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

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September 29th, 2009. Casimir force control, Santa Fe, NM.
Reducing the effective area of interaction

\[ F_{\text{Casimir}} = -\frac{\pi^2 \hbar c A}{240} \frac{1}{d^4} \]

\[ F_{\text{Casimir}} = -\frac{\pi^3 R \hbar c}{360} \frac{1}{d^3} \]

Dimples to minimize stiction

\[ F_{\text{casimir}} = \frac{1}{2} F_{\text{flat}}? \]
\[ F_{\text{casimir}} > \frac{1}{2} F_{\text{flat}}? \]
\[ F_{\text{casimir}} < \frac{1}{2} F_{\text{flat}}? \]
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  UT Brownsville  Bell Labs
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Geometry dependence of the Casimir force

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

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

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

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

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

 retardation effects: finite propagation speed of light

\[ d_1 < c \tau \]

\[ d_2 > c \tau \]

Non-pairwise additivity

\[ F_{total} \sim F_A + F_B \]

\[ F_{total} \neq F_A + F_B \]
Casimir force measurements on deformed surfaces

Normal force on sinusoidal corrugations

Chen et al., 2002.
Chiu et al., 2009.

UC Riverside

University of Florida

Chan et al., 2008.
Normal force on deep rectangular corrugations
Non-trivial boundary dependence of the Casimir force

Pairwise additive approximation (PAA)
If $d \gg z$, for all $\lambda$,
$$F_{\text{corrugated}}(z) = \frac{1}{2} F_{\text{flat}}(z)$$

Proximity force approximation (PFA) (Derjaguin approx)
If $d \gg z$, for all $\lambda$,
$$F_{\text{corrugated}}(z) = \frac{1}{2} F_{\text{flat}}(z)$$

Casimir force for perfect metal
For $\lambda \ll z$,
$$F_{\text{corrugated}}(z) = F_{\text{flat}}(z)$$

Chan et al., PRL 101, 030401 (2008).
Buscher & Emig, PRA 69, 062101 (2004).
Sample fabrication and characterization

Solid fraction $p = 0.51 \pm 0.001$

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

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

Torsional rod cross section: 1.5 x 2 µm²
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

$\Delta \omega \propto \frac{dF}{dz}$

$~1 \text{ nm/ hour drift in } z$
Calibration by electrostatic force

Finite element analysis to solve 2D Poisson equation: $N > 10000$ triangles
- Check convergence: double $N$ changes force by 0.1%
- Proximity force approximation: $F_{sphere-corrugate} = 2 \pi R E_{flat-corrugate}$

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

$V_0$: residual voltage
$z_0$: closest approach distance

Flat surface

Corrugated surface

Flat surface

Corrugated surface
Casimir force measurements

Pairwise additivity:

For solid fraction $p$:

$$F_{c,trench} = p F_{c,flat}$$

For all $\lambda$

For all material

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

$\rightarrow$ 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

Theory: Perfect metal (Emig et al.)

Theory: silicon & gold (Lambrecht & Marachevsky, PRL 2008)

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 $\varepsilon$ from Palik, modified by doping in silicon:

$$\varepsilon_{\text{silicon}}(i\xi) = \varepsilon_{\text{undoped}}(i\xi) + \frac{\omega_p}{\xi(\xi + \gamma)}$$

Plasma model for gold, Drude-Lorentz model for intrinsic silicon
New experimental results: shallow trench arrays

\[ \lambda /a = 8.16 \]

98 nm

\[ \lambda /a = 8.16 \]

400 nm

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

 Modified etching recipe

(ICIAr + SF₆) to attain flat lower surface
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

PAA/PFA

\[ F_{c,\text{flat}} (z) \times p \]

\[ F_{c,\text{flat}} (z + 2a) \times (1 - p) \]

\[ \text{Theory: Perfect metal (Emig et al.)} \]

\[ \text{PAA: both top and bottom surfaces} \]

\[ \text{PAA: Top surface only} \]

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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