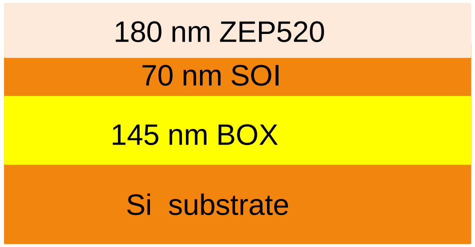
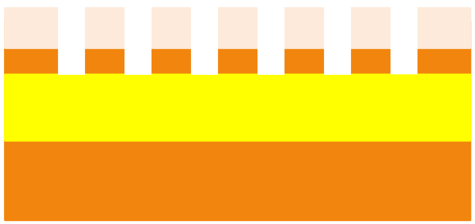
Fabrication methodology

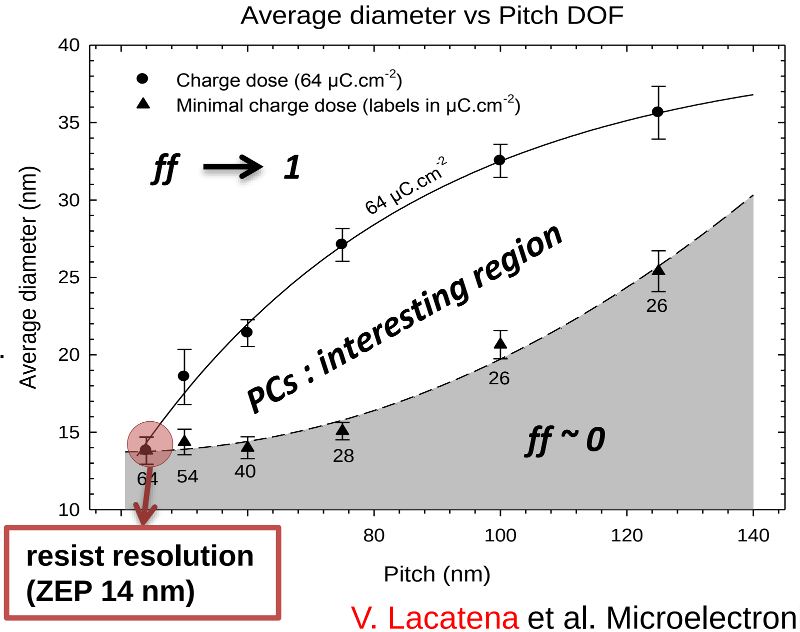


STEP n° 1:
SOI wafer, spin coating 180nm of ZEP520.

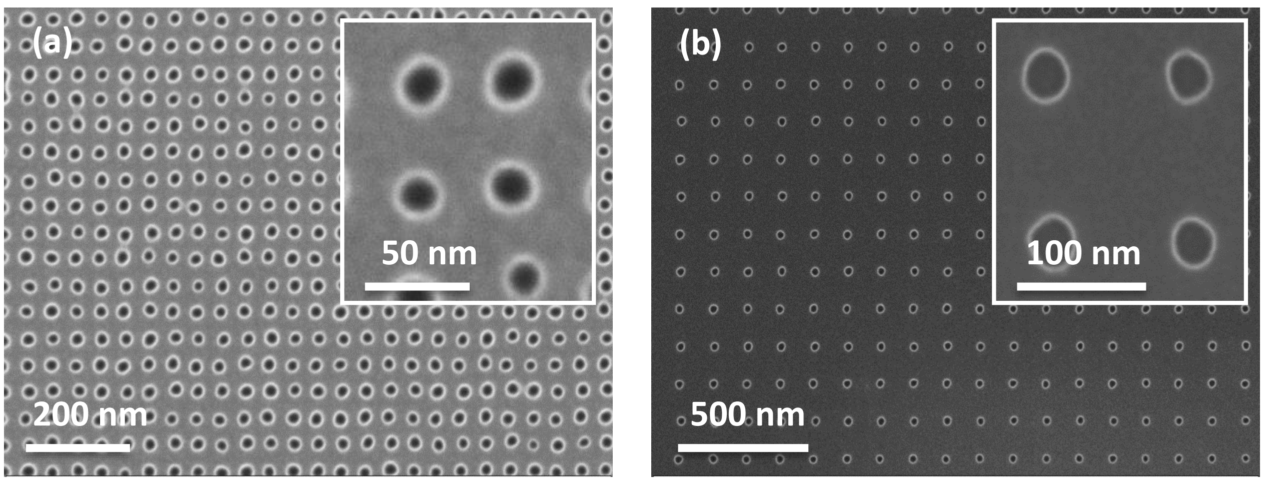


STEP n° 2:
E-beam litho exposure of PCs, ZN50 development (1') and Cl_2:30sccm, 5mTorr, 30W etching (70nm, 1'50'').

STEP n° 3:
ZEP520 cleaning by UV + Remover PG.



V. Lacatena et al. Microelectronic Eng. **121**, 131 (2014)



SEM images of PCs obtained with the "dots on the fly" strategy: a) pitch 44 nm, diameter 13.8 ± 0.9 nm and b) pitch 125 nm, diameter 25.4 ± 1.3 nm.

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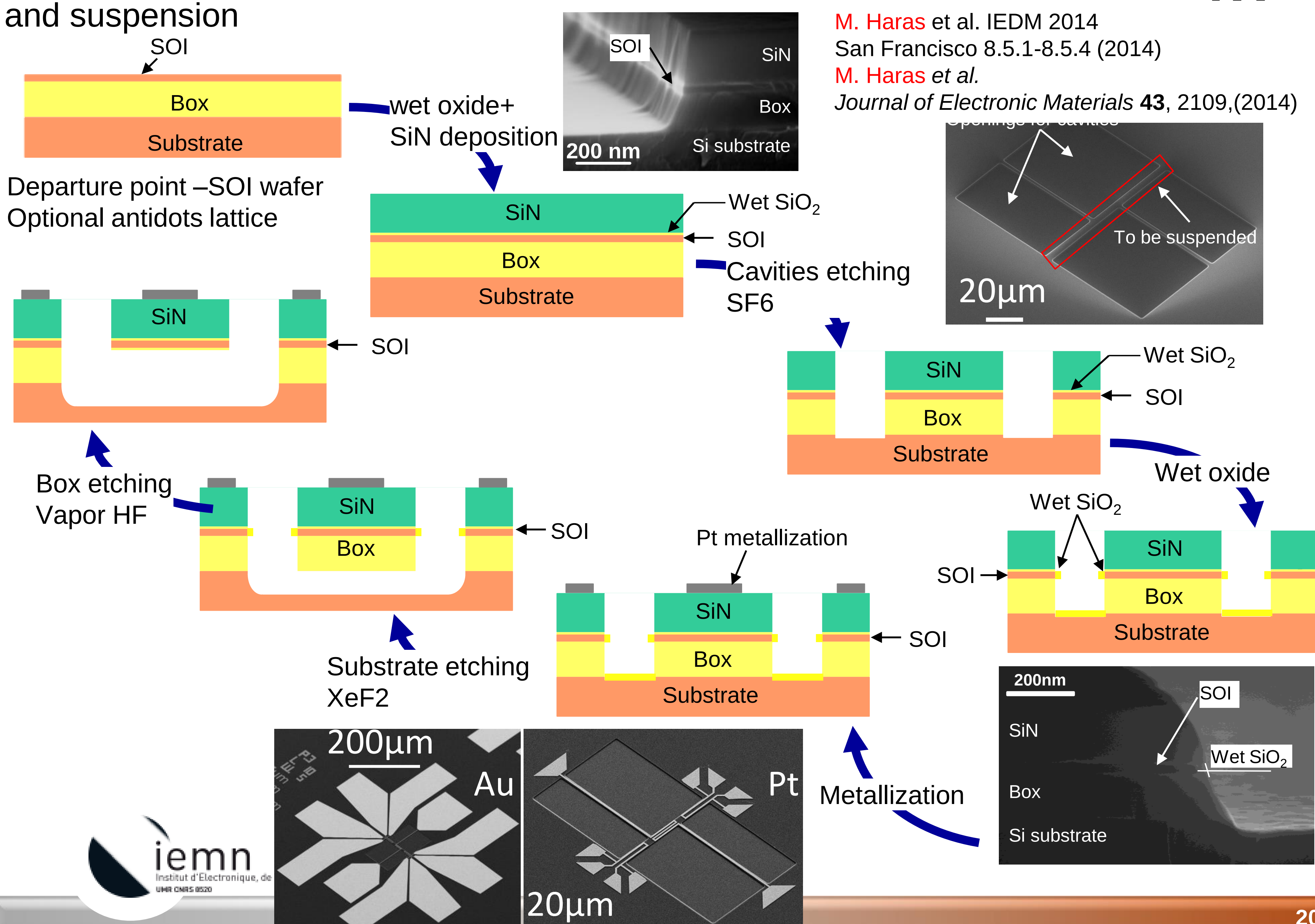
Fabrication methodology

Membranes fabrication and suspension

M. Haras et al. IEDM 2014
San Francisco 8.5.1-8.5.4 (2014)
M. Haras *et al.*
Journal of Electronic Materials **43**, 2109,(2014)



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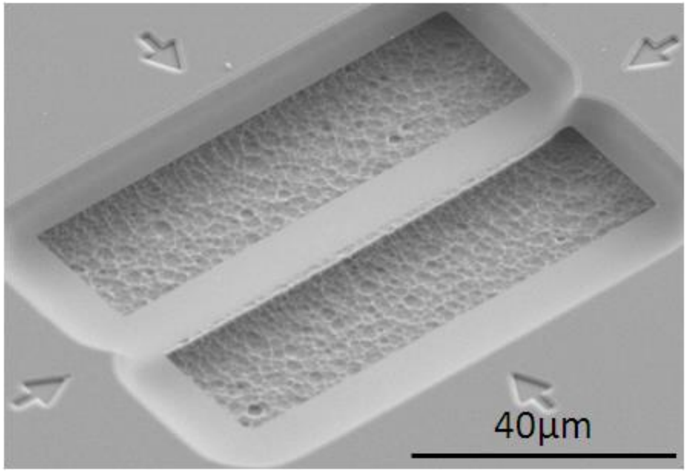
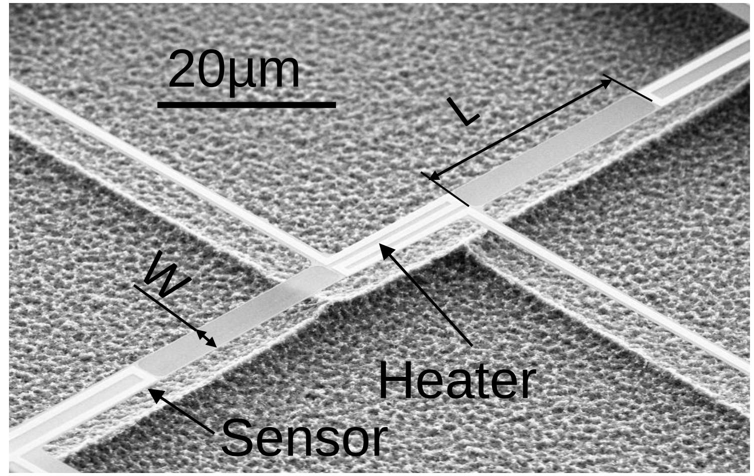
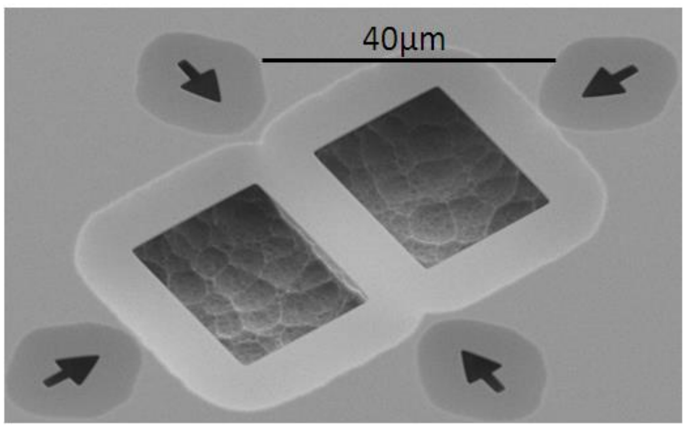
Fabrication methodology



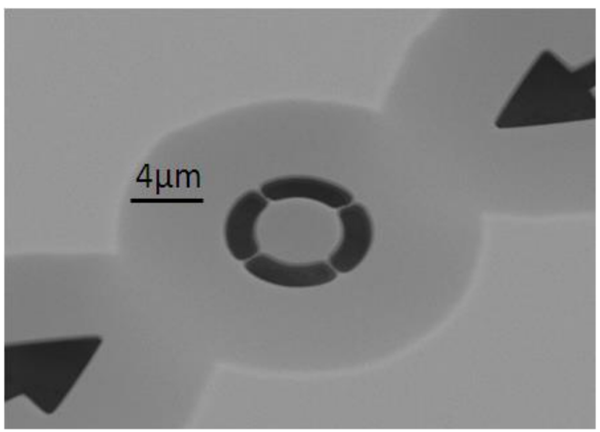
Plain Si membranes (54 nm)



Si membranes in characterization device



Plain SiN membranes (200 nm)



(almost) Arbitrary shapes

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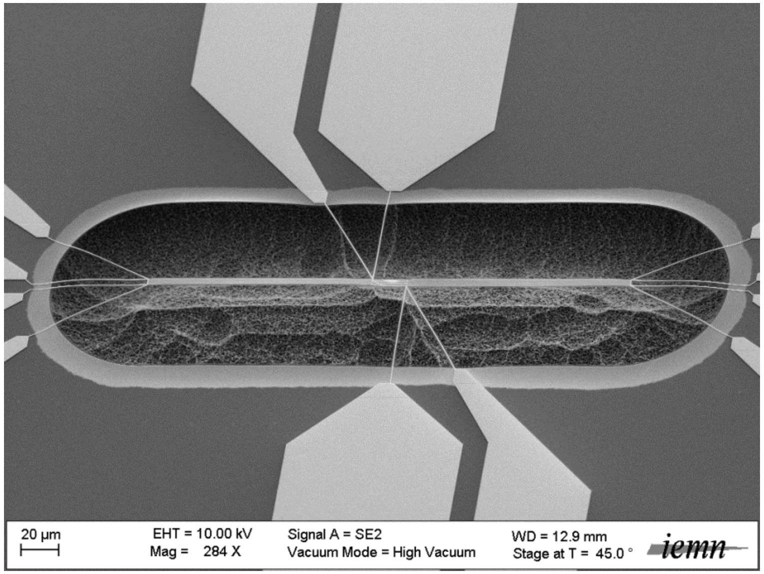
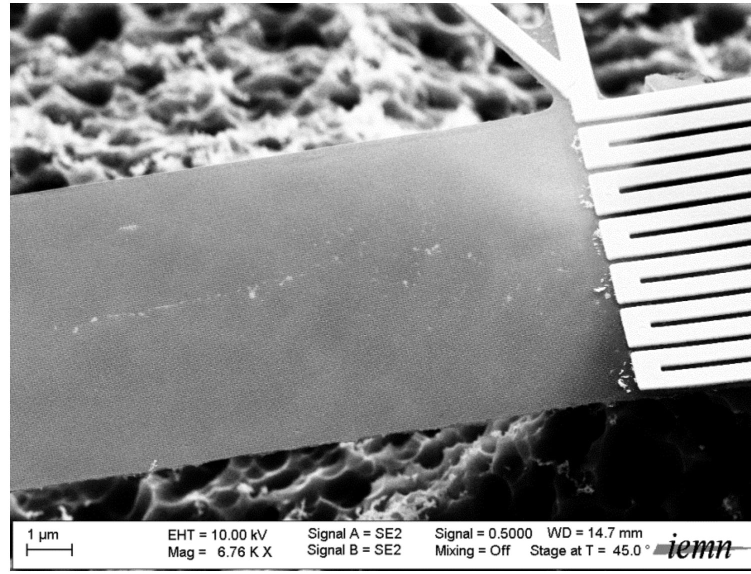
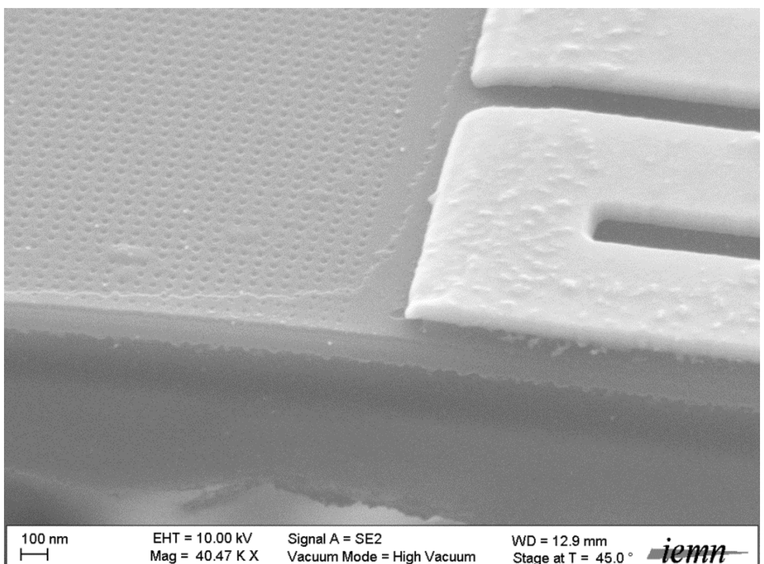
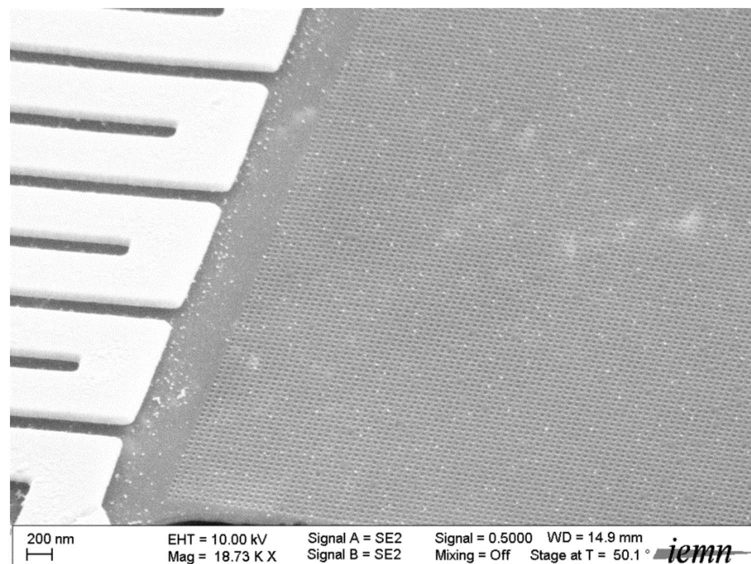
Thermal Characterization

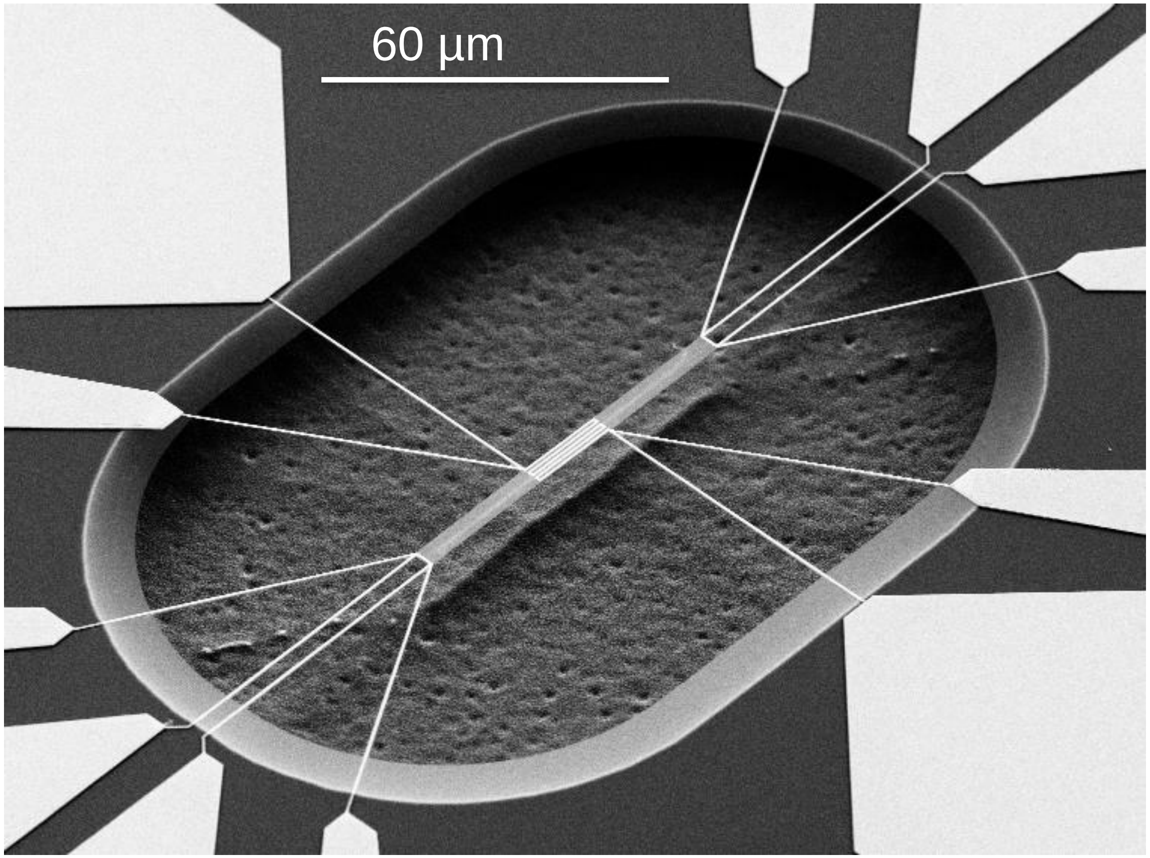








Thermal Characterization



1 central resistive element (Pt)
2 symmetric sensors (Pt)

L_m = 30,60,90,120 µm
w_m=5, 10 µm
t_{Si} = 60 nm

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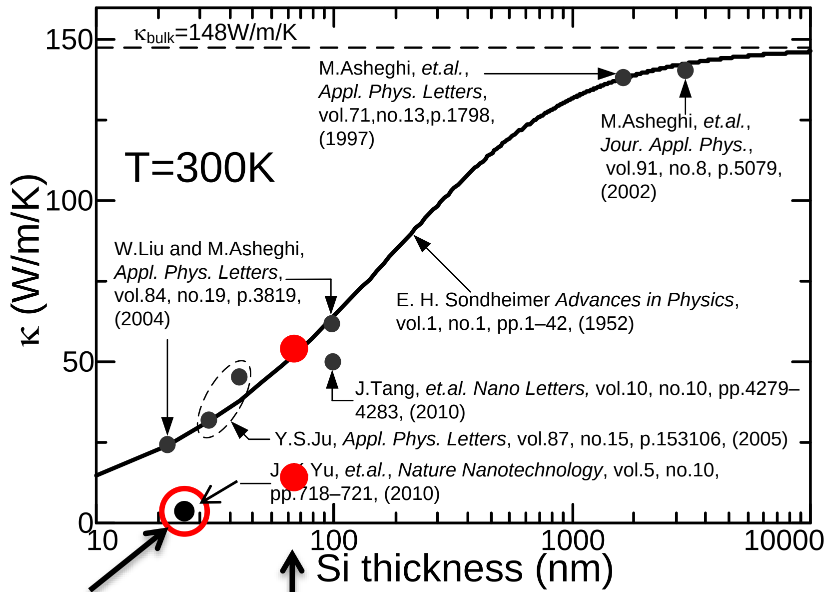
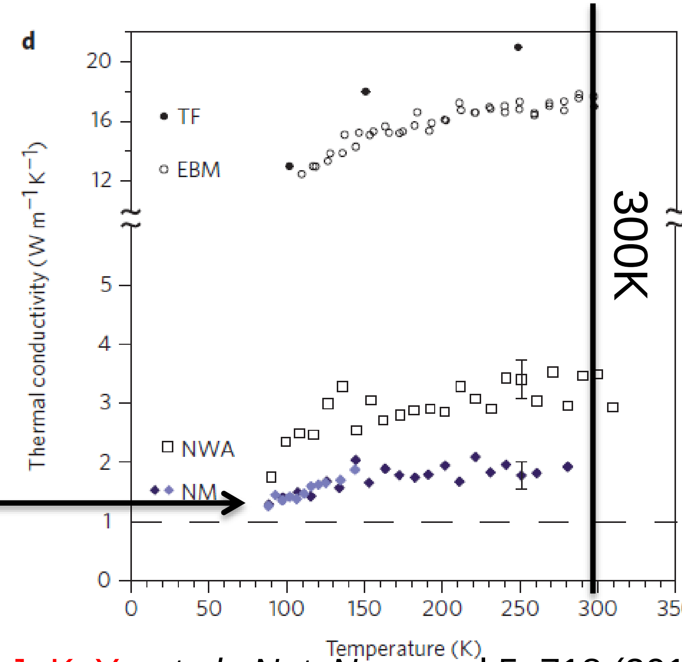
State of the art…

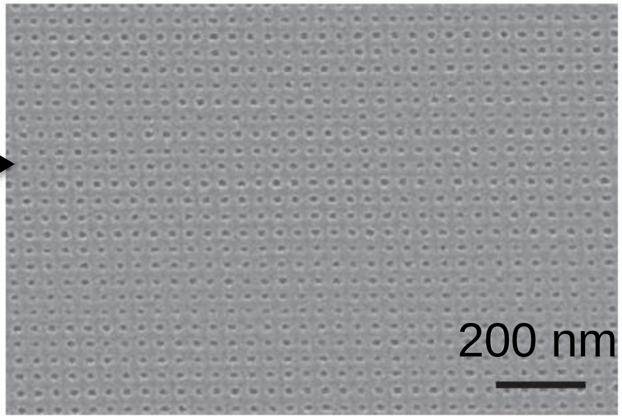
Phononic Engineering



J.-K. Yu *et.al*.



J.-K. Yu *et.al*. *Nat. Nano.* vol.5, 718 (2010)



IEMN previous results

structure	thickness	κ *measured*
Film	70 nm	55 W/m/K
nanopatterned membranes	70 nm / pitch 60 nm	12.5 W/m/K

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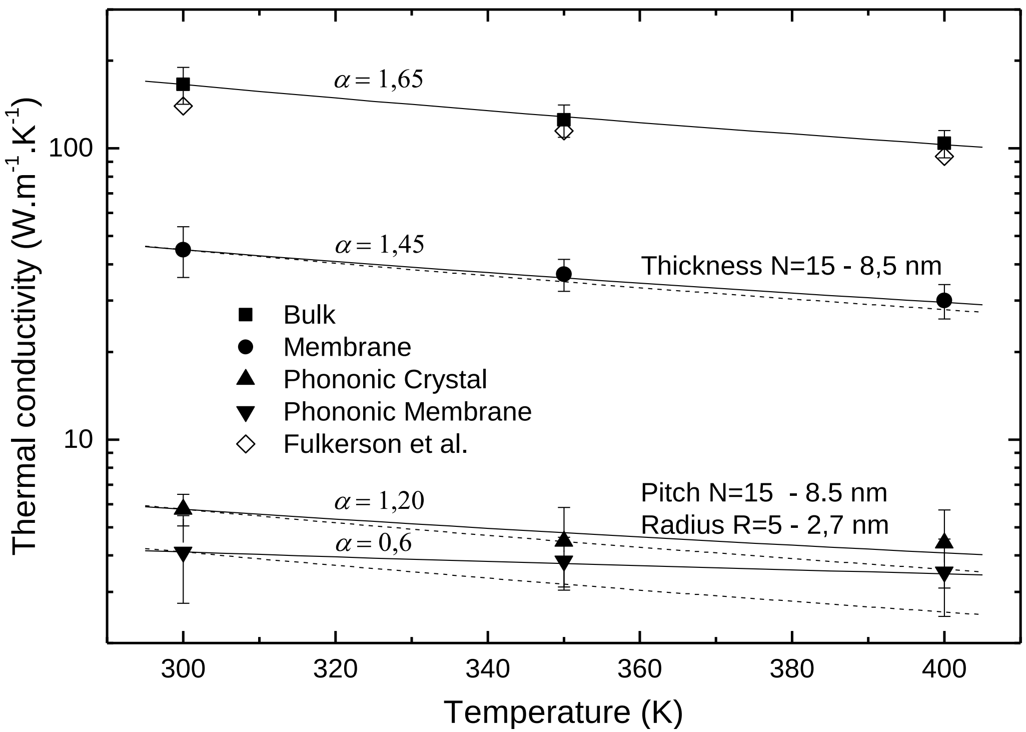
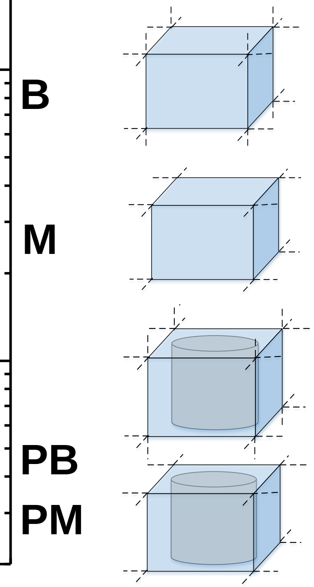
Material modeling -Molecular Dynamics



Lacatena V. *et al.*, *Applied Physics Letters* 106 (11), 2015.



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Active research…

Sensors: bolometers

Optomechanics: phonon-photon coupling in high Q resonators

Energy: enhanced/artificial thermoelectric materials “phonon glass/electron crystal”

Thermal: Insulation

Nanoelectronics: Thermal management, heat routing

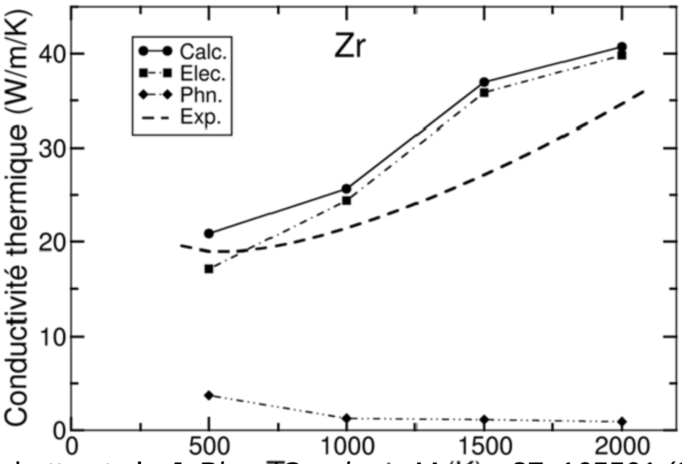
(Very) ***Advanced…***

Thermal computing: implementing non asymetric heat transfer (thermal diodes)

(see Baowen Li group)

Thermal management: “Hot conductors/Cold insulator” materials

(Useful in Automotive and Power production)



J.-P. Crocombette et al., *J. Phys. Condens. Matter* **27**, 165501 (2015)

State-of-the-art

Phononic Crystals + Nanoscale = Thermocrystals (?)
Pitch really MUST be ~ phonon coherence length to achieve band folding effects
Technology not ready at room T° (maybe epitaxy ?)
Effects demostrated at very low T°
Nevertheless, strong thermal conductivity reduction at room temperature achieved

Challenges

Modeling

Methods from the Phononic community no more valid (PWE, FEM)
Methods from the Solid State community require tremendous computing power (MD, LD, Monte Carlo)

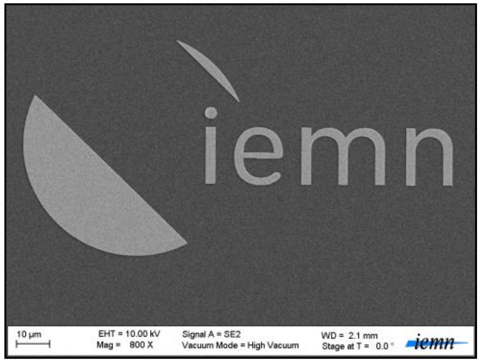
Fabrication

Need low pitch/high res. (eBeam, nanoimprint, block copolymer, epitaxy)
True 3D crystals ? (epitaxy, synthetic opals)

Characterization

Challenges of nanoscale heat transfer (insulation, error bars, interpretation)
TDTR, Raman thermometry, Electrothermal (DC, 3ω, hot wire), SThM
Need for calibrated and reliable methods to avoid controversies

Acknowledgements



life.augmented

Stéphane Monfray
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Thank you !

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