Casimir actuation between real materials towards chaotic behavior

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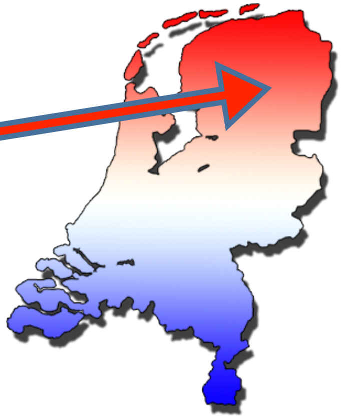
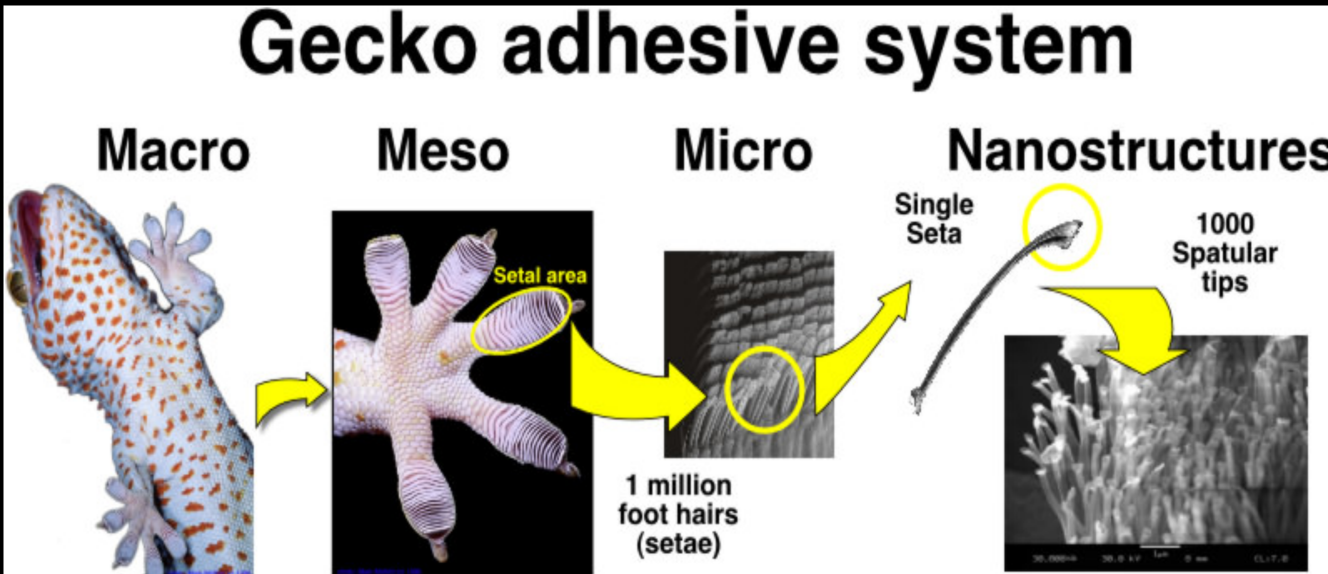
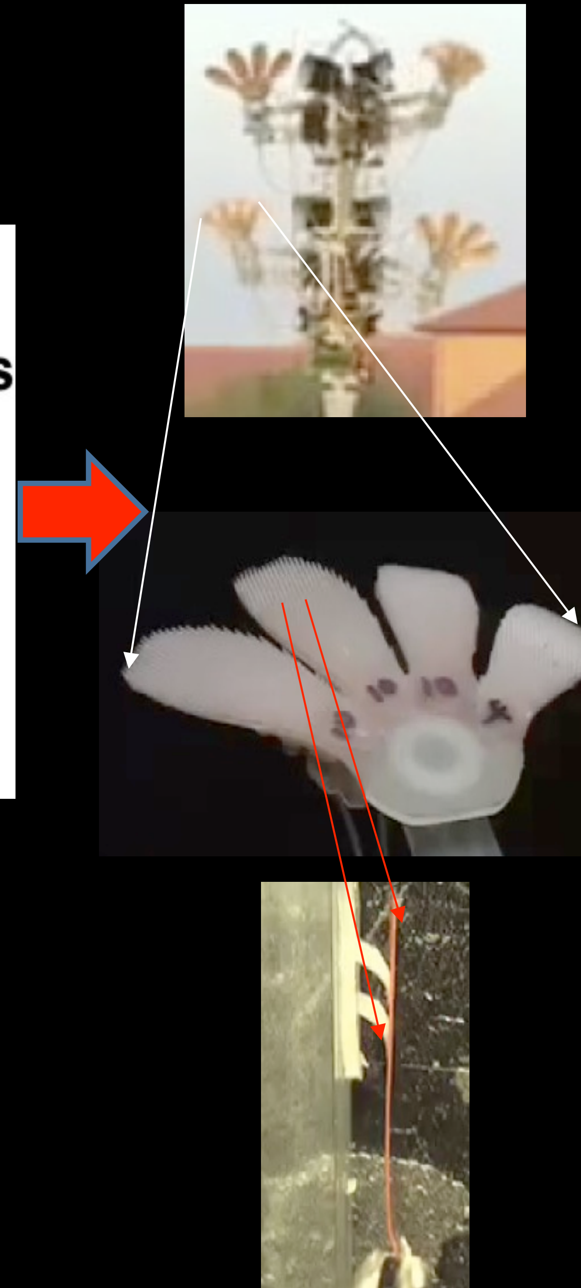


Nature inspires .....!





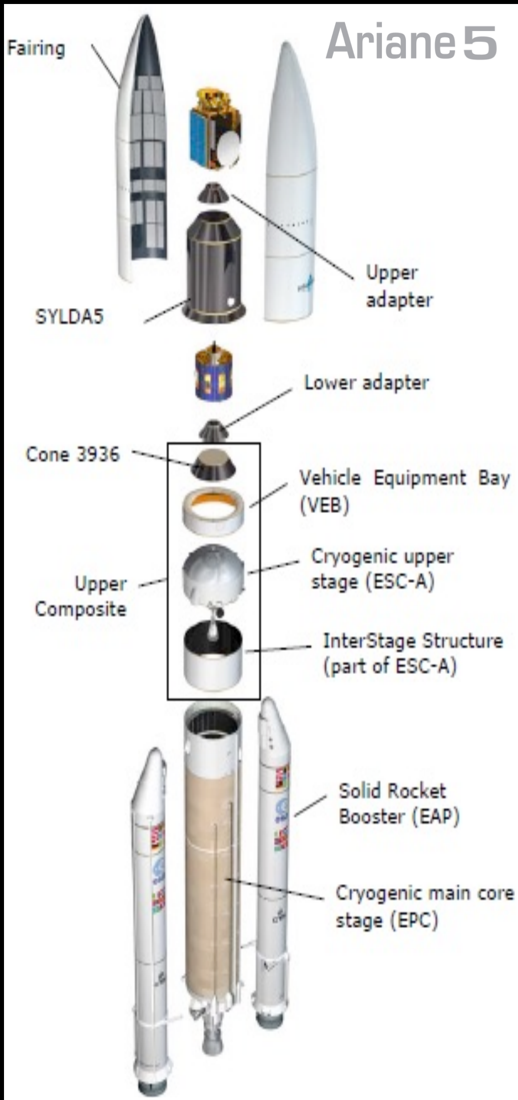
Stickybot

Z-MAN project DARPA (Army):

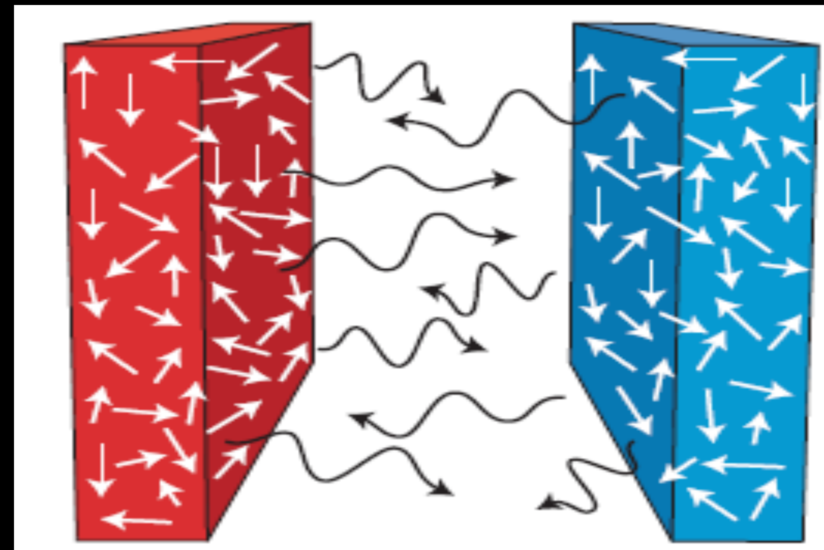
Demo 2012: 16-inch^2 Geckskin → support ~660 pounds

NASA: clean the trash in space

Gecko Gripper sticking power is not affected by temperature, pressure, or radiation



PAYLOAD FAIRING	
Diameter	5.4 m
Height	17 m
Mass	2675 kg



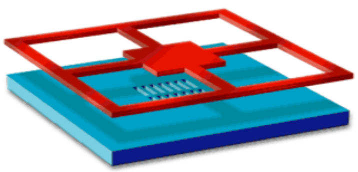
A. W. Rodriguez et al. Nature Photonics (2011)

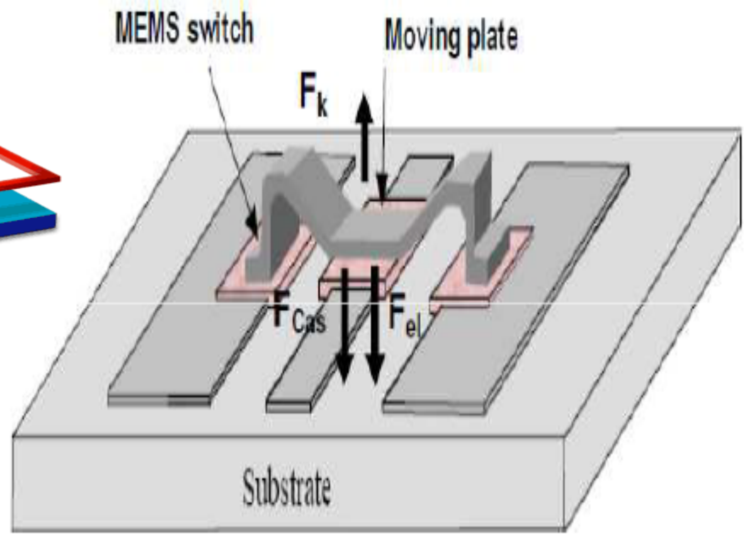
Interaction area ~1 m^2 →

$F_{cas/vdW}$~5x10^4N ? 5 tons!

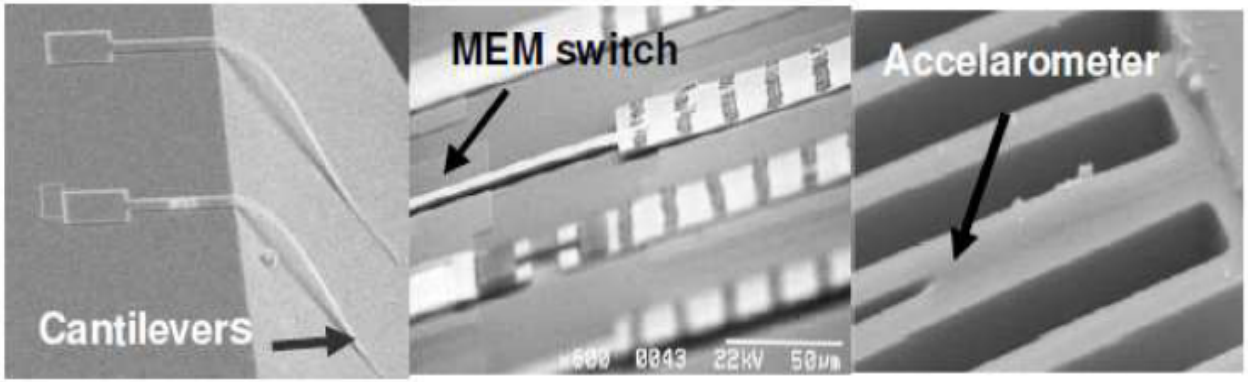
Broer, PRB (2013)

MEMS/NEMS devices ….!





Casimir force is always there



MEMS examples with stiction problems between components as the arrows indicate

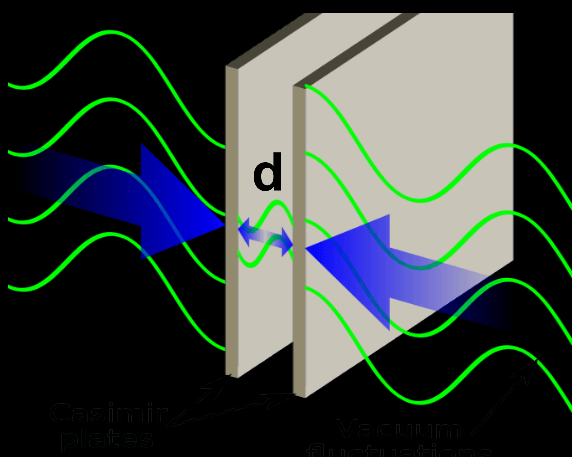
1→Casimir /vdW – Lifshitz Force...

QED says vacuum is full with fluctuating fields: ***"vacuum fluctuations"***

virtual photons

H. Casimir (1948) ....Perfectly reflecting plates

1909-2000

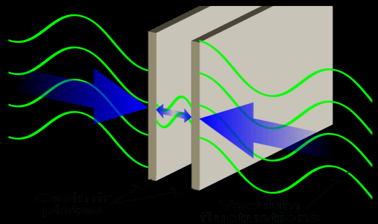


For a pair of parallel plates the force is described by:

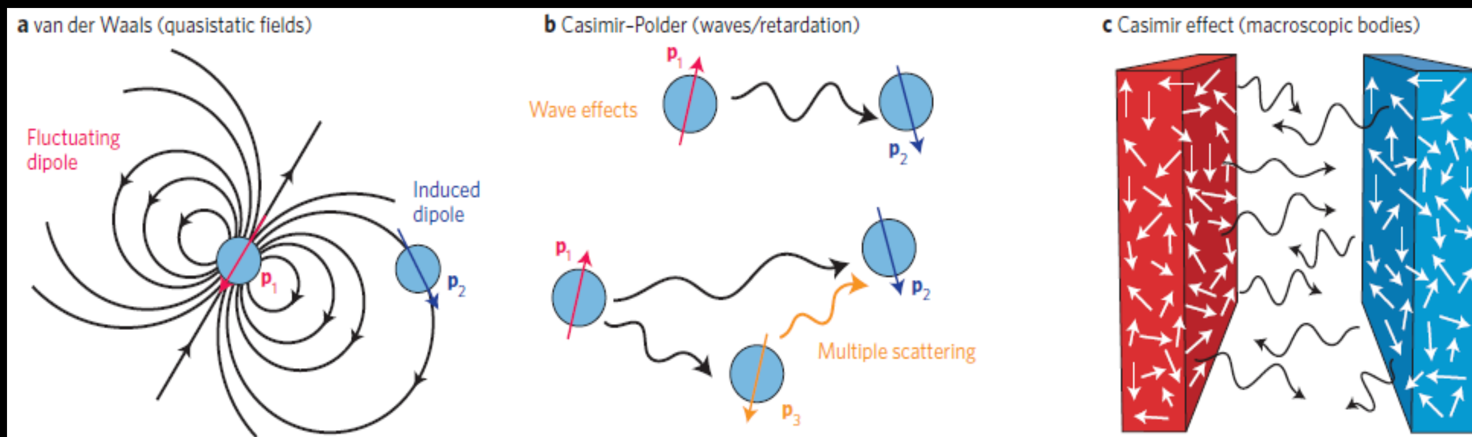
$$F = \frac{\pi^2}{240}\frac{\hbar c}{d^4}A$$

c is the speed of light,
d the plate spacing
and A the plate surface area.

First high accuracy measurement in 1997 by S. Lamoreaux



No perfect reflectors in nature → *"real dissipative" matter:* ***Lifshitz theory***



A. W. Rodriguez et al. Nature Photonics (2011)

Fluctuation dissipation theorem **(FDT): fluctuating currents ↔ dissipation**

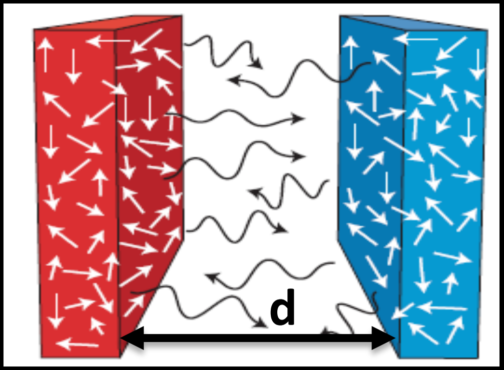
$$\langle J_\alpha(\omega,\mathbf{r})J^*_\beta(\omega',\mathbf{r}')\rangle = \omega\varepsilon''(\omega)\left(\frac{\hbar\omega}{2}+\frac{\hbar\omega}{e^{\hbar\omega/kT}-1}\right)\times\delta(\omega-\omega')\delta(\mathbf{r}-\mathbf{r}')\delta_{\alpha\beta}$$

Im[?(?)]
Dielectric function

Zero-point energy

Thermal fluctuations

vdW ↔ Casimir...



Lifshitz theory covers *vdW (short range)* & *Casimir (long range)* regimes

d < 0.1 ?p?10 nm
vdW (non-retarded) regime

d > 0.1 ?p?20 nm
Casimir (retarded) regime

E.g. plasma wavelength metals ?p ?100-150 nm

…these 'two forces' are ultimately derived from the same cause ……

power laws of the force...

The scaling exponent m of the Casimir force versus separation distance, $F \sim d^{-m}$ for the sphere-plate

Interacting materials/surfaces	Separation range	Exponent m
Au–Au[35]	25–100 nm	$m = 2.5$
Au–Au[38]	160–500 nm	$m = 2.71$
	500–750 nm	$m = 2.84$
	160–750 nm	$m = 2.76$
Au–Au[40]	98–300 nm	$m = 2.79$
	98–200 nm	$m = 2.67$
Ge–Ge[41]	550–1500 nm	$m = 2.84$
Au–ITO[42]	70–200 nm	$m = 2.75$
Au–AIST (A)[43]	55–130 nm	$m = 2.49$
Au–AIST (C)[43]	55–130 nm	$m = 2.43$
Au–Au[43]	55–130 nm	$m = 2.55$
Au–Au[45,46]	65–350 nm	$m = 2.61$
Au–HOPG[45,46]	65–350 nm	$m = 2.67$
Au–Au[47–50]	30–1000 nm	$m = 2.64$

concensus among various groups........!

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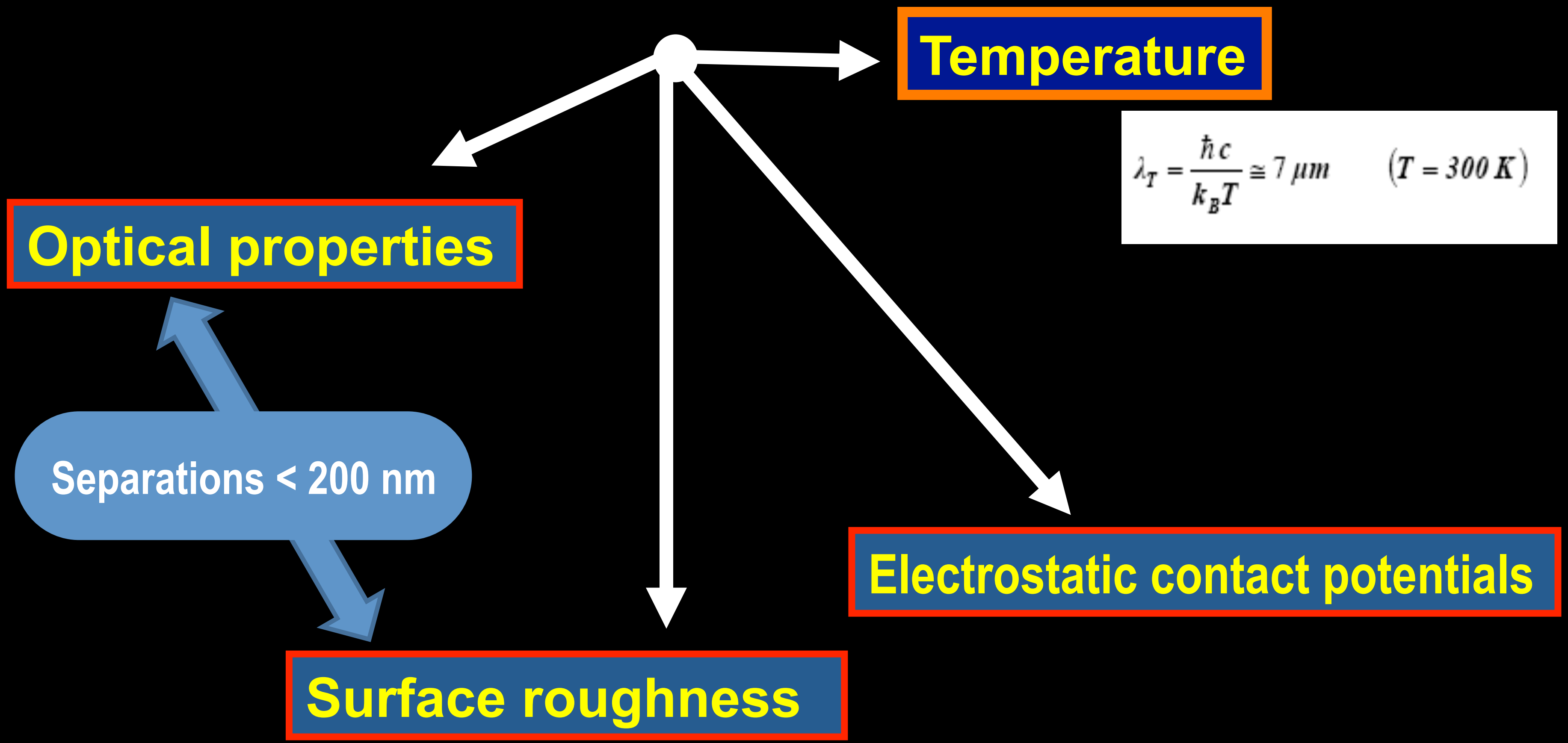
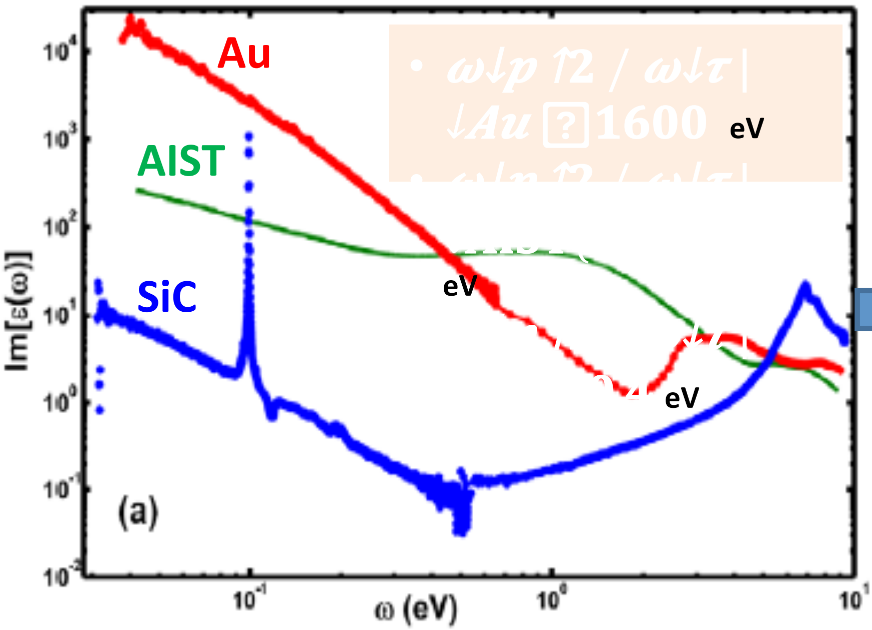
Vol. 24, No. 31 (2010) 6013–6042

Real materials.....



$$\lambda_T = \frac{\hbar c}{k_B T} \cong 7\ \mu m \qquad (T = 300\ K)$$

2→Optical properties…

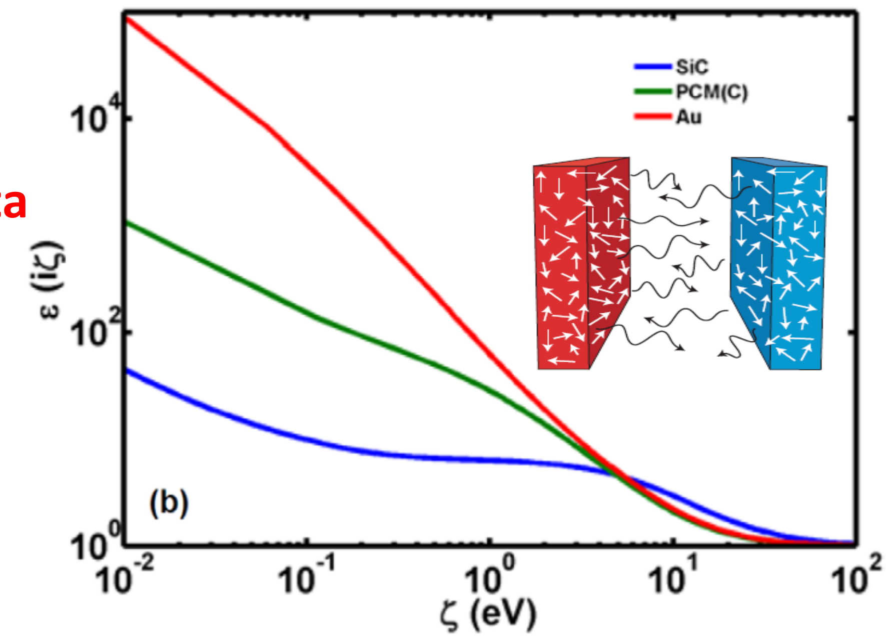


Imaginary part $\varepsilon''(\omega)$ measured with ellipsometry

Wollam , USA

$$\varepsilon(i\zeta) = 1 + \frac{2}{\pi}\int_0^\infty d\omega \frac{\omega\varepsilon''(\omega)}{\omega^2+\zeta^2}$$

dissipation $\sim \varepsilon''(\omega)$ is of principal importance!



Experimental data

$$\varepsilon(i\zeta)_D = 1 + \frac{2}{\pi}\int_{\omega_1}^{\omega_2} \frac{\omega\varepsilon''_{exp}(\omega)}{\omega^2+\zeta^2}d\omega + \Delta_L\varepsilon(i\zeta) + \Delta_H\varepsilon(i\zeta),$$

$$\varepsilon''(\omega) = \frac{\omega_p^2\omega_\tau}{\omega\left(\omega^2+\omega_\tau^2\right)}$$

$$\varepsilon''(\omega) = \frac{A}{\omega^3}.$$

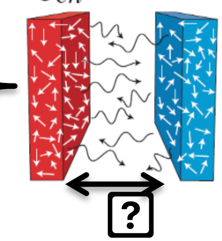
Crusial extraplation to ??0

Material optical properties: Fundamental constraints

Indirect integral dependence on the physical frequency $\varepsilon(i\zeta) = 1 + \frac{2}{\pi}\int_0^\infty d\omega \frac{\omega\varepsilon''(\omega)}{\omega^2+\zeta^2}$

Important $\zeta \sim \zeta_{ch}$ but which ω are important? It depends on the material.

$\zeta_{ch} = c/2a$



For metals $\varepsilon''(\omega) \to \frac{4\pi\sigma}{\omega} \gg 1$ when $\omega \to 0$ | Direct consequence of Ohm's law!

$$\Delta \times \mathrm{H} = \frac{4\pi}{c} j - i\frac{\omega}{c} D,$$

$j = \sigma E,$ $D = \varepsilon_0 E$

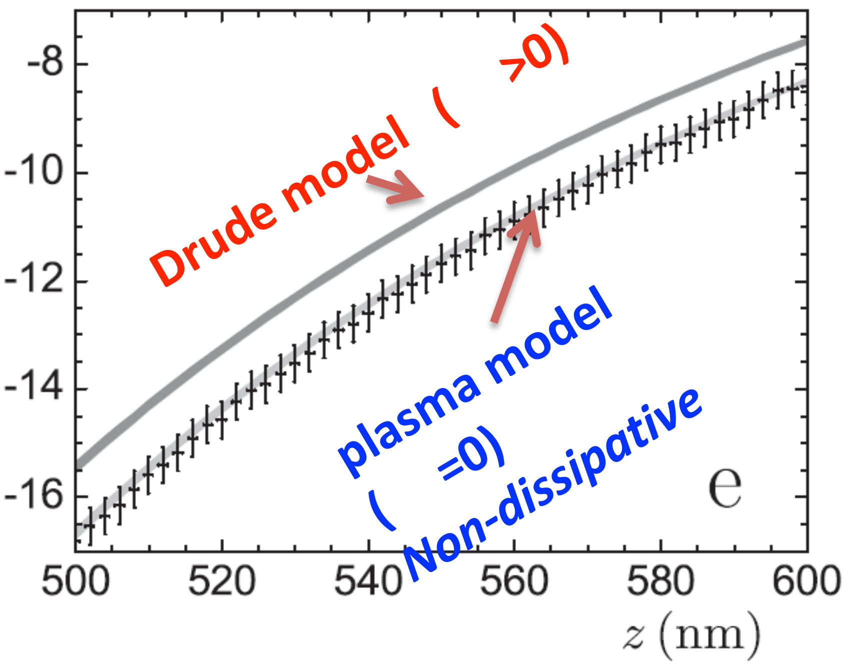
Ohm's law — static permittivity

$$\Delta \times \mathrm{H} = -i\omega\left(\varepsilon_0 + i\frac{4\pi\sigma}{\omega}\right)E,$$

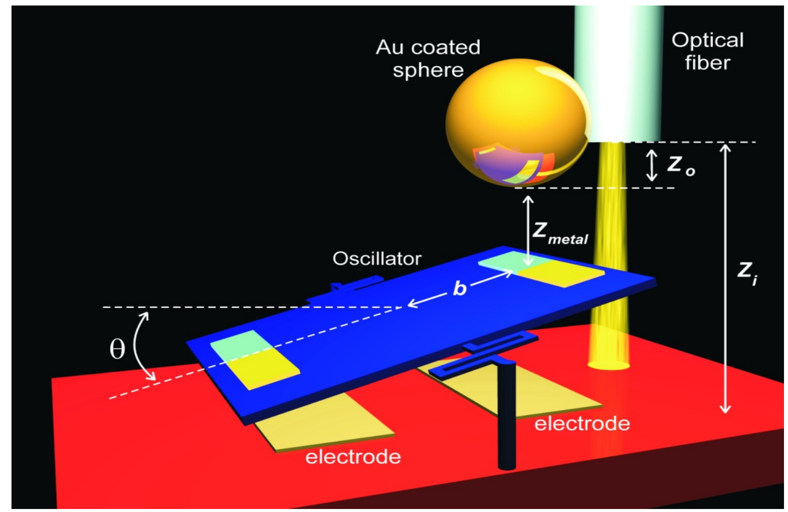
$$\varepsilon(\omega) = \varepsilon_0 + i\frac{4\pi\sigma}{\omega}, \qquad \omega \to 0$$

Comparison with theory, Decca et al.

Decca et al, PRD 2007



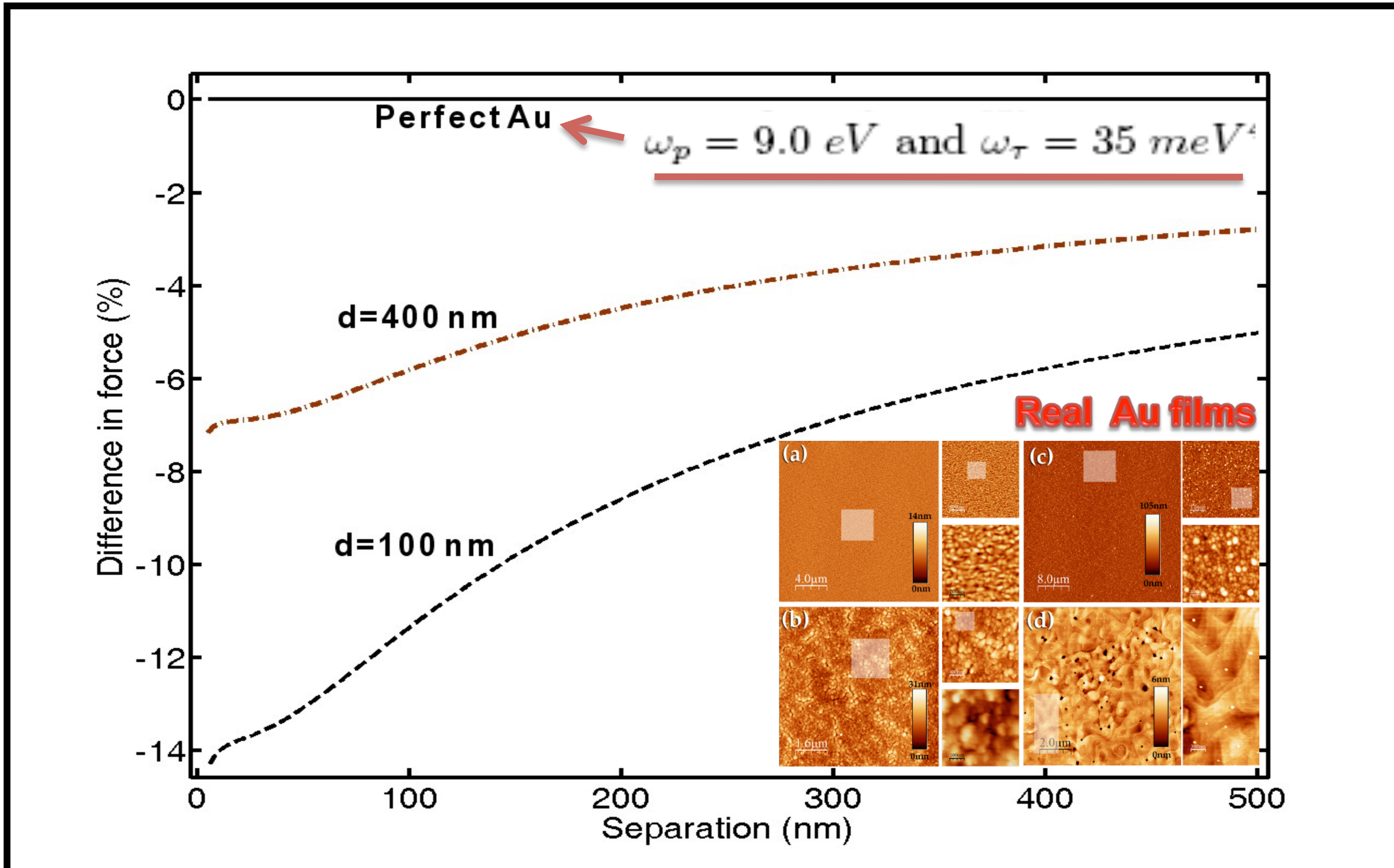
MEMS measurement



Drude Casimir ? Plasma Casimir ?

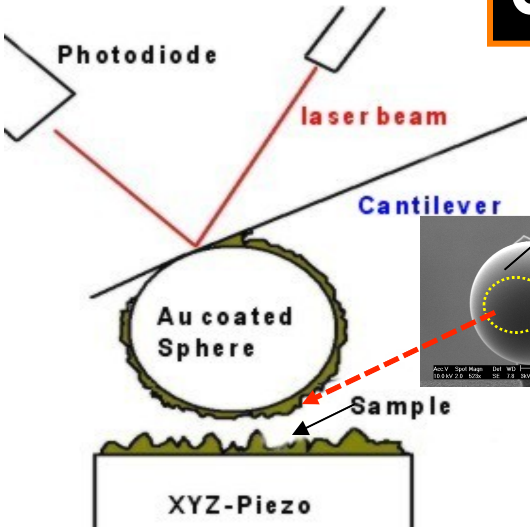
Important contribution to Casimir force from imaginary frequencies → $\zeta_{ch} = c/2a$

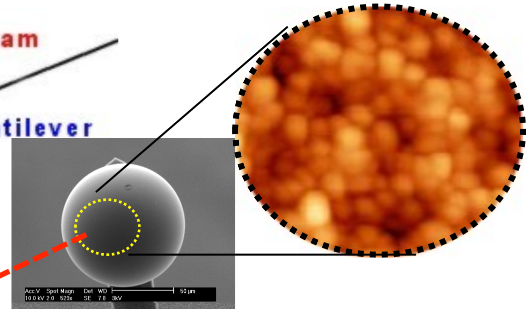
$$0.1 \lesssim \zeta_{ch} \lesssim 10 \text{ eV} \longleftrightarrow 10 \text{ nm} \lesssim a \lesssim 1 \ \mu\text{m}$$

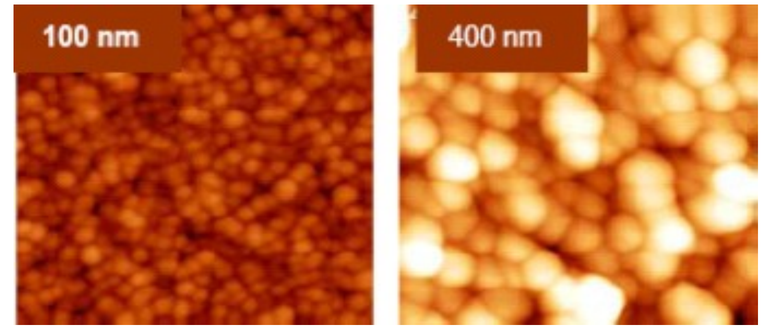


Svetovoy et al., PRB (2008)

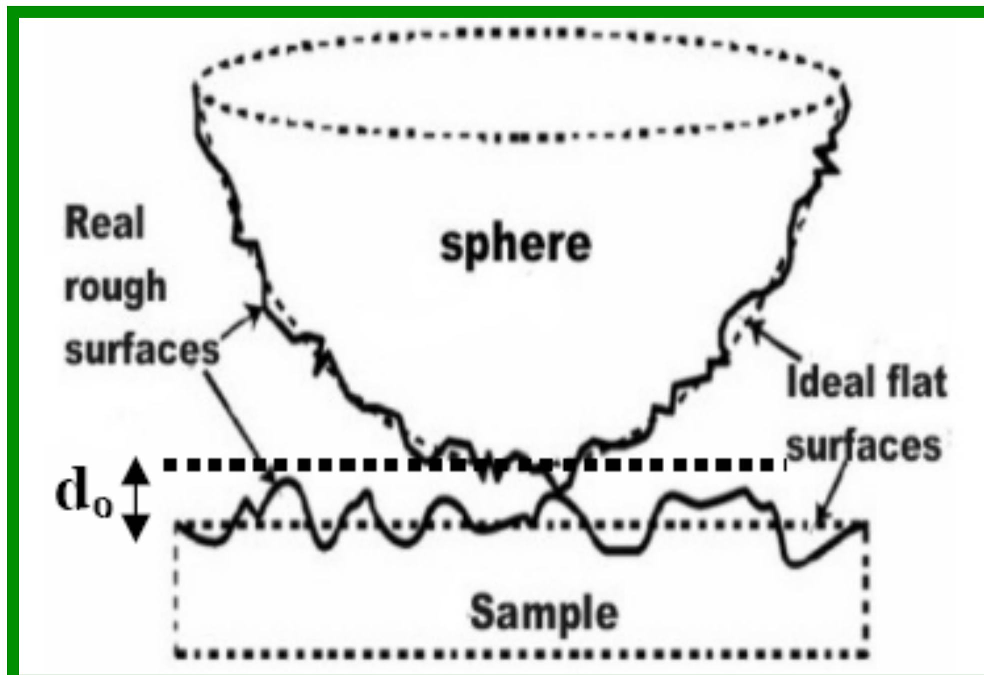
3→ Surface roughness influence





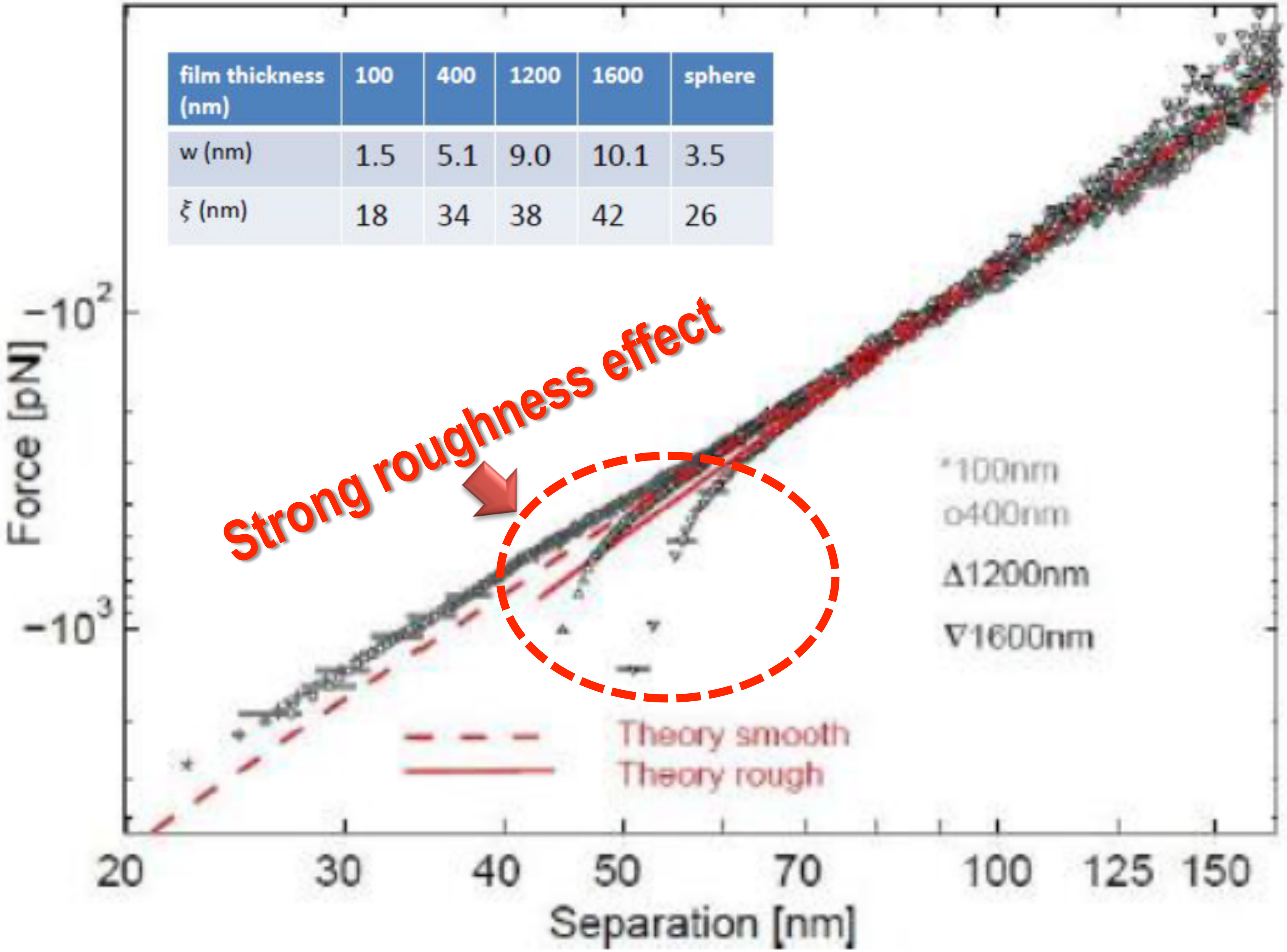


Contact mode AFM force measurement



Zwoll et al., PRB (2008)

do: Distance upon contact due to roughness



Zwoll et al., PRB (2008), Svetovoy-Palasantzas Adv. Coll. Interface Sci. 2016

Grass and trees model

Number of high peaks $d_1 < h < d_0$

w: rms roughness
[?]: correlation length

Average distance between high peaks l >> [?]

If $l > d$ the peaks can be accounted additively ⟹ condition on d_1

Typically $d_1 \gtrsim 3w$, but close to $3w$

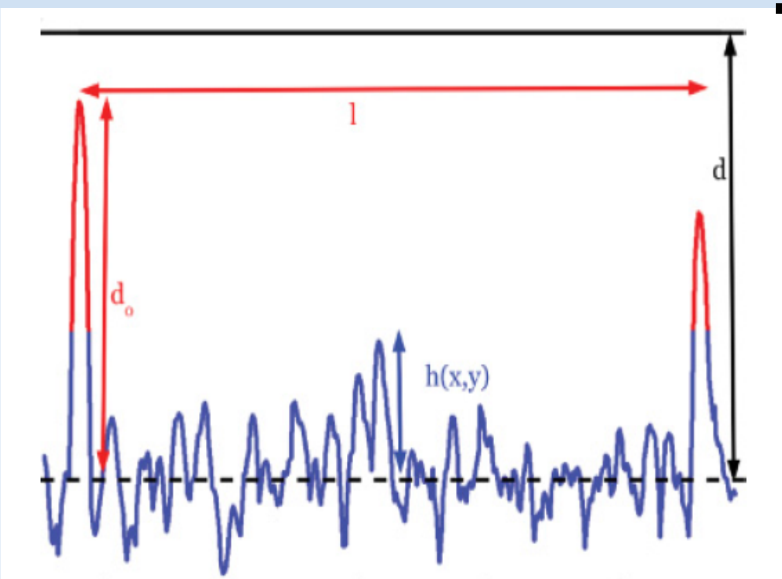
Lifshitz

"grass" contribution (perturbation theory)

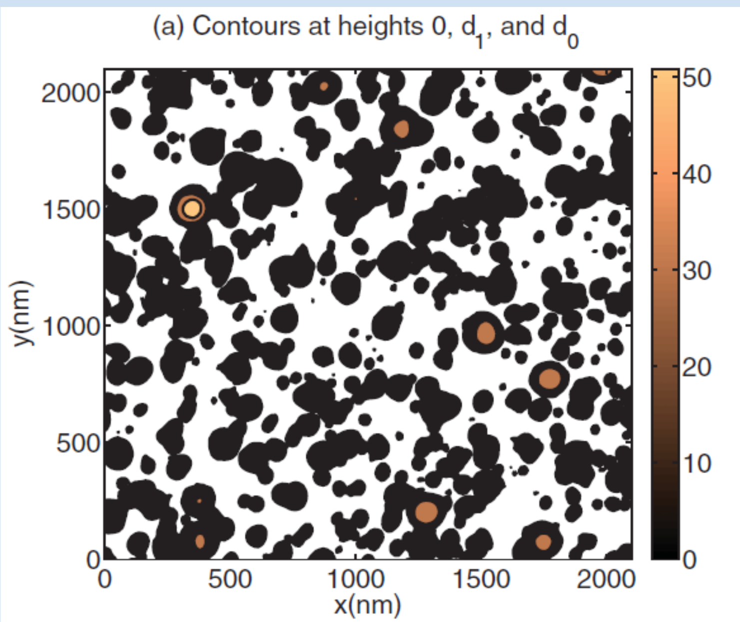
contribution of high peaks

$$F_{rough}(d) = F(d) + \Delta F_{PT}(d) + \Delta F_{HP}(d)$$

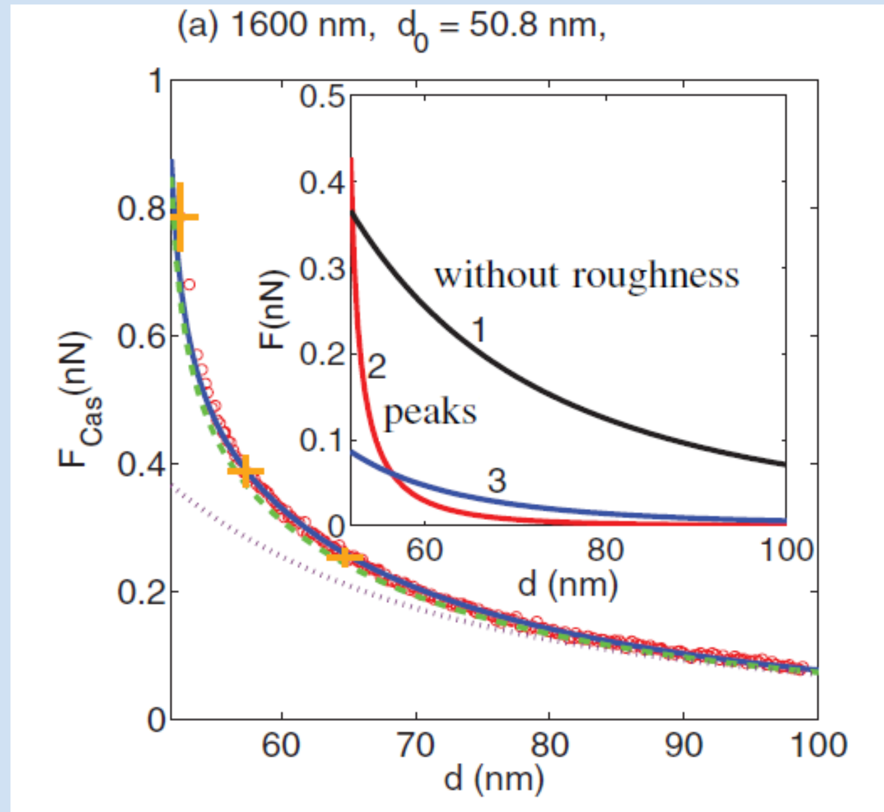
Broer et al., EPL (2012), PRB (2008), Svetovoy-Palasantzas Adv. Coll. Interface Sci. 2016



W (rms roughness) ? 10 nm



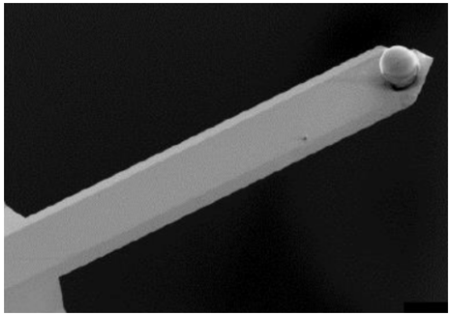
$d_1 = 30.3$ nm

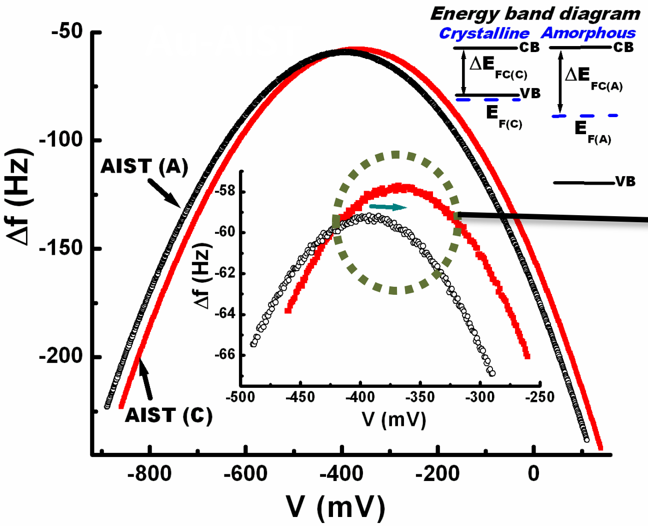


Broer et al., EPL (2012), PRB (2008), Svetovoy-Palasantzas Adv. Coll. Interface Sci.

Electrostatics....contact potentials ....

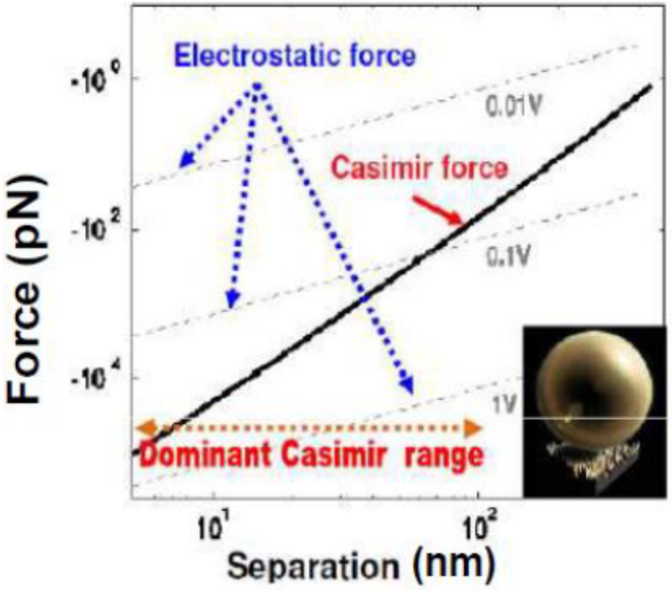
$$F_{e1} = X(z)(V - V_0)^2$$ V_0: Contact potential

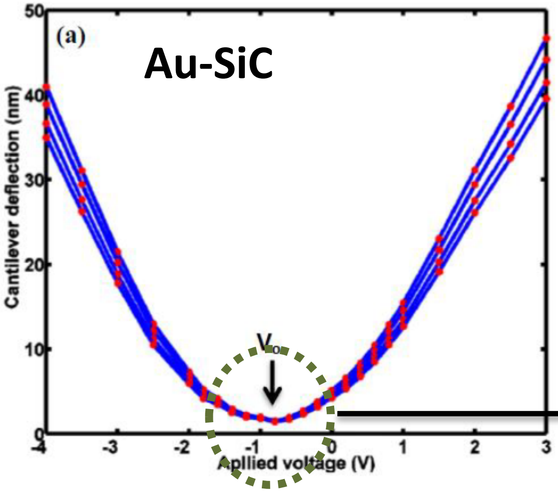




$V_{o\,(Au\text{-}AIST)}$ ~0.35 – 0.4 V

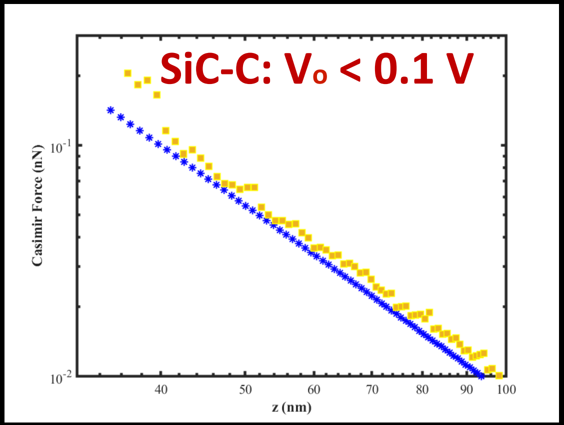
Adv. Func. Mat. 2012

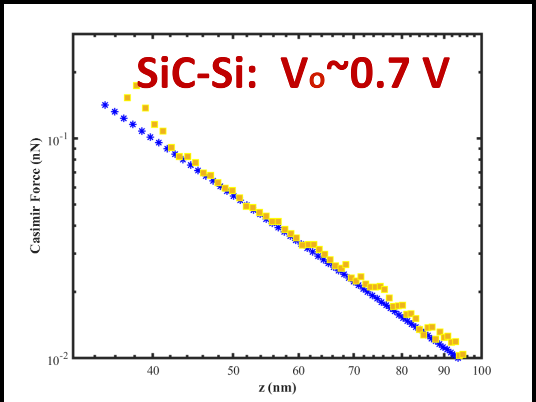


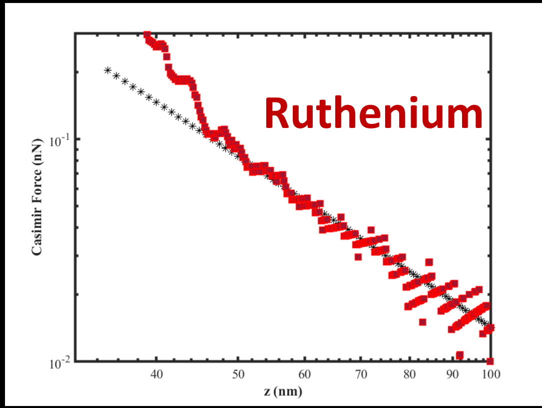


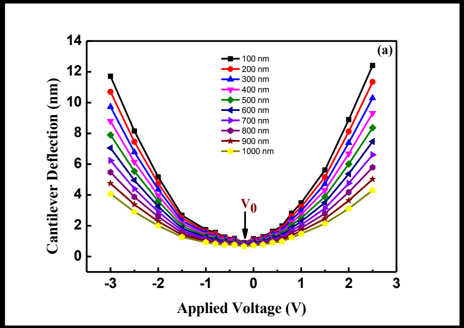
$V_{o\,(Au\text{-}SiC)}$ ~0.67 V

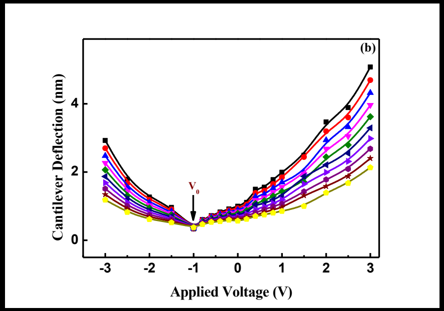
Phys. Rev. B 2016

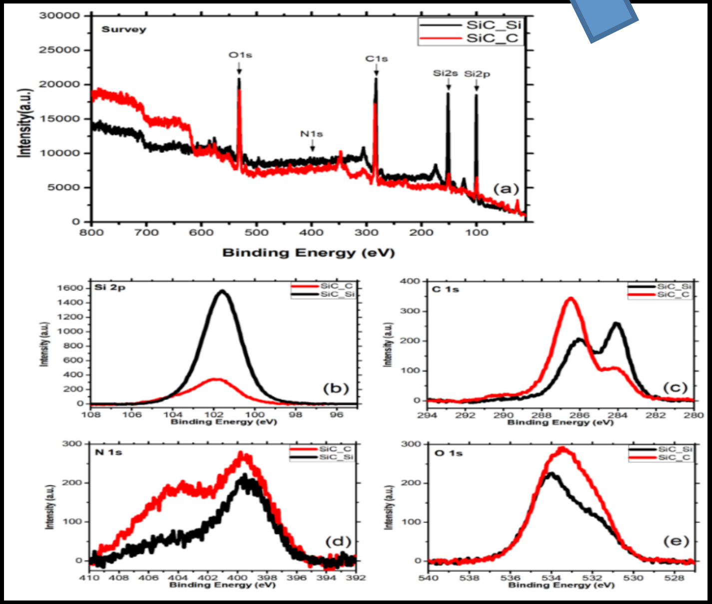






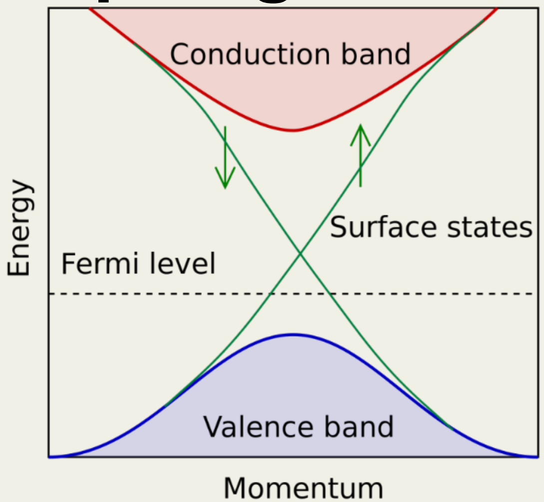


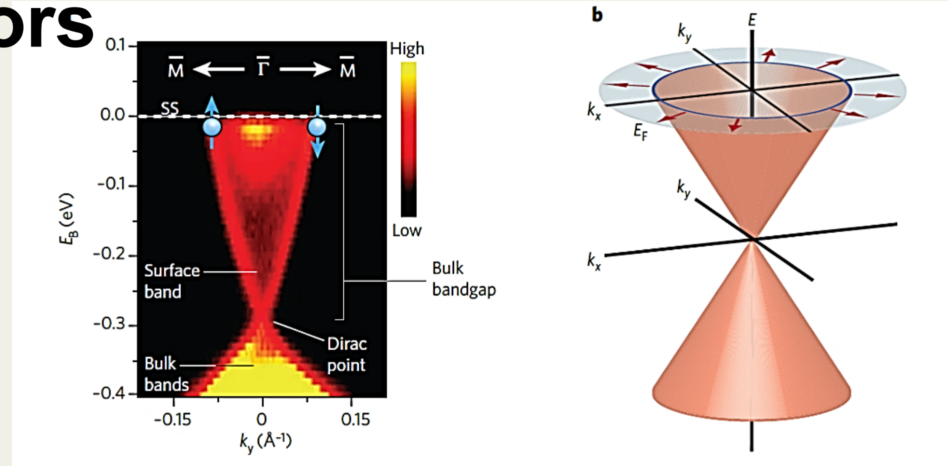




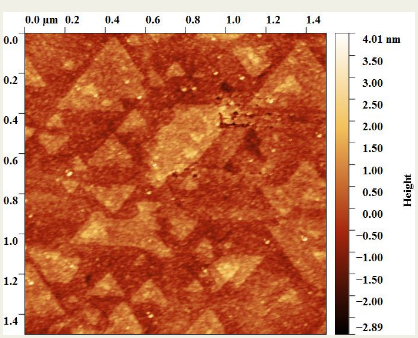
Work in progress.....!

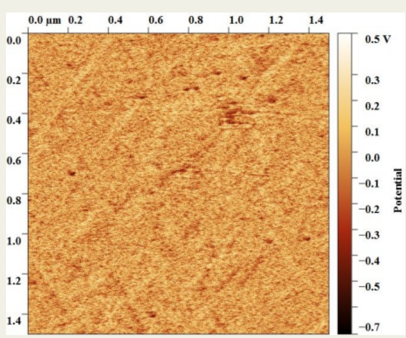
Topological Insulators



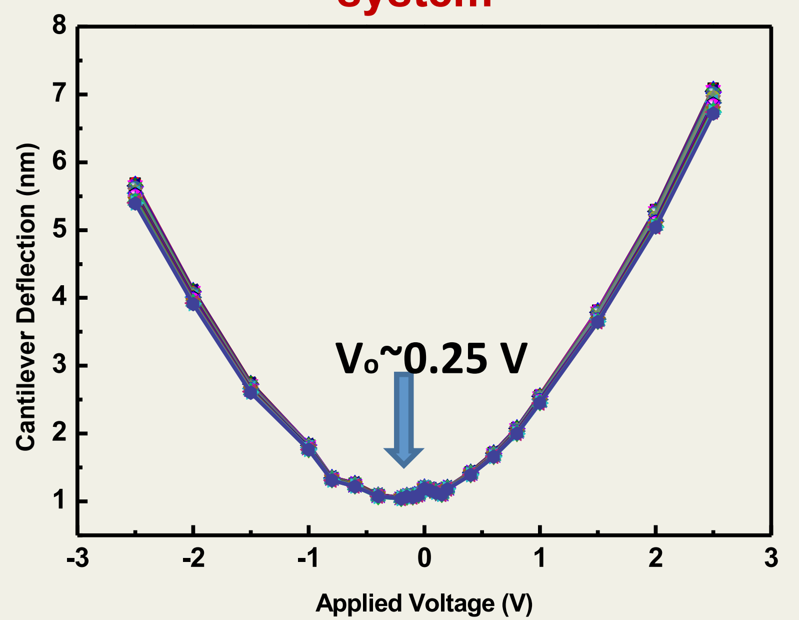


Signatures of the exotic metallic surface states in topological insulators. Theoretical ideal electronic structure of Bi2Se3

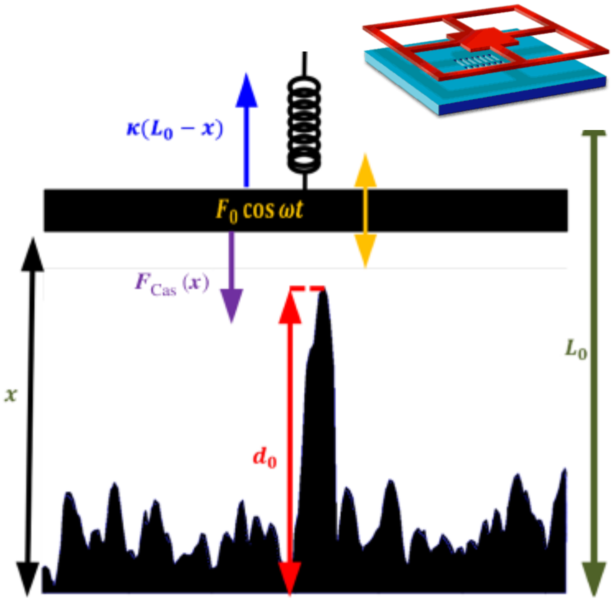




Contact Potential Measurement analysis for Bi_2Se_3 (10 nm thick) - Au system

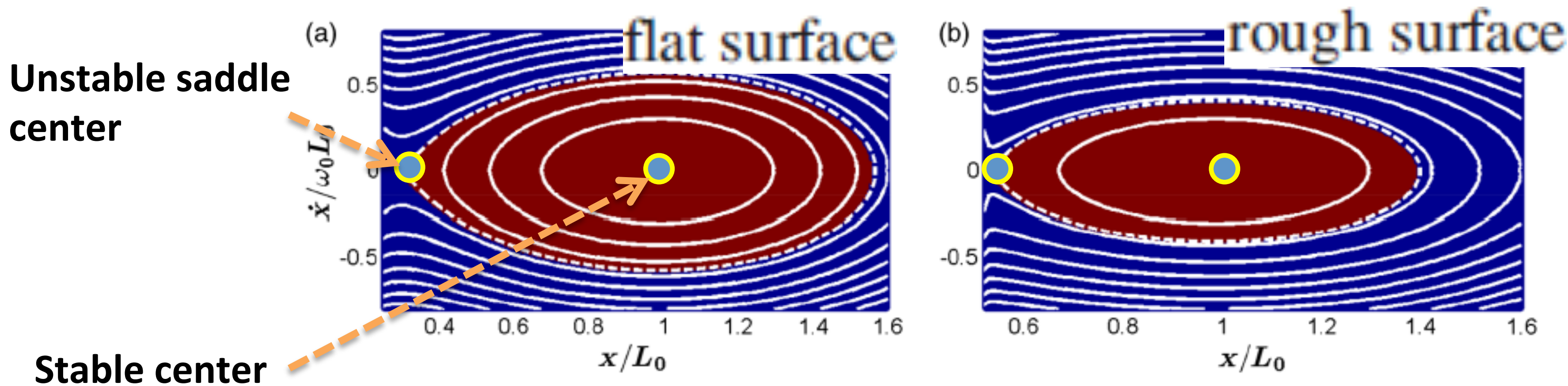


Dynamic actuation MEMS: Conservative system [?]=0



$$m\ddot{x} = \kappa(L_0 - x) - F_{Cas}(x) - \epsilon\gamma\dot{x} + \epsilon F_0 \cos \omega t.$$

$$\epsilon = 0.$$

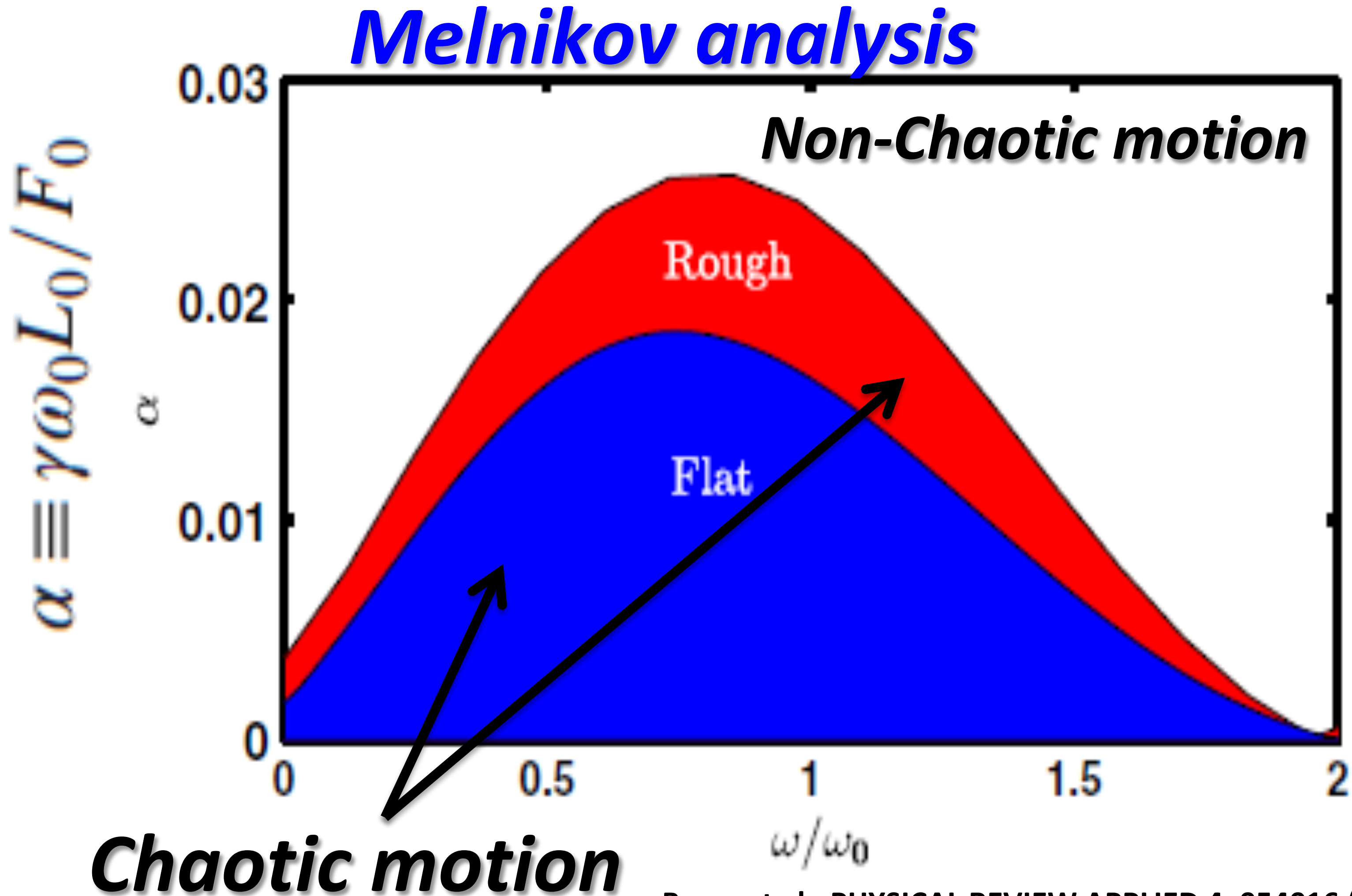


300×300 initial conditions

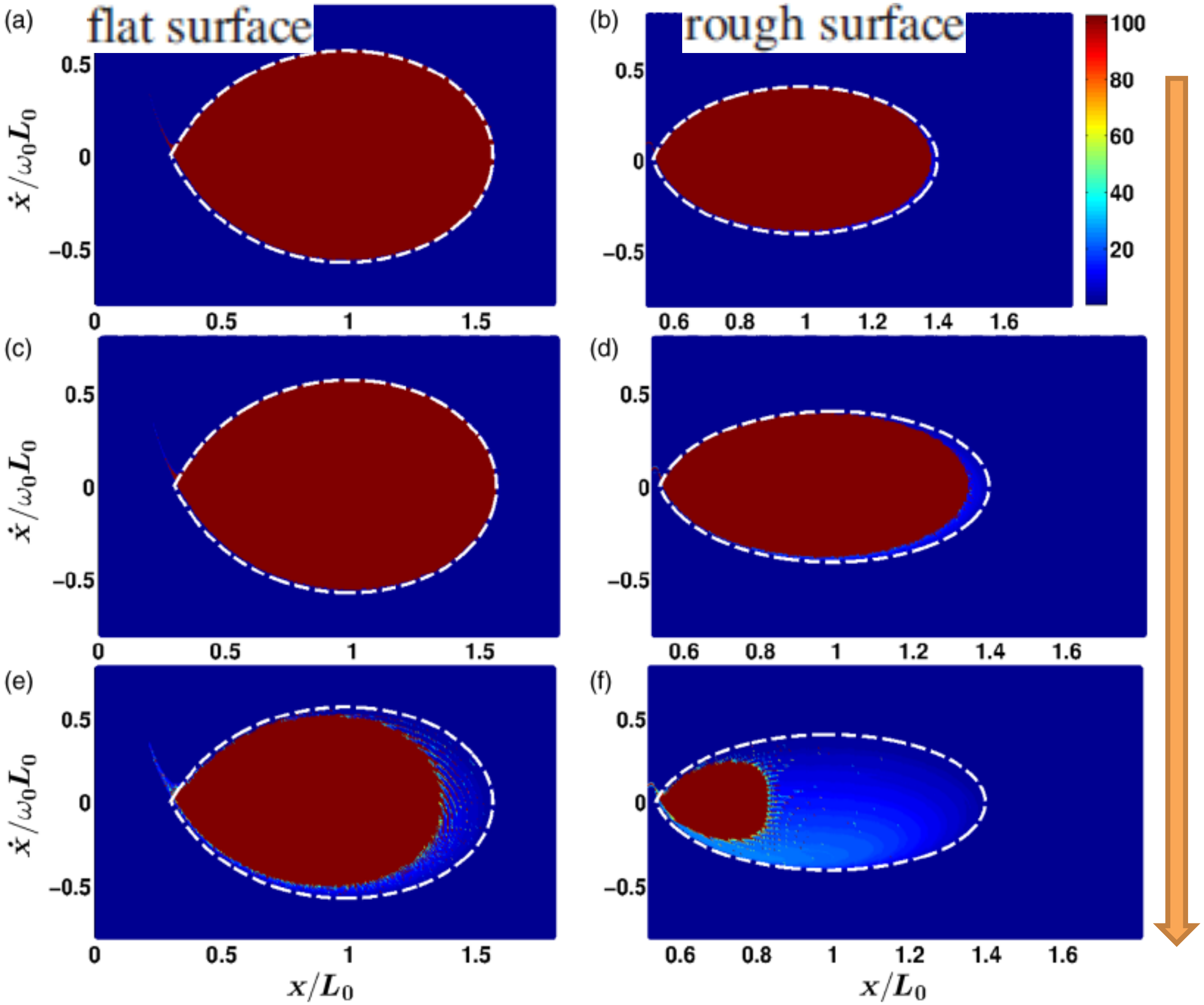
Broer et al., PHYSICAL REVIEW APPLIED 4, 054016 (2015)

Dynamic driven nononservative MEMS
?=1

$$m\ddot{x} = \kappa(L_0 - x) - F_{\rm Cas}(x) - \epsilon\gamma\dot{x} + \epsilon F_0 \cos\omega t. \qquad (\epsilon = 1)$$



Broer et al., PHYSICAL REVIEW APPLIED 4, 054016 (2015)



Scale bar: time elapses until stiction occurs within 100 oscillations.

300 × 300 initial conditions

More chaotic

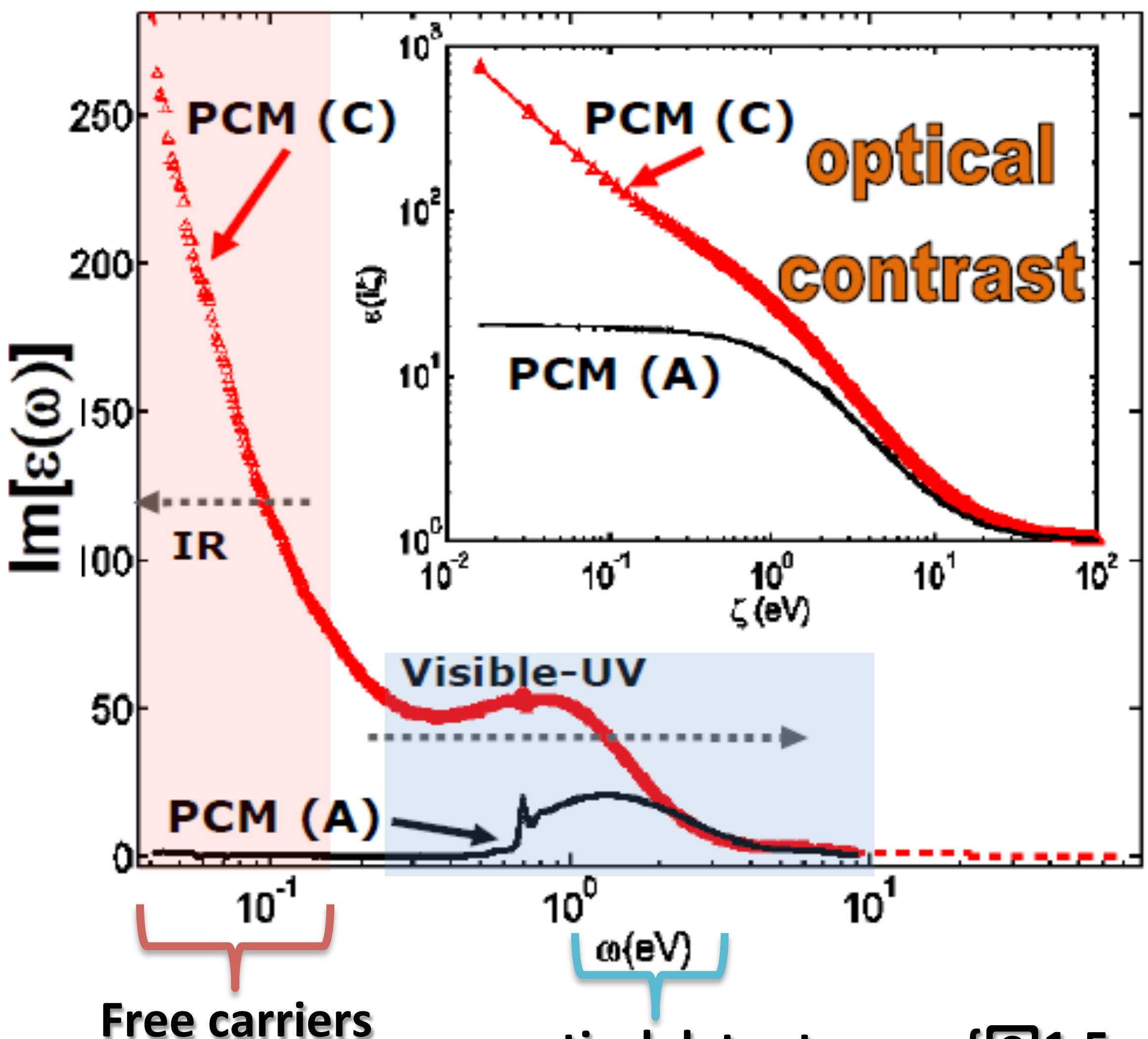
?

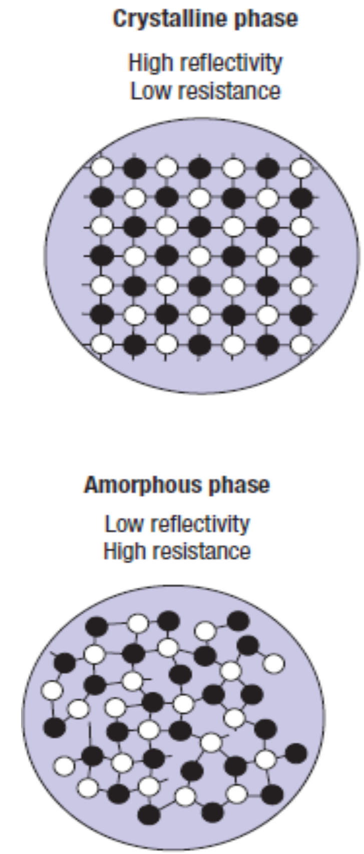
more stiction

Chaotic system: can not long term actuation state

Broer et al., PHYSICAL REVIEW APPLIED 4, 054016 (2015)

Stronger Casimir force→ …more chaoticity…

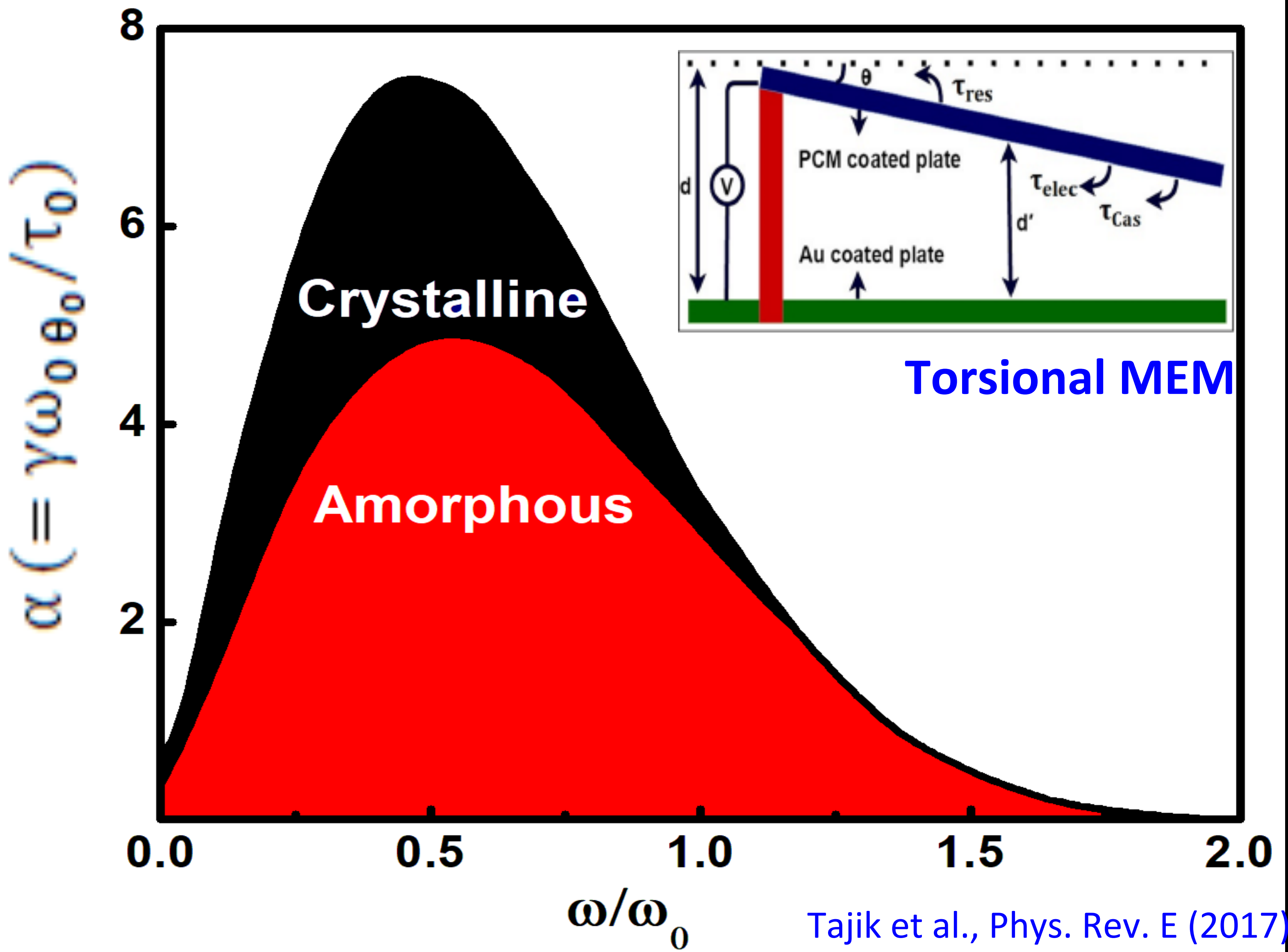




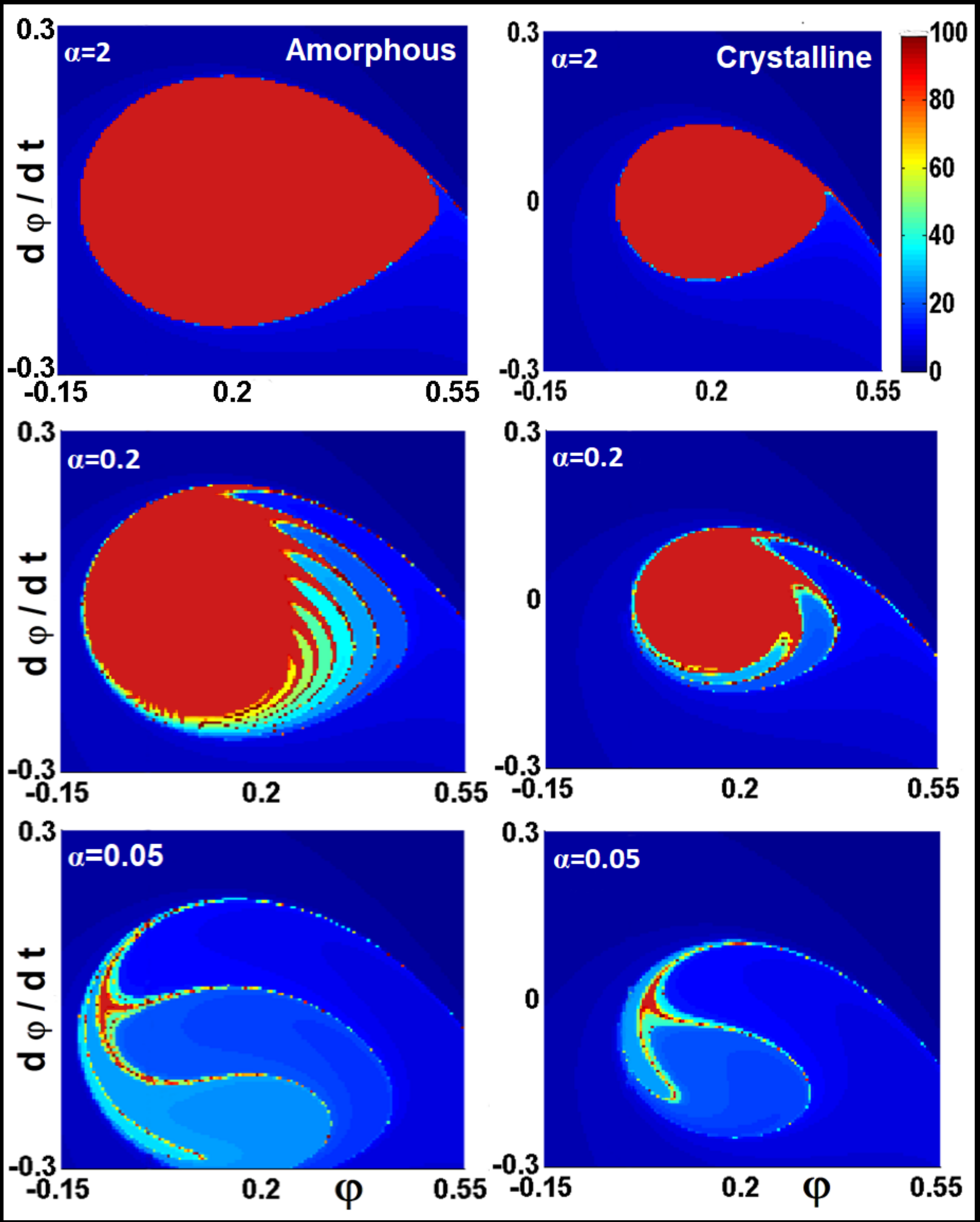
optical data storage {?1.5 eV(compact) - 3 eV (blu-ray)}

Phys. Rev. A 2010, New Scientist July 2, 2010, Adv. Funct. Mat. 2012

Melnikov analysis



Tajik et al., Phys. Rev. E (2017)



100 oscillations

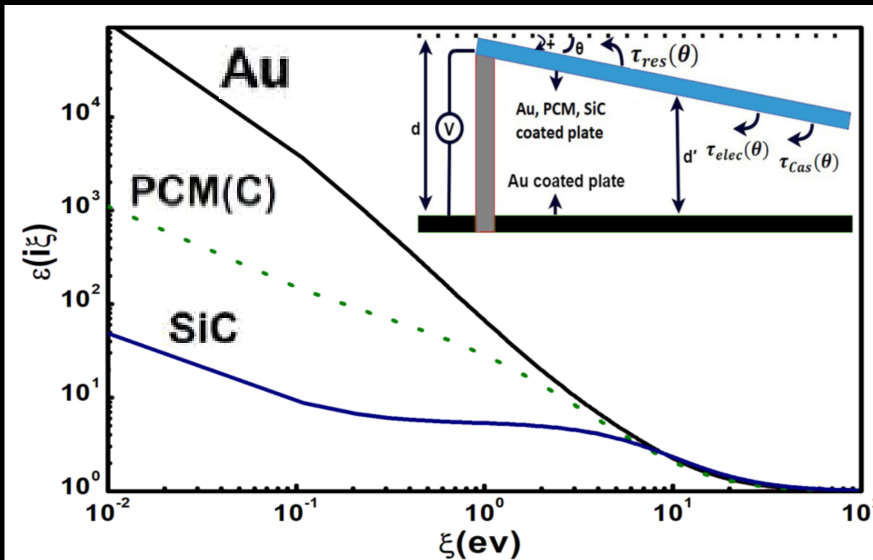
decrease ?

?

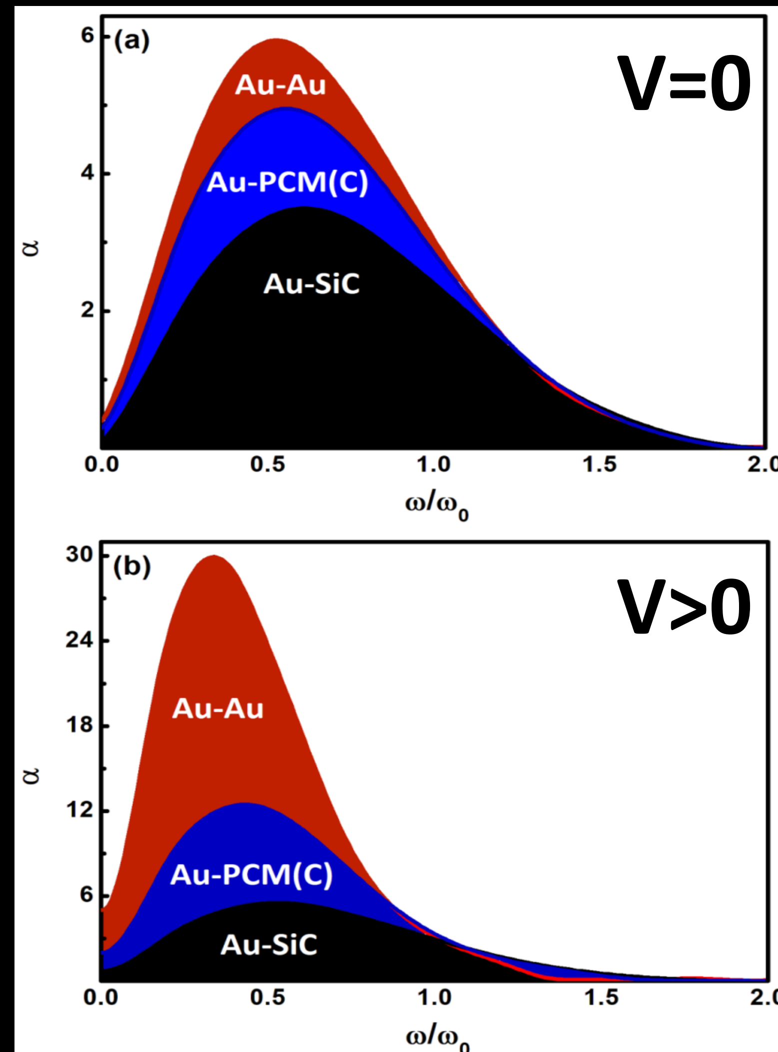
Increase chaoticity

Tajik et al., Phys. Rev. E (2017)

Higher conductivity material → More chaotic.....



Melnikov analysis



Drude model→ conductivity ratio: ω_p^2 / ω_τ

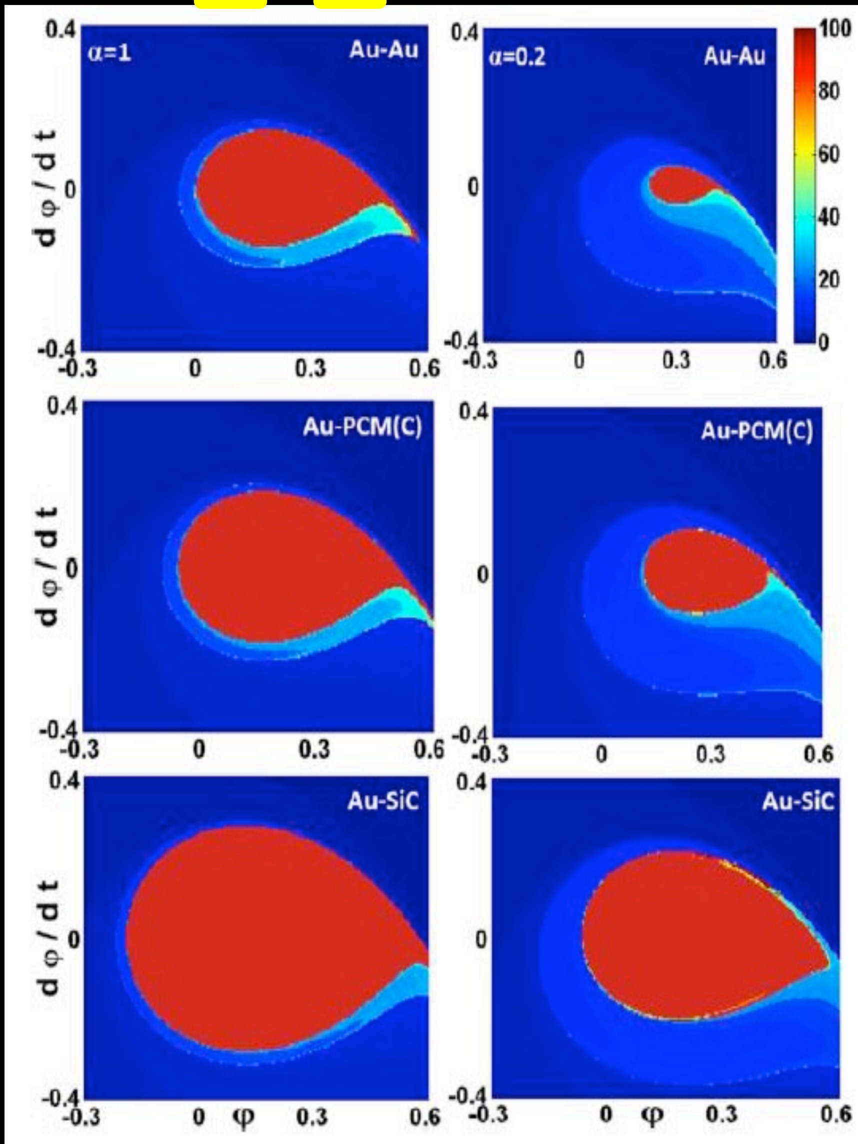
ω_p plasma frequency

ω_τ damping factor

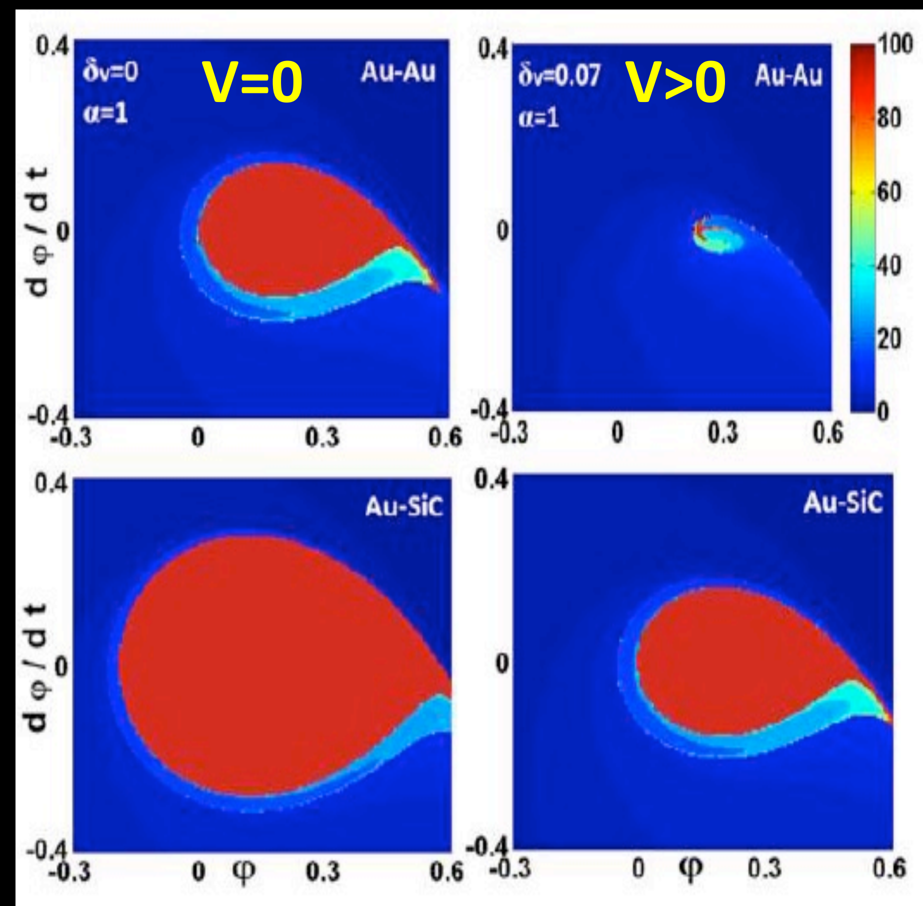
- $\omega_p^2 / \omega_\tau |_{Au}$ [?] 1600 eV
- $\omega_p^2 / \omega_\tau |_{\mathrm{AIST}(C)} = 10.1$ eV
- $\omega_p^2 / \omega_\tau |_{SiC} = 0.4$ eV

Tajik et al., Eur. J. Phys. B (2018)

V=0 ? ? → decreases



Voltage application → strong effect depending on material

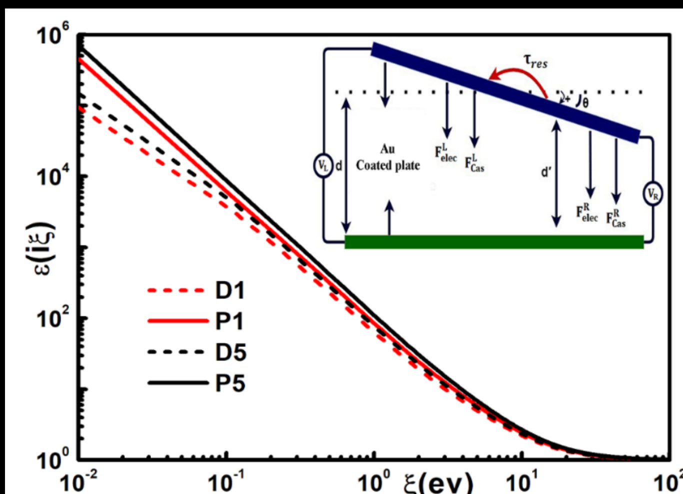


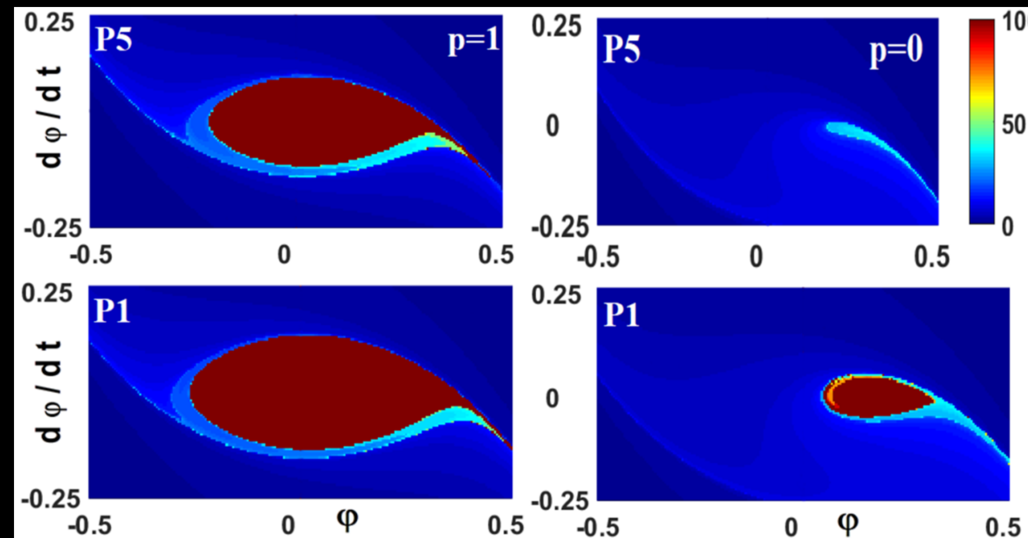
Tajik et al., Eur. J. Phys. B (2018)

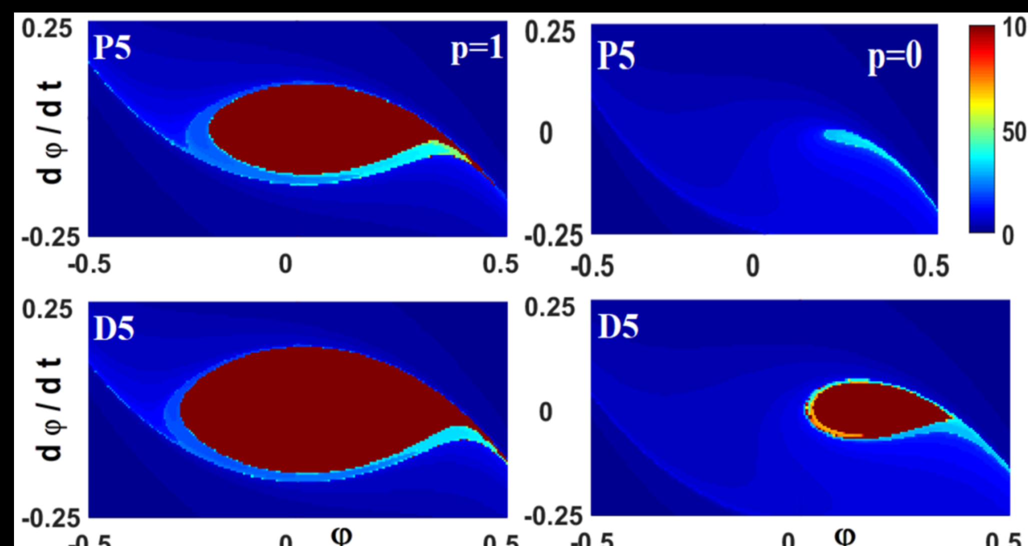
TABLE II. The Drude parameters determined by different methods described in the text. In all cases the statistical errors in the parameters are on the same level: 0.01–0.03 meV for ω_p and 0.2–0.5 meV for ω_τ. The last column shows the values of the parameters averaged on different methods and the corresponding rms errors.

Sample	Parameter	Joint ε', ε''	Joint n, k	KK ε'	KK n	Average
1	ω_p [eV]	6.70	6.87	6.88	6.83	6.82 ± 0.08
400 nm/Si	ω_τ [meV]	38.4	43.3	40.2	39.9	40.5 ± 2.1
2	ω_p	6.78	7.04	6.69	6.80	6.83 ± 0.15
200 nm/Si	ω_τ	40.7	45.3	36.1	36.0	39.5 ± 4.4
3	ω_p	7.79	7.94	7.80	7.84	7.84 ± 0.07
100 nm/Si	ω_τ	48.8	52.0	47.9	47.4	49.0 ± 2.1
4	ω_p	7.90	8.24	7.95	7.90	8.00 ± 0.16
120 nm/Si	ω_τ	37.1	41.4	35.2	29.2	35.7 ± 5.1
5	ω_p	8.37	8.41	8.27	8.46	8.38 ± 0.08
120 nm/mica	ω_τ	37.1	37.7	34.5	39.1	37.1 ± 1.9

Sensitivity of chaotic behavior: Plasma-Drude model.........

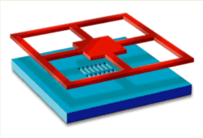






Conclusions……

Real materials are promising for applications in Casimir driven devices but many "ToDos" Still :



- **Optical properties & theory uncertaities**
- **Electrostatics**
- **Surface roughness**
- **Chaotic motion – Device predictability**

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