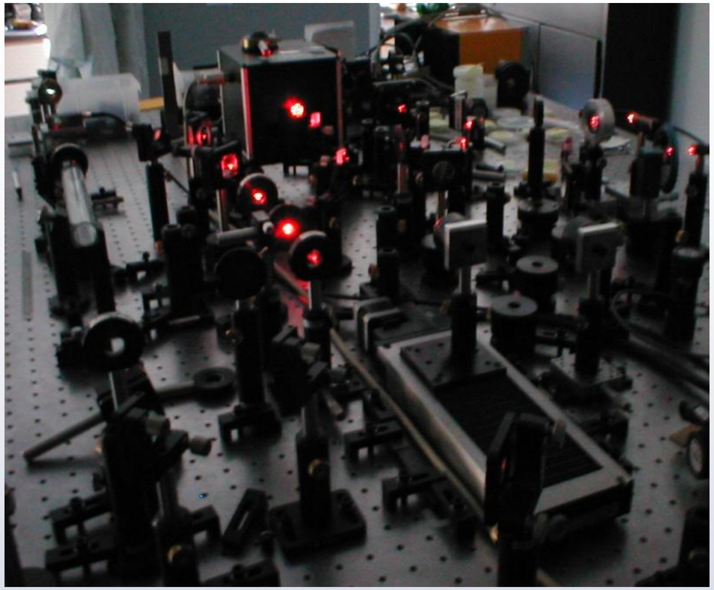
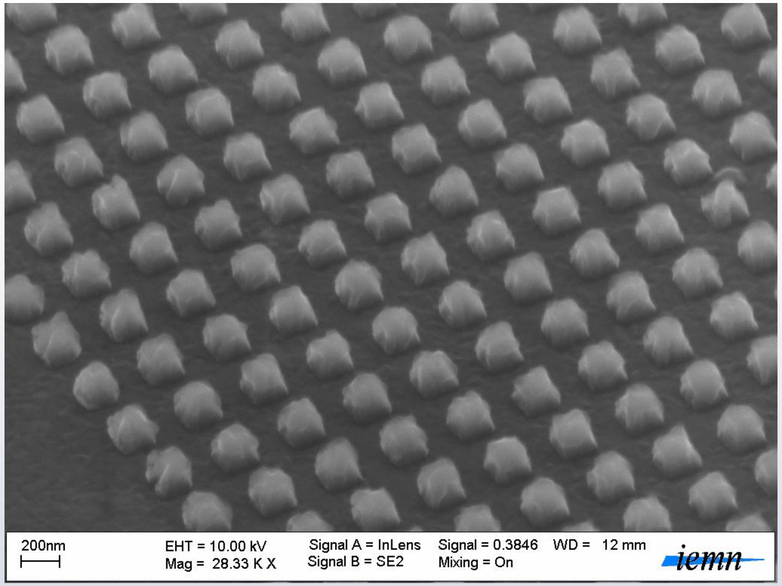
"Exciting and detecting waves in micro and nanoscale systems by Picosecond Ultrasonics"





Jean-François ROBILLARD
jrobilla@email.arizona.edu
University of Arizona - ERC TeleSeminar

August 12th 2010

Who am I ?

Master's Physics

PhD Picosecond Ultrasonics

Today's talk

Postdoc Magneto-elasticity

Research Associate Materials Science & Engineering (Pr. Deymier) NanoPhononic crystals

jrobilla@email.arizona.edu

What am I interested in ?

- **Sound waves** (Guiding, Use for metrology, Ultra-high frequencies)
- **Phononic Crystals** (Design, Functionalities, Tunability)
- **Nanoscale materials** (Thermal and acoustic properties)
- Couplings (Magneto-acoustics)

Picosecond Ultrasonics

Picosecond Ultrasonics

- Optical pump-probe experiment
- Uses femtosecond laser pulses
- To generate/detect acoustic waves

Scales the sonar principle to the µm/nm range

i.e. GHz/THz frequency range

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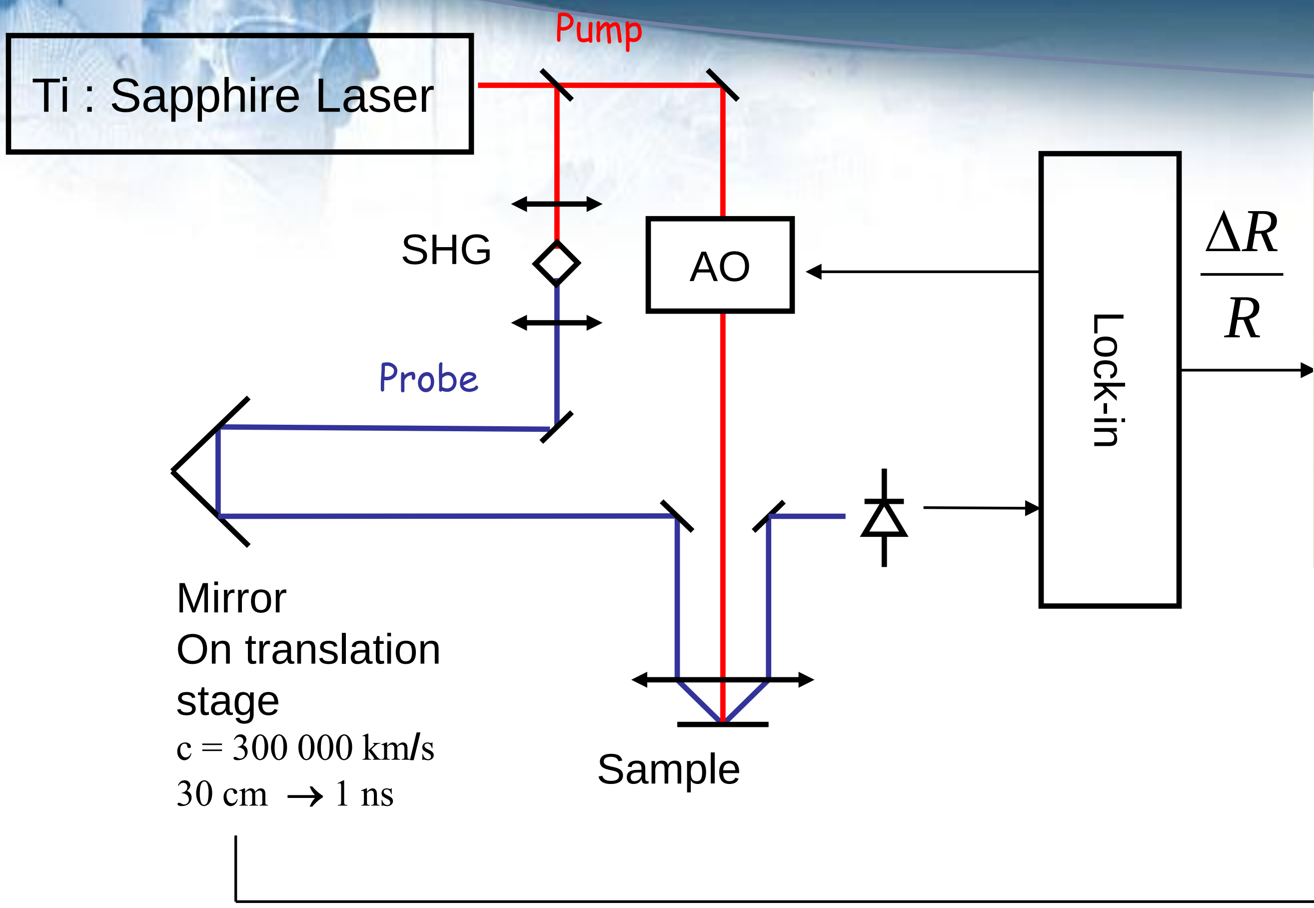
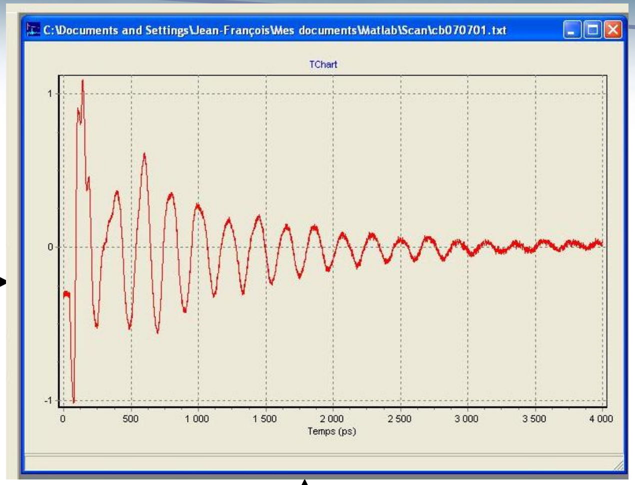
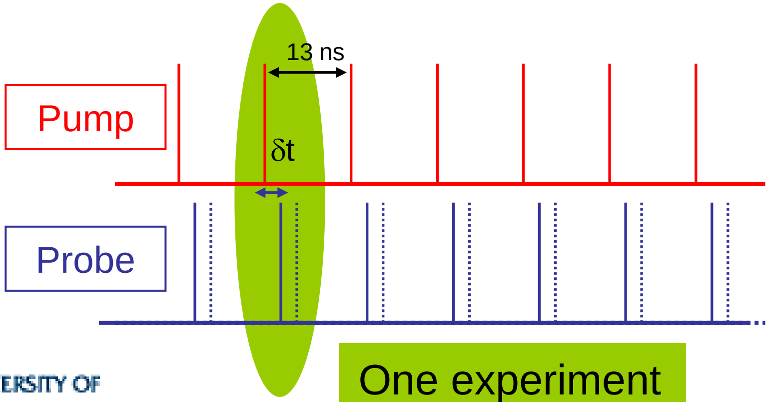
Setup – Main parameters




C:\Documents and Settings\Jean-François\Mes documents\Matlab\Scan\cb070701.txt



One experiment
every 13 ns !

Laser wavelength λ

Second Harmonic Generation

RED Pump

BLUE Probe

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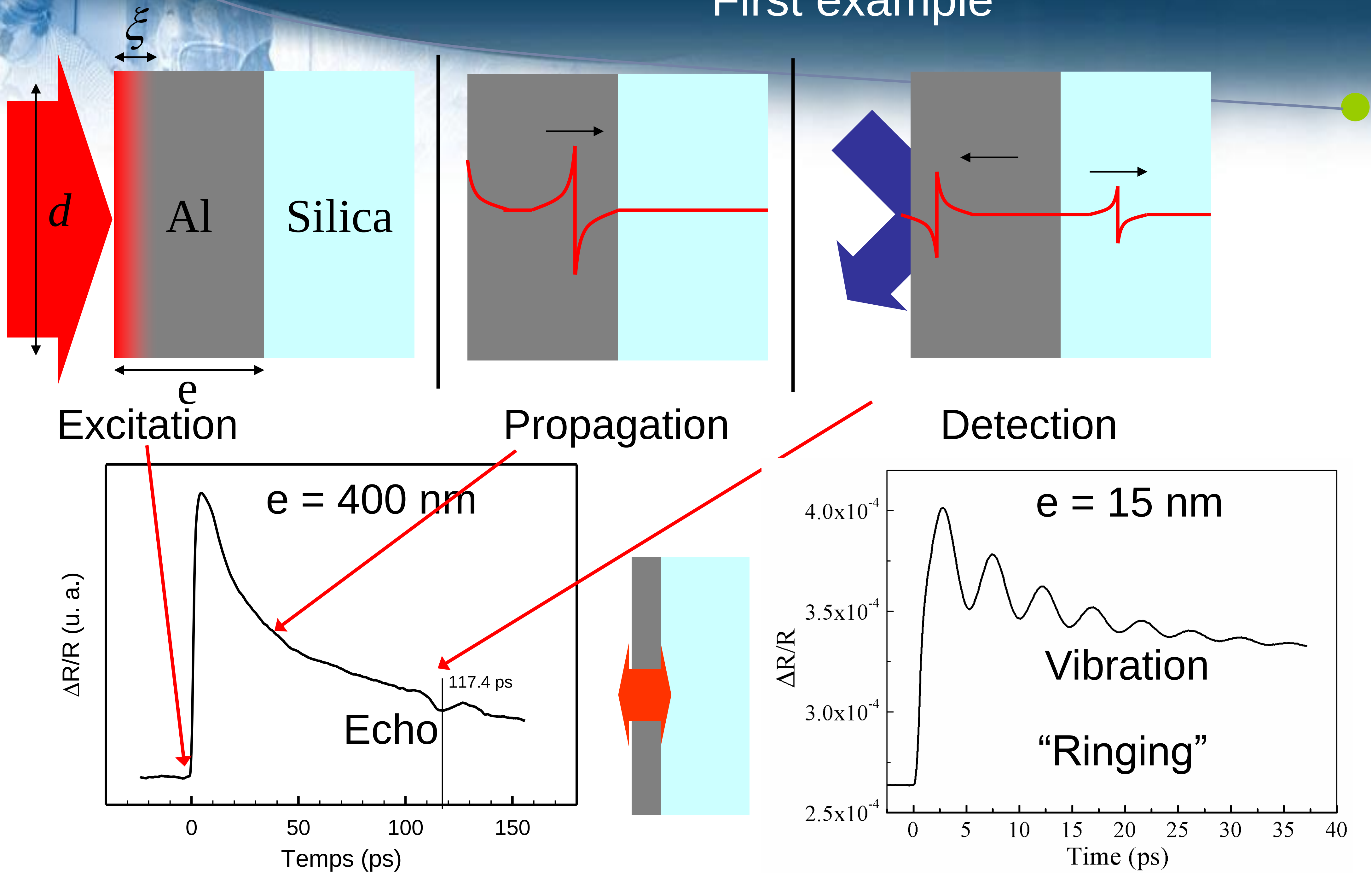
First example

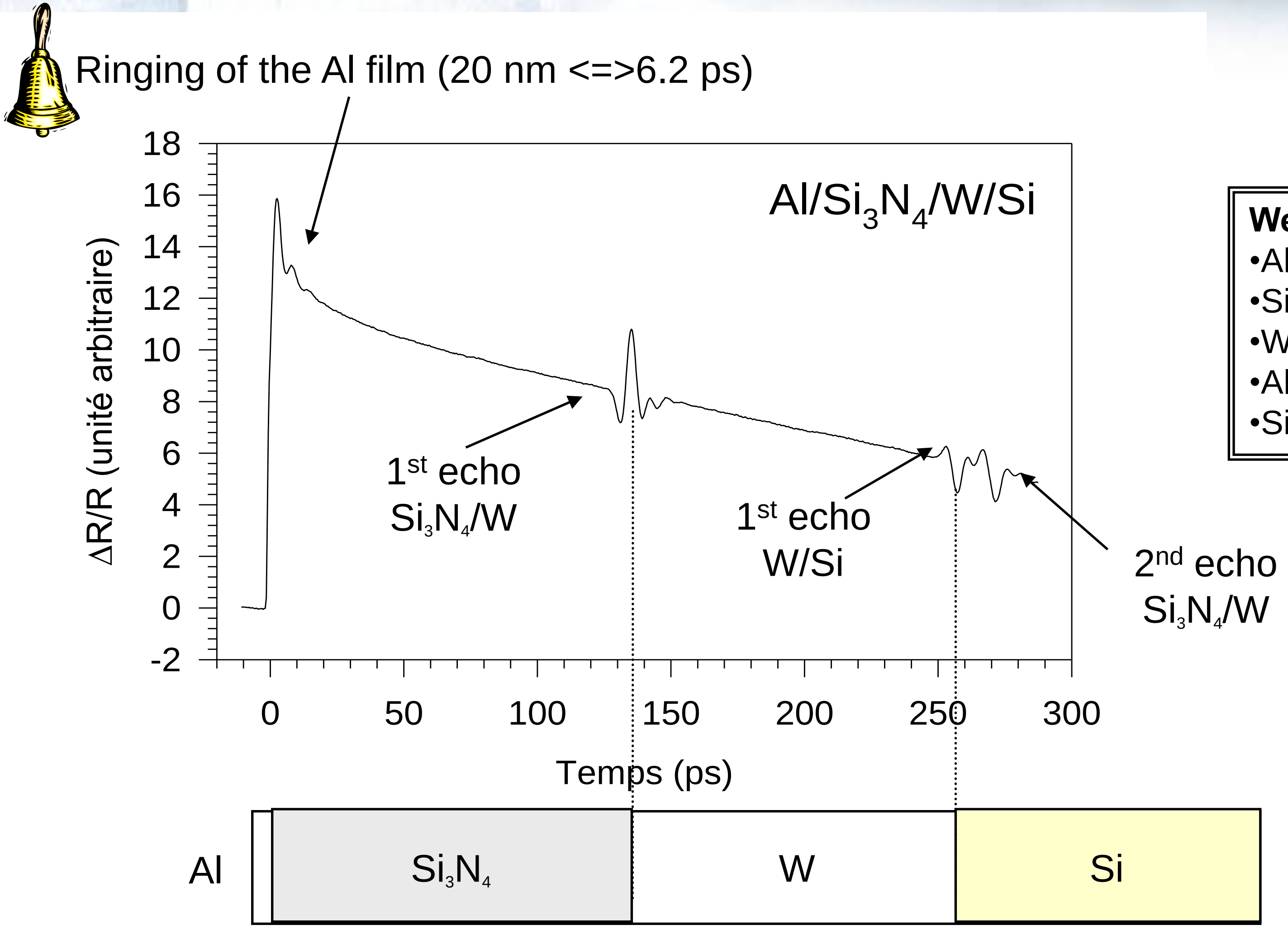


Excitation

Propagation

Detection

Another example



20 nm

500 nm /7.4 x 2 ≈ 135 ps

x 4 ≈ 270 ps

300 nm /5.2 x 2 ≈ 115 ps

115 ps + 135 ps = 250 ps

We can measure…

- Al thickness
- Si_3N_4 thickness
- W thickness
- Al/SI_3N_4 Adherence
- Si_3N_4/W Adherence

Orders of magnitude

- Acoustic pulse width = 2 * light absorbtion depth

2*10= 20 nm in metals

- Duration of pulse = pulse width/velocity

20 nm/(5 nm/ps) = 4 ps

- Frequency content of acoustic pulse = 1/duration

1 / 4ps = 250 GHz

- Max thickness of sample = ½ velocity * time between two light pulses

½ * 5(nm/ps) * 13000 ps ≈ 30µm

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A wealth of detection mechanisms…

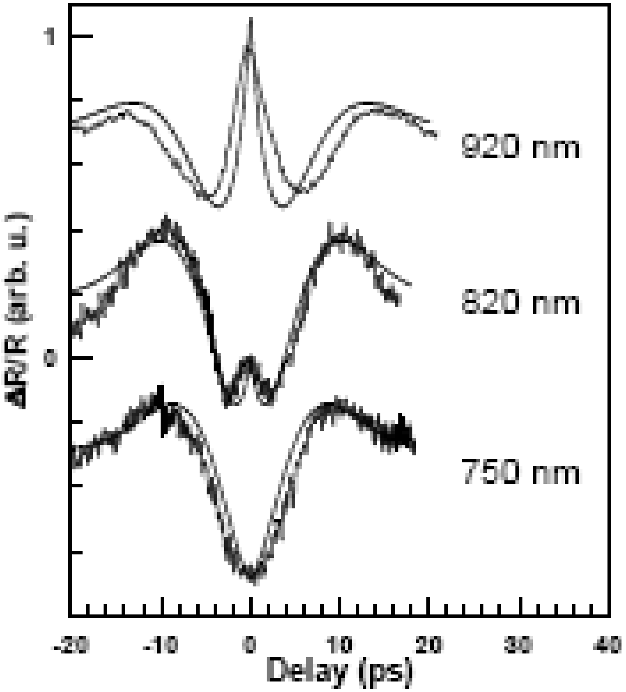
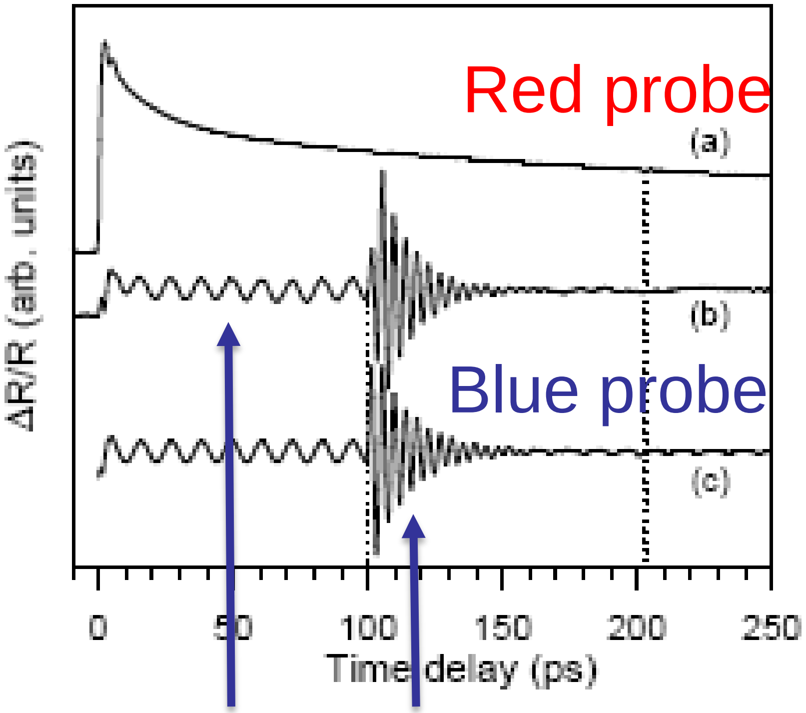
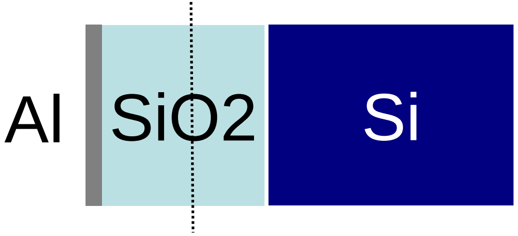


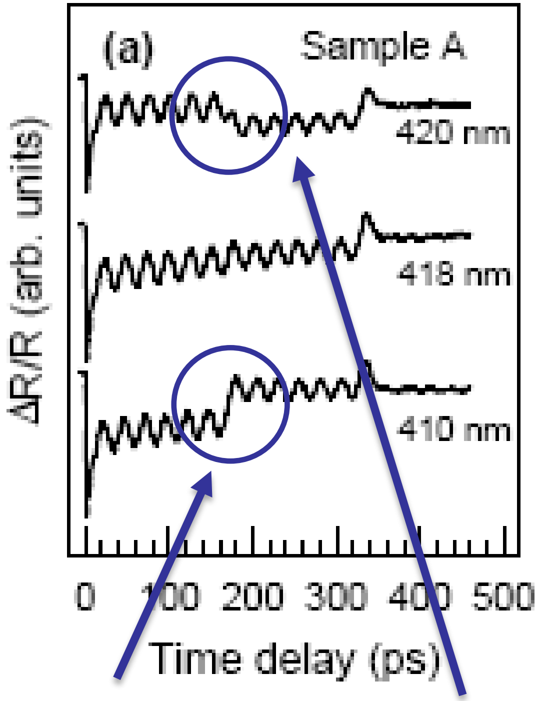
Photo-elastic Modulation of the Dielectric constant

$$\frac{\partial n}{\partial \eta}(\lambda)$$



Brillouin Oscillations





Displacement Interferometic contribution

Attenuation in SiO2 @ 250 GHz

Thickness @ ± 2 nm

A. Devos et al. App. Phys. Lett., **86**, 211903, (2005)
A. Devos et C. Lerouge. Phys. Rev. Lett., **86**, 2669, (2001)
A. Devos, J.-F. Robillard et al. Phys. Rev. B, **74**, 064114, (2006)

Summary - Abilities and Uses of Picosecond Ultrasonics

- Measures time…
  - Echos
  - Brillouin oscillations period
- To get
  - Thickness (30 Å – 10 µm)
  - Acoustic properties (Sound velocity, Elastic modulus, Attenuation)
- Solid state physics
  - Semi-conductors physics, Attenuation in glasses
  - Nanotechnologies, Superlattices, quantum dots, colloïds
- Thin films metrology
  - Sound velocity, thickness, adherence, multilayers stacks…
  - Wide variety of materials, sound waves propagate in every solid !
  - (Metals, SC, Dielectrics, Piezo)
  - Industry use PU in-line (Metapulse Rudolph techs)

RUDOLPH
Technologies, Inc.

W
Al
Cu
Cr
Mo
Ni
Pt
Ta
Ti
Au
TiNi
Si
Ge
SiGe
GaAs
GaP
GaN
AlGaN
SiO2
Si3N4
SiOC
AlN
PZT
SrTiO3
…

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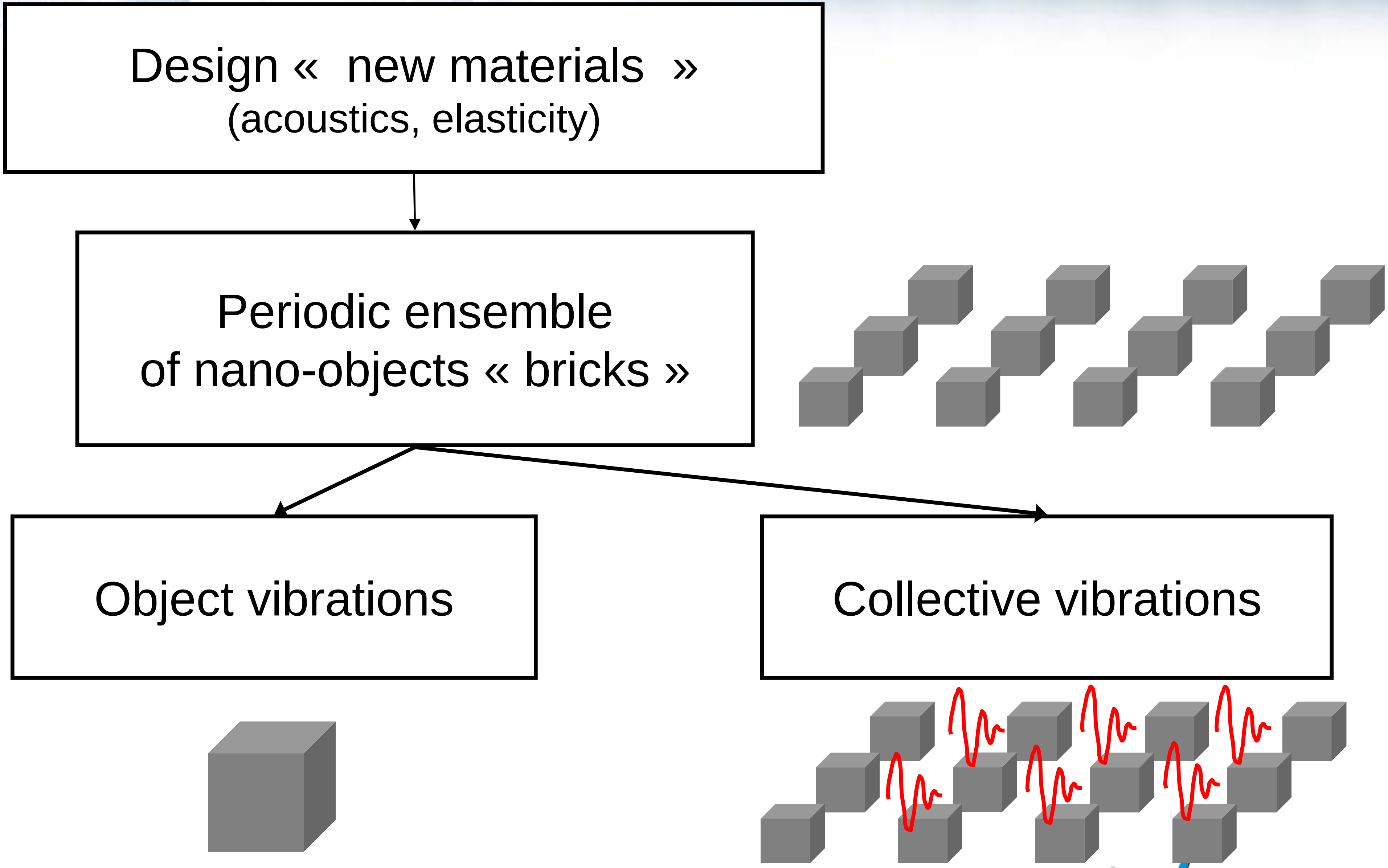
Exciting and detecting waves in lattices of nanoscale objects with Picosecond Ultrasonics

Objective…



Design « new materials »
(acoustics, elasticity)

Periodic ensemble
of nano-objects « bricks »

Object vibrations

Collective vibrations

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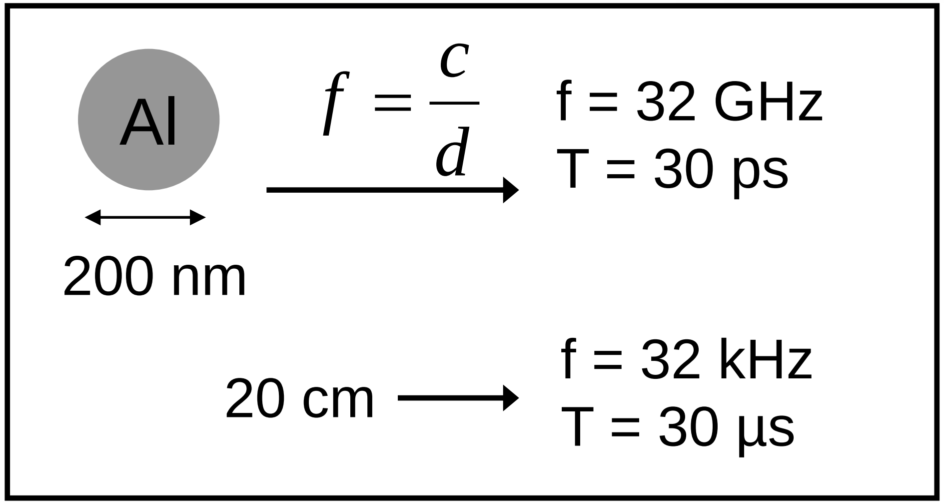
Why ?

- Nano-objects vibrations
  - GHz – THz
  - Few studies
- Hypersonic crystals
  - Acoustic devices
  - Frequency ↔ lattice constant



Al

200 nm

$$f = \frac{c}{d}$$

f = 32 GHz
T = 30 ps

20 cm

f = 32 kHz
T = 30 µs

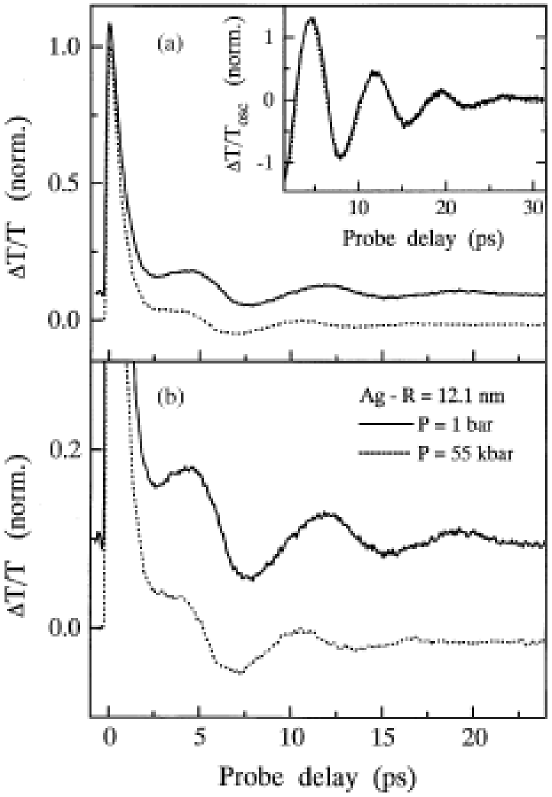
µm → GHz

- Multi-«onic» Crystals
  - Phonons
  - Photons

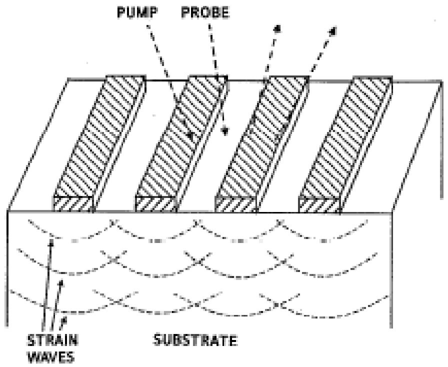
  - Plasmons

PU and nano-objects

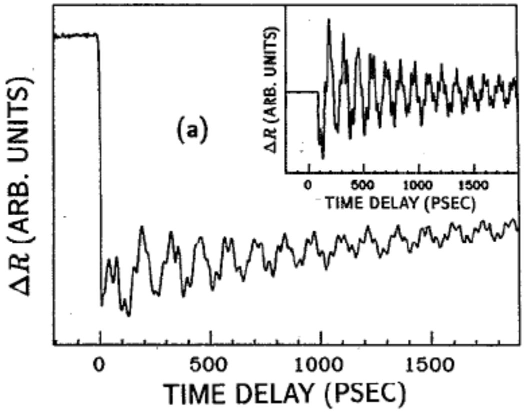
- PU is suitable for the study of eigenmodes

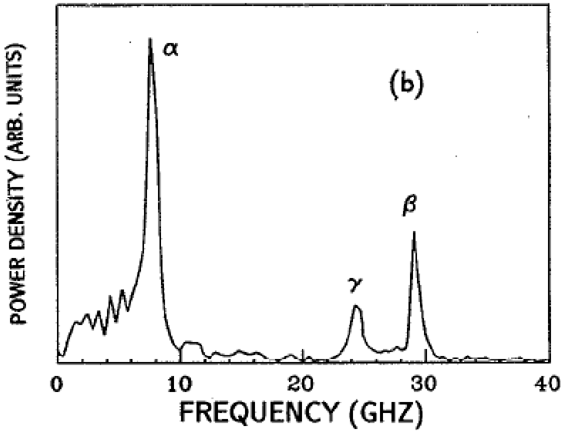


C. Voisin, D. Christofilos,
N. DelFatti and F. Vallée
Physica B **316–317**, 89–94 (2002)



H.-N. Lin, H. J. Maris et al.
J. Appl. Phys. **73**, 37-45 (1993)





What about periodic, phononic structures ?

How ? E-beam lithography

- Electrons print photo-resist
- Electrons wavelength $\lambda_e << 1$ nm
- High resolution ~ a few nm

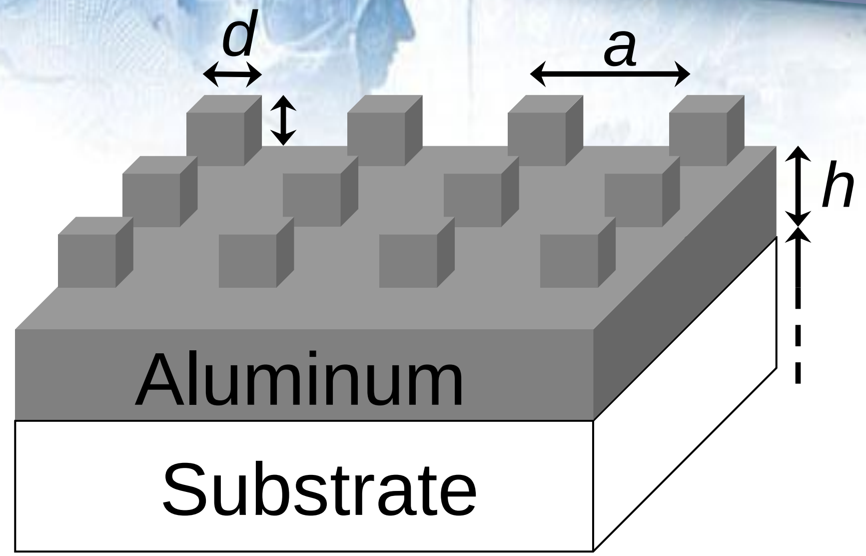
LEICA EBPG5000 plus

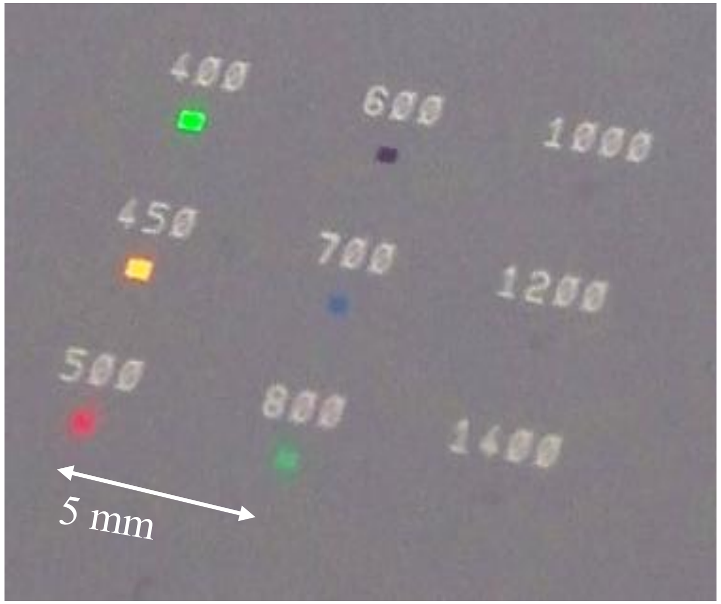
Voltage 20 – 100kV

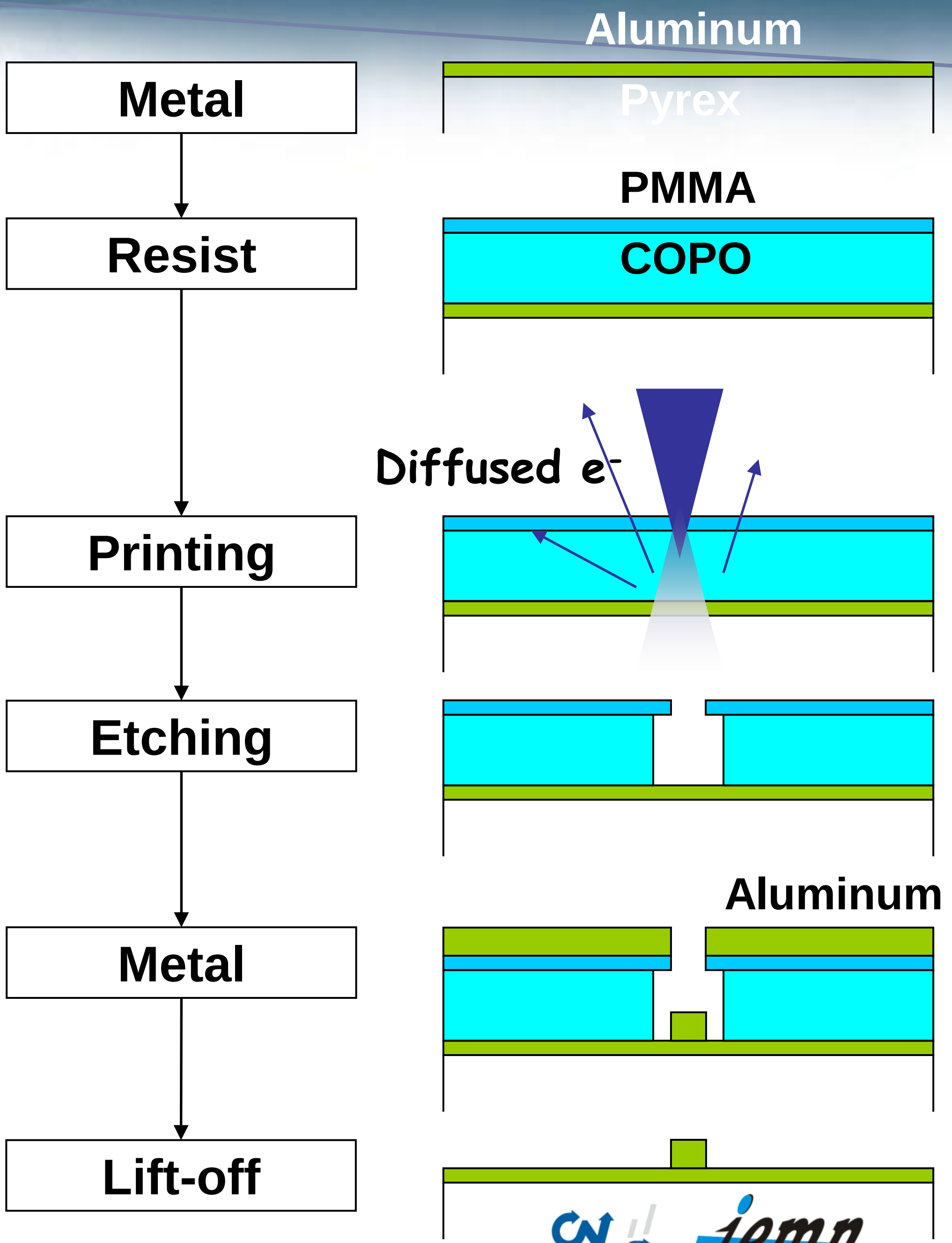
Beam Current 100pA – 200nA

Spot diameter < 10nm

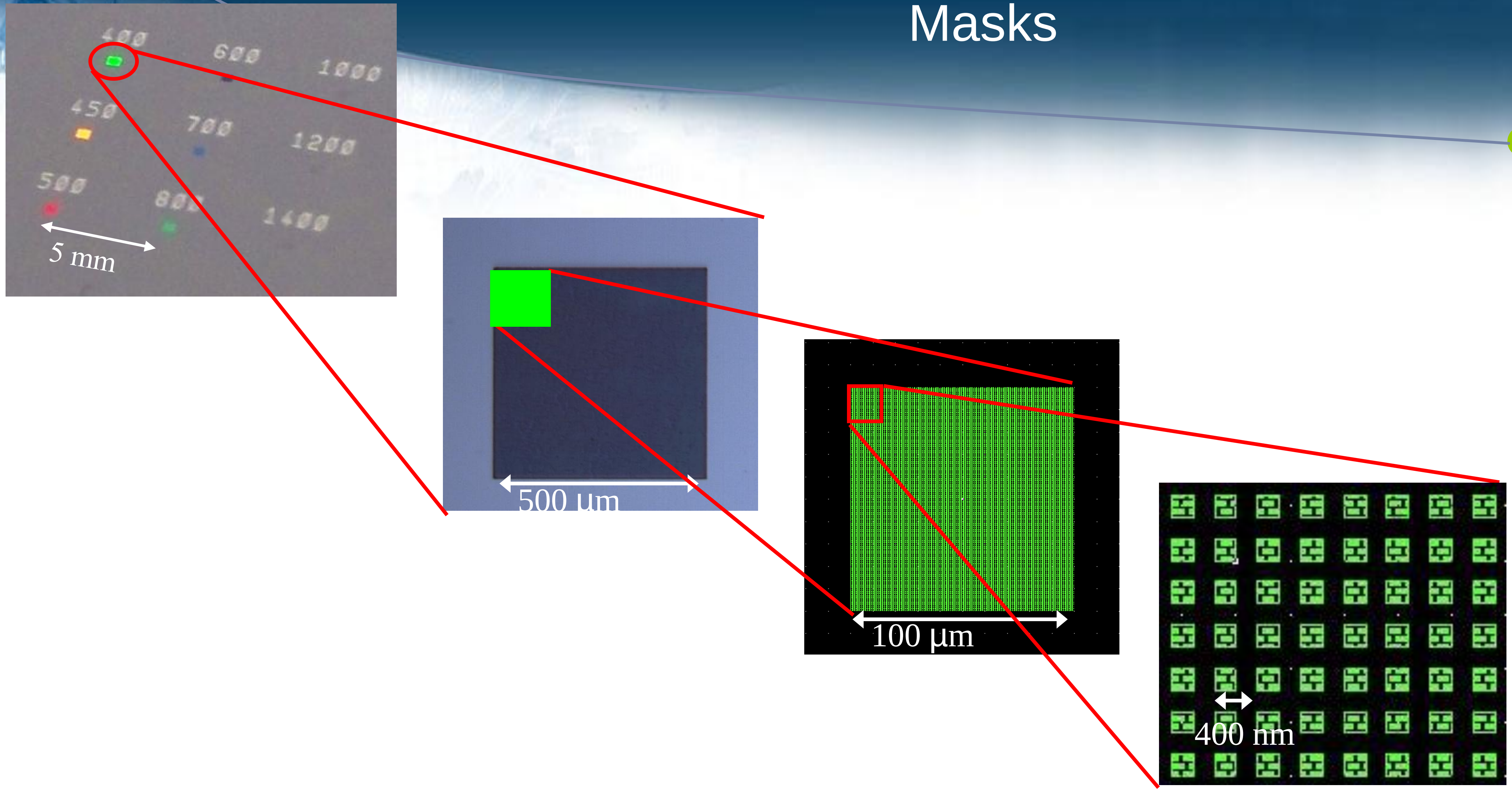
Process


d
a
h
Aluminum
Substrate

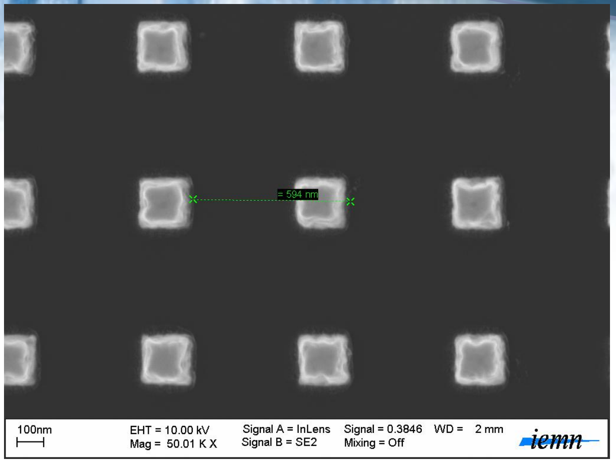

400
600
1000
450
700
1200
500
800
1400
5 mm


Metal
Resist
Printing
Etching
Metal
Lift-off
Aluminum
Pyrex
PMMA
COPO
Diffused e-
Aluminum

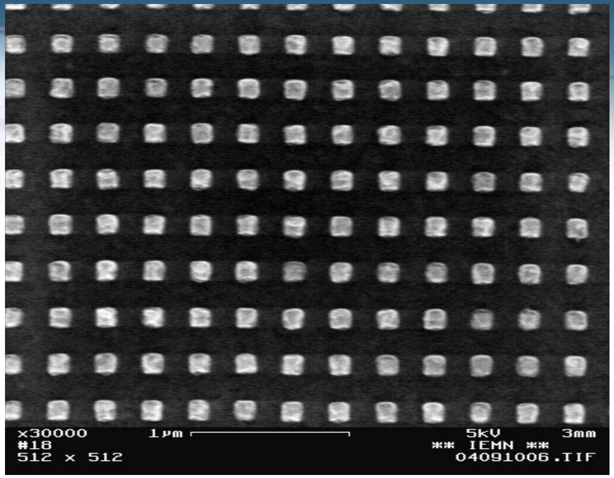
Masks



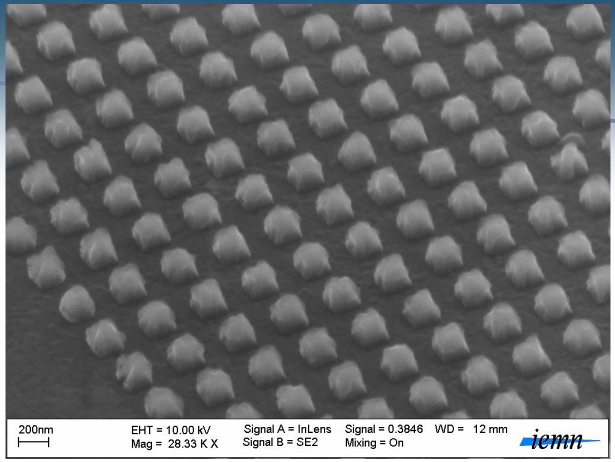
Samples



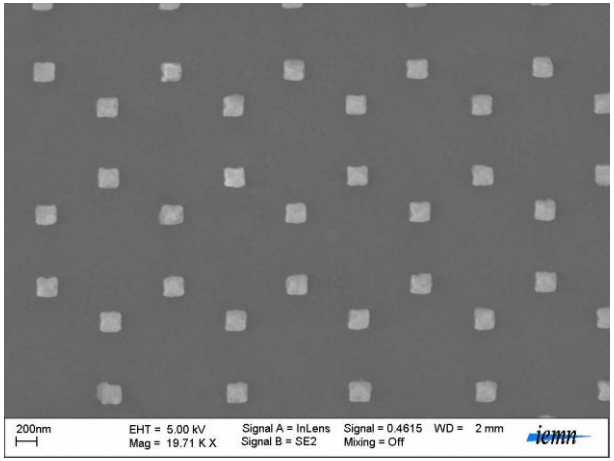
Au / Ti
a = 600 nm *d* = 200 nm
Substrate Si



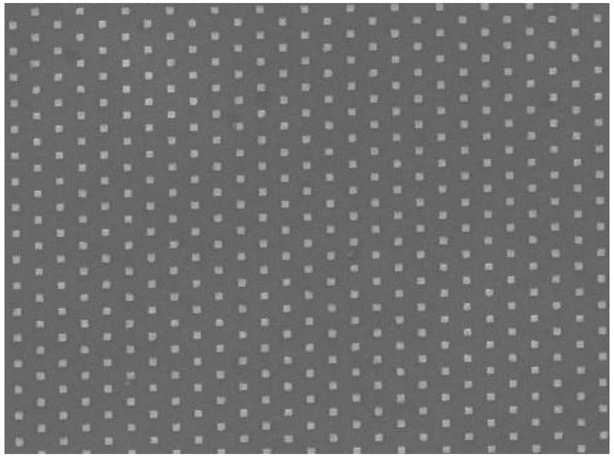
Al *a* = 300 nm *d* = 100 nm
Sur Al h = 100 nm
Substrate fused silica



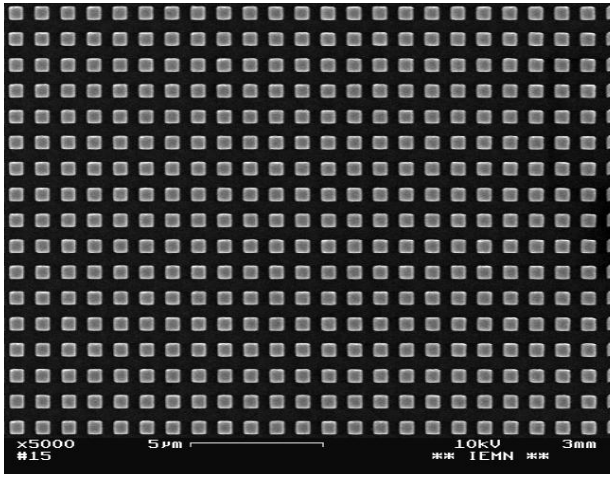
Al *a* = 400 nm *d* = 200 nm
Substrat eSi



Al *a* = 700 nm *d* = 200 nm
Sur Al h = 100 nm
Substrat pyrex



Al *a* = 700 nm *d* = 200 nm
Sur Al h = 100 nm
Substrat pyrex

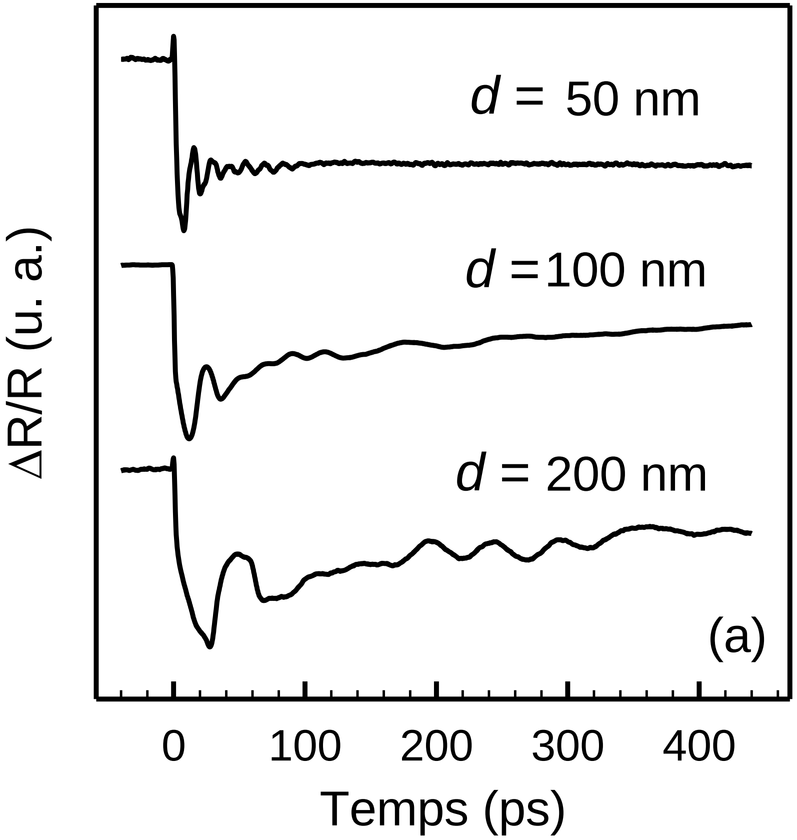


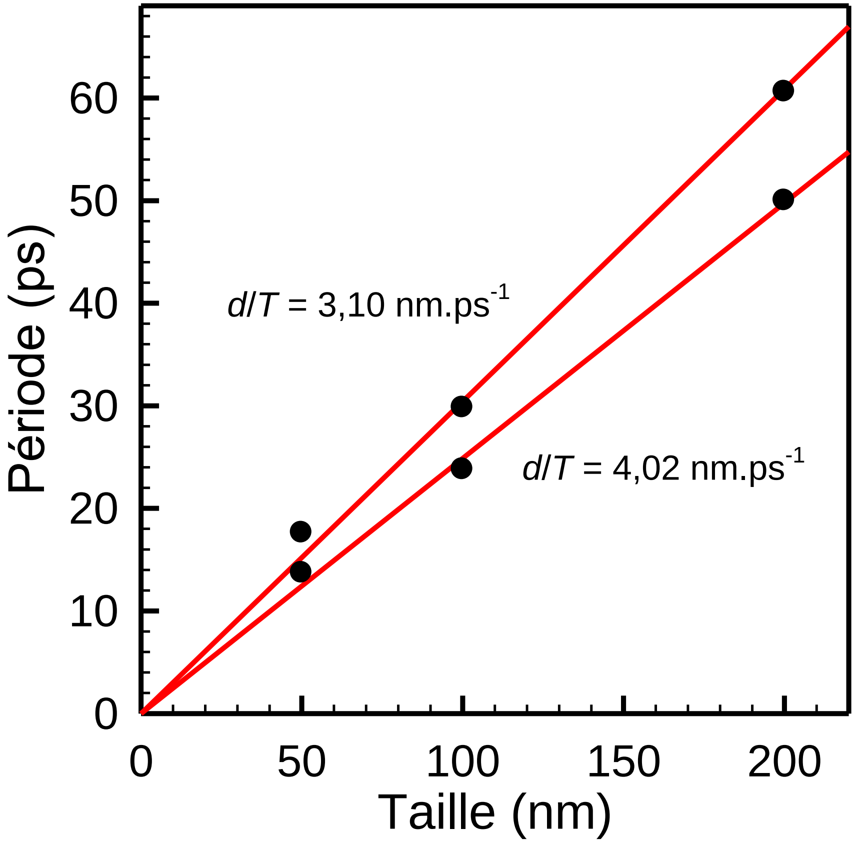
Pt *a* = 1000 nm *d* = 500 nm
Sur Al h = 100 nm
Substrat pyrex

Individual Modes

Individual modes – Experimental evidence

! The probe collects signals from a large number of cubes…



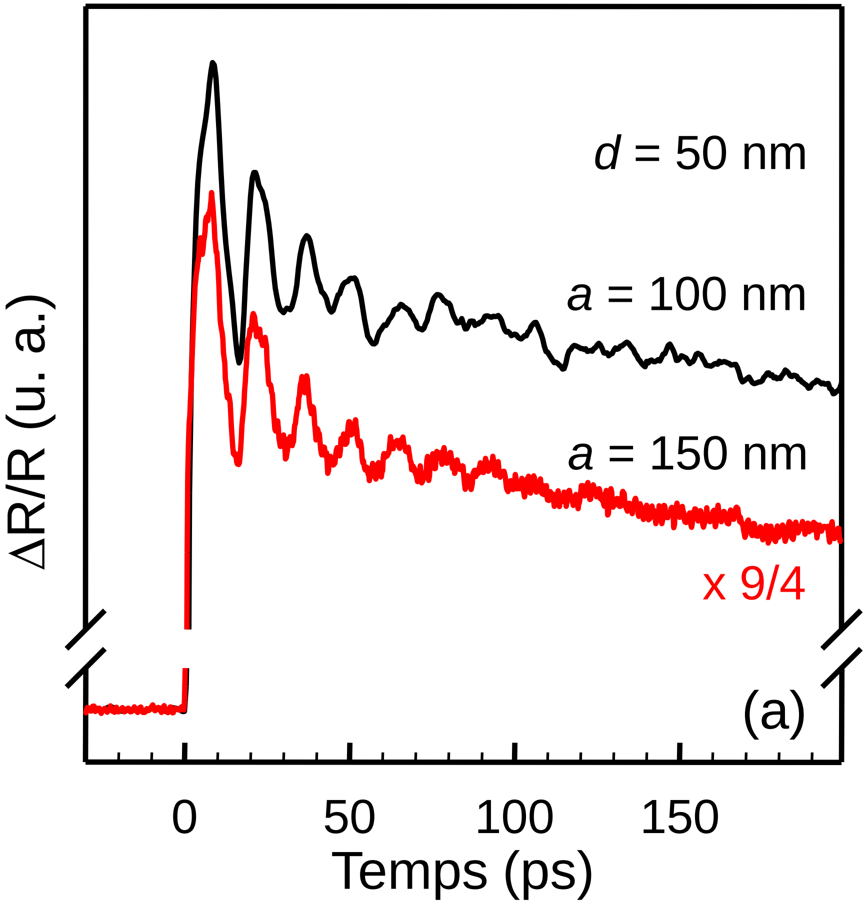


Size d ∝ lattice constant → elastics
Magnitude → sound velocity

J.-F. ROBILLARD, A. DEVOS and I. ROCH-JEUNE
Physical Review B **76**, 092301 (2007)

Elastic Contribution

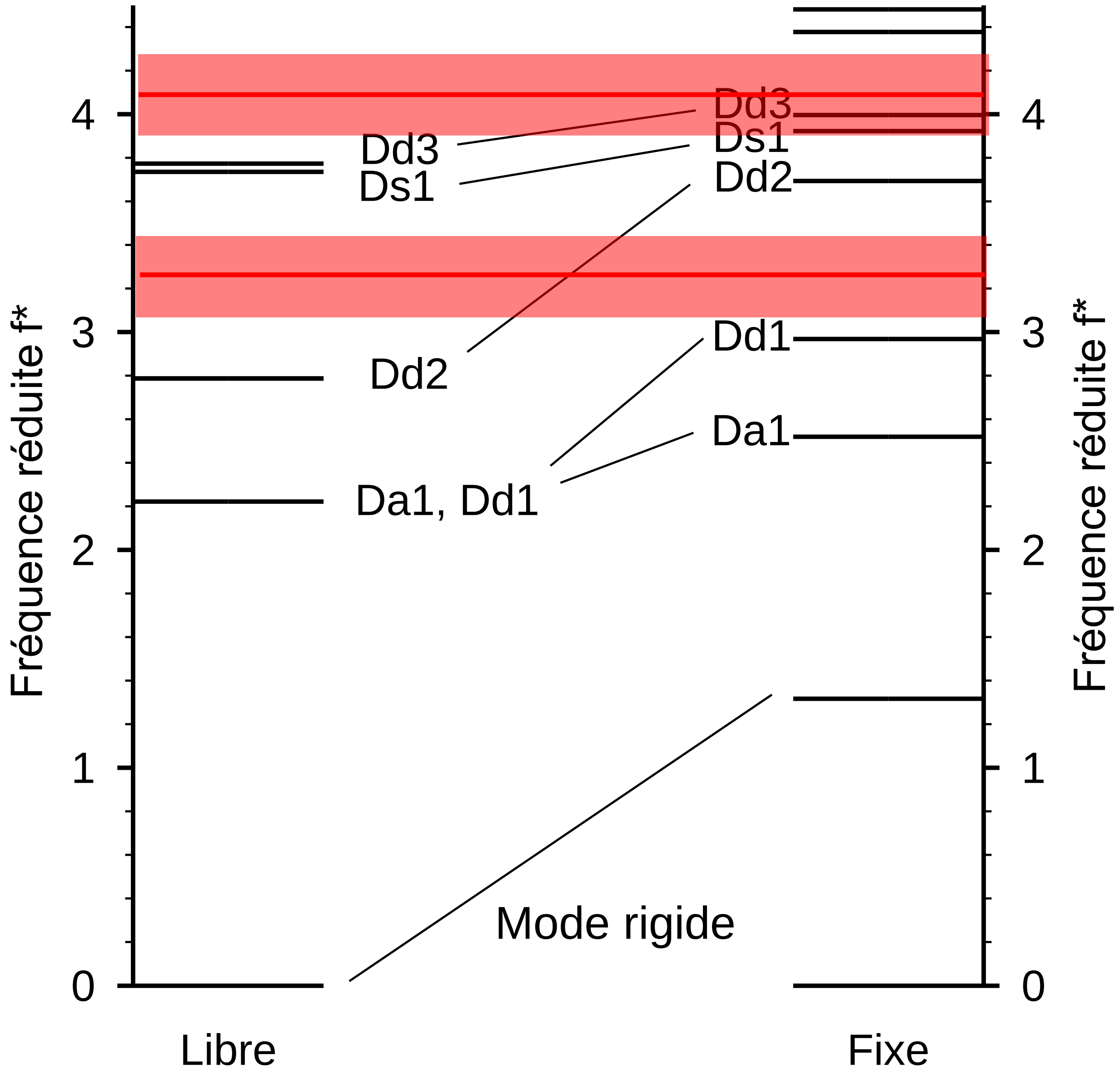
Individual modes – Experimental evidence



- Period do not depends on *a*
- Signal ∝ number of cubes per unit surface

Signal comes from cubes !

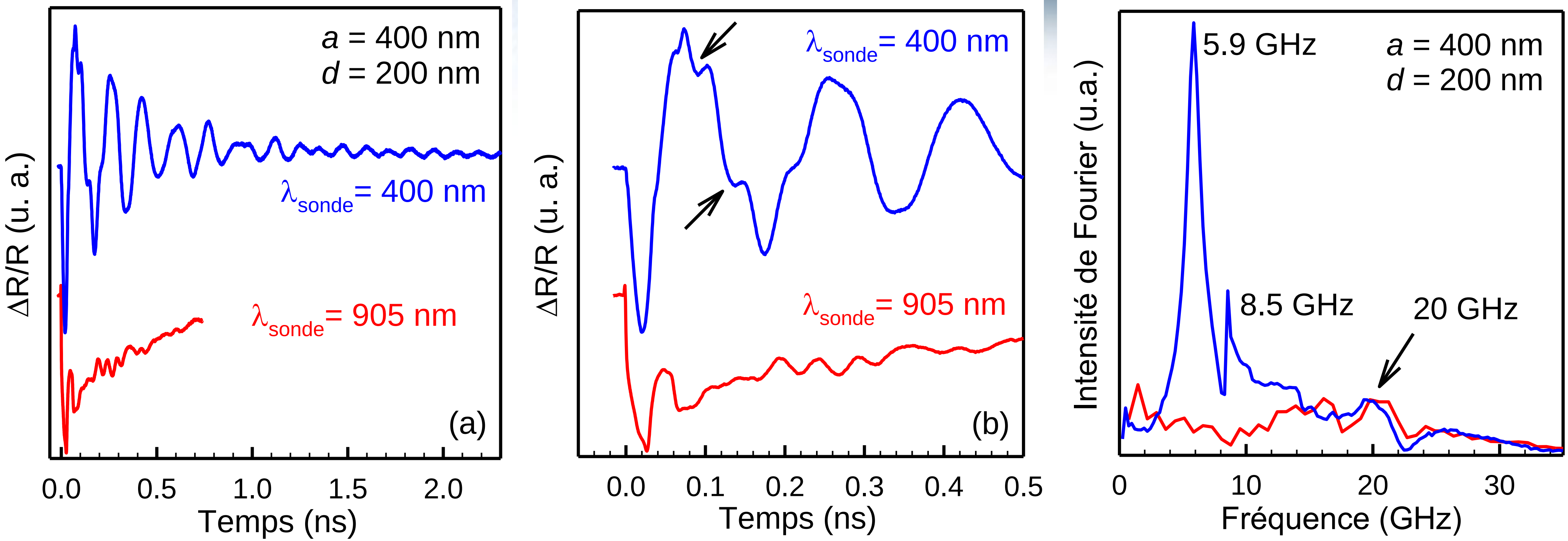
Modeling individual modes



- Complex objects
- Strong couplings (high attenuation)

Collective Modes

Collective modes



Same sample, two probe wavelengths

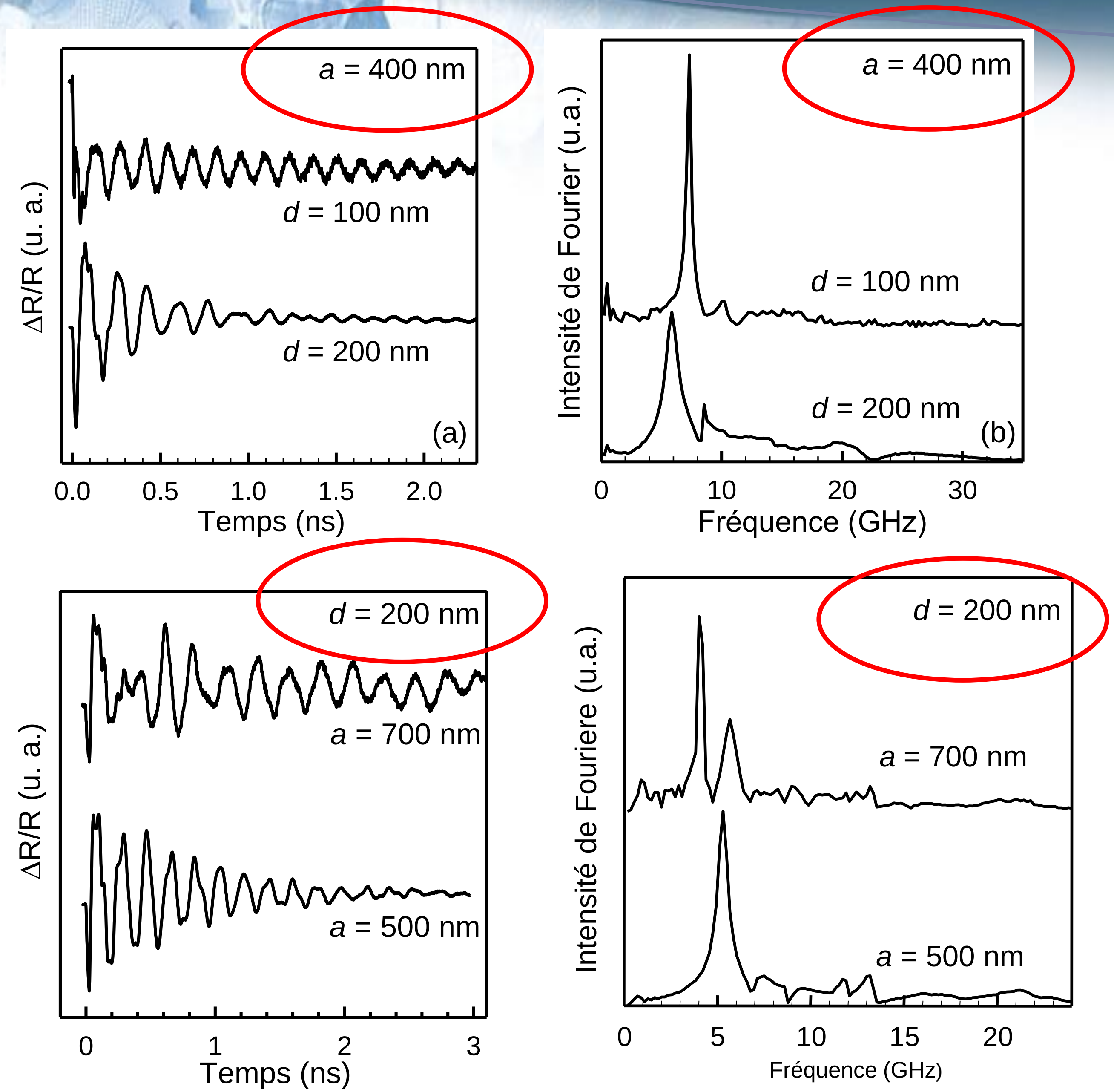
A new signal

- Lower frequency
- Higher magnitude
- Longer lifetime

Detection criterion:

$$\lambda<a$$

Collective modes



λ = 400 nm

Cubes size

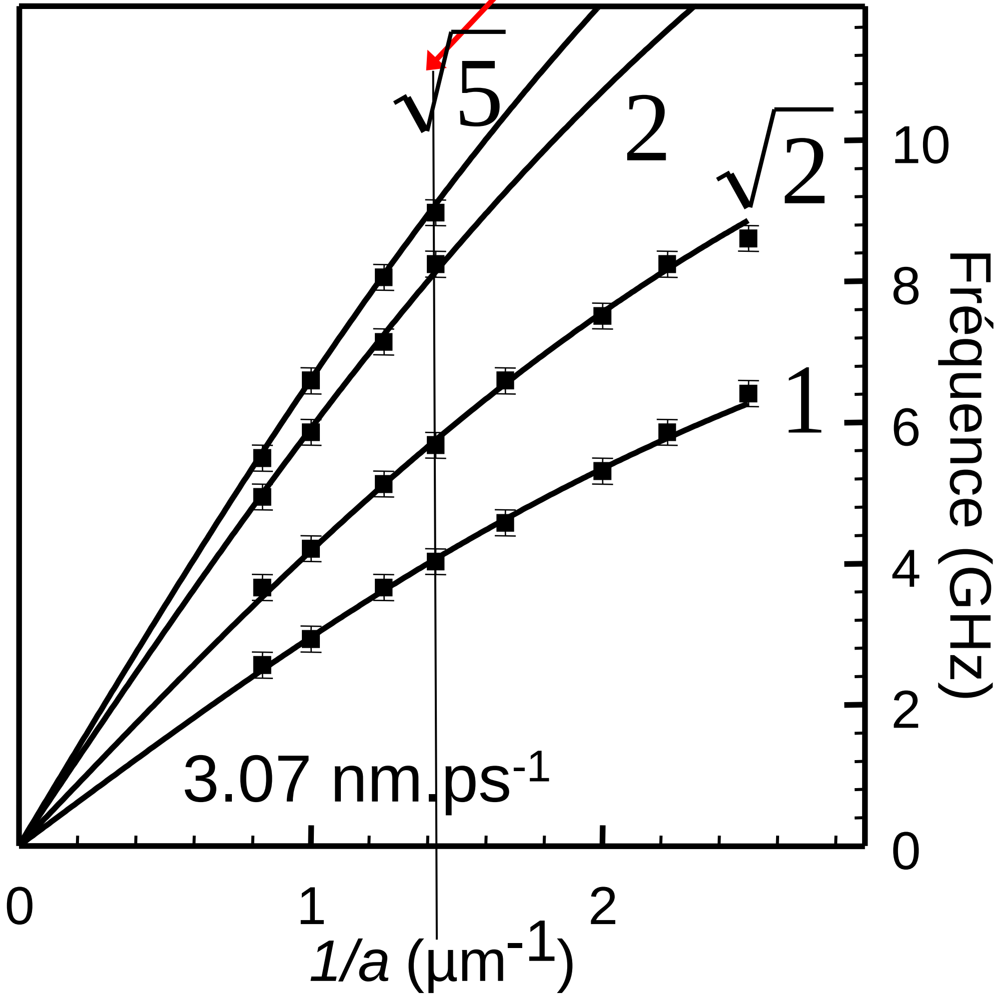
Collective Modes

Lattice constant

Method

- A series of lattices with different constants…

→ Fourier transform



Modeling

$$\omega(\vec{k}) = c(a) \times \left\| \vec{k} \right\|$$

Mode velocity

- Curvature
- Limit velocity

Wavevectors

- Branches
- Factors

Modèle élastique – Vecteurs d'onde

- The generated mode is periodic

$\forall \vec{A}$ Direct lattice

$$\eta_i(\vec{r},t) = \eta_i(\vec{r}+\vec{A},t)$$

$$\eta_i(\vec{r},t) = \eta_{0i}\exp(i\vec{k}.r-\omega t)$$

$$\boxed{\vec{k}.\vec{A} = 2n\pi}$$

Wavevectors belong to the reciprocal lattice

Exemple : Square lattice

$$\left\|\vec{k}_{10}\right\| = \frac{2\pi}{a} \qquad \left\|\vec{k}_{20}\right\| = \frac{2\pi}{a}\times 2$$

$$\left\|\vec{k}_{11}\right\| = \frac{2\pi}{a}\times\sqrt{2} \qquad \left\|\vec{k}_{21}\right\| = \frac{2\pi}{a}\times\sqrt{5}$$

Each wavevector gives a branch

In-plane propagation, several directions

Modeling – Mode velocity

- Lattice cell = harmonic oscillator

$$\omega = \sqrt{\frac{K}{M}} = \sqrt{\frac{K}{\rho(a^2h + d^3)}} = c(a)\left\|\vec{k}_{10}\right\|$$

$$c(a) = \frac{1}{2\pi}\sqrt{\frac{K}{\rho}}\sqrt{\frac{a^2}{a^2h + d^3}}$$

- Limit speed = « without cubes »

$$\lim_{a\to\infty} c(a) = c_0$$

$$\boxed{c(a) = c_0\sqrt{\frac{a^2h}{a^2h + d^3}}}$$

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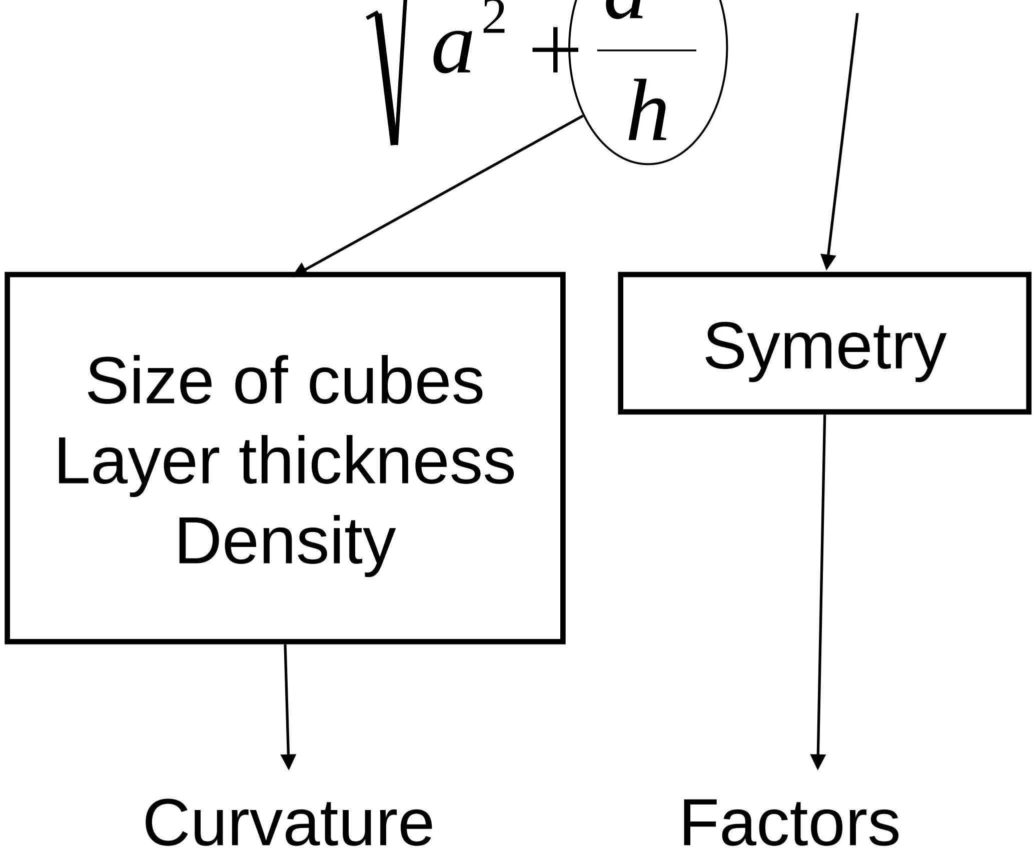
Modeling - Discussion

$$\omega(\vec{k}) = c_0 \sqrt{\frac{a^2}{a^2 + \boxed{\frac{d^3}{h}}}} \times \left\| \vec{k}_{ij} \right\|$$

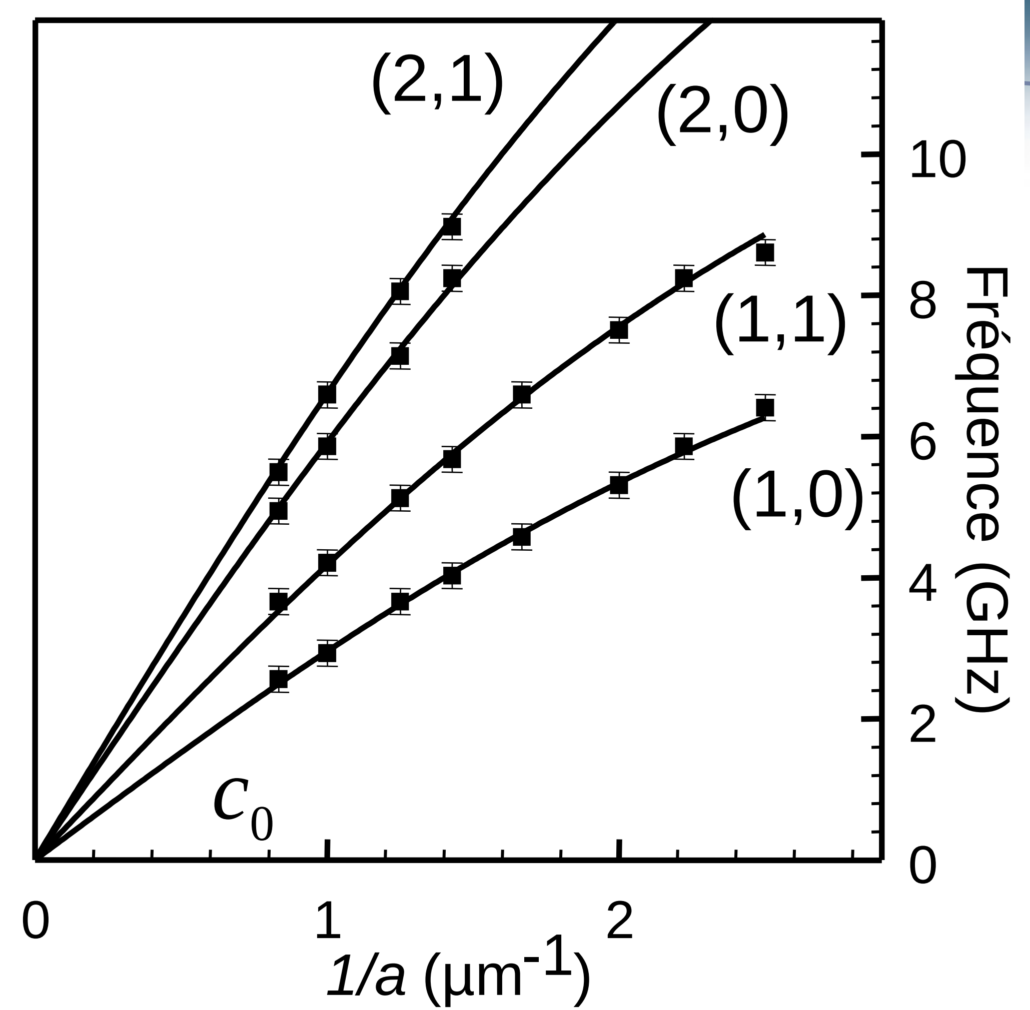


Size of cubes
Layer thickness
Density

Symetry

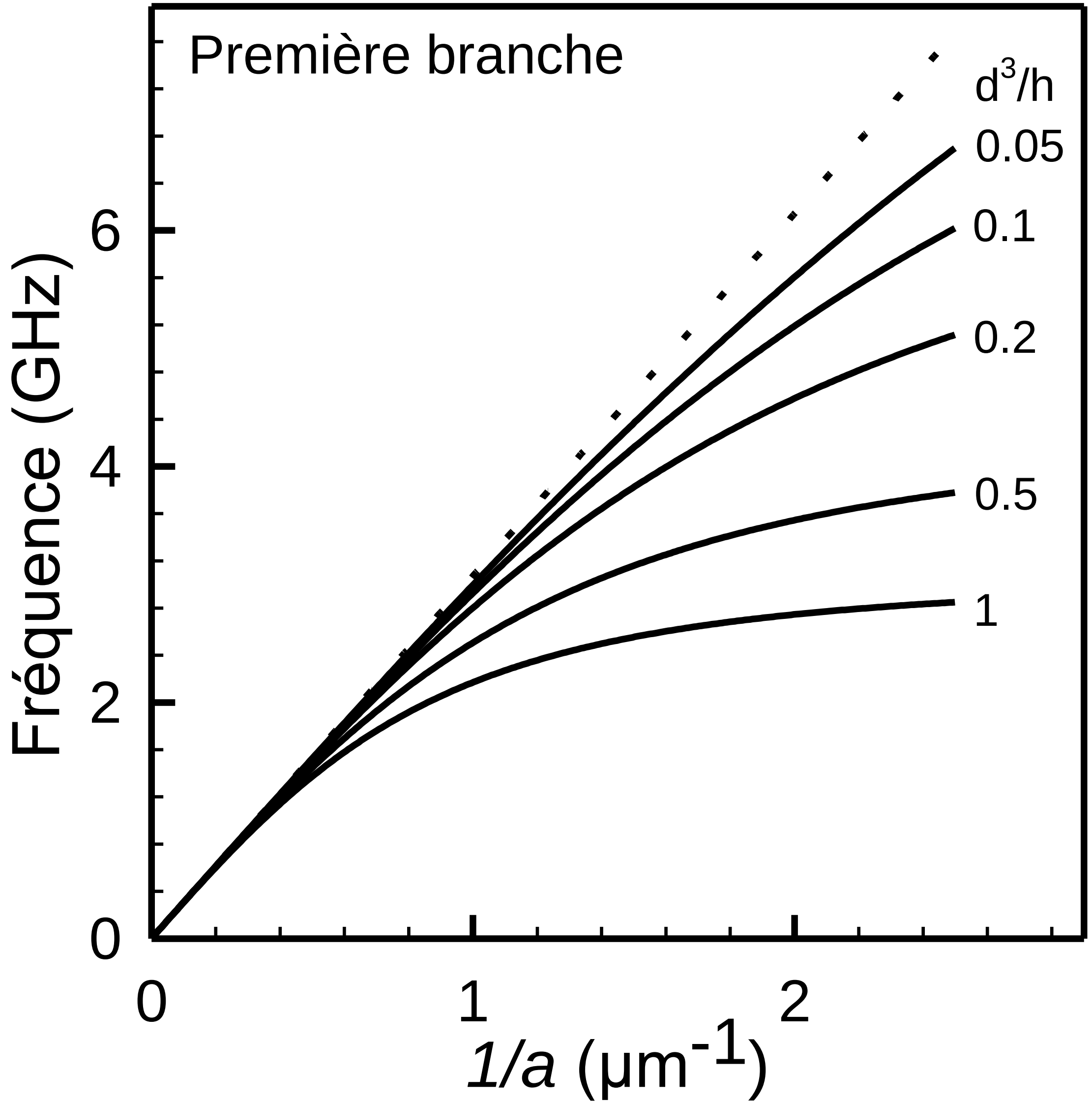
Curvature

Factors



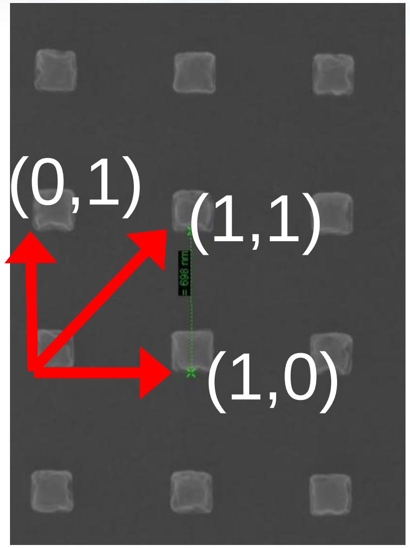
J.-F. ROBILLARD, A. DEVOS and I. ROCH-JEUNE and P. A. MANTE, Physical Review B **78**, 064302 (2008)

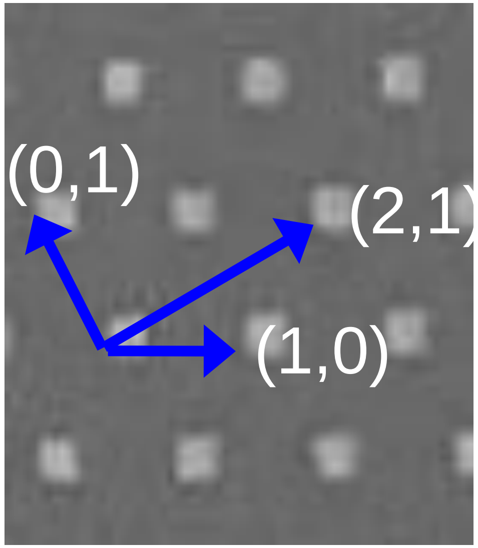
Modeling - Discussion

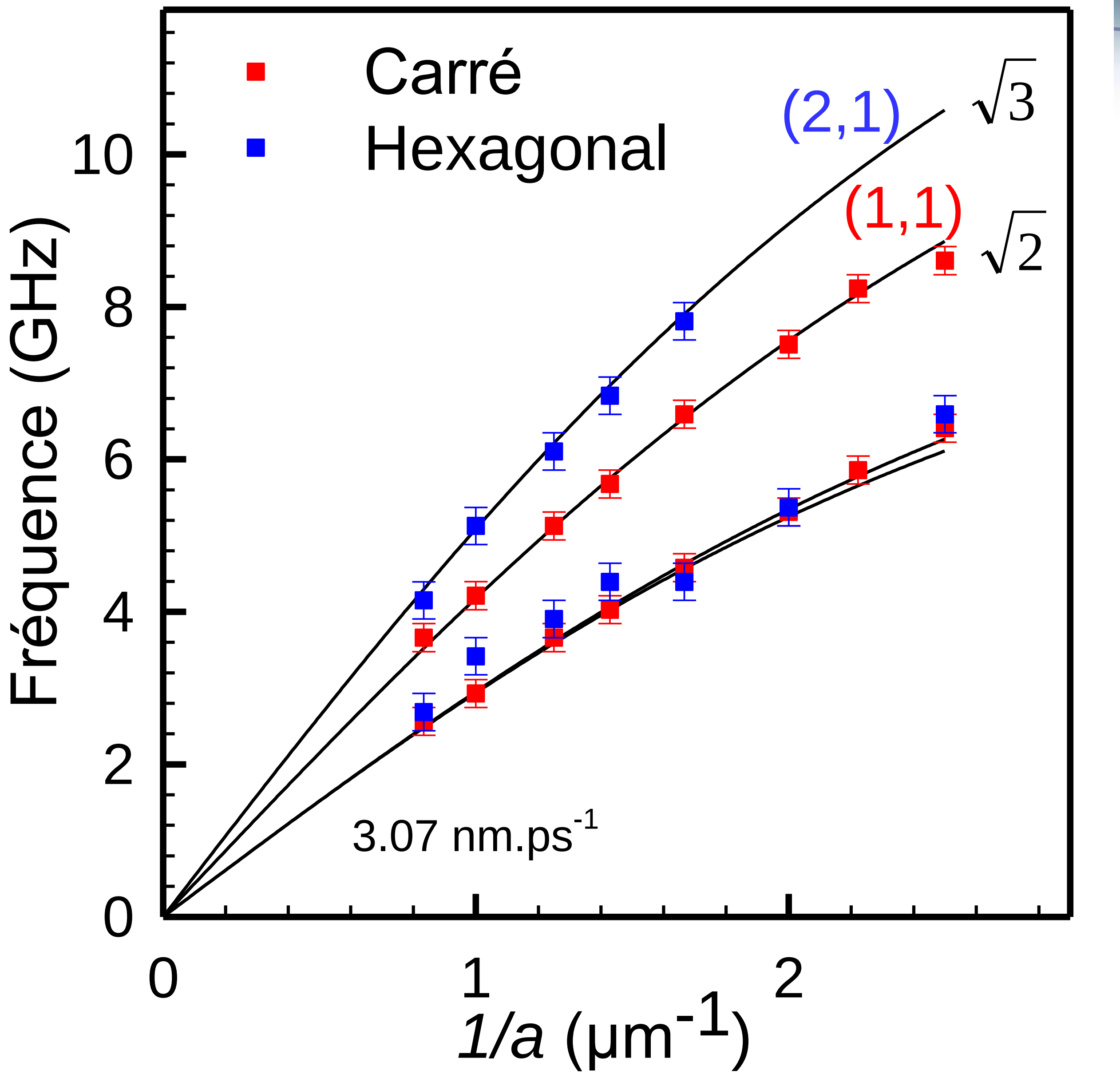


Model vs experiments

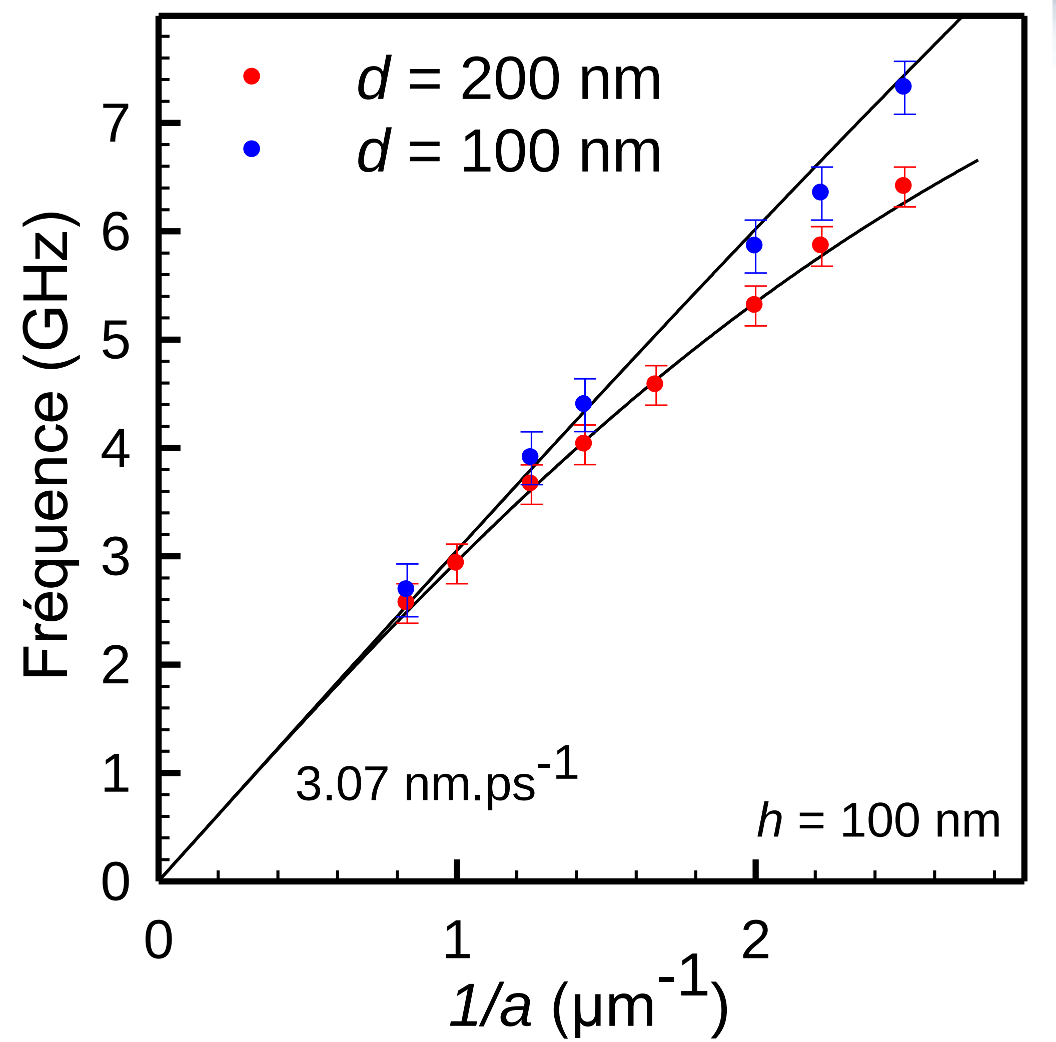
Lattice symetry



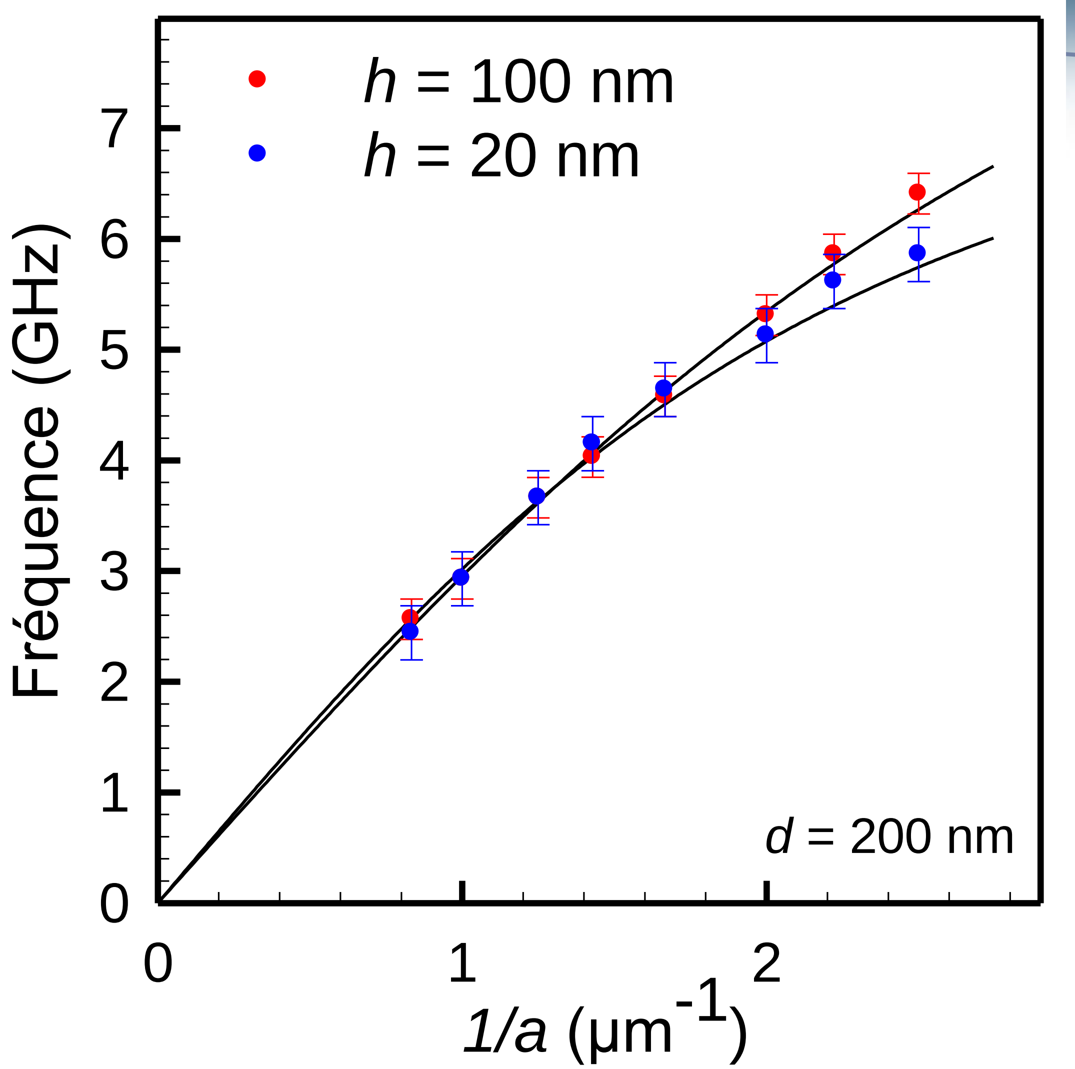




Model vs experiments



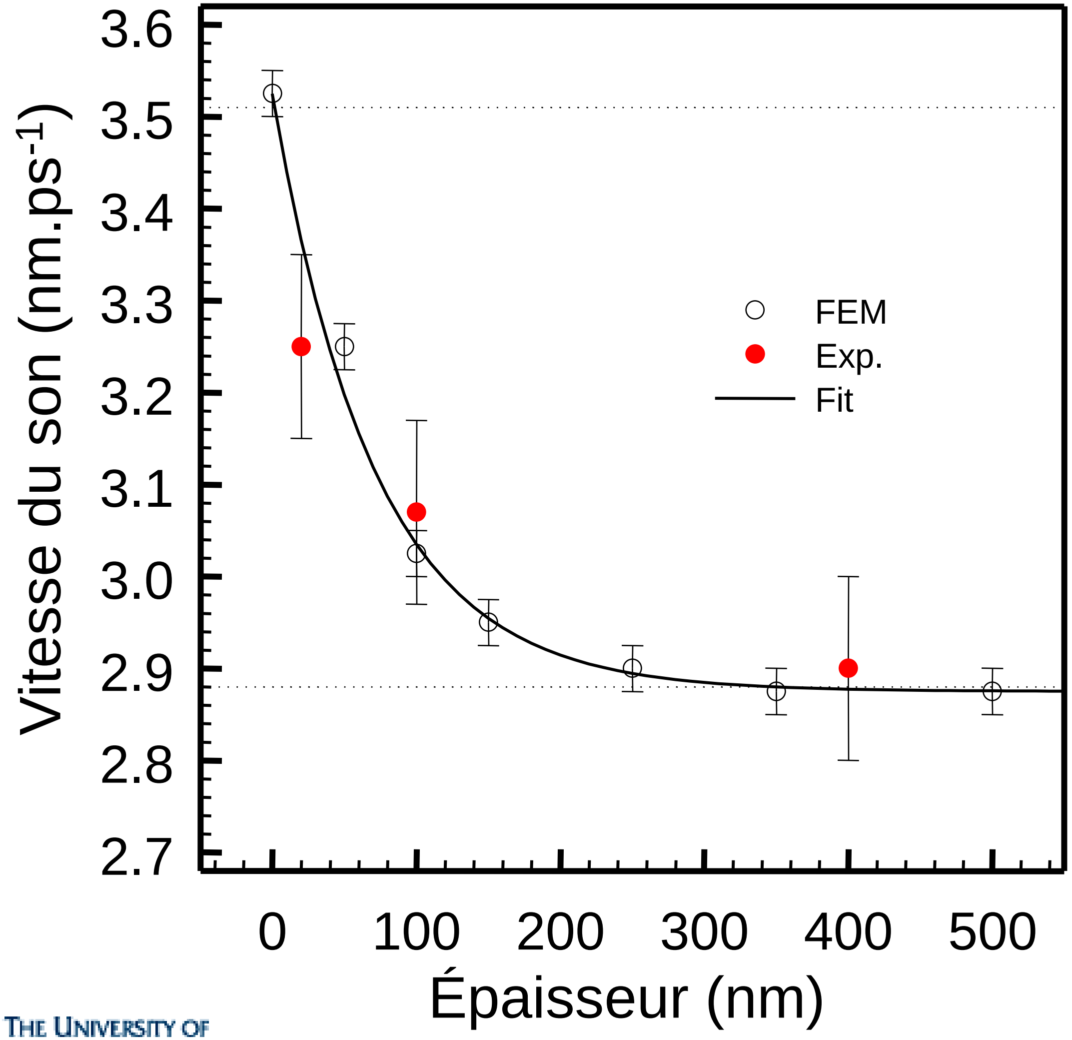
Size of cubes *d*

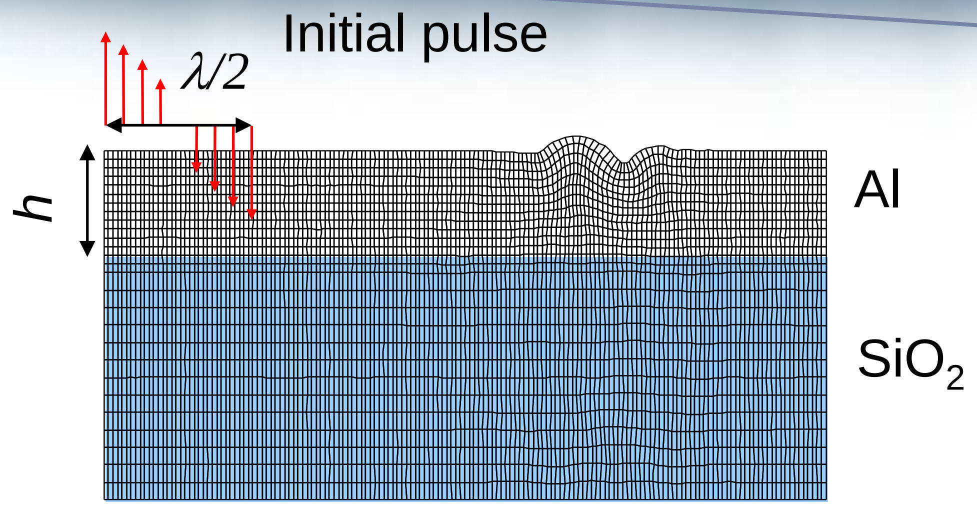


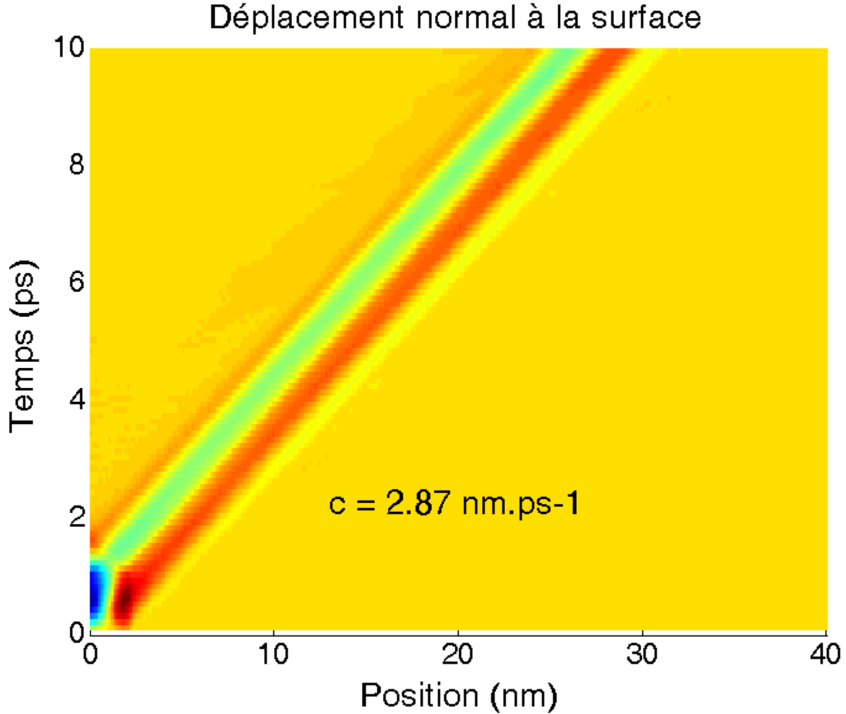
Layer thickness *h*

Layer / substrate system

- Measuring c_0 as a function of *h*







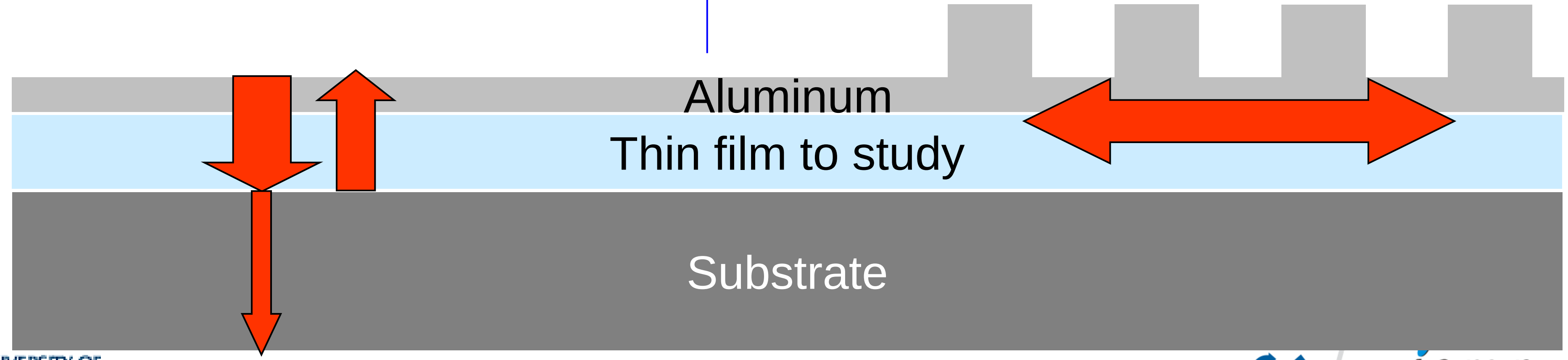
FEM - ATILA

Use for thin films metrology

Use for metrology

- PU « as usual »
  - Longitudinal waves
  - Thickness, longitudinal speed and density

- «Nano Periodic transducer»
  - Surface waves
  - Surface waves velocity
- Advantages
  - Complete characterization
  - All materials
  - Standard PU setup
  - Thin films < 100 nm



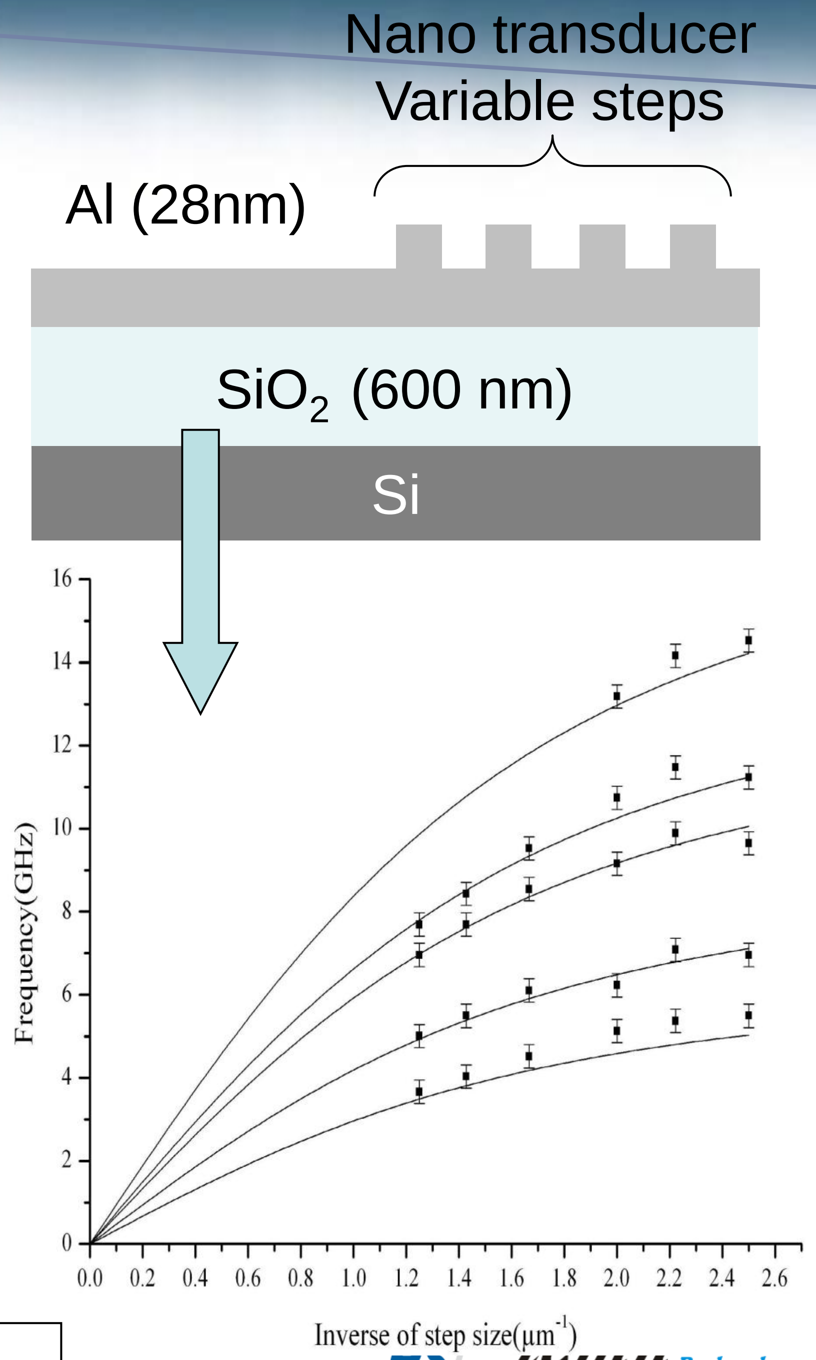
Use for metrology

- Test sample SiO_2
- Two sound velocities
  - – Longitudinale c_l
  - – Rayleigh $c_{Rayleigh}$
- Deduce:

Young modulus E = 72 ± 3 GPa

Poisson ratio $\upsilon = 0.16 \pm 0.08$

- Agreement with litterature



P. A. MANTE, **J. F. ROBILLARD** and A. DEVOS,
Applied Physics Letters **93**, 071909 (2008)

Conclusions

Picosecond Ultrasonics

- A nano to micro – GHz to THz sonar
- Useful for solid state physics and thin films metrology

Lattices of nanoscale objects

- Individual modes
  - Complex objects (many modes, strong couplings)
- Collective modes
  - Technology, e-beam
  - Efficient analytic model
  - Opens up another metrologic capacity

Thanks for your attention !

Perspectives

- Semiconductors lattices, namowires, nanocrystals
- Anisotropic materials
- Thermal properties
- Higher frequency phononic crystals… « Thermonic crystals»

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