Measuring the Geometry Dependence of the Casimir force on Nanostructured Silicon Surfaces

Ho Bun Chan

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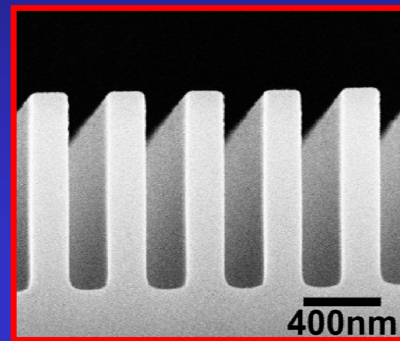
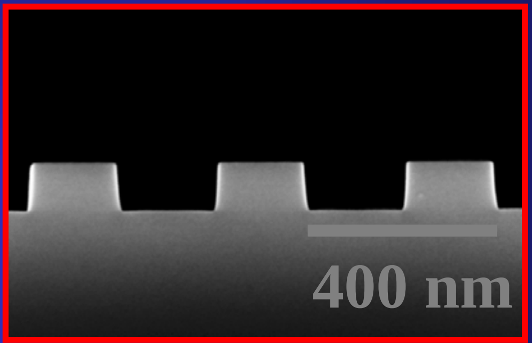
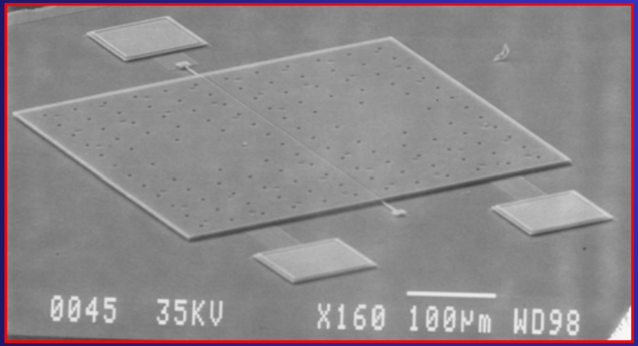
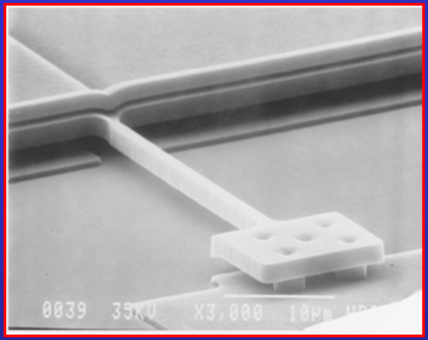
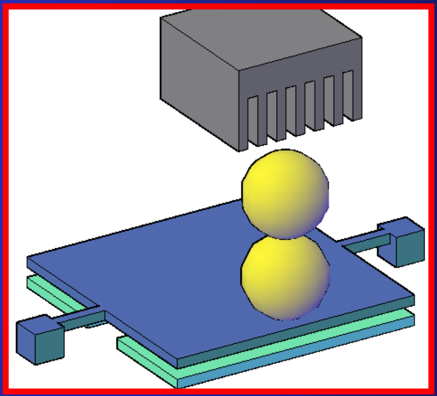




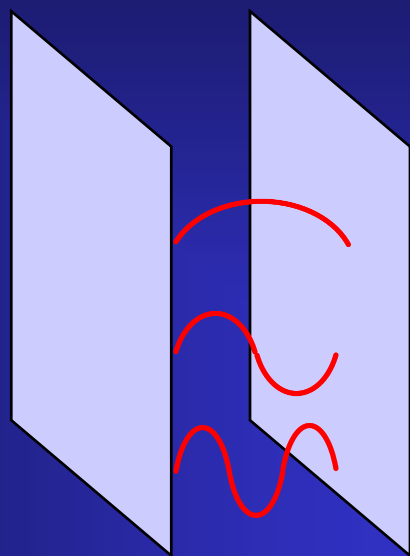




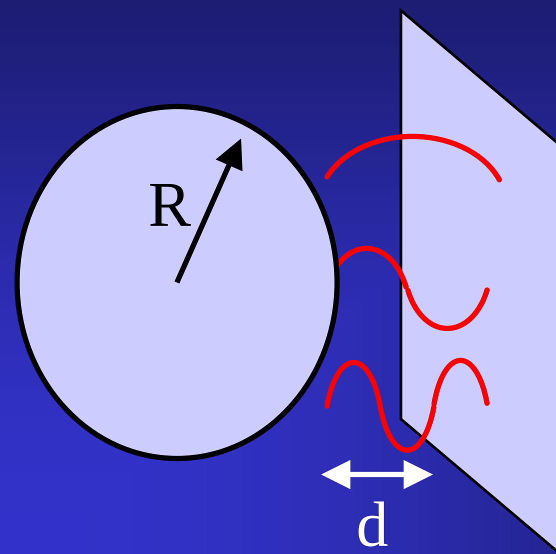


September 29th, 2009. Casimir force control, Santa Fe, NM.

Reducing the effective area of interaction

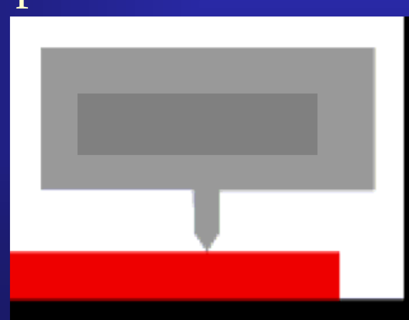


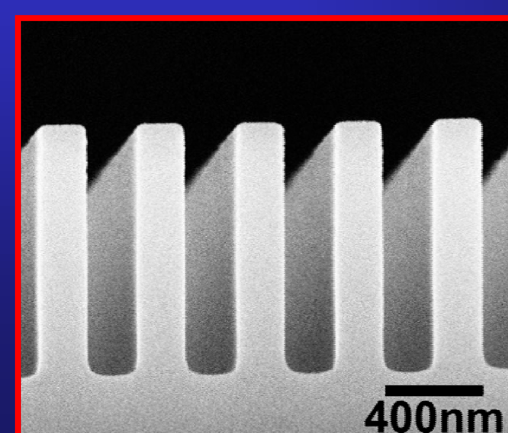
$$F_{Casimir} = -\frac{\pi^2}{240}\frac{\hbar c A}{d^4}$$



$$F_{Casimir} = -\frac{\pi^3 R}{360}\frac{\hbar c}{d^3}$$

Dimples to minimize stiction





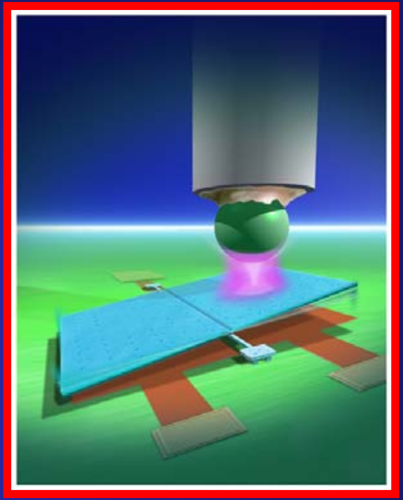
$F_{casimir} = \frac{1}{2} F_{flat}$?

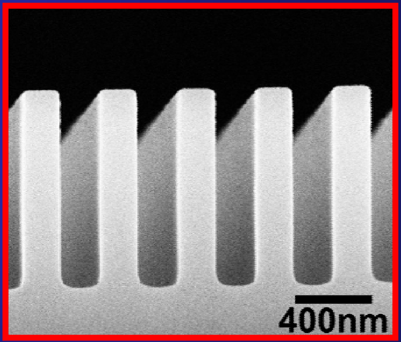
$F_{casimir} > \frac{1}{2} F_{flat}$?

$F_{casimir} < \frac{1}{2} F_{flat}$?

Outline

- Non-trivial dependence of the Casimir force on geometry:
  - Proximity Force Approximation (PFA)
  - Pairwise Additive Approximation (PAA)
- Experiment on strongly deformed surface:
  - Measure Casimir force on an array of nanoscale trenches with a micromechanical torsional oscillator.
  - Up to 30% deviation from PFA and PAA.
  - Evidence of non-trivial boundary dependence of the Casimir force.
  - ~ 30% smaller than theory on perfect metals.





Collaborators

University of Florida
Yiliang Bao
Jie Zou

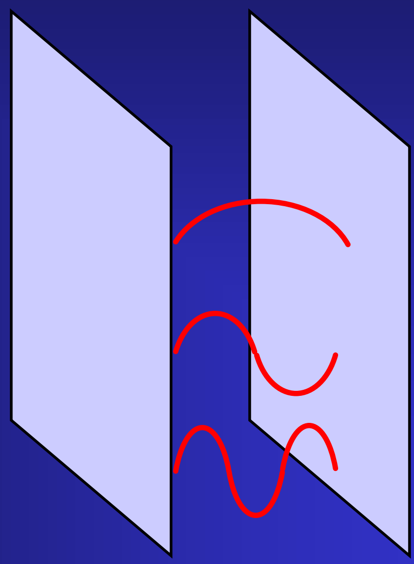
University Paris-Sud
Thorsten Emig

UT Brownsville
Andreas Hanke

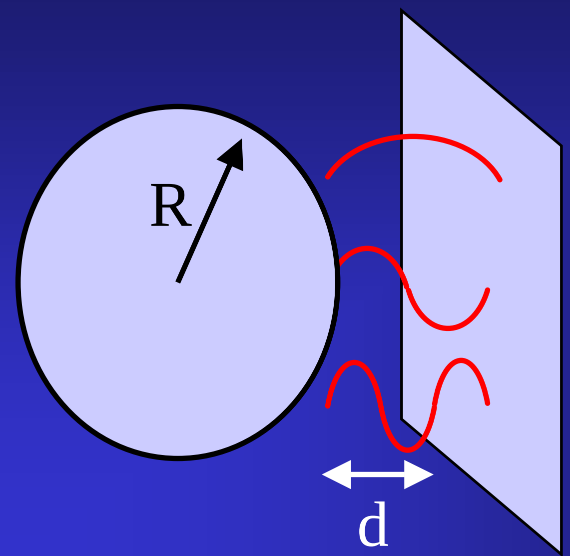
MIT
Steven Johnson

Bell Labs
Ray Cirelli
Fred Klemens
Bill Mansfield
C.S. Pai

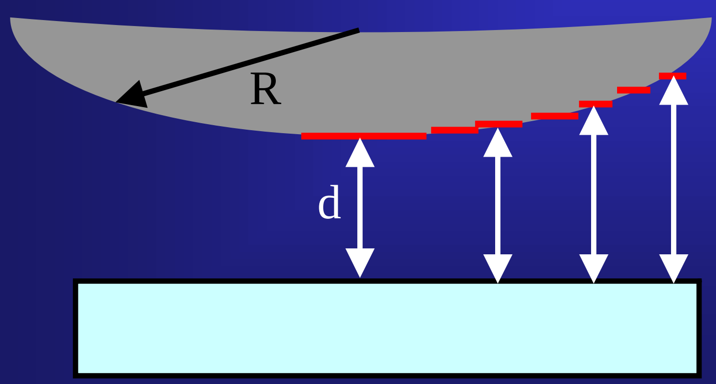
Geometry dependence of the Casimir force



$$F_{Casimir} = -\frac{\pi^2}{240}\frac{\hbar c A}{d^4}$$



$$F_{Casimir} = -\frac{\pi^3 R}{360}\frac{\hbar c}{d^3}$$

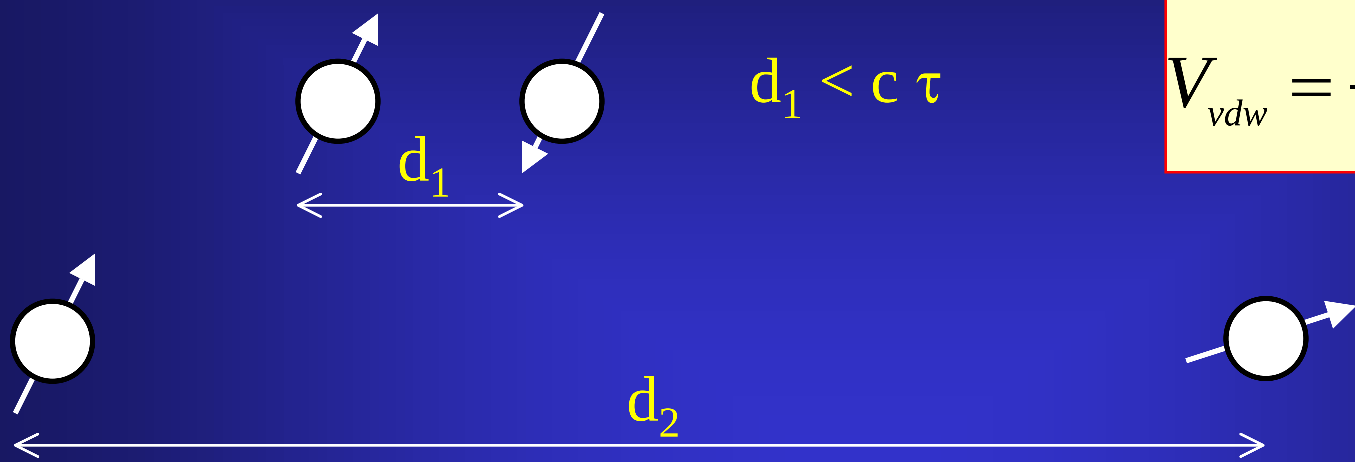


Two common ways to obtain the Casimir force for non-planar objects:

PFA: Proximity force Approximation (Derjaguin approx)

PAA: Pairwise Additive Approximation

Quantum fluctuations: Casimir force vs van der Waals' force



$d_1 < c\,\tau$

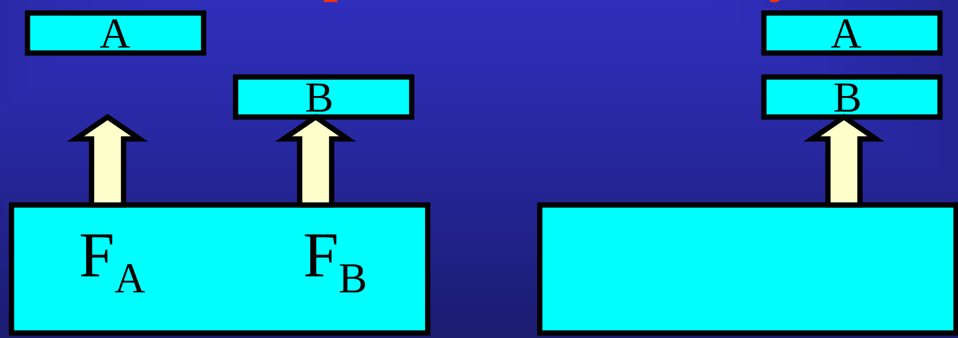
$$V_{vdw} = -\frac{B}{r^6}$$

$d_2 > c\,\tau$

$$V_{retarded\ vdw} = -\frac{B'}{r^7}$$

retardation effects: finite propagation speed of light

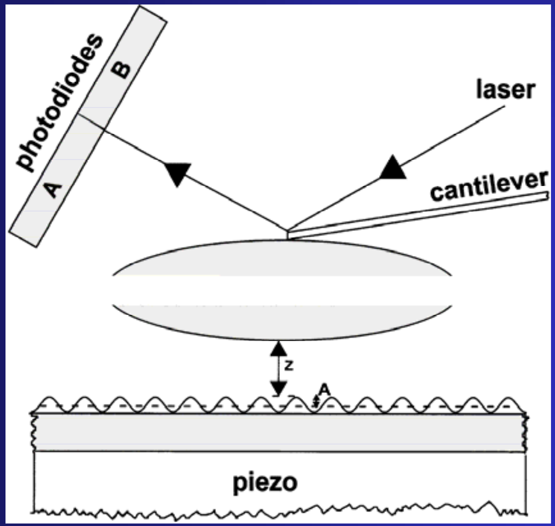
Non-pairwise additivity



$F_{total} \sim F_A + F_B$ $\qquad$ $F_{total} \neq F_A + F_B$

Casimir force measurements on deformed surfaces

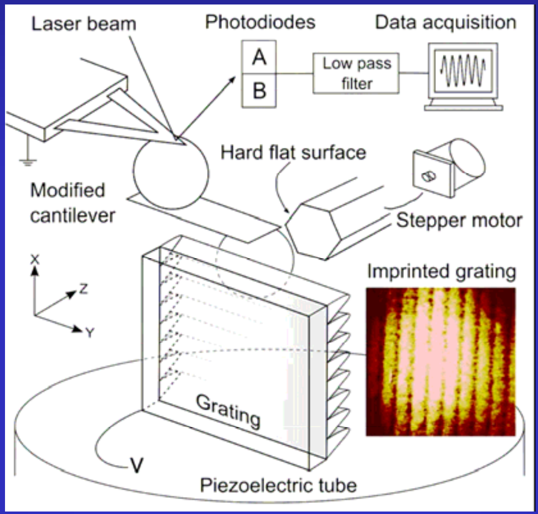
UC Riverside



Roy & Mohideen, 1999.

Normal force on sinusoidal corrugations

UC Riverside

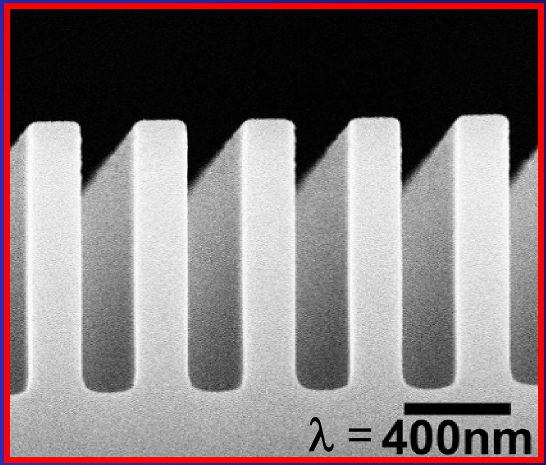


Chen et al., 2002.

Chiu et al., 2009.

Lateral force on sinusoidal corrugations

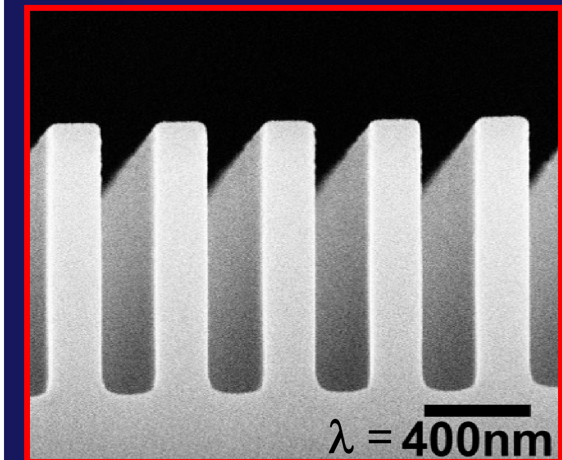
University of Florida

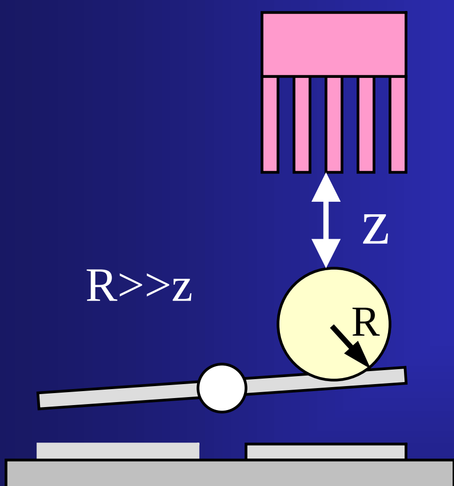


Chan et al., 2008.

Normal force on deep rectangular corrugations

Non-trivial boundary dependence of the Casimir force



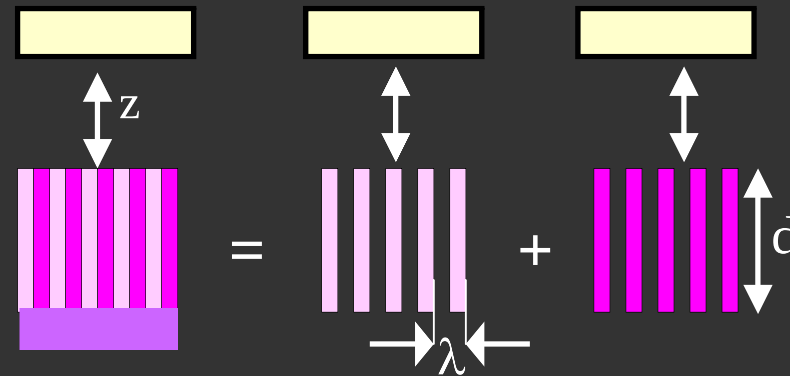


Chan et al., PRL 101, 030401 (2008).

Pairwise additive approximation (PAA)

If d>>z, for all λ,

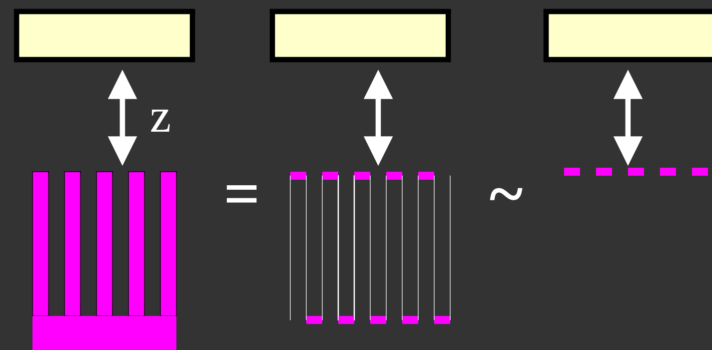
$F_{corrugated}(z) = ½ F_{flat}(z)$



Proximity force approximation (PFA) (Derjaguin approx)

If d>>z, for all λ,

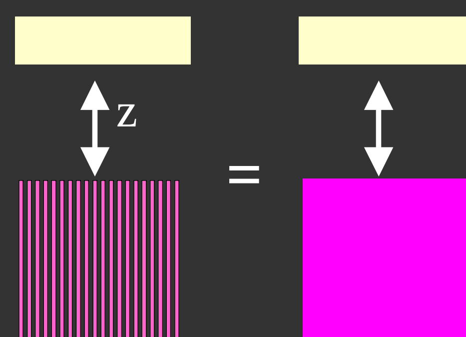
$F_{corrugated}(z) = ½ F_{flat}(z)$



Casimir force for perfect metal

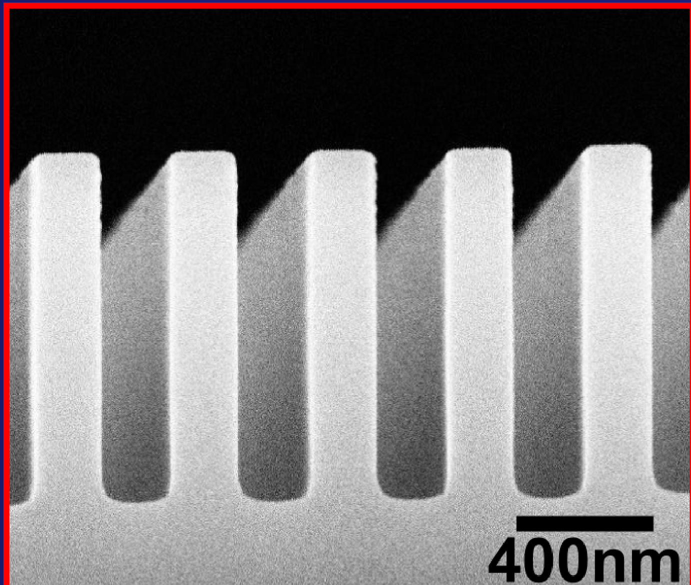
for λ << z,

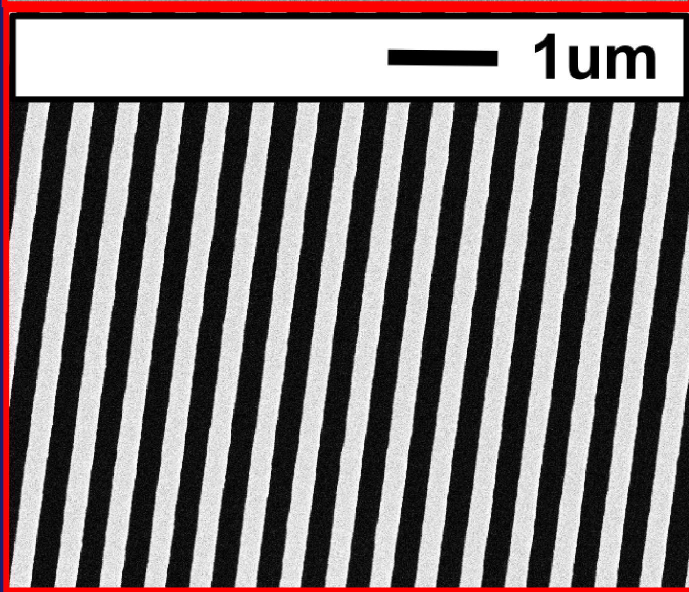
$F_{corrugated}(z) = F_{flat}(z)$

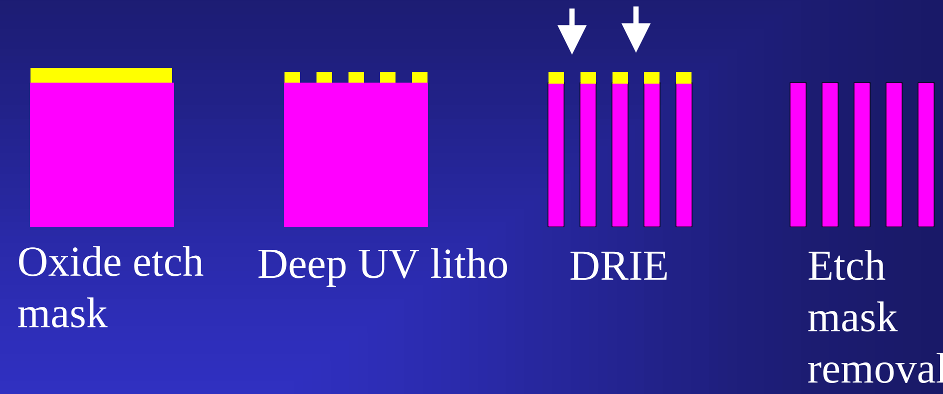


Buscher & Emig, PRA **69**, 062101 (2004).

Sample fabrication and characterization





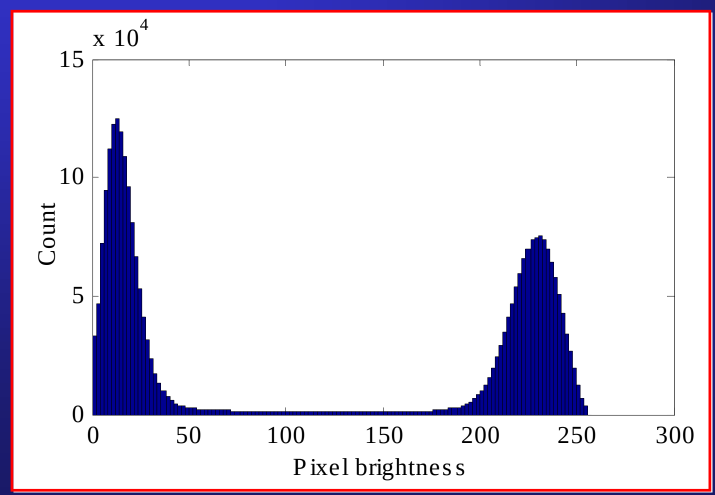


Solid fraction p = 0.51+ 0.001

histogram of pixel brightness in top view

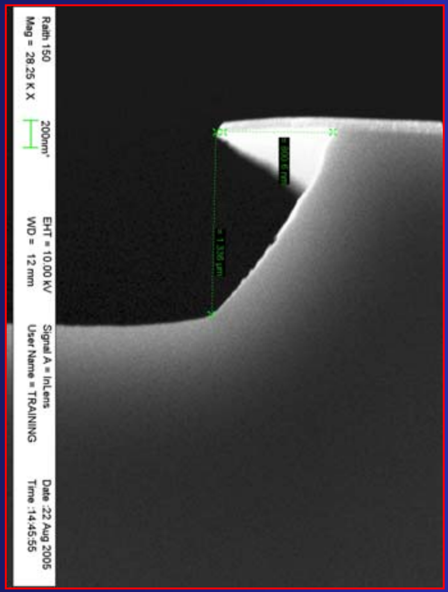
average from 10 pictures

Depth = 1.07 um

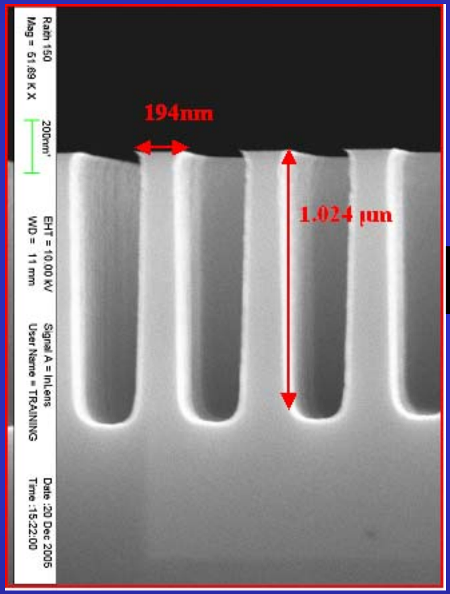


Developing etching recipe for vertical sidewalls

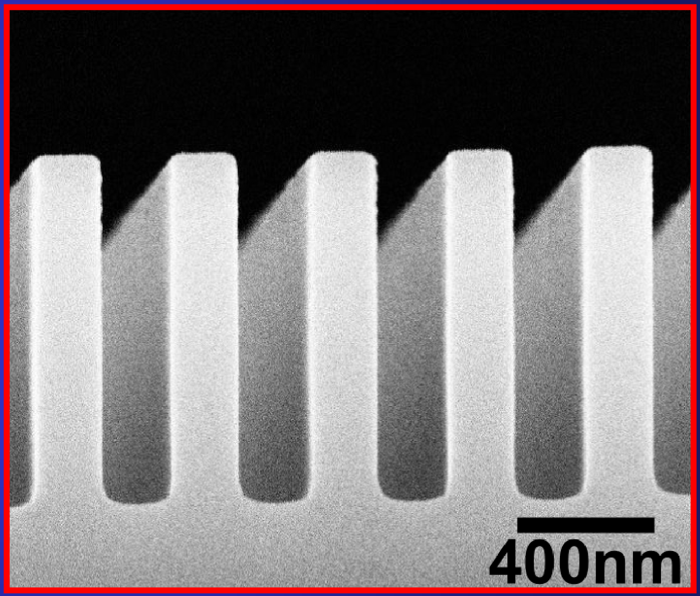
1st week



4 months

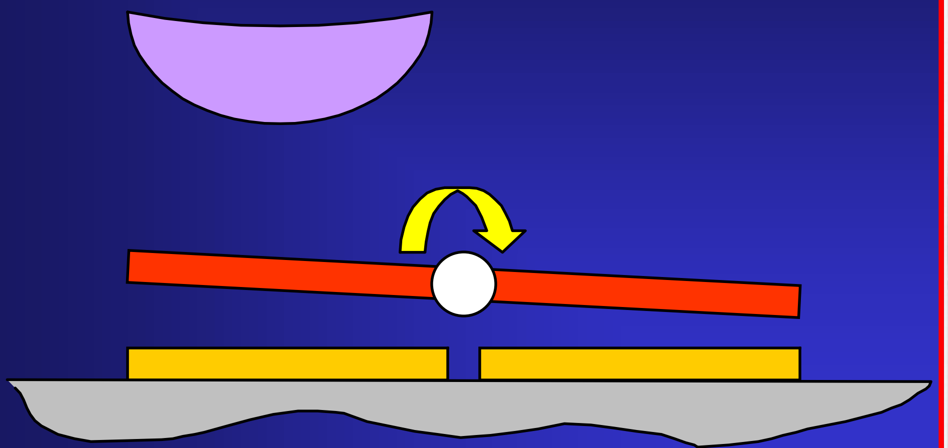


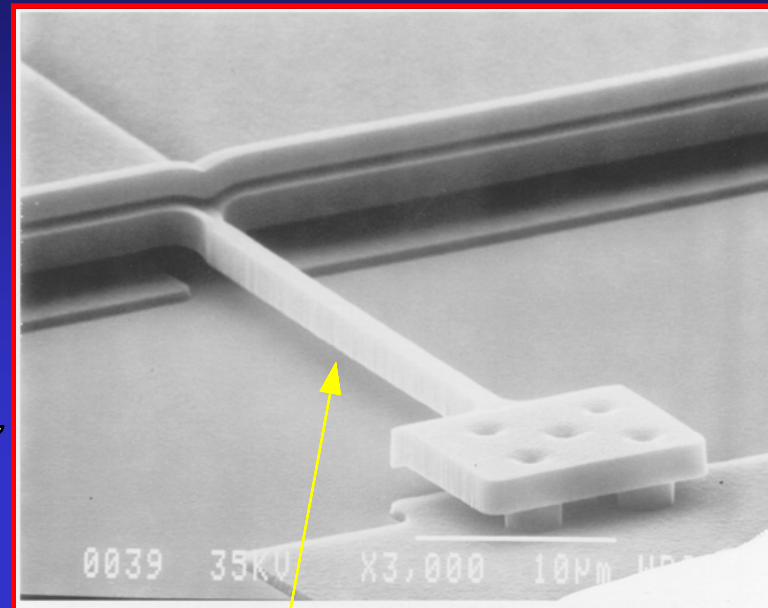
12 months



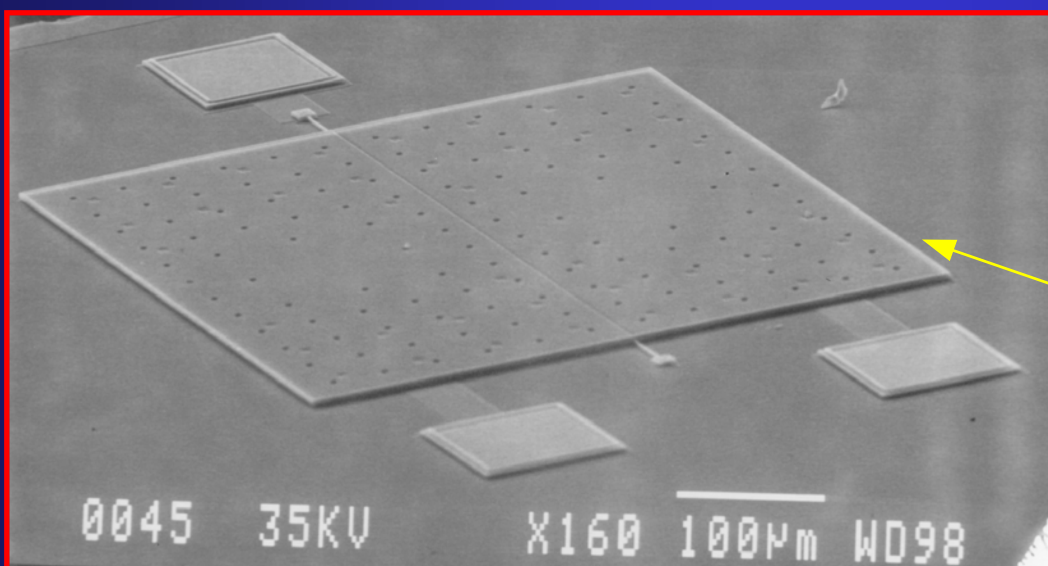
Etching performed by J. Zou and Y. Bao at University of Florida Nanofabrication Facility

Micromechanical torsional oscillator





Torsional rod
cross section: 1.5 x 2 μm^2

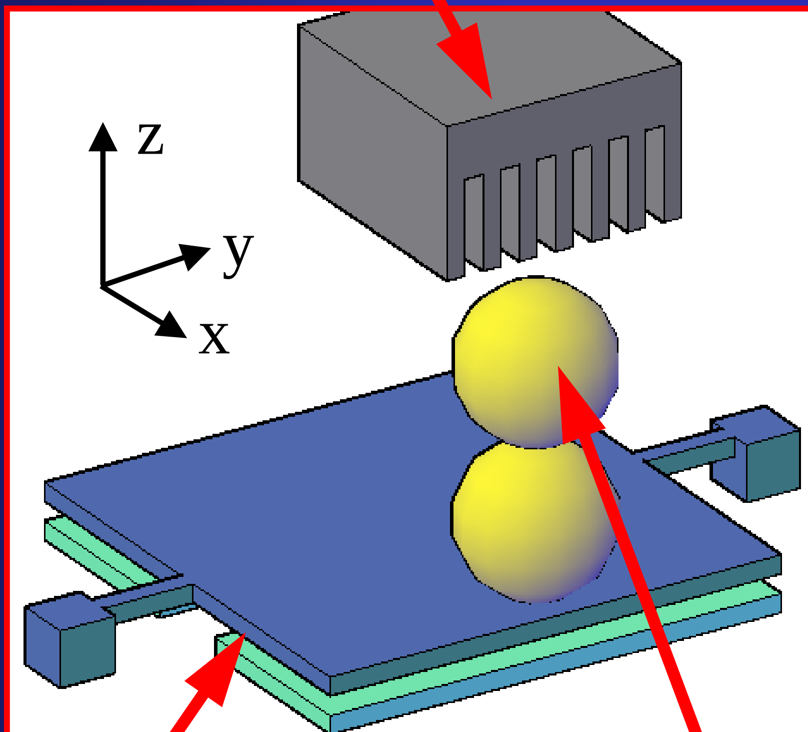


poly-Si plate:
500 μm x 500 μm x 3.5 μm

Experiment setup

Sample orientation eliminate lateral motion.

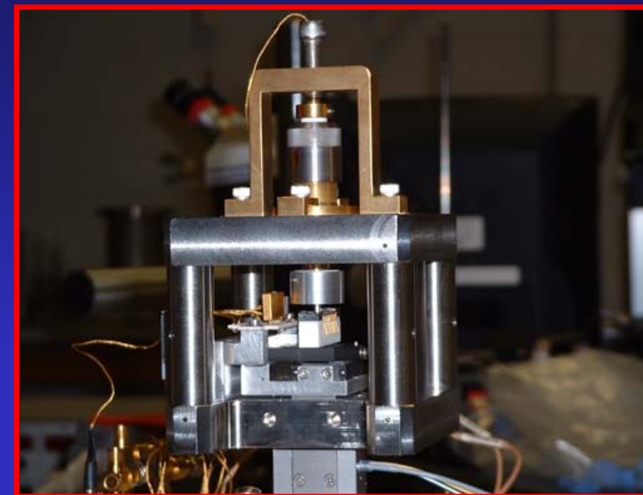
Immediately before pump down
HF remove native oxide layer, hydrogen termination of the surface



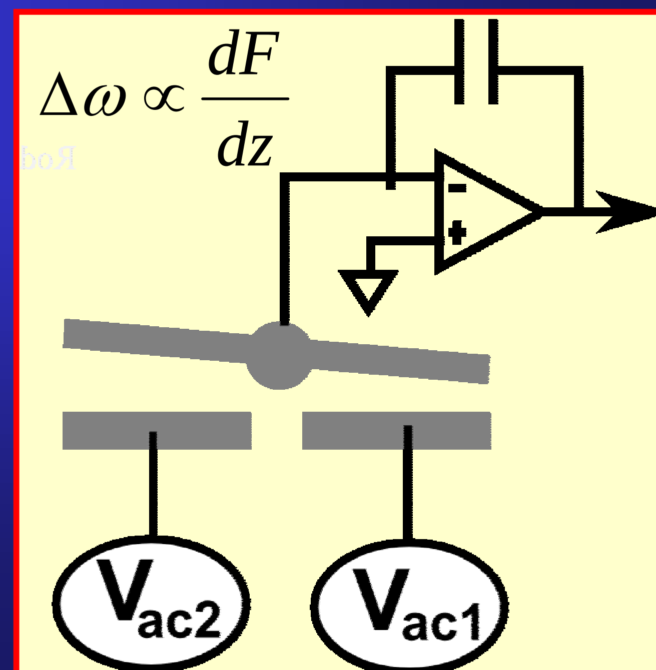
poly-Si plate:
500 µm x 500 µm x 3.5 µm

Glass sphere: d~100µm

Sputtering: 400nm gold



~ 1 nm/ hour drift in z



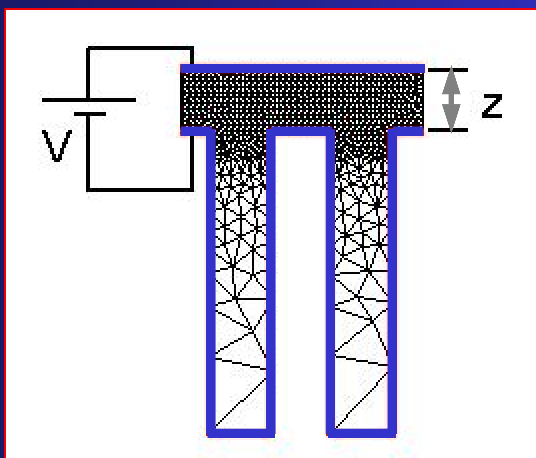
Calibration by electrostatic force

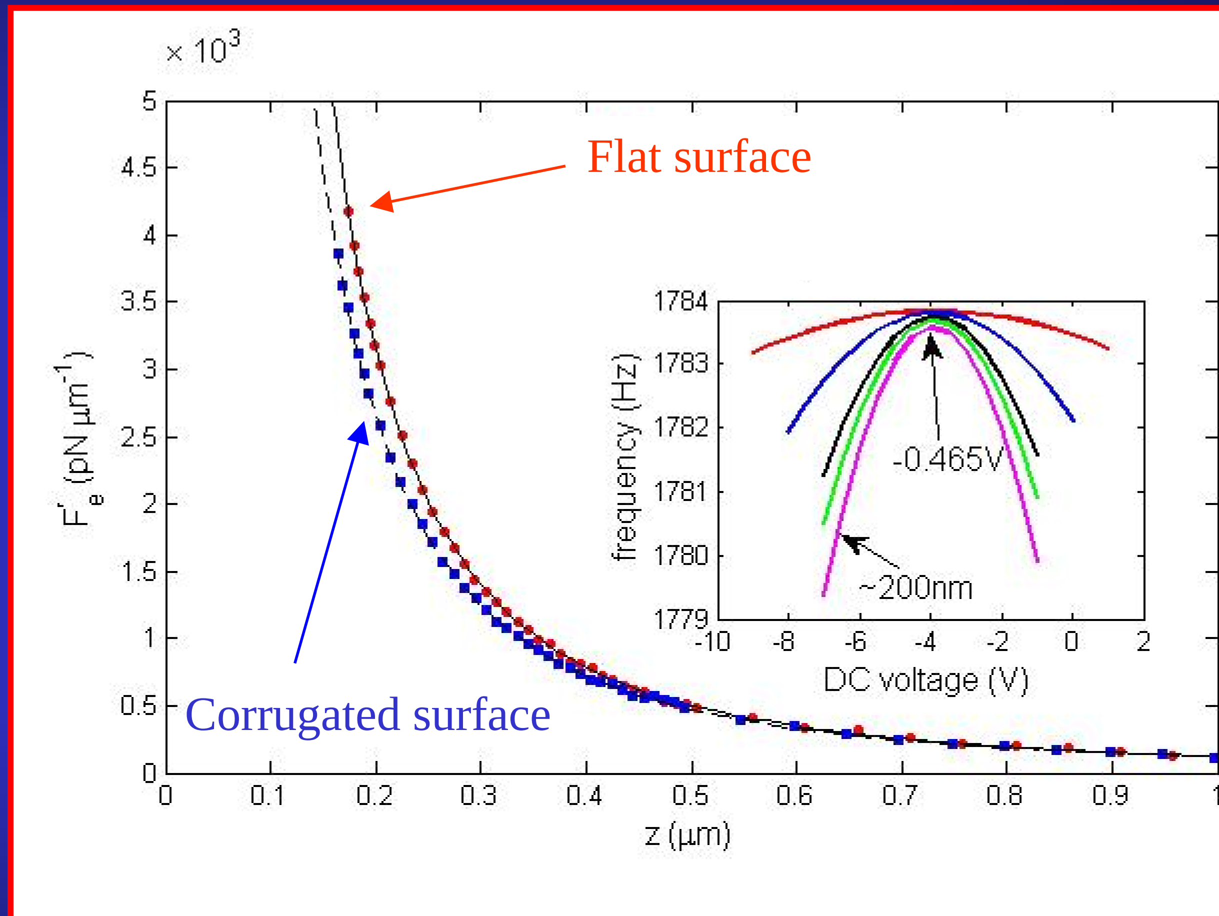
Flat surface

$$F_e^{'} = \varepsilon_0 \pi R \frac{(V - V_0)^2}{(z + z_0)^2}$$

V_0: residual voltage
z_{0}: closest approach distance

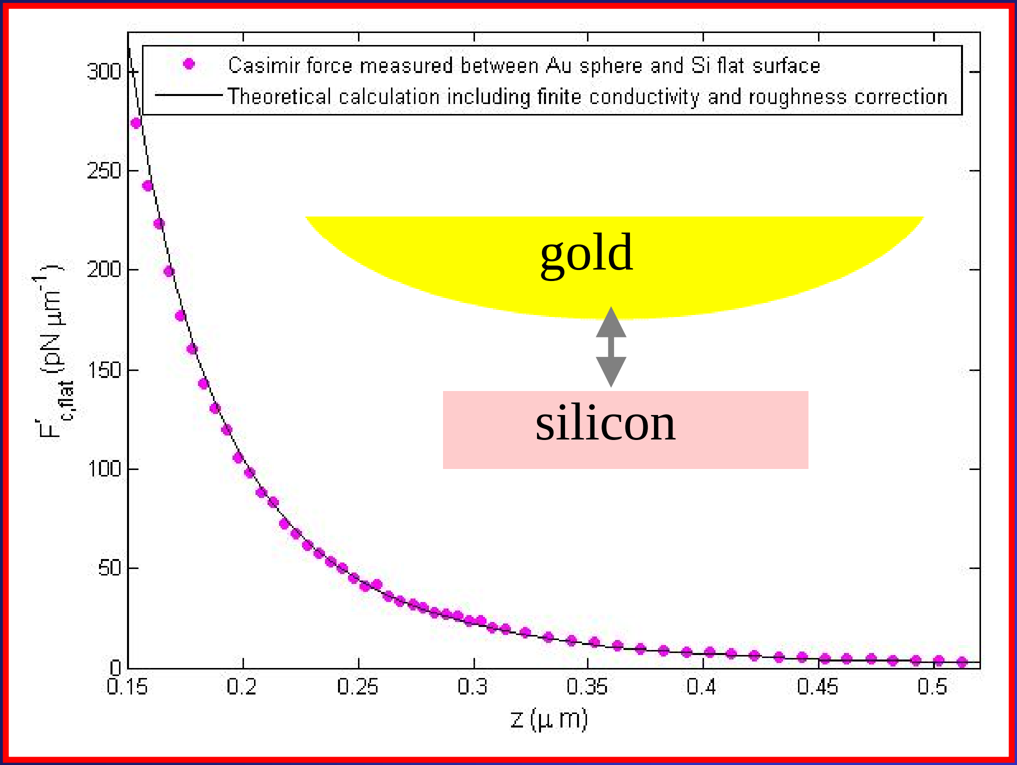
Corrugated surface



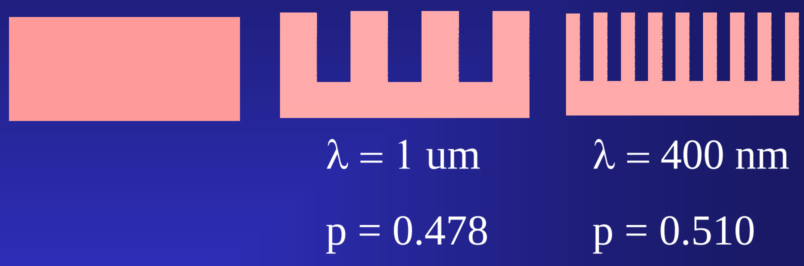


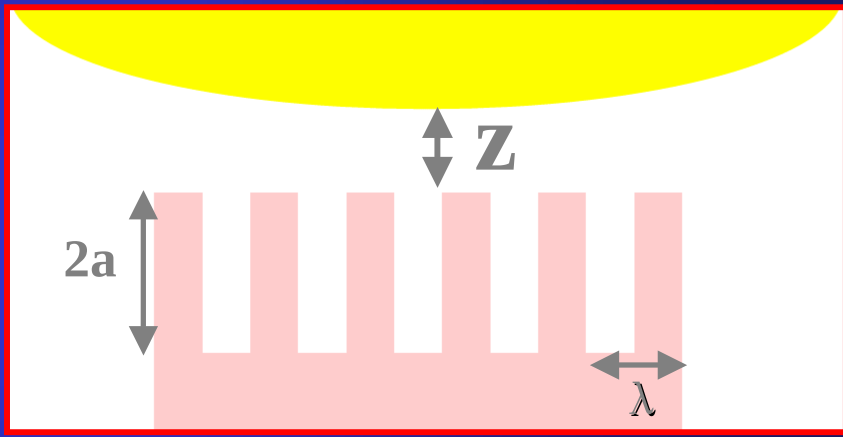
- Finite element analysis to solve 2D Poisson equation: N >10 000 triangles
- Check convergence: double N changes force by 0.1%
- Proximity force approximation: $F_{sphere\text{-}corrugate} = 2 \pi R E_{flat\text{-}corrugate}$

Casimir force measurements



3 samples made from the same silicon wafer





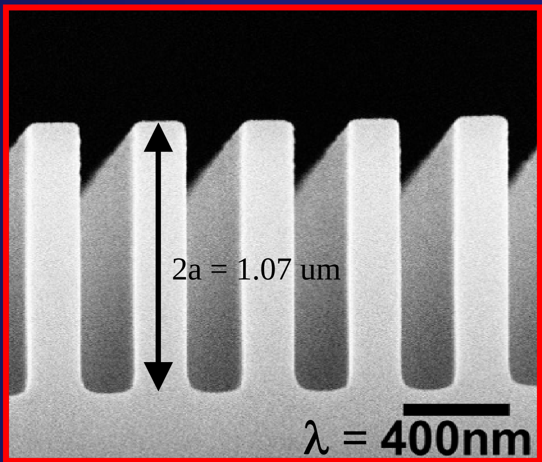
Pairwise additivity: $F_{c,trench} = \frac{1}{2} F_{c,\,flat}$ For all λ

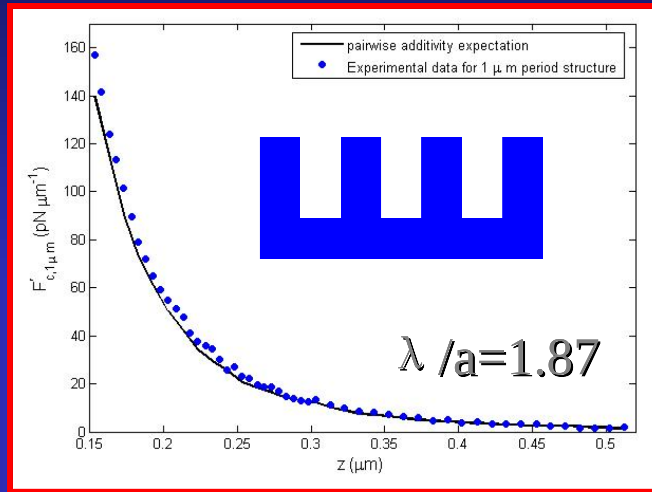
For solid fraction p: $F_{c,trench} = pF_{c,\,flat}$ For all material

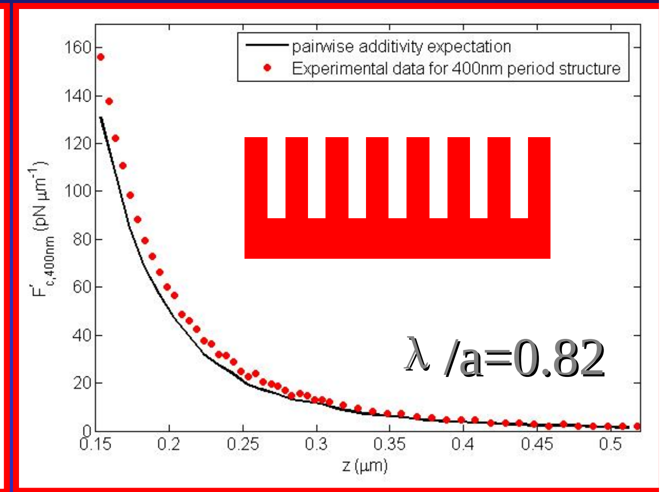
Any deviation of measured force on corrugation from $pF_{c,\,flat}$

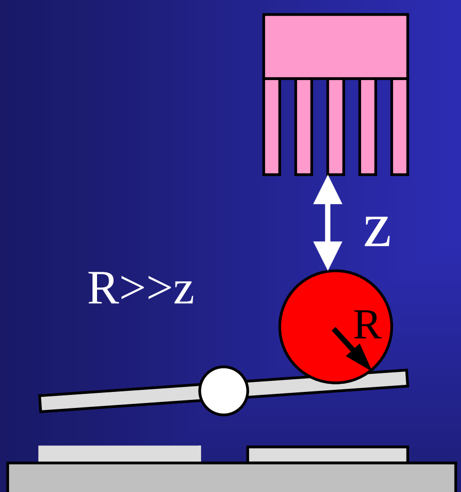
➔ deviation from pairwise additivity (dependence of Casimir force on geometry)

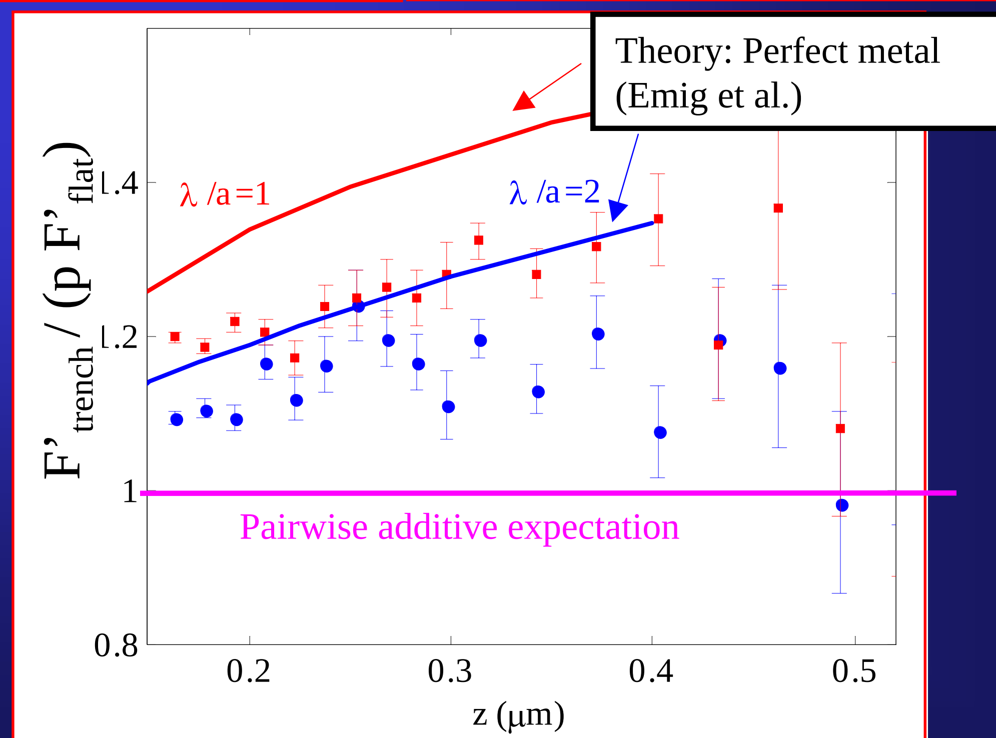
Non-trivial boundary dependence of the Casimir force





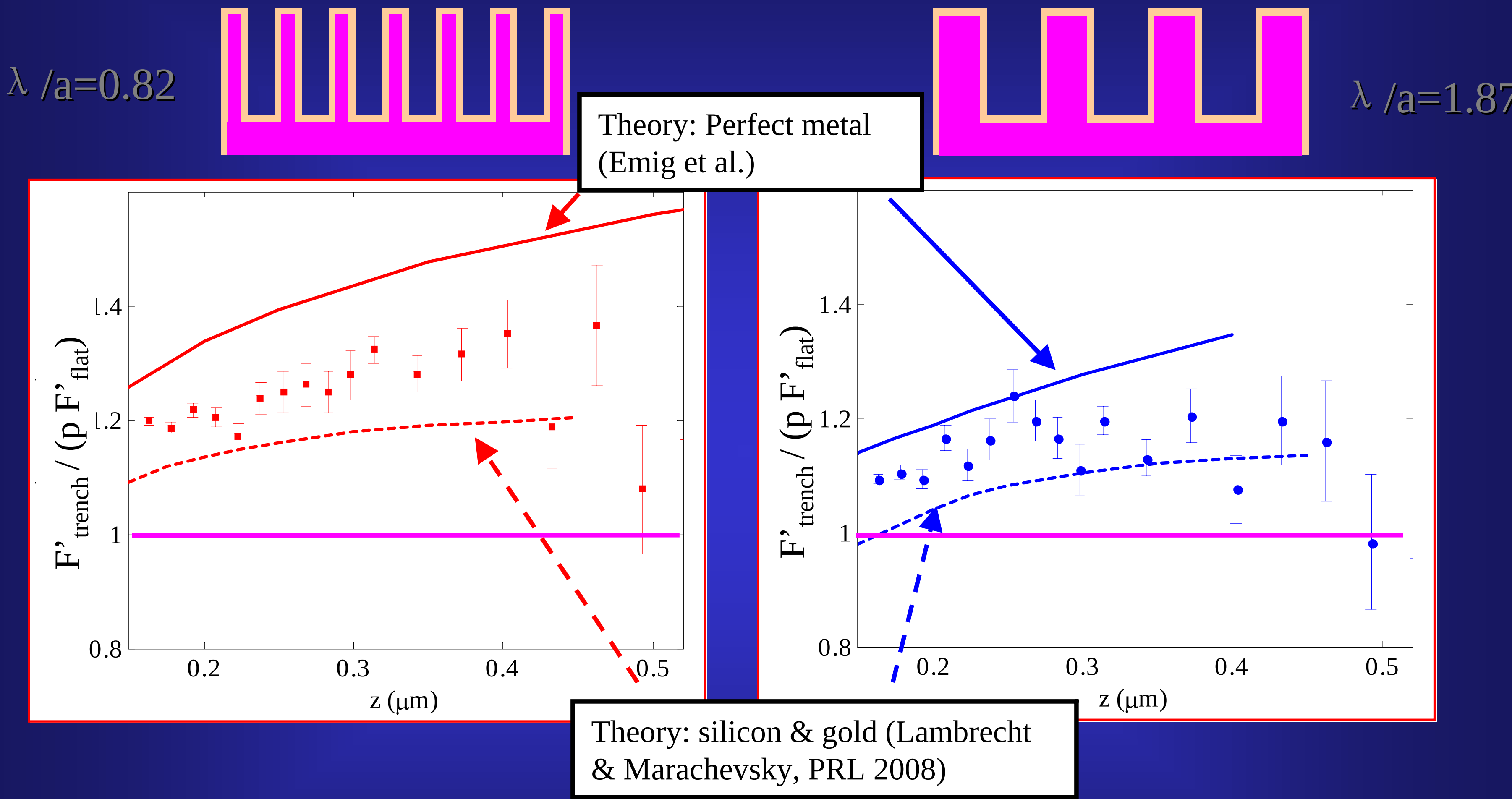






Chan *et al*., PRL 101, 030401 (2008).

Interplay of finite conductivity and geometry effects



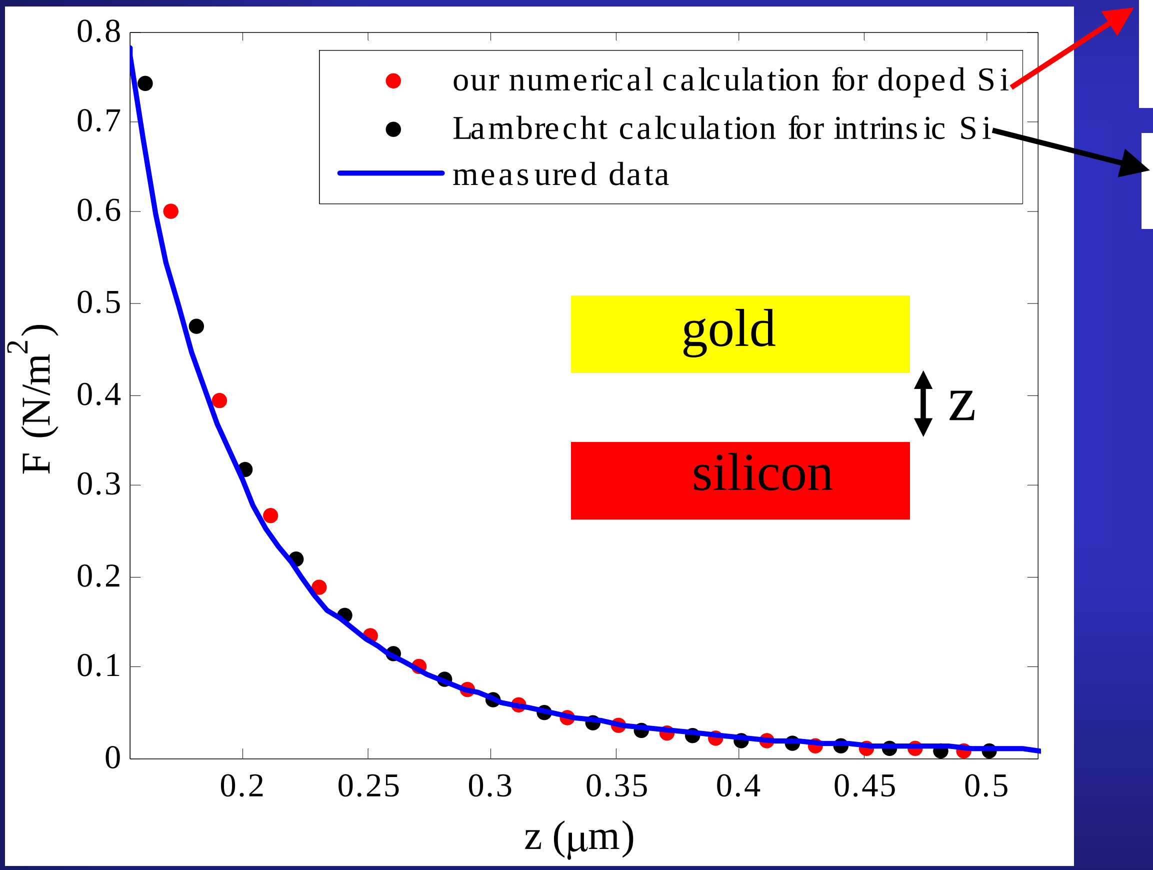
Lambrecht & Marachevsky 2008: includes both finite conductivity and geometry effects.

Using scattering theory.

Possible reason for discrepancy:

uncertainties in the optical properties of gold and silicon

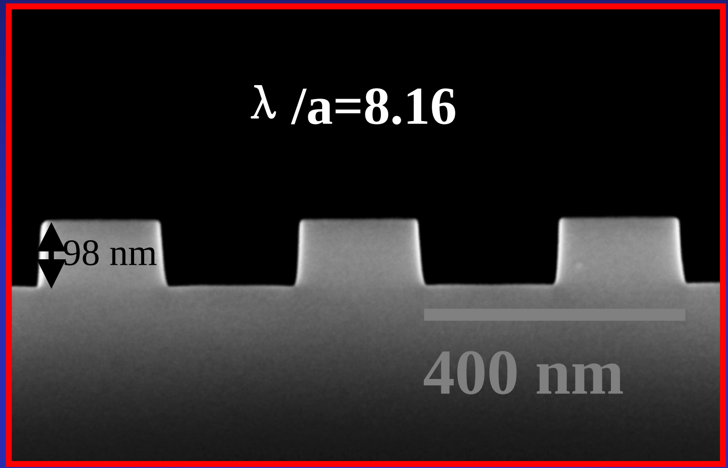
Consistency of measured force on flat plate with optical properties

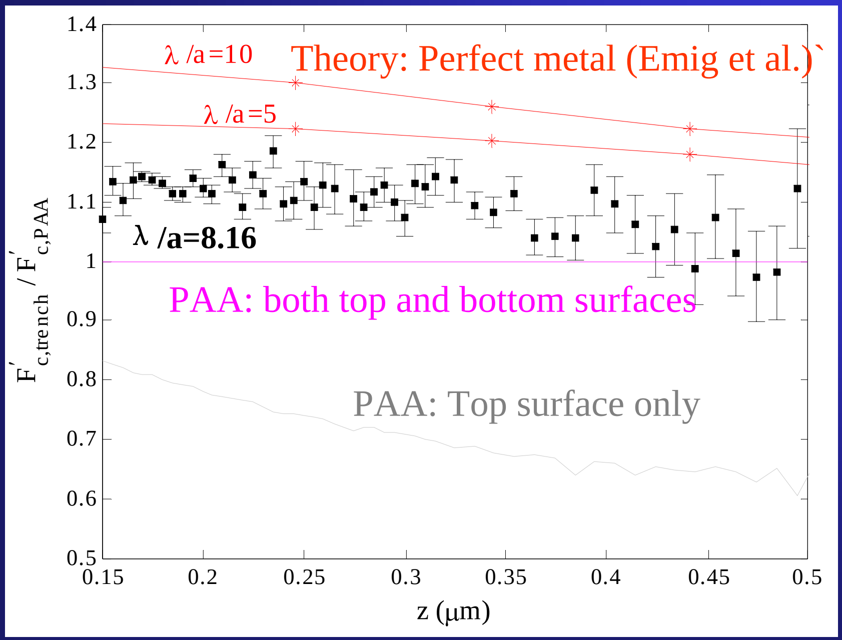


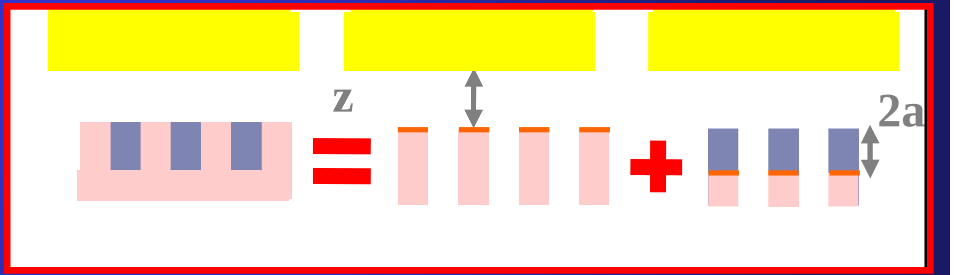
Tabulated ε from Palik, modified by doping in silicon: $\varepsilon_{silicon}(i\xi) = \varepsilon_{undoped}(i\xi) + \frac{\omega_p^2}{\xi(\xi+\gamma)}$

Plasma model for gold, Drude-Lorentz model for intrinsic silicon

New experimental results: shallow trench arrays



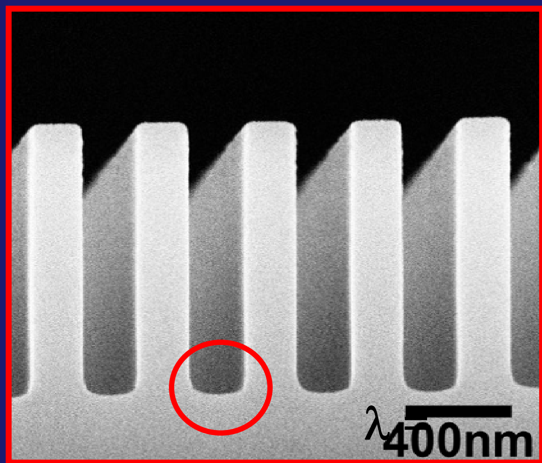




For both PAA and PFA:

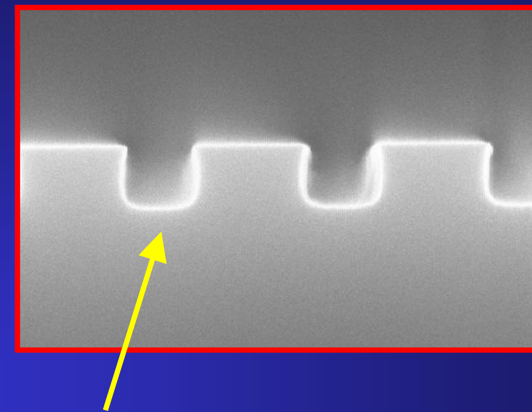
$$F_{c,trench}(z) = pF_{c,flat}(z) + (1-p)F_{c,flat}(z+2a)$$

Fabrication of shallow trench arrays

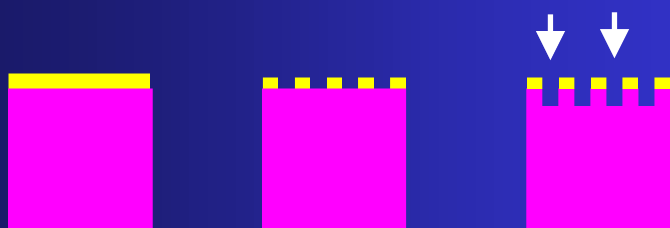


DRIE C_4F_8 + SF_6

Reduce etching time



Rounded bottom

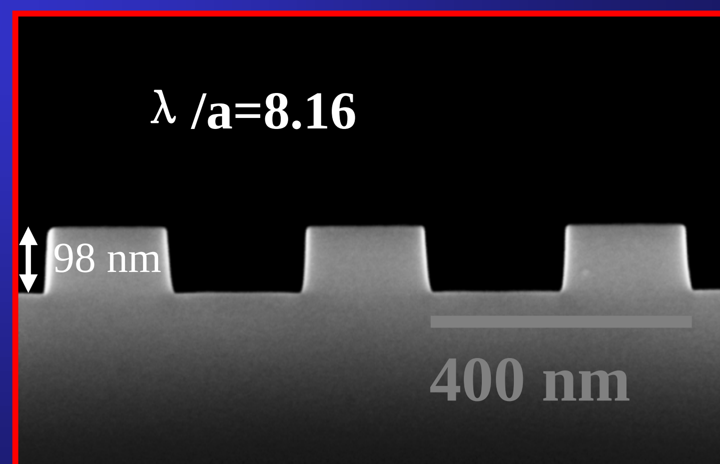


Oxide etch mask

Deep UV litho

RIE

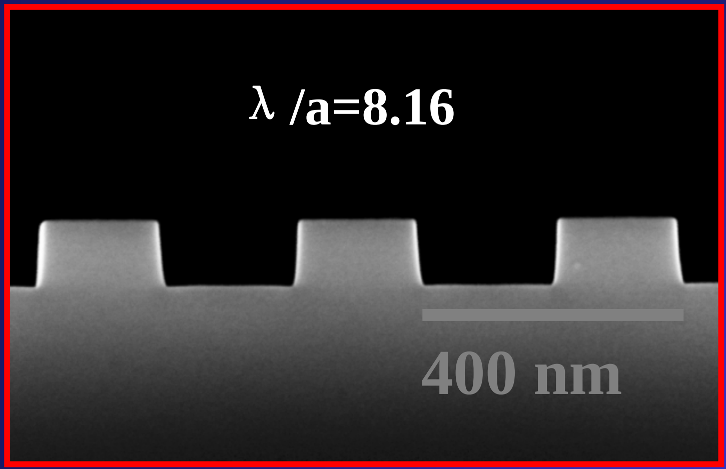
Etch mask removal

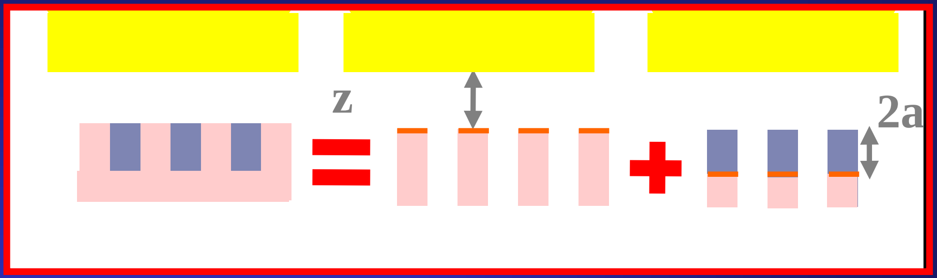


Modified etching recipe

(ICP Ar + SF_6) to attain flat lower surface

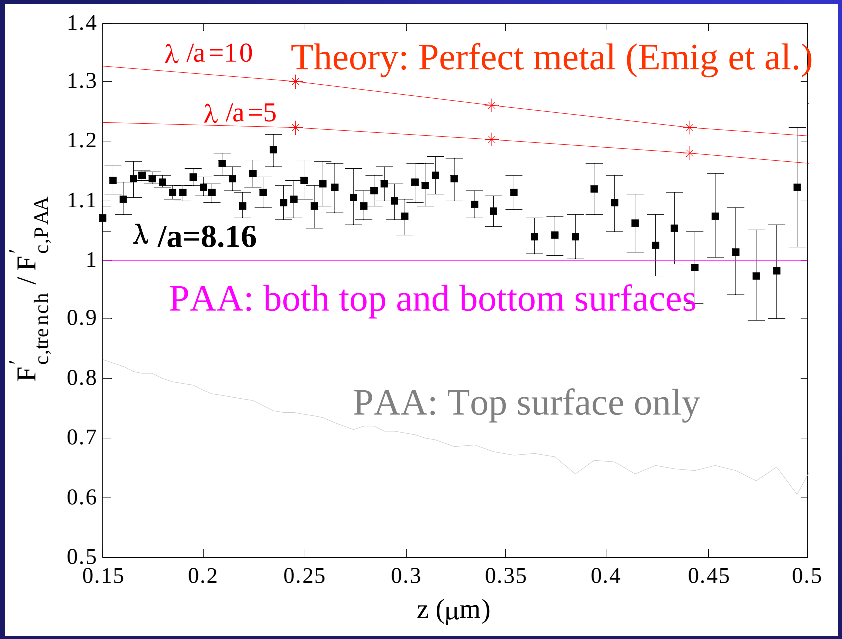
PAA and PFA in shallow trench arrays





Pairwise additive approx (PAA)/proximity force approx (PFA):

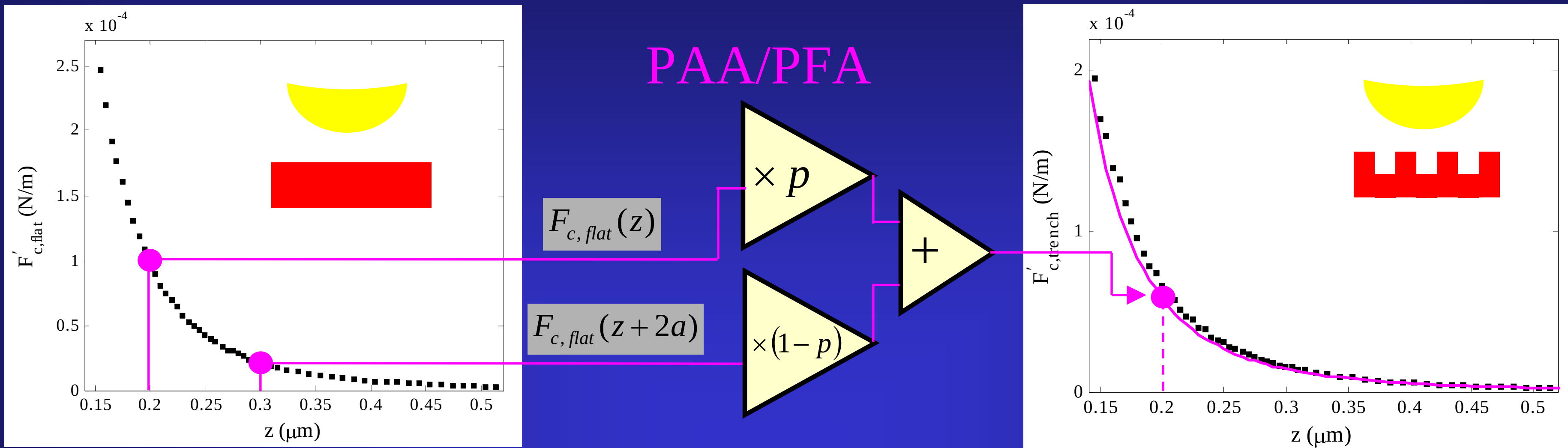
$$F_{c,trench}(z) = pF_{c,\,flat}(z) + (1-p)F_{c,\,flat}(z+2a)$$

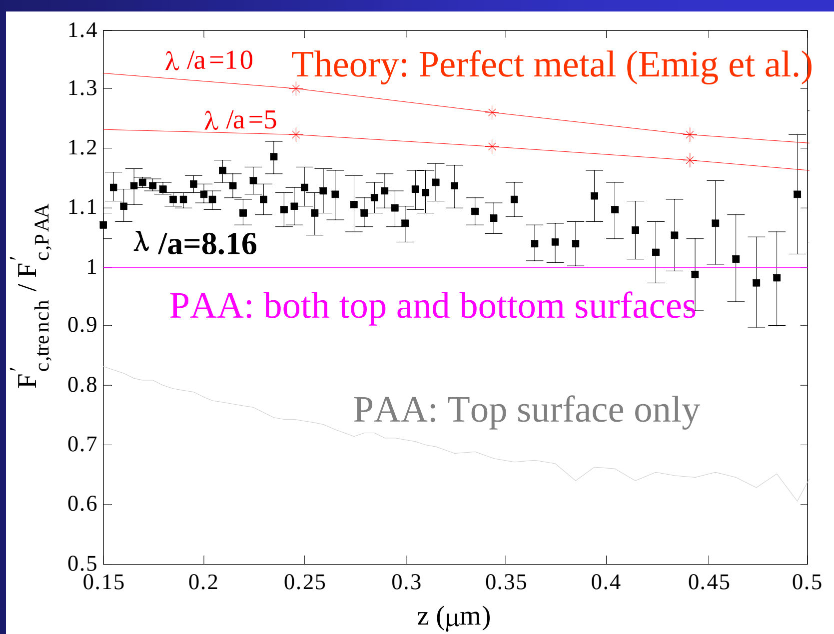


Contribution of bottom surface not negligible

Easier for comparison to theory (perturbative approaches)

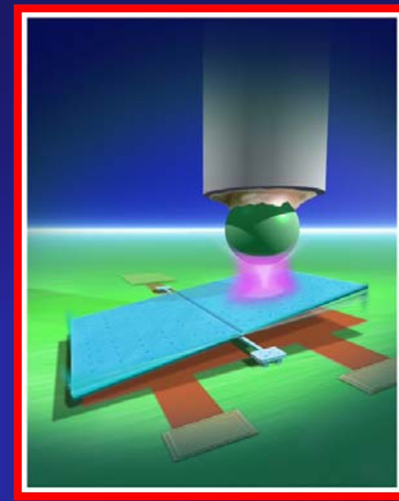
New experimental results: shallow trench arrays





Ongoing collaboration with Emig, Hanke and Johnson in calculating the Casimir force including finite conductivity.

Summary



- Experiment on strongly deformed surface:

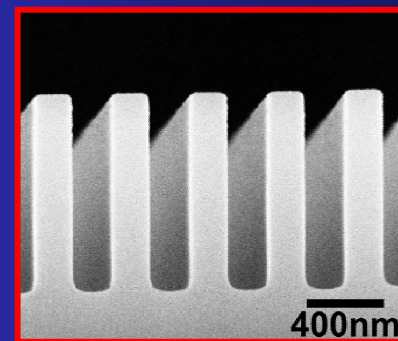
  Measure Casimir force on an array of nanoscale trenches with a micromechanical torsional oscillator

  Up to 30% deviation from PFA and PAA

  Evidence of non-trivial boundary dependence of the Casimir force

  ~ 30% smaller than theory on perfect metals

  ~ 30% higher than theory on gold/silicon



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DE-FG02-05ER46

DMR-0645448