Matériaux et Phénomènes Quantiques

High frequency Nano-Optomechanical disk resonators in liquids

Erice, 3th August 2016

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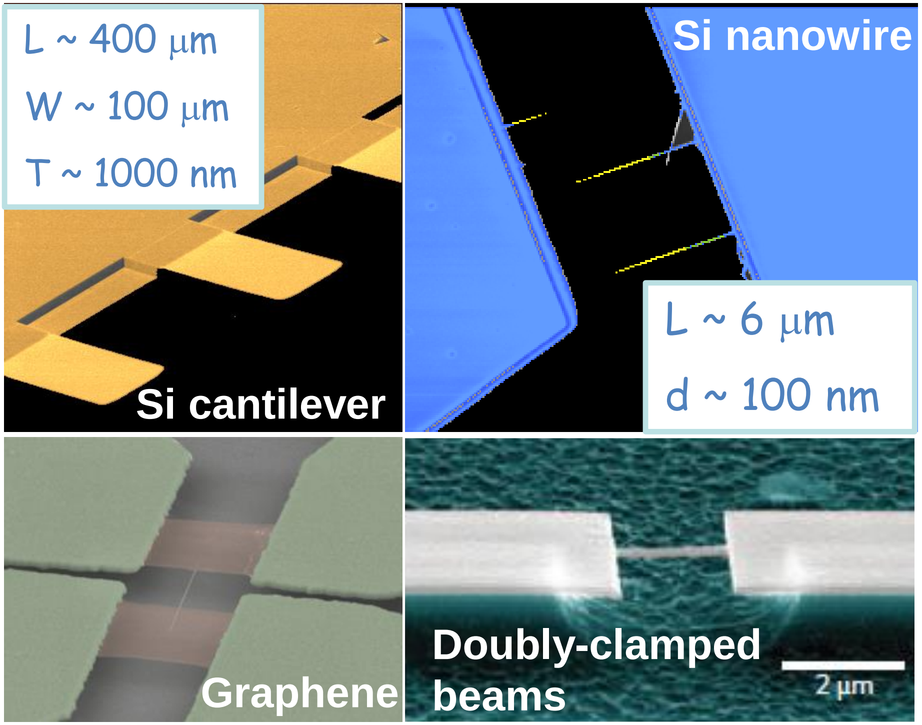
Overview

High frequency Nano-Optomechanical disk resonators in liquids

- Nanomechanical mass sensing
- Optomechanical systems
- Nano-Optomechanical disk resonators
- Optomechanical characterization in liquids
- Analytical and FEM modeling
- Experimental results: Stability and sensitivity
- Conclusions

Nanomechanical mass sensing



Mechanical frequency $\omega_m=\sqrt{(k/m)}$

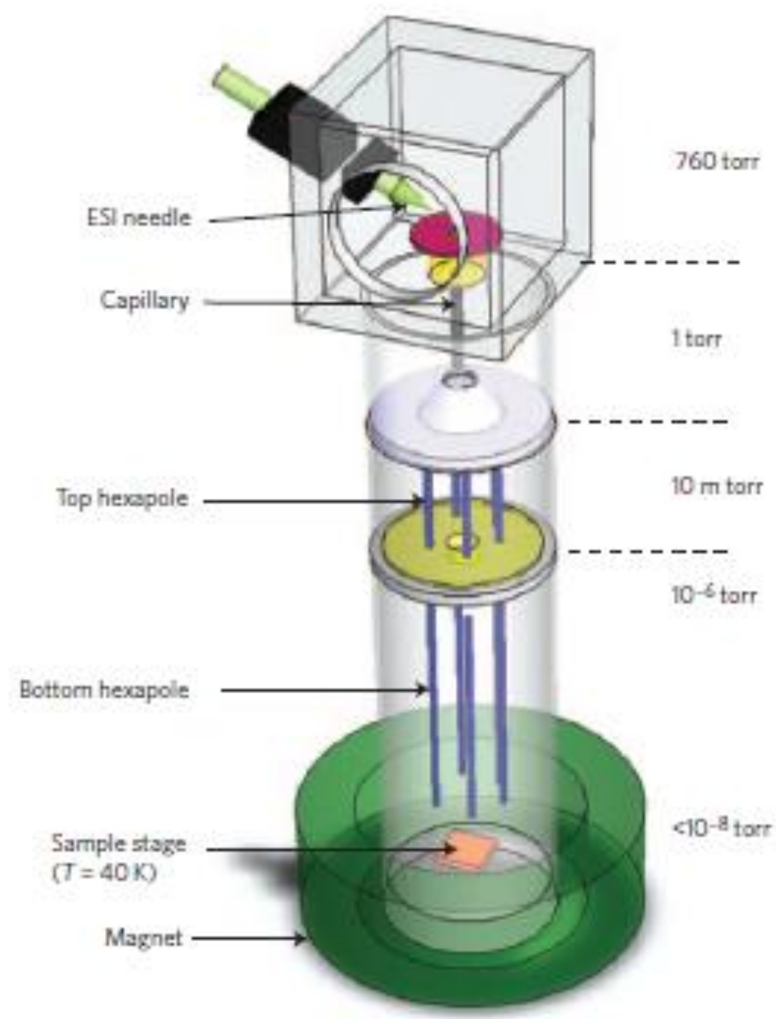
Principle of detection:

Mass depositions induce frequency shifts

$$\Delta\omega_0 \approx \frac{1}{2}\omega_0\frac{\Delta m}{m}$$

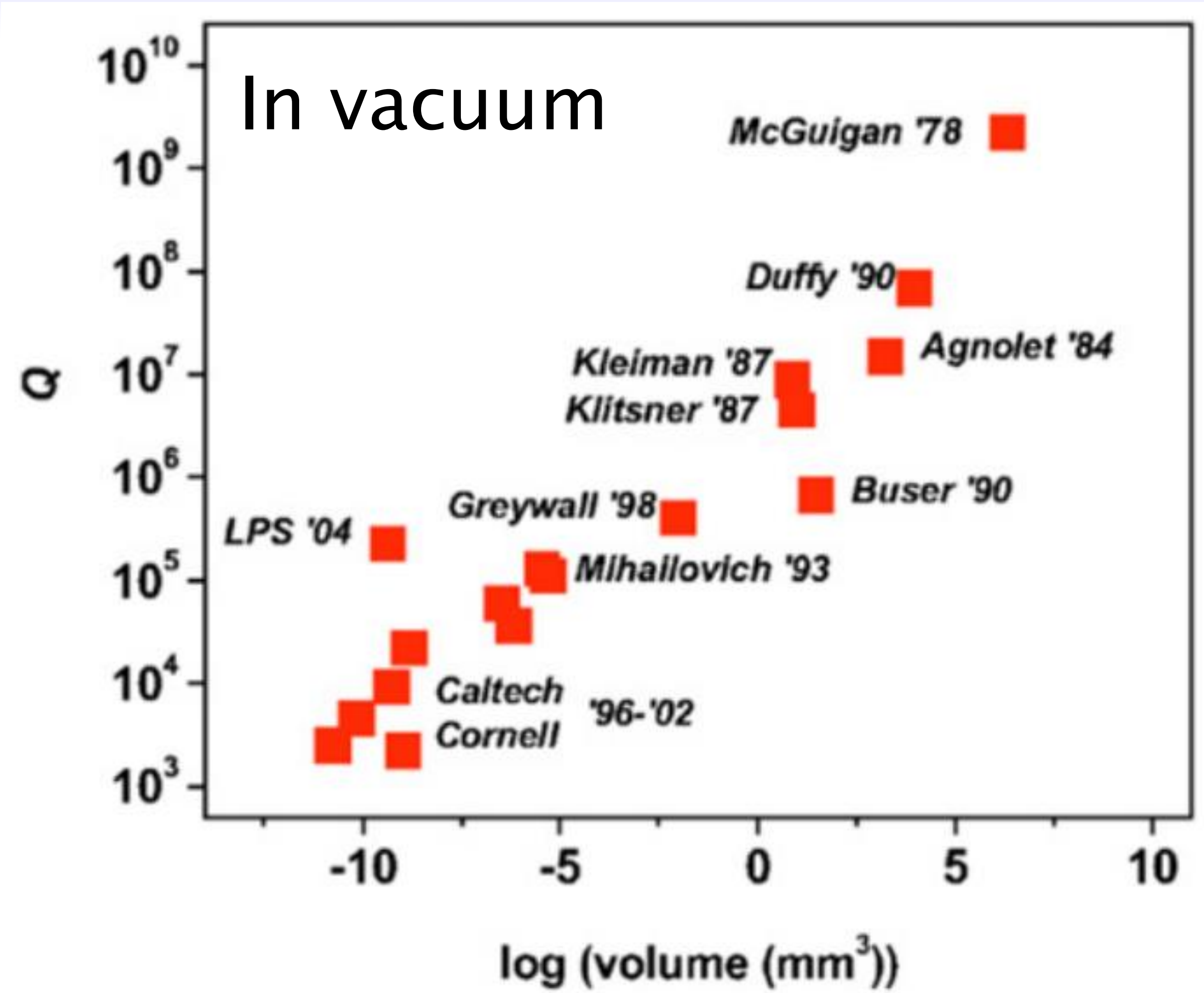
$$\Delta m_{min} \approx \frac{2m_{eff}}{Q}$$

Nanomechanical mass spectrometry



Single atom detection and identification

Nanomechanical mass sensing



Even more important when immersed in a fluid

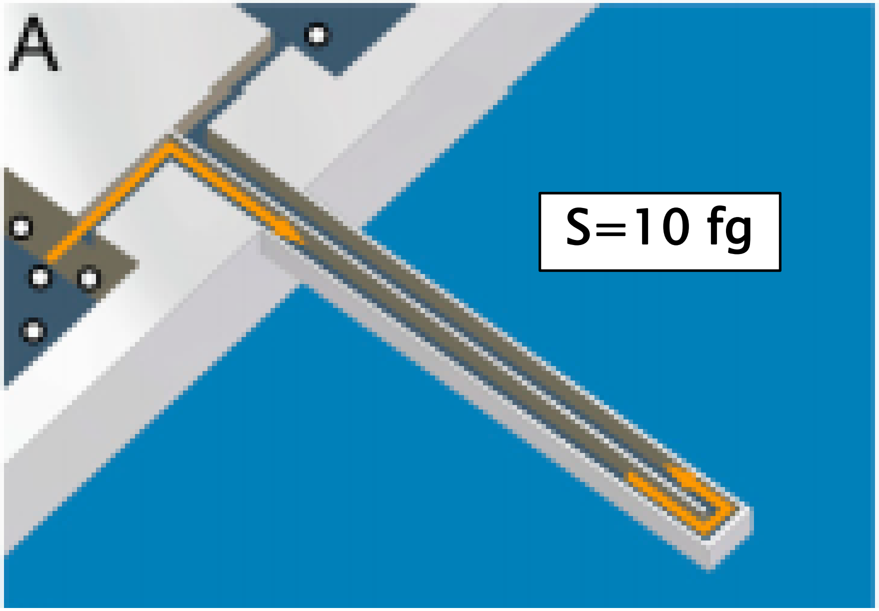
i.e. Microcantilever Q<5 in water

Miniaturization → Decreases Mass → Higher sensitivity

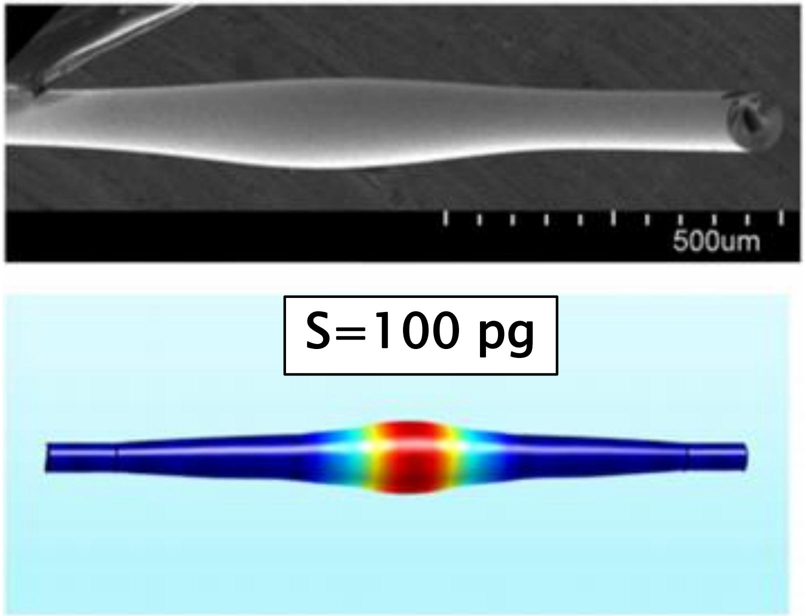
Miniaturization → Reduces Q factor → Lower sensitivity

Nanomechanical mass sensing in liquids

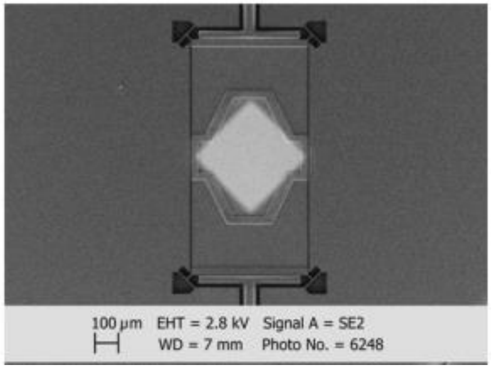
Microchannels



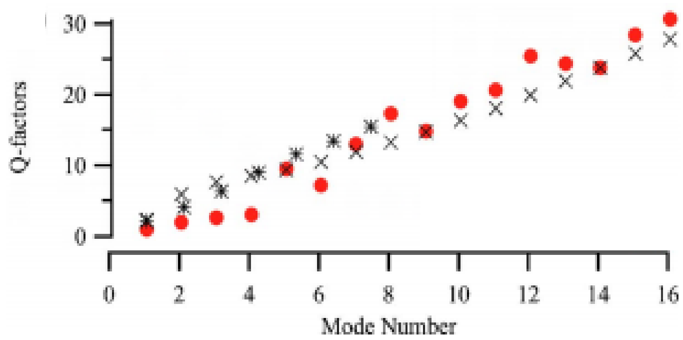
Microcapillars



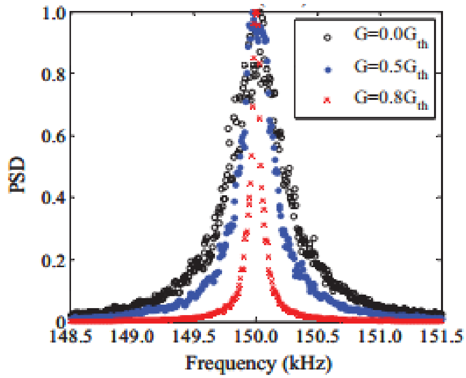
Contour modes



Higher order modes



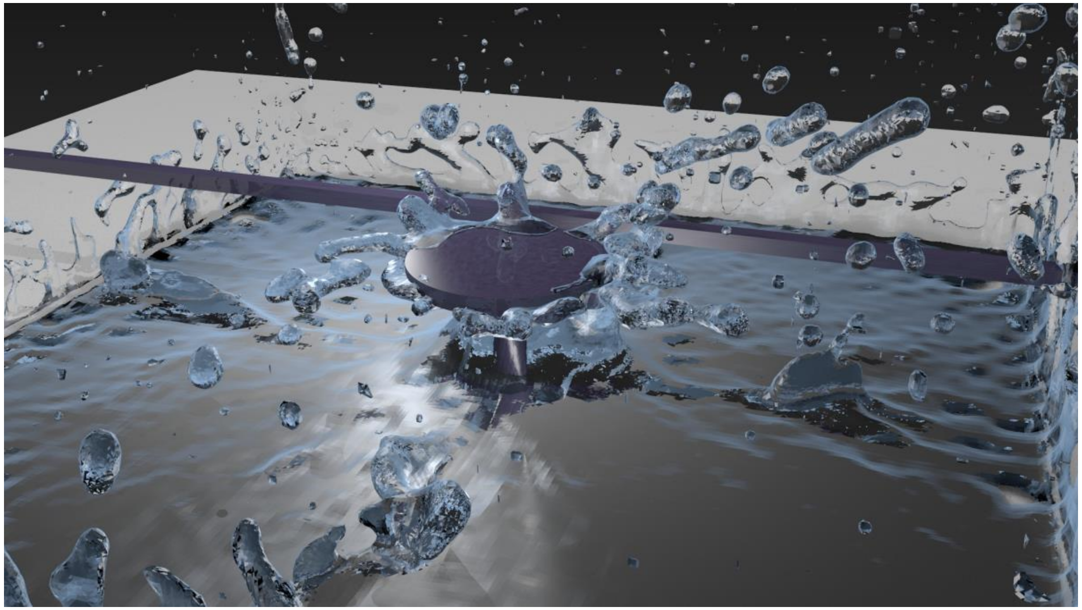
Self-oscillation



Nanomechanical mass sensing in liquids

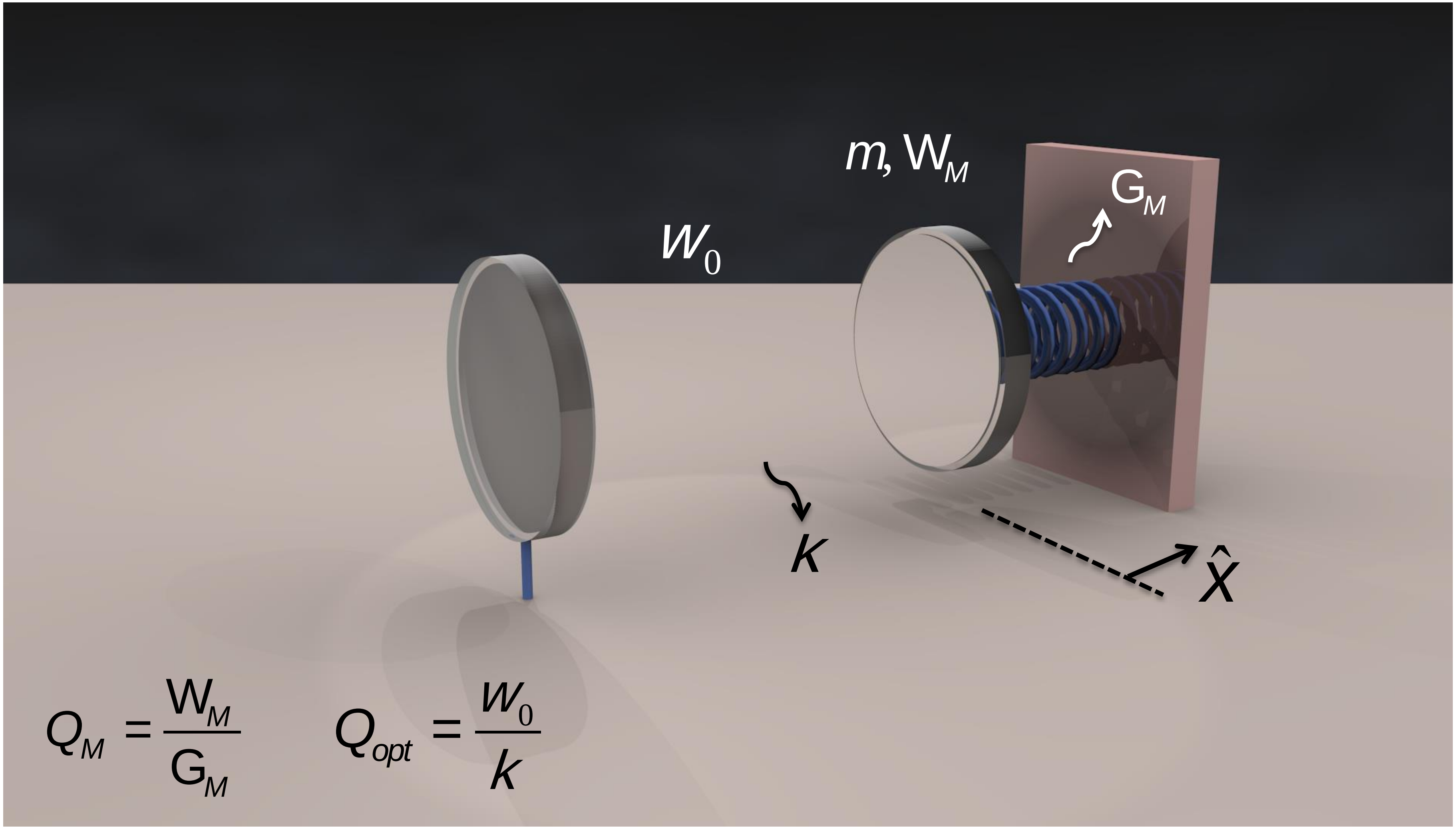
Nano-optomechanical disk resonators

- In plane modes ⟶ Low dissipation?
- Strong optomechanical coupling ⟶ High displacement sensitivity
- Lower mass than microchannels, microcapillars,… ⟶ Higher sensitivity?
- Lower dimensions ⟶ Multiple detection in a single chip
- Higher frequencies: GHz range ⟶ Ultrafast detection



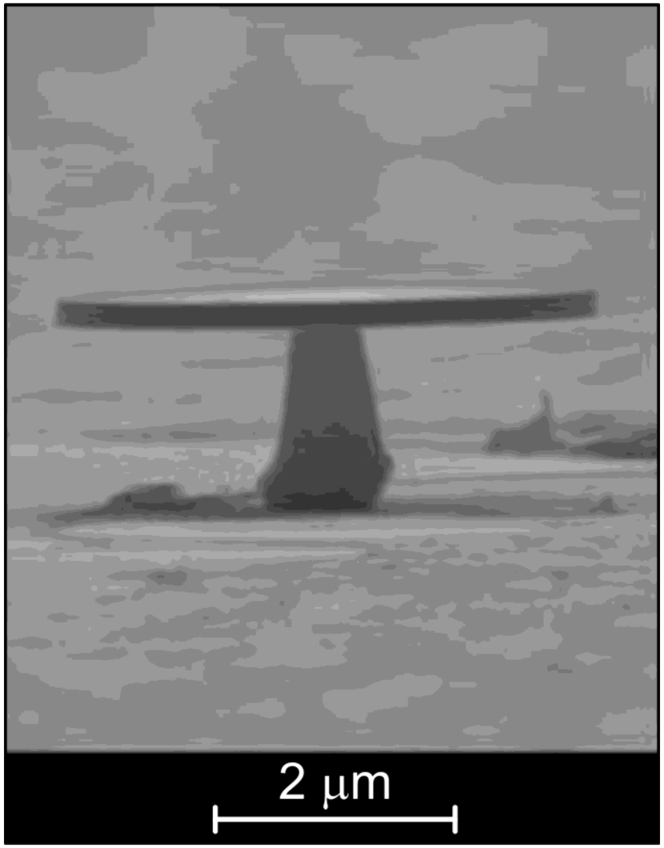
J. Tamayo « Mass sensing: Optomechanics to the rescue » Nature Nanotechnology 10, 738–739 (2015)

Optomechanical systems



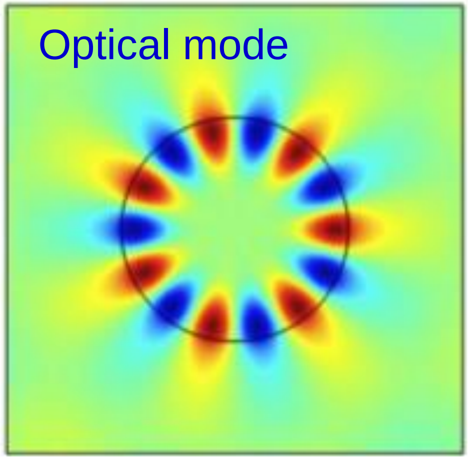
I. Favero, K. Karrai, Nature Photonics 3, 201 (2009)
M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, RMP 86, 1391 (2014)

Nano-Optomechanical disk resonators

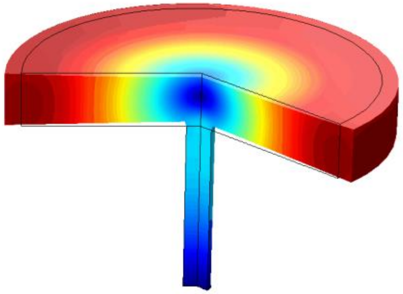


Optically
. Small mode volume (sub-micron^3)
. High optical Q_{opt} over 10^5

Mechanically
. High frequency Ω_m (GHz)
. Small mass (pg)
. Low mechanical dissipation Γ_m



Mechanical mode

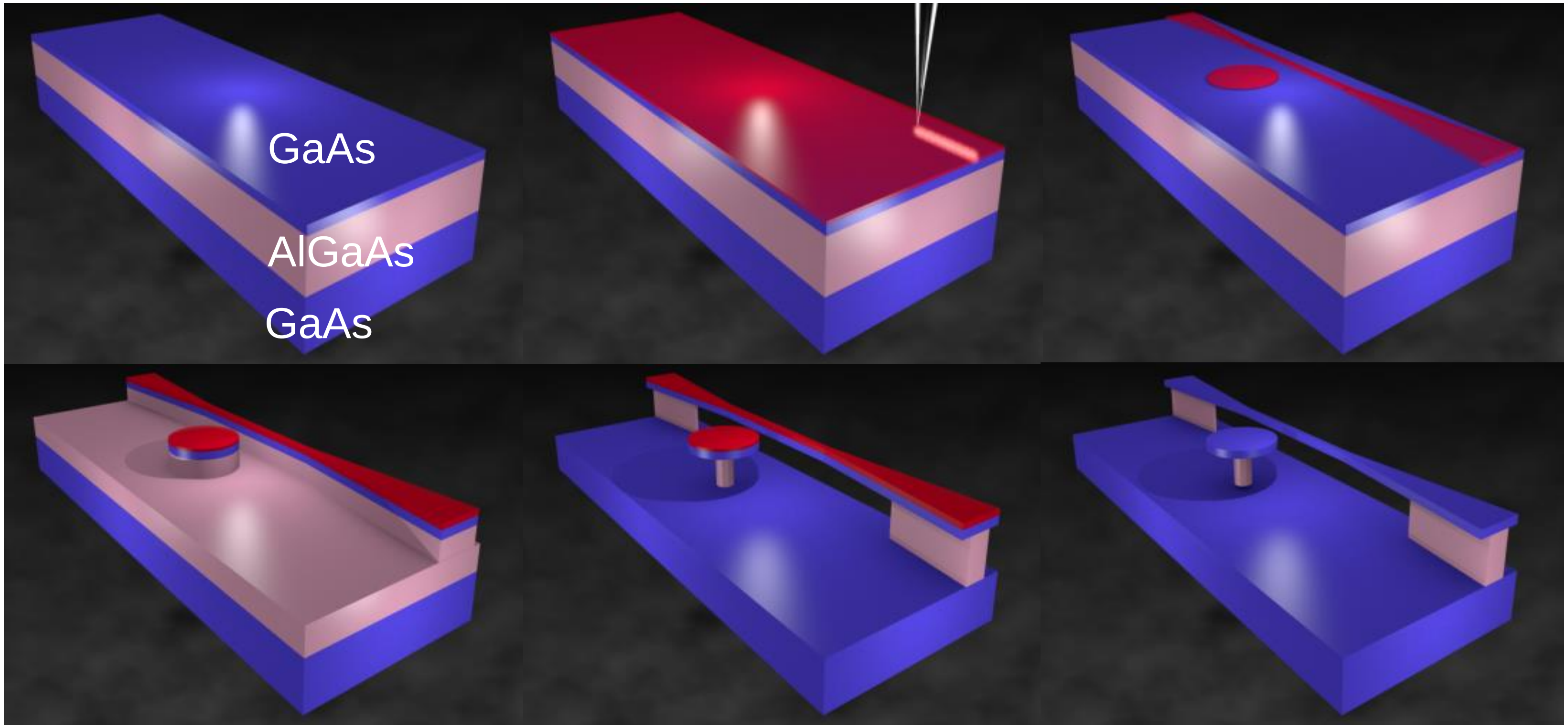


L. Ding, C. Baker et al. PRL, 105(26), 263903 (2010)

L. Ding, et al. APL98, 113108 (2011)

$S_d=10^{-17}$ m/Hz$^{-1/2}$

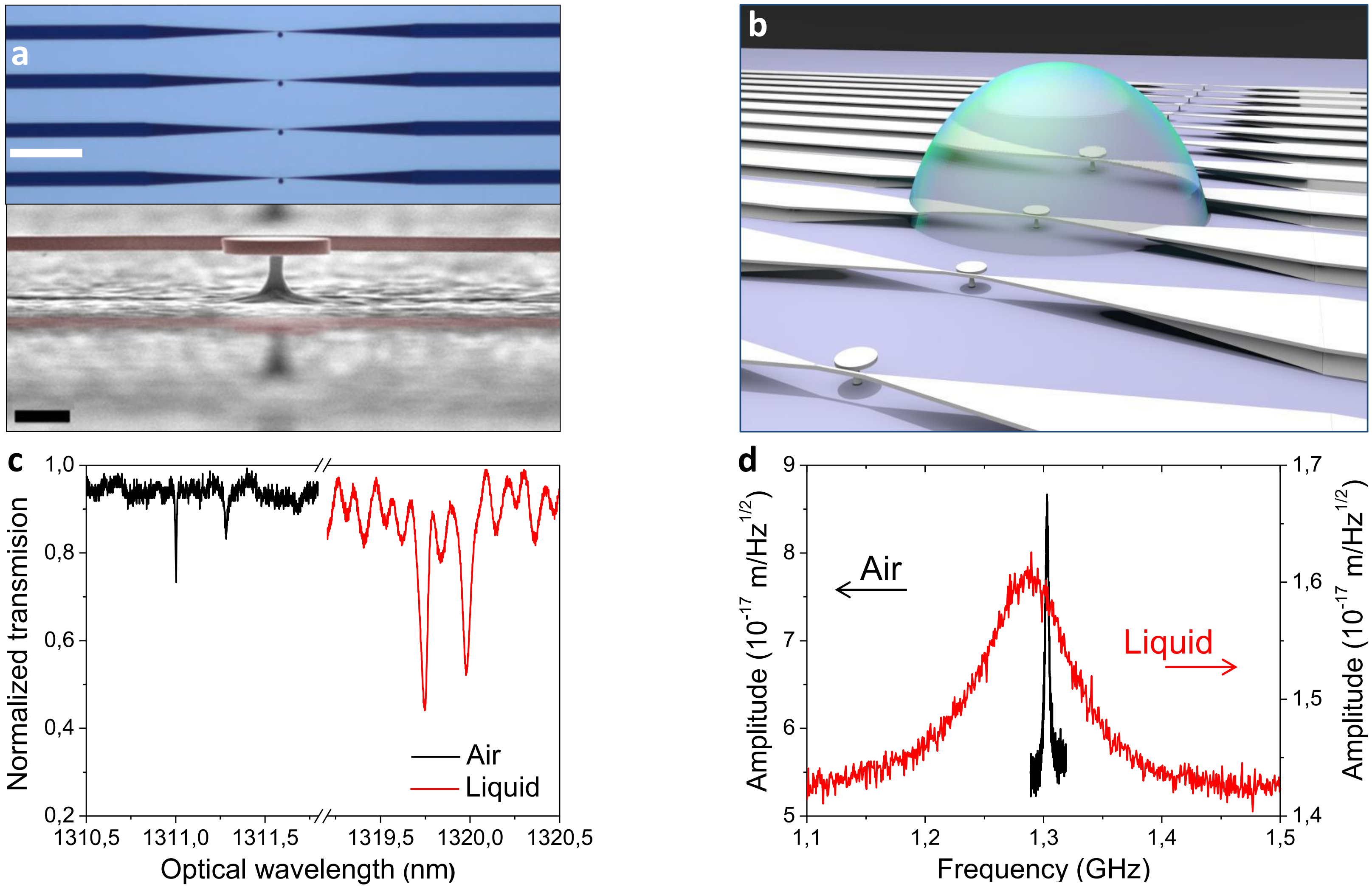
On-chip GaAs optomechanical disks fabrication



1. Multilayer wafer grown by MBE: GaAs substrate, 1.8 μm AlGaAs layer and GaAs top layer 320 nm.
2. Resist deposition.
3. Electron Beam Lithography.
4. Dry etching (ICP-RIE).
5. HF etching.
6. Resist removal.

Optomechanical characterization in liquids

High optomechanical sensitivity allows resolving the disk Brownian motion in a liquid



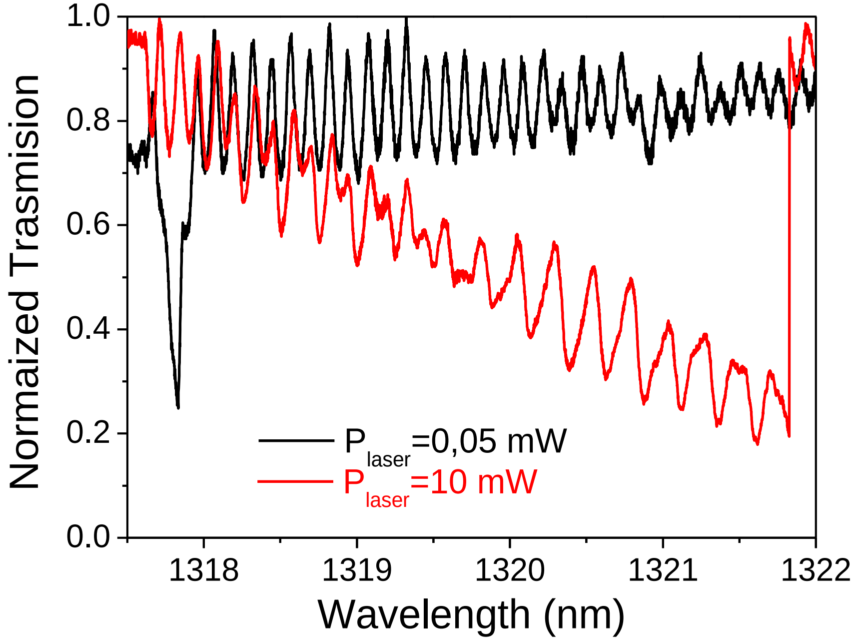
E. Gil-Santos et al. Nature Nanotechnology 10, 810–816 (2015)

Q_m=11 in a viscous liquid (perfluorinated liquid)

Optomechanical characterization in liquids

Optics

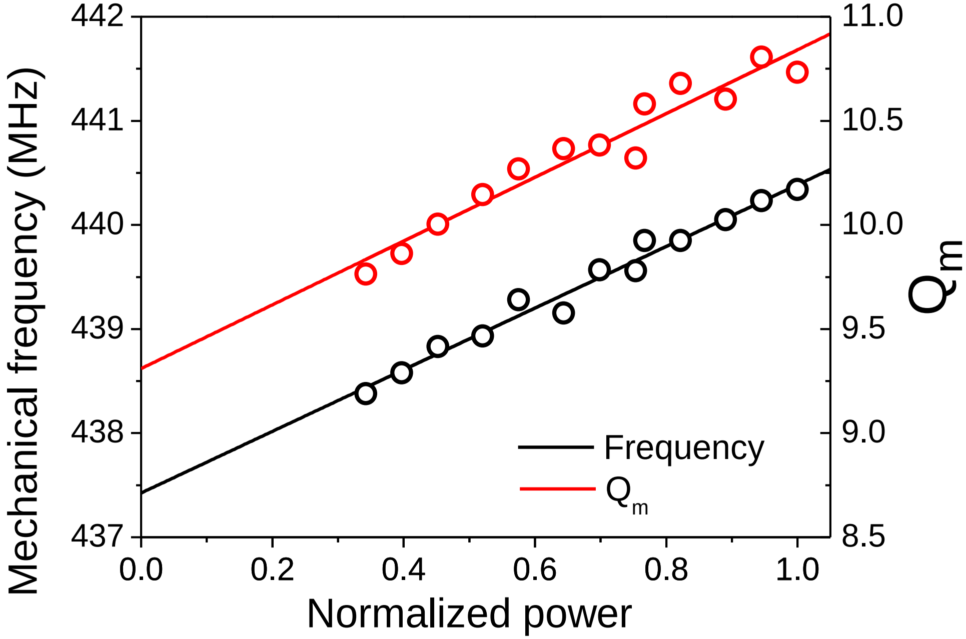
$n=n(T)$



The temperature in the disk increases from 20 to 70 degrees celsius while measuring

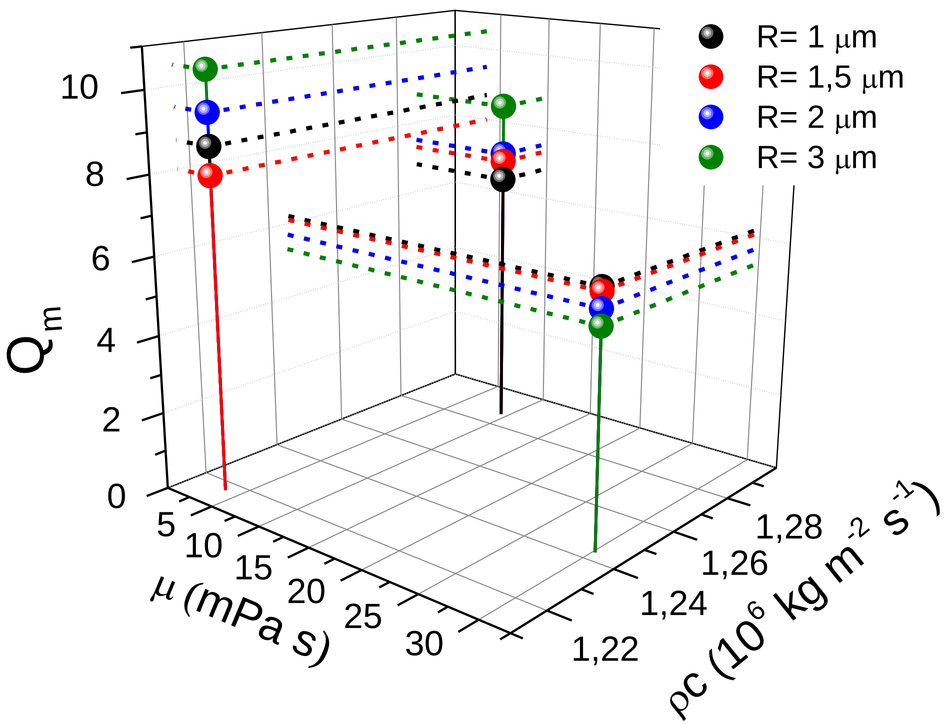
Mechanics

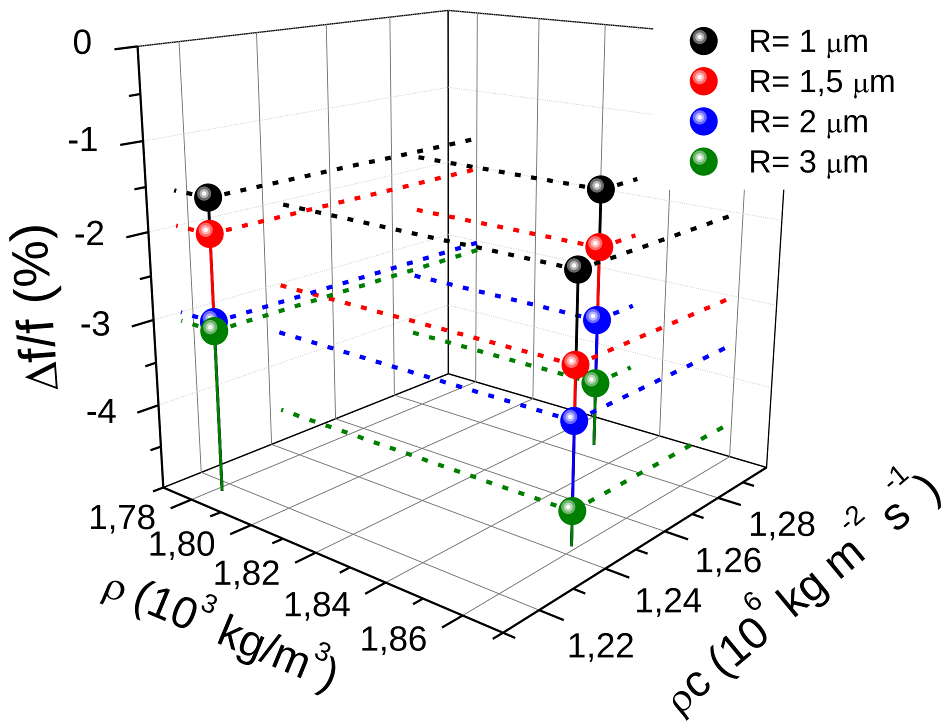
$E=E(T) \quad \rho=\rho(T) \quad \mu=\mu(T)$



We extrapolate the measured values to extract the mechanical frequencies and quality factors at room temperature

Dispersive and dissipative interaction in various liquids





	ρ (kg/m³)	μ (Pa s)	c(m/s)
Water	1000	0.001	1500
HT 170	1782	0.0035	669
HT 230	1831	0.009	702
HT 270	1859	0.030	683

Viscous and acoustic interactions: a novel analytical approach

Based on the force experienced by a sphere vibrating in a viscoelastic fluid, for which an analytical expression was derived (Oestreicher 1951)

No fitting parameters

Only depending on:

- The mechanical properties of the disks
- Their dimentions
- The properties of the fluid

Viscous regime

$$Q_{viscous} = \frac{\rho \cdot \omega \cdot t \cdot R}{8.36\mu_f + (3.18 \cdot t + R)\sqrt{2\rho_f \omega \mu_f}}$$

$$\left(\frac{\Delta f}{f}\right)_{viscous} = -\frac{1.27 \cdot t}{2R}\frac{\rho_f}{\rho} - \frac{3.18/R + 1/t}{2\rho}\sqrt{2\rho_f \mu_f/\omega}$$

Acoustic regime

$$Q^{-1}_{acoustic} = f\left(\frac{t}{R}, \frac{\rho_f}{\rho}, \frac{c_s}{c_f}, \nu\right)$$

$$\left(\frac{\Delta f}{f}\right)_{acoustic} = g\left(\frac{t}{R}, \frac{\rho_f}{\rho}, \frac{c}{c_f}, \nu\right)$$

Contributions analyzed numerically

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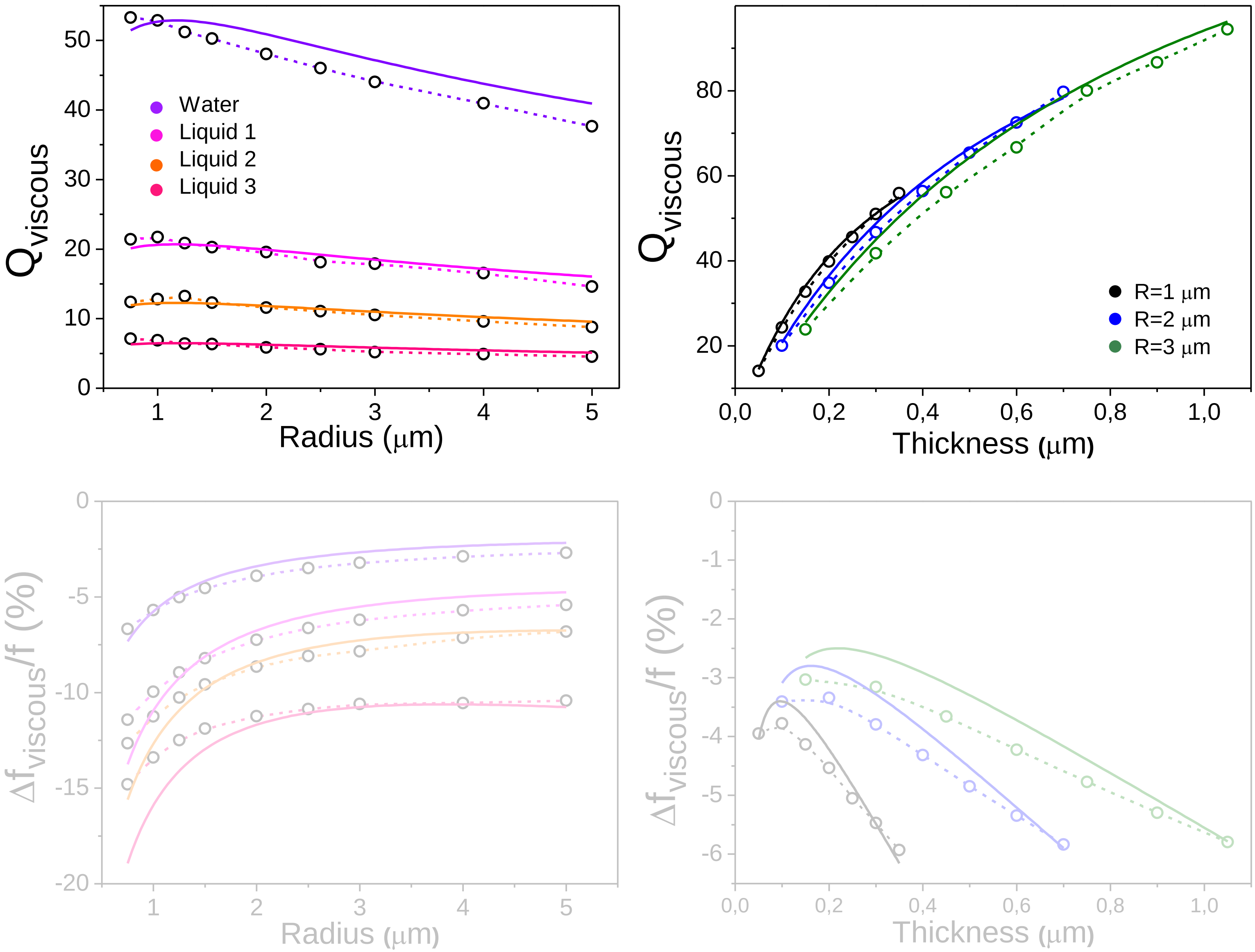
Viscous interactions: analytics and numerics



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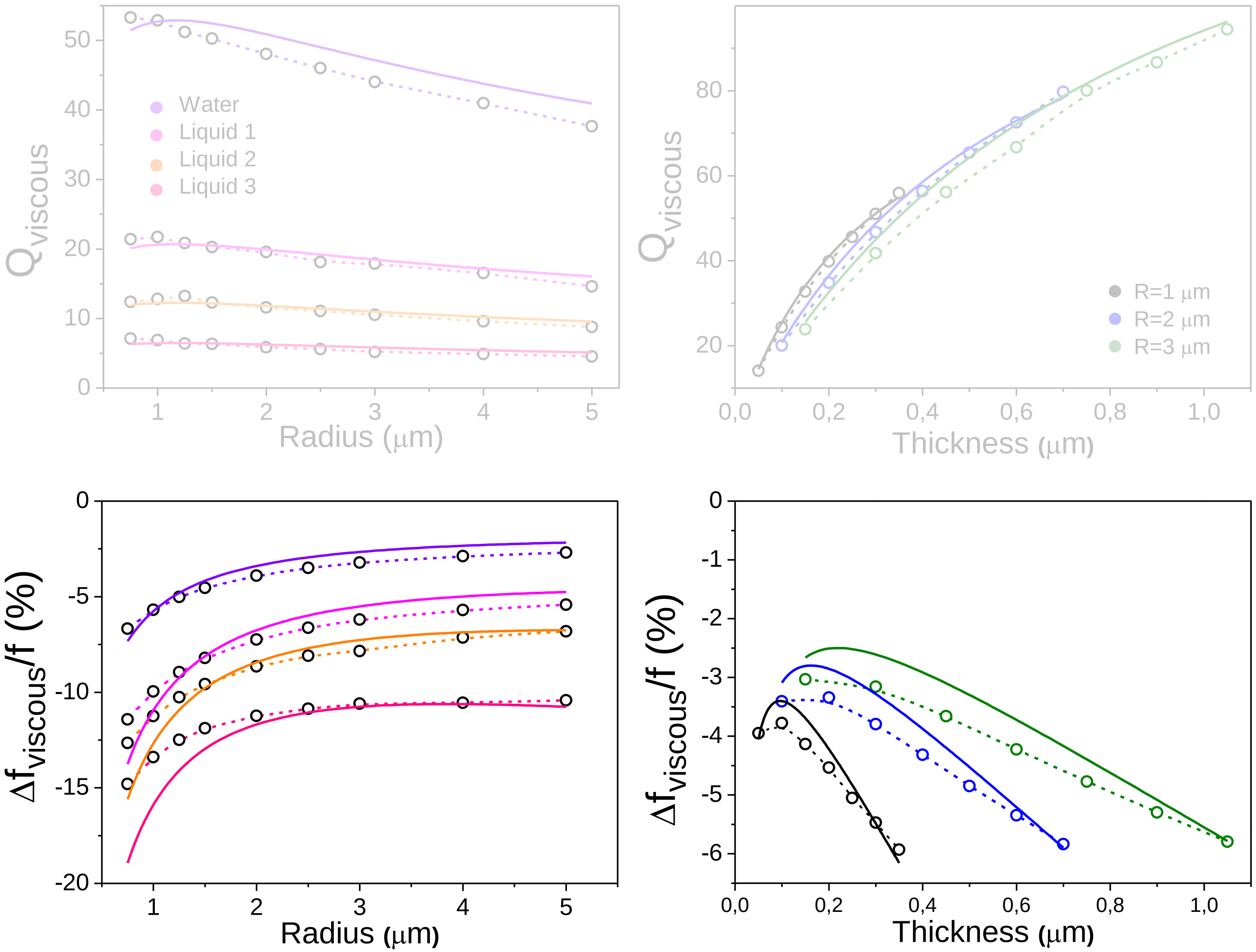

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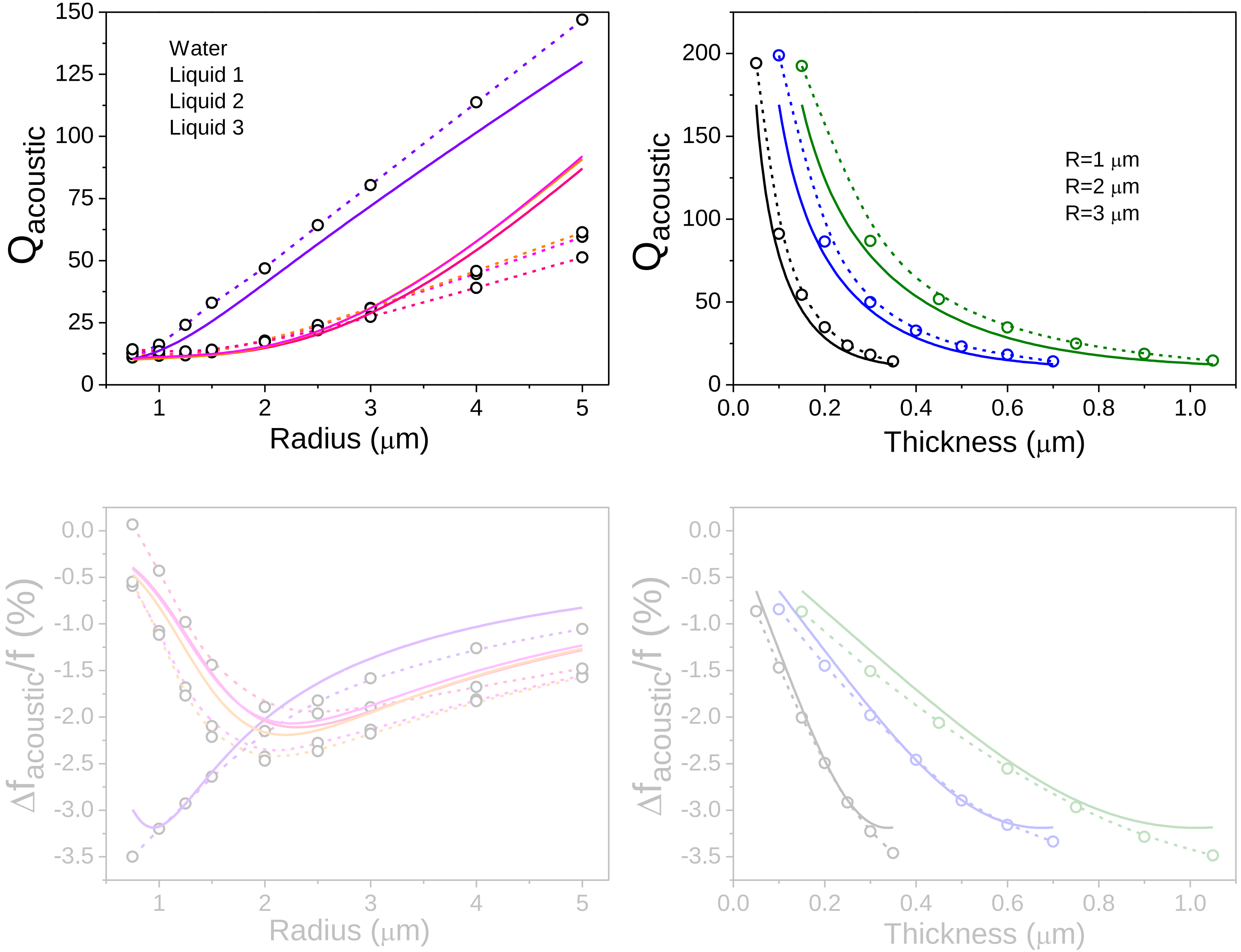

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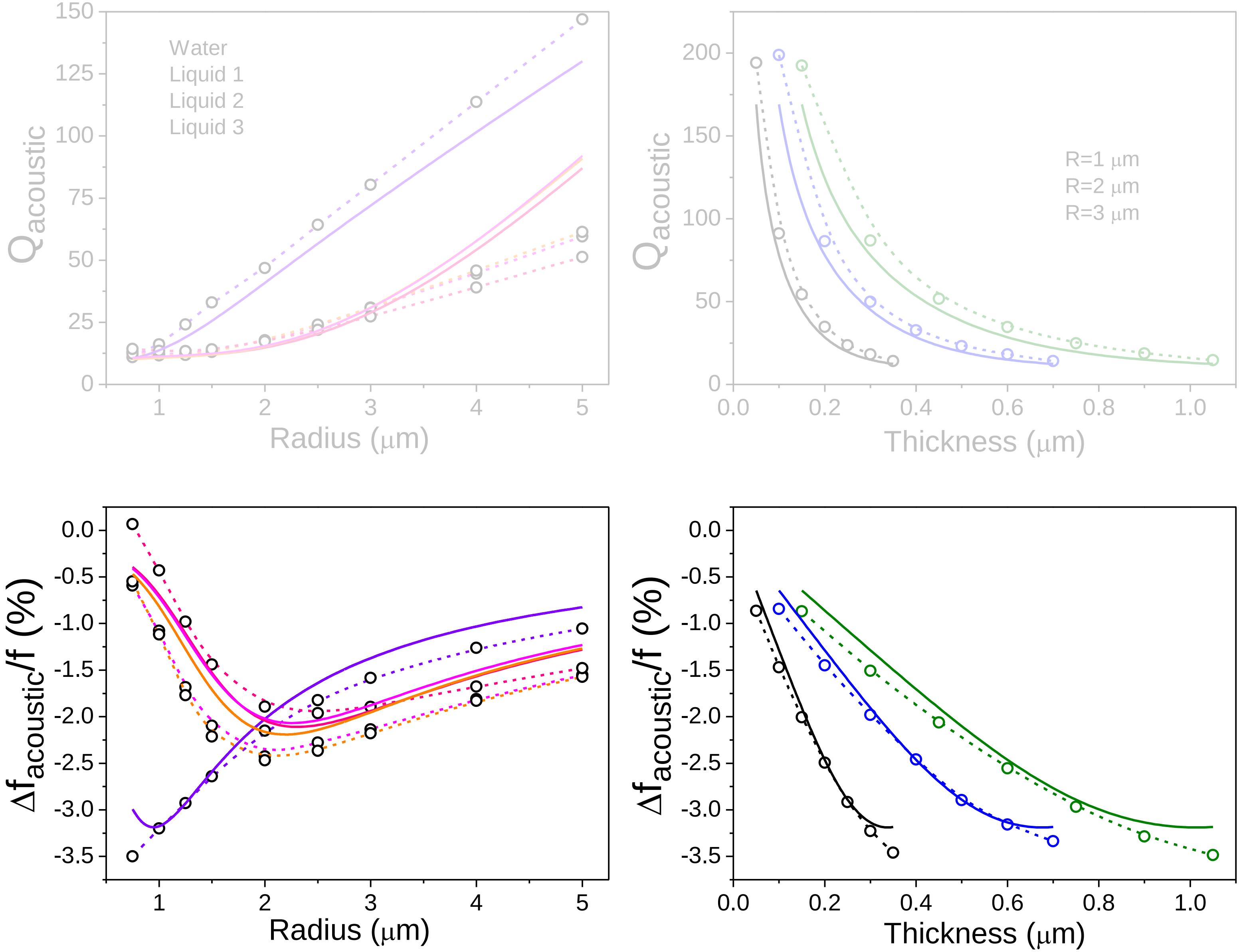
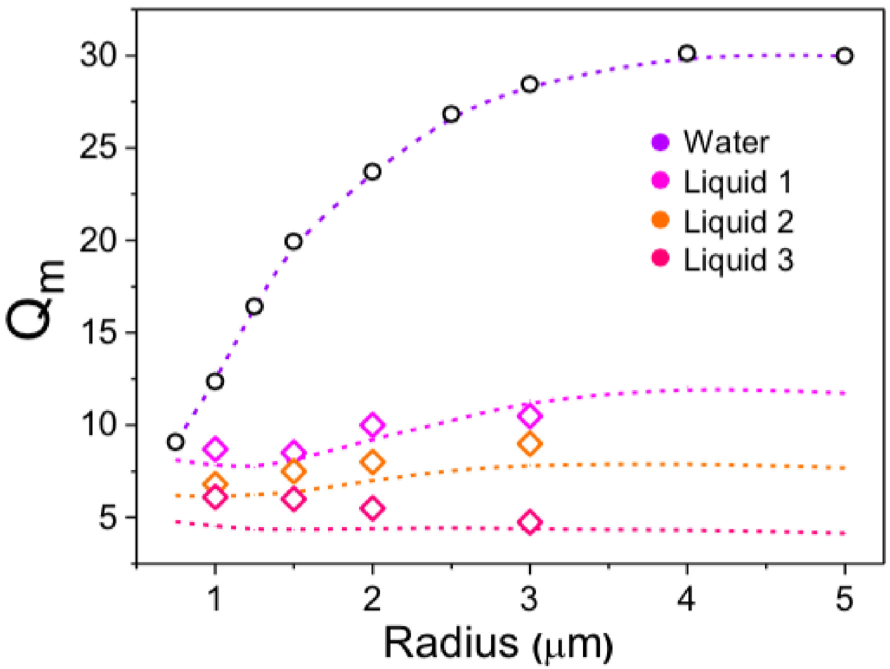
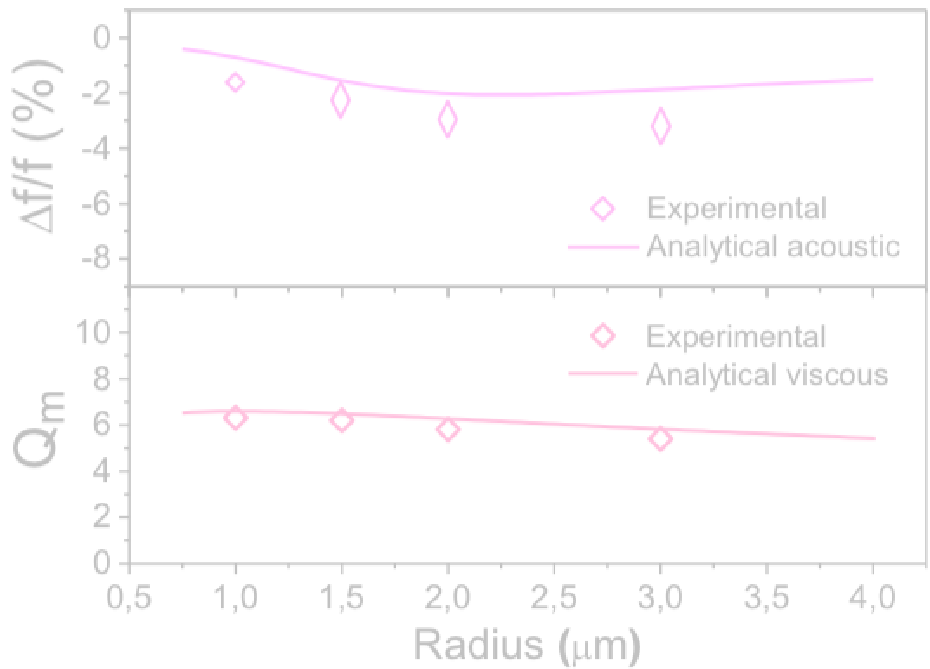


Comparing experiments and models: sensing perspectives





- **Q_m>30** in water
- **Highest Q×f /m** reported in liquids
- **Sensitive** and **ultrafast** sensors

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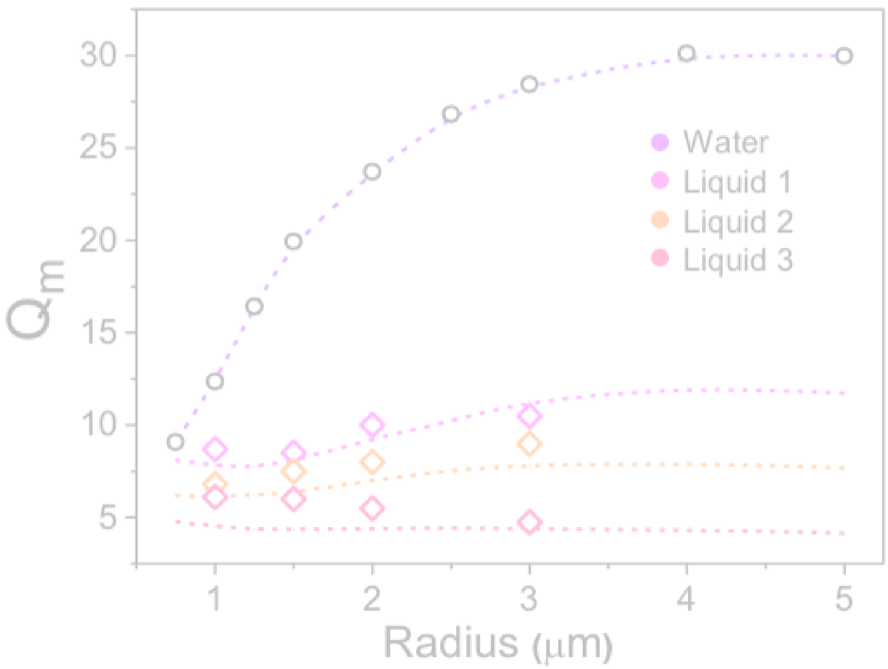
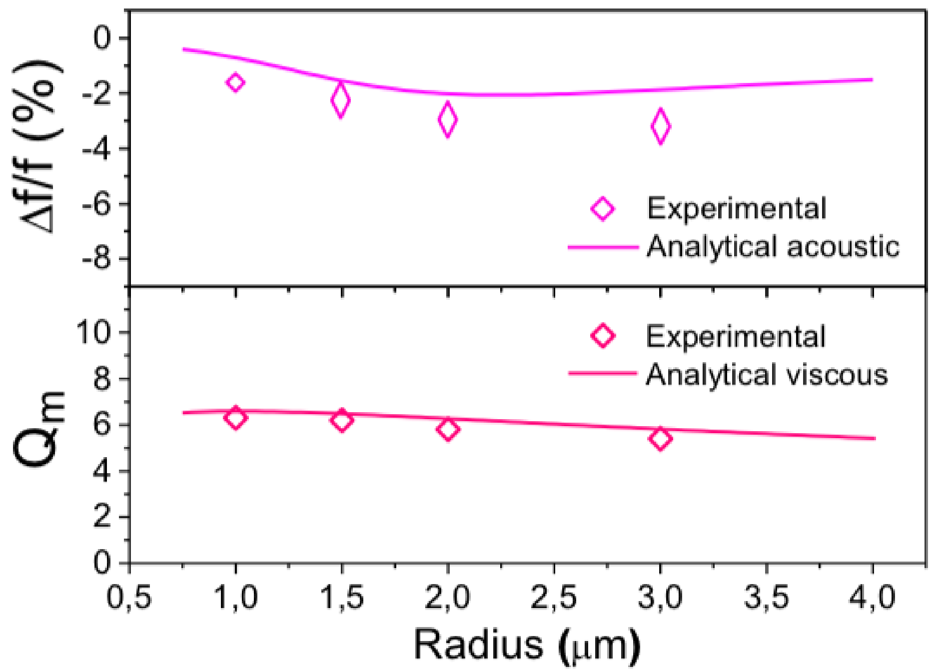
Comparing experiments and models: sensing perspectives





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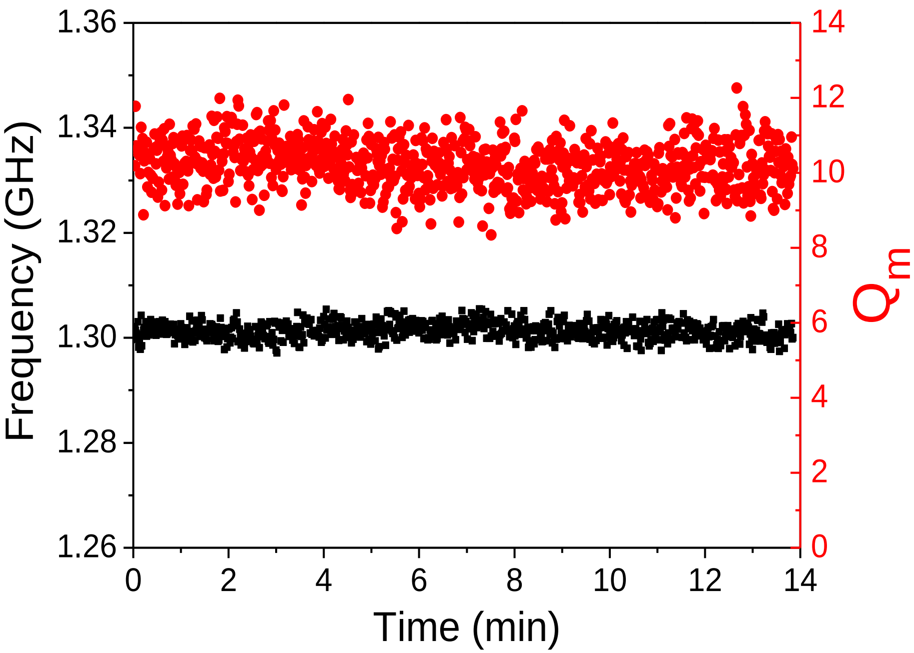
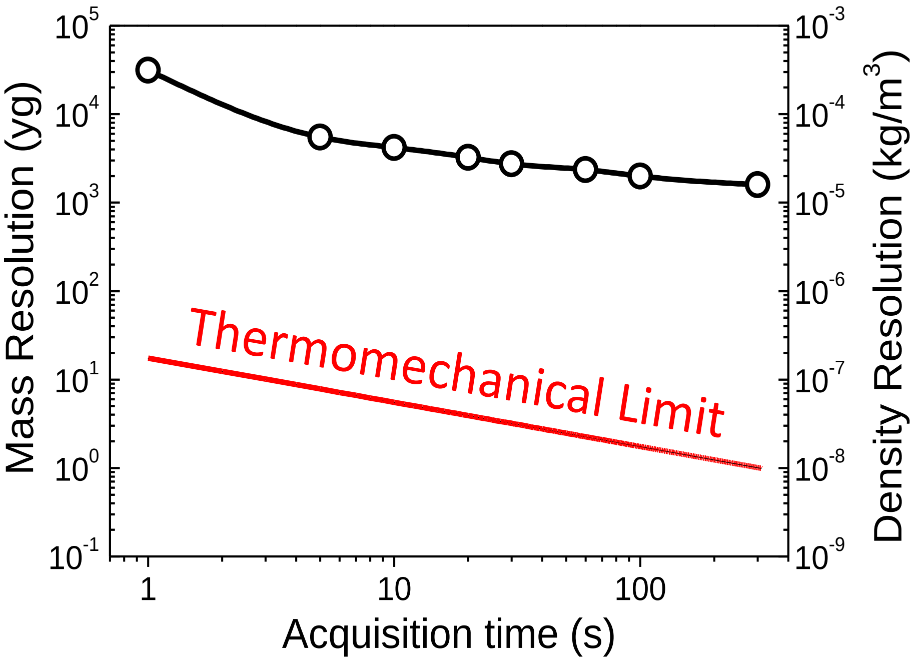
Stability in liquids: monitoring thermomechanical noise

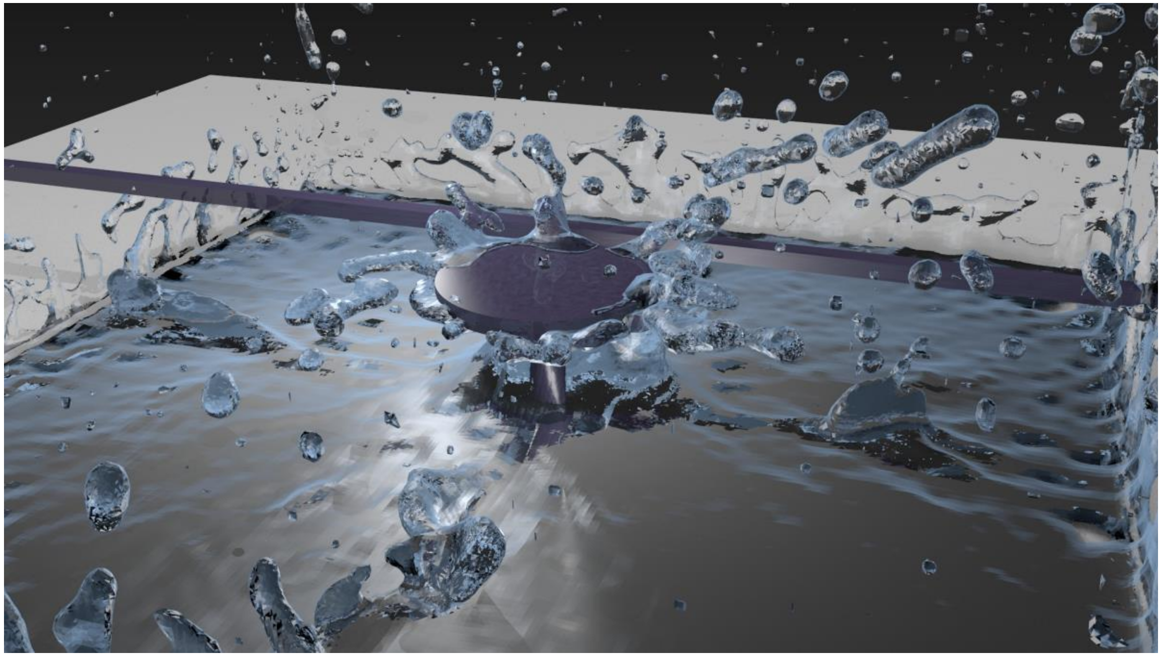




- **10^{-24} g/√Hz** potential sensitivity in **mass** deposition
- **10^{-10}** precision in **density** and **viscosity** measurement (1s acquisition time)

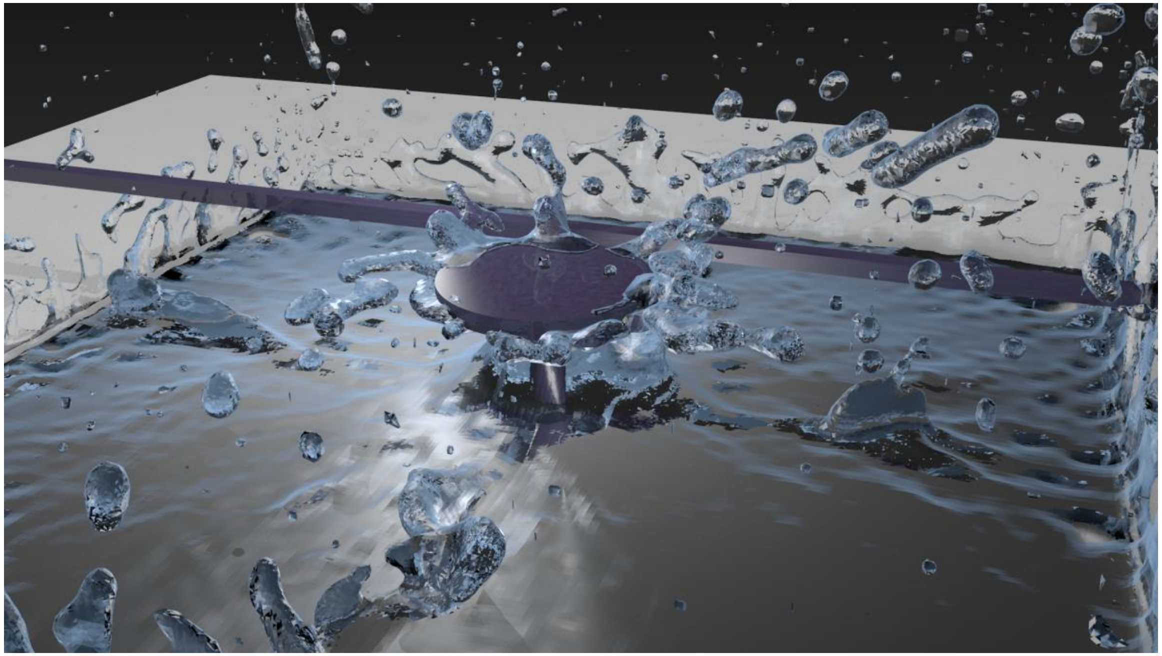
Conclusions

- Strong coupling of optics and mechanics
- Motional sensitivity reaches 10^{-17} m/√Hz in liquid at the GHz
- Develop and validate a novel analytical model
- Controlled dissipation   (Q>30 in water)
- 10^{-24} g/√Hz potential sensitivity in mass deposition
- 10^{-10} precision in density and viscosity measurements



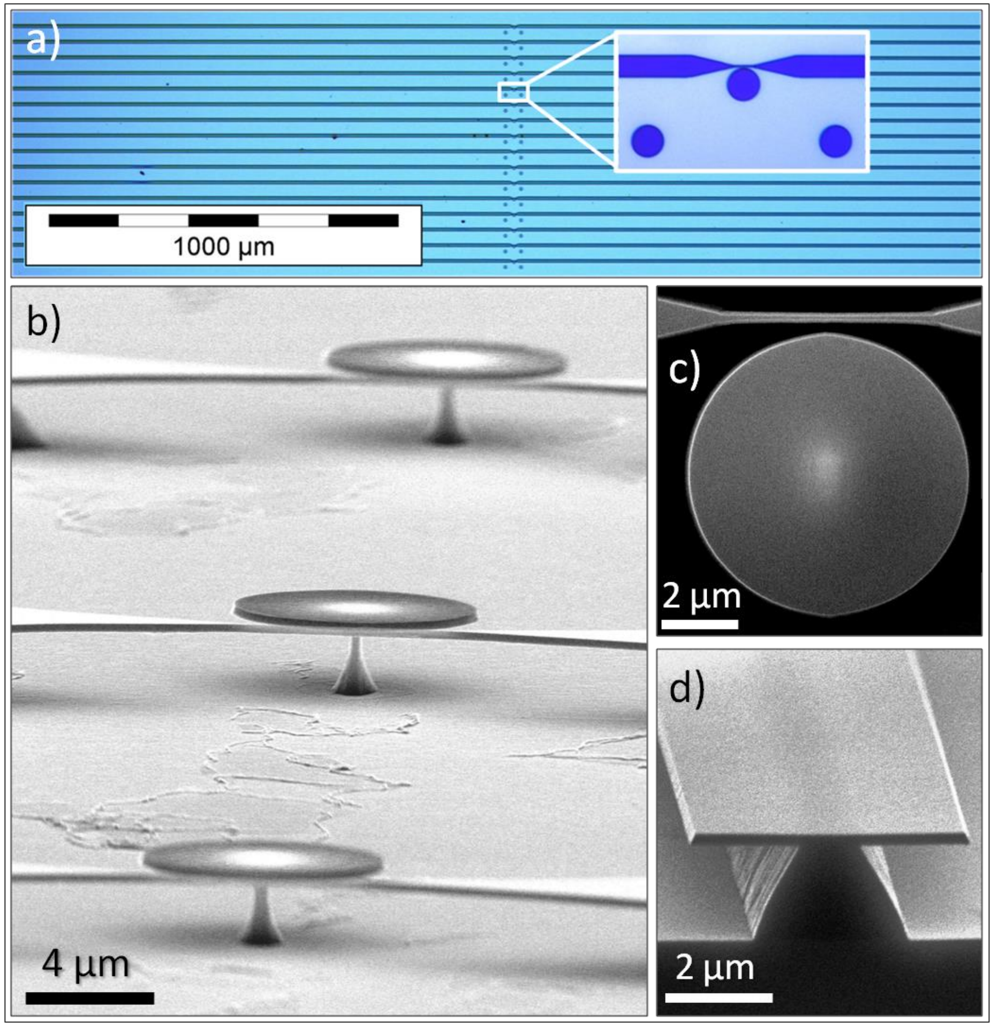
Future work

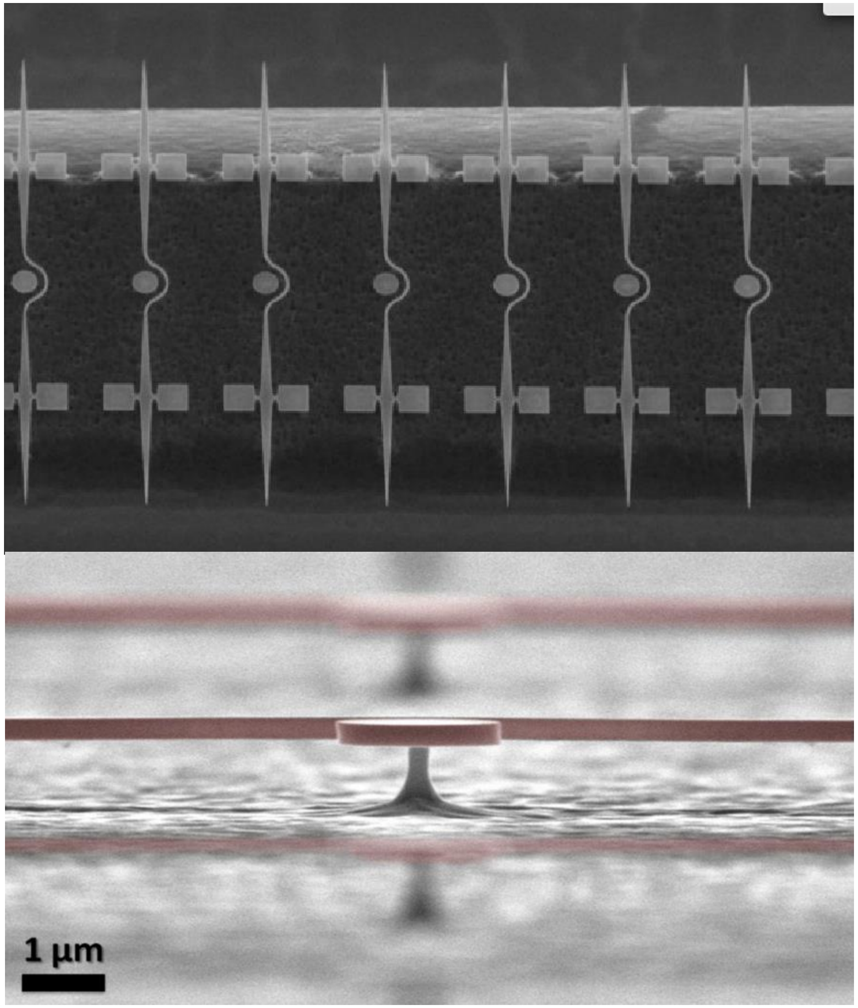
- Biological sensing
- UltraFast rheometer and densitometer
- High frequency hydrodynamics in liquids/polimers




Thank you
Questions???

On-chip GaAs optomechanical disk resonators

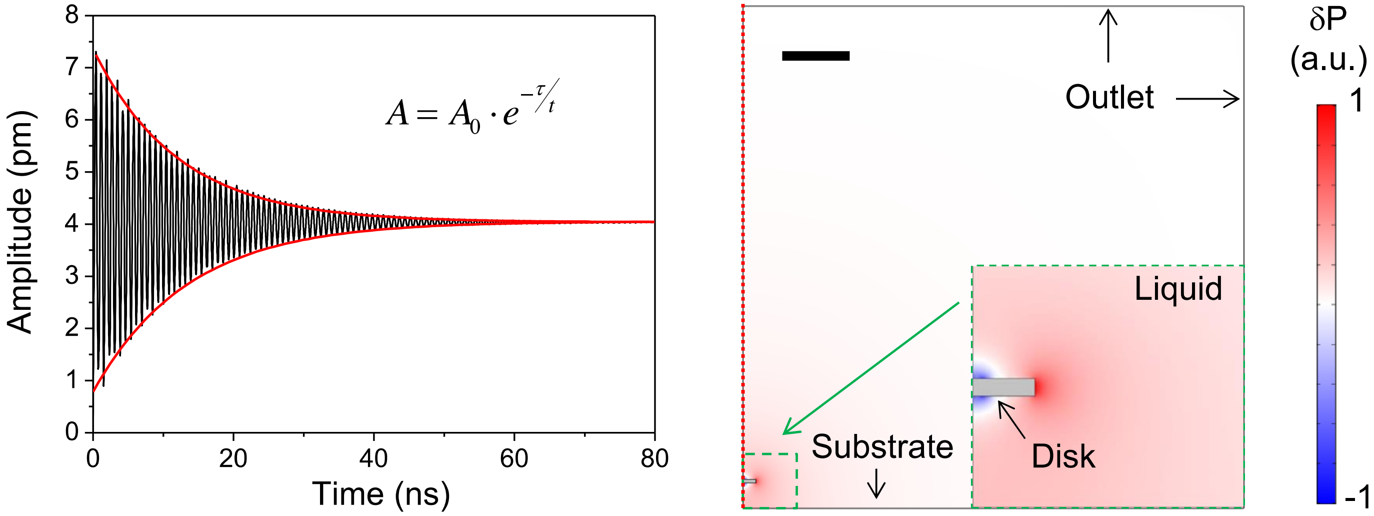




C. Baker et al. Applied Physics Letters 99, 151117 (2011)

FEM modeling of liquid interactions

Viscous interactions



Acoustic interactions