THERMOMECHANICAL EXCITATION OF ARRAYS OF NANOSTRUCTURES

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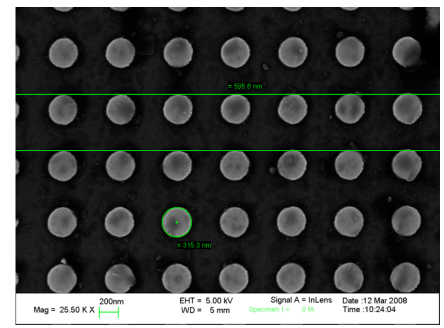

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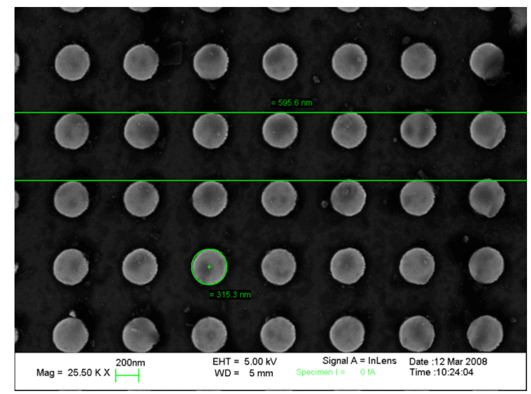
OUTLINE

- Introduction
- SAWs and ultrafast heat transfer
- Coherent excitation of GHz SAWs
- Birth of a SAW
- Calorimetry at the nanoscale
- Magnetoelastic interaction



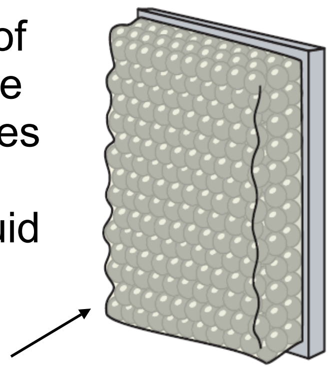
WHY INTEREST IN LATTICES OF NANOSTRUCTURES ?

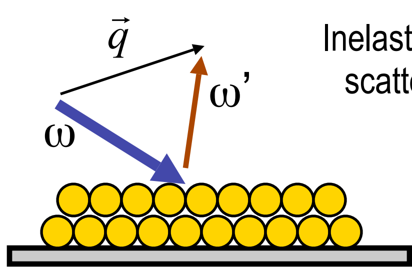
1) COUPLING OF THE SOUND WAVES TO PERIODICITY: HYPERSONIC BANDGAPS

→ Phononic crystals in the GHz range

•Acoustic waves at GHz frequencies are generated by **thermal excitation**, i.e. phonons

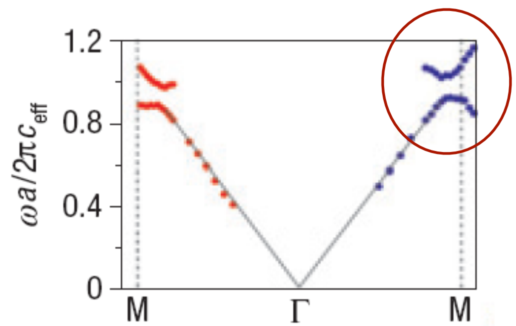
3D lattice of polystyrene nanoparticles + viscous liquid





$$\hbar\omega' = \hbar\omega \pm \hbar\omega_{Ph}(\vec{q})$$

Gap opening at the border of the Brillouin zone

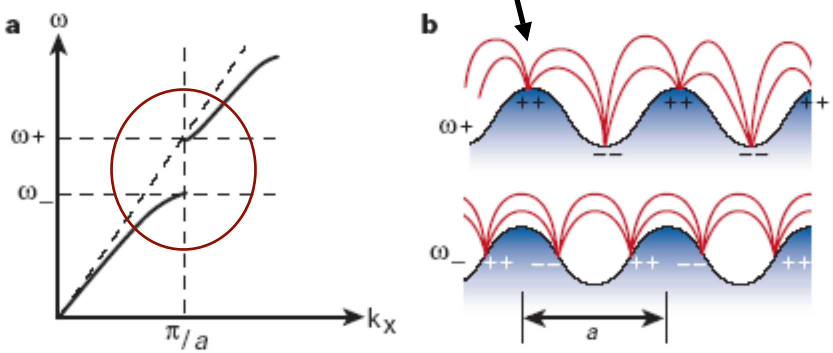


W. Cheng *et al.*, *Nature Materials* **5**, 830 (2006)

2) COUPLING OF SURFACE PLASMONS TO THE PERIODICITY: EXTRAORDINARY TRANSMISSION & SUBWAVELENGTH OPTICS IN THE VISIBLE

Periodically corrugated metal surface

Surface plasmon electric field

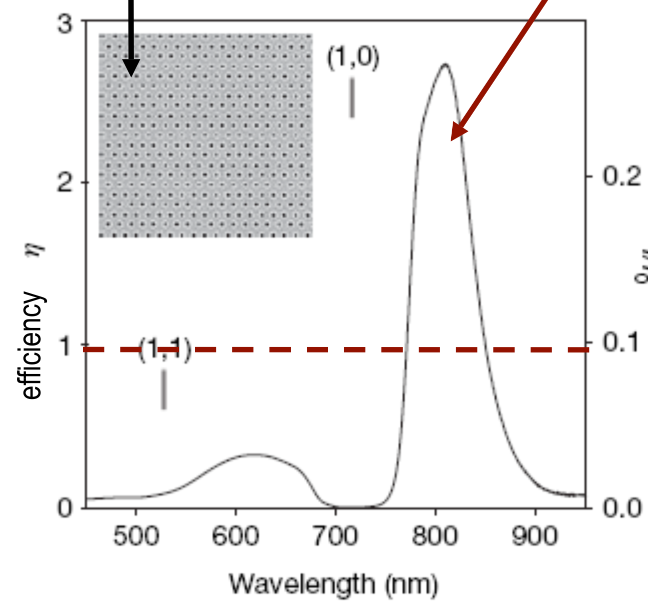


opening of bandgap in SP modes

holes metal array

extraordinary diffraction

d~200 nm



W.L. Barnes *et al.*, *Nature* **424**, 824 (2003)

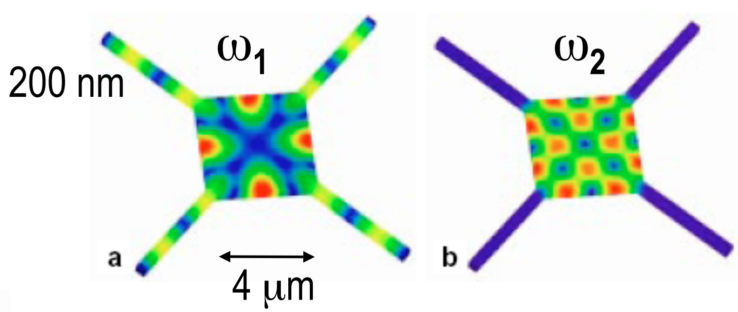
C. Genet *et al.*, *Nature* **445**, 39 (2007)

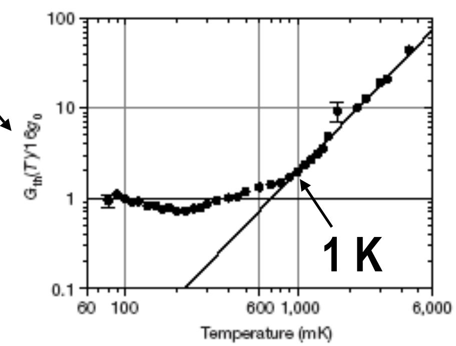
2) THERMODYNAMICS AT NANOSCALE

Nanometric structures, in thermal contact with the substrate, are suitable to study the dynamical **heat exchange** at the solid interface.

- Fundamental physics → limits of classical thermodynamics
  C. Bustamante *et al.*, *Physics Today* **58**, 43 (2005)
- Technological problems → measuring without perturbing the nano-system
  T.S. Tighe *et al.*, *Appl. Phys. Lett.* **70**, 20 (1997)

QUANTIZATION OF THERMAL CONDUCTANCE





$K_BT < \Delta\omega$

K. Schwab *et al.*, *Nature* **404**, 974 (2000)

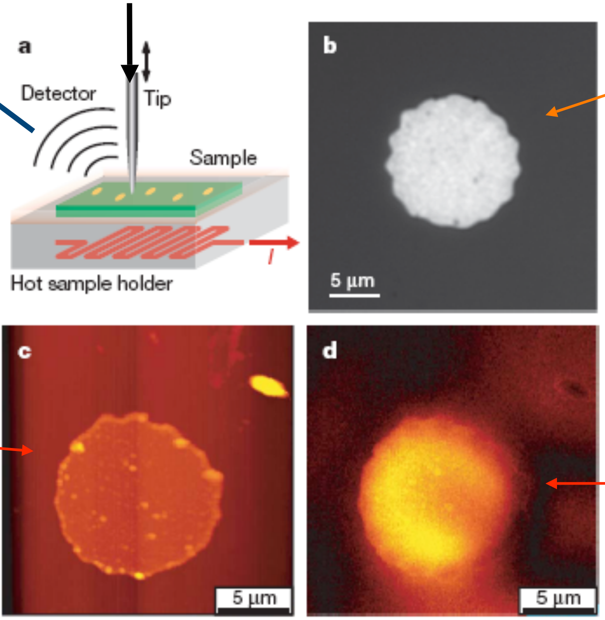
4) THERMAL MICROSCOPY AT NANOSCALE

Thermal Radiation AFM

IR optics and detectors

AFM tip

Optical microscopy



AFM microscopy

Thermal microscopy

Measuring the IR thermal radiation emitted by a small object with subwavelength resolution

→ Possibility to couple time resolution to spatial resolution

Y. De Wilde *et al.*, *Nature* **444**, 740 (2006).

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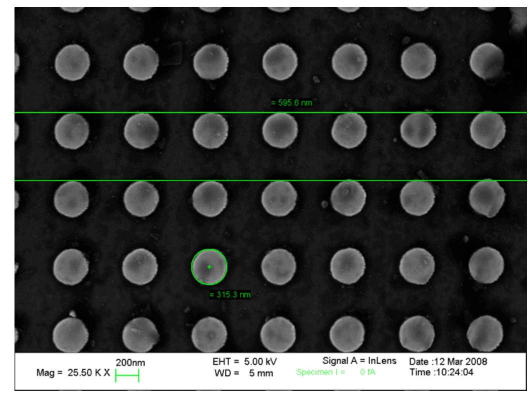


THEORY OF ELASTICITY

3 equations $$\overrightarrow{\nabla} \cdot (c \overrightarrow{\nabla} \overrightarrow{u}) = \rho \frac{\partial^2 \overrightarrow{u}}{\partial t^2}$$

tensorial product

(6x1) $$\overrightarrow{\nabla} \overrightarrow{u} = \left(\frac{\partial u}{\partial x}, \frac{\partial v}{\partial y}, \frac{\partial w}{\partial z}, \frac{\partial w}{\partial y}, \frac{\partial u}{\partial z}, \frac{\partial v}{\partial x} \right)$$

$\overrightarrow{u}$ Displacement (u, v, w)

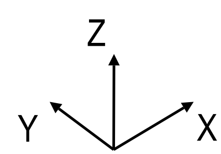
ρ Density

c Elastic stiffness matrix for cubic crystal

$$\begin{pmatrix} c_{11} & c_{12} & c_{12} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{12} & 0 & 0 & 0 \\ c_{12} & c_{12} & c_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{44} \end{pmatrix}$$

example u-component:

$$c_{11} \frac{\partial^2 u}{\partial x^2} + c_{44} \left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + (c_{12} + c_{44}) \left(\frac{\partial^2 v}{\partial x \partial y} + \frac{\partial^2 w}{\partial x \partial z} \right) = \rho \frac{\partial^2 u}{\partial t^2}$$



L. Landau and E. Lifshitz, *Theory of Elasticity*, Butterworth-Heinemann, Oxford, 1986.

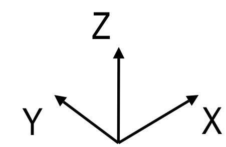
BULK WAVES

In isotropic bulk:

$$\frac{\partial^2 u}{\partial z^2} - \frac{1}{v_T^2}\frac{\partial^2 u}{\partial t^2} = 0$$

$$\frac{\partial^2 v}{\partial z^2} - \frac{1}{v_T^2}\frac{\partial^2 v}{\partial t^2} = 0$$

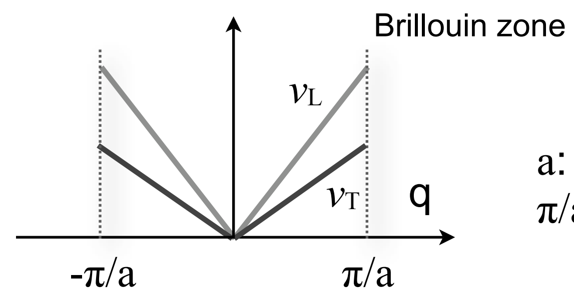
transverse waves



general solution
$u(z,t)=A\cdot e^{i(qz-\omega_q t)}+B\cdot e^{-i(qz-\omega_q t)}$

$$\frac{\partial^2 w}{\partial z^2} - \frac{1}{v_L^2}\frac{\partial^2 w}{\partial t^2} = 0$$

longitudinal wave



a: lattice parameter
$\pi/a \sim 10^7$-10^8 cm^{-1}

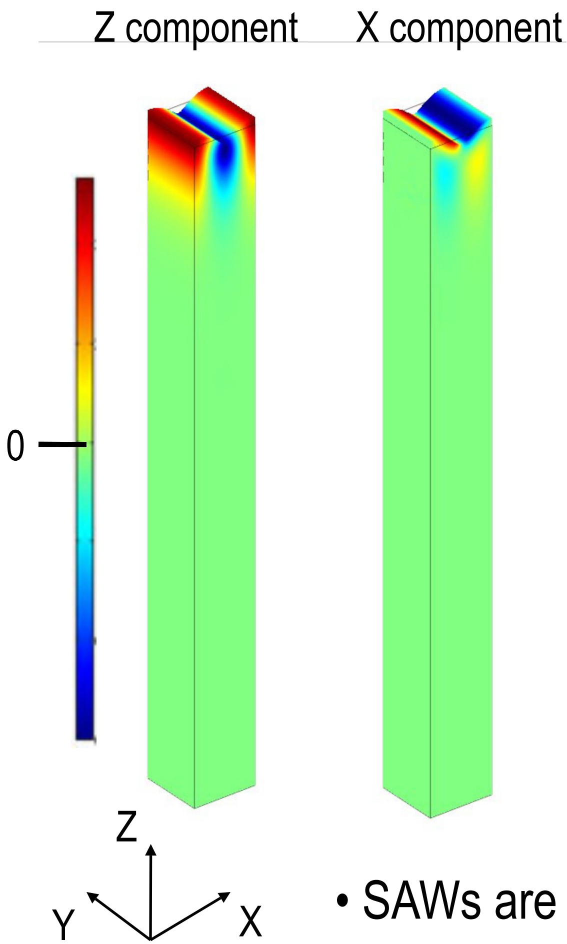
linear dispersion
(neglecting border zone effects)

$\omega_q = v_T|q|$

$\omega_q = v_L|q|$

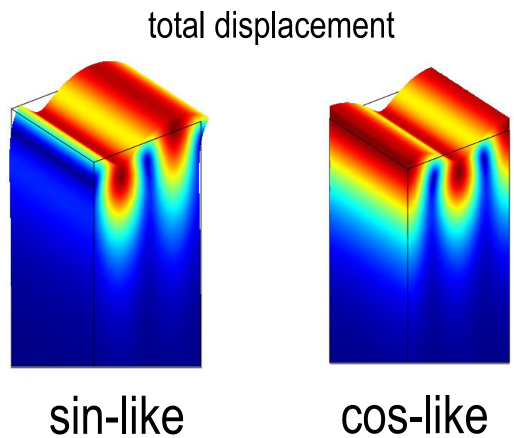
Si
$v_T \sim$ 5800 m/s
$v_L \sim$ 8400 m/s

SURFACE ACOUSTIC WAVES



Particular solution of the eigenvalue problem at the surface:

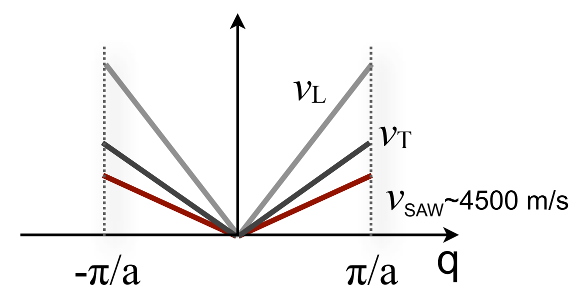
$$\vec{\nabla} \cdot (c\vec{\nabla}\vec{u}) = \rho\omega_k^2\vec{u}$$



two degenerate eigenmodes

$$\omega_q = \xi v_T |q|$$

isotropic silicon $\xi \cong 0.92$



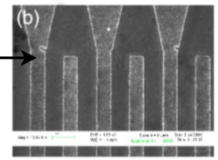
- SAWs are mixed modes → u,w displacement
- Eigenmodes → no damping

SAWs in the GHz

InterDigital Transducers (IDT)

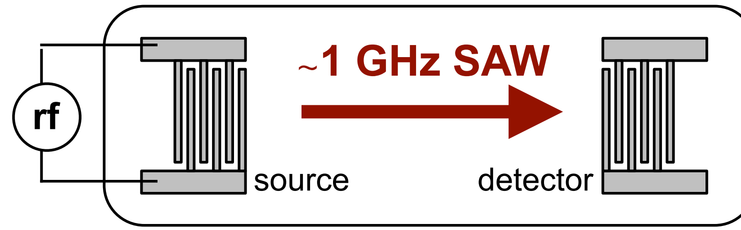
piezo-electric material

~3 μm

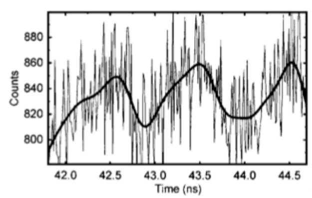


SEM image

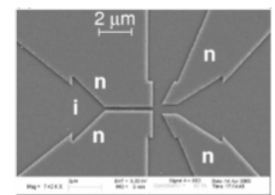
heterostructure



- Manipulation of electrons through acoustoelectric effect in:
  - pLED



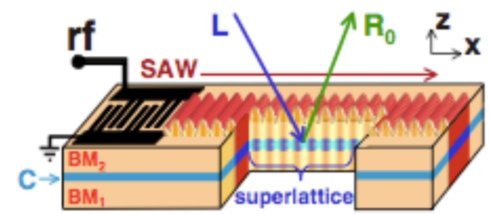
  - n-i-n device



M. Cecchini et al., *Appl. Phys. Lett.* **86**, 241107 (2005)

M. Cecchini et al., *Appl. Phys. Lett.* **88**, 212101 (2006)

- Manipulation of light in:
  - semiconductor photon microcavity
    M.M. de Lima et al., *Phys. Rev. Lett.* **94**, 126805 (2005)
  - semiconductor polariton microcavity
    M.M. de Lima et al., *Phys. Rev. Lett.* **97**, 045501 (2006)
    J. Rudolph et al., *Phys. Rev. Lett.* **99**, 047602 (2007)



PHONONS

Displacement operator in 2nd quantization:

annihilation and creation operators

$$\hat{\vec{u}}_\mu(\mathbf{r},t) = \sum_q \sqrt{\frac{\hbar}{2\rho\omega_{q\mu}}}\vec{e}_{q\mu}\left[\hat{a}_{q\mu}e^{i(\mathbf{q}\cdot\mathbf{r}-\omega t)} + \hat{a}^\dagger_{q\mu}e^{i(\mathbf{q}\cdot\mathbf{r}-\omega t)}\right]$$

classical solutions

$$\left[\hat{a}_{q\mu}, \hat{a}^\dagger_{k\nu}\right] = \delta_{qk}\delta_{\mu\nu}$$

$$\hat{a}_{q\mu}|n_{q\mu}\rangle = \sqrt{n_{q\mu}}|n_{q\mu}-1\rangle$$

$$\hat{a}^\dagger_{q\mu}|n_{q\mu}\rangle = \sqrt{n_{q\mu}+1}|n_{q\mu}+1\rangle$$

PHONON STATE

$$|n_{q\mu}\rangle$$

$$\langle n_{q\mu}|\hat{\vec{u}}|n_{q\mu}\rangle = 0$$

no classical displacement !

$$\Delta\vec{u}^2 = \frac{\hbar}{2\rho\omega_{q\mu}V}\left(n_{q\mu}+\frac{1}{2}\right)$$

COHERENT STATE

$$\hat{a}_{q\mu}|\alpha_{q\mu}\rangle = \alpha_{q\mu}|\alpha_{q\mu}\rangle \longrightarrow |\alpha_{q\mu}\rangle = e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n_{q\mu}}{\sqrt{n!}}|n_{q\mu}\rangle$$

$$\langle\alpha_{q\mu}|\hat{\vec{u}}|\alpha_{q\mu}\rangle = \sqrt{\frac{\hbar}{2\rho\omega_{q\mu}}}\vec{e}_{q\mu}2\left[cos(\mathbf{q}\cdot\mathbf{r}-\omega t)\right]$$

classical displacement

$$\Delta\vec{u}^2 = \frac{\hbar}{2\rho\omega_{q\mu}V}\frac{1}{2}$$

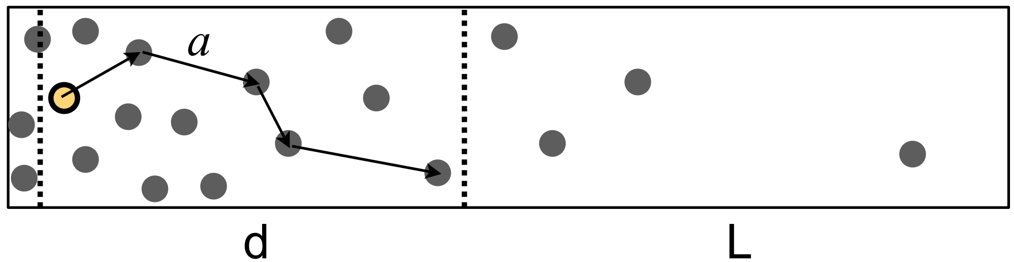
phonon is not a “small” classical displacement moving in the bulk!

CLASSICAL HEAT TRANSPORT BY PHONONS

$n_{ph}(T) \approx e^{-E/K_BT}$

$K_BT \approx 26$ meV, @300 K

$\lambda = h v_s / K_BT \sim 10$ Å



phonons→

- moving particles carrying $\hbar\omega_0$ energy
- a mean free path between ph-ph scattering
- τ mean free time between ph-ph scattering

SPACE DOMAIN		*← approximations →*		*TIME DOMAIN*	
$\lambda \ll a$	phonon is actually a wavepacket with $\Delta k < k_0$	SLOWLY VARYING APPROXIMATION	phonon is actually a wavepacket with $\Delta k < k_0$	$2\pi/\omega_0 \ll \tau$	
$a \ll d$	the size of the heat transfer process is larger than a (~10 nm in metals)	STATISTICAL APPROACH (quasi-equilibrium)	the timescale of the heat transfer process is larger than τ (~2 ps in metals)	$\tau \ll t$	***micro-scale heat transfer***
$\lambda \ll L$	the mode distance $2\pi/L$ can be neglected	CONTINUOUS CLASSICAL MEDIUM	the phonon period is shorter than the time necessary to travel through the system	$2\pi/\omega_0 \ll L/v_s$	***quantum effects***

MACRO-SCALE THERMODYNAMICS

conservation energy equation:

$$C_p \frac{\partial T(\mathbf{r},t)}{\partial t} = w(\mathbf{r},t) - \overrightarrow{\nabla} \cdot \overrightarrow{q}(\mathbf{r},t)$$

heat capacity [J/K·m^3]

volumetric heat source [W/m^3]

heat flux vector [W/m^2]

thermal conductivity [W/K·m]

constitutive equation relating the heat flux to the temperature gradient (Fourier's law)

$$\overrightarrow{q}(\mathbf{r},t) = -k\overrightarrow{\nabla}T(\mathbf{r},t)$$

the response of the heat flux to the temperature gradient is immediate, i.e. at the same time

partial derivative equation for T(**r**,t)

$$\overrightarrow{\nabla}^2 T(\mathbf{r},t) + \frac{w(\mathbf{r},t)}{k} = \frac{C_p}{k}\frac{\partial T(\mathbf{r},t)}{\partial t}$$

APPROXIMATIONS:

- infinite speed of heat propagation
- timescale larger than heat propagation
- no cause-effect discrimination

MICRO-SCALE THERMODYNAMICS

conservation energy equation at time t: $$C_p \frac{\partial T(\mathbf{r},t)}{\partial t} = w(\mathbf{r},t) - \overrightarrow{\nabla} \cdot \overrightarrow{q}(\mathbf{r},t)$$

constitutive equation relating the heat flux to the temperature gradient

$$\overrightarrow{q}(\mathbf{r}, t+\tau_q) = -k\overrightarrow{\nabla} T(\mathbf{r}, t+\tau_T)$$

1st order expansion

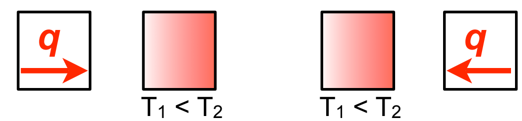
$$\overrightarrow{q}(\mathbf{r},t) + \tau_q \frac{\partial \overrightarrow{q}}{\partial t} \simeq -k\left[\overrightarrow{\nabla} T(\mathbf{r},t) + \tau_T \frac{\partial \overrightarrow{\nabla} T}{\partial t}\right]$$

$$\overrightarrow{\nabla}^2 T + \tau_T \frac{\partial}{\partial t}(\overrightarrow{\nabla}^2 T) + \frac{1}{k}\left(w + \tau_q \frac{\partial w}{\partial t}\right) = \frac{C_p}{k}\frac{\partial T}{\partial t} + \frac{C_p \tau_q}{k}\frac{\partial^2 T}{\partial t^2}$$

mixed-derivative term — apparent heat source — thermal wave $v_{th}^2 = k/C_p\tau_q$

the local response of the heat flux to the temperature gradient can be delayed

$\tau_T > \tau_q$ — $\tau_T < \tau_q$



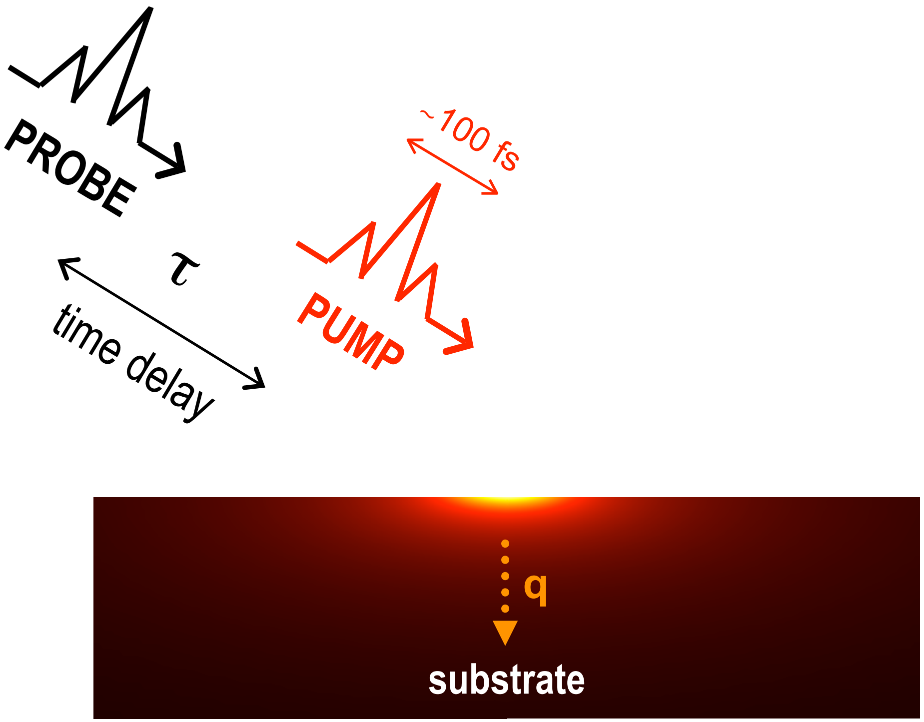
temperature gradient follows heat flux — heat flux follows temperature gradient

MICRO-SCALE PHYSICS:

- finite speed of heat propagation
- dynamics of heat propagation
- cause-effect discrimination
- classical limit if τ_T, $\tau_q \rightarrow 0$

ULTRAFAST HEAT TRANSFER

Ultrashort laser pulses are the ideal tool to investigate non-equilibrium and micro-scale heat transfer



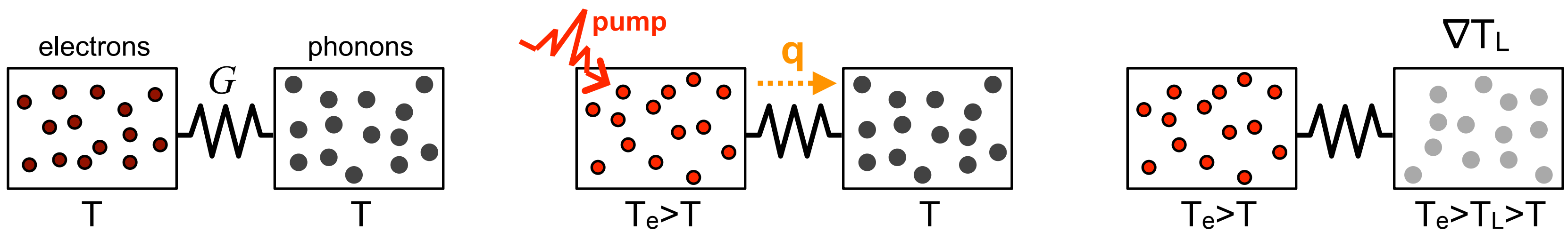
MAIN ADVANTAGES:

- 100 fs time resolution
- non-contact and non-perturbing probe
- investigation of electron-phonon thermalization
- investigation of heat-transfer at the nanoscale (ex. metallic thin films)

MAIN PROBLEMS:

- indirect measurement of electronic properties

TWO TEMPERATURE MODEL IN METALS



t=0
equilibrium

t~100 fs
electron heating and heat flux to phonons

t~1-2 ps
phonon heating and temperature gradient

laser intensity profile

coupled energy equations for T_e and T_L

$$\begin{cases} C_e \frac{\partial T_e}{\partial t} = w(t) - G \cdot (T_e - T_L) + \vec{\nabla} \cdot (k_e \vec{\nabla} T_e) \\ C_L \frac{\partial T_L}{\partial t} = G \cdot (T_e - T_L) + \vec{\nabla} \cdot (k \vec{\nabla} T_L) \end{cases}$$

phonon diffusion neglected ($k \ll k_e$)

non-linear solutions

$C_e = C_e(T_e) \cong \gamma_e \cdot T_e$

$k_e = k_e(T_e)$

$G = G(T_e)$

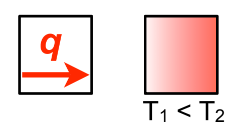
single energy equations for T_L

$$\vec{\nabla}^2 T_L + \frac{C_L}{G}\frac{\partial}{\partial t}(\vec{\nabla}^2 T_L) + \frac{w(t)}{k_e} = \frac{C_e + C_L}{k_e}\frac{\partial T_L}{\partial t} + \frac{C_L C_e}{k_e G}\frac{\partial^2 T_L}{\partial t^2}$$

$\tau_T = C_L/G \cong 90$ ps

$\tau_q = (C_e/G)\cdot(k/k_e) \cong 0.7$ ps

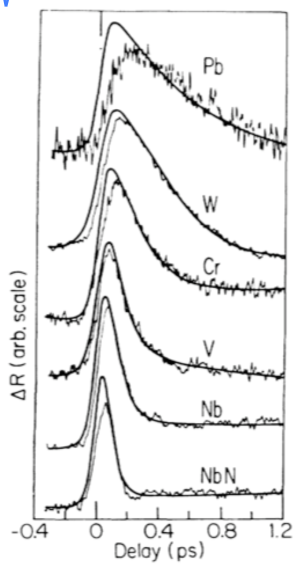
@ Au



temperature gradient follows heat flux

D.Y. Tzou, *Macro- to Microscale Heat Transfer,* Taylor&Francis, 1997.

BULK EXPERIMENTS



time-resolved reflectivity experiments:

$\Delta R(t)/R=(T_e(t)-T_{e0})/T_{eo}$

el-ph coupling $\lambda<\omega^2>$ constant is direct accessible

$$G=3\hbar\lambda<\omega^2>\gamma_e/\pi k_B$$

P.B. Allen, *Phys. Rev. Lett.* **59**, 1460 (1987)

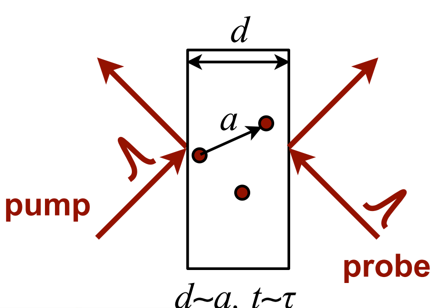
determination of $\lambda<\omega^2>$ in metallic superconductors

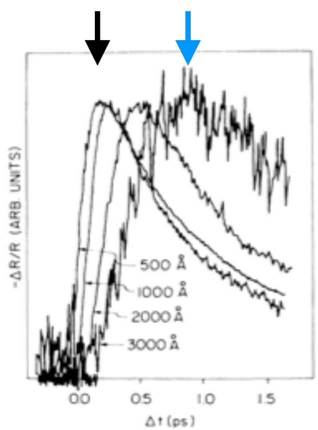
	$T_c(0)$ (K)[a]	$\lambda_{exp}\langle\omega^2\rangle$ (meV^2)	$\langle\omega^2\rangle$ (meV^2)	λ_{exp}	λ_{th}
Cu	590	29 ± 4	377[b]	0.08 ± 0.01	0.10[b]
Au	650	23 ± 4	178[c]	0.13 ± 0.02	0.15[c]
Cr	716	128 ± 15	987[d]	0.13 ± 0.02	...
W	1200	112 ± 15	425[e]	0.26 ± 0.04	0.26[e]
V	700	280 ± 20	352[f]	0.80 ± 0.06	0.82[f]
Nb	790	320 ± 30	275[g]	1.16 ± 0.11	1.04[g]
Ti	820	350 ± 30	601[g]	0.58 ± 0.05	0.54[g]
Pb	570	45 ± 5	31[i]	1.45 ± 0.16	1.55[i]
NbN	1070	640 ± 40	673[j]	0.95 ± 0.06	1.46[j]
V_3Ga	1110	370 ± 60	448[k]	0.83 ± 0.13	1.12[k]

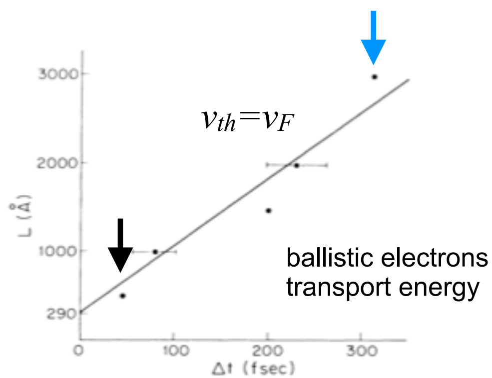
S.D. Brorson et al., *Phys. Rev. B* **64**, 2172 (1990)

THIN FILM EXPERIMENTS

time-resolved **back** reflectivity experiments on metal thin films







S.D. Brorson et al., *Phys. Rev. Lett.* **59**, 1962 (1987)

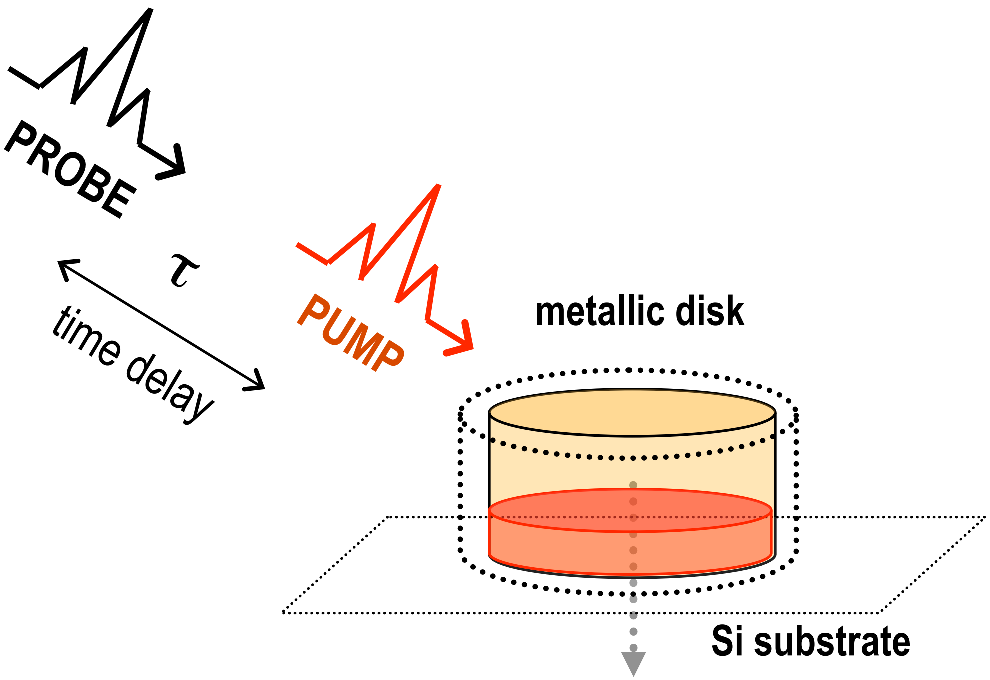
good agreement with the two-lags model when the thickness d ~100 nm

PROBLEMS:

- role of electron cooling
- role of planar diffusion of electrons
- role of planar diffusion of phonons and heat exchange problem

ULTRAFAST HEAT TRANSFER IN NANOSTRUCTURES

OUR GOAL



ADVANTAGES:

- simple ideal and “isothermal” system
- investigation of heat-transfer at the nanoscale through a simple interface
- confinement of the heat transfer
- possibility to scale down sizes ($\lambda \cong L$) and temperatures ($K_B T \cong E_{ph}(n+1) - E_{ph}(n)$)

BY-PRODUCT:

- thermomechanical coupling

- Introduction
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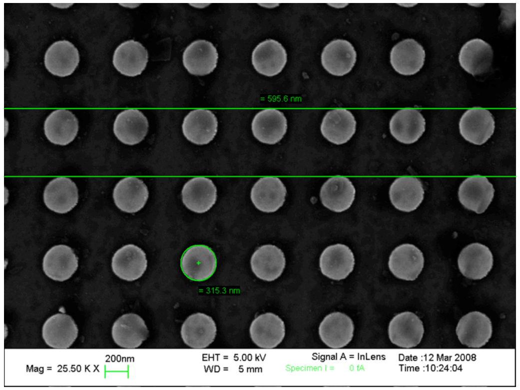
- Coherent excitation of GHz SAWs
- Birth of a SAW
- Calorimetry at the nanoscale
- Magnetoelastic interaction



FEEDBACK AND SAMPLES

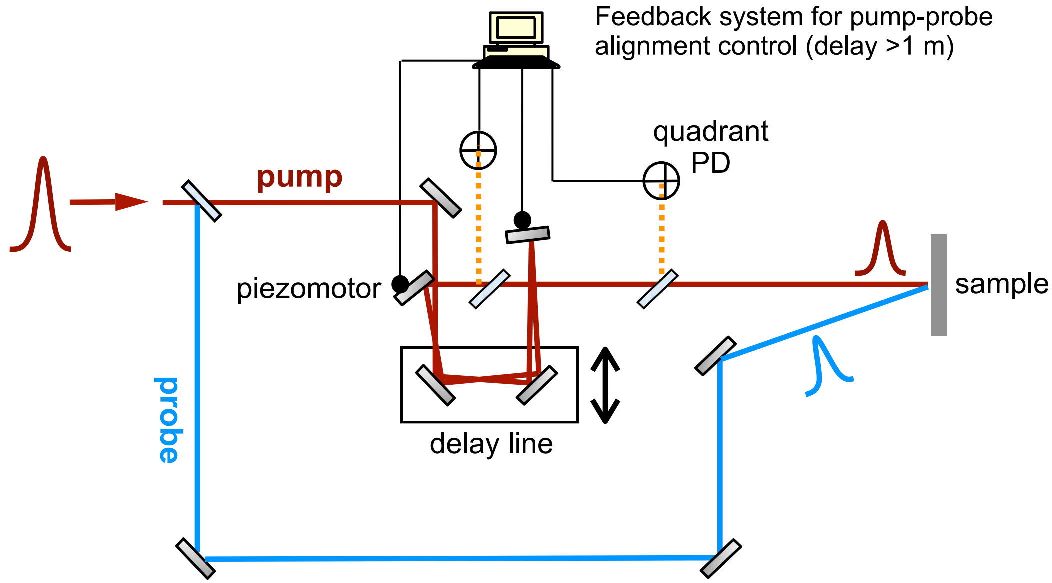
LIGHT SOURCE

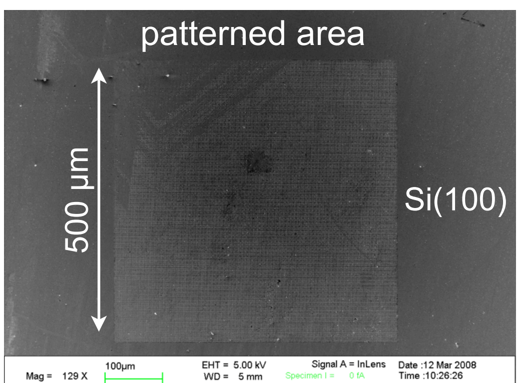
Ti:Sapphire oscillator

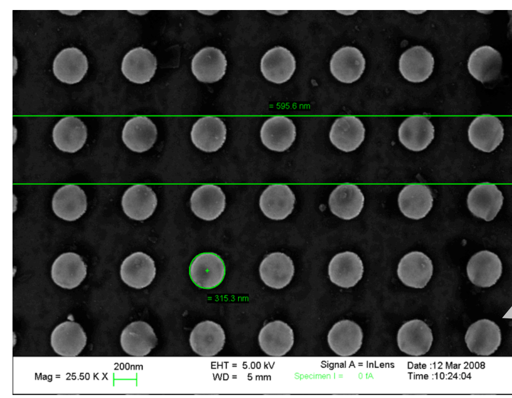
λ= 800 nm
τ =120 fs
80 MHz

E_{PUMP}≈10 nJ/pulse fwhm≈60 μm

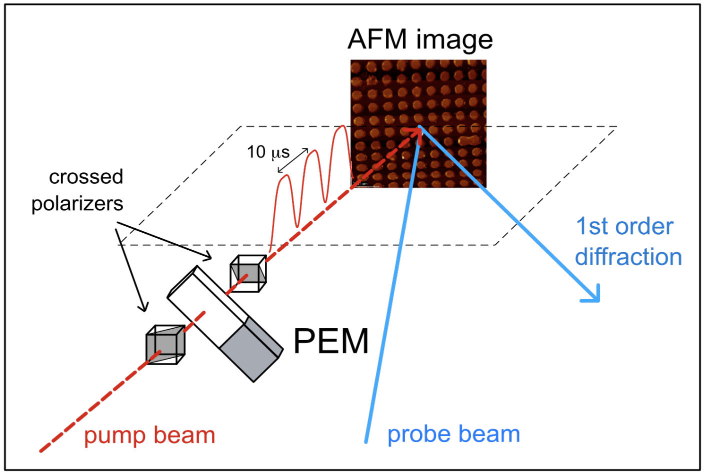
E_{PROBE}<1 nJ/pulse fwhm≈40 μm



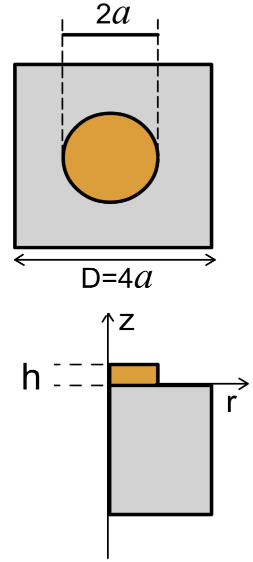




DIFFRACTED PATTERN



UNIT CELL



silicon — reflected intensity — disks

$$I_{refl} = \frac{R_{Si}(D^2 - \pi a^2) + R_{Py}\pi a^2}{D^2} I_{inc}$$

inverse disks array — diffracted intensity — disks array

$$I_{1d} = \frac{4\pi^2}{G^4}\left[R_{Si} y^2 J_1(y)^2 + R_{Py} y^2 J_1(y)^2\right]$$

$G=2\pi/D$ reciprocal wavevector
$y=Ga$

$$\frac{\delta I_{refl}}{I_{refl}} = \frac{1}{I_{refl}} \frac{\partial I_{refl}}{\partial a} \delta a \simeq 0.28 \frac{\delta a}{a}$$

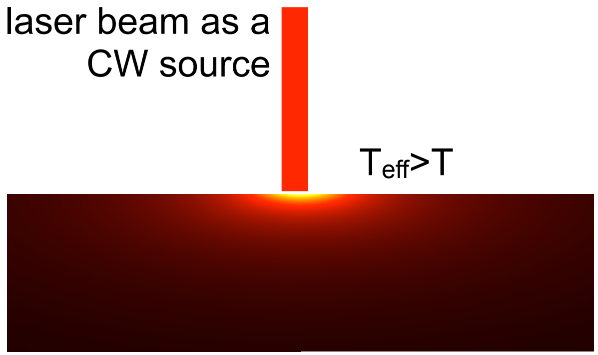
Reflected intensity variation

$$\frac{\delta I_{1d}}{I_{1d}} = \frac{1}{I_{1d}} \frac{\partial I_{1d}}{\partial a} \delta a \simeq 2.5 \frac{\delta a}{a}$$

Diffracted intensity variation

DIFFRACTION TECHNIQUE ENHANCES S/N RATIO

DECOUPLING AVERAGE HEATING



The average heating problem can be avoided by means of:

- Laser rep. rate decrease (pulse picker)

  ADV.: physical decrease of T_{eff}
  PROBL.: low statistics

- Fast pump modulation (PEM)

  ADV.: high statistics and lock-in technique
  PROBL.: **no** physical decrease of T_{eff}

FAST PUMP MODULATION

$P(t)=P_0\cos(\omega_{PEM}t)$

$$C_p \frac{\partial \Delta T(t)}{\partial t} = P(t) - a\Delta T(t)$$

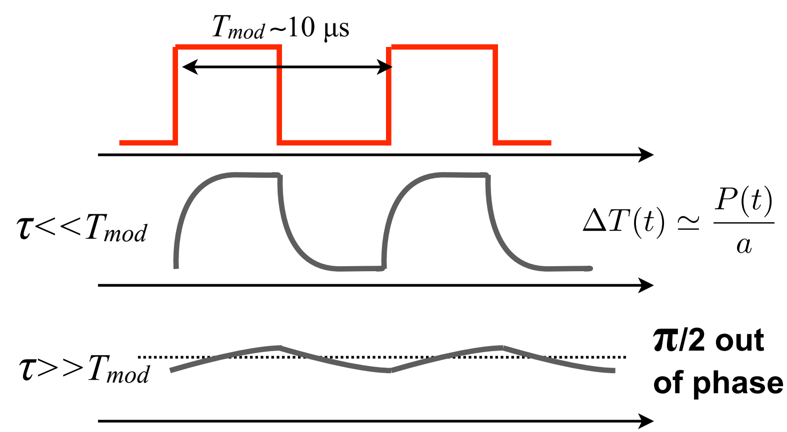
solution

power density dissipated/K

$$\Delta T(t) = \frac{1}{a}\int_{-\infty}^{+\infty} P(t-t')\frac{e^{-t'/\tau}}{\tau}H(t')dt' + \Delta T(0)e^{-t/\tau}H(t)$$

step function

$\tau = C_P/a \sim 1$ ms



$$\Delta T(t) \simeq \frac{1}{a\tau}\int_{-\infty}^{+\infty} P(t)dt + \Delta T(0)H(t)$$

THREE TIMESCALES

1) IMPULSIVE HEATING

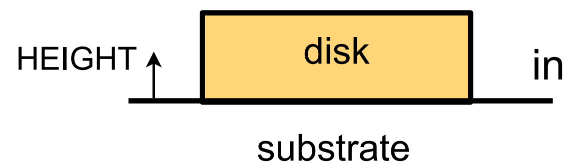
→ ISOTHERMAL DISK ($\Delta T \approx 8$ K) IN 1 ps

$$\frac{\delta a}{a} = \alpha \Delta T \simeq 2 \cdot 10^{-5}$$

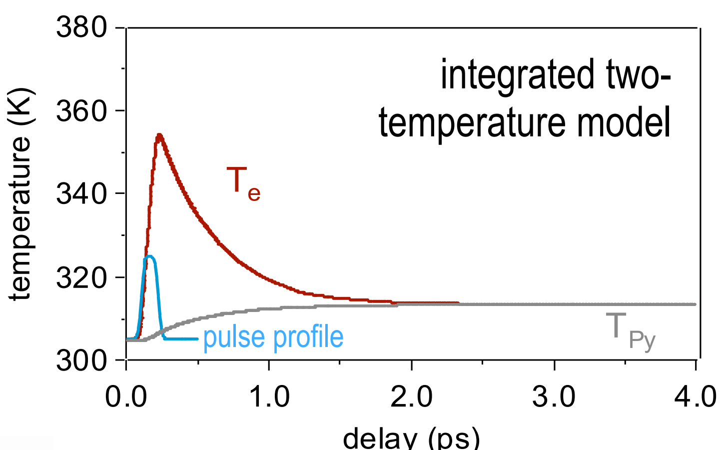
thermal expansion coefficient
$\alpha = 2 \cdot 10^{-6}\ K^{-1}$ @ Si

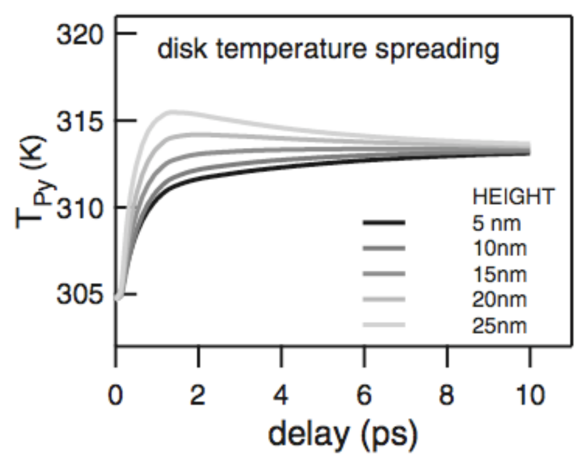
$C_e = C_e(T_e)$ — pen. depth

$$\begin{cases} C_e \frac{\partial T_e}{\partial t} = w(t) - G \cdot (T_e - T_{Py}) + \vec{\nabla} \cdot (k_e \vec{\nabla} T_e) \\ C_{Py} \frac{\partial T_{Py}}{\partial t} = G \cdot (T_e - T_{Py}) + \vec{\nabla} \cdot (k \vec{\nabla} T_{Py}) \end{cases}$$

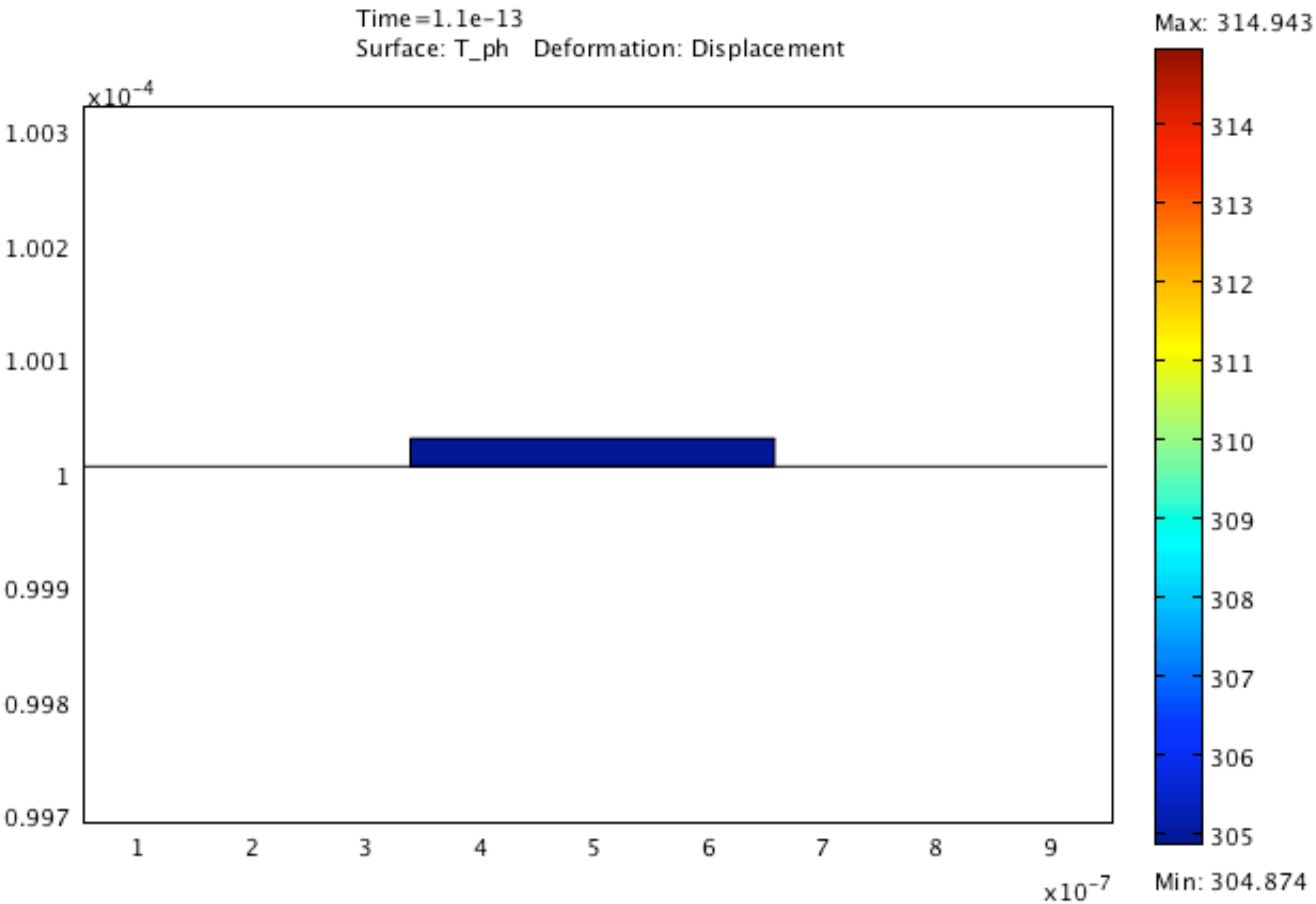


insulation boundary conditions





C.Giannetti et al., *Phys. Rev. B* **76**, 125413 (2007).

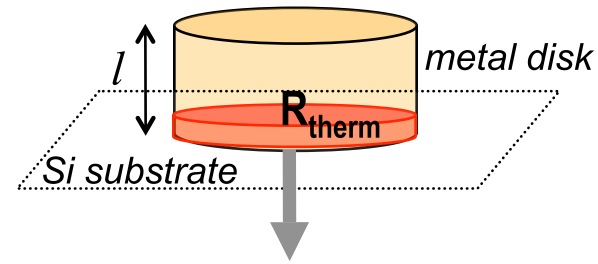

Time=1.1e-13
Surface: T_ph Deformation: Displacement
x10^-4
1.003
1.002
1.001
1
0.999
0.998
0.997
1
2
3
4
5
6
7
8
9
x10^-7
Max: 314.943
314
313
312
311
310
309
308
307
306
305
Min: 304.874

2) HEAT EXCHANGE PROCESS

boundary conditions

$$\hat{\mathbf{n}}_{Py} \cdot k_{Py} \nabla T_{Py} + (T_{Py} - T_{Si})/R_{th} = 0$$

$$-\hat{\mathbf{n}}_{Si} \cdot k_{Si} \nabla T_{Si} - (T_{Py} - T_{Si})/R_{th} = 0$$



$$\begin{cases} \Delta T(t) = \Delta T_0 \cdot e^{-t/\tau} \\ \tau = l C_s R_{therm} \end{cases}$$

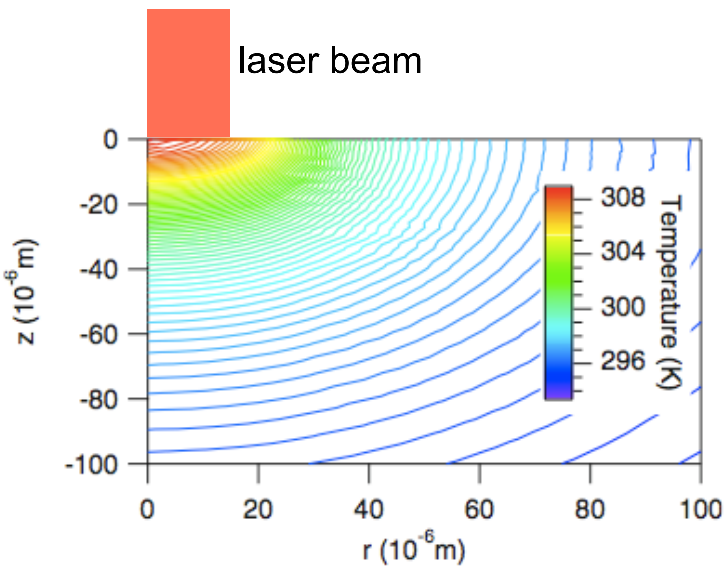
$R_{Therm} \sim 10^{-8}$ K·m²/W
$C_s \sim 2.2 \cdot 10^6$ J/(m³·K) $\rightarrow \tau \sim$ 1ns
$l \sim 50$ nm

R_{th}: interface thermal resistance (phonon mismatch, oxide,...)

3) AVERAGE HEATING

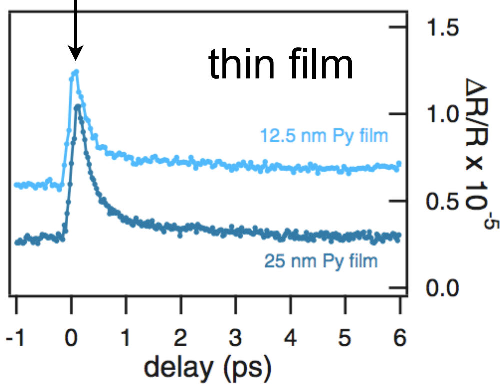
P_0=400 mW → $T_{eff} \sim 310$ K

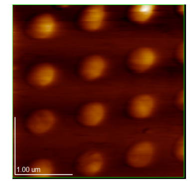
uniform heating in 10x20 μm²



FEMTOSECOND TIMESCALE

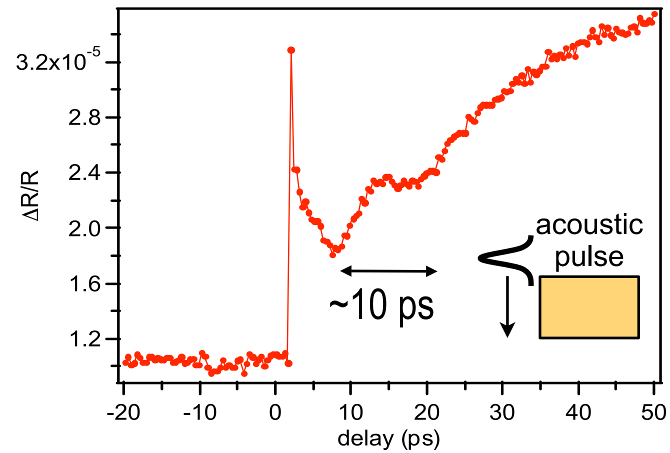
fast electronic dynamics
within two-temperature model



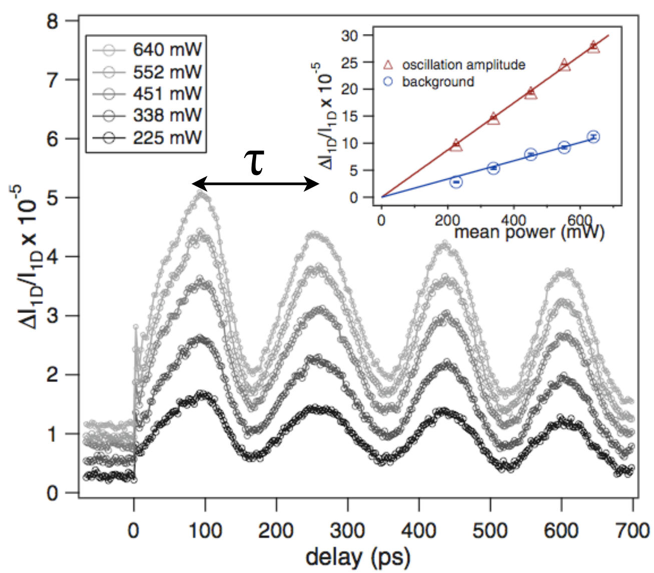


D=810±10 nm
$2a$=380 ±20 nm

patterned sample

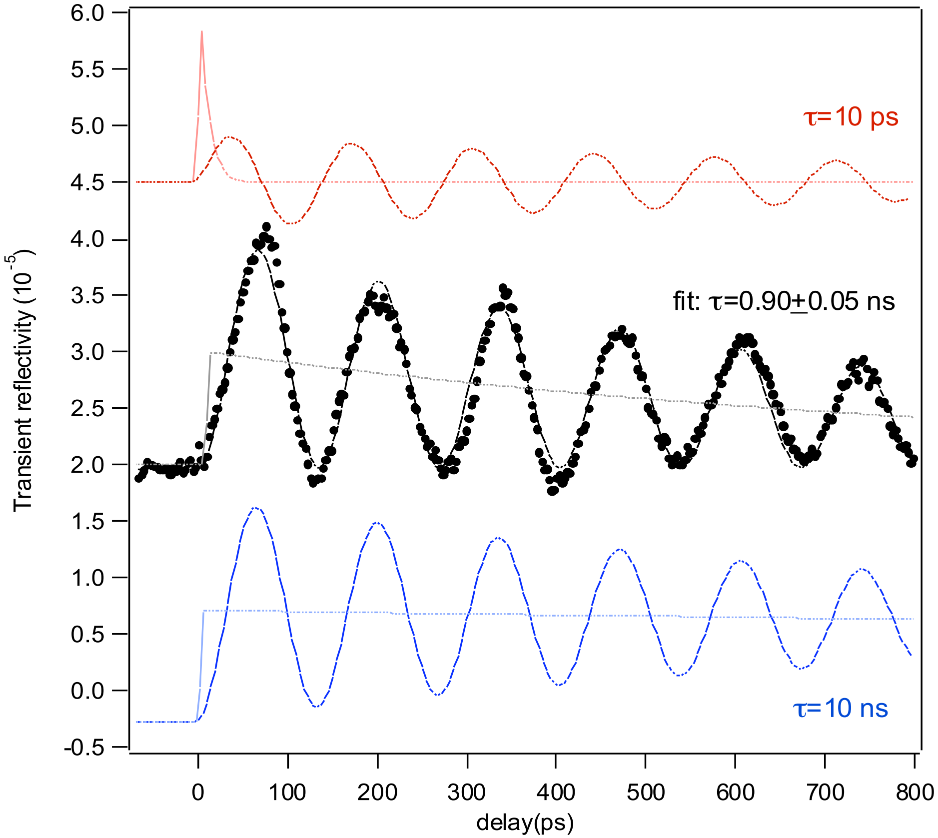


SUB-ns TIMESCALE



OSCILLATIONS:

- linear with pump power
- $\tau \cong 175$ ps



Harmonic oscillator model: the radial displacement $u_r(t)$ depends on the temperature of the disk.

$$\ddot{u}_r(t) = -\omega_0^2[u_r(t) - u_{r0}(t)] - 2\gamma\dot{u}_r(t)$$

$$u_{r0}(t) \propto H(t)e^{-t/\tau}$$

Solution:

$$u_r(t) \propto (e^{-t/\tau} - e^{-\gamma t}\cos\varpi t + \frac{\alpha}{\varpi}e^{-\gamma t}\sin\varpi t)$$

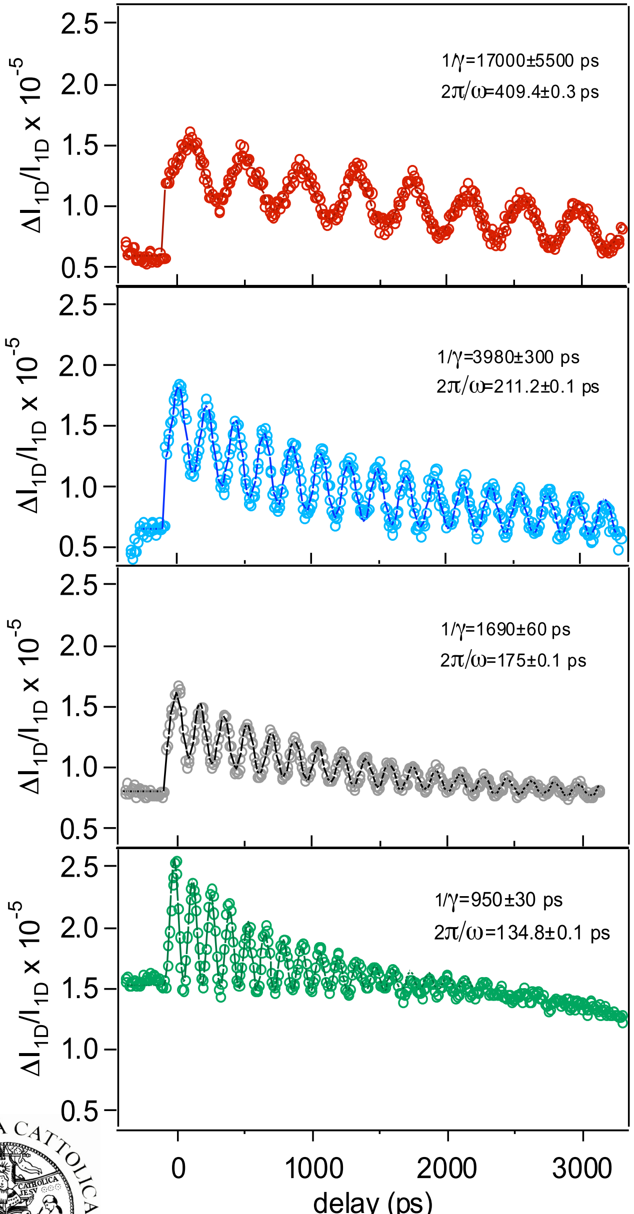
where $\varpi^2=\omega_0^2-\gamma^2$ and $\alpha=1/\tau-\gamma$

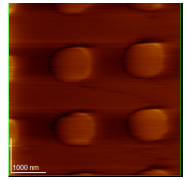
ω frequency → eigenfrequency of the mechanical oscillations

γ damping → elastic energy dissipation

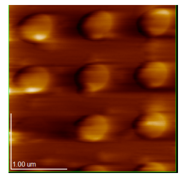
τ relaxation → heat exchange between the disk and the substrate

TIME-RESOLVED DIFFRACTION AS A FUNCTION OF THE ARRAY PERIODICITY

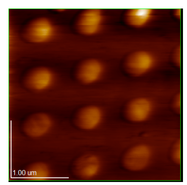




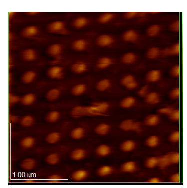
D=2018±30 nm
2*a*=990 ±10 nm



D=1020±50 nm
2*a*=470 ±10 nm



D=810±10 nm
2*a*=380 ±20 nm



D=610±3 nm
2*a*=320 ±10 nm

OSCILLATION PERIOD

400 ps

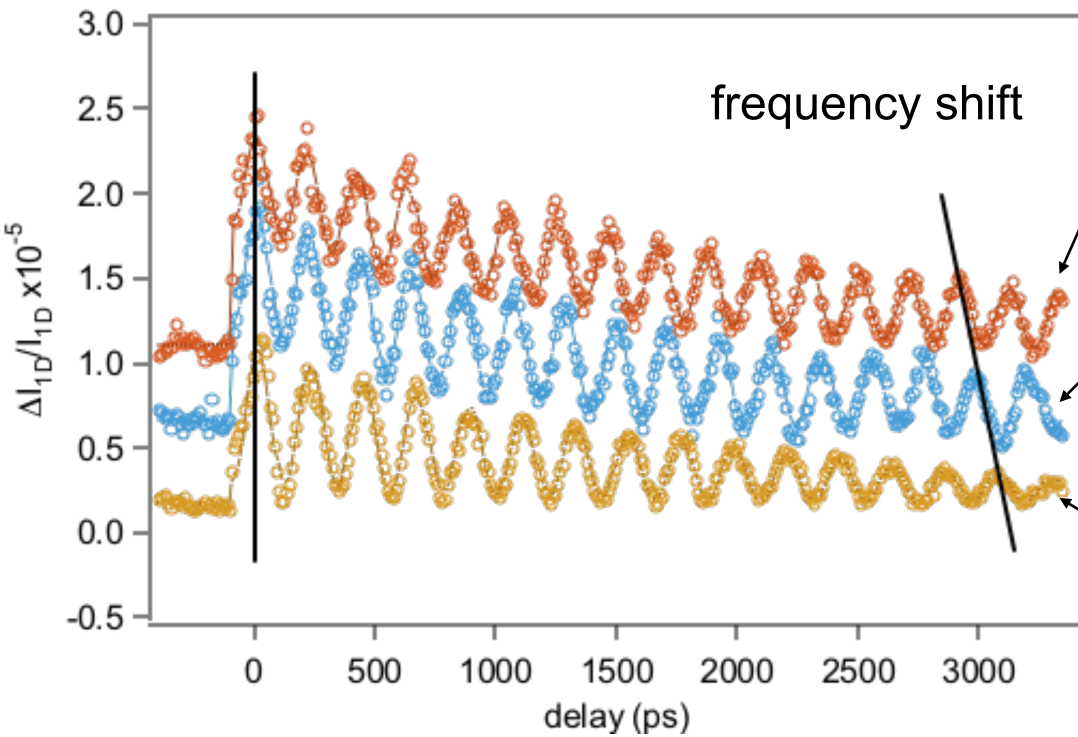
↓

150 ps

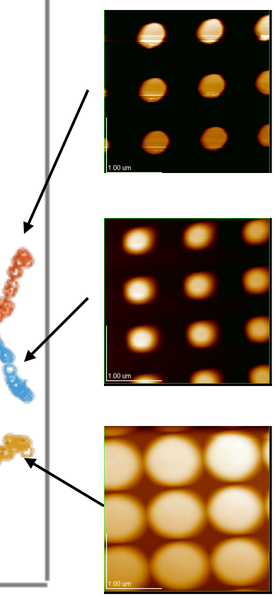
CONSTANT FILLING FACTOR

C.Giannetti et al., *Phys. Rev. B* **76**, 125413 (2007).

CHANGING THE DISK RADIUS



Constant periodicities and thicknesses
D=1000 nm; h=50 nm



$2a$=320 ±10 nm
T=207.6±0.1 ps

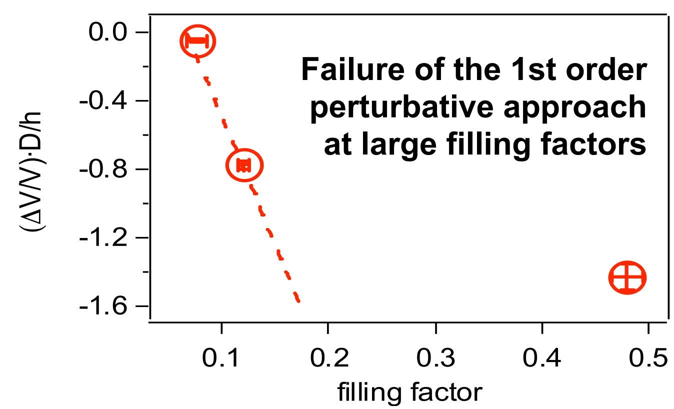
$2a$=395 ±7 nm
T=212.4±0.1 ps

$2a$=785 ±7 nm
T=218.9±0.1 ps

1st order perturbation theory predicts a frequency-shift, due to the mechanical loading, linear with the filling factor:

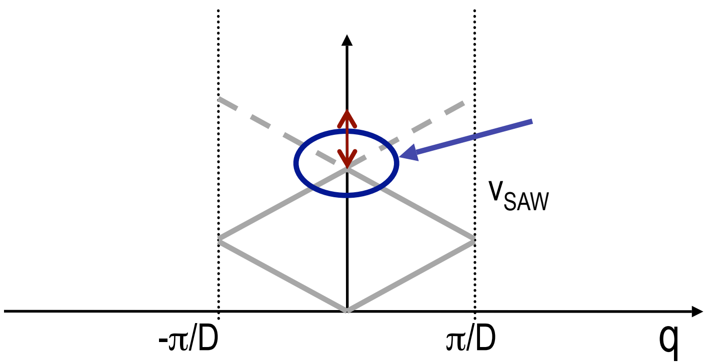
$$\frac{\Delta v_{SAW}}{v_{SAW}} = r_s \frac{h}{D}\eta \longrightarrow \boxed{\frac{\Delta v_{SAW}}{v_{SAW}}\frac{D}{h} \propto \eta}$$

r_S: reflection coeff. $\eta=\pi a^2/D^2$ filling factor



2D Surface Acoustic Waves

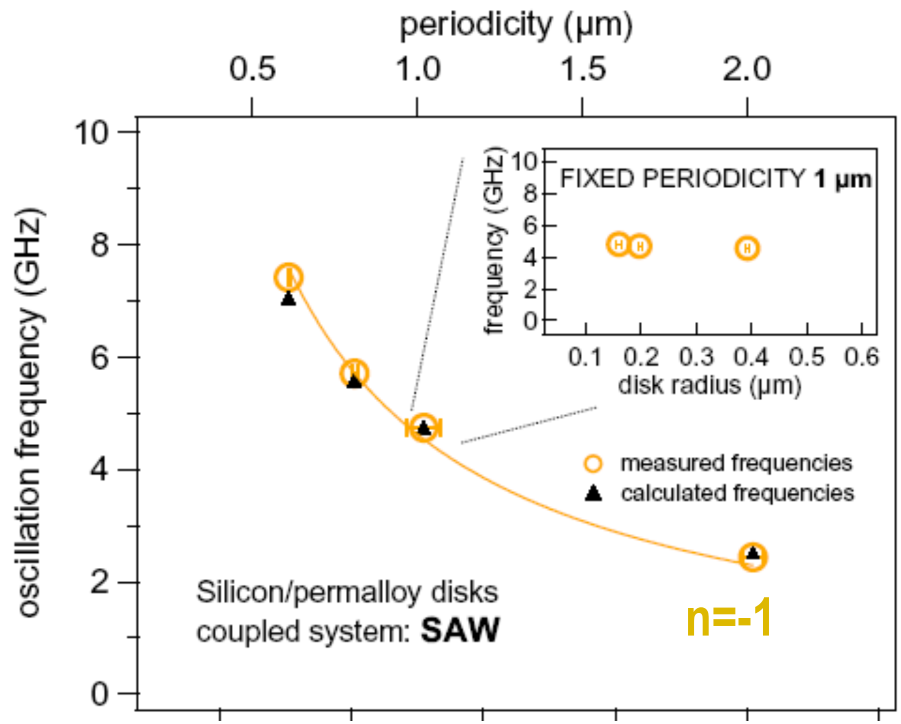
Dispersion relation of the 2D SAW excited at the center of the Brillouin zone.



$$\nu = \frac{V_{SAW}}{\lambda}$$

SURFACE WAVE VELOCITIES
V_{SAW}=4900 m/s @ Si(100)
V_{SAW}=5100 m/s @ Si(110)

SAW dispersion

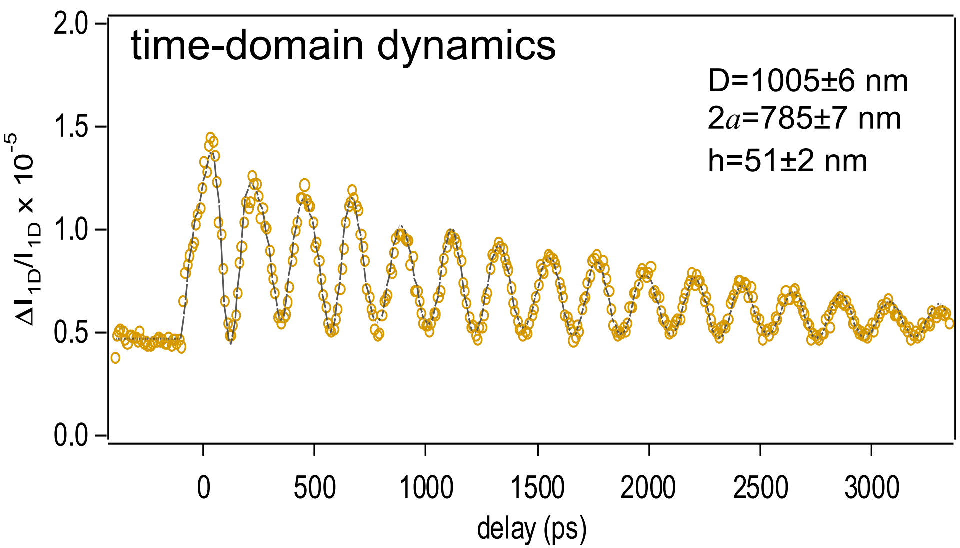


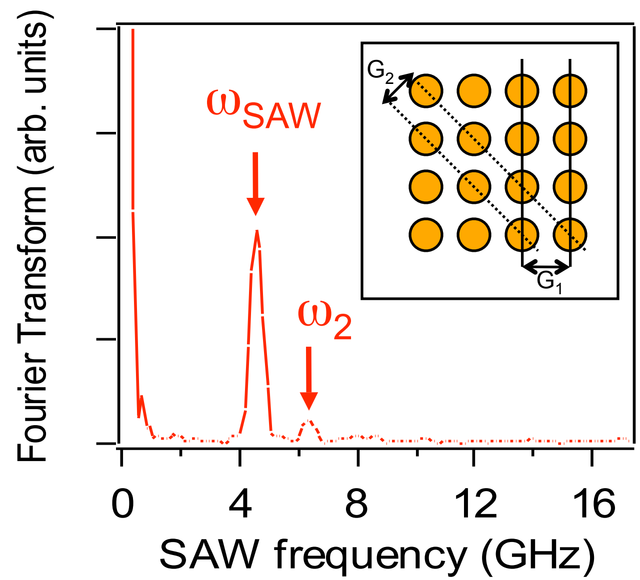
→ FREQUENCY DEPENDS ON PERIODICITY

→ V_{SAW}=4800±100 m/s

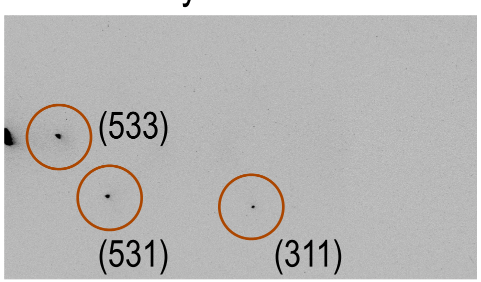
C.Giannetti et al., *Phys. Rev. B* **76**, 125413 (2007).

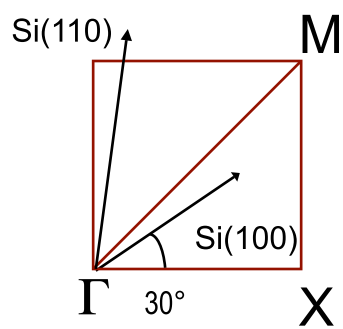
FREQUENCY ANALYSIS OF THE DIFFRACTED SIGNAL





X-ray diffraction





Detection of the diagonal collective mode:

ω_2/ω_{SAW}=1.386±0.004

influence of the substrate anisotropy (θ=35°)

C.Giannetti et al., *Phys. Rev. B* **76**, 125413 (2007).

SAW damping as a function of the array period

The energy radiation of SAWs to bulk modes γ, is calculated to be:

perpendicular stress at the interface

$$\sigma_{zz} = \rho_{Py} h_{Py} u_{z0} \omega^2$$

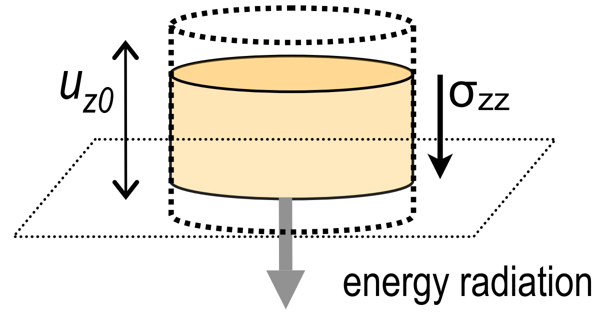
radiation rate per unit surface [J/(s·m²)]

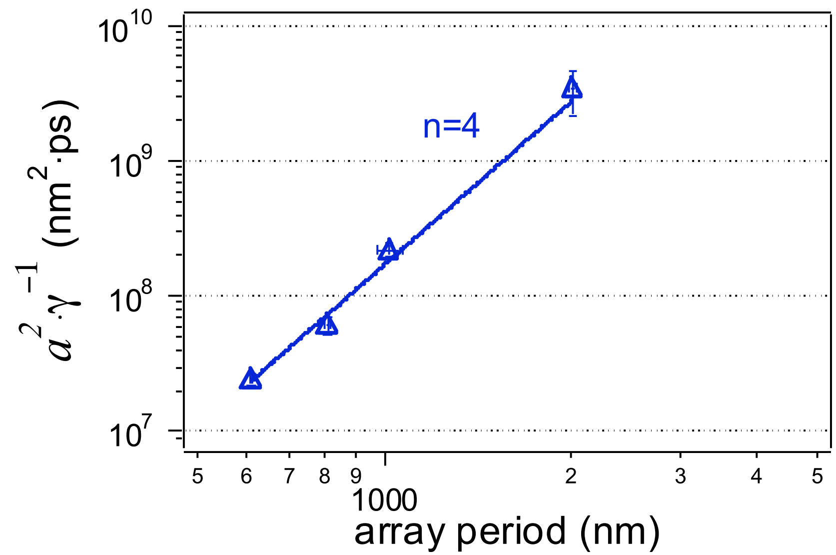
$$\frac{\gamma}{A} \propto \frac{\rho_{Py}^2 h_{Py}^2 u_{z0}^2 \omega^4}{\rho_{Si} v_{l,Si}}$$

$$u_{z0} \propto \Delta T \propto 1/h_{Py}$$

$$\boxed{\frac{1}{\gamma} \propto \frac{D^4}{a^2}}$$

perturbative regime

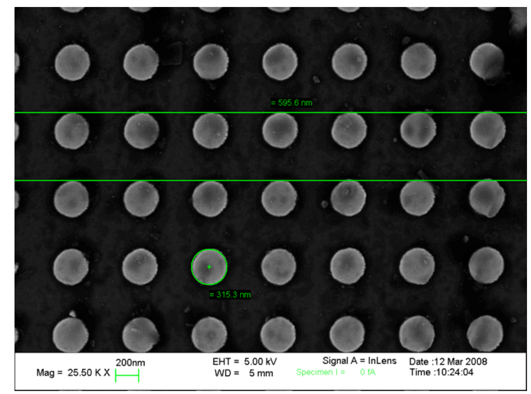




H. Lin, *et al.*, J. Appl. Phys. **73**, 37 (1993).

C.Giannetti et al., *Phys. Rev. B* **76**, 125413 (2007).

- Introduction
- SAWs and ultrafast heat transfer
- Coherent excitation of GHz SAWs
- Birth of a SAW
- Calorimetry at the nanoscale
- Magnetoelastic interaction

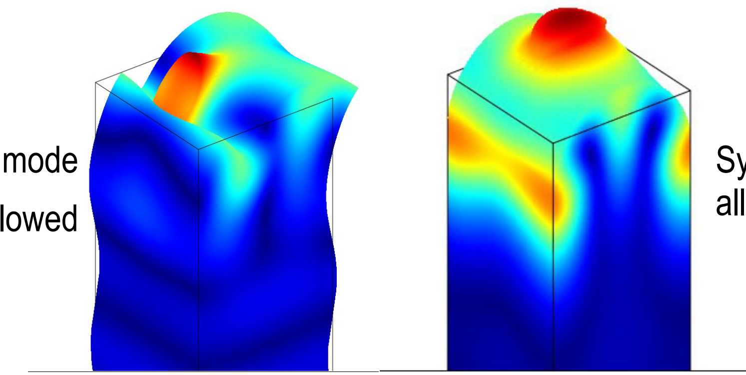


FINITE ELEMENT ANALYSIS OF EIGENMODES WITH DISKS

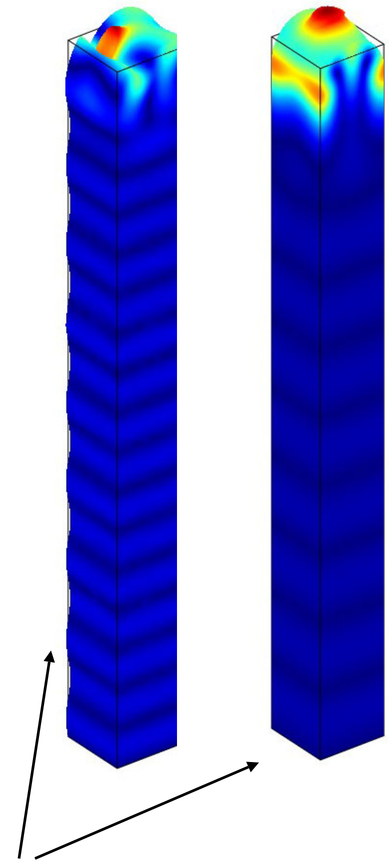
sin-like cos-like

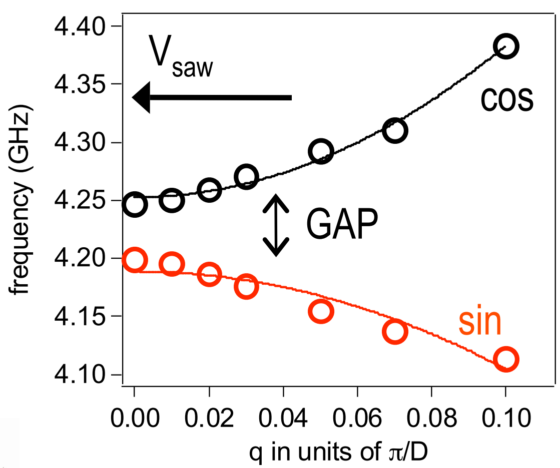
2a=320 nm

Asymmetric mode not allowed



Symmetric mode allowed



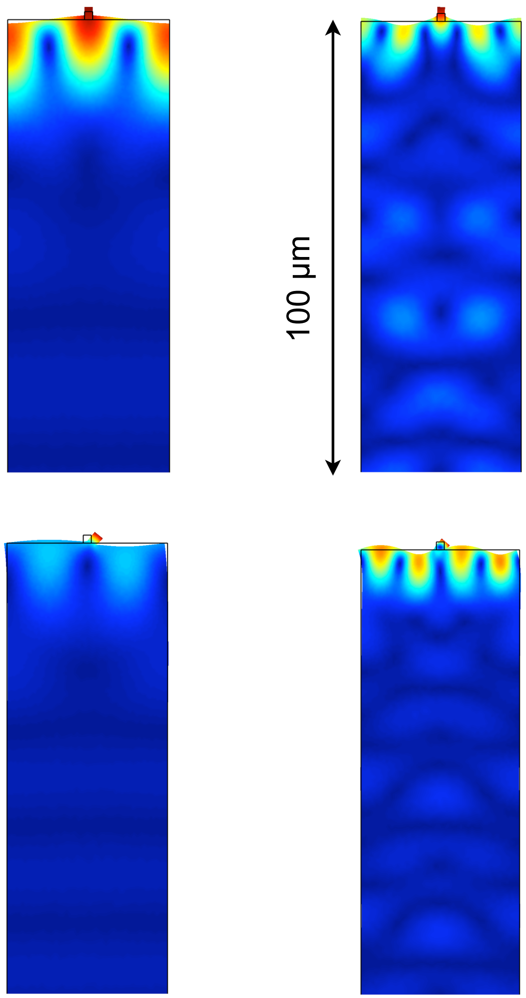


Opening of a gap in the surface modes

Coupling of SAWs with bulk modes: damping due to energy radiation in the substrate

2D COUPLING TO BULK MODES AND LIFETIME

1st harmonics | 2nd harmonics



cos-like
symmetric
5.05 GHz

cos-like
symmetric
9.63 GHz

sin-like
antisymmetric
4.94 GHz

sin-like
antisymmetric
10.6 GHz

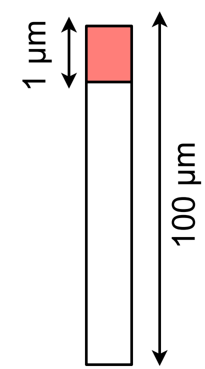
perturbative regime:
small nanostructure (50 nm) in 2D

coupled SAWs are forced as eigenvalues of 100 µm cell

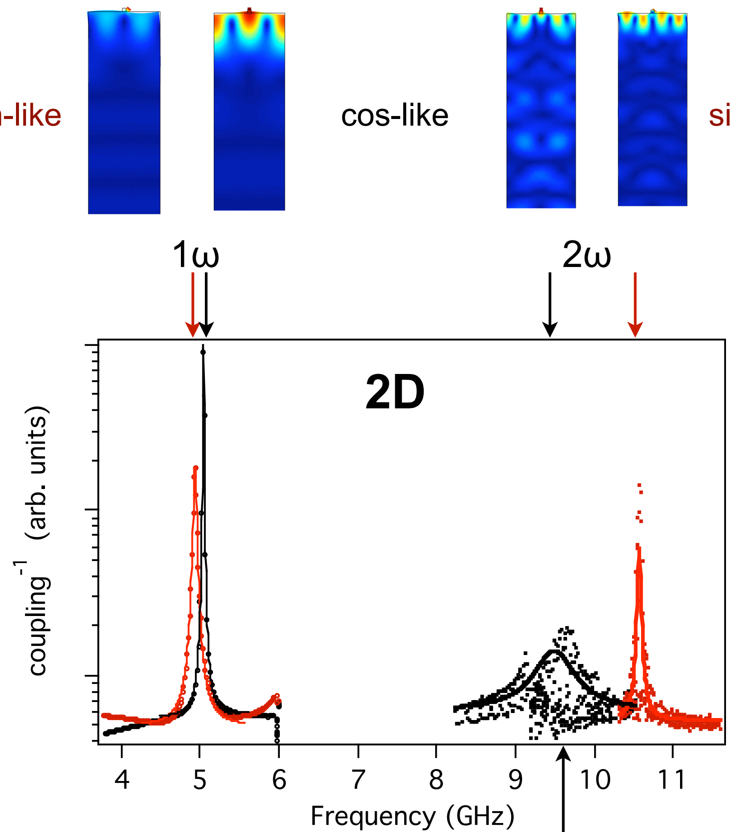
→ large number of modes

criterion for SAW discrimination?

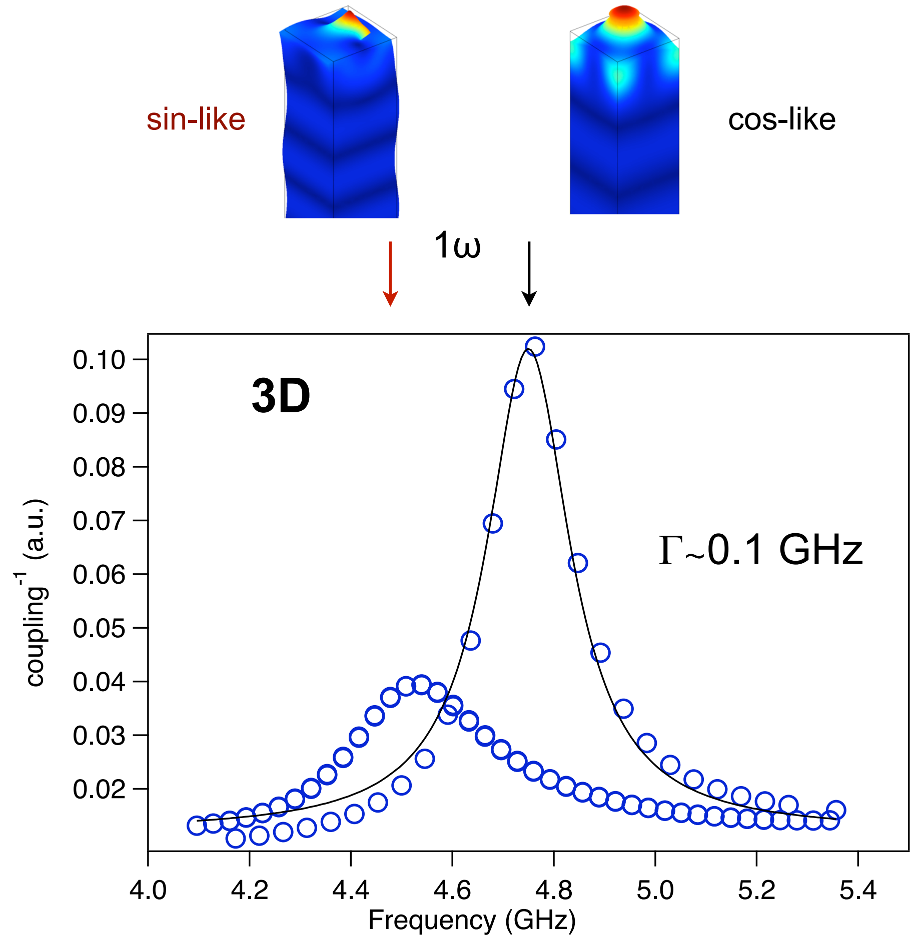
$$\frac{\text{energy within 1 µm}}{\text{energy within 100 µm}}$$



COUPLING TO BULK MODES AND LIFETIME

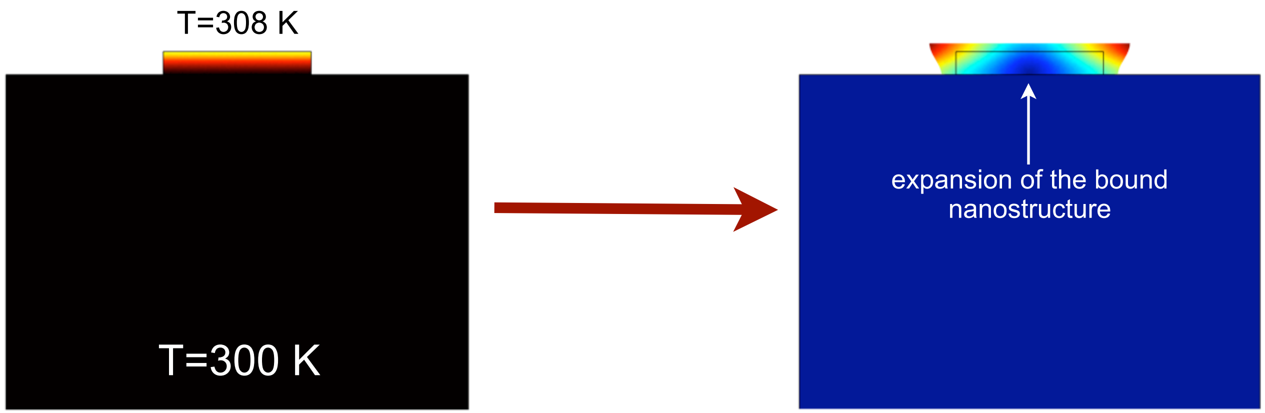


different coupling to bulk modes:
the symmetric mode radiates in the far field



$$F(t)=e^{-2\pi i\omega_0}e^{-2\Gamma|t|}$$

DISPLACEMENT RELATED TO IMPULSIVE HEATING



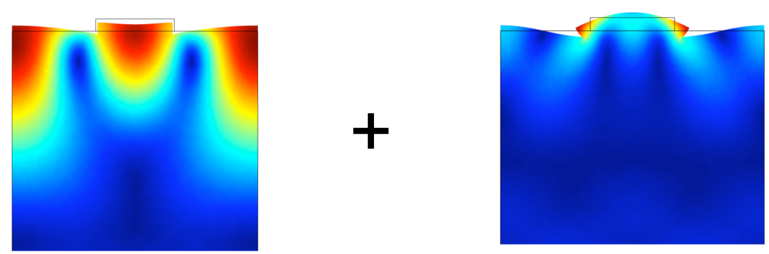
$$\frac{\delta a}{a} = \alpha \cdot \Delta T$$

temperature profile within 1 ps

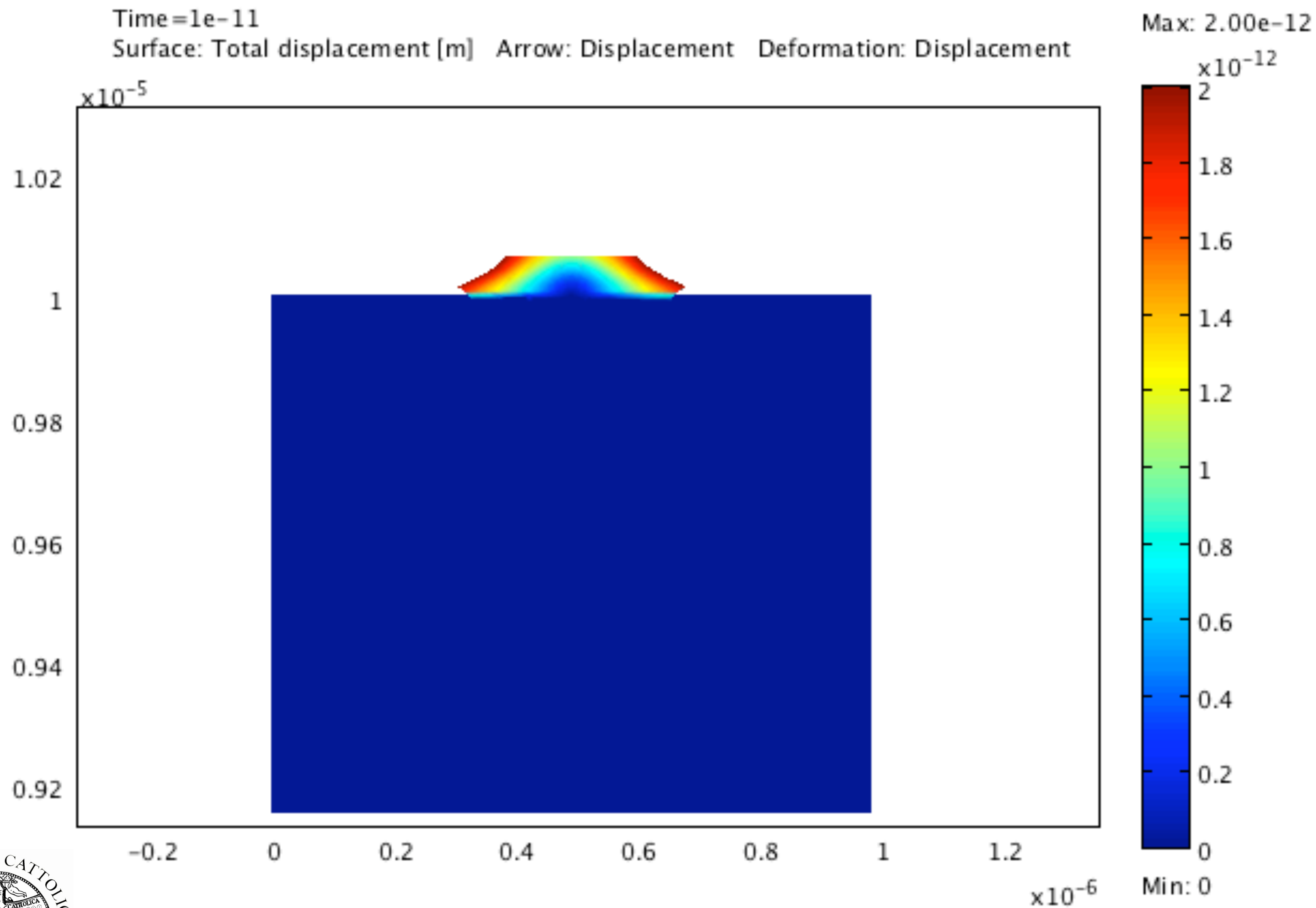
displacement due to thermal expansion

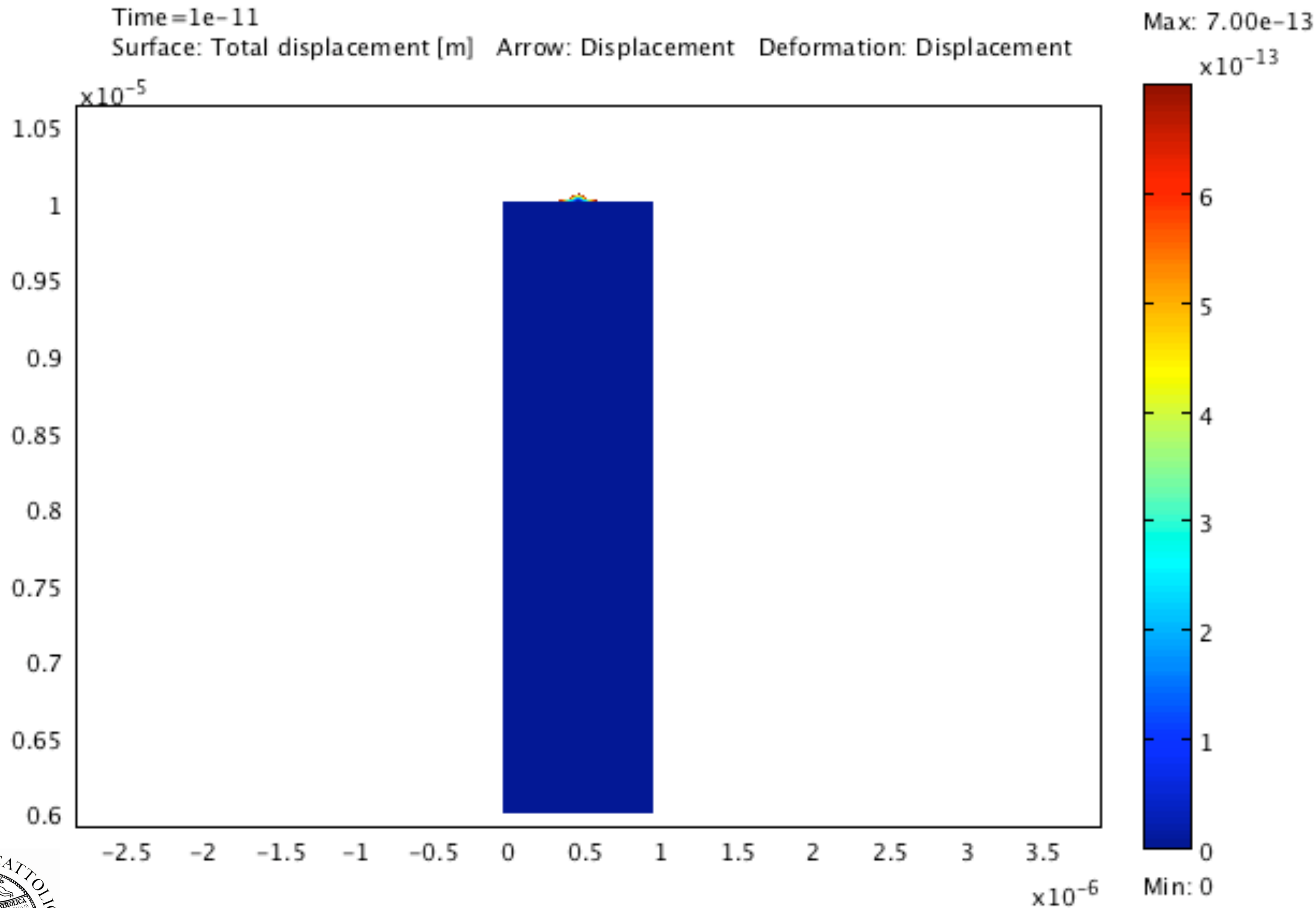
The initial displacement is the superposition of the calculated eigenmodes:

$$u(\mathbf{r},t)=\Sigma A_n u_n(\mathbf{r},t)$$

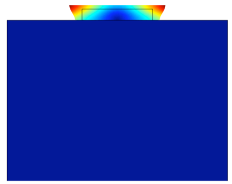


$u_1(\mathbf{r},0)$ + $u_2(\mathbf{r},0)$

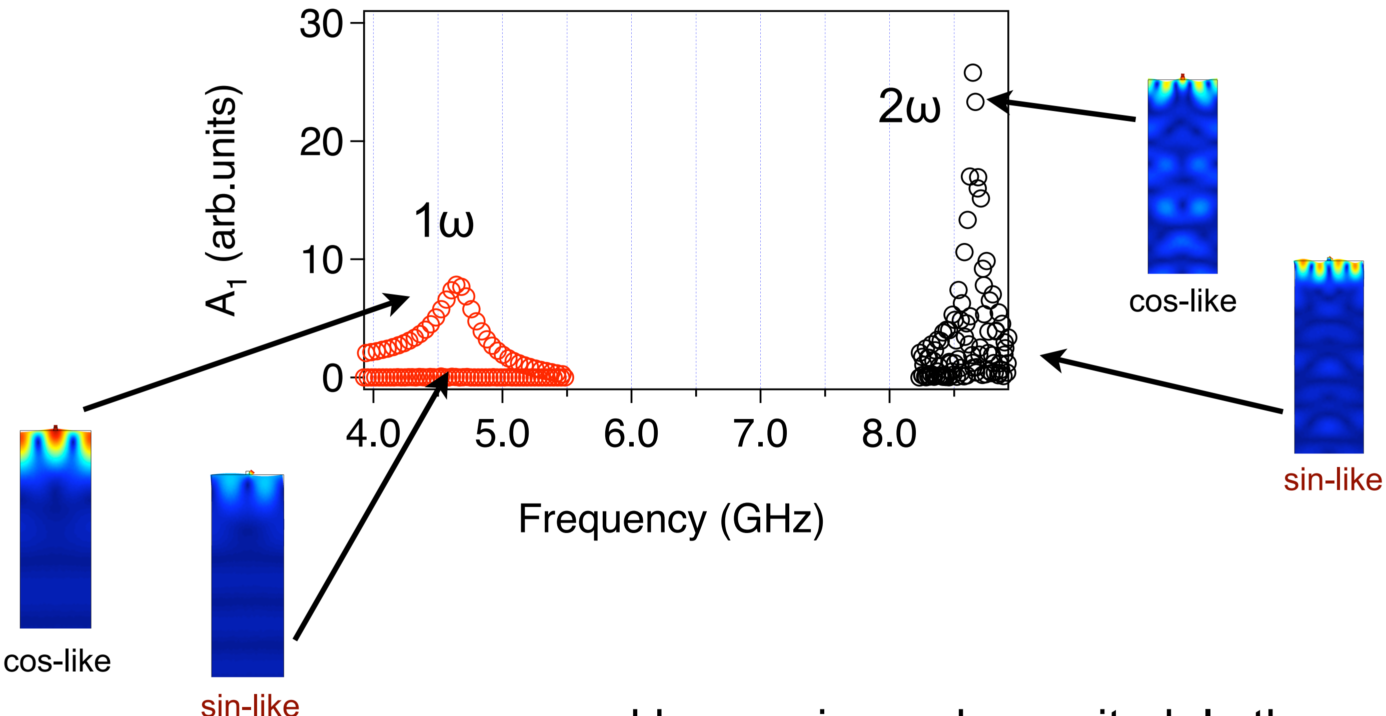

Time=1e-11
Surface: Total displacement [m]   Arrow: Displacement   Deformation: Displacement
Max: 2.00e-12
x10^-12
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Min: 0
x10^-5
1.02
1
0.98
0.96
0.94
0.92
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
x10^-6


Time=1e-11
Surface: Total displacement [m] Arrow: Displacement Deformation: Displacement
Max: 7.00e-13
x10^-13
x10^-5
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
x10^-6
6
5
4
3
2
1
0
Min: 0

PROJECTION OF THE INITIAL DISPLACEMENT ON THE EIGENMODES



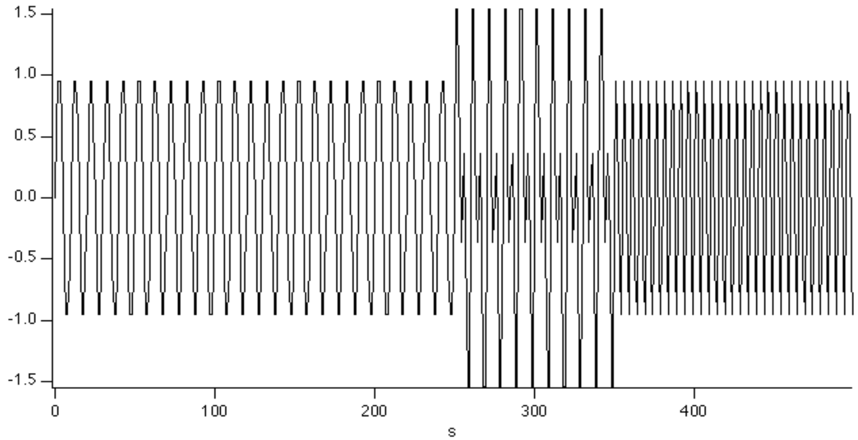
$$u(\mathbf{r},t)=\sum A_n u_n(\mathbf{r},t)$$



second harmonic can be excited. Is there any signature in the measurements?

Signal *x(t)*

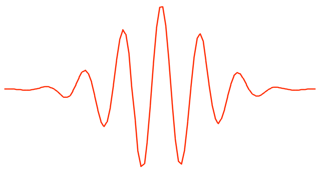
signal=sin(2 π*x*50/500) for t=[0,350]sec
signal=sin(2 π*x*100/500) for t >250sec



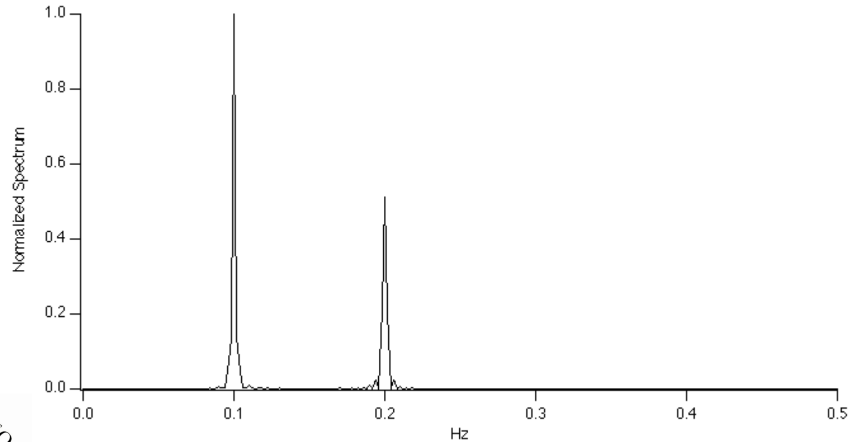
Wavelet

$$W(s,t)=\int x(t')\cdot\psi(t-t'/s)dt'$$

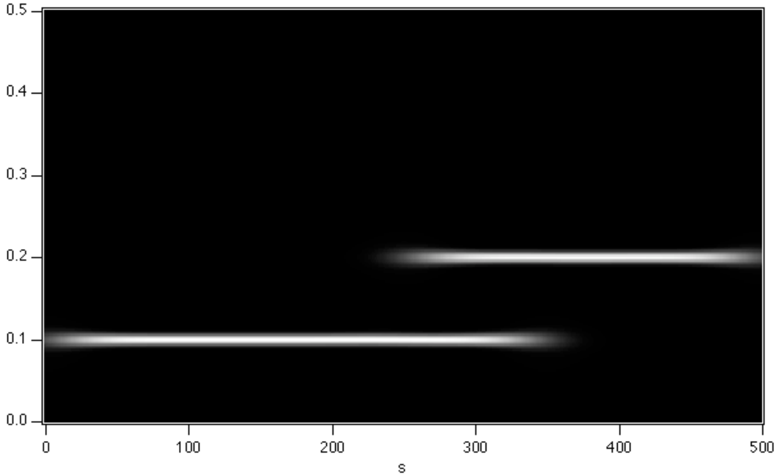
C-Morlet wavelet $\psi(\eta) = \pi^{-\frac{1}{4}} s^{-\frac{1}{2}} e^{-i\omega_0\eta} e^{-\eta^2}$



Fourier Transform

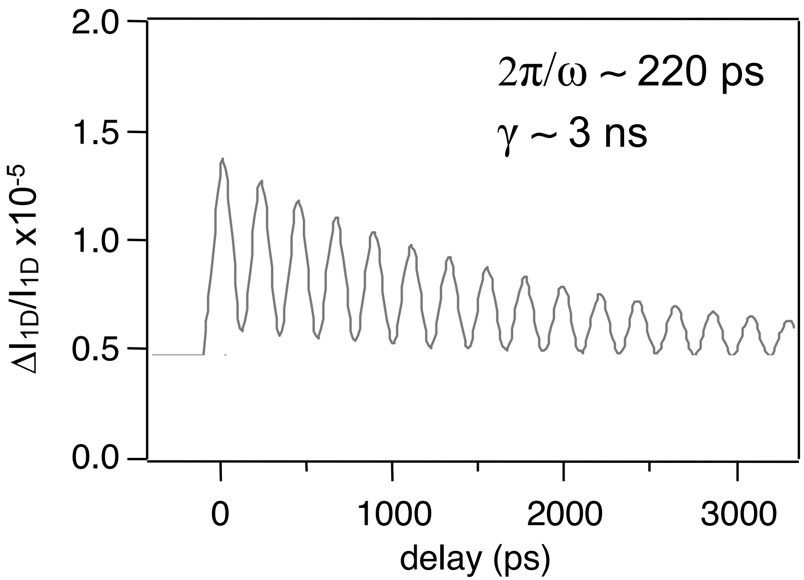


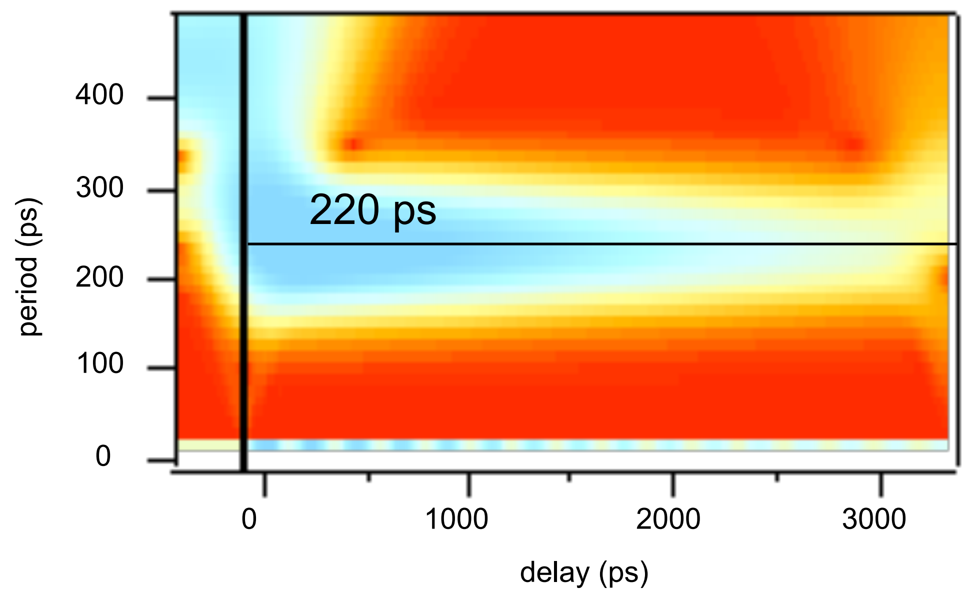
WAVELET ANALYSIS



WAVELET ANALYSIS

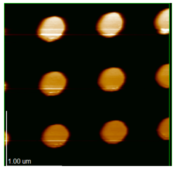
$$u_r(t) \propto (e^{-t/\tau} - e^{-\gamma t}\cos\varpi t + \frac{\alpha}{\varpi} e^{-\gamma t}\sin\varpi t)$$





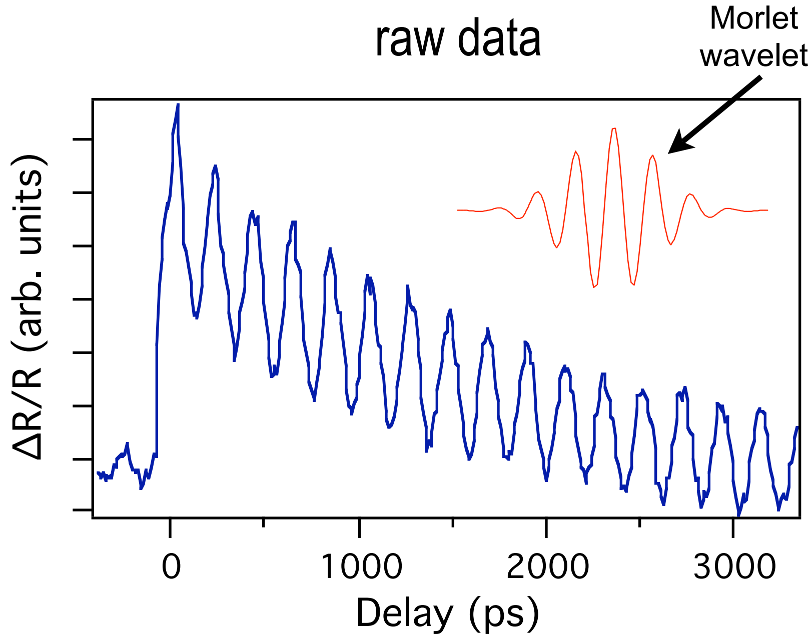
WAVELET ANALYSIS OF THE DIFFRACTED SIGNAL

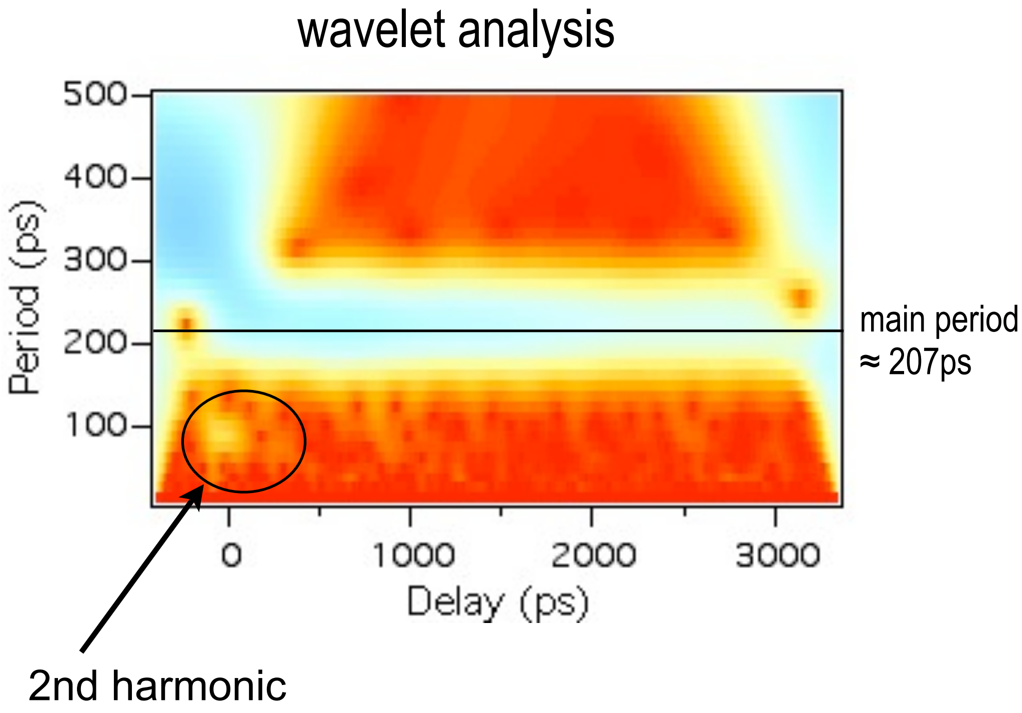
frequency content within time-windows



2a=320 ±10 nm

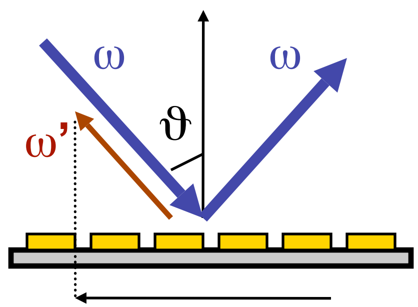
T=207.6±0.1 ps





THERMAL EXCITATION

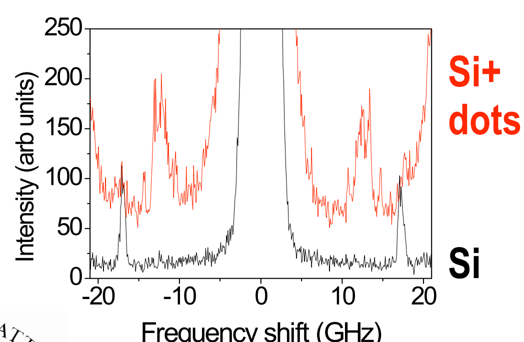
Acoustic waves at GHz frequencies can be formed merely by **random thermal motion** of the atoms of a material, i.e. phonons



$$Q_{\|} = \frac{4\pi}{\lambda}\sin\vartheta$$

ϑ=70°
λ=514.5 nm

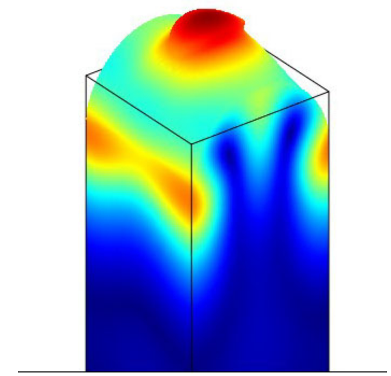
$Q_{\|}$=7.3 π/D



PHONON NUMBER

$$n_k = \frac{1}{e^{\hbar\omega_k/k_B T} - 1}$$

COHERENT EXCITATION

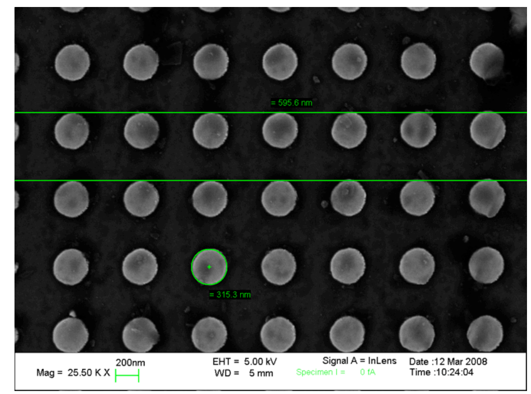


MACROSCOPIC DISPLACEMENT

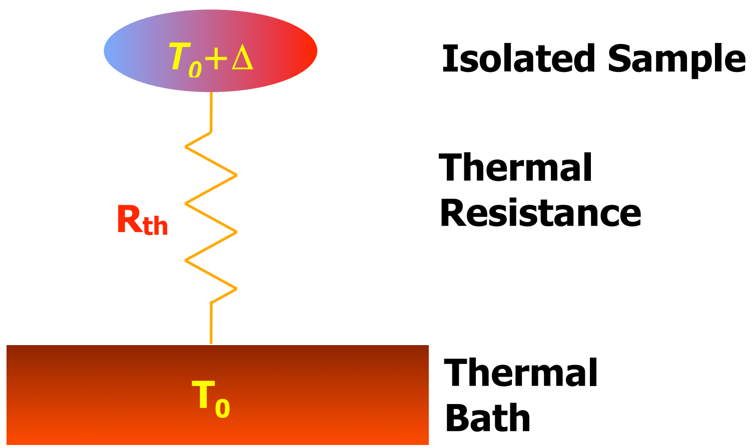
laser pulse excites a coherent state

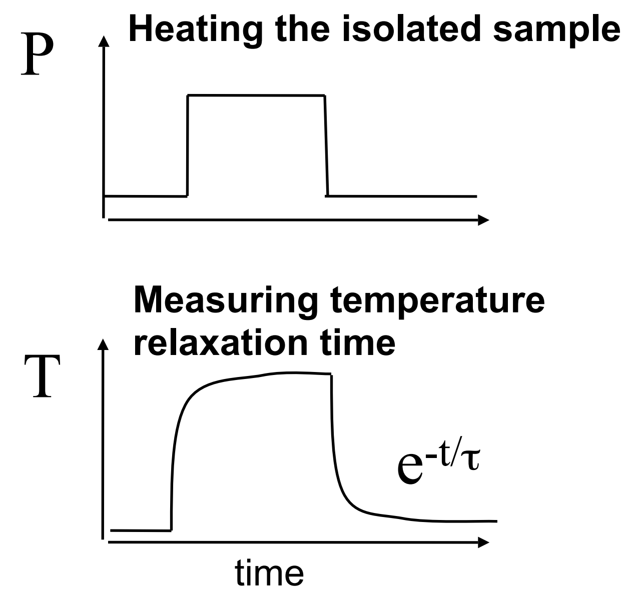
$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_n \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

- Introduction
- SAWs and ultrafast heat transfer
- Coherent excitation of GHz SAWs
- Birth of a SAW
- Calorimetry at the nanoscale
- Magnetoelastic interaction



CALORIMETRY AT NANOSCALE?





$$\Delta T(t)=\Delta T_0 \cdot e^{-t/\tau}$$
$$\tau = lC_s R_{therm}$$

→ The steady-state temperature is determined by the dissipation

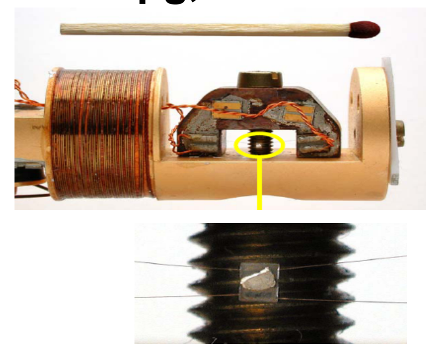
→ The time-constant is related to the heat capacity C_p

With standard techniques *a* can be reduced in order to measure the τ of 10 μg.

DIMENSIONS vs DECAY TIMES

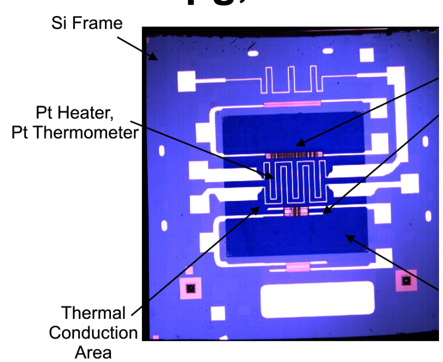
Sample mass

>50 µg, 0.1-100 s



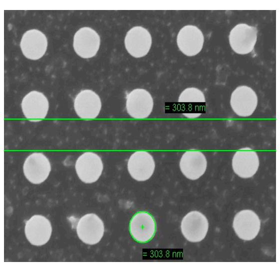
Corbino, 1910

>1 µg, 1ms-10s



Hellmann, 1993

~10^{-15} g, 0.1-10 ns



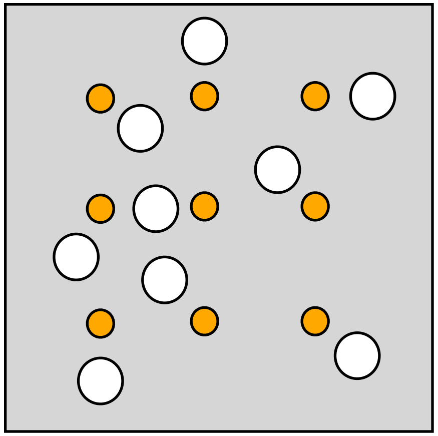
today

fast
non-perturbing probe

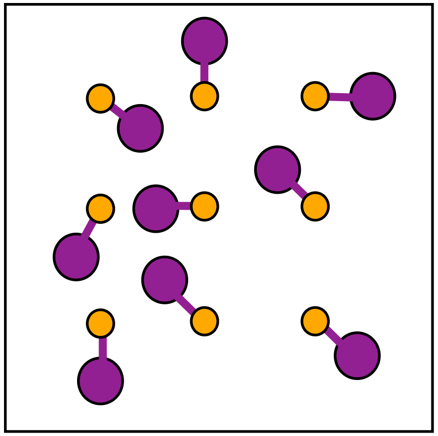
Relaxation time

STRATEGIES TO QUENCH THE SAW

- Array of metallic nano-dots with aperiodic holes (1 μm)

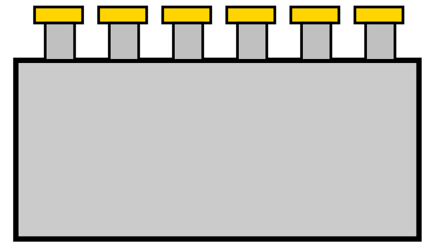


- Array of metallic nano-dots with aperiodic thermal reservoirs



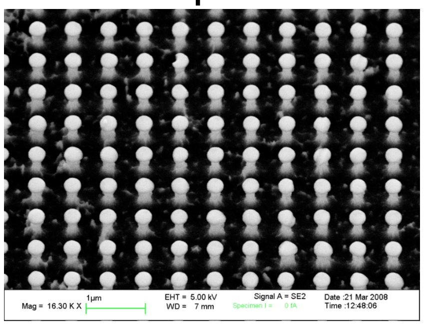
- Calorimetry on single nanoparticle

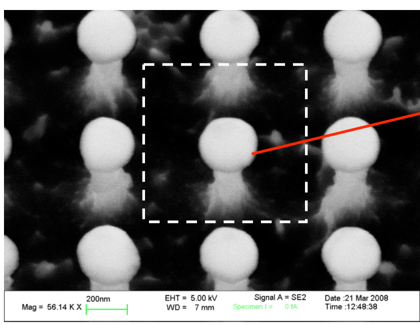
STRATEGIES TO QUENCH THE SAW



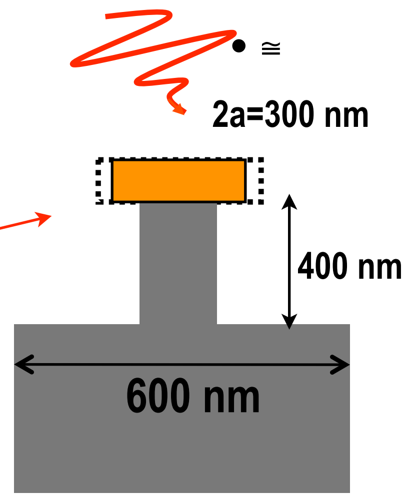
- Array of suspended metal nano-dots

anisotropic R.I.E.



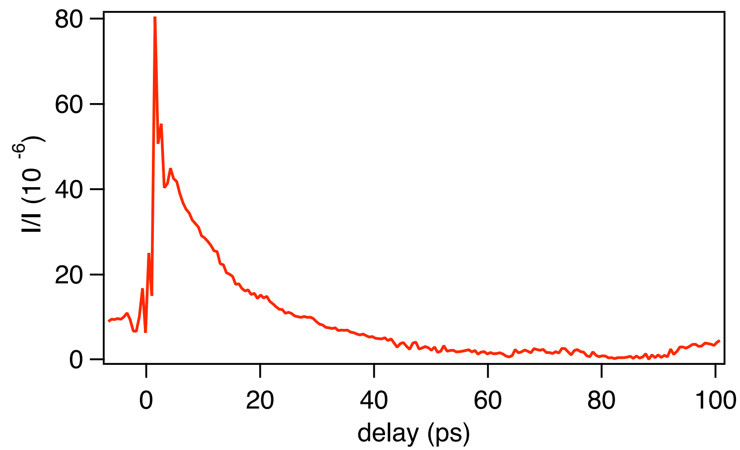


NEST, Pisa

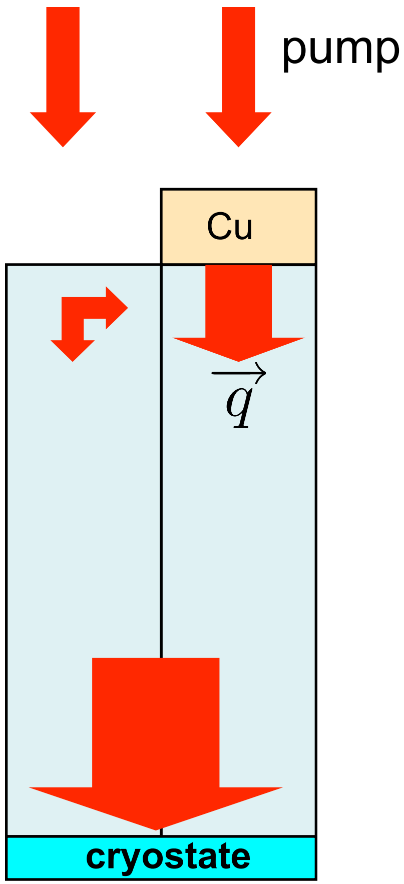


SAW period ≅ 100 ps

preliminary measurement



CASE STUDY FOR OPTICAL CALORIMETRY AT LOW TEMPERATURE

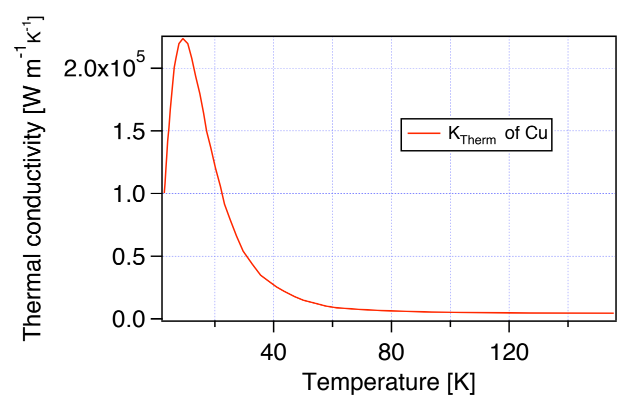


everything interesting happens at low temperature!

which is the temperature limit to apply an optical pump probe technique?

WHY Cu?

- easy
- high k



TWO-TEMPERATURE MODEL AT LOW TEMPERATURE

coupled energy equations for T_e and T_L

$$\begin{cases} C_e \frac{\partial T_e}{\partial t} = w(t) - \Gamma\left(T_e, T_L\right) + \overrightarrow{\nabla} \cdot (k_e \overrightarrow{\nabla} T_e) \\ C_L \frac{\partial T_L}{\partial t} = \Gamma\left(T_e, T_L\right) + \overrightarrow{\nabla} \cdot (k \overrightarrow{\nabla} T_L) \end{cases}$$

Interaction term gives the rate of energy exchange between electrons and crystal lattice in the metal

$$\Gamma(T_e, T_{ph}) = 2\pi N_C N(\varepsilon_F) \int_0^\infty d\Omega \alpha^2 F(\Omega)(\hbar\Omega)^2 [n(\Omega, T_{ph}) - n(\Omega, T_e)]$$

$\alpha^2 F(\omega)$

is the Eliashberg function, which gives the coupling between electrons and phonons.

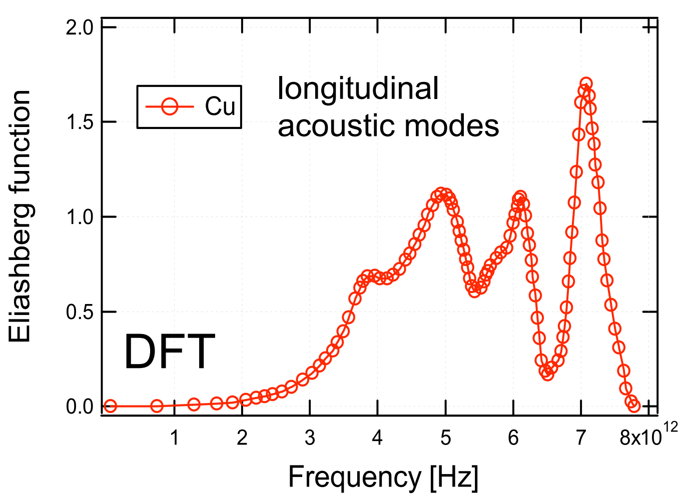
$n(\Omega, T_{e,ph})$

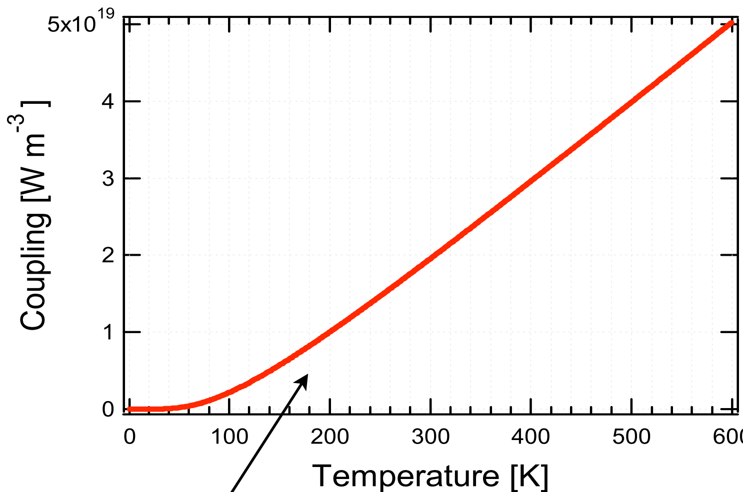
is the Bose-Einstein distibution function.

Allen, PRL, 59, 1460 (1987)
Kaganov et al., *JETP*, **4**, 178 (1957)

CASE STUDY

$\alpha^2 F(\omega)$





$$\Gamma(T_e, T_{ph}) = 2\pi N_C N(\varepsilon_F) \int_0^\infty d\Omega \alpha^2 F(\Omega)(\hbar\Omega)^2 [n(\Omega, T_{ph}) - n(\Omega, T_e)]$$

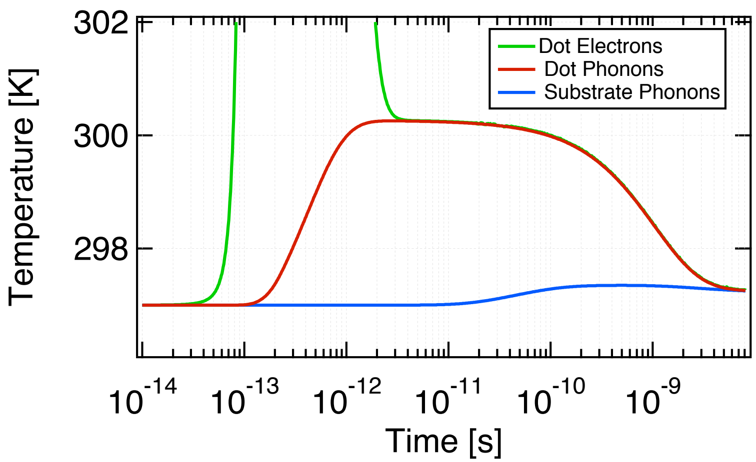
LIMITS

high-temperature limit $\Gamma(T_{ph}, T_e) = G(T_{ph} - T_e)$ → standard 2TM

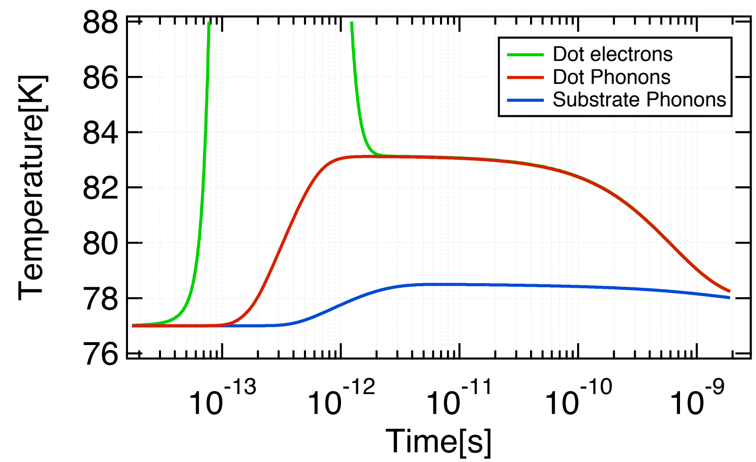
low-temperature limit (T<T_{debye}/10) $\Gamma(T_{ph}, T_e) = \Sigma(T_{ph}^5 - T_e^5)$ → low *e-ph* coupling

SIMULATIONS

300 K



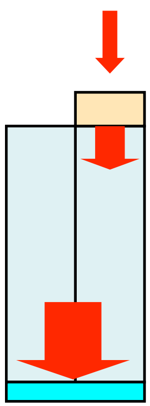
77 K



the technique works

$\tau \sim 1$ ns

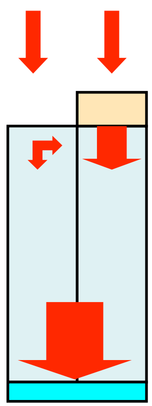
- the process is dominated by the disk-sub. heat exchange
- Si acts as a reservoir



the technique works

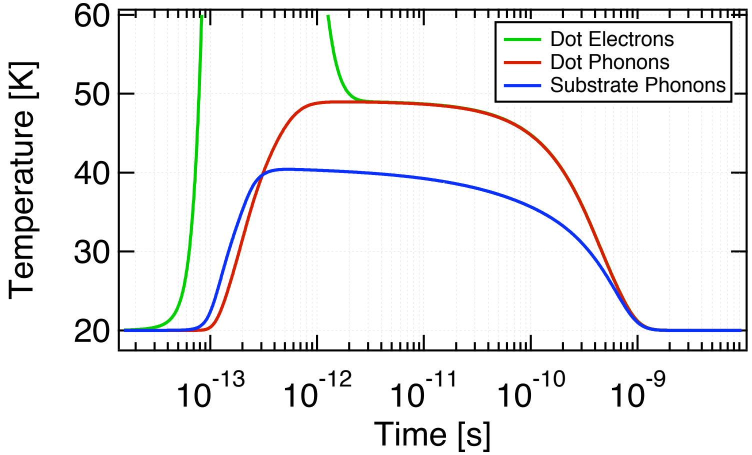
$\tau \sim 0.6$ ns

- the Si heating starts to play
- Si acts as a reservoir

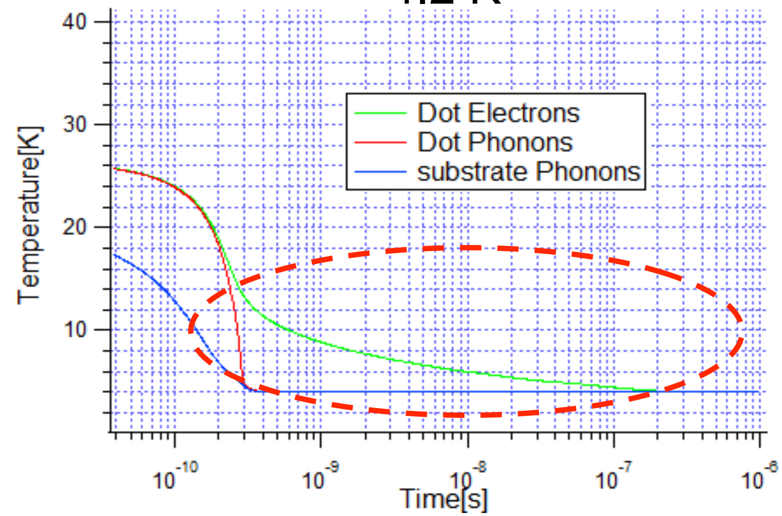


SIMULATIONS

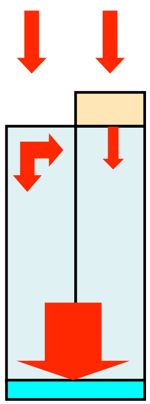
77 K



4.2 K

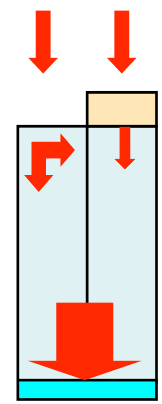


the technique works
NO single τ



- the process is dominated by the substrate heating
- Si does not act as a reservoir

the technique does not work !



- electron-phonon decoupling
- SAWs and localized modes have been neglected

FUTURE

- Decoupling the thermic and elastic contributions
  → CALORIMETRY of NANOPARTICLES

- Diffraction technique with High-Harmonics generation (λ~30 nm)

- Study of localization of SAWs in disordered systems

- Applications to sub-wavelength optics and coupling to surface plasmons

•Ultrafast optics group (Università Cattolica, campus di Brescia)
F. Banfi, Damiano Nardi, Federico Pressacco, Gabriele Ferrini,

•Group leader
Fulvio Parmigiani

•Thermodynamics
B. Revaz (EPFL, Lausanne)

•Samples
P. Pingue (NEST, Pisa)

- Introduction
- SAWs and ultrafast heat transfer
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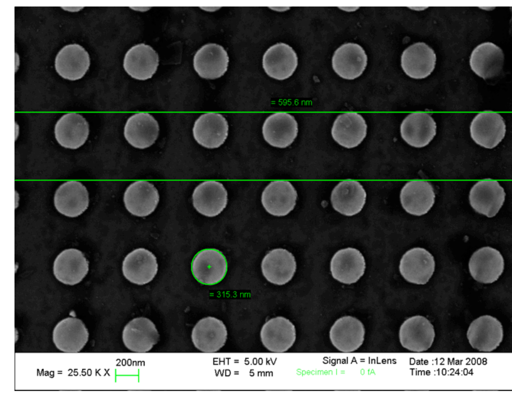
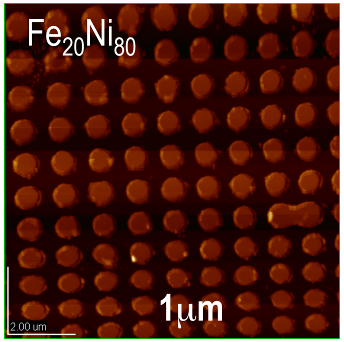


ARRAYS OF MAGNETIC DISKS



•Fundamental physics → Vortex configuration

T. Shinjo *et al.*, *Science* **289**, 930 (2000).

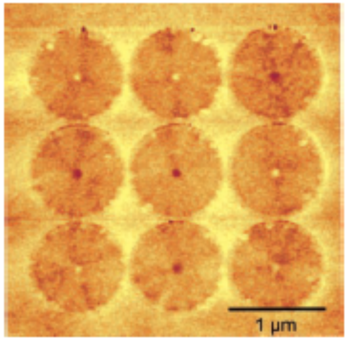


Fig. 2. MFM image of an array of permalloy dots 1 μm in diameter and 50 nm thick.

Manipulation of magnetic vortex cores with magnetic field

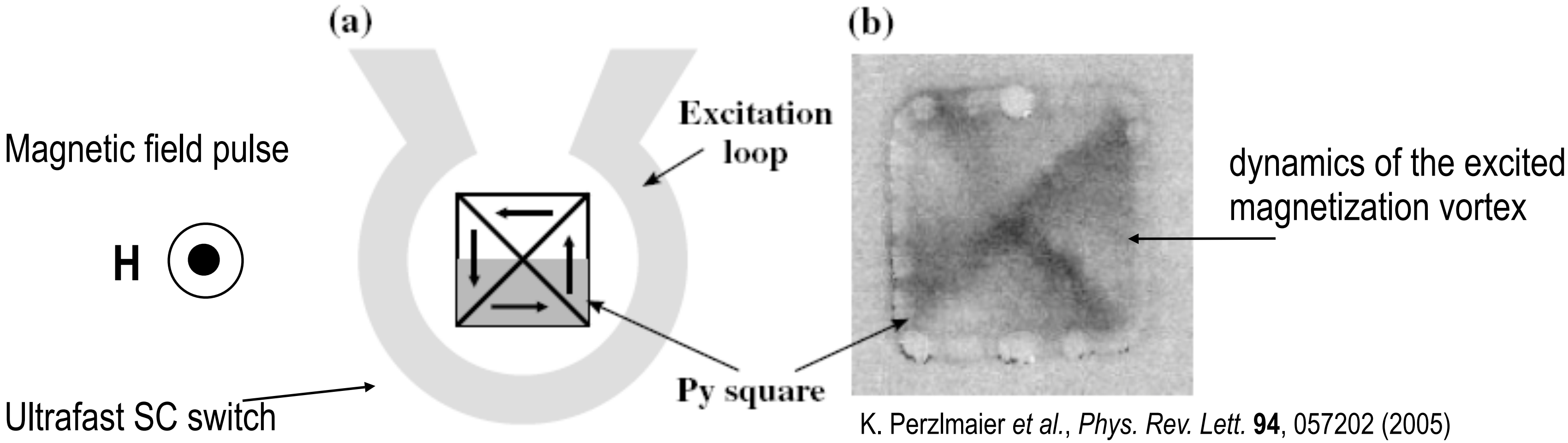
K. Perzlmaier *et al.*, *Phys. Rev. Lett.* **94**, 057202 (2005).

B. Van Waeyenberge *et al.*, *Nature* **444**, 461 (2006).

→ Possibility to manipulate the magnetization with femtosecond laser pulses

A. Comin *et al.*, *Phys. Rev. Lett.* **97**, 217201 (2006).

The excitation modes of the vortex state phase can be studied by TR-Kerr microscopy



K. Perzlmaier *et al.*, *Phys. Rev. Lett.* **94**, 057202 (2005)

Is it possible to excite the magnetic spectrum without magnetic pulses?

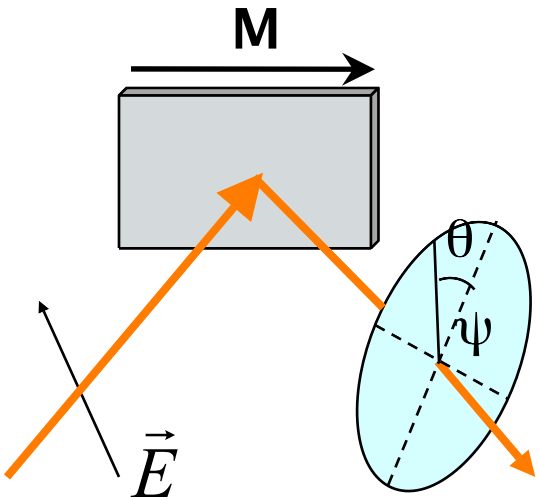
Magnetoelastic interaction ⟶

$$g(\mathbf{M}, \sigma) = \sigma_{ij} \lambda_{ijkl} M_k M_l$$

thermodynamic potential

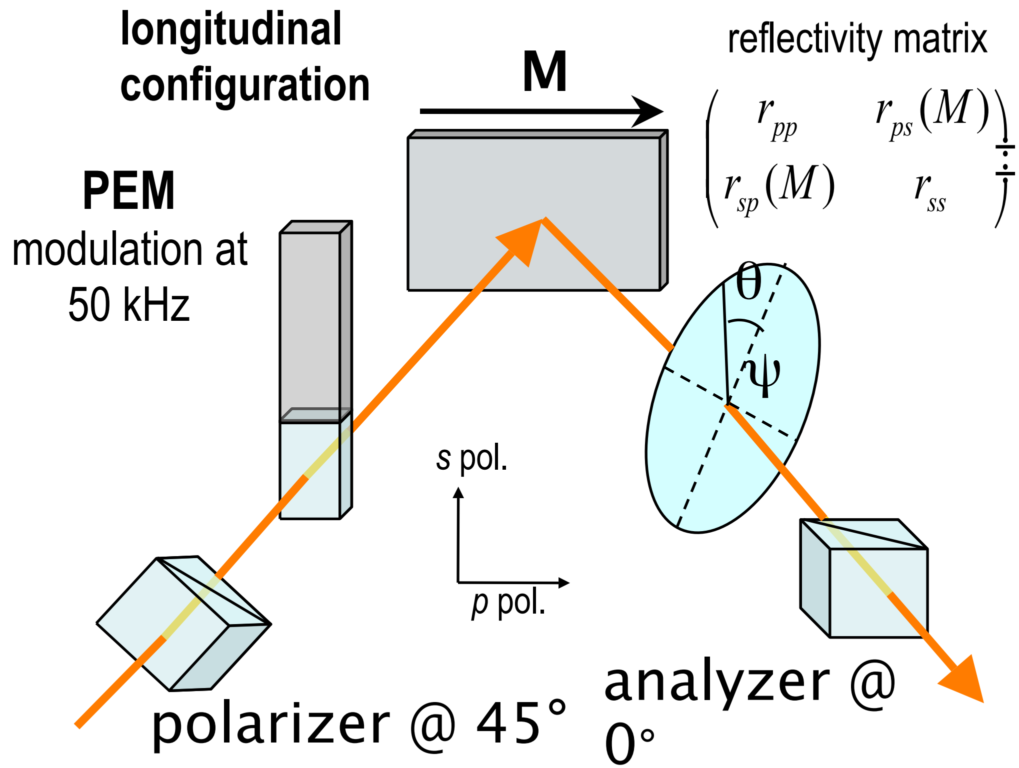
magnetostriction coefficient

MAGNETO-OPTICAL KERR EFFECT



Polarization rotation induced by the interaction with **M**

θ is the rotation
ψ is the ellipticity
→ θ, ψ ∝ M



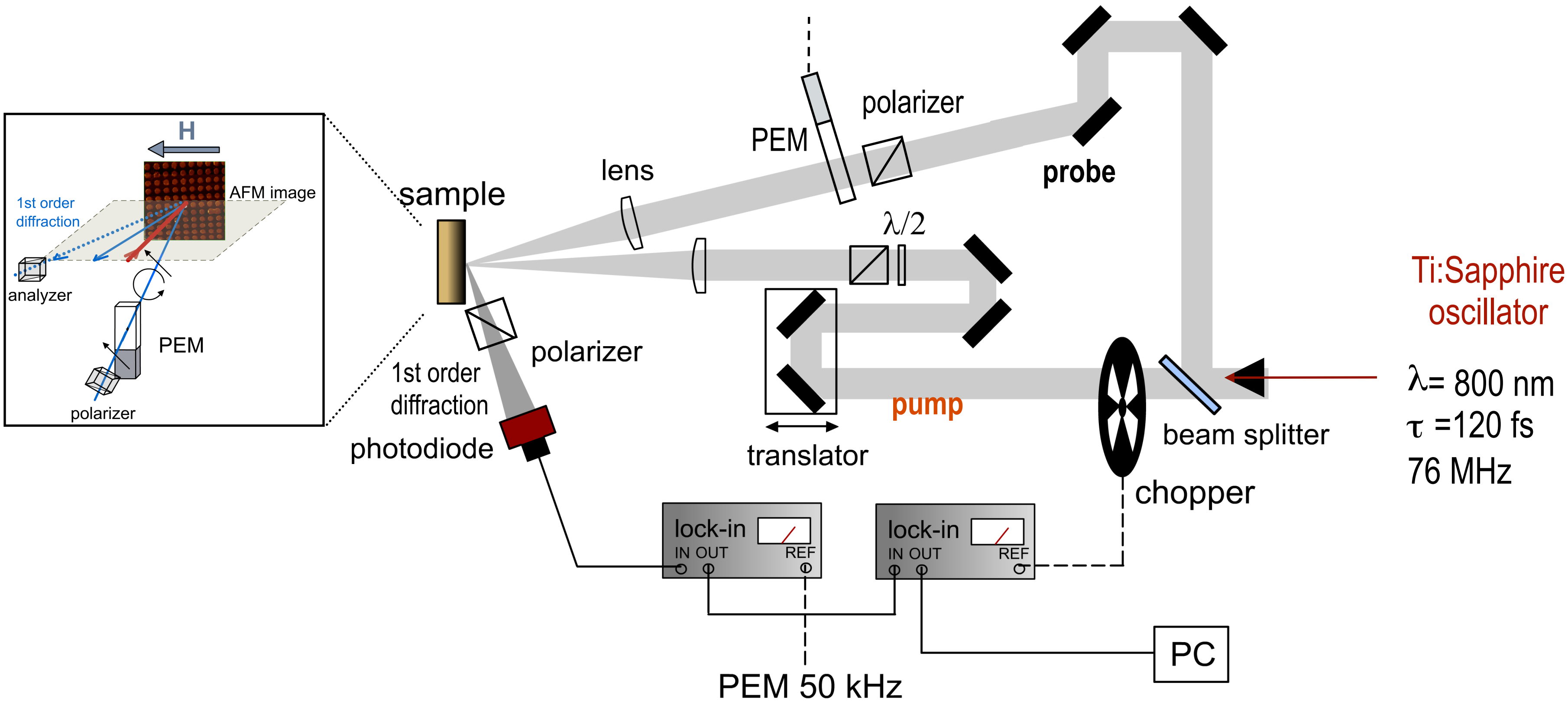
1ω → rotation
2ω → ellipticity

$$I_{1\omega} \propto J_1(\Delta)\,\mathrm{Im}(r_{pp}^{*} r_{ps})$$

J_1: 1st order Bessel function
Δ=2.407 PEM modulation amplitude

TIME-RESOLVED MAGNETO-OPTICS

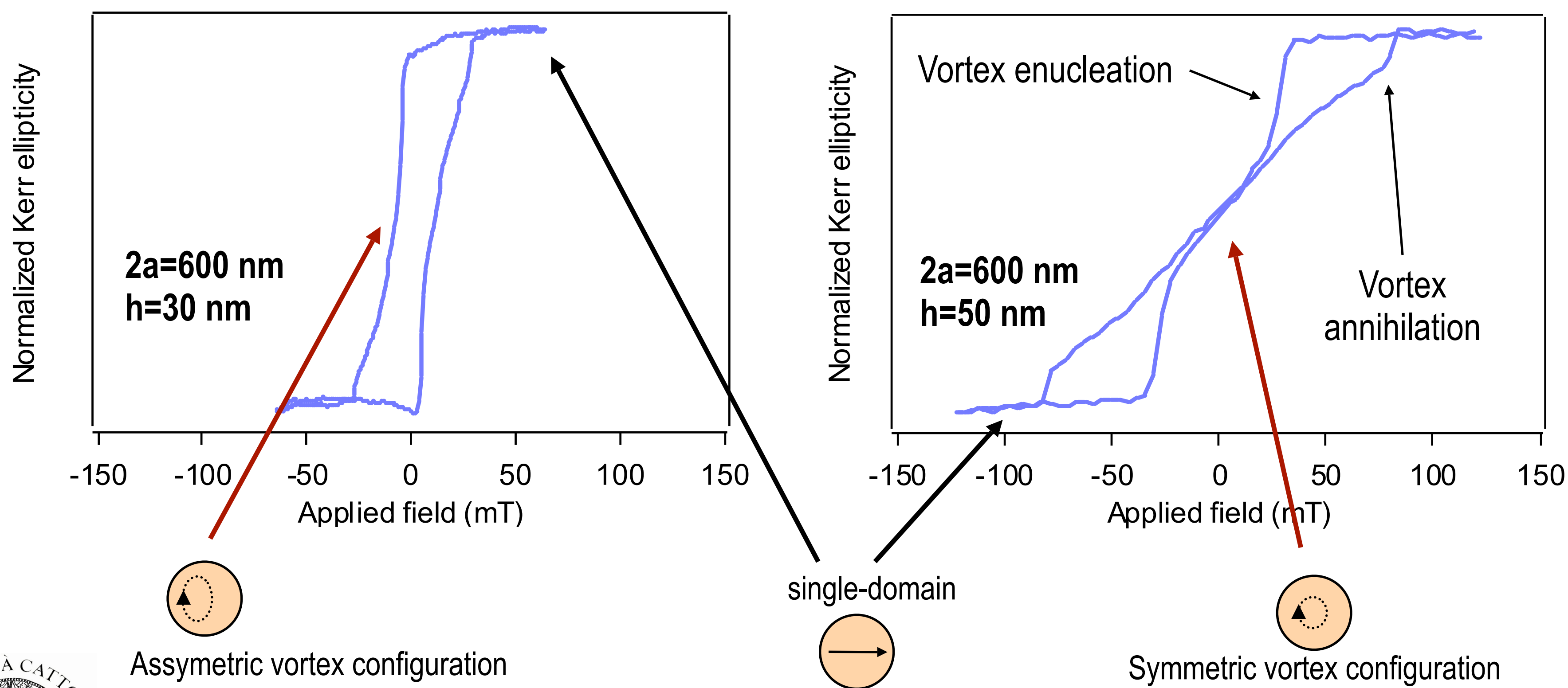
DIFFRACTION: The contribution from the periodic structure is decoupled from the substrate contribution



time-resolved MOKE → $S/N<10^{-5}$

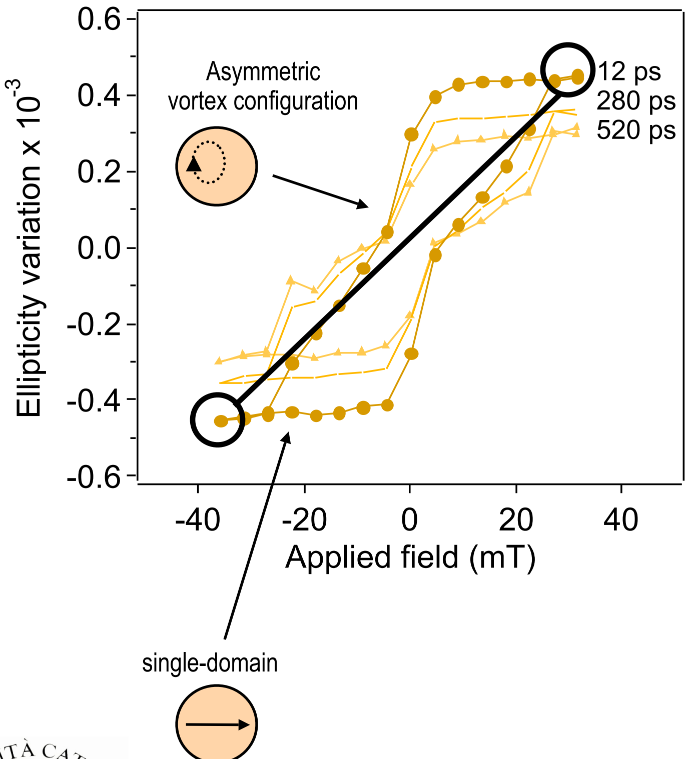
STATIC KERR ELLIPTICITY

The hysteresis cycles can be reproduced via micromagnetic simulation software OOMMF. The vortex phase is the ground state of a nano-sized magnetic system, where the surface alignment of the magnetic moment dominates.



LASER INDUCED VARIATION of KERR ELLIPTICITY

Kerr ellipticity variation
vs pump probe delay



•Signal variation induced by pump excitation:

$$\delta I_{1\omega} \propto \delta R + J_1(\Delta)\delta\left(f_1 M_{\parallel}\,\mathrm{Im}(r_{pp}^{*} r_{ps})\right)$$

non-magnetic contributions — 1st form factor — parallel magnetization

•Subtracting measurements taken at opposite values of the external magnetic field, eliminates non-magnetic contributions

Ellipticity variation

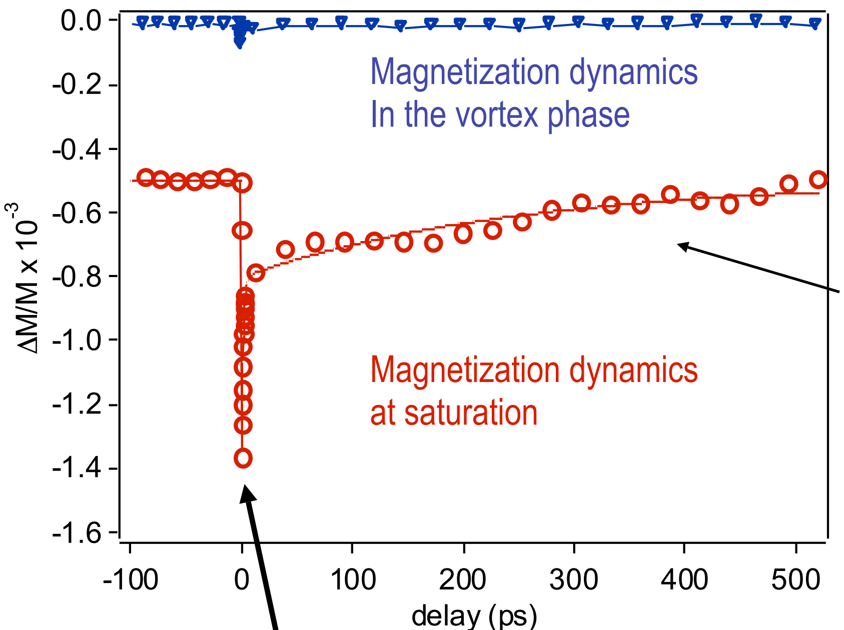
$$\frac{\delta I_{1\omega}}{I_{1\omega}} = \frac{\delta R}{R} + \frac{\delta M}{M} \quad \longrightarrow \quad \frac{\delta M}{M} = \frac{1}{2}\left(\left.\frac{\delta I_{1\omega}}{I_{1\omega}}\right|_{+M} - \left.\frac{\delta I_{1\omega}}{I_{1\omega}}\right|_{-M} \right)$$

non-magnetic contribution

A. Comin *et al.*, *Phys. Rev. Lett.* **97**, 217201 (2006).

TIME-RESOLVED MAGNETIZATION DYNAMICS

Kerr ellipticity variation as a function of the delay between the pump and probe pulses

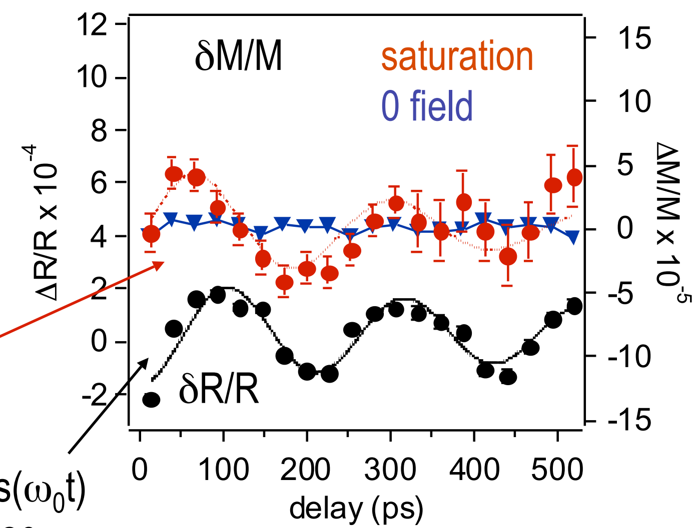


fast electronic response

heat-exchange process between the nanodot and the substrate

exponential decay
τ@1 ns

After subtraction of the background, a small oscillation of the magnetization is evidenced



$e^{-\gamma t}\sin(\omega_0 t)$
τ@240 ps

$1-\cos(\omega_0 t)$
τ@220 ps

Magneto-elastic coupling: $$g(\mathbf{M},\sigma) = \sigma_{ij}\lambda_{ijkl}M_kM_l$$

•Ultrafast optics group (Università Cattolica, campus di Brescia)
F. Banfi, Damiano Nardi, Federico Pressacco, Gabriele Ferrini

•Group leader
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