Thermal Properties Characterization of Advanced Materials: Application to Nanoelectronics

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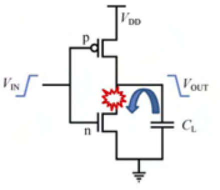
Outlook

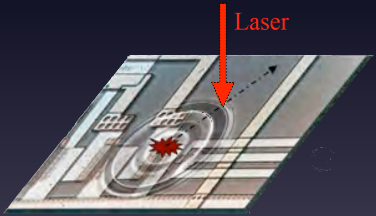
Motivation : Nano Earthquakes

$I(t).V(t) \Rightarrow p(t) \Rightarrow \Delta T(x,y,t) \Rightarrow d(x,y,t)$

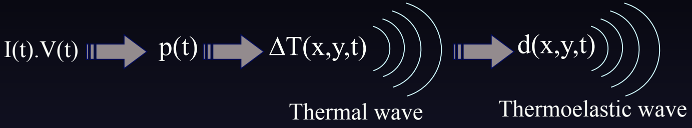
Thermal wave

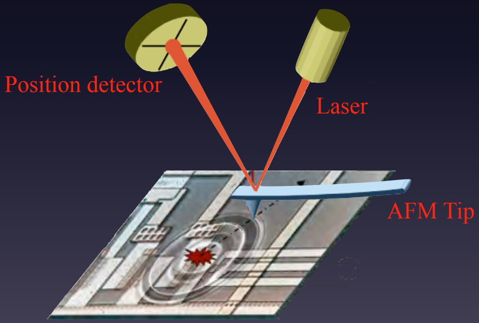
Thermoelastic wave

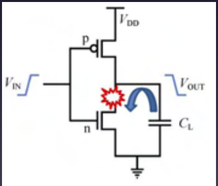




Motivation : Nano Earthquakes



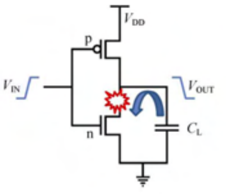


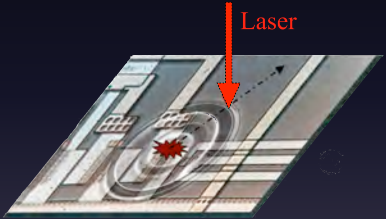


Motivation : Nano Earthquakes

I(t).V(t) → p(t) → ΔT(x,y,t) → d(x,y,t)

Thermal wave — Thermoelastic wave

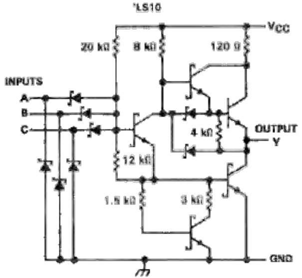




Orders of Magnitude

- Temperature elevation : $\Delta T = 1K$
- Heat Source Thickness : $e = 100nm$
- Expansion coefficient : $\alpha = 10^{-6}$
- Surface expansion : $\alpha.e.\Delta T = 100fm$

Motivation : Fault Detection in ICs



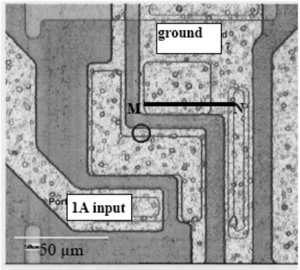


Figure 2: top view of the ESD protection circuit

Motivation : Fault Detection in ICs

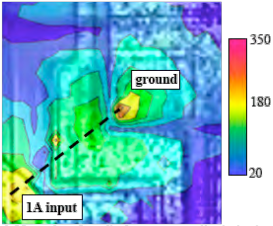


Figure 4: Normal surface displacement amplitude (pm) superimposed to the optical image

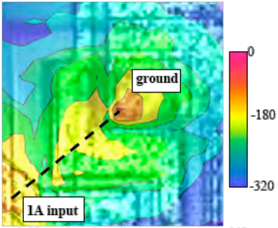
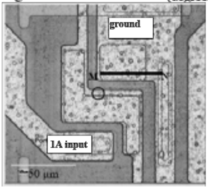


Figure 5: Normal surface displacement phase shift (degrees) superimposed to the optical image



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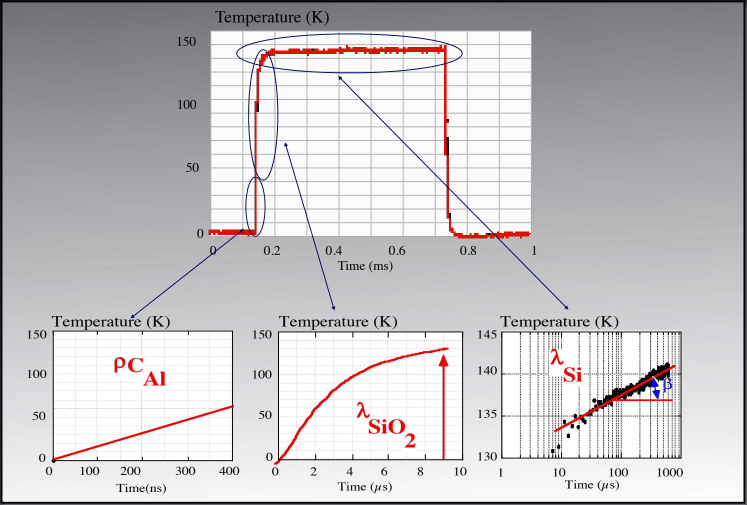
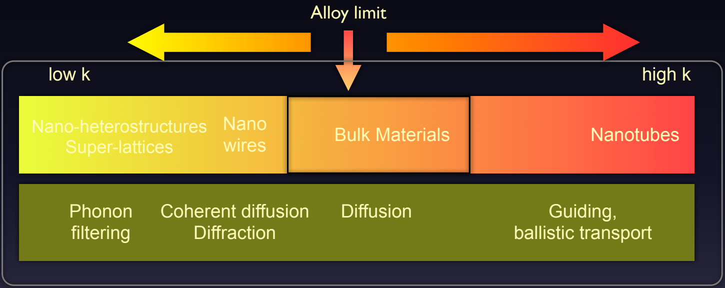
Motivation : Temperature Measurement



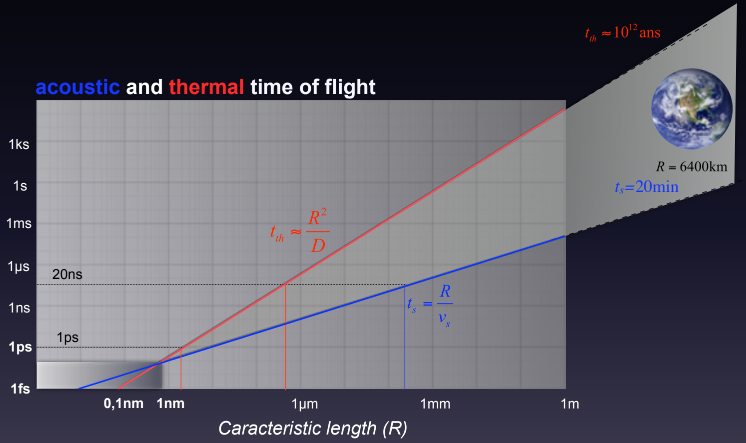
Motivation : Material Thermal Properties



Decrease thermal conductivity of electrical conductors through nanostructuring

Increase thermal conductivity of insulators with novel nanoparticles

Motivation : Time and Space scales



$D = 5\ 10^{-6}\ m^2/s$

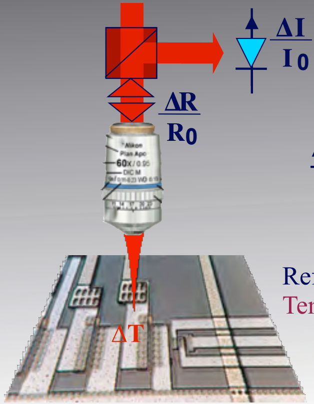
$v_s = 8nm/ps$

Pump-Probe Laser Metrology at the Nanoscale

Thermoreflectance Principle

Thermoreflectance Principle

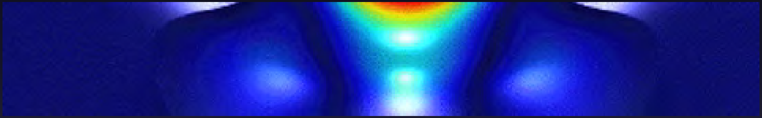
Thermoreflectance Principle



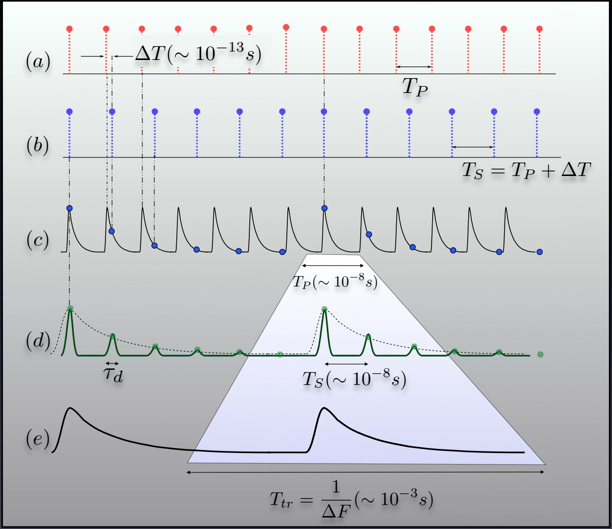
$$\frac{\Delta I}{I_0} = \frac{\Delta R}{R_0} = \kappa . \Delta T$$

Reflectance measurement
Temperature measurement

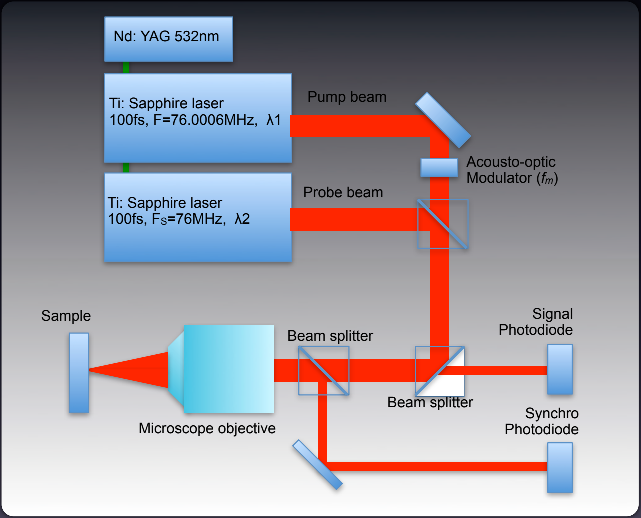
Thermo Acoustic effects in thin films



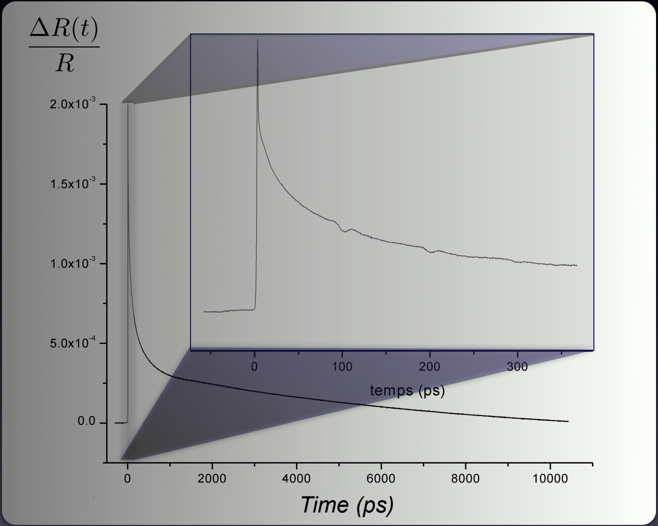
Picosecond Optical Sampling



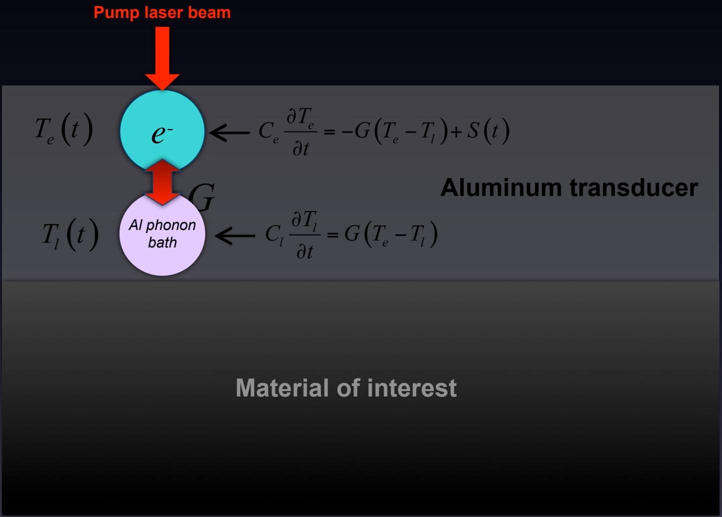
Experimental set-up



Typical Signal



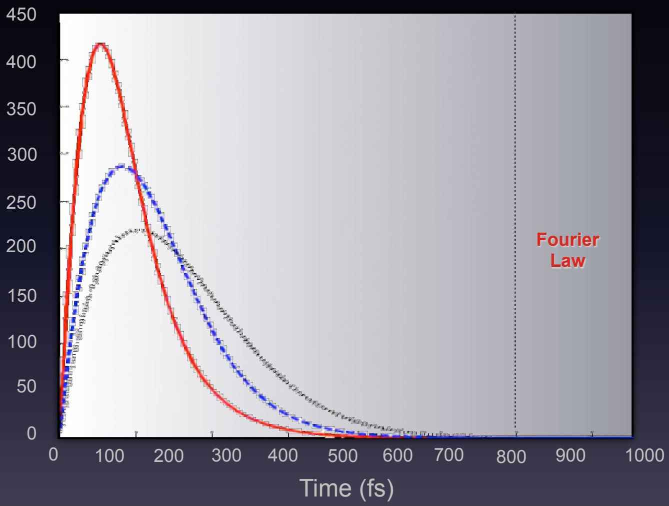
Is the notion of temperature still valid ?



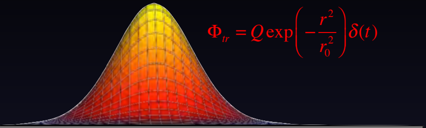
$$C_e \frac{\partial T_e}{\partial t} = -G(T_e - T_l) + S(t)$$

$$C_l \frac{\partial T_l}{\partial t} = G(T_e - T_l)$$

Is the notion of temperature still valid ?



Thermal Model



$$\Phi_{tr} = Q \exp\left(-\frac{r^2}{r_0^2}\right)\delta(t)$$

Optical penetration depth

Al transducer

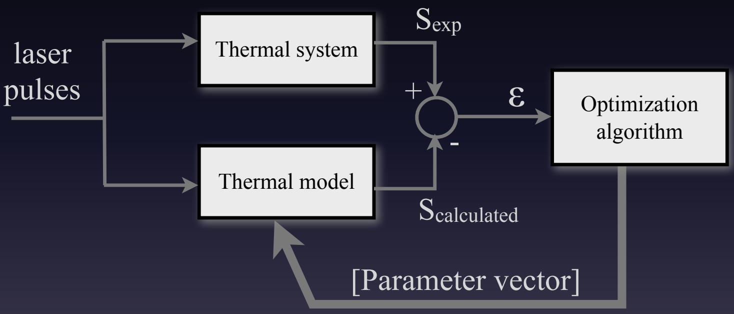
$$\begin{bmatrix}\Theta_{in}\\ \Phi_{in}\end{bmatrix} = \begin{bmatrix}A & B\\ C & D\end{bmatrix}\cdot\begin{bmatrix}\Theta_{out}\\ \Phi_{out}\end{bmatrix}$$ Layer 1

Semi-infinite substrate

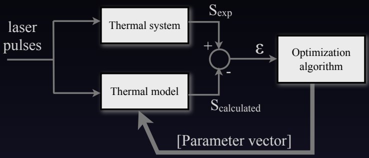
$$\begin{bmatrix}\Theta_{tr}\\ \Phi_{tr}\end{bmatrix} = \begin{bmatrix}1 & 0\\ k_{tr}e_{tr}q_{tr}^2 & 1\end{bmatrix}\cdot\begin{bmatrix}A_{Al} & B_{Al}\\ C_{Al} & D_{Al}\end{bmatrix}\cdot\begin{bmatrix}1 & Z_{Al/1}\\ 0 & 1\end{bmatrix}\cdot\begin{bmatrix}A_1 & B_1\\ C_1 & D_1\end{bmatrix}\cdot\begin{bmatrix}1 & Z_{1/Sub}\\ 0 & 1\end{bmatrix}\cdot\begin{bmatrix}\Theta_{Sub}\\ \Phi_{Sub}\end{bmatrix}$$

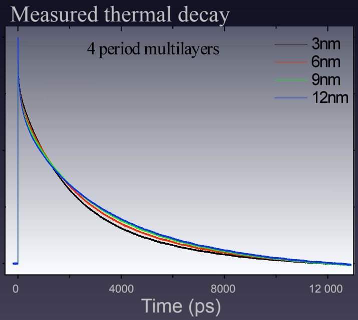
$$\Theta_{tr} = f(\Phi_{tr}, thermal\ paramters)$$

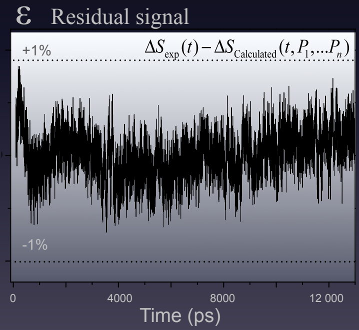
Parameter identification



Parameter identification



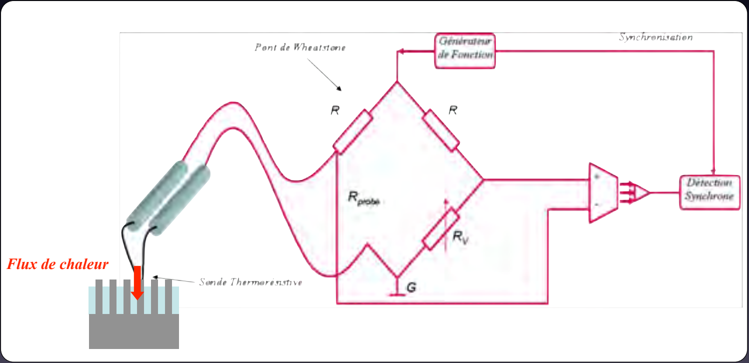




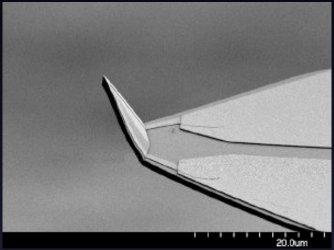
"Pump-Probe" Near Field Metrology

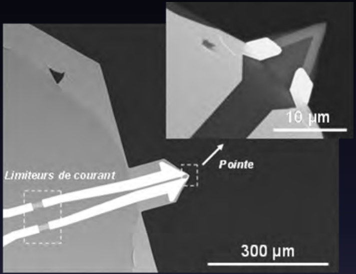
When the Tip heat and probe the temperature : 3ω Technique

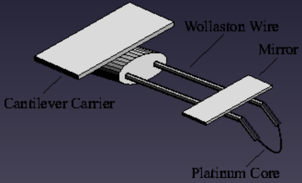
$$I \sim 1\omega \xrightarrow{\textit{Joule Effect}} I^2 \sim T \sim 2\omega \xrightarrow{\textit{Thermal effect}} R \sim T \sim 2\omega \xrightarrow{\textit{Ohm's Law}} V \sim IR \sim 3\omega$$



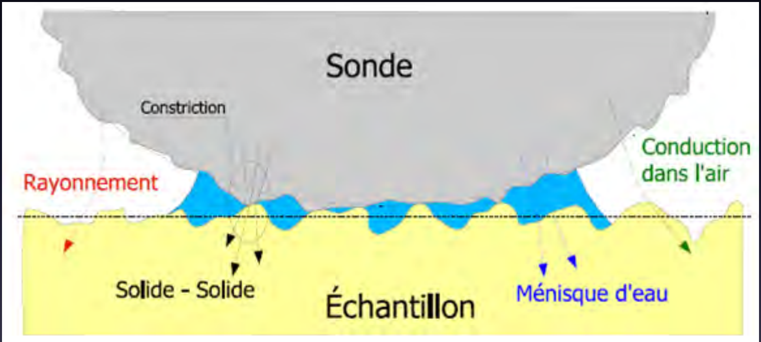
Thermal Tips



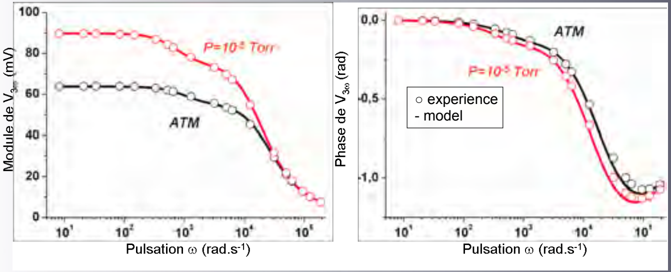




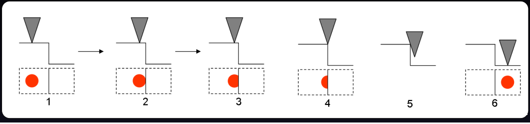
Tip-Surface Interactions

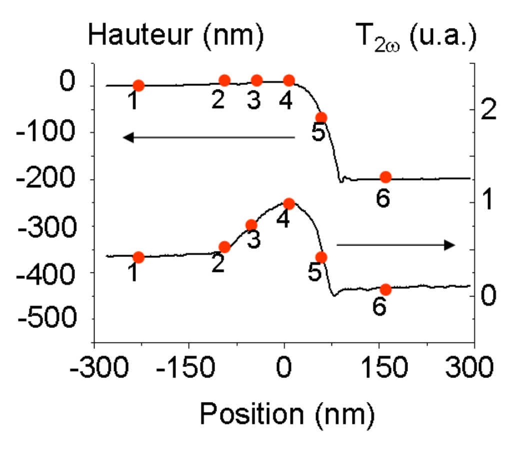


Frequency Response



Thermal Lateral Resolution





SThM vs Thermoreflectance

Performances SThM

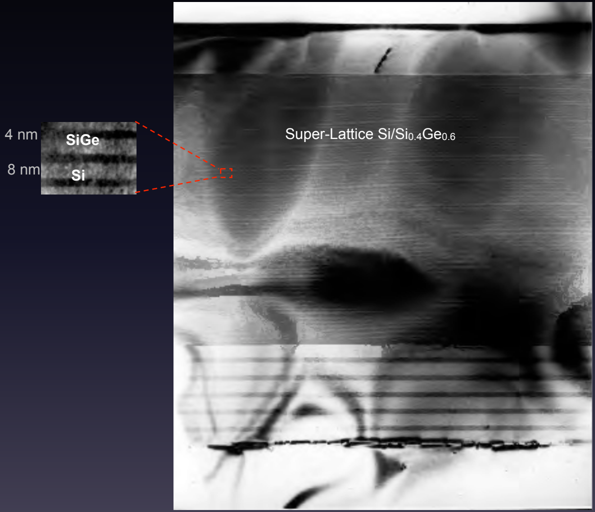
- Temperature sensitivity $100\mu K$
- Thermal Lateral resolution $100nm$
- Topographic Lateral resolution $10nm$
- Time resolution $10 \sim 100\mu s$

Performances Picosecond Thermoreflectance

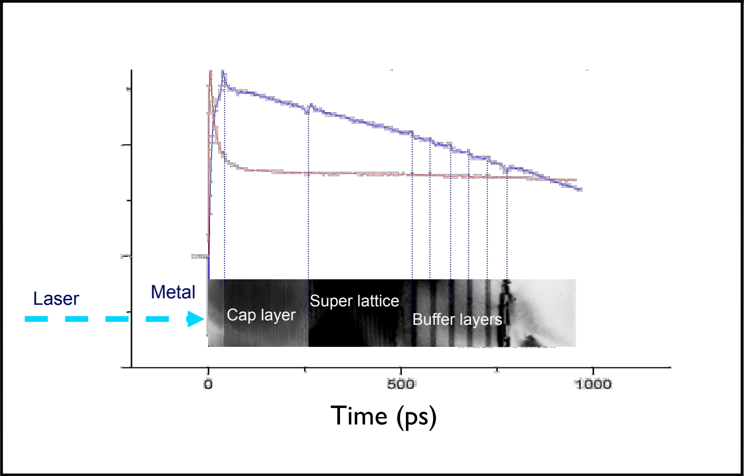
- Temperature sensitivity $100\mu K$
- Thermal Lateral resolution $1\mu m$
- Time resolution $100fs$

Case studies : Super Lattices

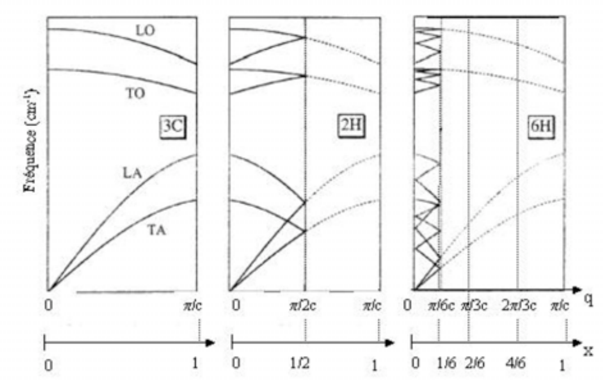
Superlattices



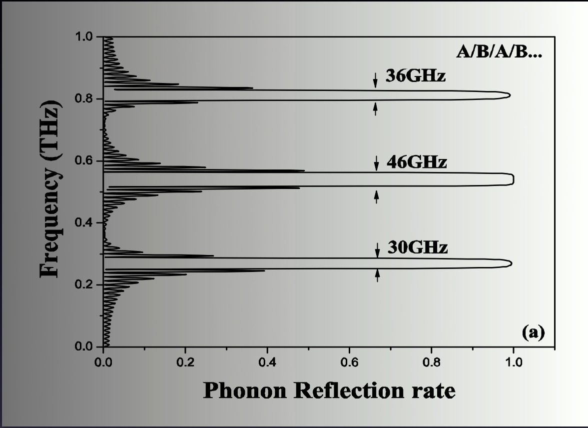
Nano Ultrasonics on Superlattices

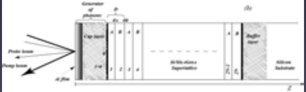


Mini Brillouin Zones

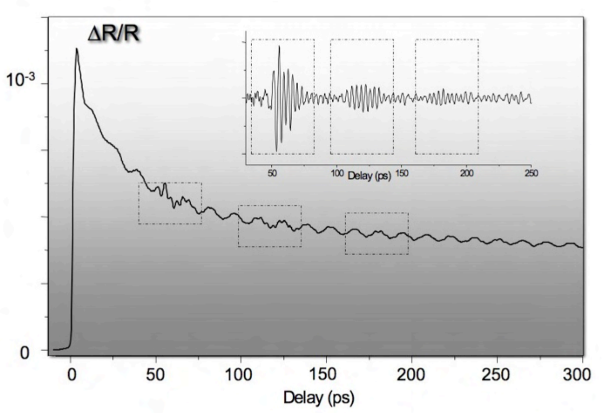


Phonon Reflexion Rate

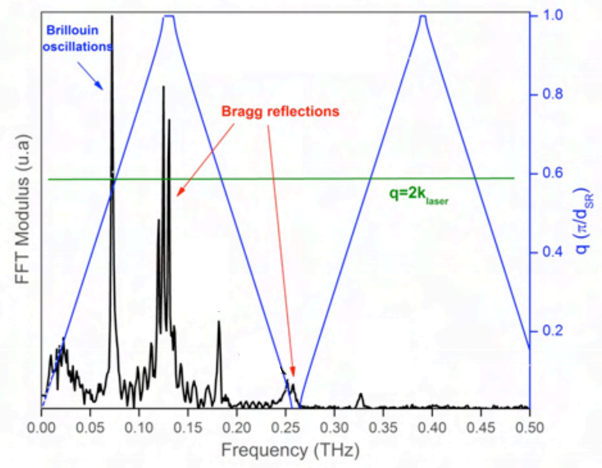




Zoom on Thermoreflectance Signal



Dispersion Curves



Thermal Conductivity

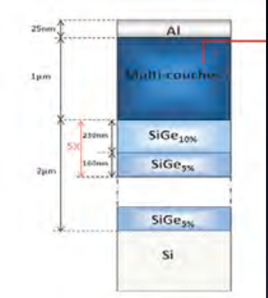
Thermal Conductivity from microscopic point of view

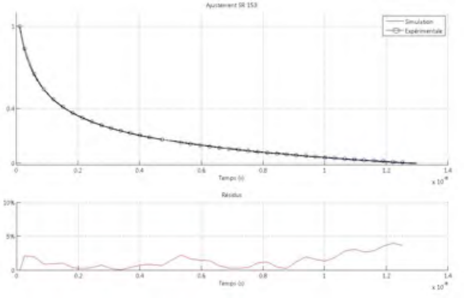
- $k = \frac{h}{8\pi^3} \sum_{j=1...3} \int \omega \; v_g^2 \; \tau \; \frac{\partial n}{\partial T} \; dk^3$

with

- $v_g^2 = \frac{d\omega}{dk}$ group velovity obtained from the Dispersion Curve
- τ relaxation time
- $\frac{\partial n}{\partial T}$ derivative of the distribution function with respect to temperature

Thermal Conductivity

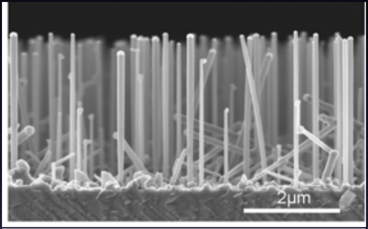


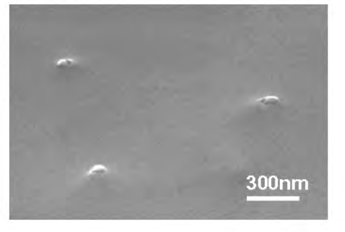


Identified parameters	Al Thermal conductivity W/m-K	Contact resistance Al/ SL Km^2/W	SL Thermal conductivity W/m-K
Values	235	$6.1\ 10^{-9}$	2.6

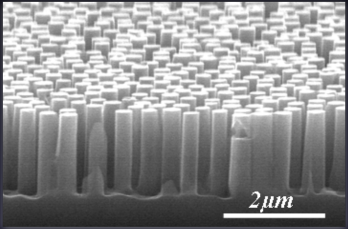
Case studies : Nano Wires

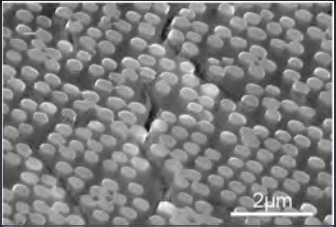
Silicon Nano Wires





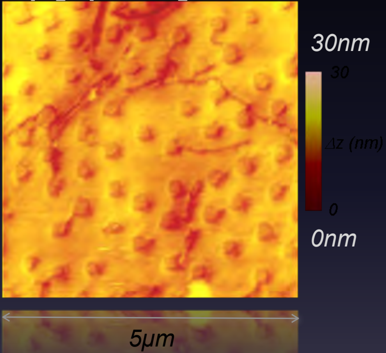
Silicon Nano Wires



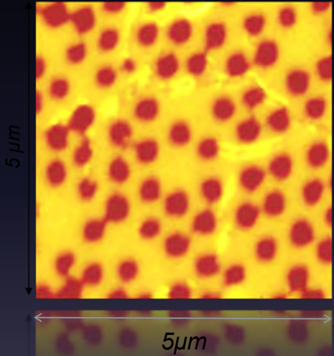


Silicon Nano Wires

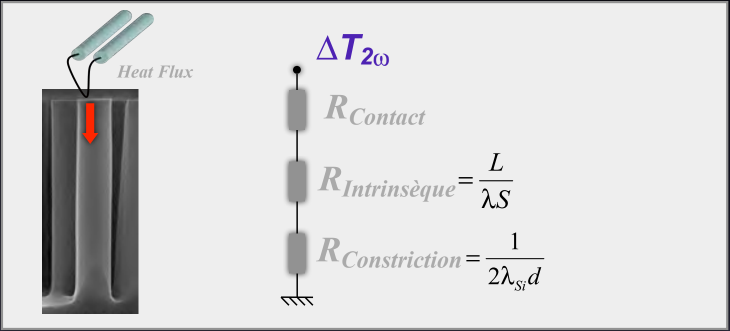
Topographic Image



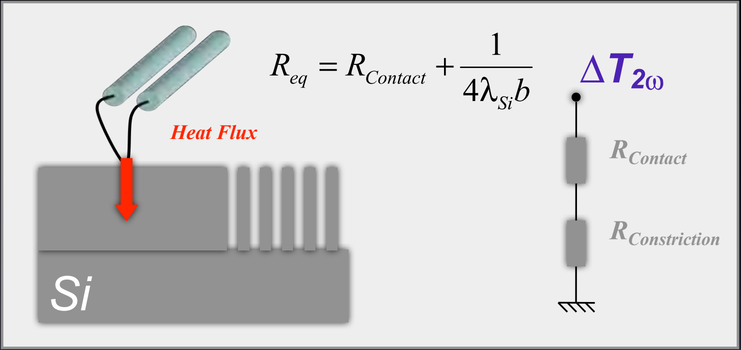
Thermal Image ($V_{3\omega}$)



Nano Wire Methodology

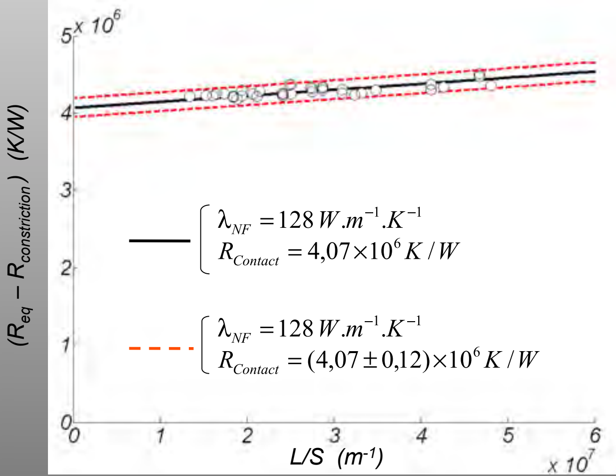


Nano Wire Methodology : Contact Resistance



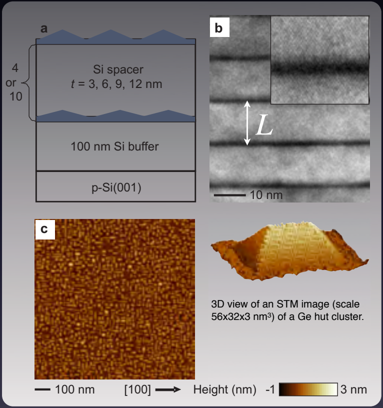
Nano Wire Methodology : Identification

$$R_{eq} - R_{Constriction} = R_{Contact} + \frac{1}{\lambda}\frac{L}{S}$$



Case studies : Nano Dots

Nano Silicon



«Precise control of thermal conductivity at the nanoscale via individual phonon scattering barriers»
Nature Materials (2010)

Coll.
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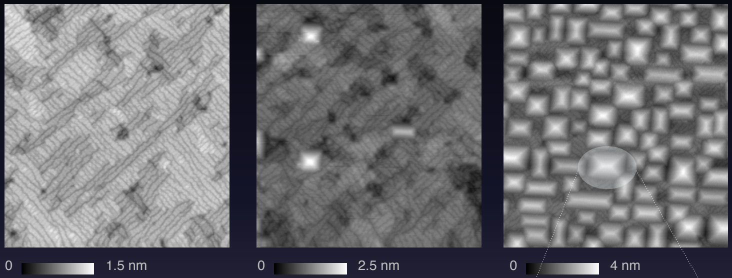
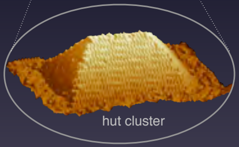
Nano Silicon

4 ML Ge   5 ML Ge   6 ML Ge



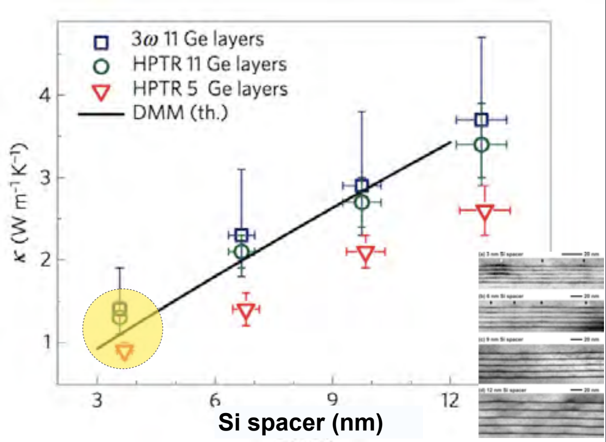
Scale 180×180 nm^2 (1 ML=1 Monolayer = 0.14 nm)

nominal substrate temperature: 450°C
the “hut cluster” regime: islands are small, Ge rich, and have high surface density



A. Rastelli, H. von Kaenel, Surf. Sci. 532, 769 (2003)

Lowest thermal conductivity obtained on a crystalline material : <1W/m-K



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- Chemistry : Pr Serge Ravaine (UBx1), Dr Renaud Vallée (UBx1)
- Mechanics : Pr Bertrand Audoin (UBx1), Jean-Christophe Batsale (UBx1), Dr Christophe Pradère
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