Thermomechanics of Hypersonic Surface Phononic Crystals

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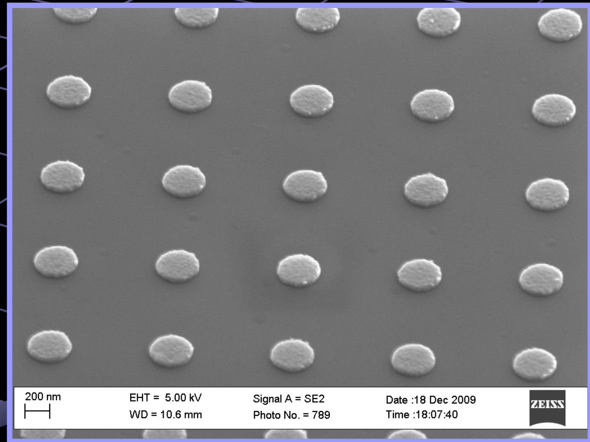
SCOPE

Description of the thermomechanics of hypersonic surface phononic crystals excited by ultrafast laser pulses

- **Introduction**
- Mechanical model and pseudo-SAWs
- Thermomechanics
- Conclusion and perspectives

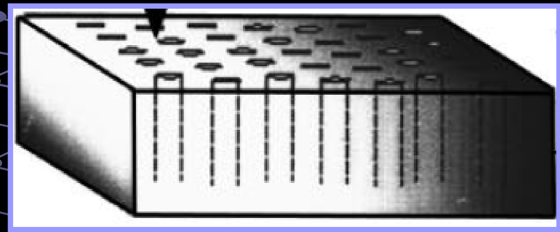


PHONONIC CRYSTAL

Periodic elastic composite of two or more vibrating materials

2D phononic crystals

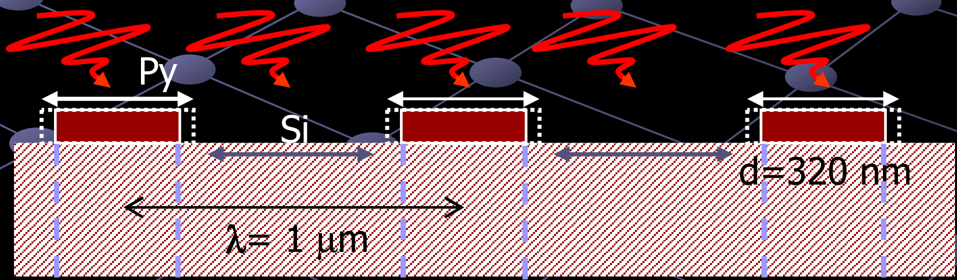
Embedded parallel metallic rods

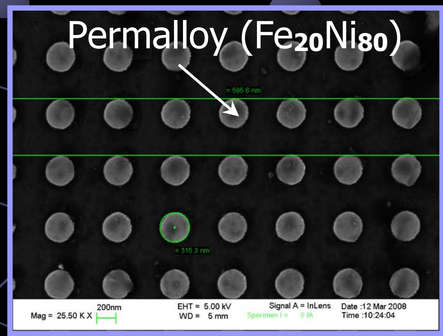


Drilled holes lattice

Y. Tanaka et al., *Phys. Rev. B* **60**, 13294 (1999)

2D **surface** phononic crystal





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

OUR INTERESTS IN LATTICE OF NANOSTRUCTURES

✓ Phononic crystals in the GHz range

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

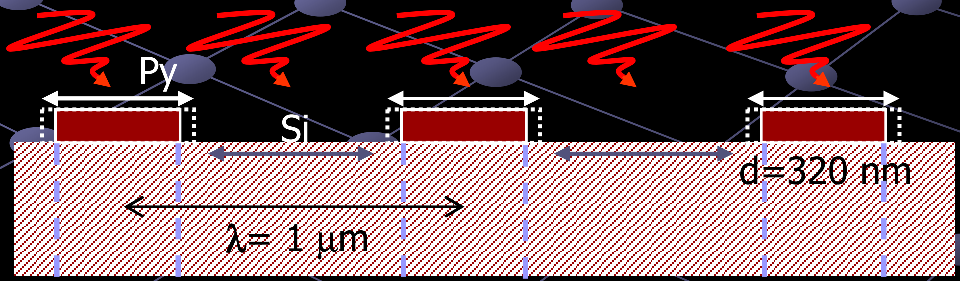
✓ Excite and control SAWs with fs laser pulses

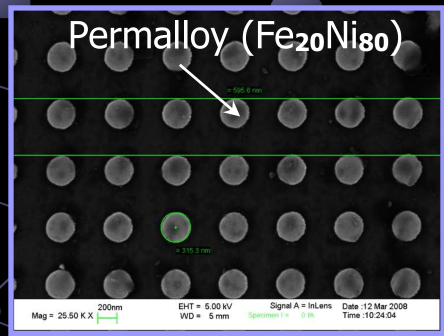
D. M. Profunser et al., *Phys Rev. B* **80**, 014301 (2009)
C. Giannetti et al., *IEEE Photonics Journal* **1**, 20 (2009)

✓ All-optical time-resolved calorimetry at the nanoscale

F. Banfi et al., *Phys. Rev. B* **81**, 155426 (2010)

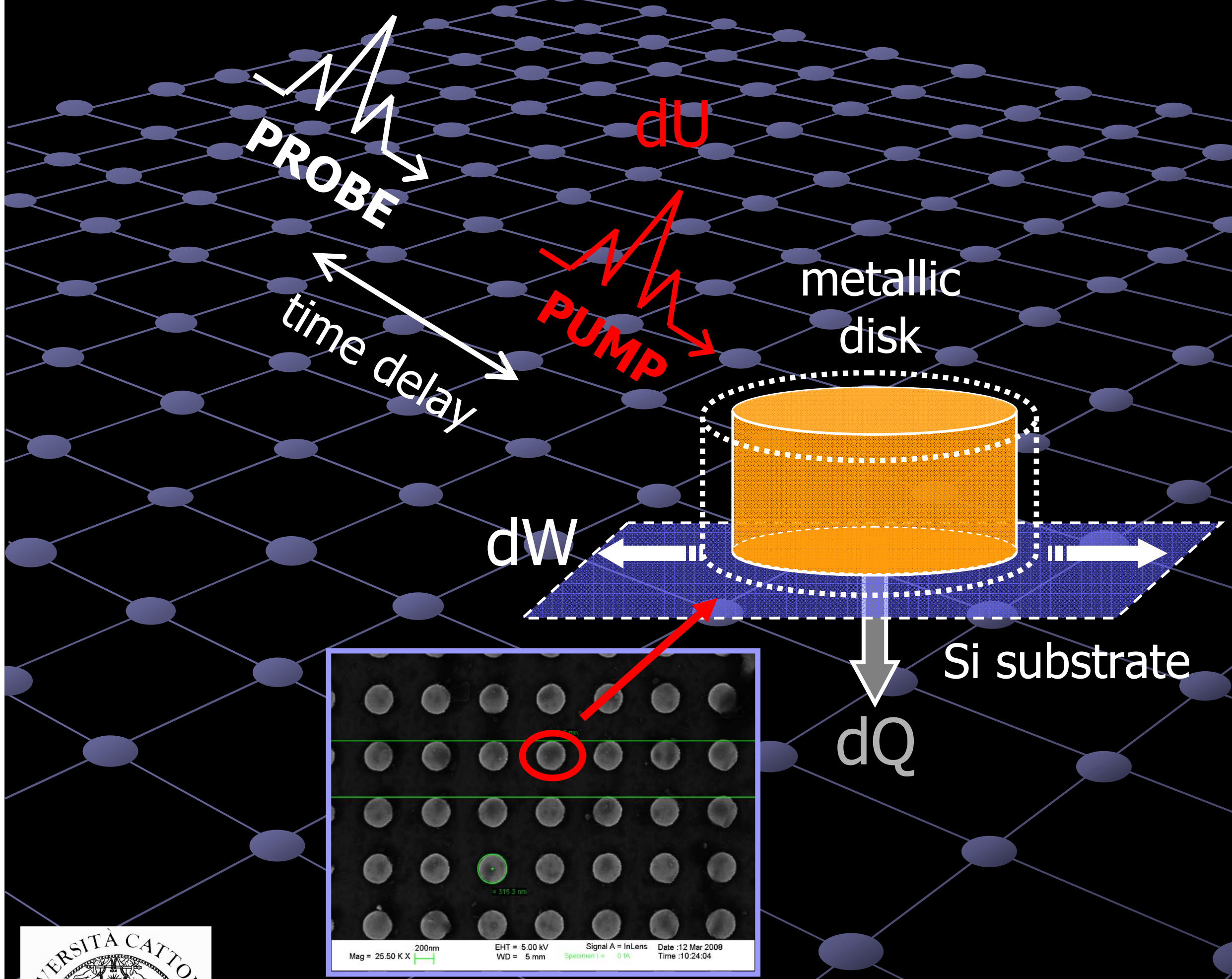
2D **surface** phononic crystal





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

THERMOMECHANICS OF PHONONIC CRYSTALS



$dU = dQ + dW$

thermal dynamics:
Nanocalorimetry

F. Banfi et al.,
Phys. Rev. B **81**, 155426 (2010)

mechanical dynamics:
Surface Acoustic Waves

OUTLINE

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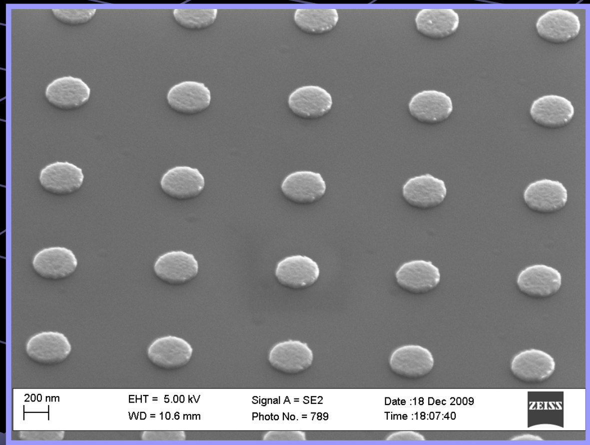
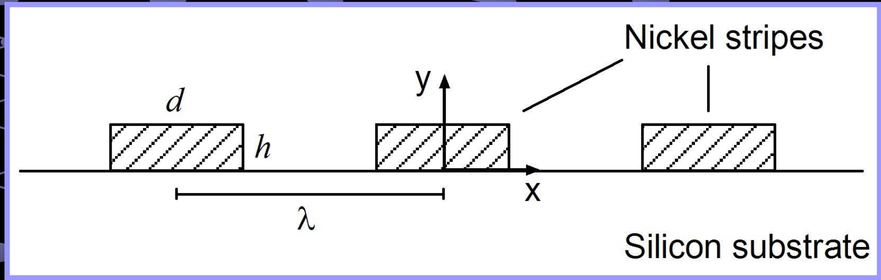
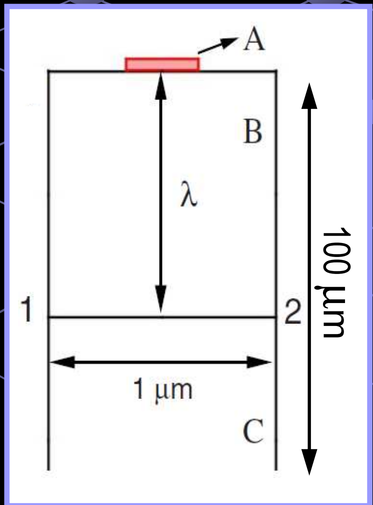


SURFACE-BASED PHONONIC CRYSTAL

Influence of a periodically structured overlayer on the acoustic-field eigenmodes of an homogeneous slab



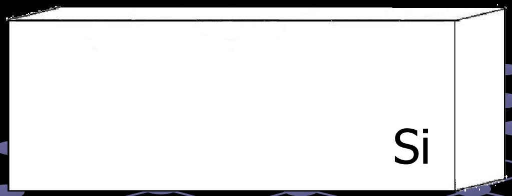
Solution of the acoustic eigenvalue problem via finite-elements method

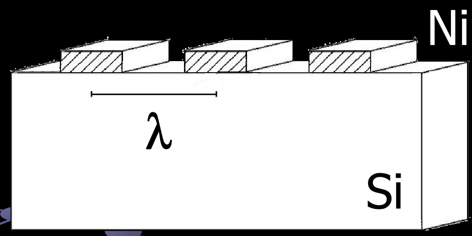


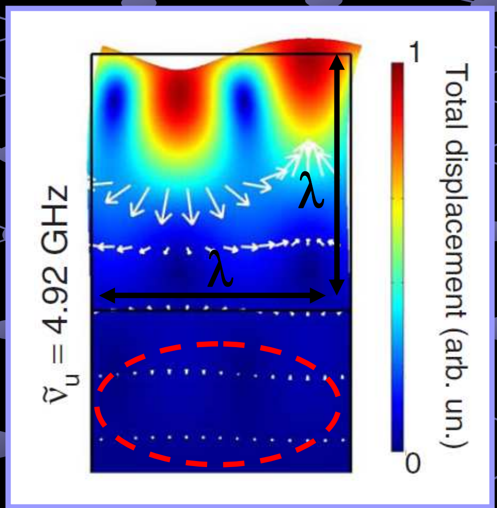
$$\partial_j[c_{ijmn}(\mathbf{r})\partial_n u_m] = -\rho(\mathbf{r})\omega^2 u_i$$

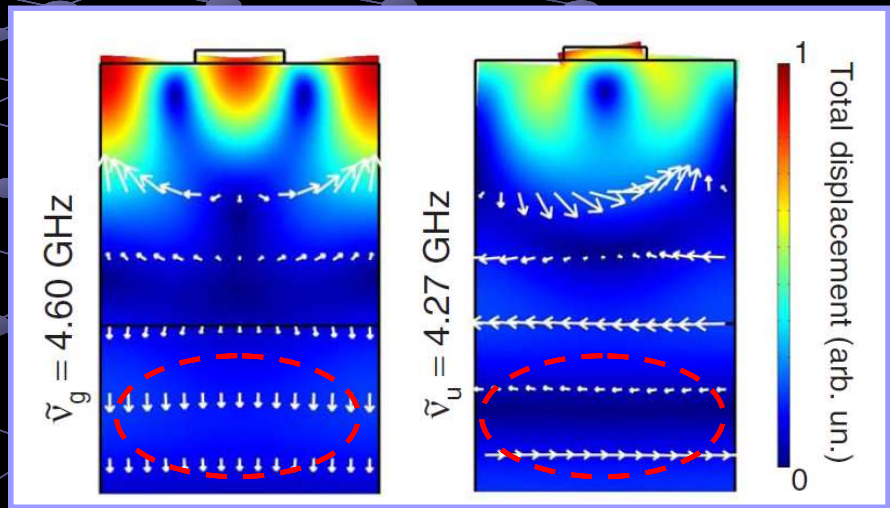
D. Nardi et al., *Phys. Rev. B* **80**, 104119 (2009)

Pseudo-SAW SOLUTIONS









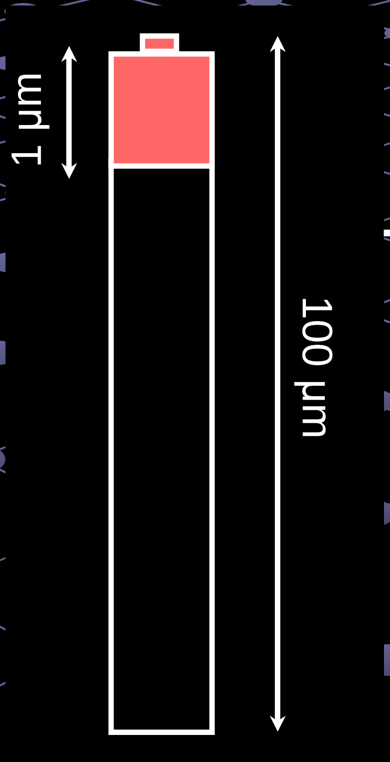
cos-like sin-like

SAW solutions:
- ✓ No radiation into the bulk

Pseudo-SAW solutions:
- ✓ radiating into the bulk
- ✓ degeneracy is lifted

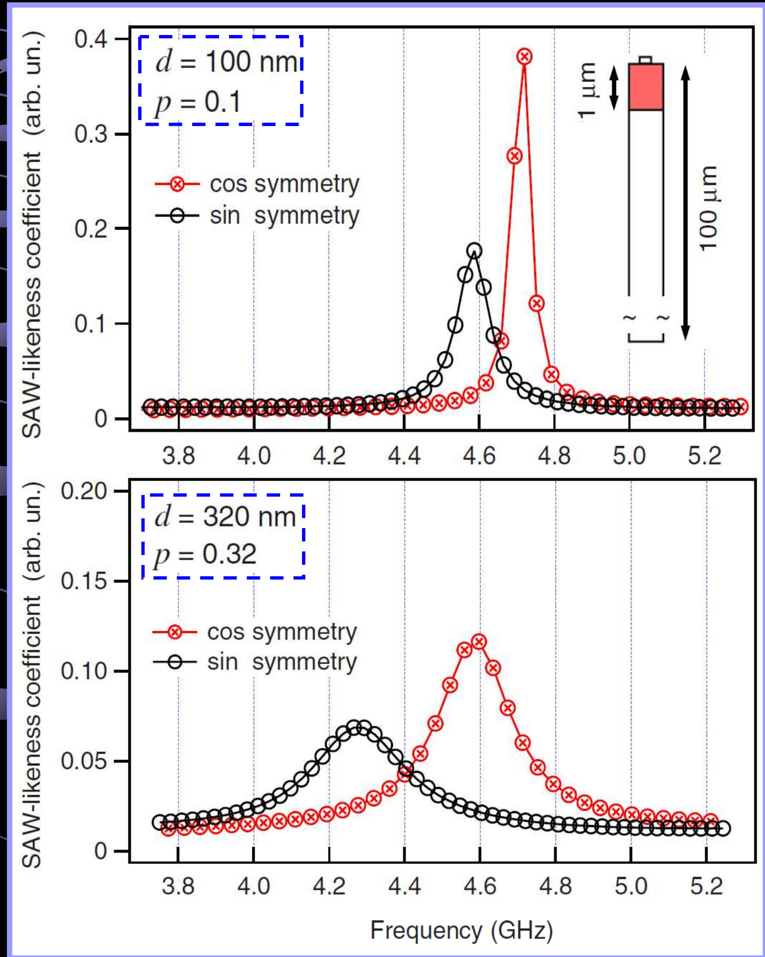
SAW-LIKENESS COEFFICIENT

It outlines which eigenmodes have mechanical energy mainly localized within a depth ~ λ



$$\frac{\textbf{Energy within 1 µm}}{\textbf{Energy within 100 µm}}$$

$$\alpha(\nu) \doteq \frac{\langle E_{\mathrm{A}}(\nu)\rangle + \langle E_{\mathrm{B}}(\nu)\rangle}{\langle E_{tot}(\nu)\rangle}$$



D. Nardi et al., *Phys. Rev. B* **80**, 104119 (2009)

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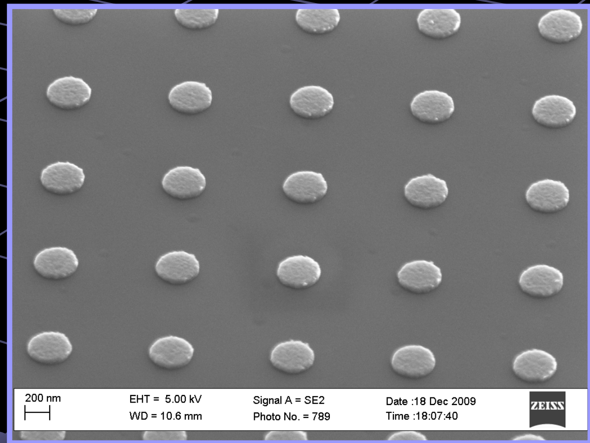
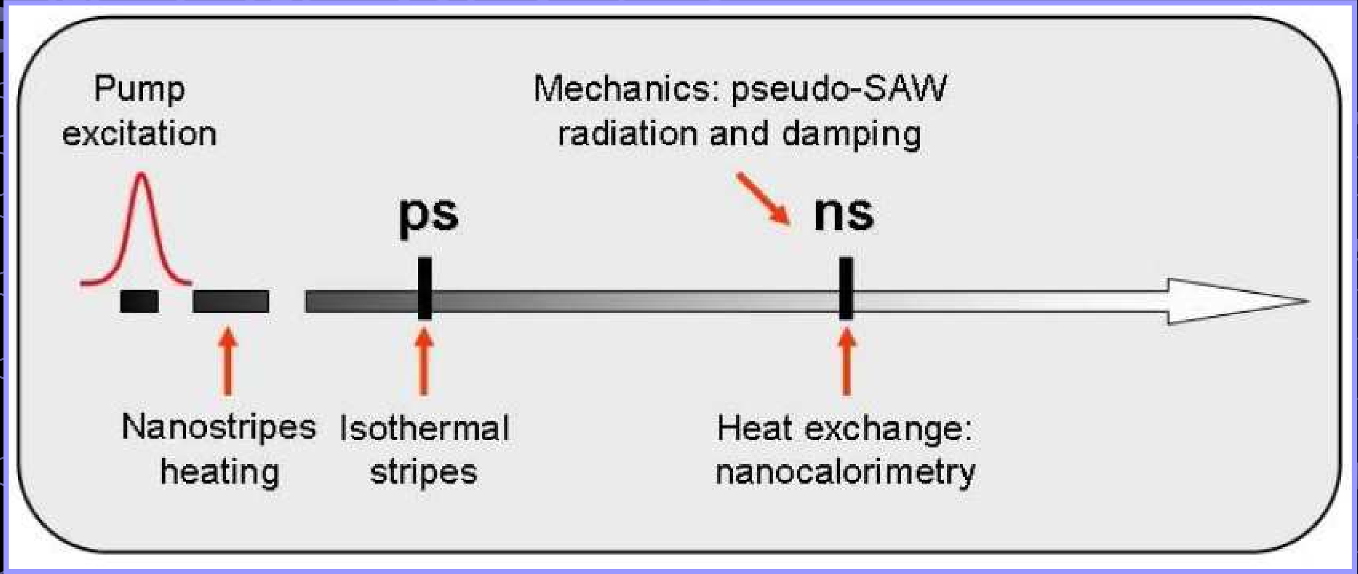
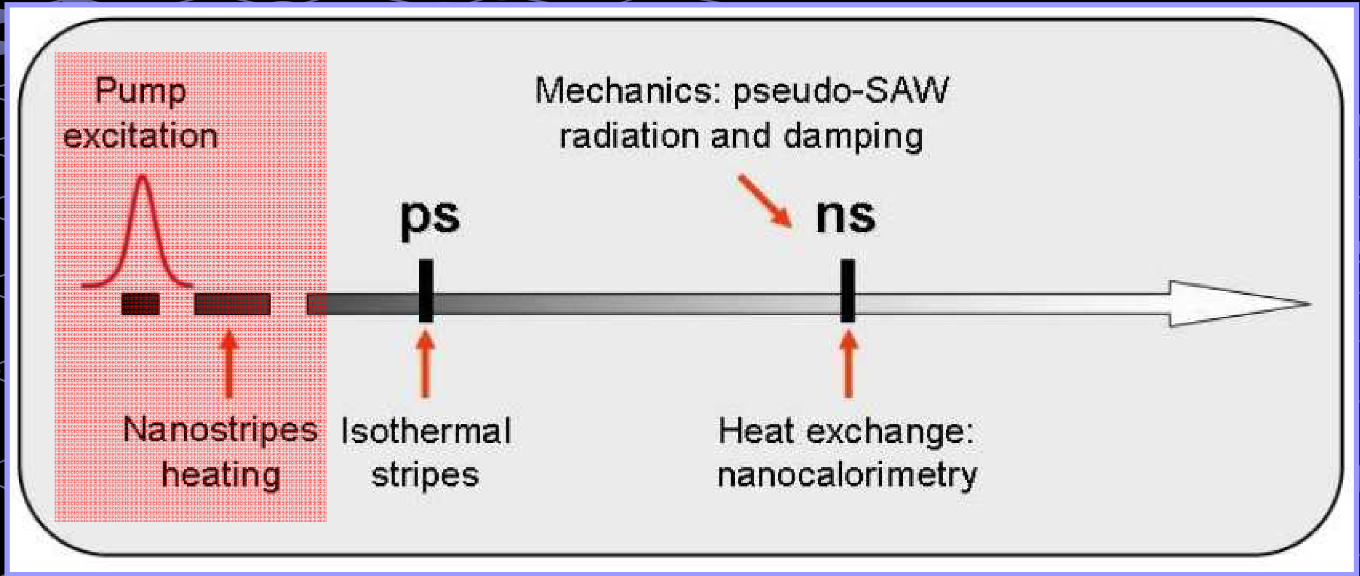


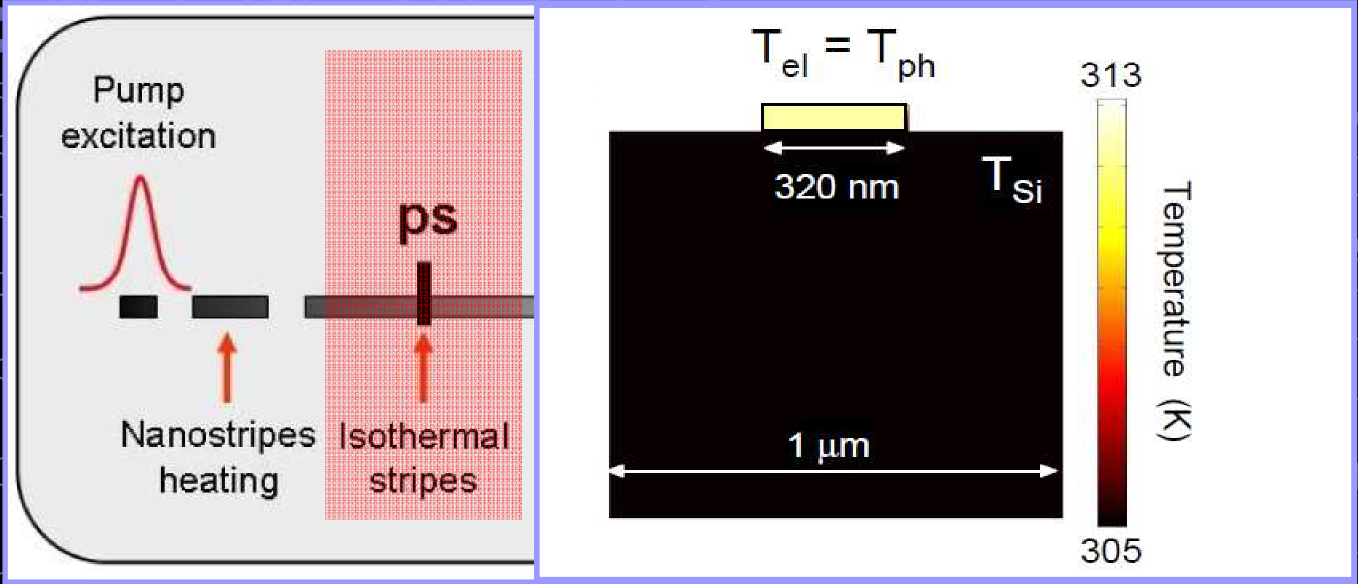
THERMOMECHANICAL TIME SCALE



THERMOMECHANICAL TIME SCALE

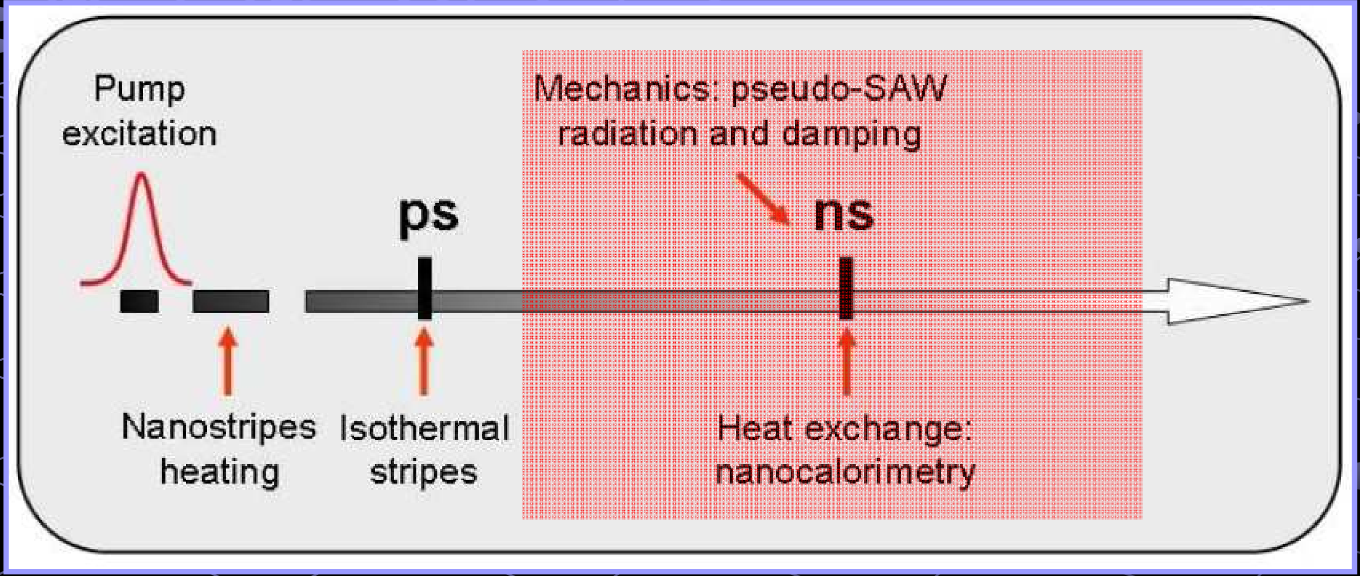


THERMOMECHANICAL TIME SCALE

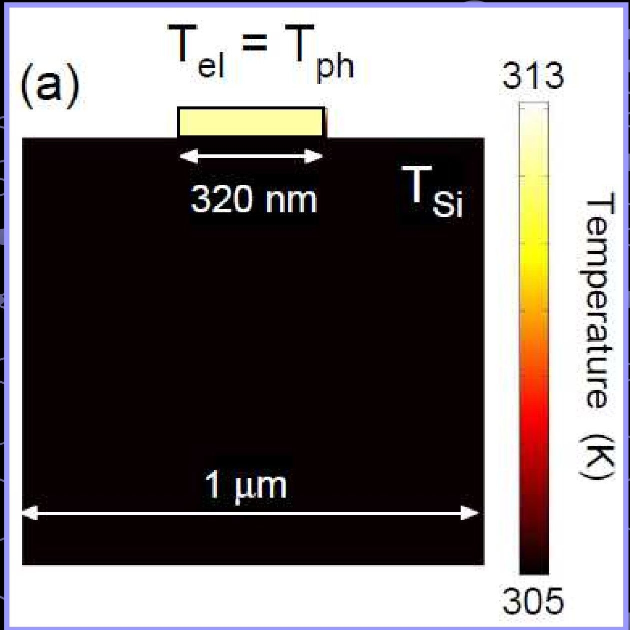


Calculated temperature profile at t_0 = 10 ps

THERMOMECHANICAL TIME SCALE

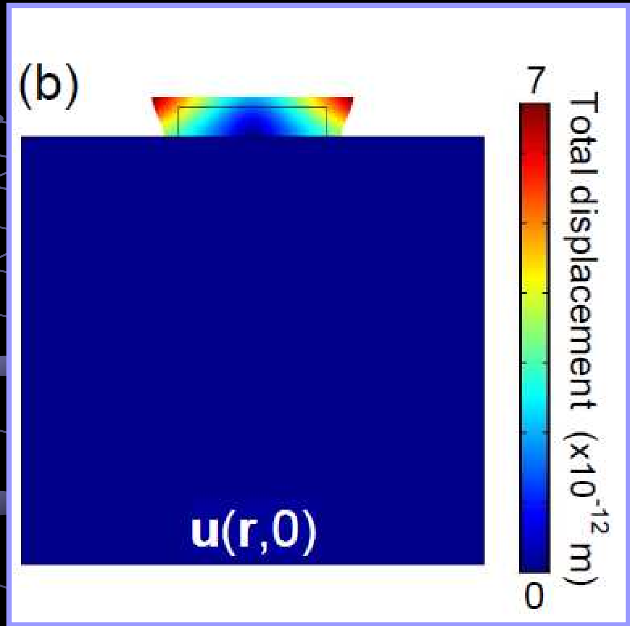


IMPULSIVE HEAT-DRIVEN DISPLACEMENT



Calculated temperature profile at t_0 = 10 ps

$$\frac{\delta d}{d} = \alpha^* \Delta T$$

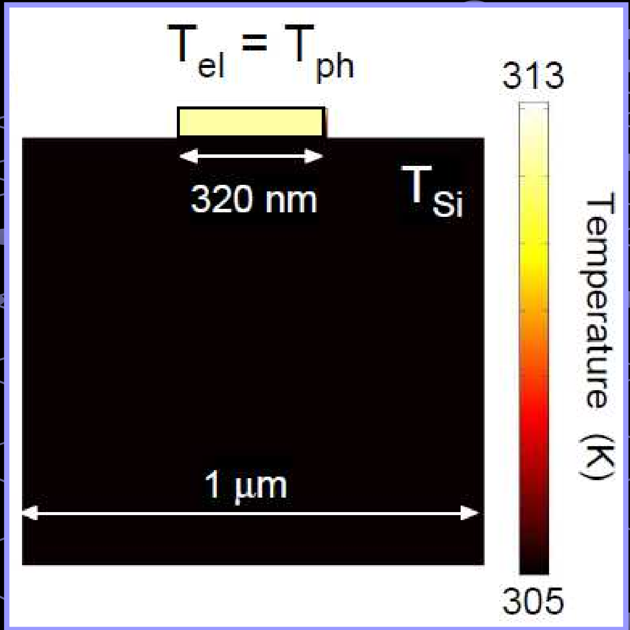


Total displacement profile at t_0 = 10 ps

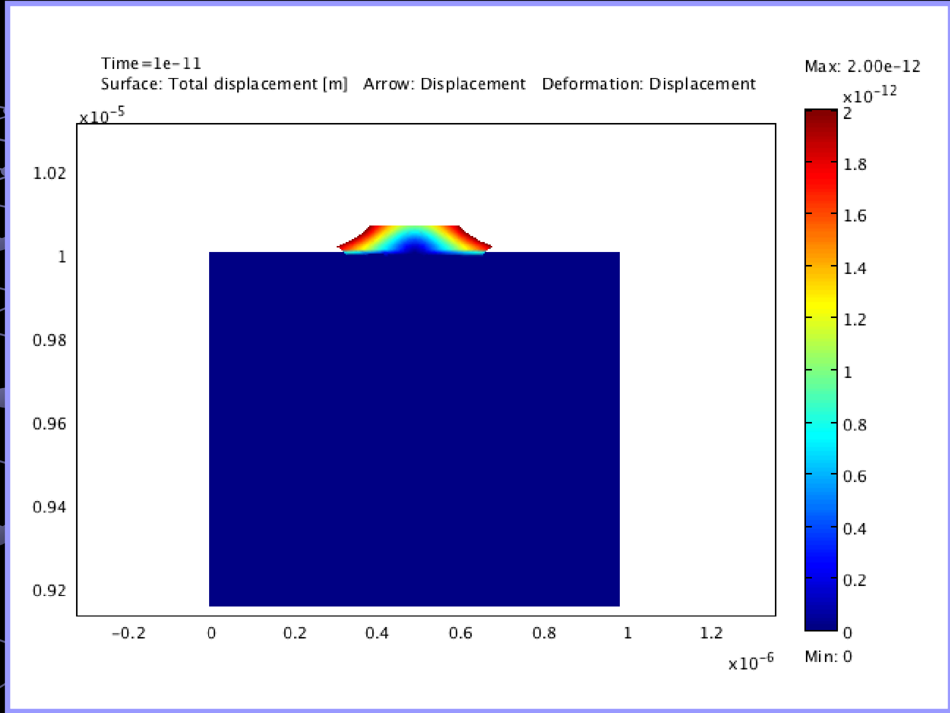
$\alpha \sim 10^{-6}$ thermal expansion coefficient

ΔT = 8 K

IMPULSIVE HEAT-DRIVEN DISPLACEMENT



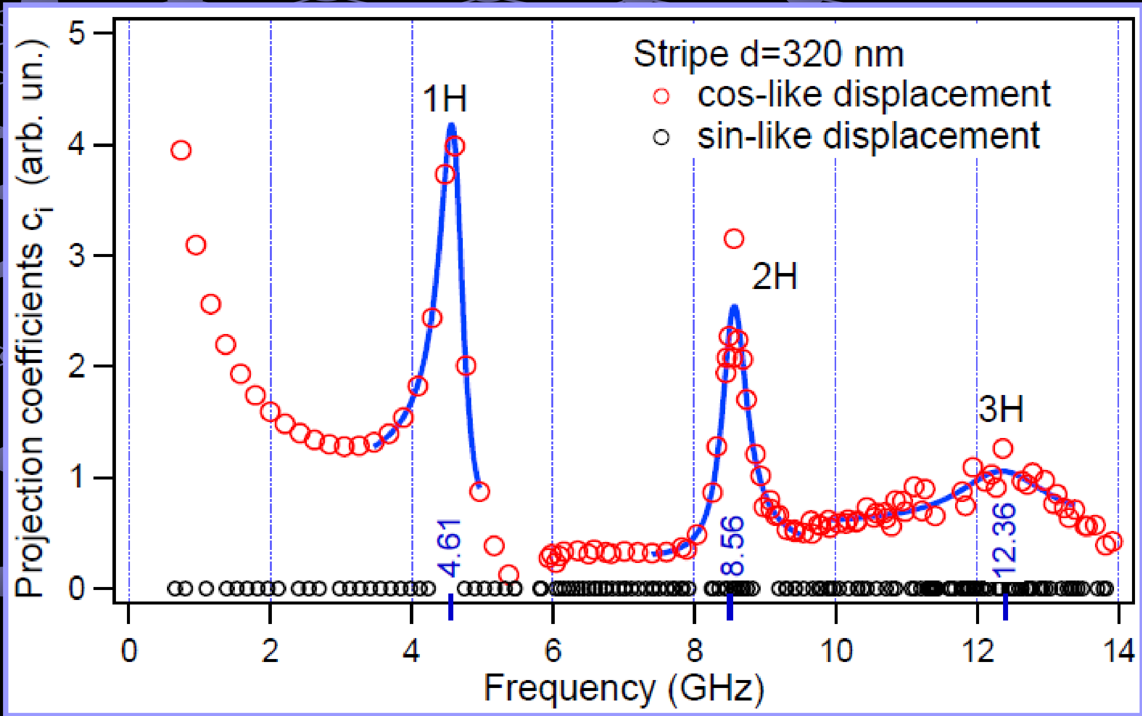
Calculated temperature profile at t_0 = 10 ps

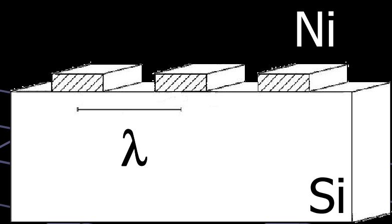


Mechanical time evolution

2D PROJECTIONS: Stripes (d=320 nm)

Projection of the thermal expansion displacement on the eigenmodes of the composite system:

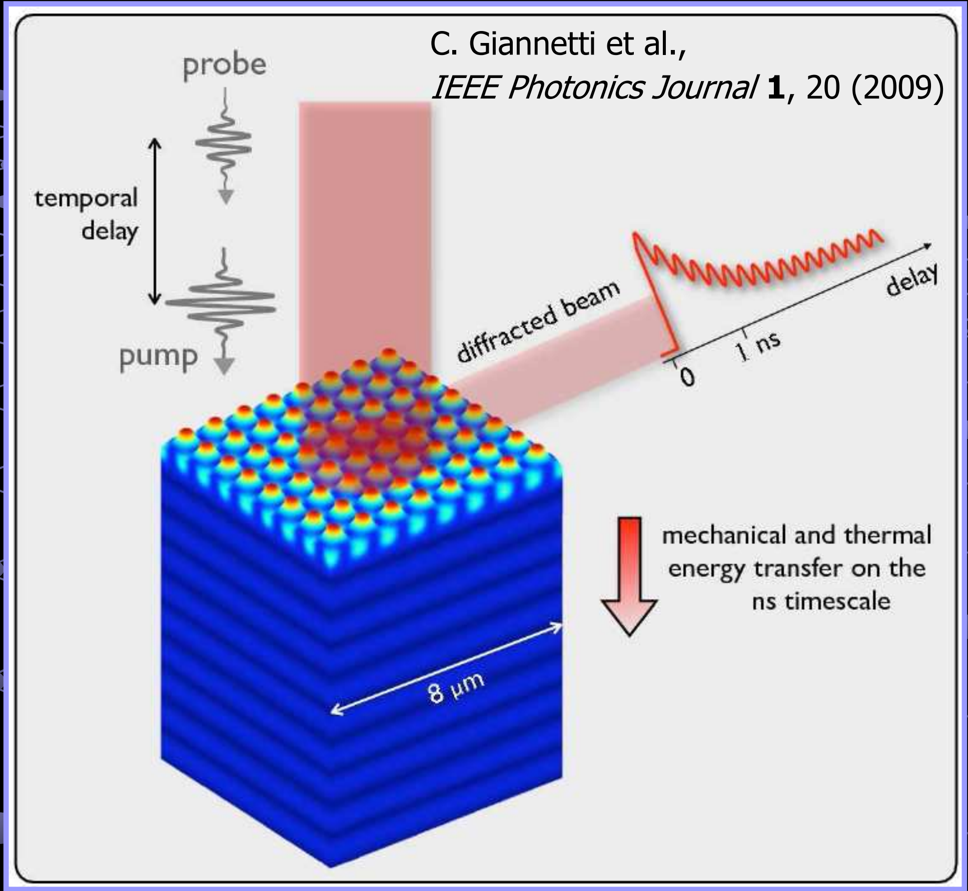




Fano lineshape profiles

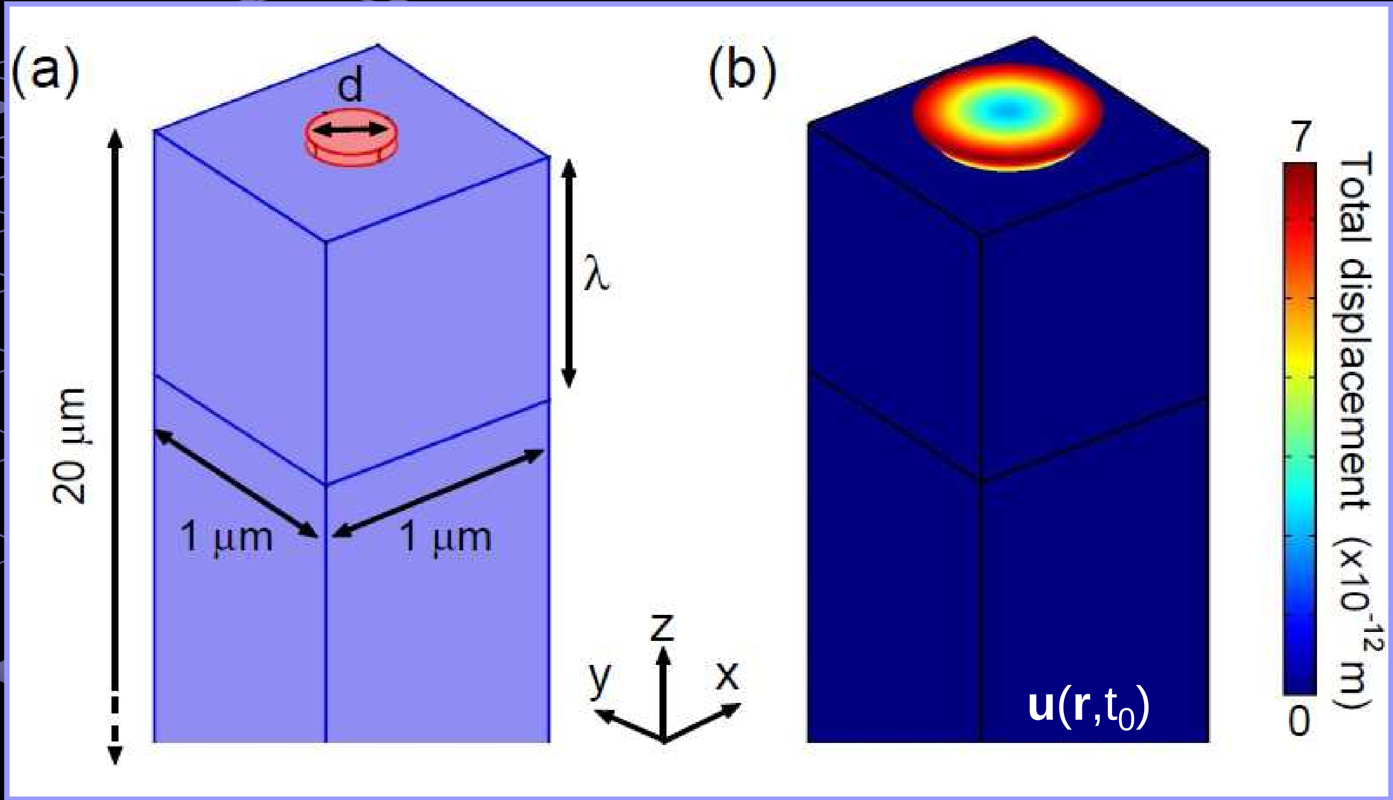
$$|\mathbf{u}(\mathbf{r},t_0)\rangle = \sum_i \boxed{\langle \tilde{\mathbf{u}}_i | \mathbf{u}(\mathbf{r},t_0)\rangle} \, |\tilde{\mathbf{u}}_i\rangle$$

BENCHMARK: TR DIFFRACTION MEASUREMENTS



R. I. Tobey et al., *Appl. Phys. Lett.* **85**, 564 (2004)
C. Giannetti et al., *Phys. Rev. B* **76**, 125413 (2007)
M. E. Siemens et al., *Appl. Phys. Lett.* **94**, 093101 (2009)

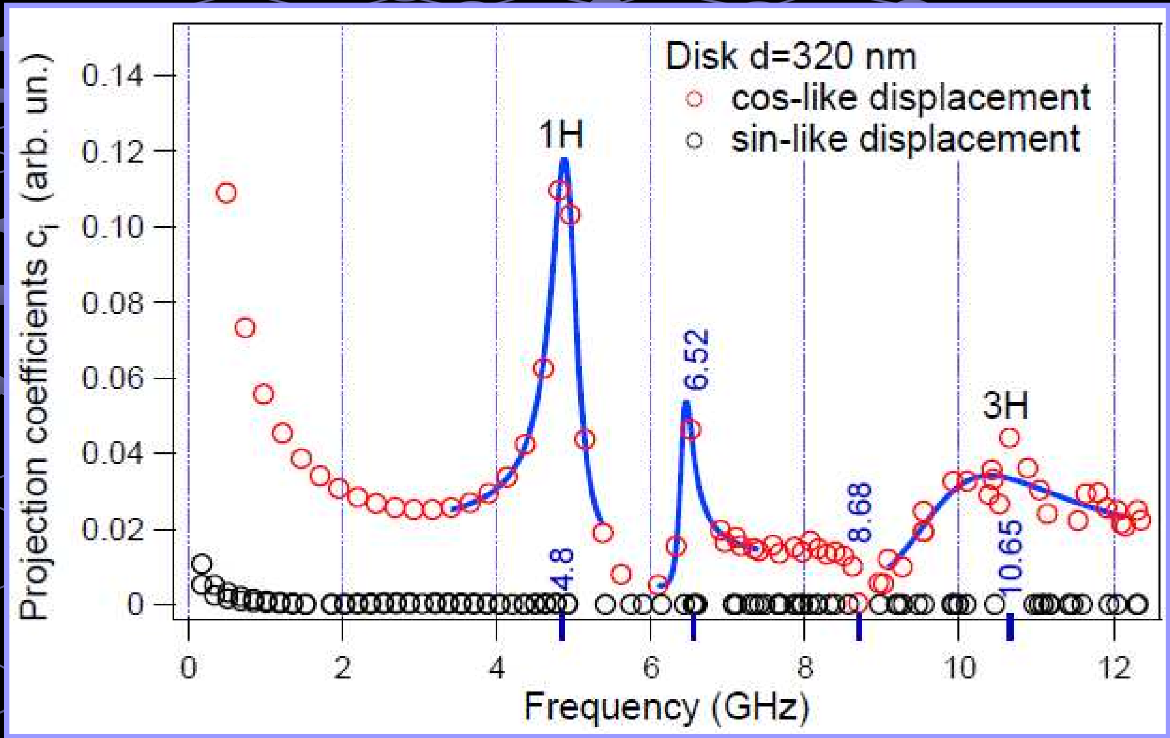
EXTENSION TO 3D PHONONIC CRYSTALS

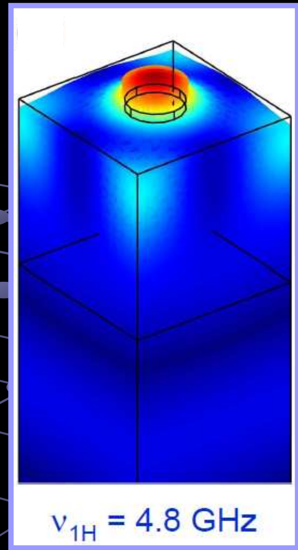


3D simulation cell geometry

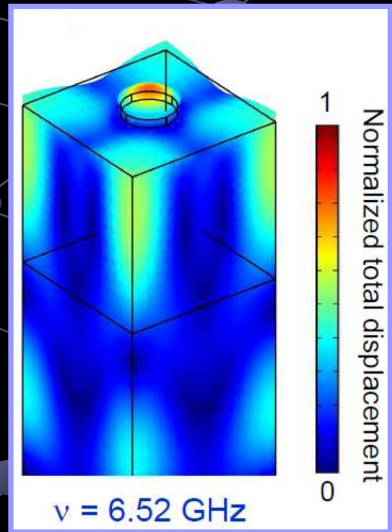
Total displacement profile at t_0 = 10 ps

3D PROJECTIONS: Disks (d=320 nm)



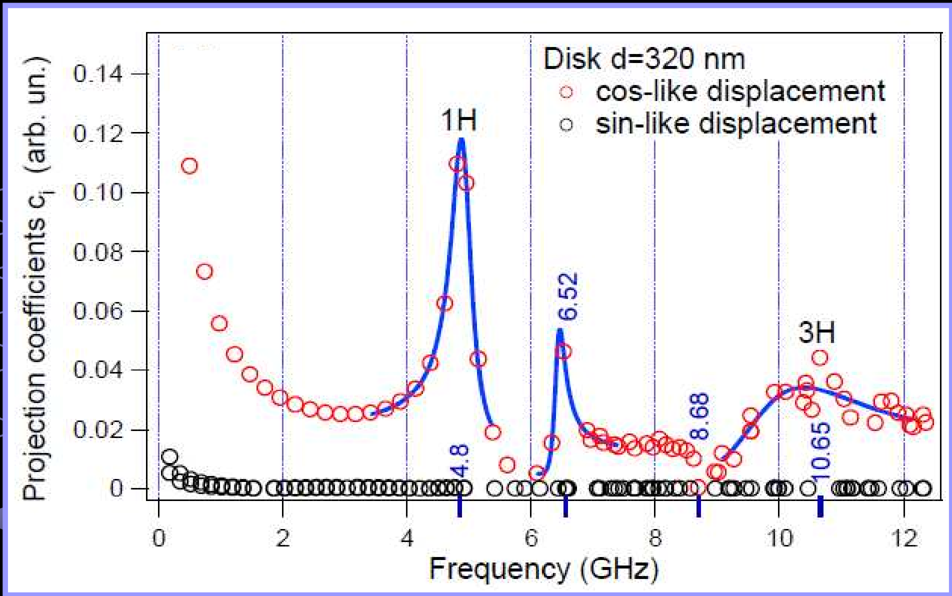


Pseudo-SAW
1H

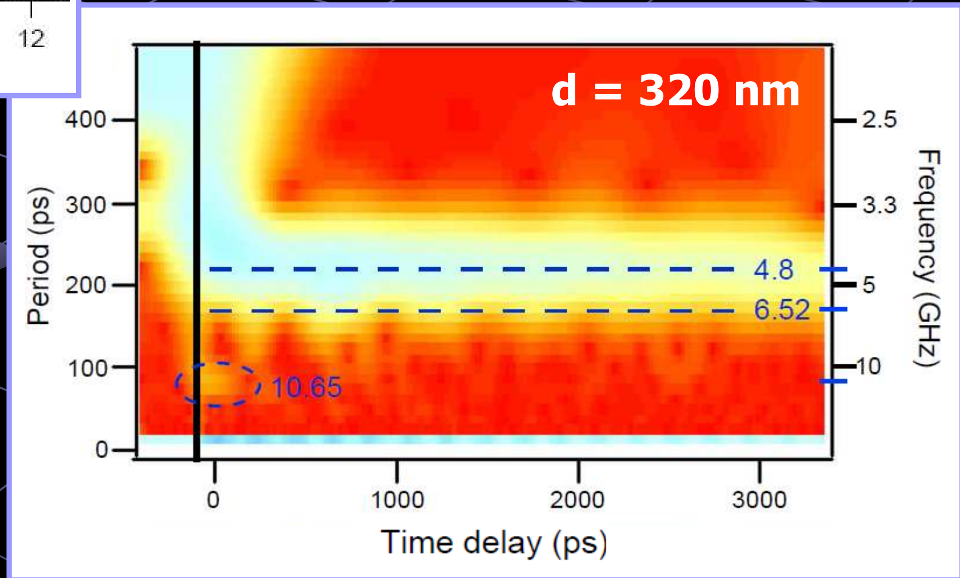


Bulk mode with strong surface component
$\alpha \sim 0.4$

BENCHMARK: EXPERIMENTAL WAVELET



Disks $d = 320$ nm	ν_{1H}		ν_{3H}
ν (GHz)	4.8	6.52	10.65
τ (ns)	2.46		0.425



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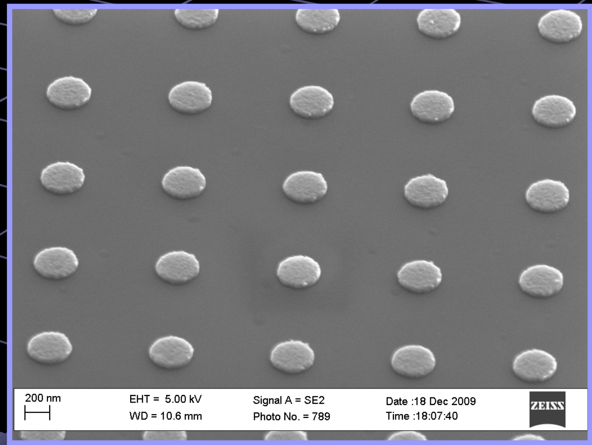


CONCLUSION

✓ Tool to address the nature of surfacelike eigenmodes in a hypersonic surface phononic crystal:

SAW-likeness coefficient

✓ Address the full thermomechanical problem and identify the launched **pseudosurface acoustic waves**

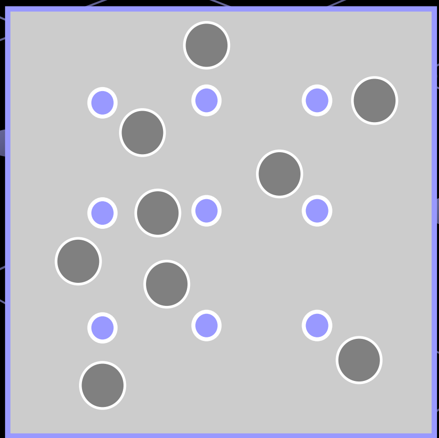
PERSPECTIVES

- ✓ Fully relate the excited mechanical modes to the detected optical signal;

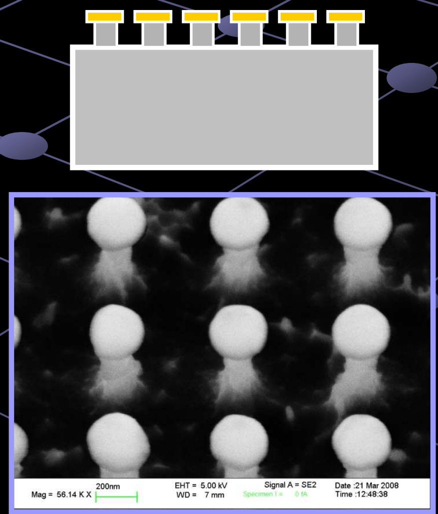
PERSPECTIVES

- ✓ Fully relate the excited mechanical modes to the detected optical signal;
- ✓ Disentangle mechanical and thermal energy decay channels.

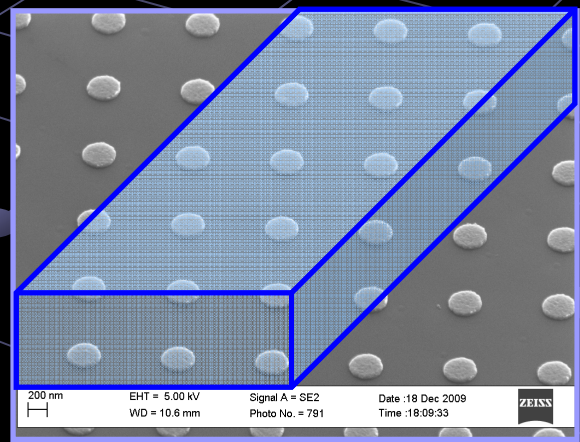
Array of metallic nanodots with aperiodic holes



Array of suspended metal nanodots



Polymeric coating as damping layer for pseudo-SAWs



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  Fulvio Parmigiani
- Thermodynamics and nanomechanics
  Bernard Revaz (EPFL, Lausanne), Federico Pressacco (Regensburg),
- Devices fabrication
  Pasqualantonio Pingue (NEST, Pisa)

Thank you