Metrology Using Laser Induced Ultrasonic Waves

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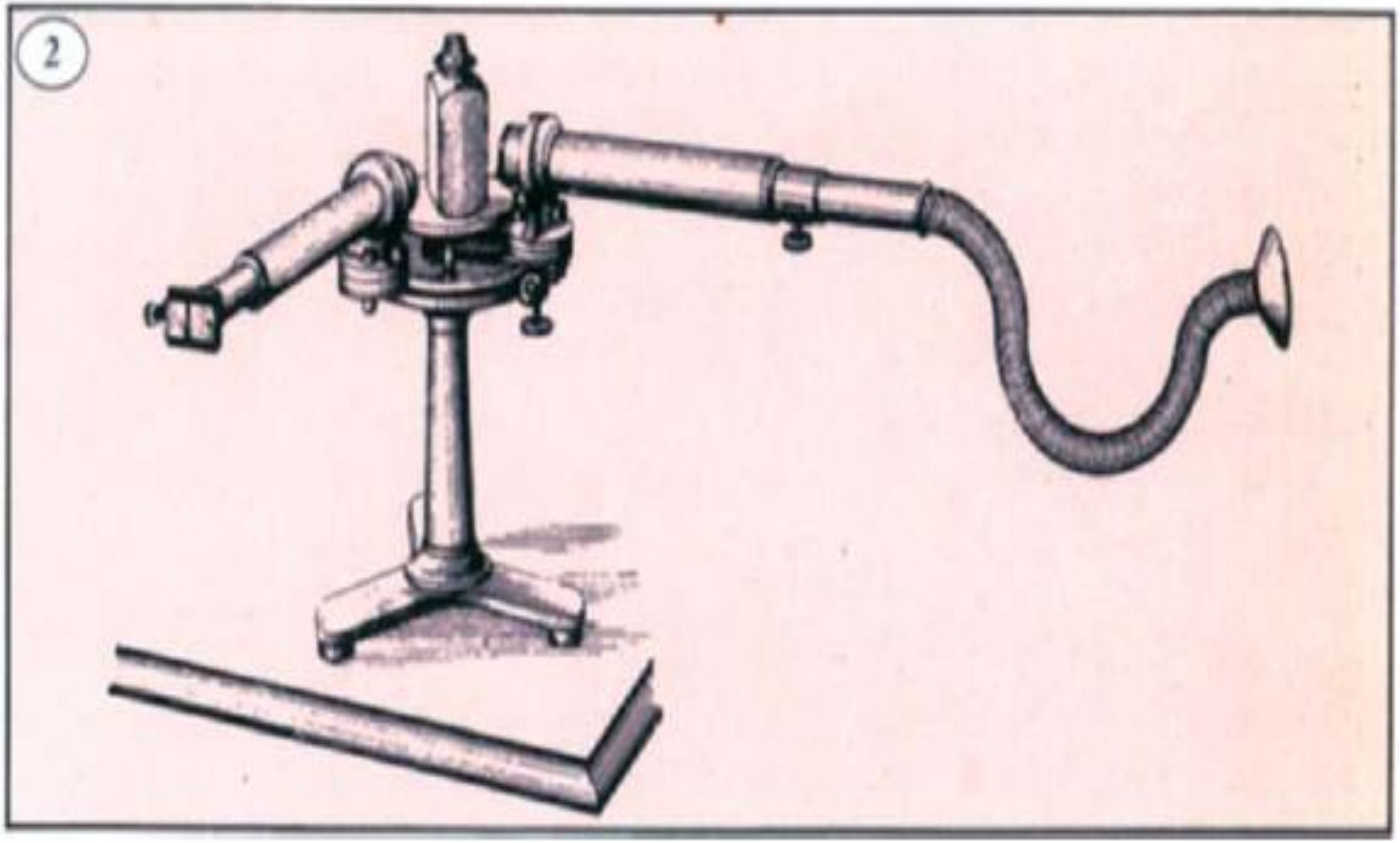
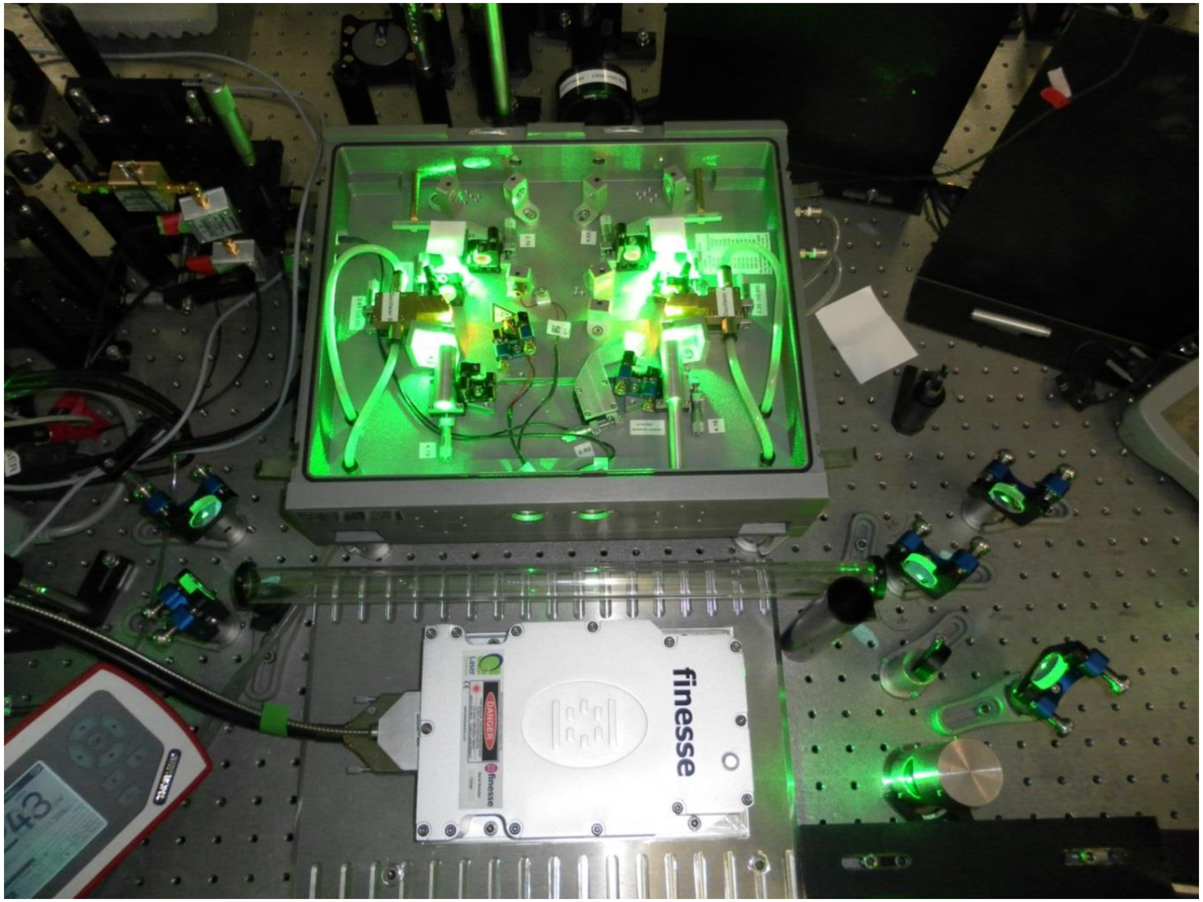
Son et lumière



Graham Bells „Spectrophone“, Phil Mag. **11**, 510 (1881)

Son et lumière



A. Bartels et al., Rev. Sci. Instr. **78**, 035107 (2007)
R. Gebs et al., Opt. Express **18**, 5974 (2010)

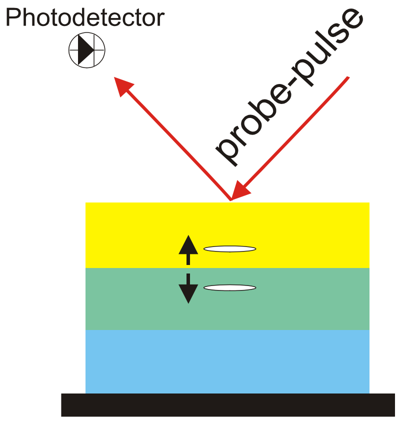
Outline

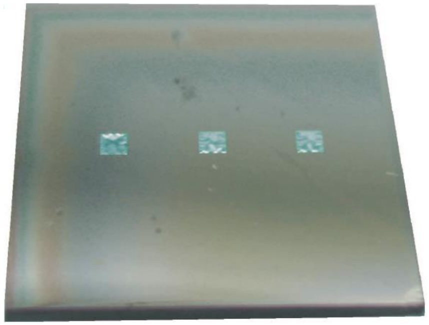
- Laser based metrology: Picosecond ultrasonics
  - high-speed asynchronous optical sampling (ASOPS)

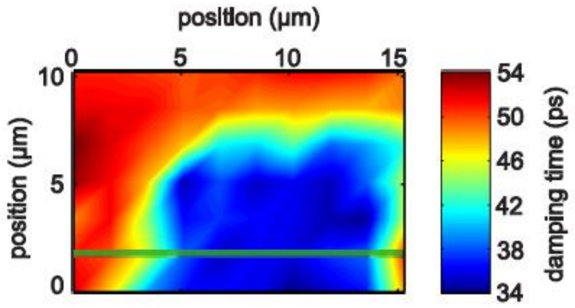
- Characterization of multilayer systems
  - Bragg mirrors for the extreme UV

- Membranes and metal films
  - Adhesion of metals films on Si membranes
  - Investigation of mechanical coupling of thin films

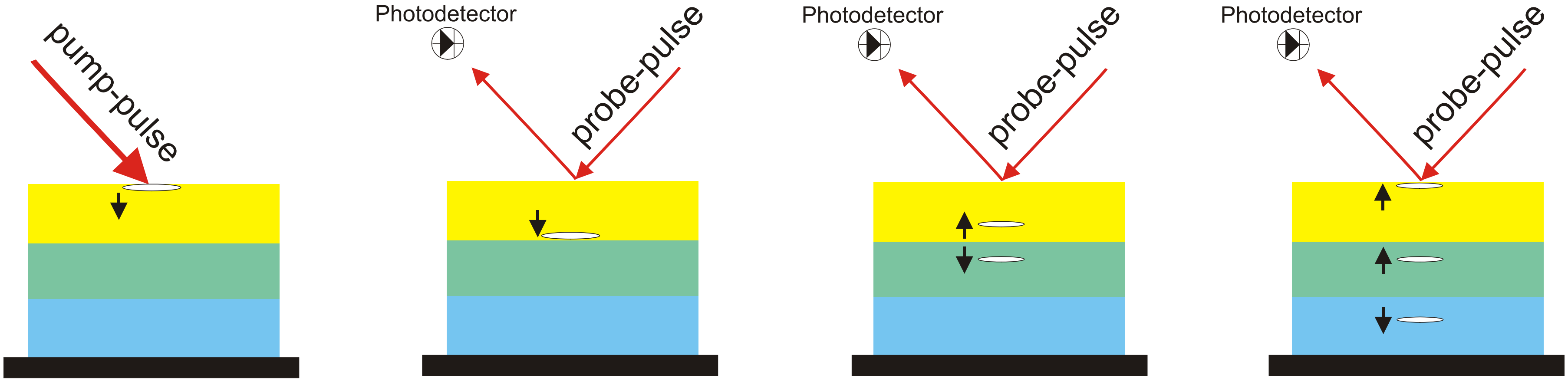
- Conclusions







Picosecond ultrasonics



- Excitation of strain pulses by femtosecond pump pulse
- Detection of phonon dynamics through elasto-optic modulation
- Time-resolved investigation of acoustic phonon dynamics
- **Non-invasive** characterization of multilayer systems with sub-picosecond temporal resolution

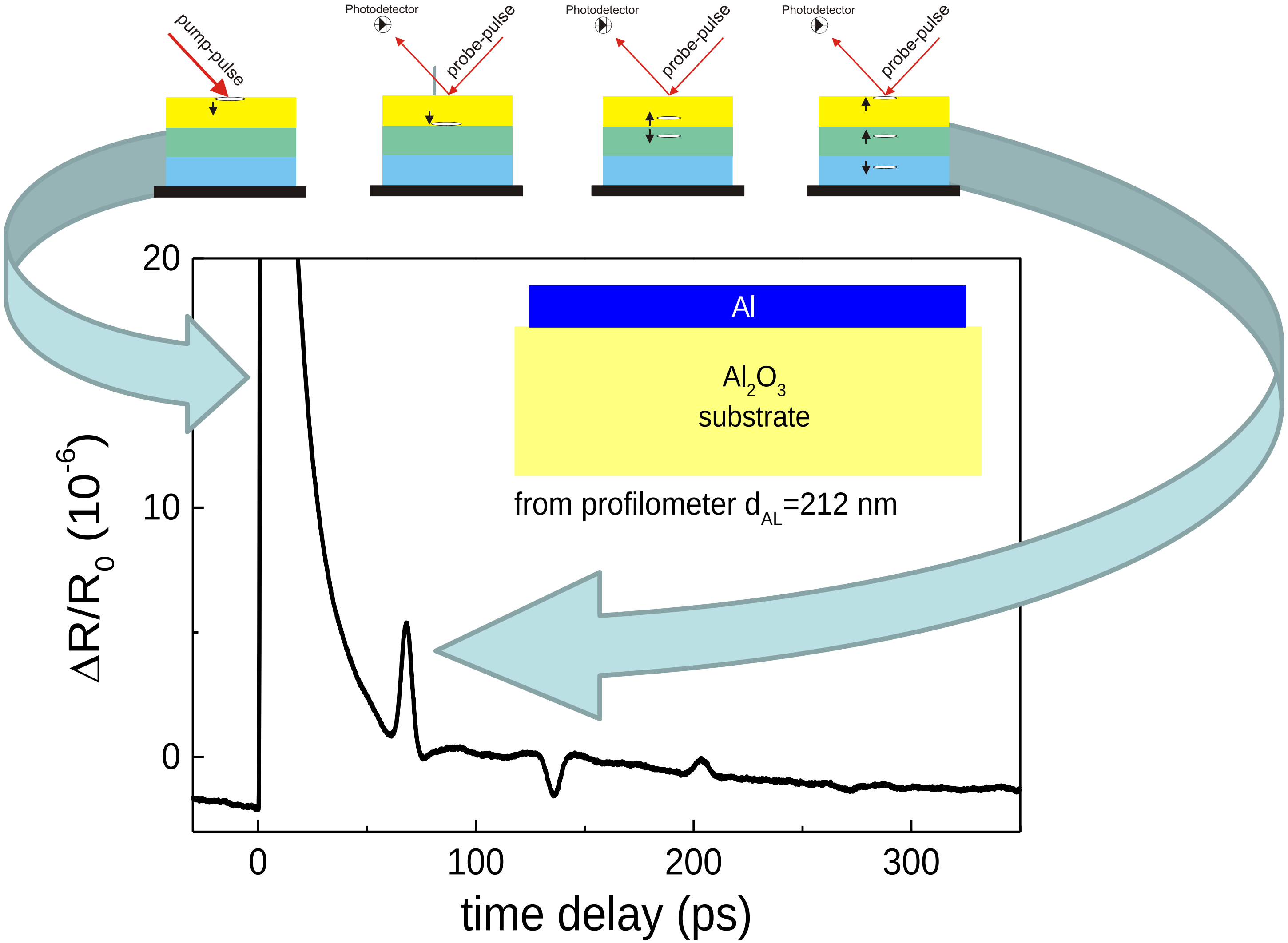
  ⇒ metrology with sub-nm depth resolution

  ⇒ adhesion properties

  ⇒ investigation of hidden layers (under opaque top layers)

Thomsen, Grahn, Maris, Tauc, Phys. Rev. B **34**, 4129 (1986)

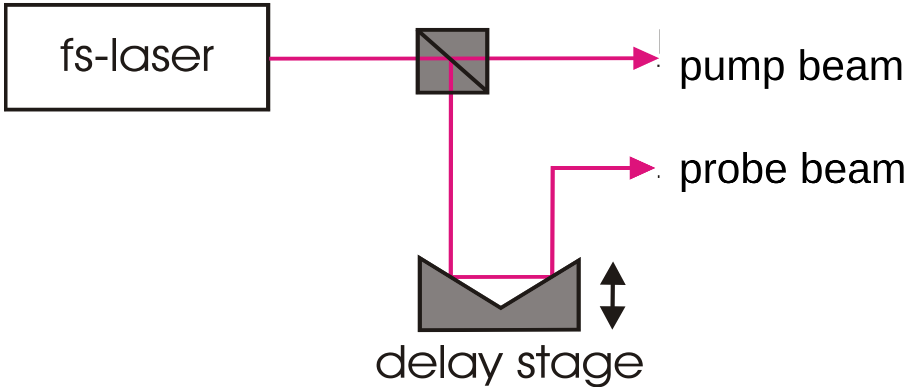
Picosecond ultrasonics



Conventionally performed as pump-probe experiment with single femtosecond laser

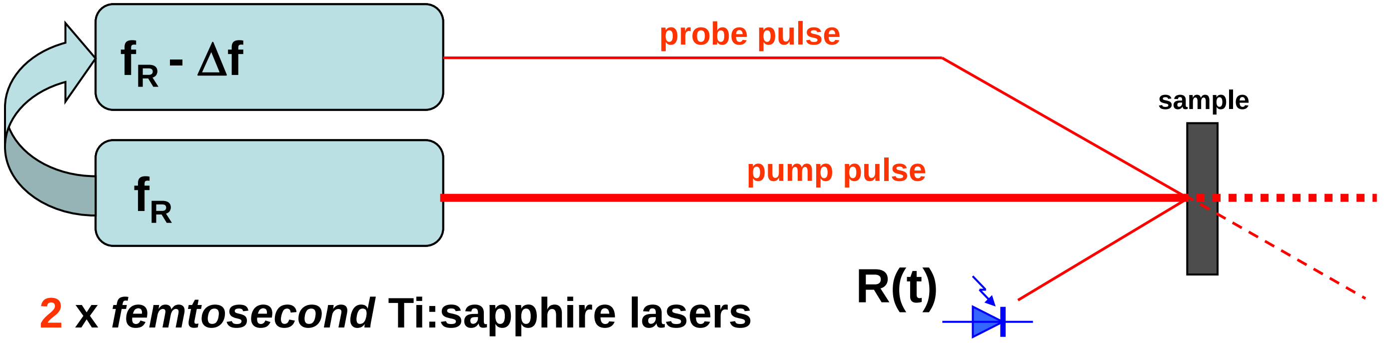
Motivation for implementation of asynchronous optical sampling (ASOPS)

- Interesting time delays for acoustic excitations in 100 ps to ns range
- problem with conventional pump-probe technique



- time delay controlled via motorized delay stage (15 cm = 1 ns)
  - slow, temporal scan takes minutes
  - no video-rate signal for signal optimization (lock-in technique)
  - mechanical moving device ⇒ acoustic noise
  - pointing variation of pump or probe spot
  - spot size variation

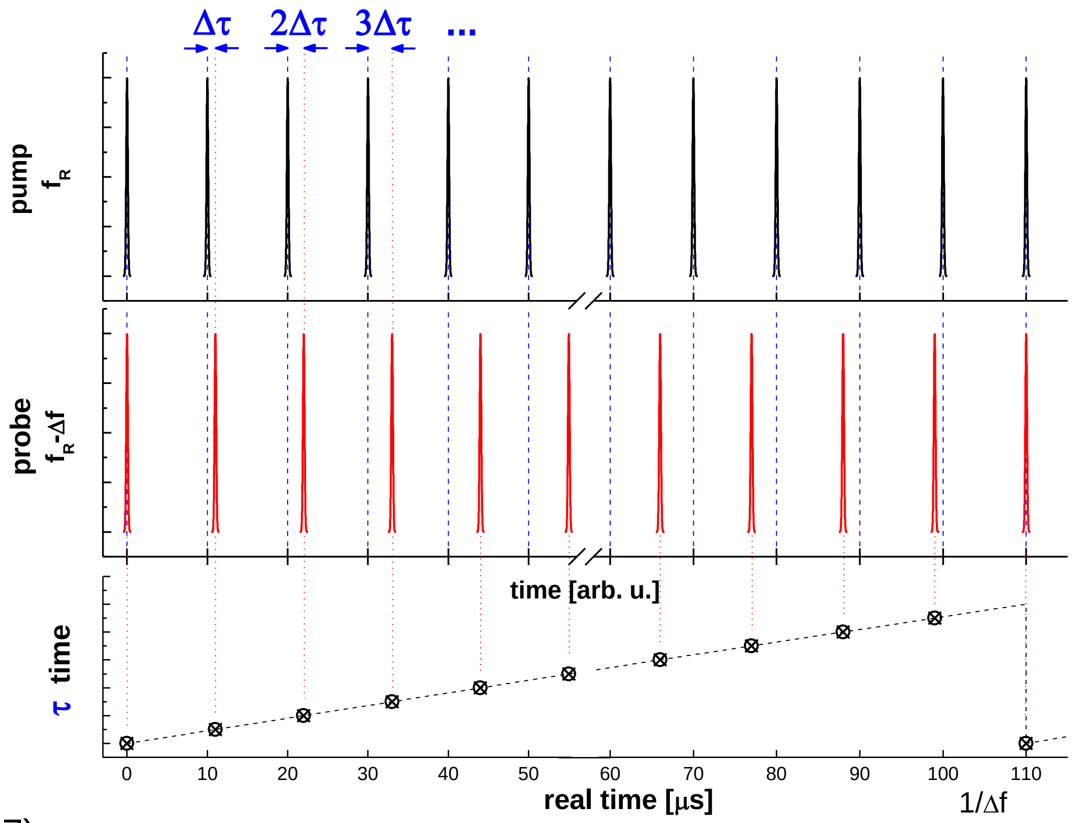
Asynchronous Optical Sampling (ASOPS)



2 x *femtosecond* Ti:sapphire lasers

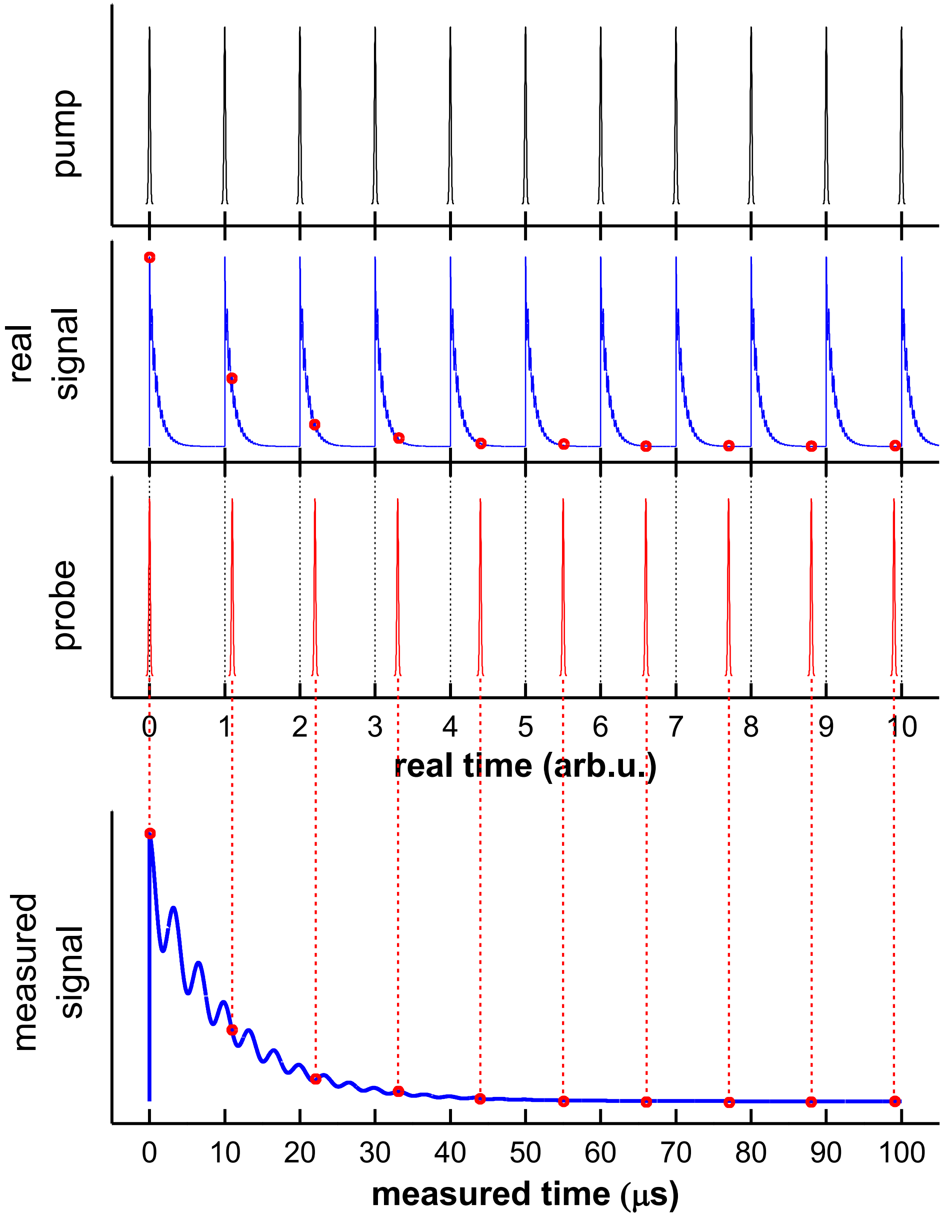
f_R~ 1 GHz
Δf = 2 kHz to 10 kHz

Δτ ~ 50 fs



Elzinga et al., Appl. Opt. **26**, 4303 (1987)
Bartels et al., Rev. Sci. Instr. **78**, 035107 (2007)
Gebs *et al*., Opt. Express **18**, 5974 (2010)

Asynchronous Optical Sampling (ASOPS)



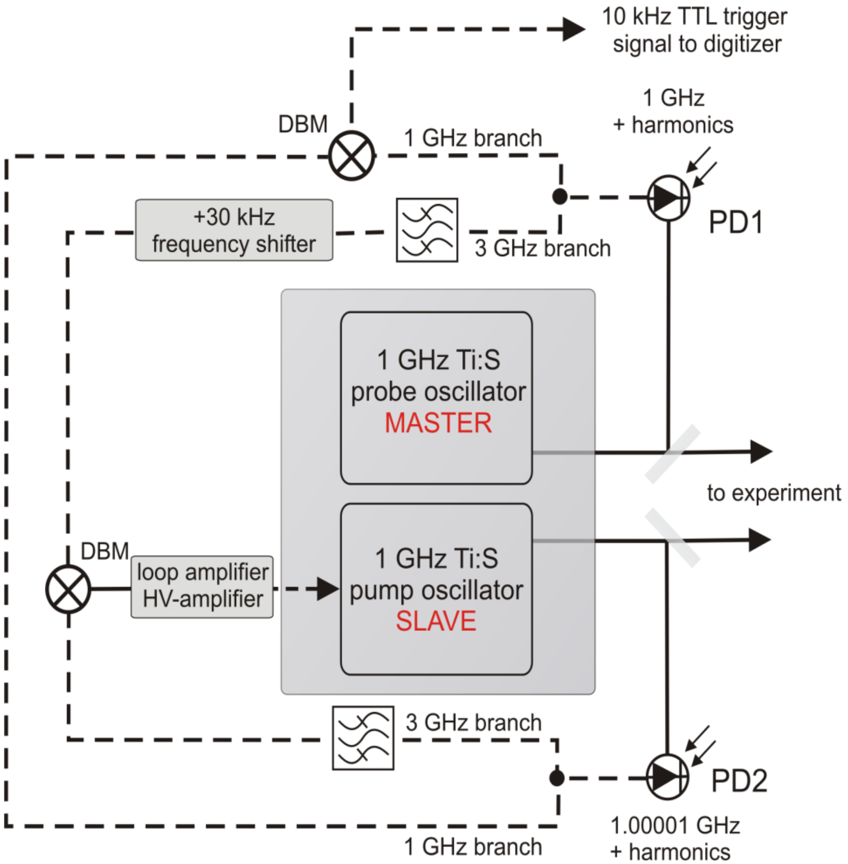
Signal of 1 ns is stroboscopically stretched to 100 µs

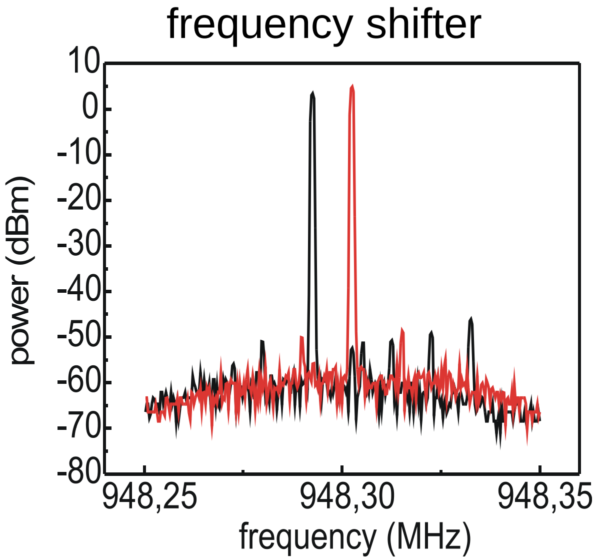
Some advantages of ASOPS:

- video rate signal
- signal-noise ratio: ~10^7 in a characteristic time of min.
- scan: 1*ns* in 100 *µs*
- 50 *fs* time resolution
- *no* moving mechanical parts
- *no* modulation/lock-in methods
- *two color* pump-probe experiments

A. Bartels et al., Rev. Sci. Instr. **78**, 035107 (2007)
R. Gebs *et al*., Opt. Express **18**, 5974 (2010)

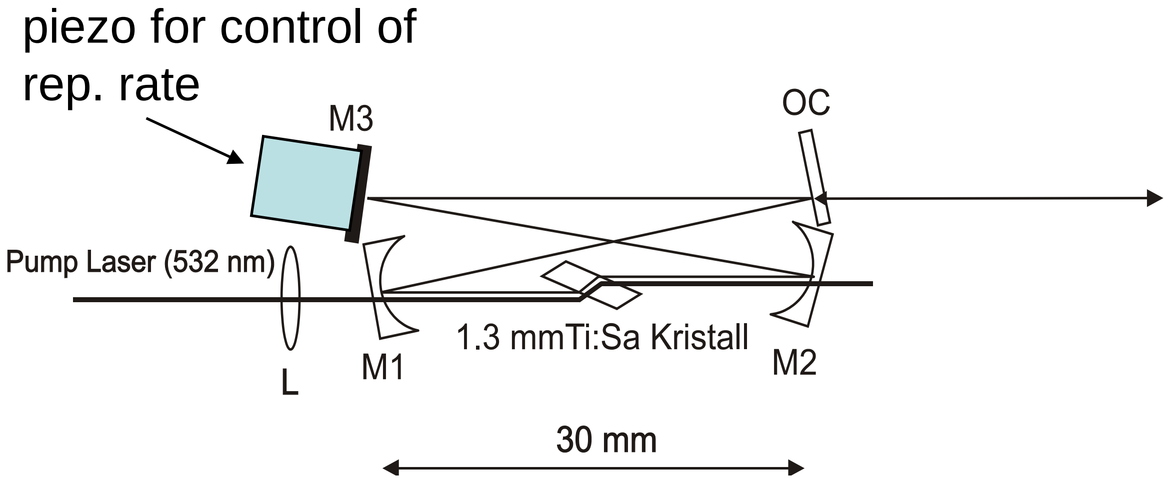
High-speed asynchronous optical sampling

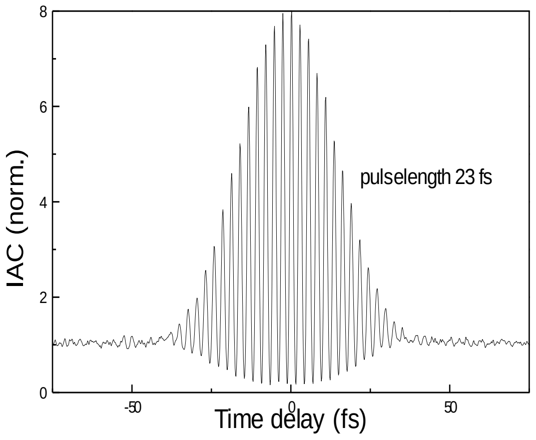



frequency shifter

- 2 tunable Ti:sapphire lasers (1 GHz rep rate, 30 fs pulse width, 500 mW average power with 3 W pump power)
- 1 ns delay time (inverse laser repetition rate) scanned with 10 kHz
- no mechanical moving part
- timing jitter < 50 fs ⇒ >10 THz bandwidth “all optical scope”

Compact femtosecond Ti:sapphire laser

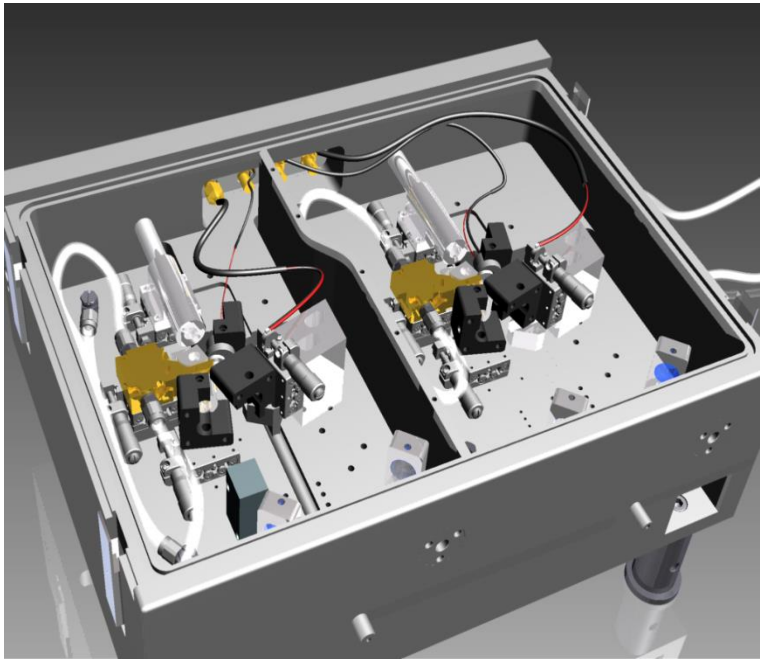




- 1 GHz uni-directional ring-cavity with negative dispersive mirrors for dispersion control1)
- Control of repetition rate through cavity length
- wavelength tuning (730 nm – 860 nm) through prism inserted in ring cavity

1) Bartels, Dekorsy, Kurz, Optics Letters 1999

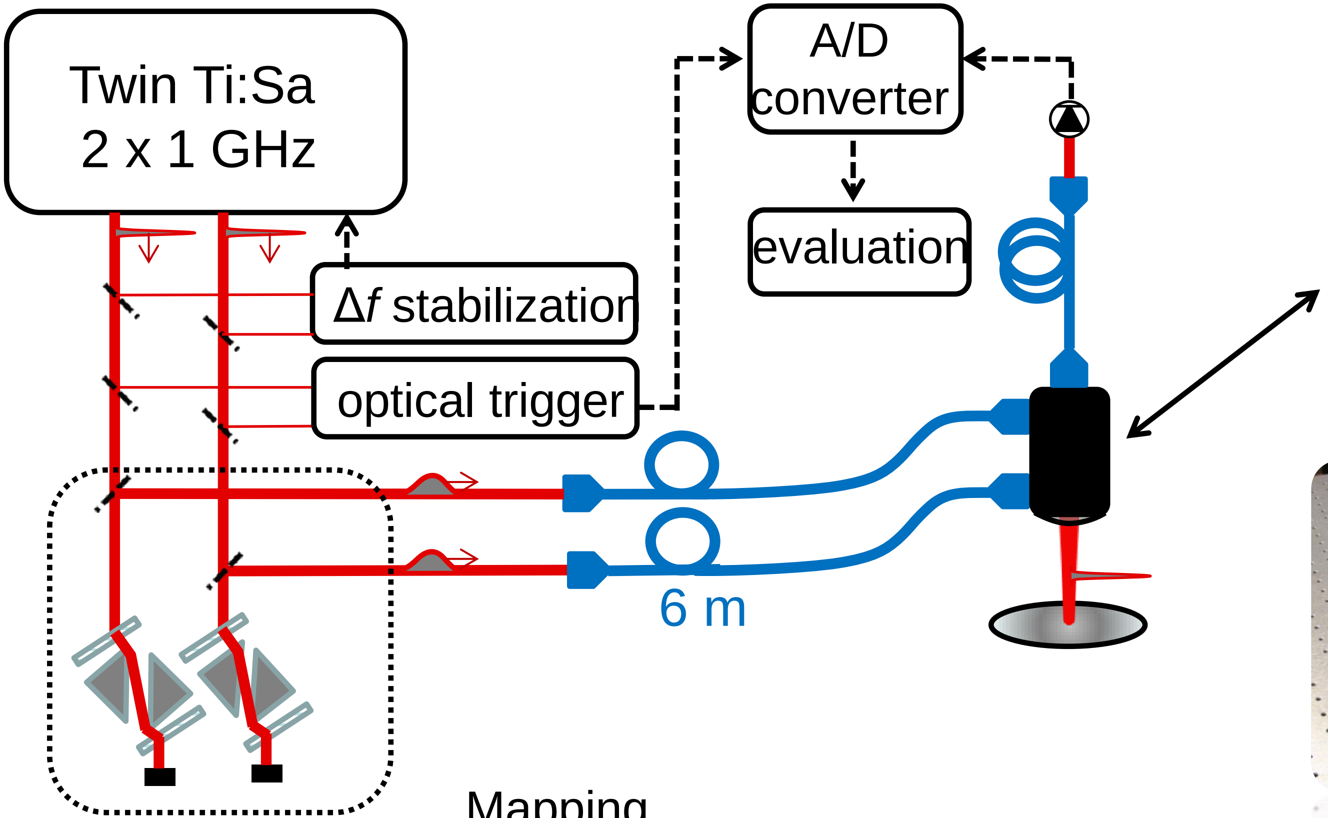
Compact femtosecond Ti:sapphire twin-laser



- Highly stable twin-laser in single housing
- Both lasers independent tunable ⇒ two colour experiments
- 30 x 30 cm^2 (more compact than conventional 80 MHz Ti:sapphire laser)

GIGAOPTICS femtosecond technologies now Laser QUANTUM INNOVATIVE RELIABLE INTELLIGENT

Fiber-coupled ASOPS system



Twin Ti:Sa
2 x 1 GHz

Δf stabilization

optical trigger

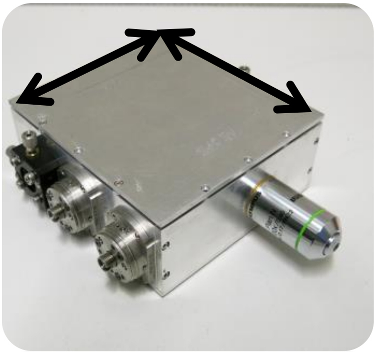
A/D converter

evaluation

6 m

Dispersion compensation

12 x 11 cm^2



Twin Laser System

Mapping

- Few-µm lateral resolution
- Scan-range limited by length of fiber (6 m)

N. Krauß and T. Dekorsy, Photonik 1/2014

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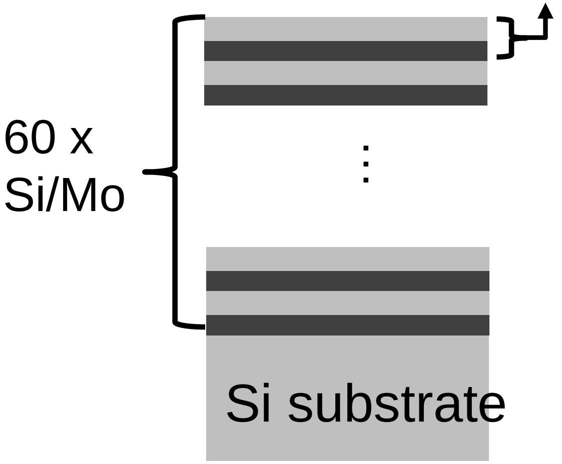
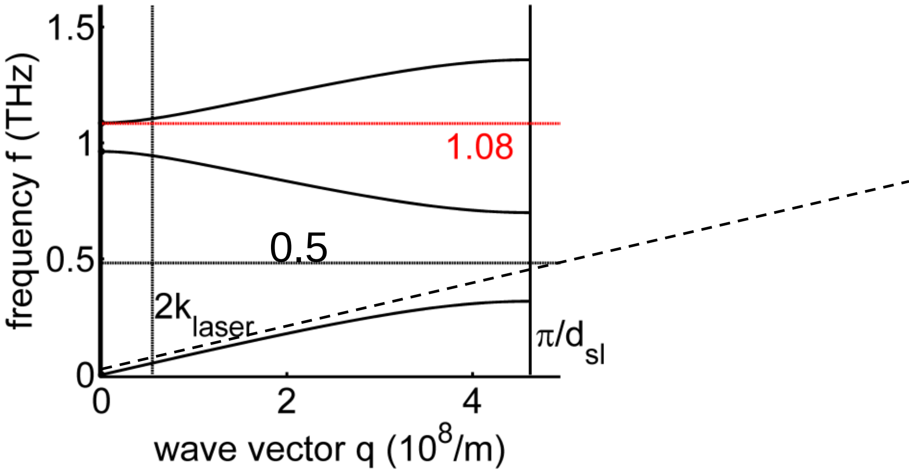
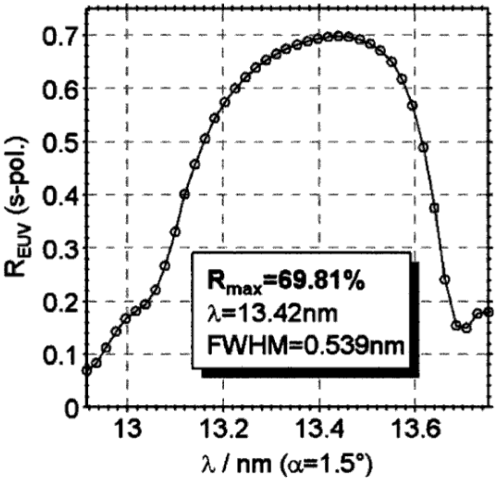
X-ray mirrors for EUV lithography

Superlattice period (6.8 nm)



Dispersion relation





<u>Ultrasonics in a Si/Mo superlattice</u>

- Reflection of the stress pulse at the substrate generates acoustic echo
- Folding of the Brillouin zone
  - → Mini-Brillouin-zone
  - → coherent acoustic phonons
  - → dominant mode at ≈ 1 THz

Braun et al., *Japanese Journal of Applied Physics* 41.6S (2002) 4074.

Laser-based inspection of Si/Mo superlattice

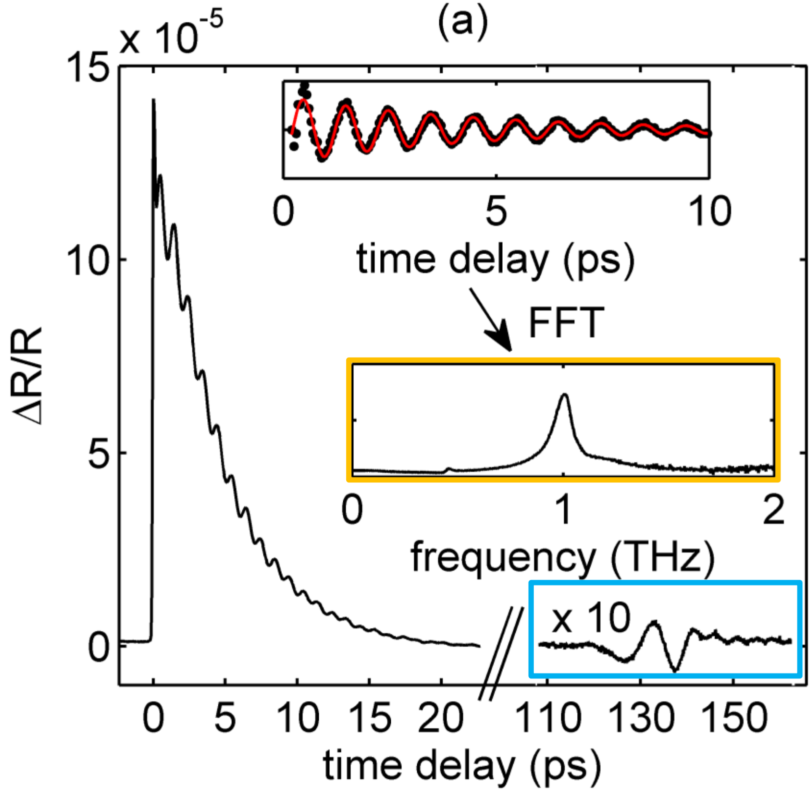
Period of Bragg mirror d_{sl} :

$$\boxed{d_{\mathrm{sl}} = v_{\mathrm{l}}/f_{\mathrm{ph}}}$$

Thickness of Bragg mirror d_{tot} :

$$\boxed{d_{\mathrm{tot}} = v_{\mathrm{l}} \cdot \tau_{\mathrm{echo}} /2}$$

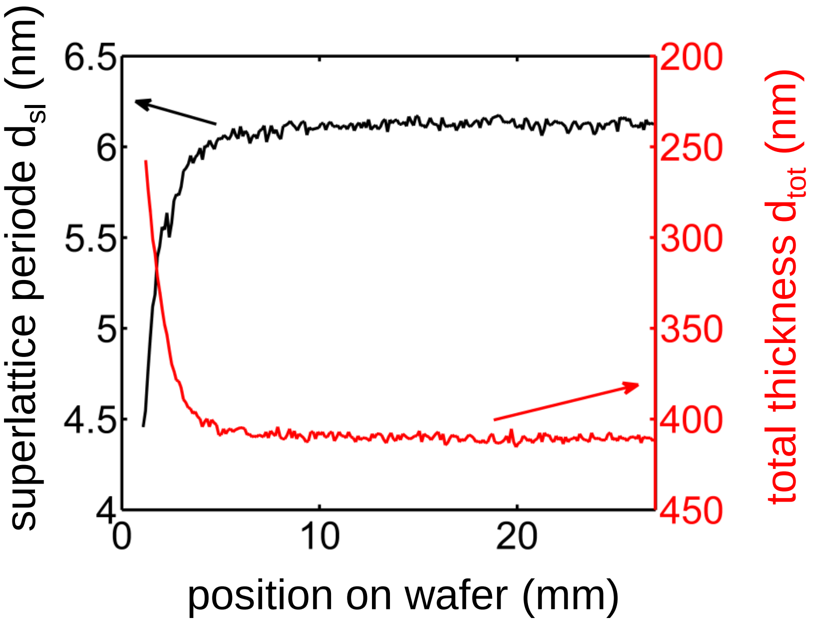
(longitudinal sound velocity v_{l})



Laser-based inspection of Si/Mo superlattice

Linescan:

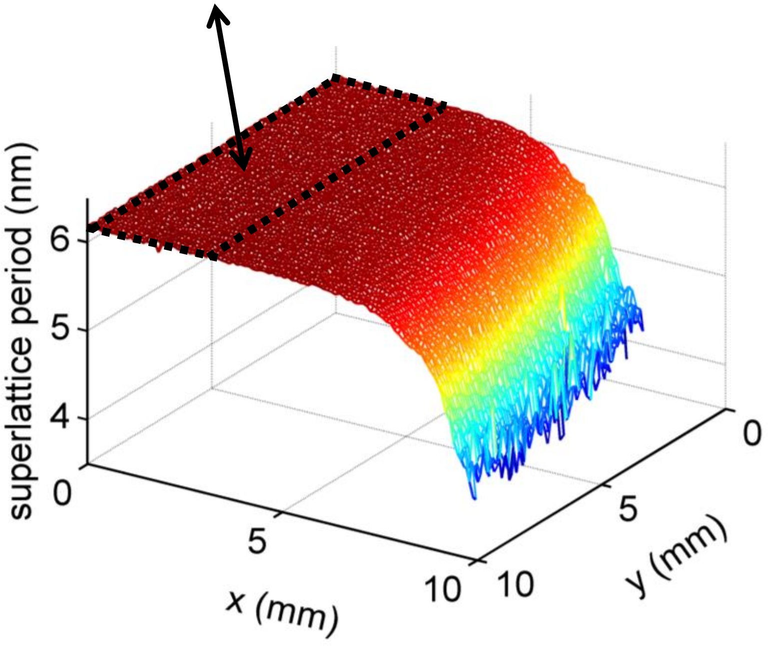
- sub-nm accuracy in thickness homogeneity
- thickness variation due to growth inhomogeneities at the wafer edge



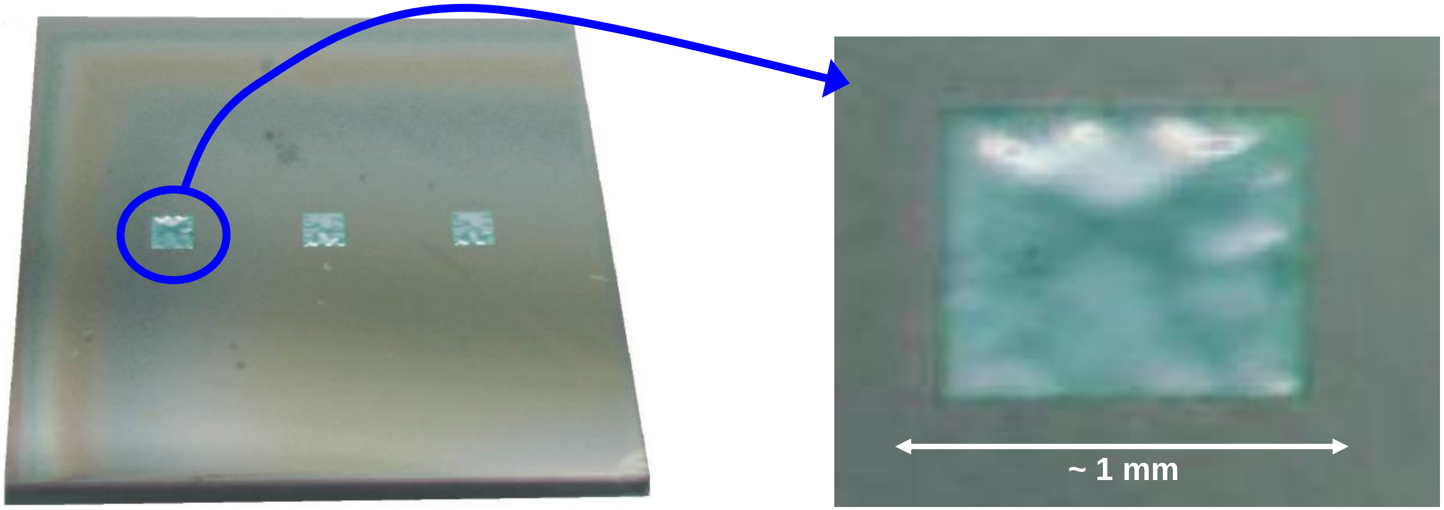
Mapping:

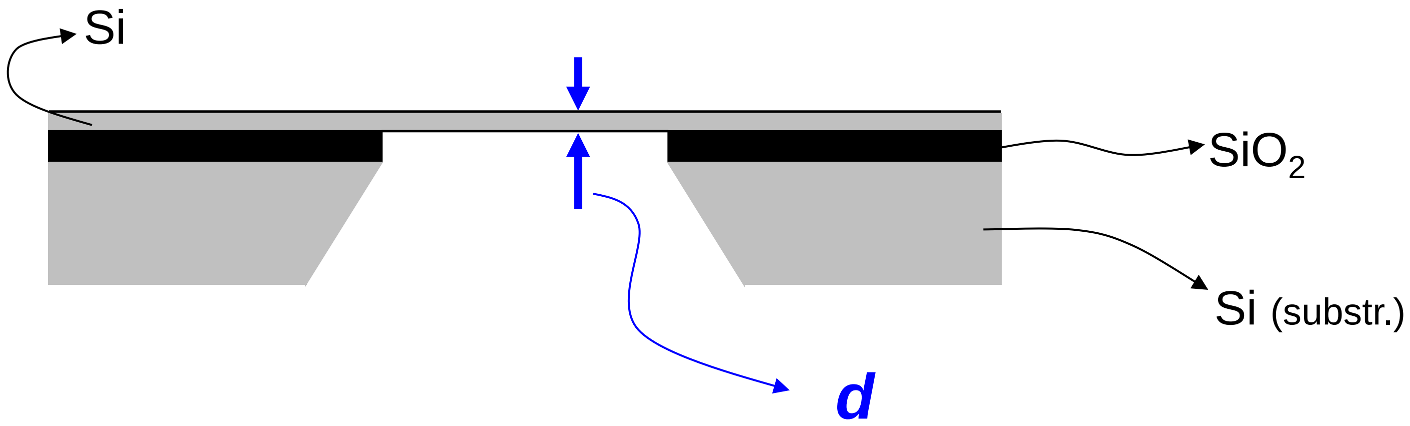
- 6 s per pixel
- 100 x 100 pixels with 100 µm distance

$$d_{sl} = 6.16 \pm 0.05 \text{ nm}$$



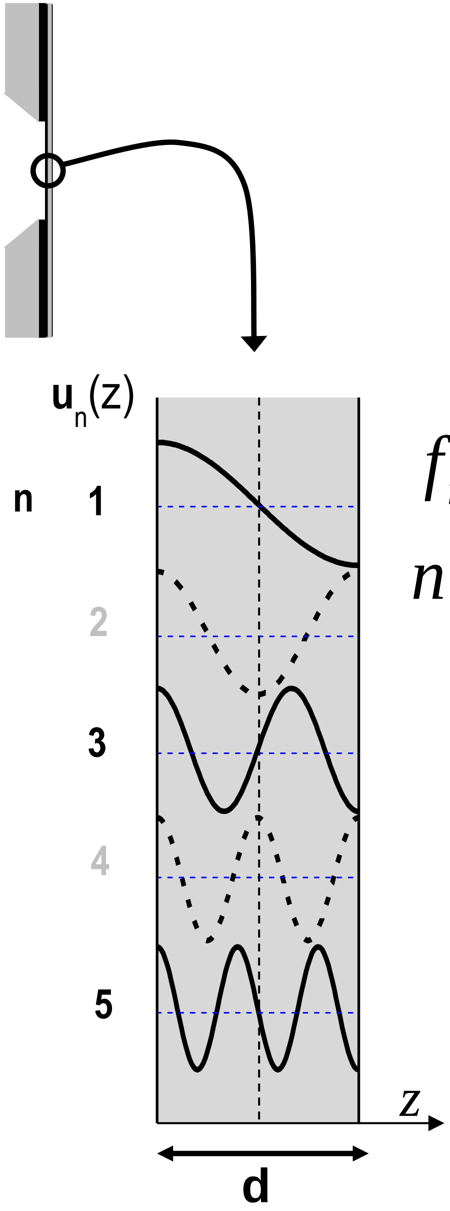
Free-standing silicon membranes





M. Bruel *et al.*, Jpn. J. Appl. Phys. **36**, 1636 (1997).
R. Waitz, *et al.*, Rev. Sci. Instrum. **79**, 093901 (2008).

Free-standing silicon membranes



longitudinal acoustic (LA) phonons are *confined perpendicularly* to the membranes surface

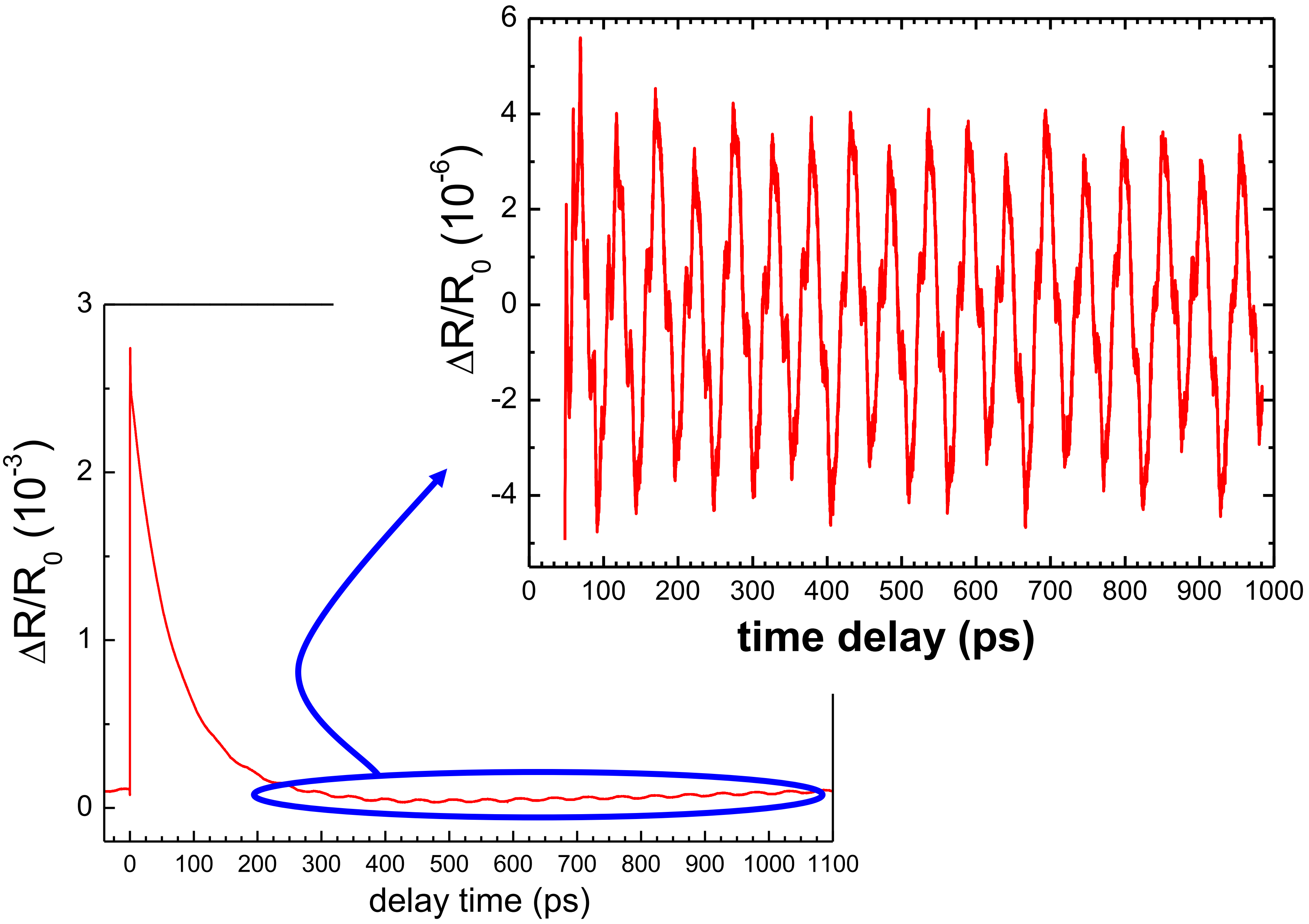
$$f_n = n\,\frac{v_{LA}}{2d}$$

$$n = 1,2,3\ldots$$

eigenmodes $u_n(z)$ of the membrane are quantized

v_{LA} : long. sound velocity

Free-standing silicon membranes



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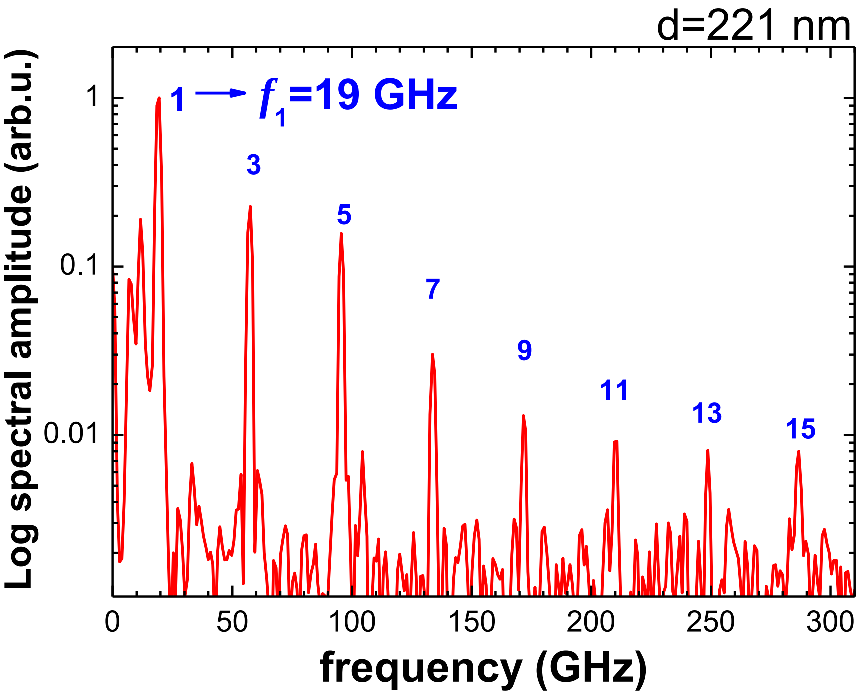
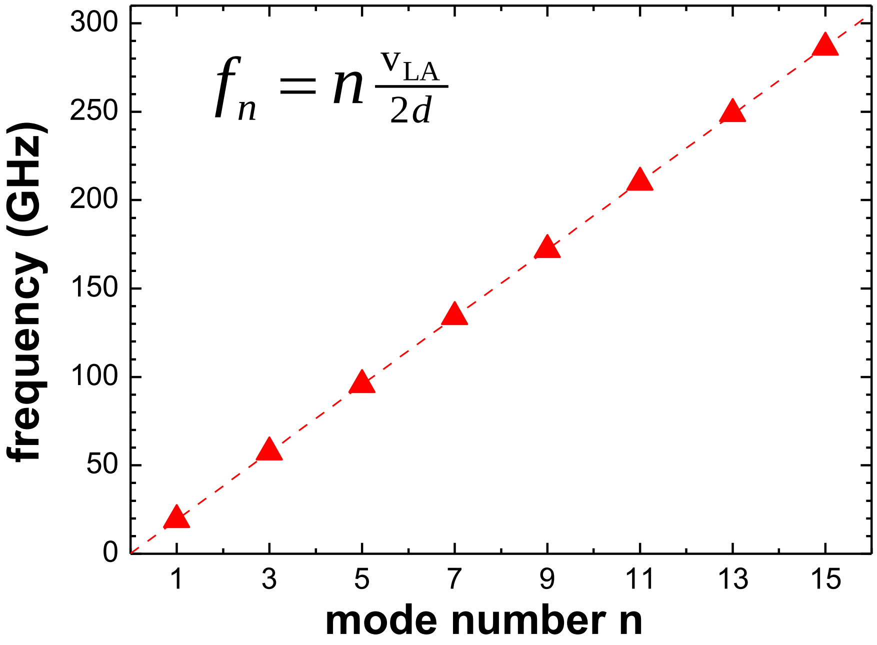




Equally spaced *discrete* modes corresponding to the *odd*-harmonic orders of the membrane's fundamental frequency f_1

⇩

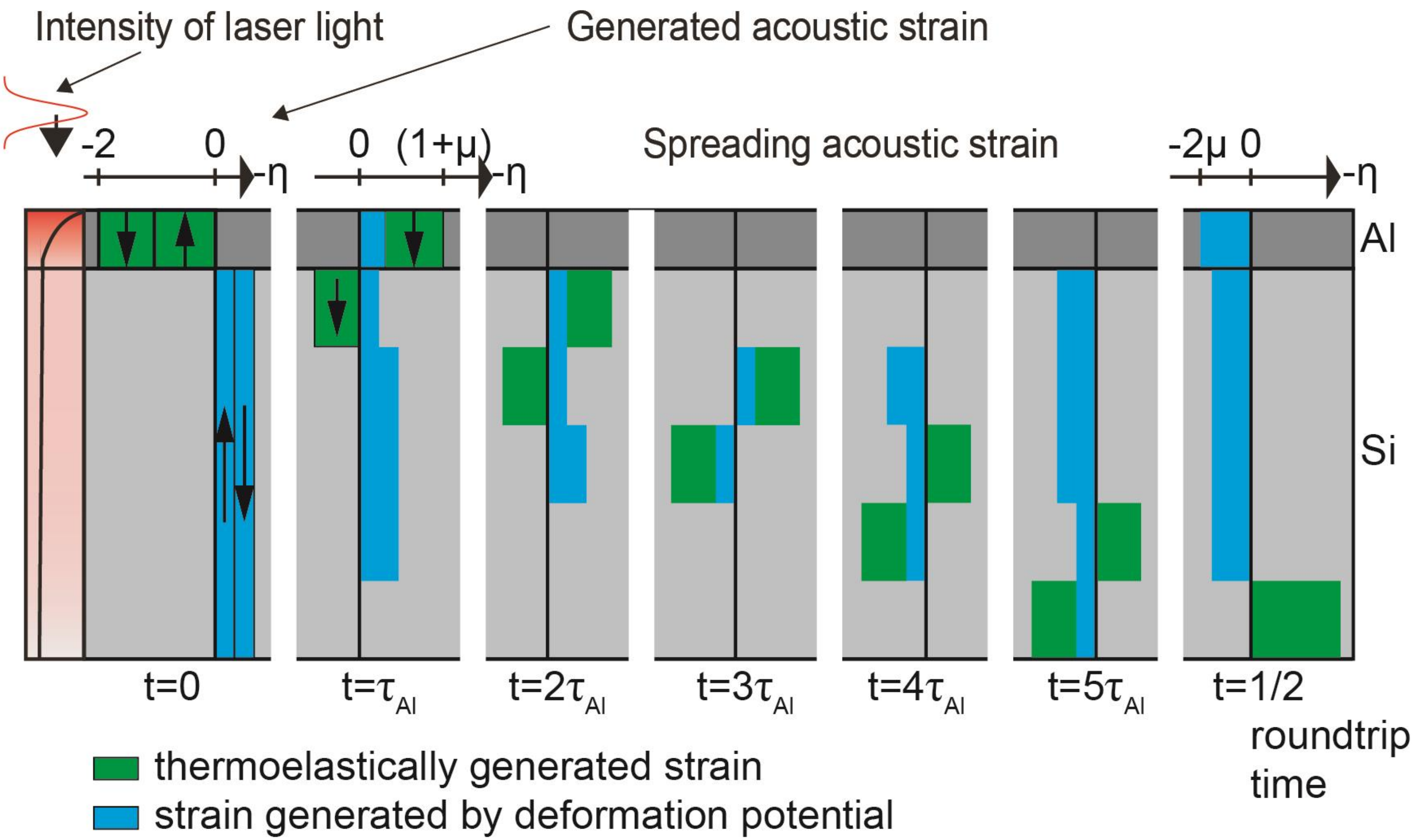
confined longitudinal acoustic (LA) phonons

F. Hudert *et al.*, Phys. Rev. B **79**, 201307(R) (2009)

Al/Si-system: strain generation and propagation

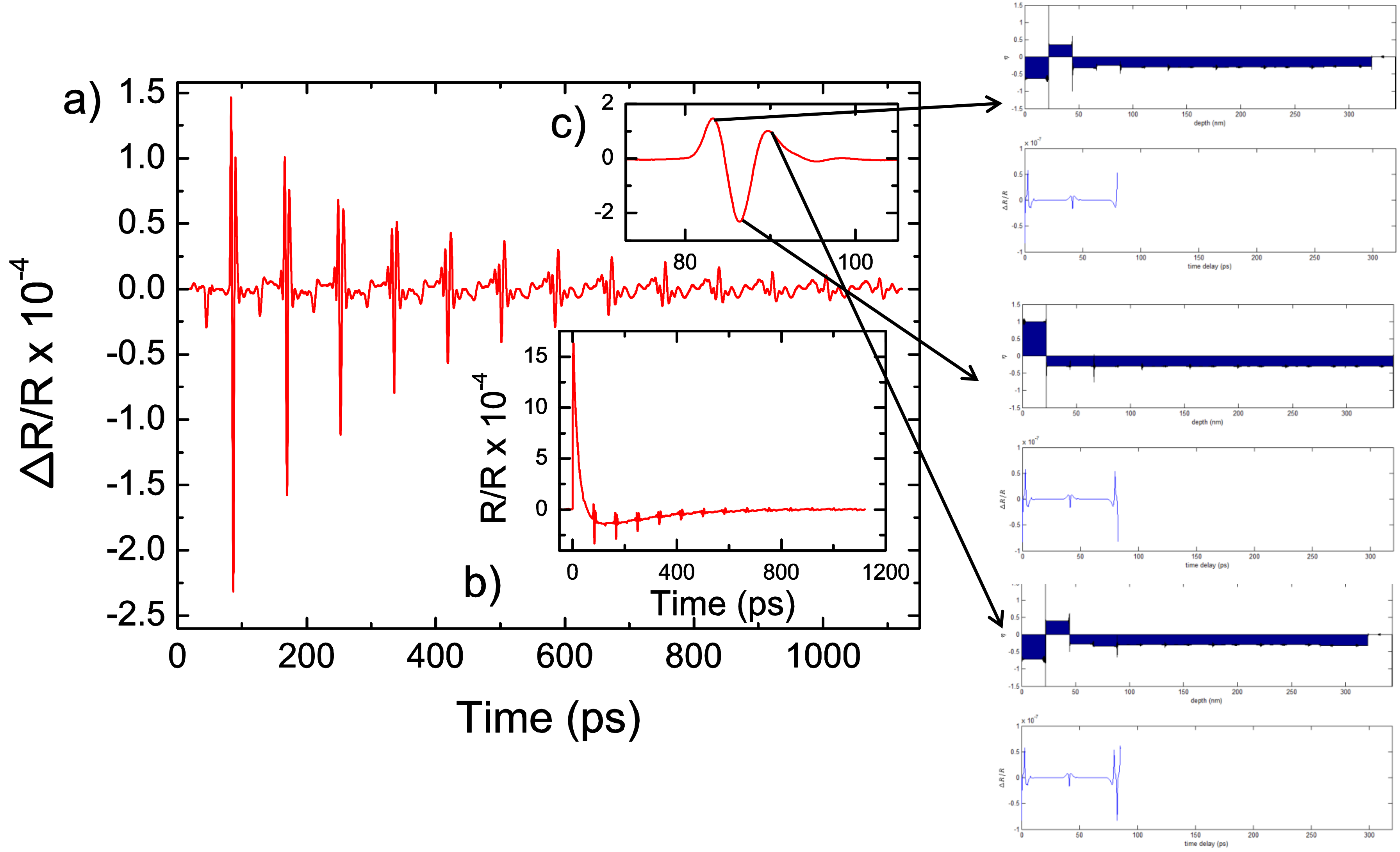
17nm Al

326nm Si

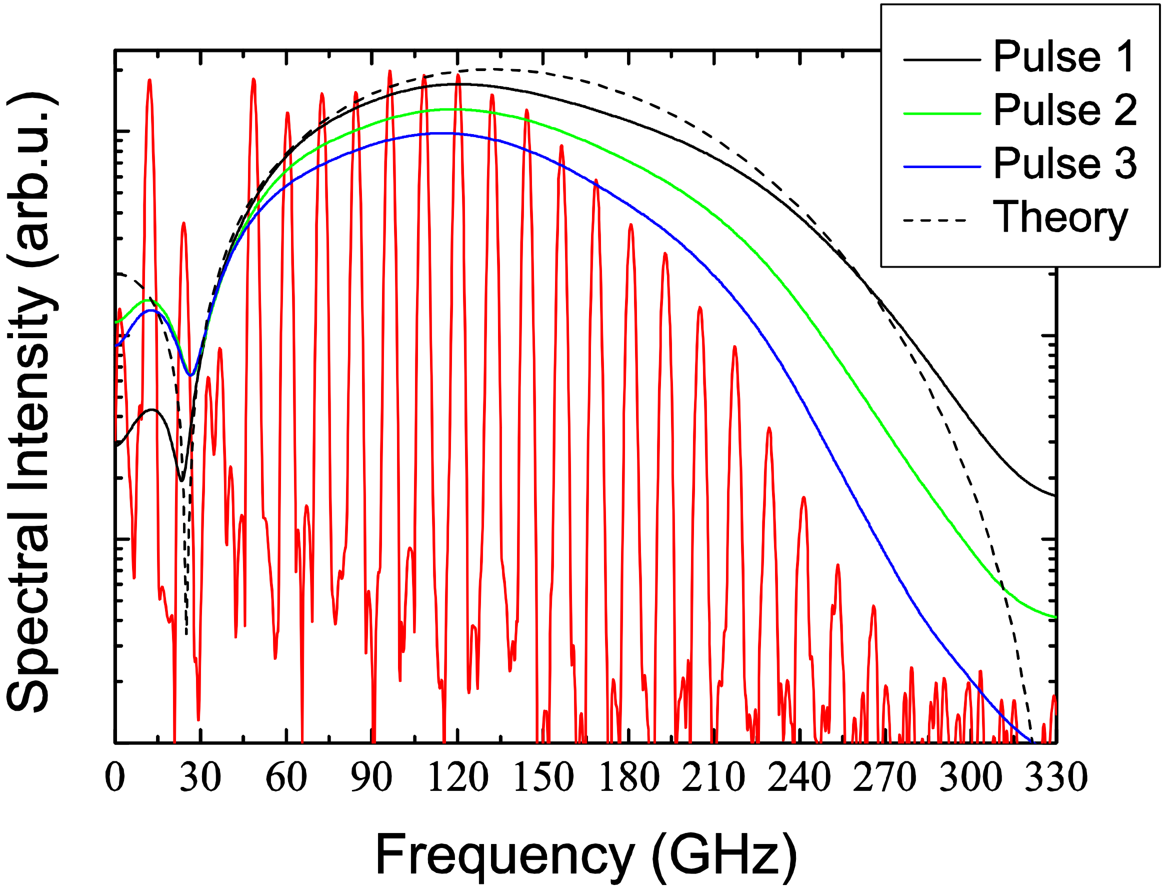


M. Grossmann et al. Physical Review B **88**, 205202 (2013)

Al/Si-system: strain generation and propagation

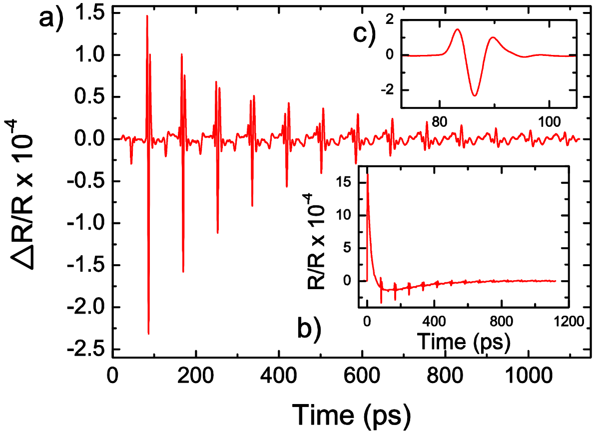


Al/Si-system: acoustic mode spectrum

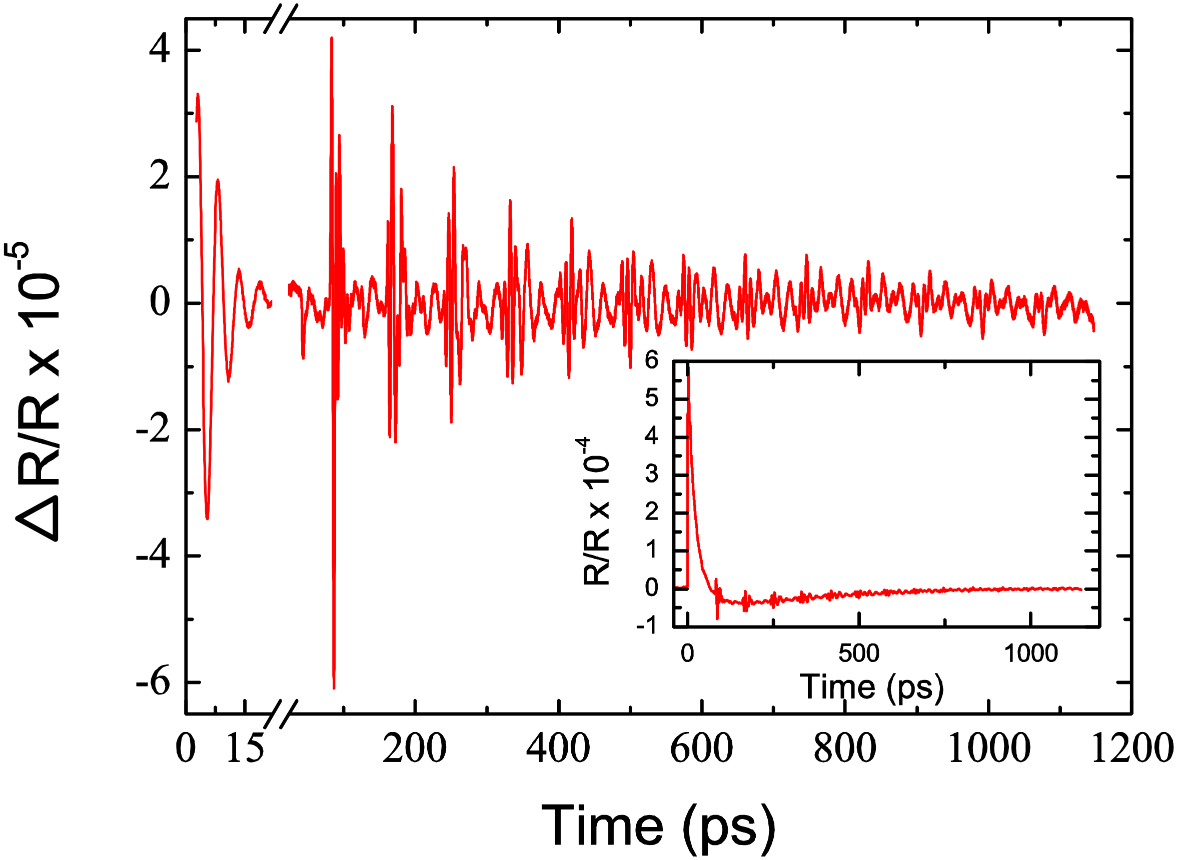


Al/Si-system: influence of adhesion

“good adhesion“



“bad adhesion“



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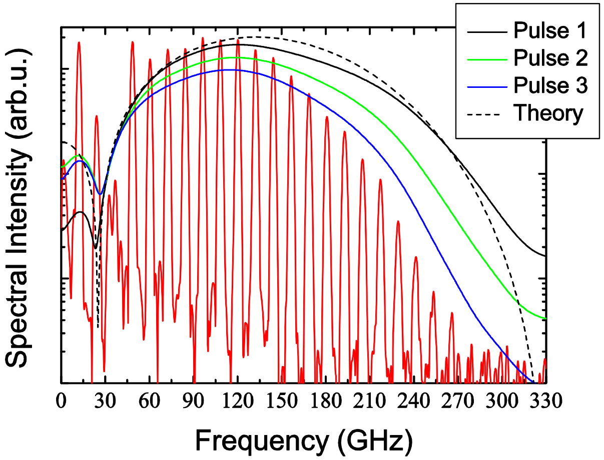

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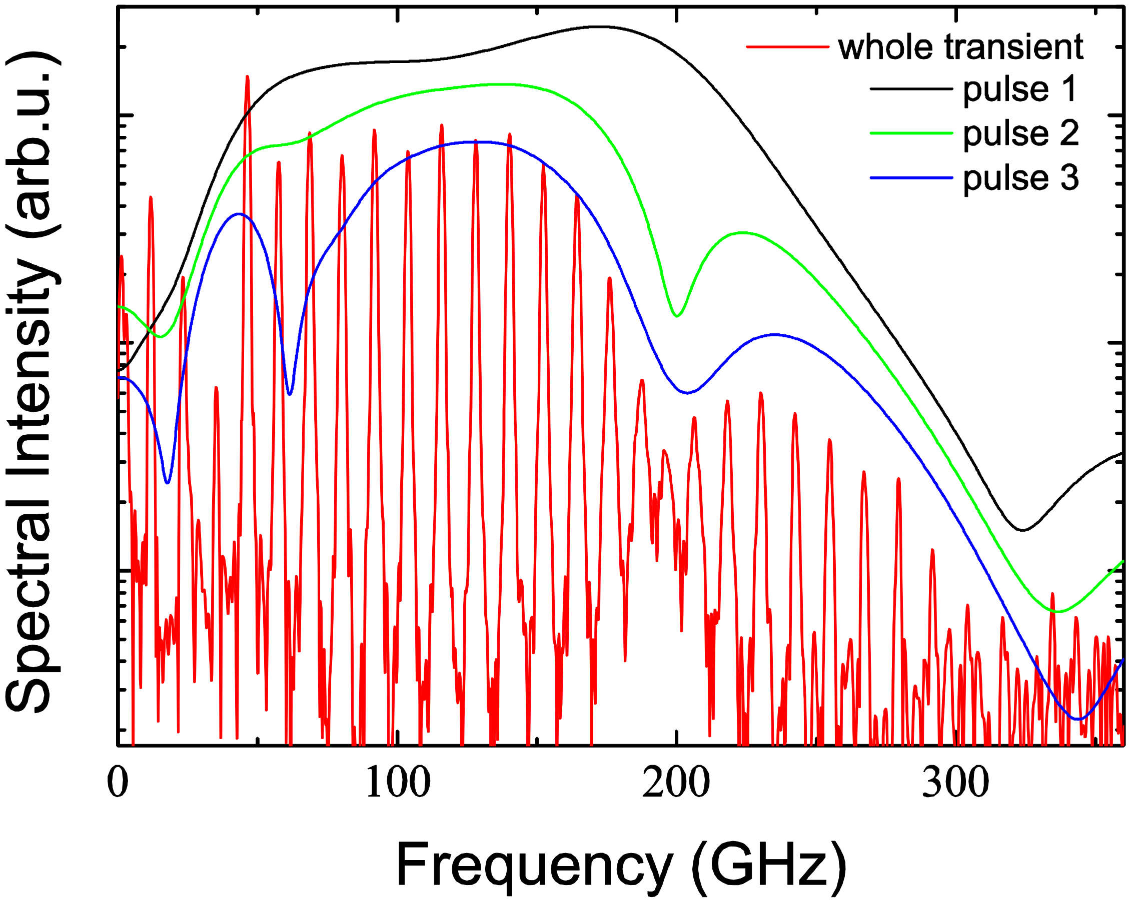
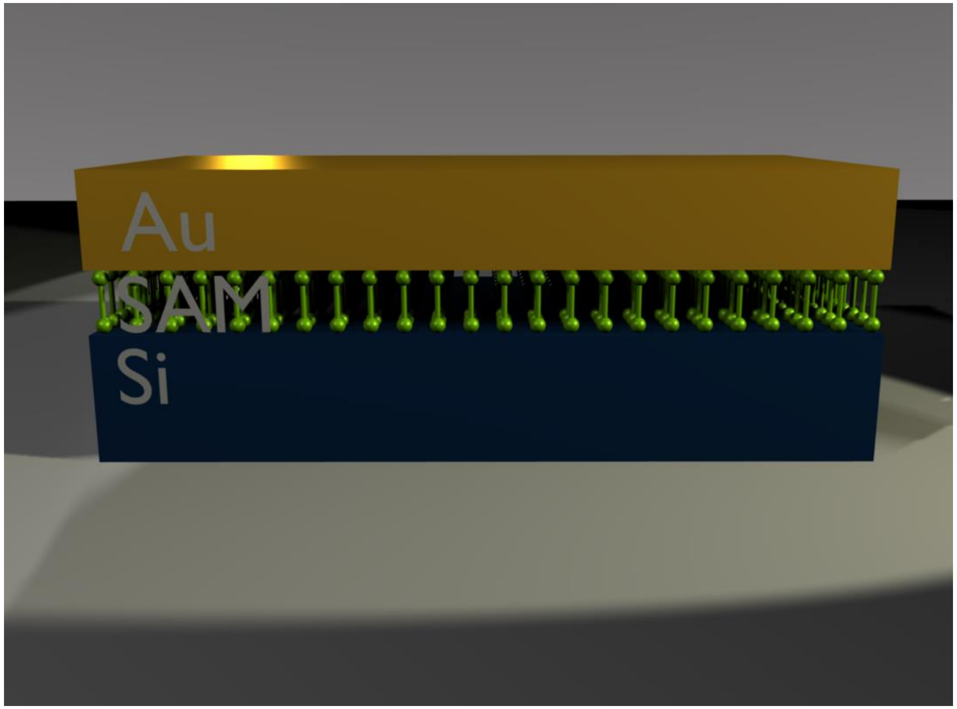


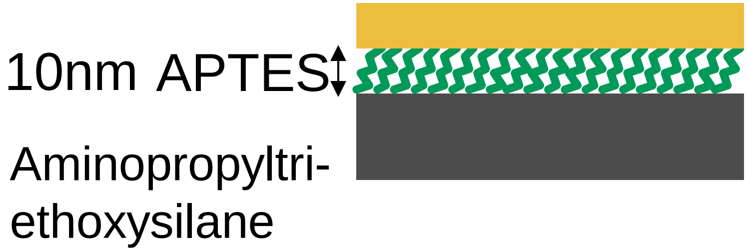
Damping of acoustic modes of metal films: influence of coupling to substrate



Influence of an organic interface layer

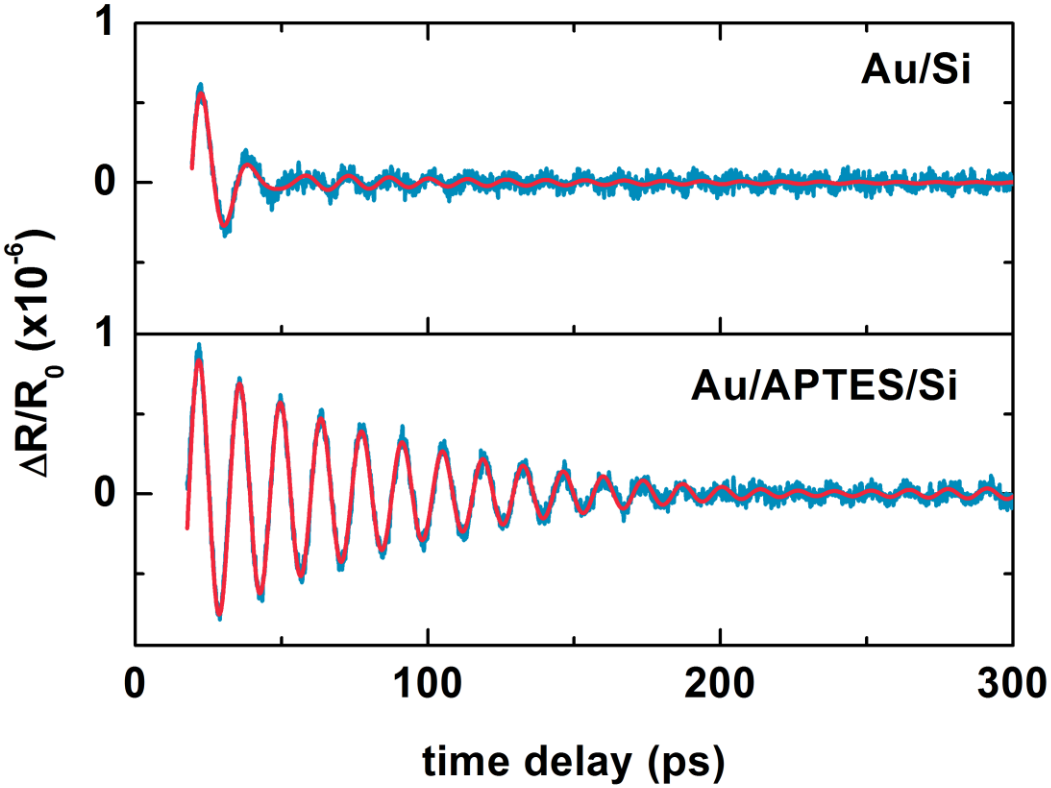
25nm gold film

Si(substrate)



10nm APTES

Aminopropyltri-ethoxysilane

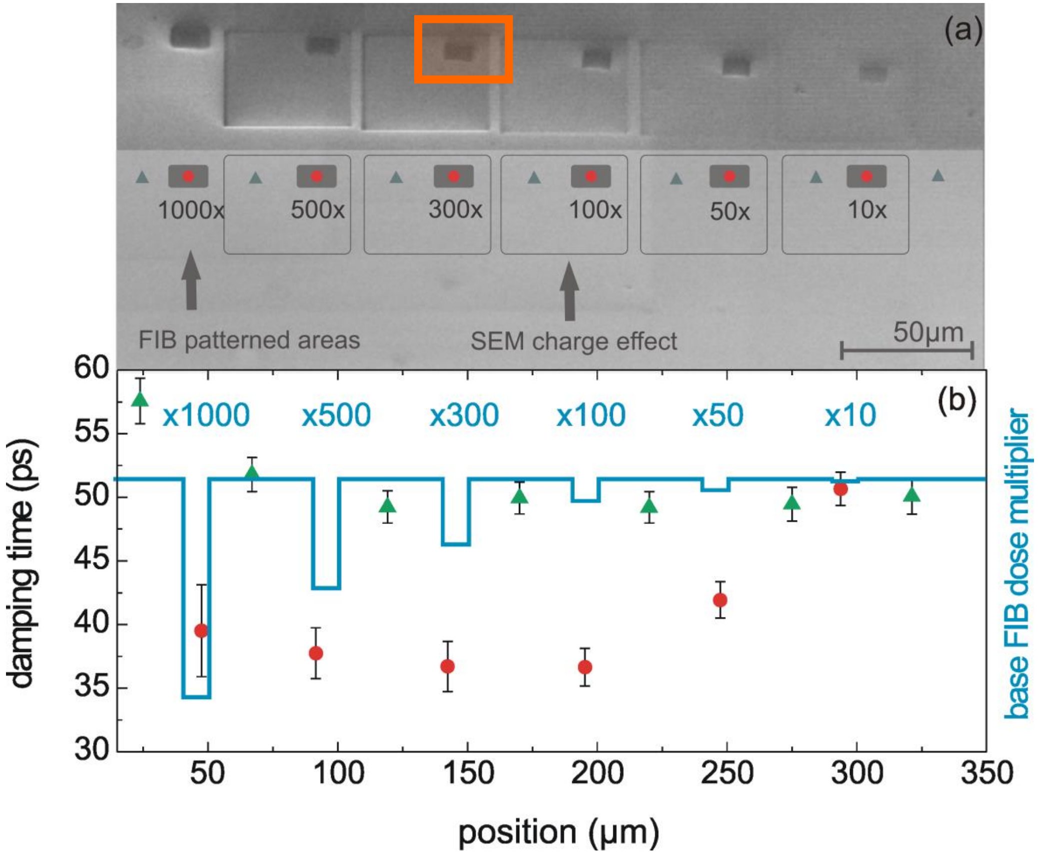


Effective acoustic decoupling from the substrate

M.Hettich et al., Appl. Phys. Lett. **98**, 261908 (2011)

Imaging of patterned and burried organic layers

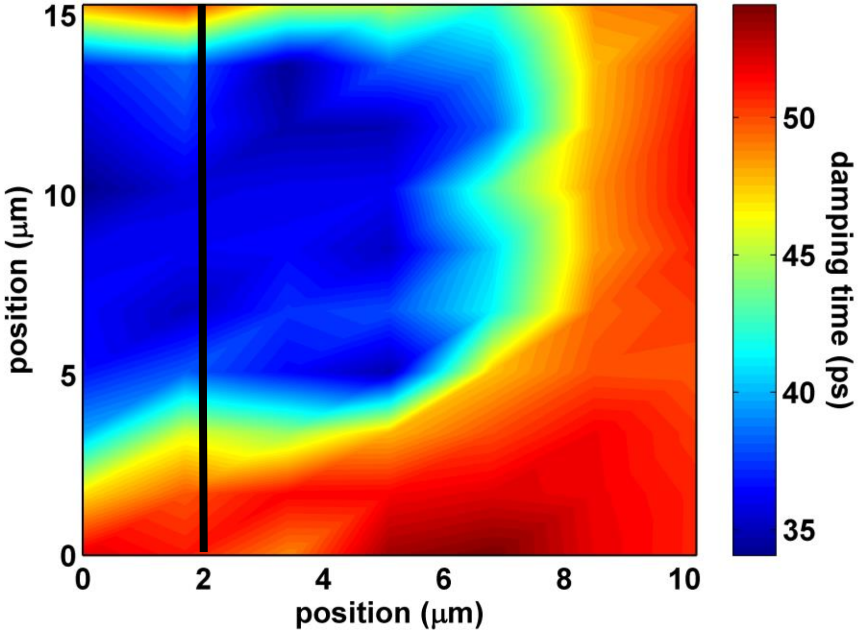
Utilize damping time difference for imaging:



- 10x10 micron squares fabricated with focused ion beams (FIB) in an APTES layer
- Base FIB dose of $3.24 \times 10^2 \frac{Ions}{\mu m^2}$
- 25nm gold top-layer
- Patterned and unpatterned areas are well distinguishable

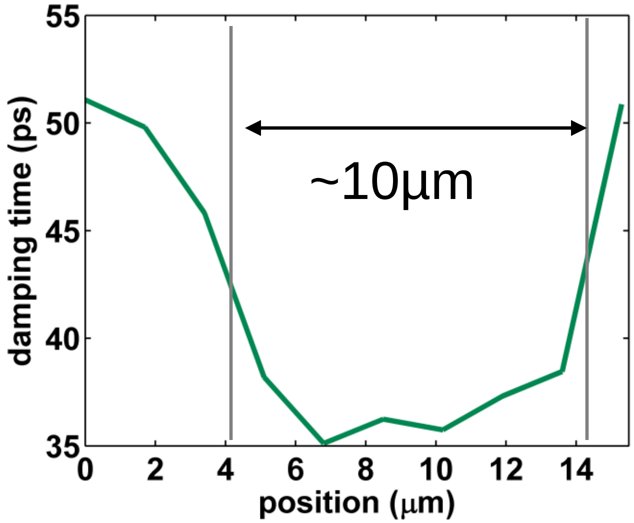
Mapping the 300x square

2D mapping of a patterned organic layer



7x10 grid with 1.7μm spacing

Line profile:



Good agreement with specified dimensions

2D imaging tool for patterned and embedded layers

M. Hettich et al., Appl. Phys. Lett. **101**, 191606 (2012)

Conclusions

- ✓ Picosecond ultrasonics as metrology tool
- ✓ Asynchronous optical sampling as new technique
- ✓ Investigation of layer thickness in membranes, metal films, multilayers with (sub-) nm resolution
- ✓ Non-invasive access to adhesion and interface properties, thermal properties

N. Krauß and T. Dekorsy, Photonik 1/2014

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