Precise Measurements of the Casimir Force: Experimental Details

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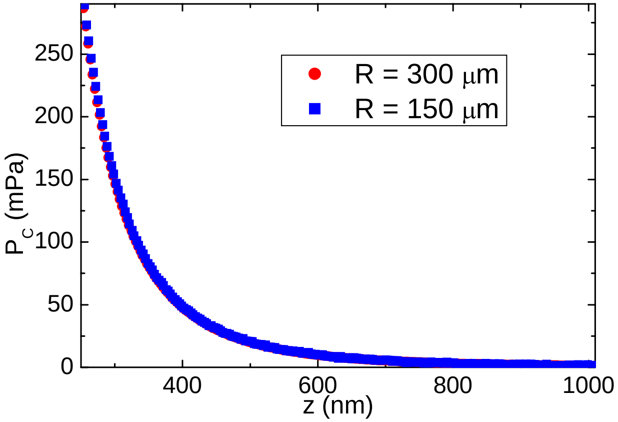
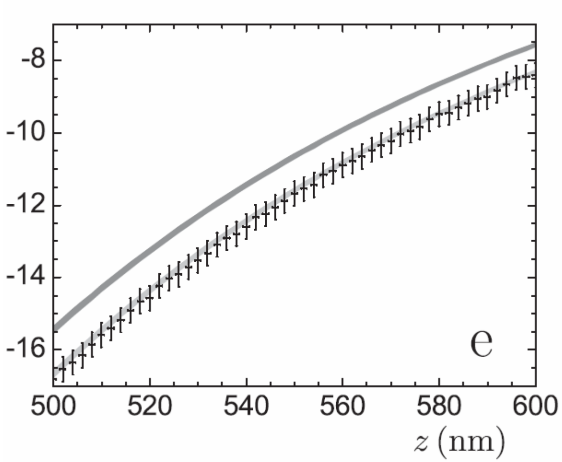
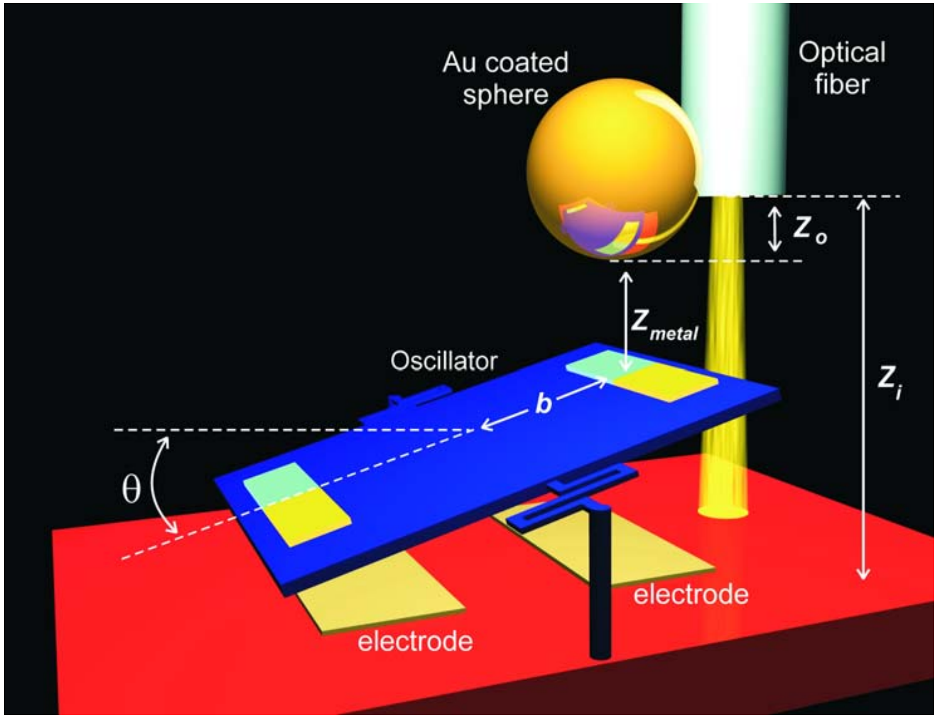
IUPUI

Motivation

- Precise measurements of the Casimir force
    - -Background for hypothetical forces
    - -Allows for comparison with theory
    - -Temperature dependence and effects on nanosystems



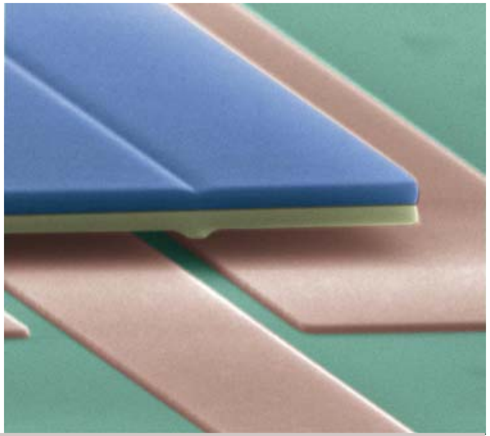


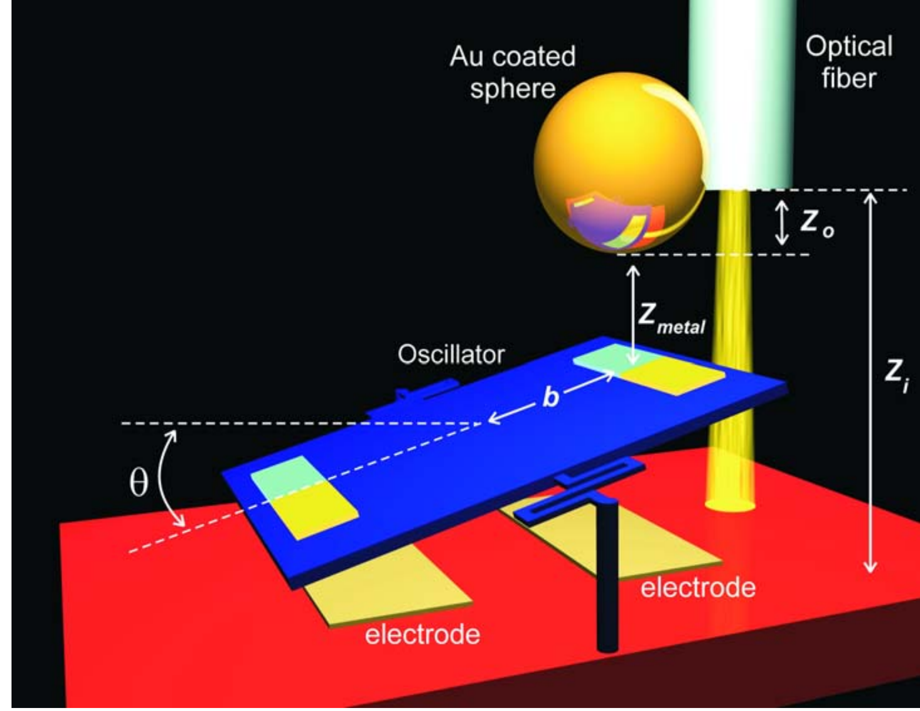


Outline

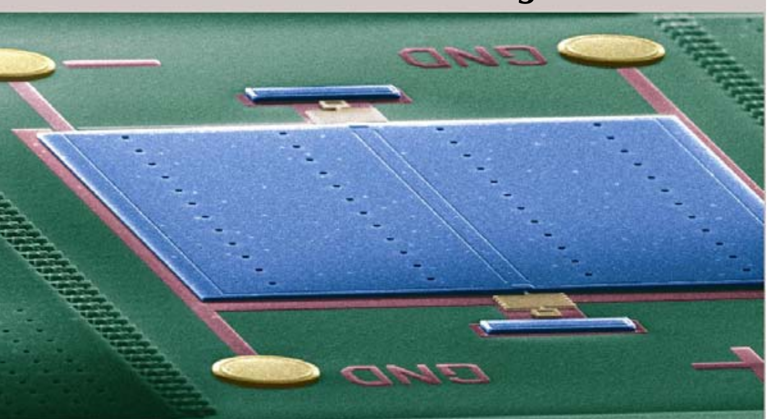
- Experimental setup, sample preparation, and characterization
- Measurement of the interaction
- Measurement of the separation dependence
- Comparison with theory
- Proposed measurements to see the effects of geometry
- Summary

Experimental setup





$$z_{metal} = z_i - z_o - z_g - b\Theta$$



In our last measurements we have changed the setup, the sphere is on the oscillator, the plate is on top

MEMS plate: 500 μm x 500 μm

Plate thickness: 3.5 μm

Spring lengths: 500 μm

-Larger sample, requires different deposition.

$K_{torsion}$ ~ 10^{-10} Nm/rad

Sphere radii: 10 μm – 150 μm

-Measurements done in vacuum at room temperature, in an oil-free chamber.

Resonance frequency ~ 1000 Hz

Quality factor ~ 10000 (@ 10^{-6} Torr)

Sample preparation and characterization

-Au on the sapphire sphere is deposited by thermal evaporation.

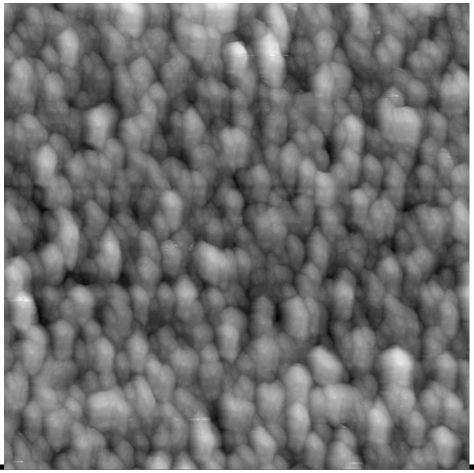
-Au on the oscillator is also deposited by thermal evaporation

-In new, larger samples it is deposited by electroplating (on Si[111])

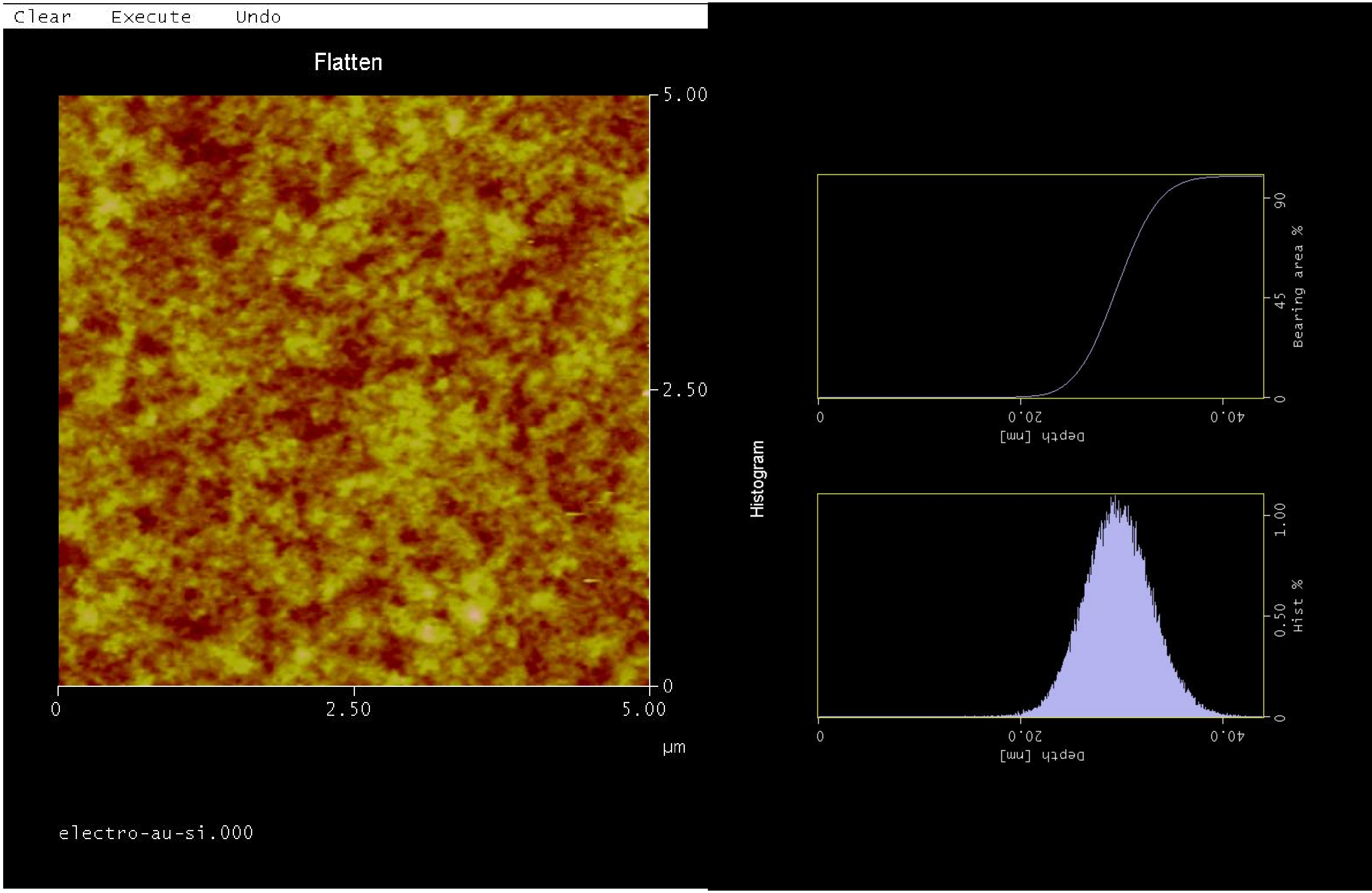
-Samples are characterized by measuring resistance as a function of temperature, AFM measurements and also ellipsometry in the electrodeposited sample.

-The sample is mounted into the system, baked to ~ 60 ºC for ½ hour.

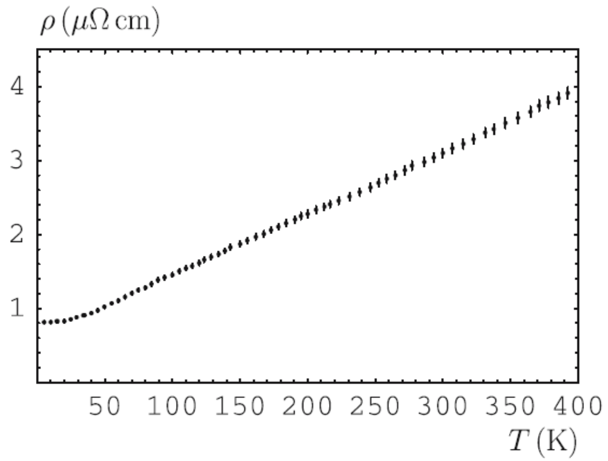
(10x10 μm^2)
~ 20 nm_{pp}



AFM measurements



Resistivity and spectroscopic ellipsometry



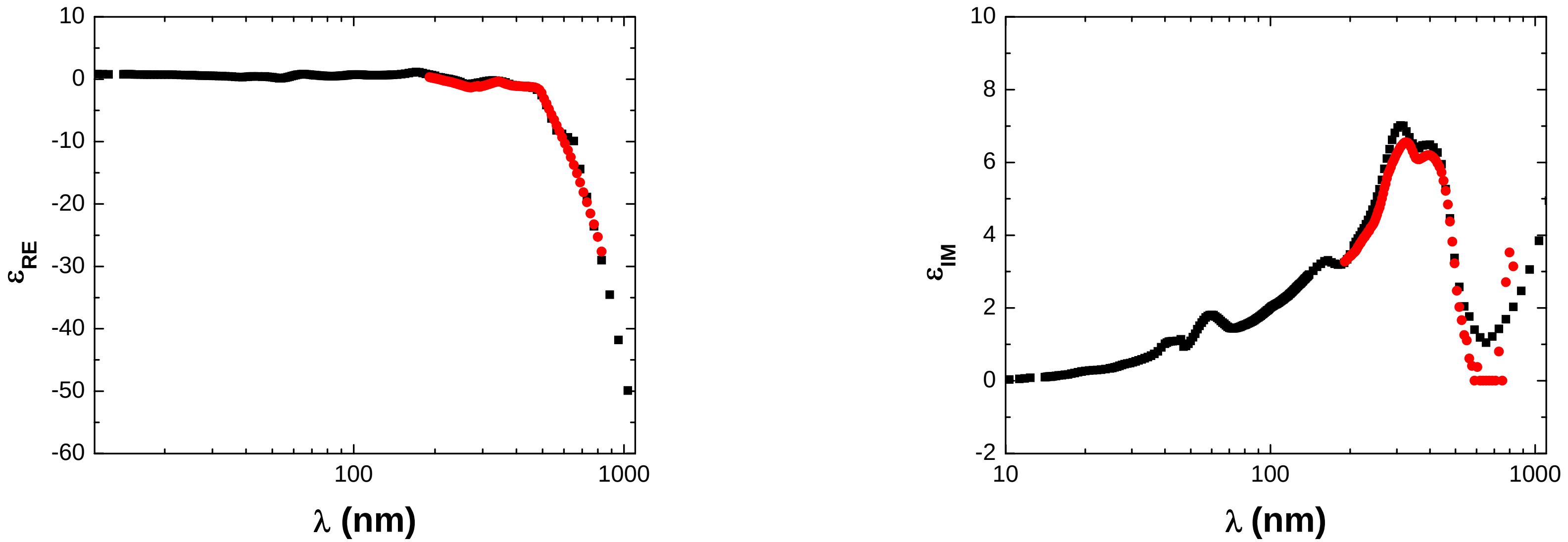
-R vs T and spectroscopic ellipsometry (190 nm to 830 nm) used to determine ω_p.

$$\rho(T) = \frac{4\pi}{\omega_p^2 \cdot \tau(T)} \propto \frac{T}{\omega_p^{3/2}}$$

-Both methods indicate a rather good Au sample

$$\omega_p = (8.9 \pm 0.1)\mathrm{eV}$$

Resistivity and spectroscopic ellipsometry



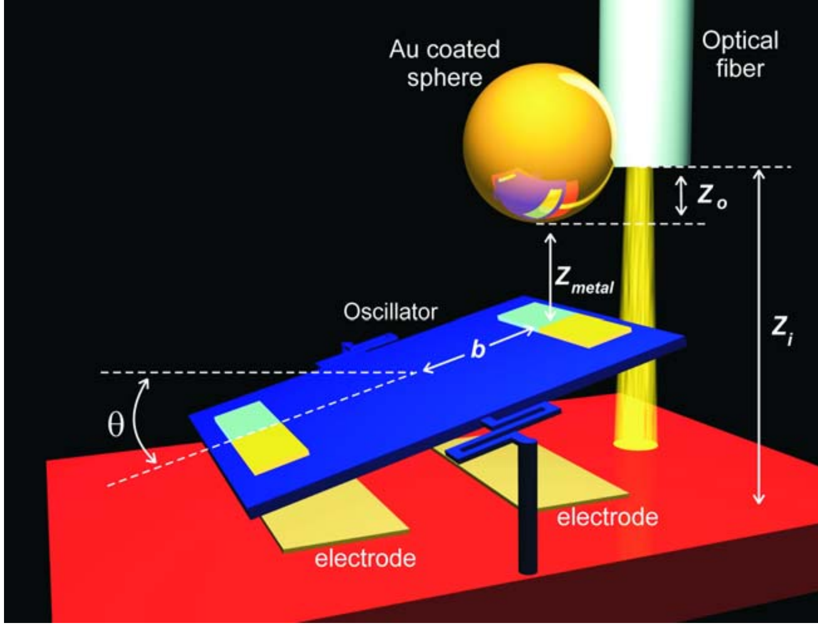
-Measured real and imaginary parts of the dielectric functions (red circles) are similar to published values (Palik, black squares)

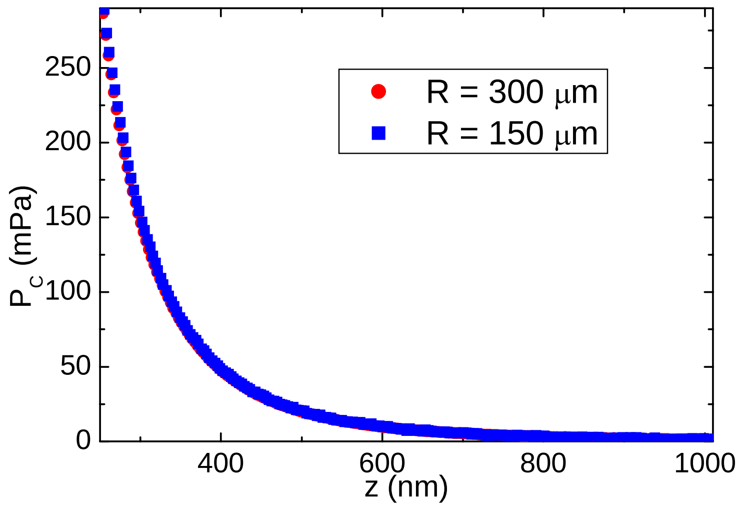
-It was checked that either can be used, giving similar results. Palik values are used on the rest of this presentation.

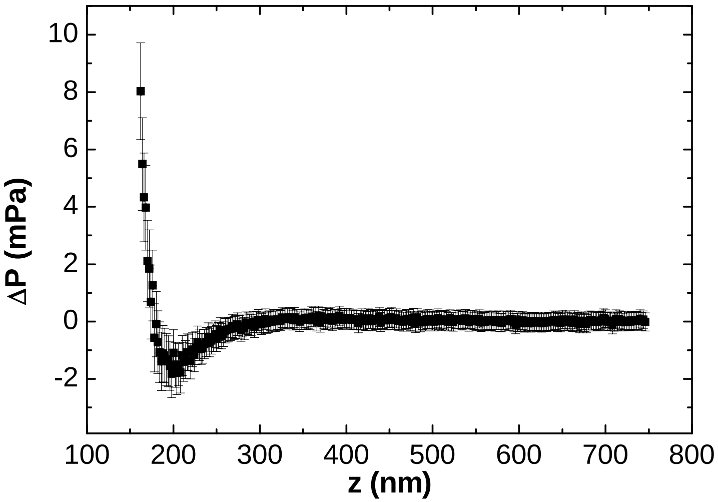
Pressure measurements

$$\omega_r^2 = \omega_o^2\left(1 - \frac{b^2}{I\omega_o^2}\frac{\partial F_C}{\partial z}\right)$$

$$F_C = 2\pi R \times E_C \Rightarrow \frac{\partial F_C}{\partial z} = 2\pi R \times P_C$$







Pressure determination

$$\omega_r^2 = \omega_o^2\left(1 - \frac{b^2}{I\omega_o^2}\frac{\partial F_C}{\partial z}\right)$$

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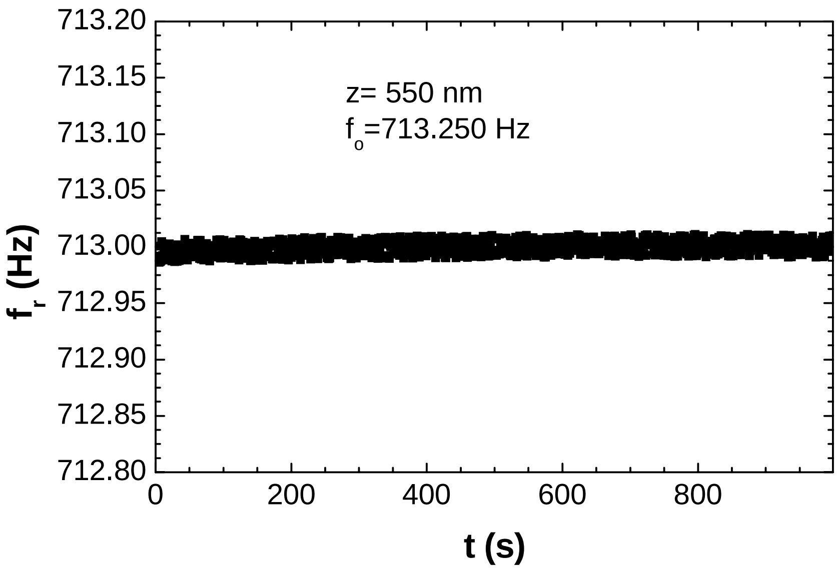
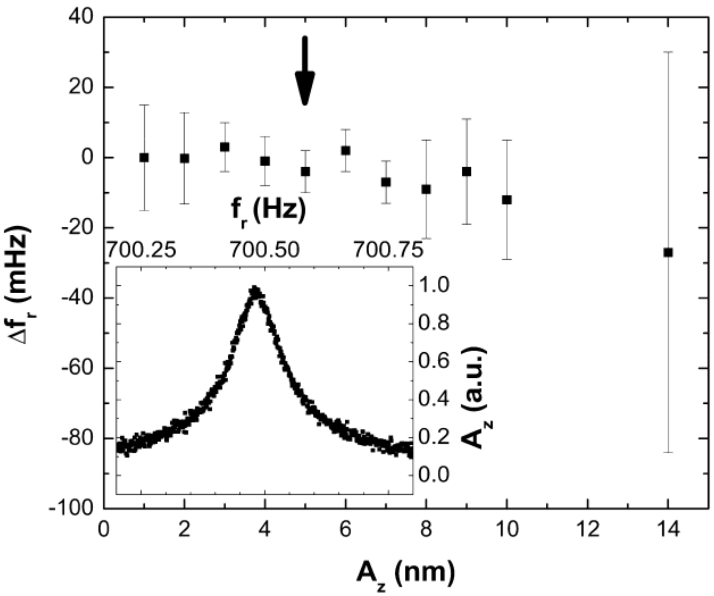


Determined by:
-Looking into the response of the oscillator in the thermal bath
-Inducing a time dependent separation between the plate and the sphere



Pressure measurements

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	Errors	Minimum values
Frequency:	6mHz	~28 mHz (at 750 nm)
R:	0.2 μm	150 μm
b^2/I:	0.0005 μg^{-1}	1.2432 μg^{-1}

Errors:

Random: 0.46 mPa (162 nm)
0.11 mPa (300 nm)

Systematic: 2.12 mPa (162 nm)
0.44 mPa (300 nm)

Separation measurement

z_o is determined using a known interaction

z_i, Θ are measured for each position

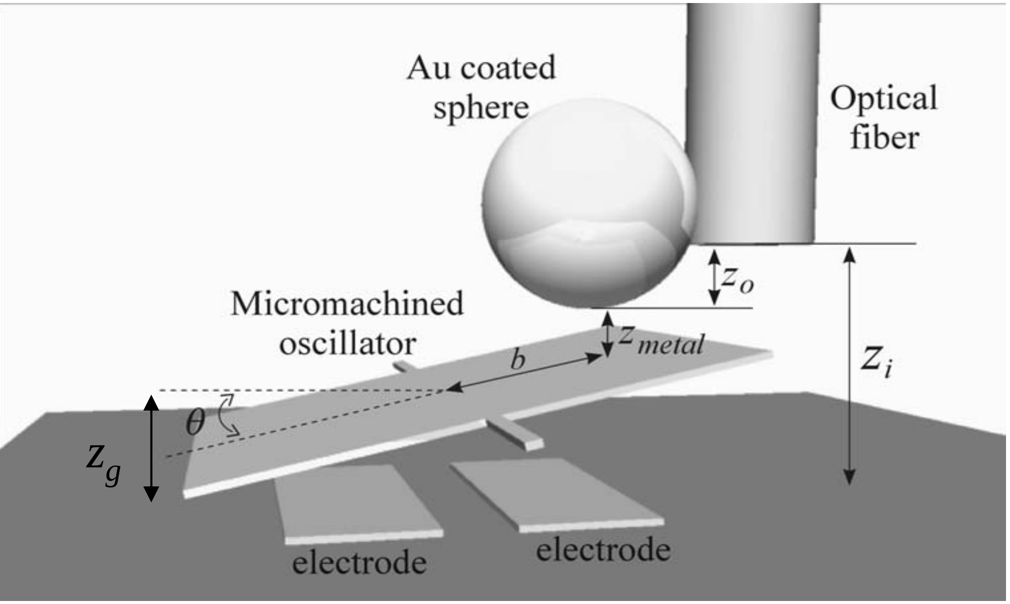
z_g = (2172.8 ± 0.1) nm, interferometer

z_i = ~(12000.0 ± 0.2) absolute interferometer

z_o = (8162.3 ± 0.5) nm, electrostatic calibration

b = (207 ± 2) μm, optical microscope

Θ = ~(1.000 ± 0.001) μrad



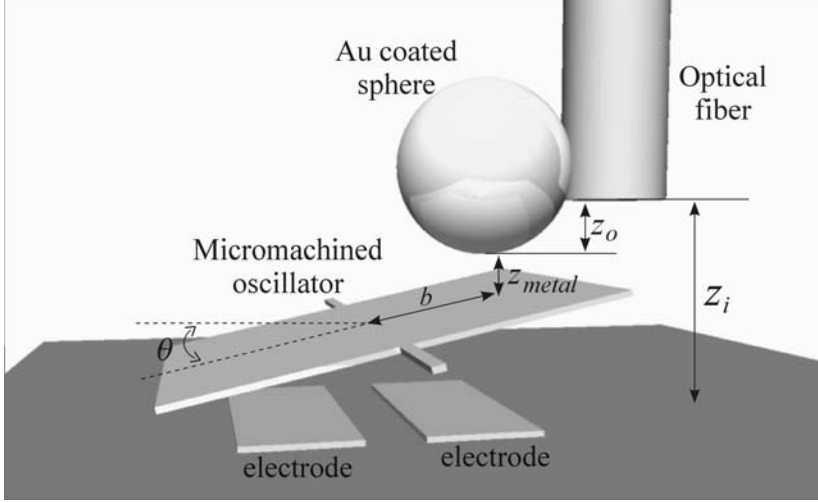
Separation measurement

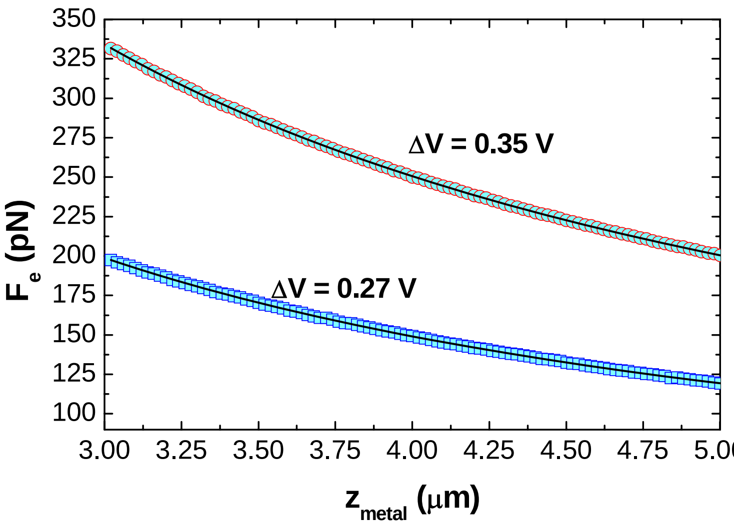
Electrostatic force calibration

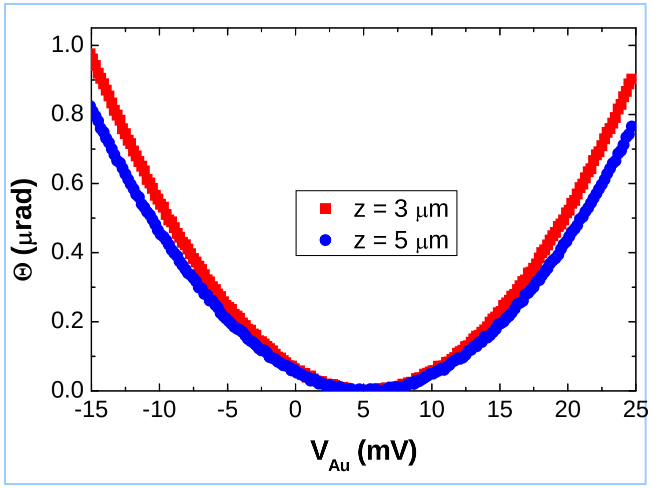
$$F_e = -2\pi\varepsilon_o (V - V_{Au})^2 \sum_n \frac{\coth u - n \coth nu}{\sinh nu} \sim$$

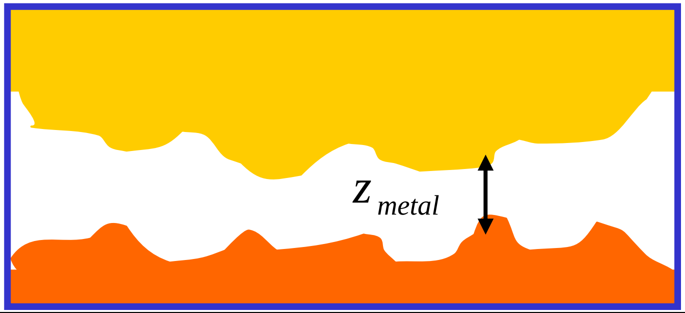
$$-2\pi\varepsilon_o (V - V_{Au})^2 \sum_0^7 A_i \left(\frac{R}{(z_{metal} + \bar{z})} \right)^{1-i}$$

$$u = 1 + \frac{(z_{metal} + \bar{z})}{R}$$



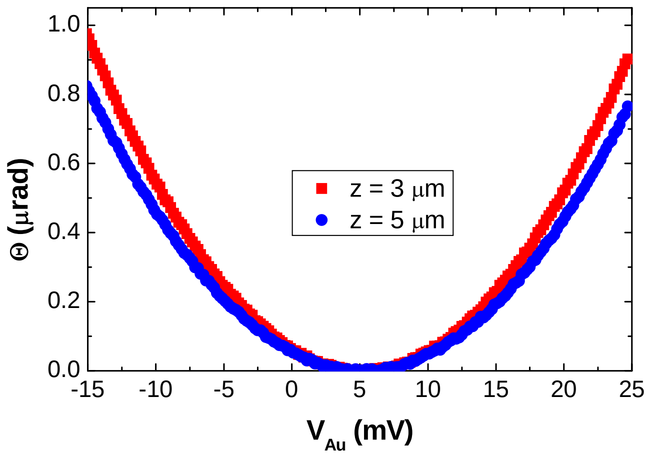


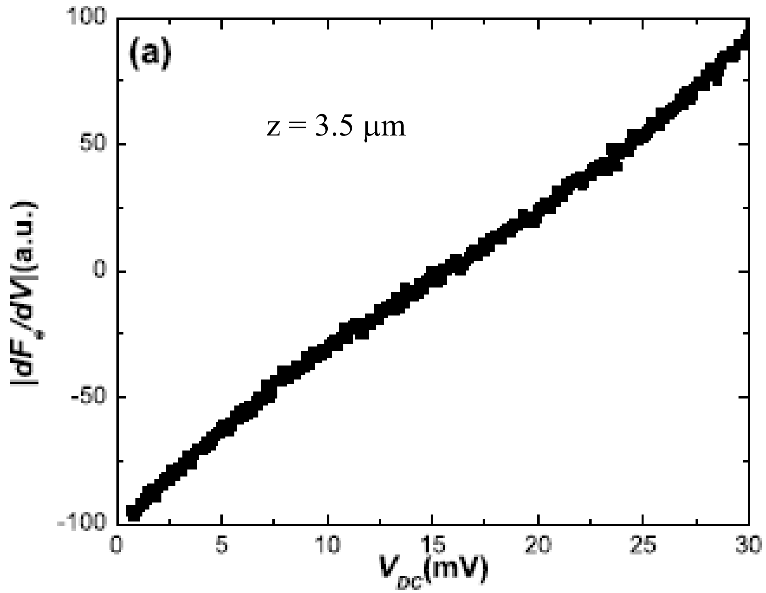


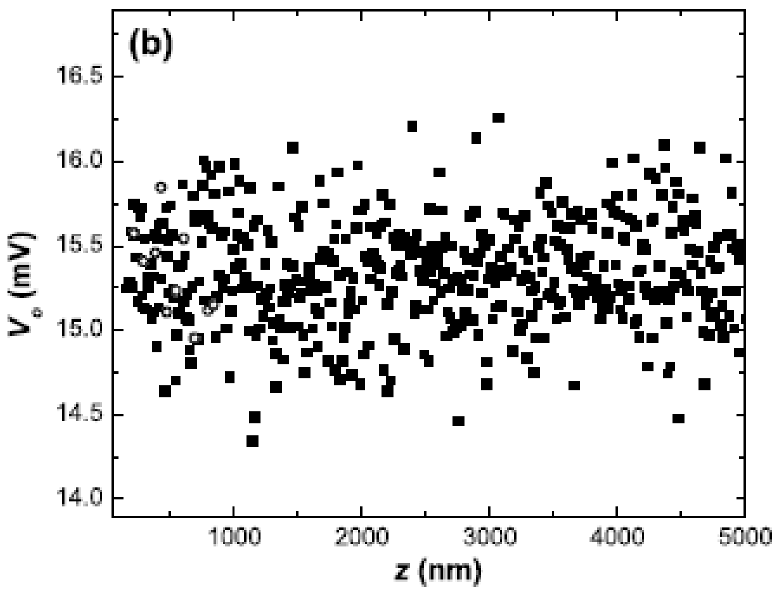


Separation measurement

Electrostatic force calibration

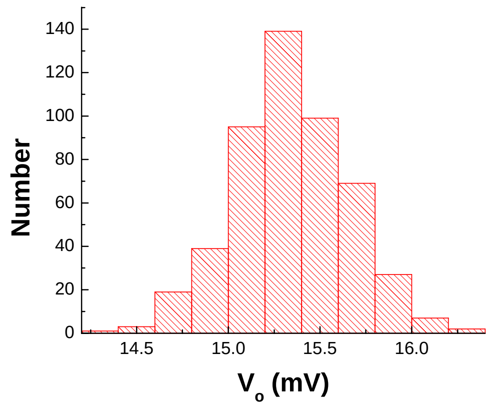


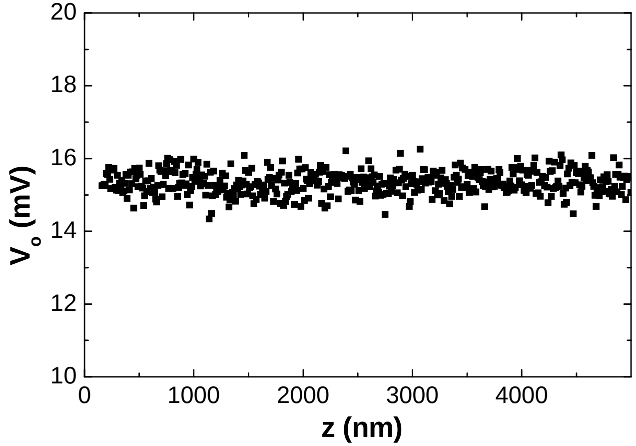




Separation measurement

Electrostatic force calibration

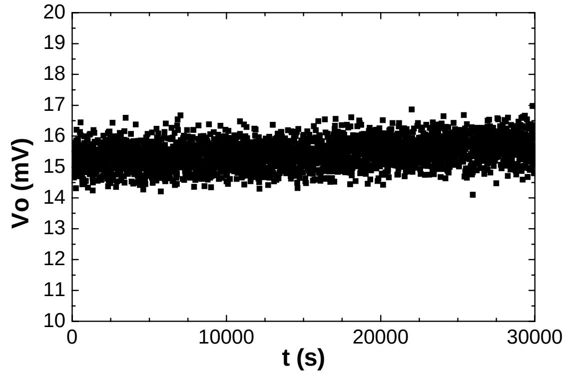


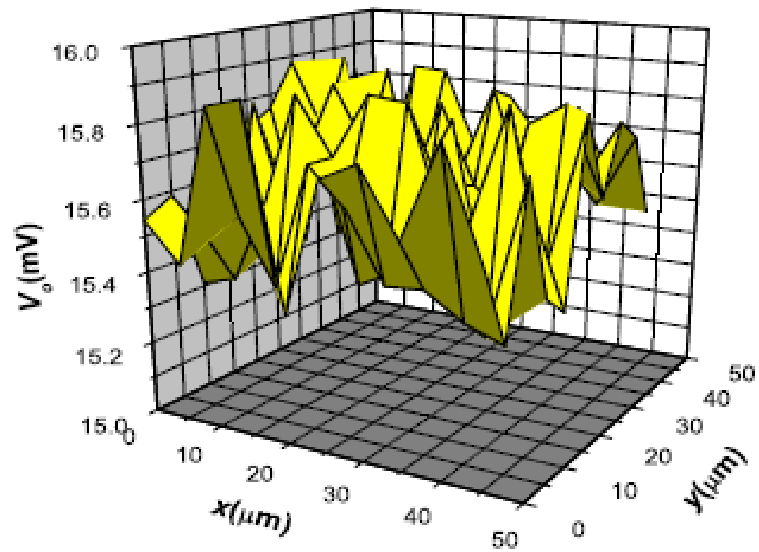


V_o **must** be constant as a function of separation…

Otherwise, V_o needs to be determined at each point

… and time





10 x 10 grid, 5 μm pitch

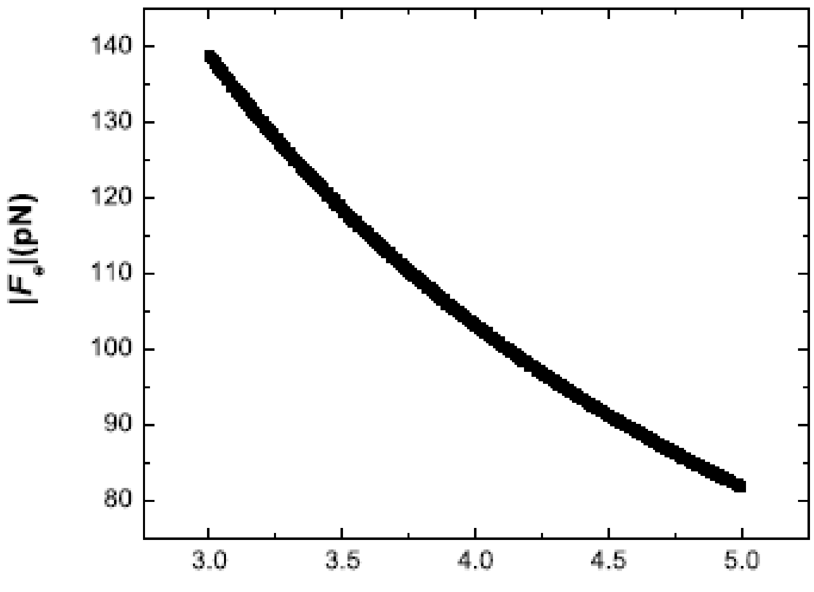
Separation measurement

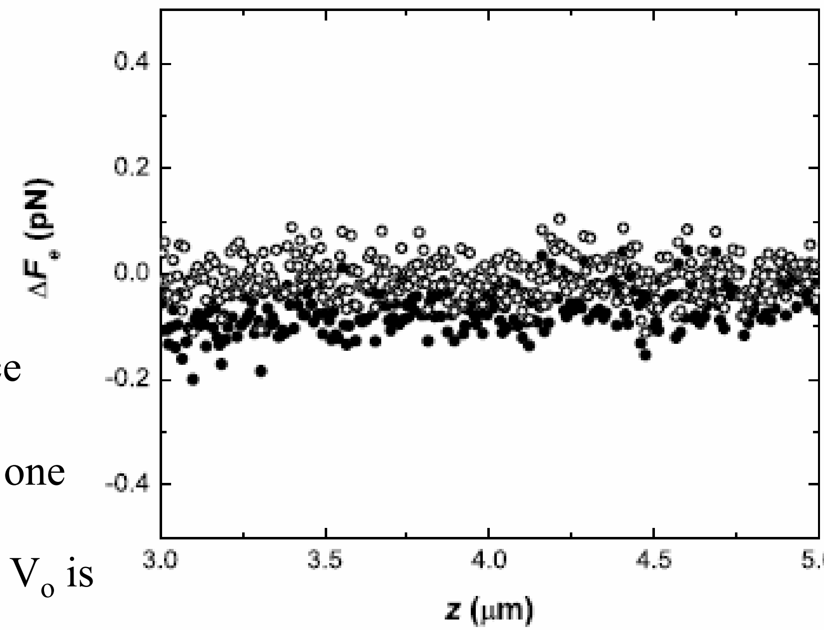
Electrostatic force calibration

$$F_e = -2\pi\varepsilon_o (V - V_{Au})^2 \sum_n \frac{\coth u - n \coth nu}{\sinh nu} \sim$$

$$-2\pi\varepsilon_o (V - V_{Au})^2 \sum_0^7 A_i \left(\frac{R}{(z_{metal} + \bar{z})} \right)^{1-i}$$

$$u = 1 + \frac{(z_{metal} + \bar{z})}{R}$$



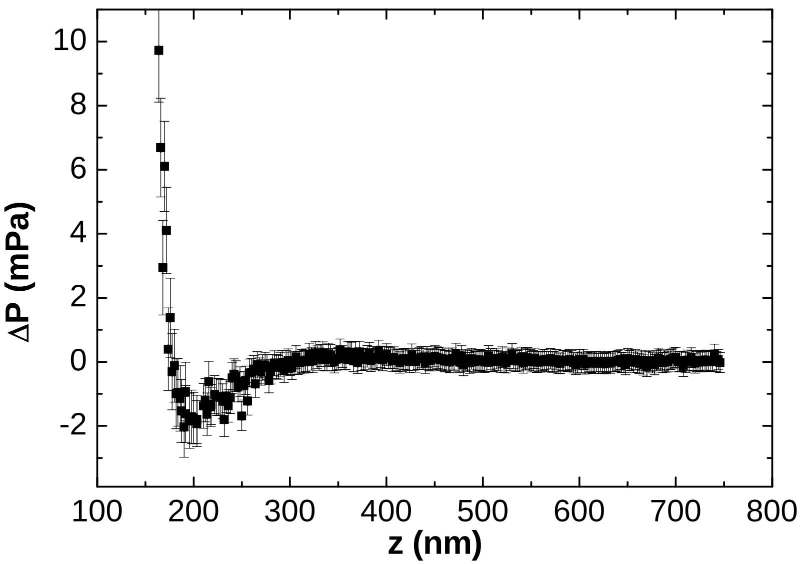


-After measuring the deflection (expressed as force here), we adjust for the unknown separation.

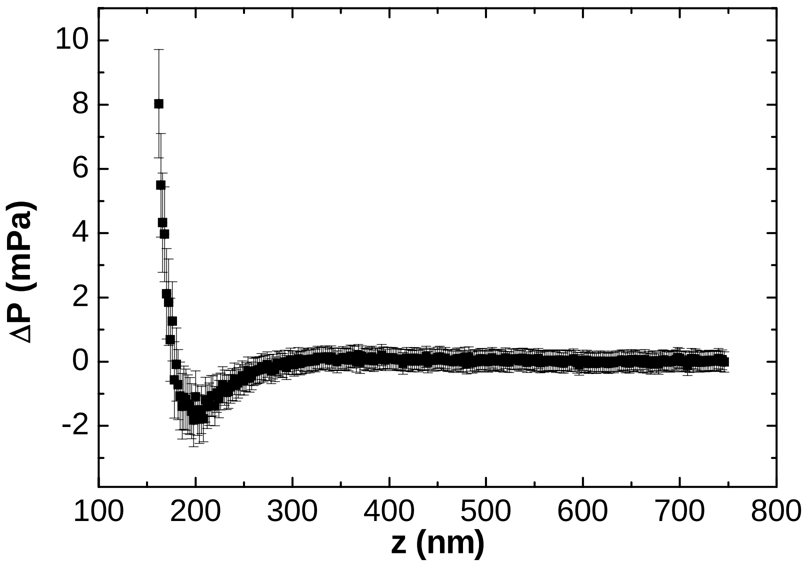
-The figure shows the ΔF_e for the optimal and one off by 1.5 nm

-The error in the force associated with the error in V_o is < 1 fN.

Equivalent P_C measurement



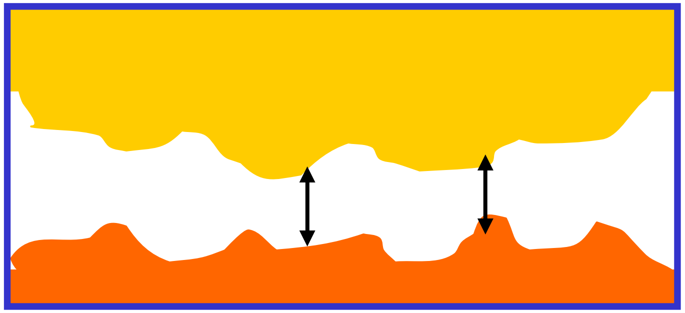
New sample (September 2009)



Old data (2005)

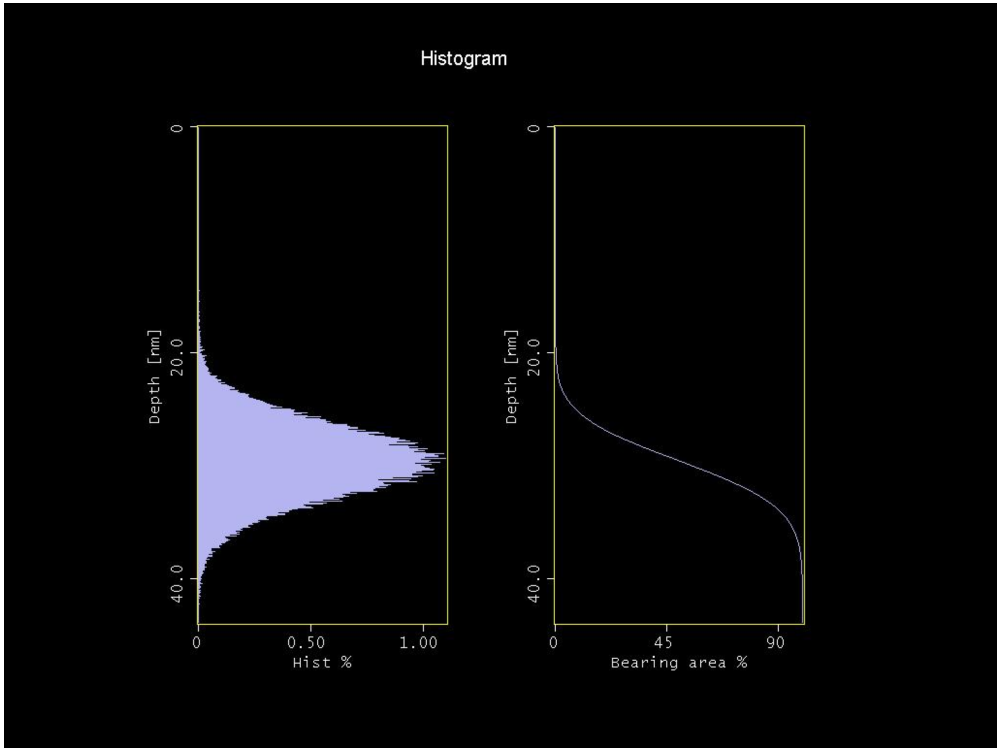
Comparison with theory

Roughness corrections



$$F_C = \sum_i v_i F_{CS}(z)$$

v_i: Fraction of the sample at separation z_i



Roughness corrections are ~0.5% to the Casimir force at 160 nm

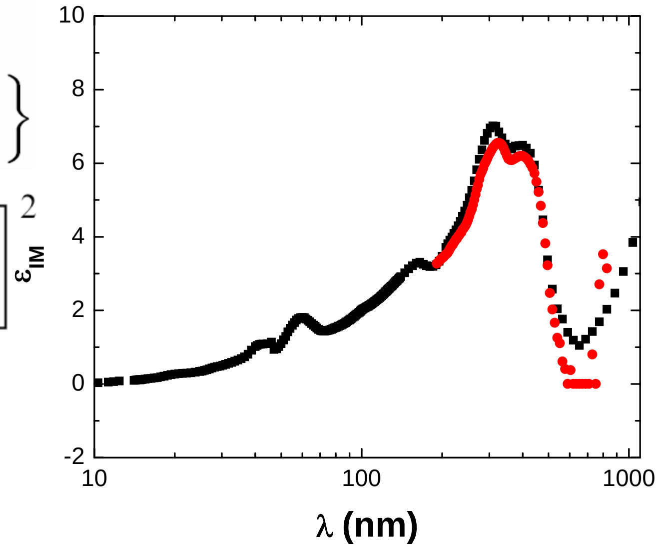
Comparison with theory

Finite conductivity and finite temperature

$$P(z) = -\frac{k_B T}{\pi} \sum_{l=0}^{\infty}{}' \int_0^\infty k_\perp \, dk_\perp q_l \times \left\{ \left[r_\parallel^{-2}(\xi_l, k_\perp) e^{2q_l z} - 1 \right]^{-1} + \left[r_\perp^{-2}(\xi_l, k_\perp) e^{2q_l z} - 1 \right]^{-1} \right\}$$

$$r_{\parallel,L}^{-2}(\xi_l, k_\perp) = \left[\frac{k_l + \varepsilon(i\xi_l) q_l}{k_l - \varepsilon(i\xi_l) q_l} \right]^2, \quad r_{\perp,L}^{-2}(\xi_l, k_\perp) = \left[\frac{k_l + q_l}{k_l - q_l} \right]^2$$

$$q_l^2 = k_\perp^2 + \left(\frac{4\pi^2 k_B T l}{hc} \right)^2$$

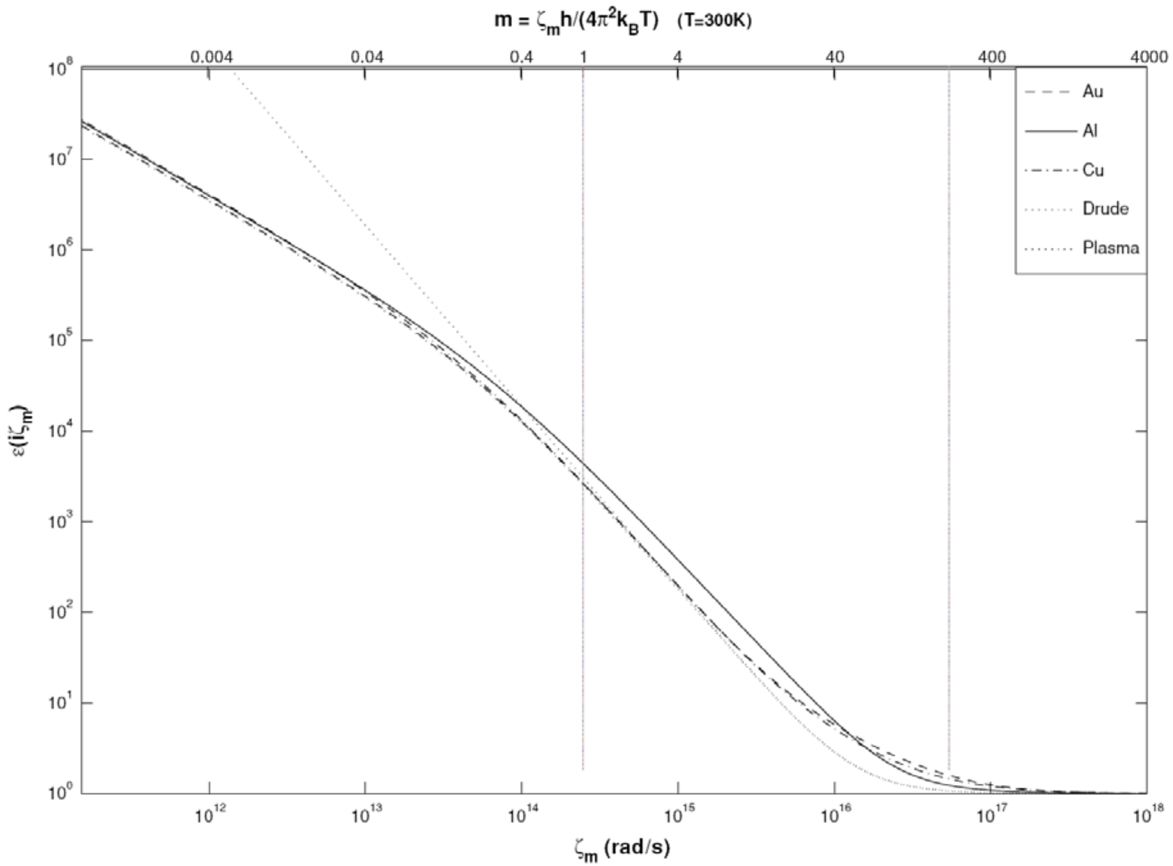


$$\varepsilon(i\xi) = 1 + \frac{2}{\pi} \int_0^\infty \frac{\omega \, \mathrm{Im}\, \varepsilon(\omega)}{\omega^2 + \xi^2} d\omega$$

$$k_l^2 = k_\perp^2 + \varepsilon(i\xi_l) \xi_l^2 / c^2$$

Comparison with theory

$$\varepsilon(i\xi) = 1 + \frac{2}{\pi}\int_0^\infty \frac{\omega \operatorname{Im}\varepsilon(\omega)}{\omega^2+\xi^2}\,d\omega$$



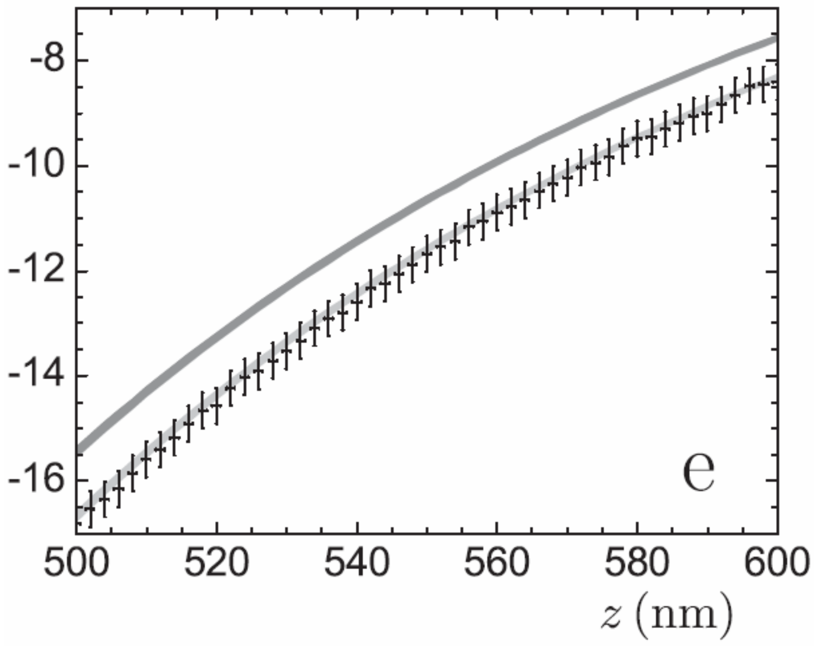
$$\varepsilon(\omega) = 1 - \frac{\omega_p^{\,2}}{\omega(\omega + i\gamma)}$$

$$\varepsilon(\omega) = 1 - \frac{\omega_p^{\,2}}{\omega^2}$$

Bentsen et al., J. Phys. A (2005)

Pressure determination

PRD **75**, 077101



There is a significant issue: Drude does not agree with the data
-Experimental problem?
-Theoretical problem?
-Theory not applied to the right experiment?

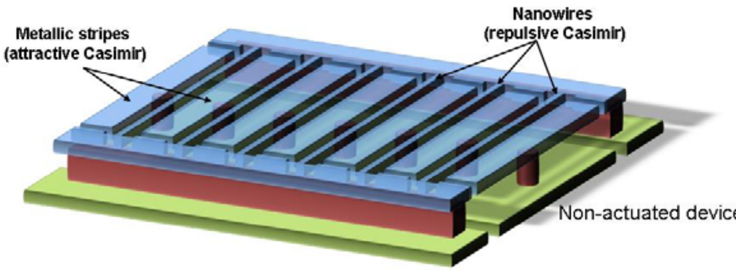
Theoretical errors:

-Sample dependence:	0.5%
-Separation dependence:	1.5% (162 nm)
	0.32%(750 nm)

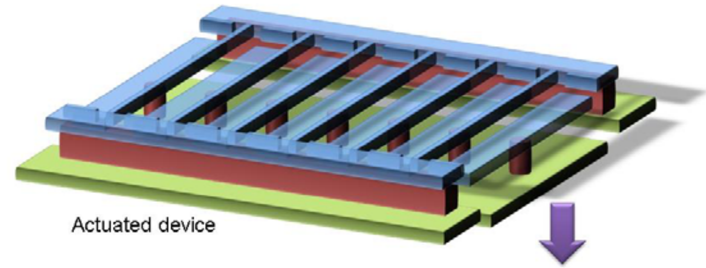
-Dark grey, Drude model approach
-Light grey, impedance approach

~19 mPa @162 nm (Exp: ~2.5 mPa @162 nm)

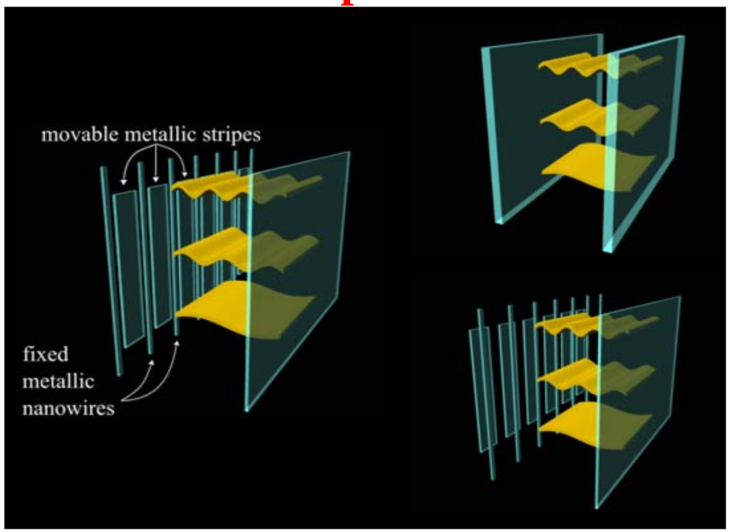
Geometrical effects



"Role of surface plasmons in the Casimir effect", F. Intravaia et al., PRA 76 (2007)

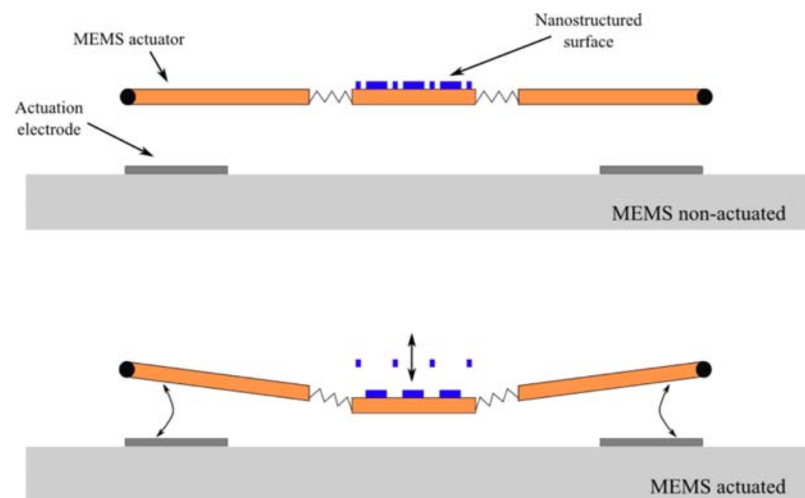


Real-time manipulation



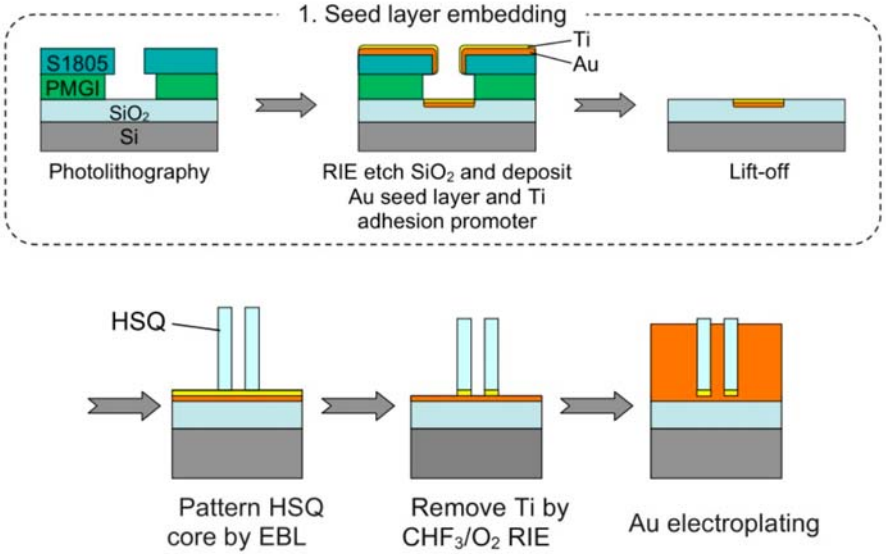
Dynamically deformable nanostructure

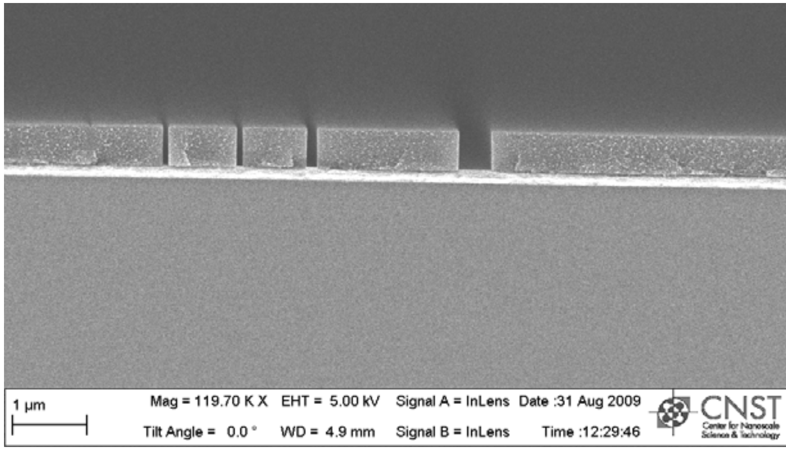
- Integration of nanostructure with MEMS
- Displacement ~ 500nm
- Precise control of motion (± 1nm)
- Shielded surfaces (fringe fields)

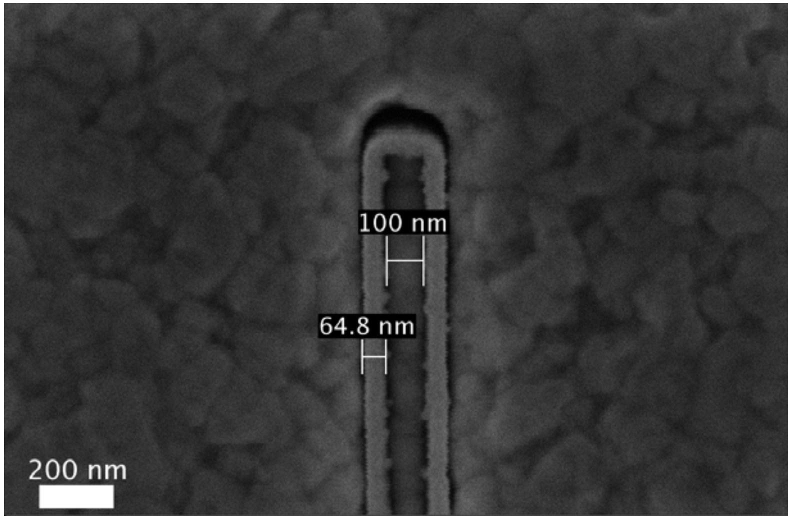


Geometrical effects

Metallic nanostructures



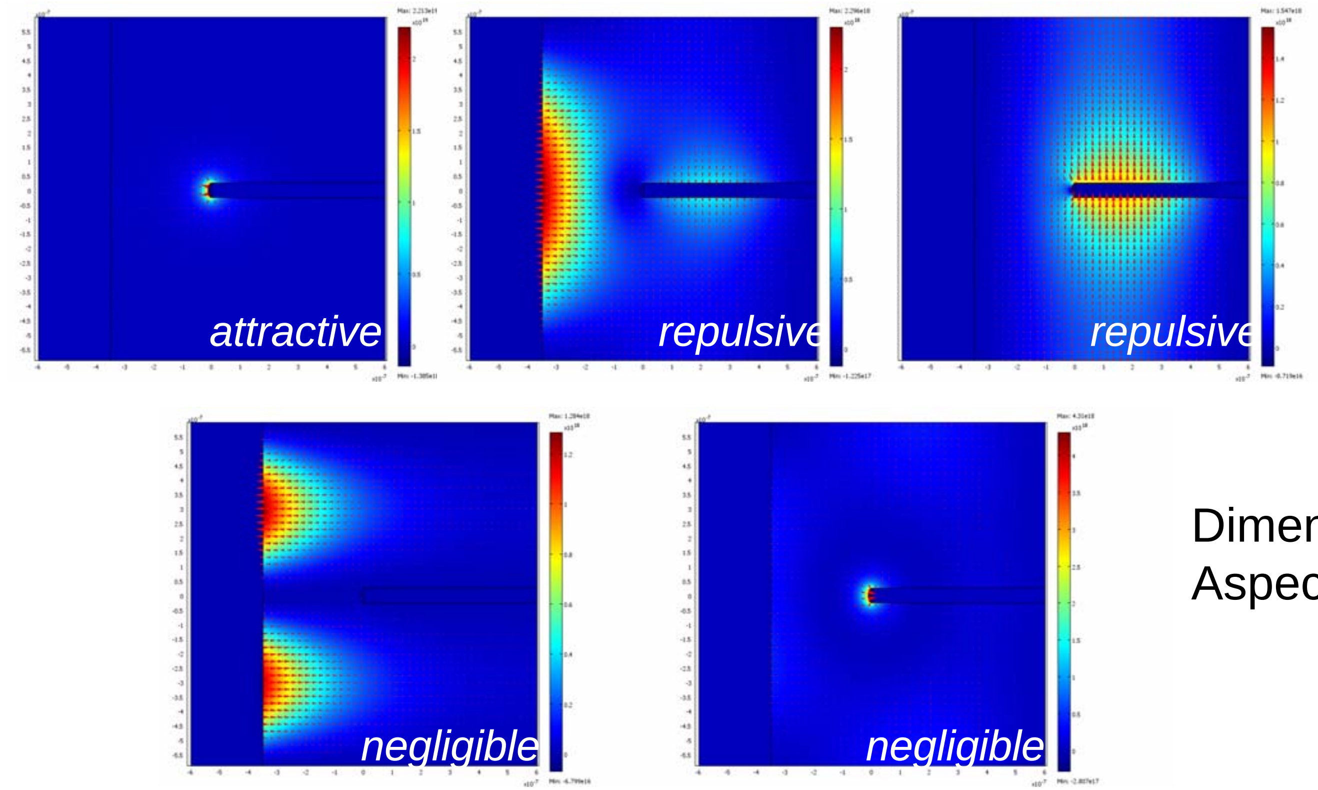




- Electroplating process
- HSQ molds (highest resolution resist)
- 100keV electron beam lithography tool
    - pattern thick resist (1 µm)
    - large depth of focus
    - small electron scattering

Geometrical effects

- “Role of surface plasmons in the Casimir effect”, F. Intravaia et al., PRA 76 (2007)
- Metallic nanowire ($w < \lambda_p$) close to a flat metallic surface



Dimension < 100nm
Aspect ratio > 5:1

Net contribution from the first 5 plasmonic modes is repulsive for $d \geq 200$nm

Summary

• **Precise experiments of the Casimir force between Au-Au surfaces**

• **Good agreement with plasma model**

Differences with Drude model **cannot** be explained as a problem in the separation measurement, or the Au layer properties. It appears that any model with a finite relaxation time will give discrepancies when comparing with the Casimir force. **Why do Casimir modes decouple from the dissipative part?**

• **Geometrical effects**

An innovative MEMS that allows to modify the geometry *in situ* is being designed and tested. This system will be used to investigate the plasmonic contributions to the Casimir effect.