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Near-field radiative heat transfer and non-contact friction

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Near-Field Radiative Heat Transfer and Non-Contact Friction

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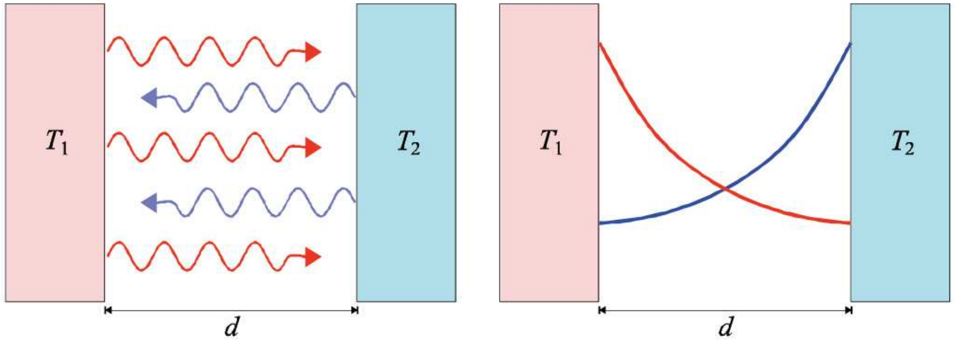
- Near field radiative heat transfer
- Van der Waals friction
- Electrostatic friction

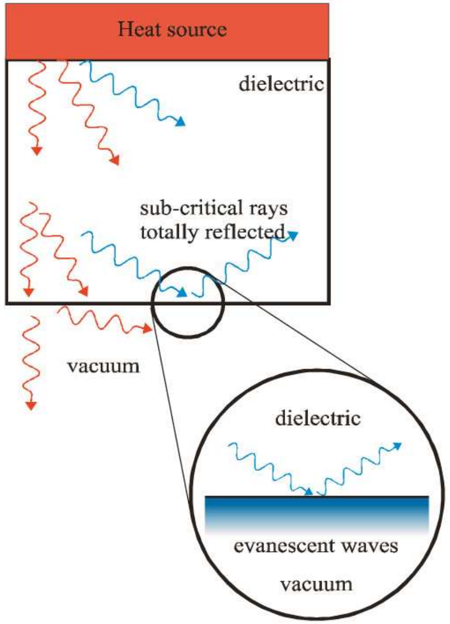
Introduction

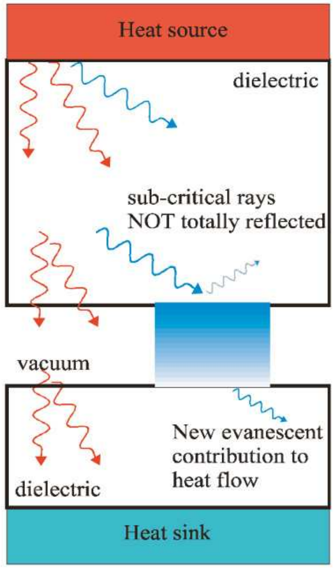


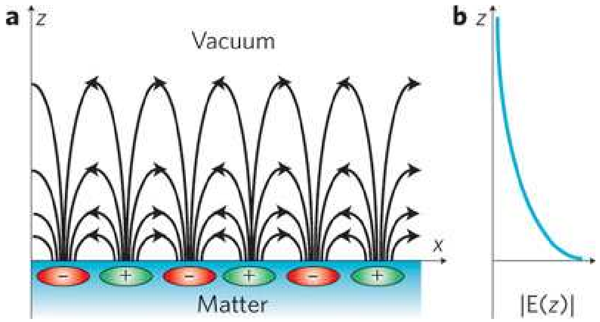
The radiative heat transfer between two black bodies separated by $d \gg \lambda_T = c\hbar/k_B T$ is given by the Stefan-Boltzmann law:

$$S = \frac{\pi^2 k_B^4}{60\hbar^3 c^2}\left(T_1^4 - T_2^4\right),$$

Evanescent electromagnetic waves

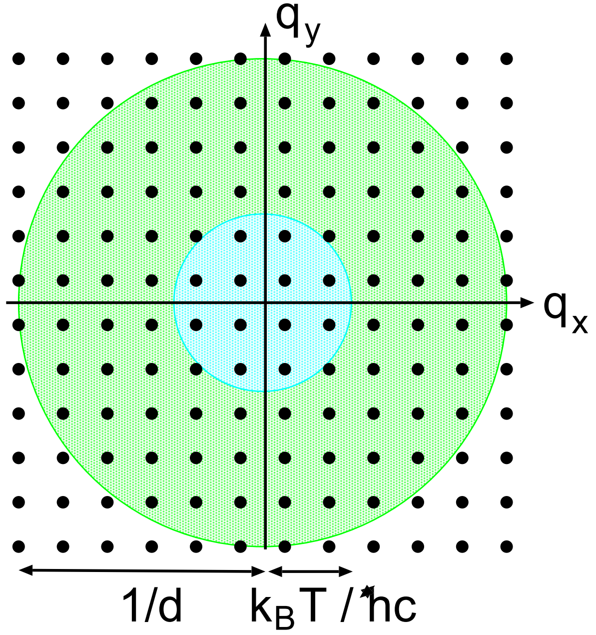






Evanescent electromagnetic waves

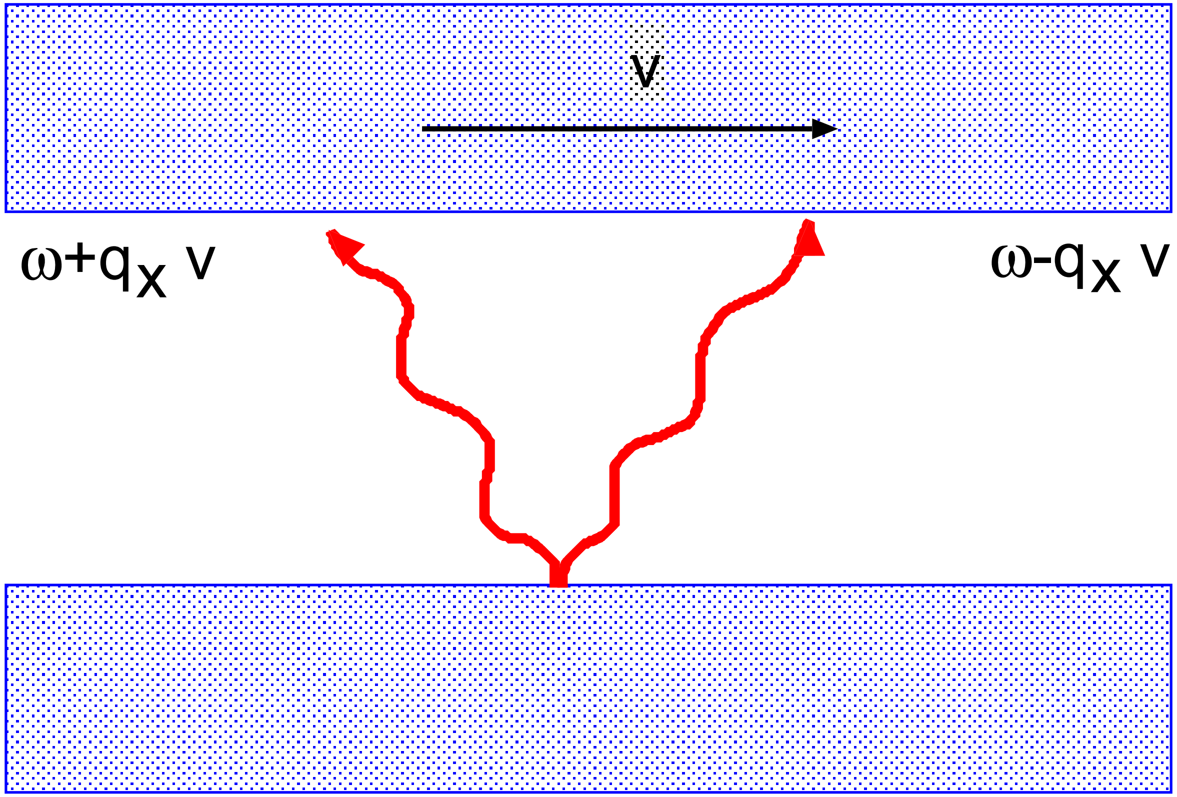
Why at short separation the evanescent electromagnetic waves give the most important contribution?



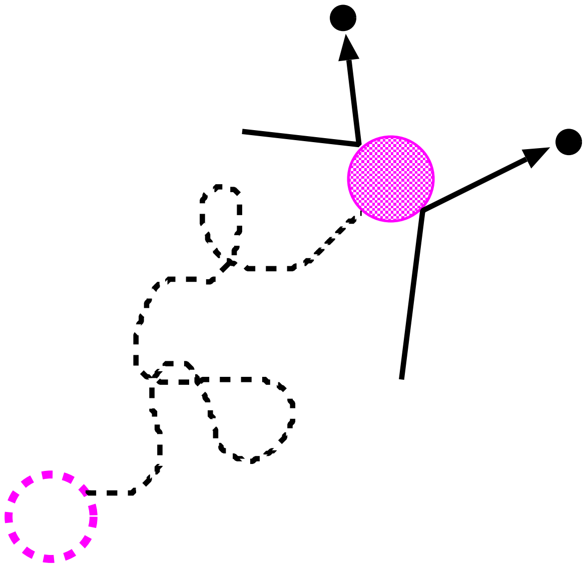
T(K)	λ_T(μm)
1	2298.8
4.2	545.2
100	22.9
273	8.4
1000	2.3

Table.Critical distance λ_T as a function of temperature. For surface separation $d < \lambda_T$ the heat transfer is dominated by the contribution from the evanescent electromagnetic modes.

Origin of the van der Waals friction



Theory of Brownian motion.



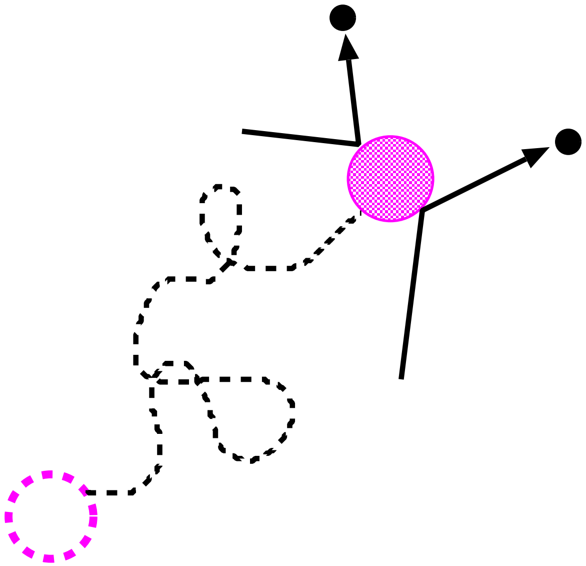
$$m\ddot{x} + m\omega_0^2 x + \Gamma\dot{x} = F(t)$$

$$\Gamma = \frac{1}{k_B T}\int_0^\infty \langle F(t)F(0)\rangle dt$$

The random force that makes a small particle jitter would also cause friction if the particle were dragged through the medium

Rytov's theory of the fluctuating electromagnetic field

Rytov S.M. 1953



$$\nabla \times \mathbf{E} = i\frac{\omega}{c}\mathbf{B}$$

$$\nabla \times \mathbf{H} = -i\frac{\omega}{c}\mathbf{D}+\frac{4\pi}{c}\mathbf{j}^f$$

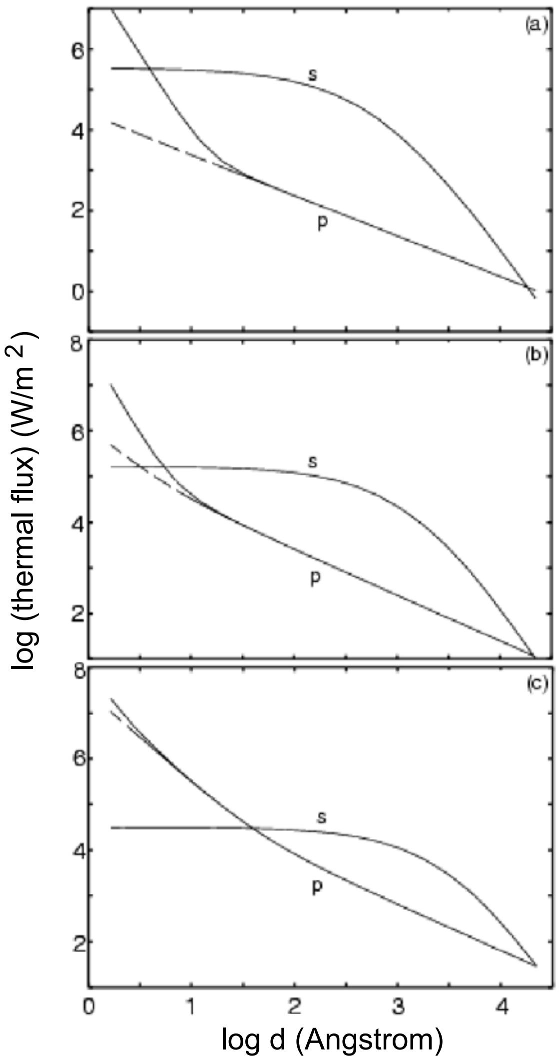
$$\left\langle j_i^f(\mathbf{r}) j_k^{f*}(\mathbf{r}')\right\rangle_\omega = \frac{\hbar}{(2\pi)^2}\left(\frac{1}{2}+n(\omega)\right)\omega^2 \mathrm{Im}\varepsilon_{ik}(\mathbf{r},\mathbf{r}',\omega)$$

$$n(\omega) = \frac{1}{e^{\hbar\omega/k_B T}-1}$$

Application of Rytov's theory

- Lifshitz E.M. Theory of the van der Waals interaction 1955
- Polder D. and Van Hove M. Theory of the radiative heat transfer 1971
- Volokitin A.I. and Persson B.N.J. Theory of the van der Waals friction 1998.

Radiative heat transfer: Results.

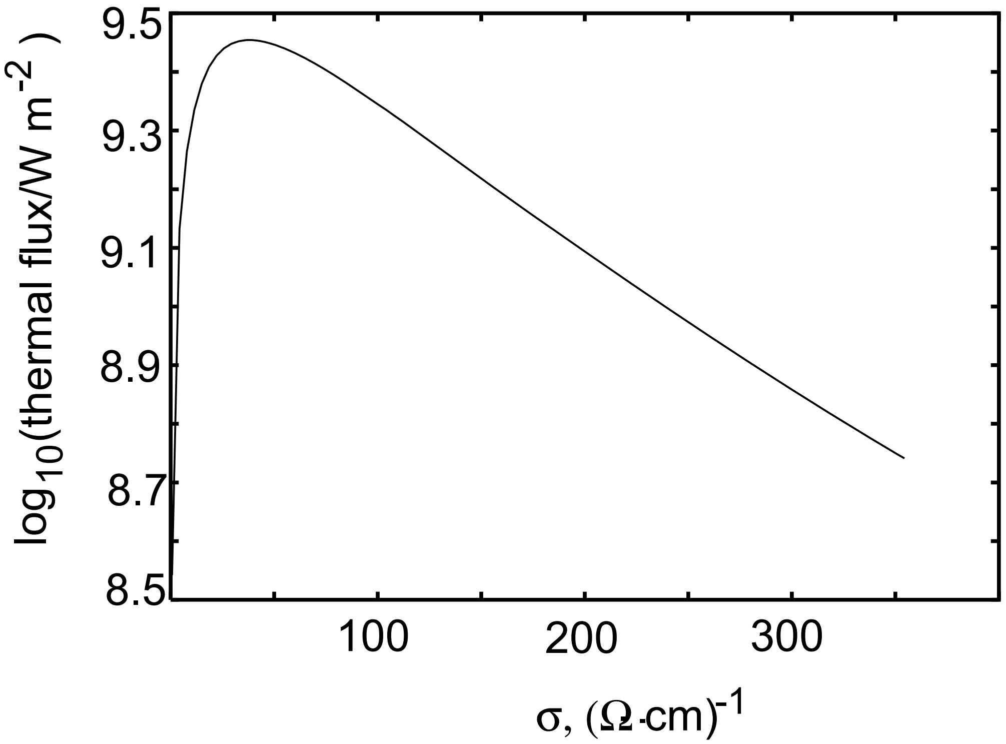


(a) The heat transfer flux between two semi-infinite silver bodies, one at temperature $T_1 = 273$ K and another at $T_2 = 0$ K, as a function of the separation d.

(b) The same as (a) except that we have reduced an electron mean free path for solid 1 from a value $l = 560$ Å to 20 Å.

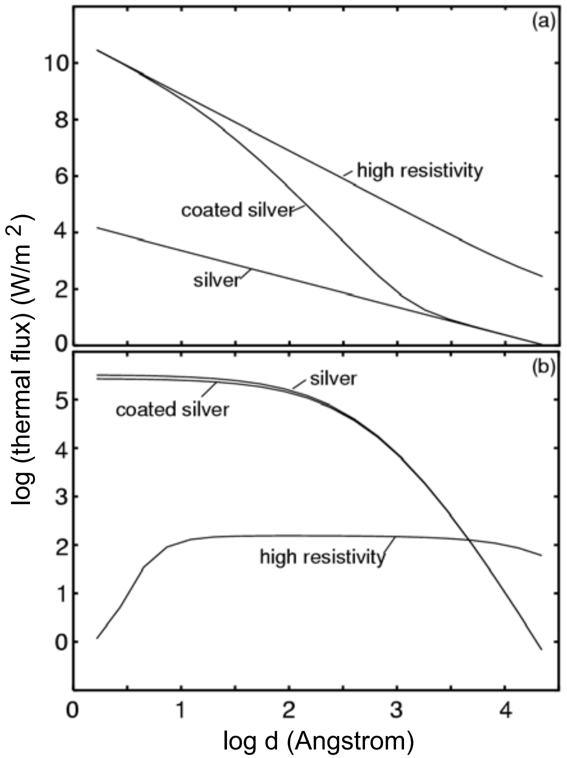
(c) The same as (a) except that we have reduced l to 3.4 Å. The dashed lines correspond to the results obtained within local optic approximation.

Radiative Heat Transfer: Results.



The thermal flux as a function of the conductivity of the solids. The surfaces are separated by $d = 10$ Å.

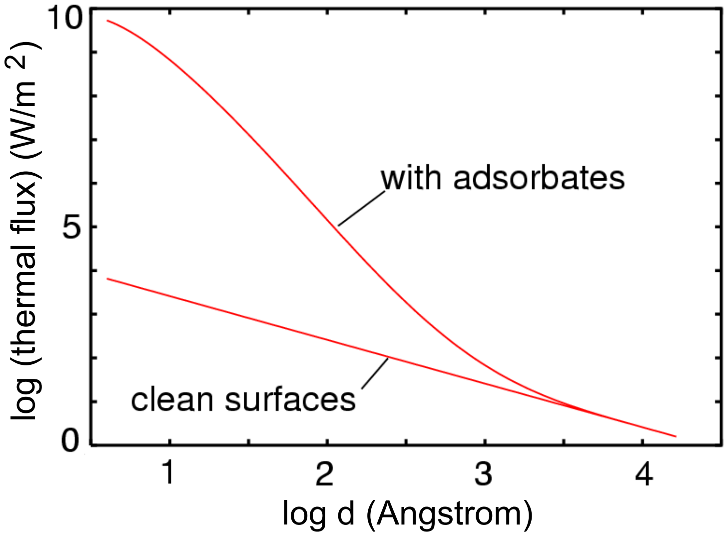
Radiative Heat Transfer. Results.



The heat flux between two semi-infinite silver bodies coated with 10 Å high resistivity ($\rho = 0.14\ \Omega$ cm) material. Also shown is the heat flux between two silver bodies, and two high-resistivity bodies. One body is at zero temperature and the other at $T = 273$ K. (a) and (b) show the $p-$ and $s-$wave contributions, respectively.

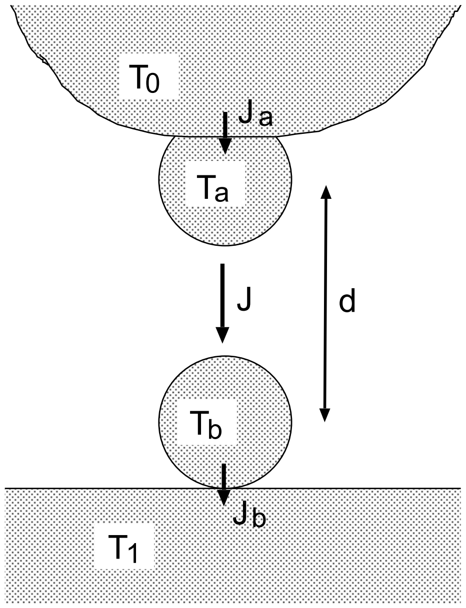
Resonant photon tunneling enhancement

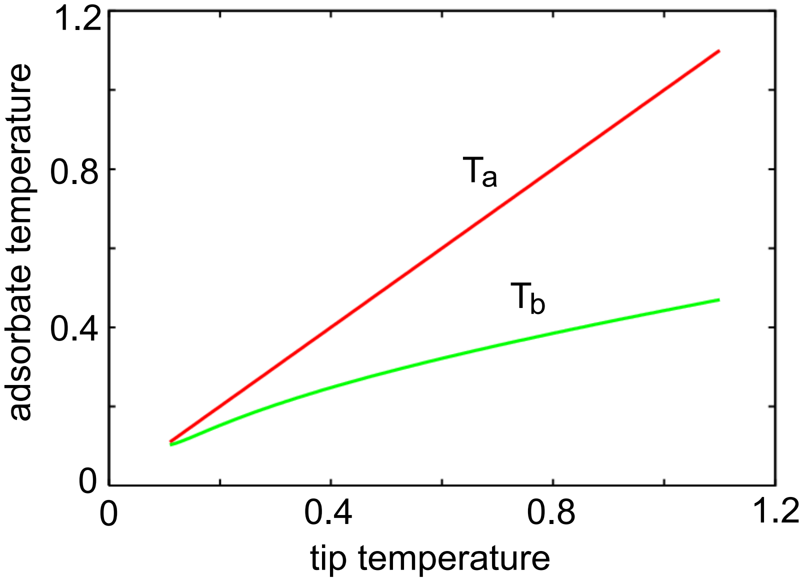
Adsorbate Vibrational Mode Enhancement of the Radiative Heat Transf



The heat flux between two surfaces covered by potassium atoms and between two clean surfaces, as a function of the separation d. One body is at zero temperature and the other at $T = 273$ K.

Vibrational heating by localized photon tunneling

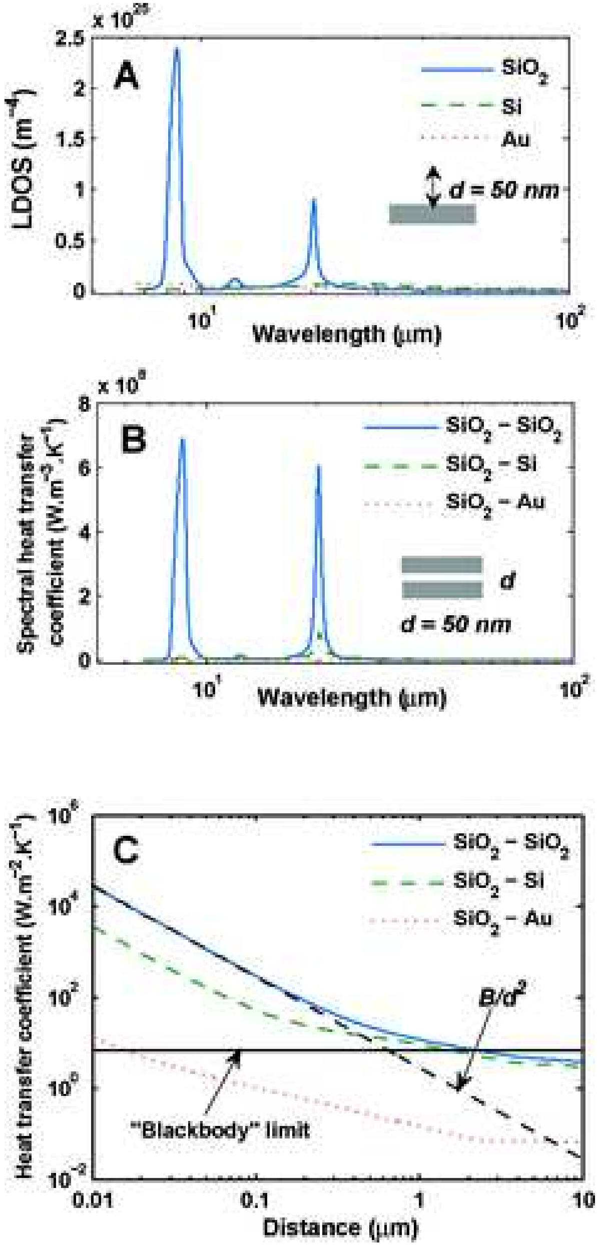




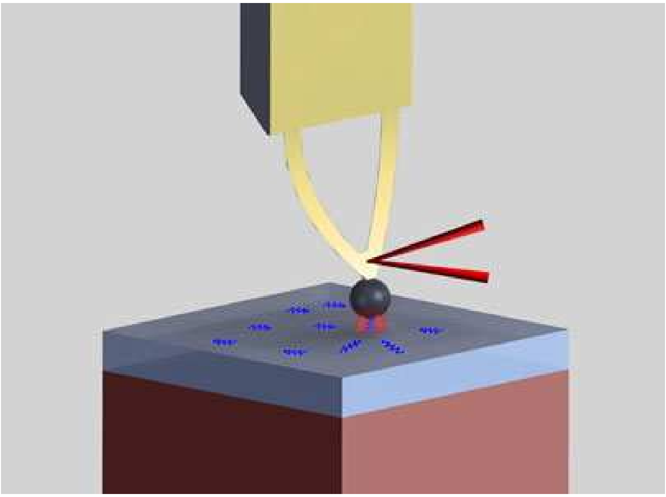
The adsorbate temperatures T_a and T_b as a function of the tip temperature T_0 (all in units of $\hbar\omega_b/k_B$). For $T_1 = 0.1\hbar\omega_b/k_B$.

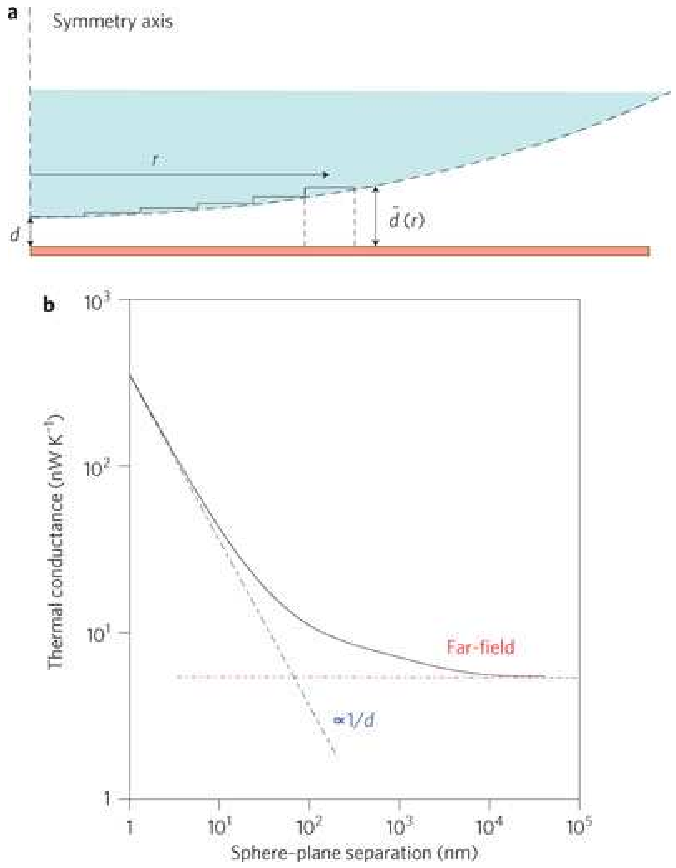
Resonant photon tunneling enhancement

Surface Phonon Polaritons Enhancement



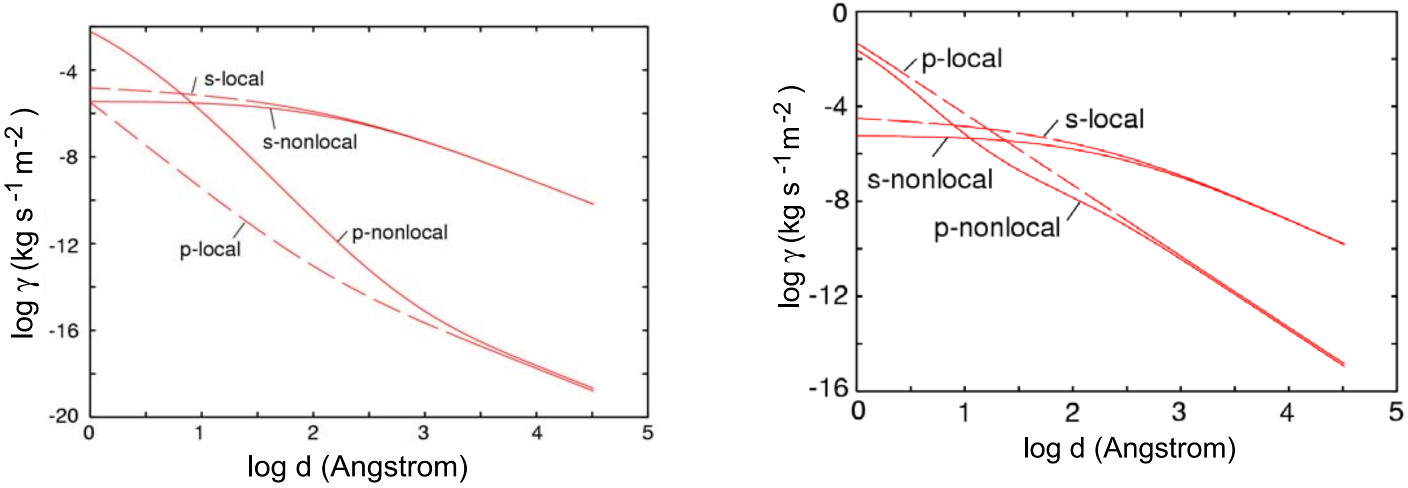
Radiative Heat Transfer. Experiment.





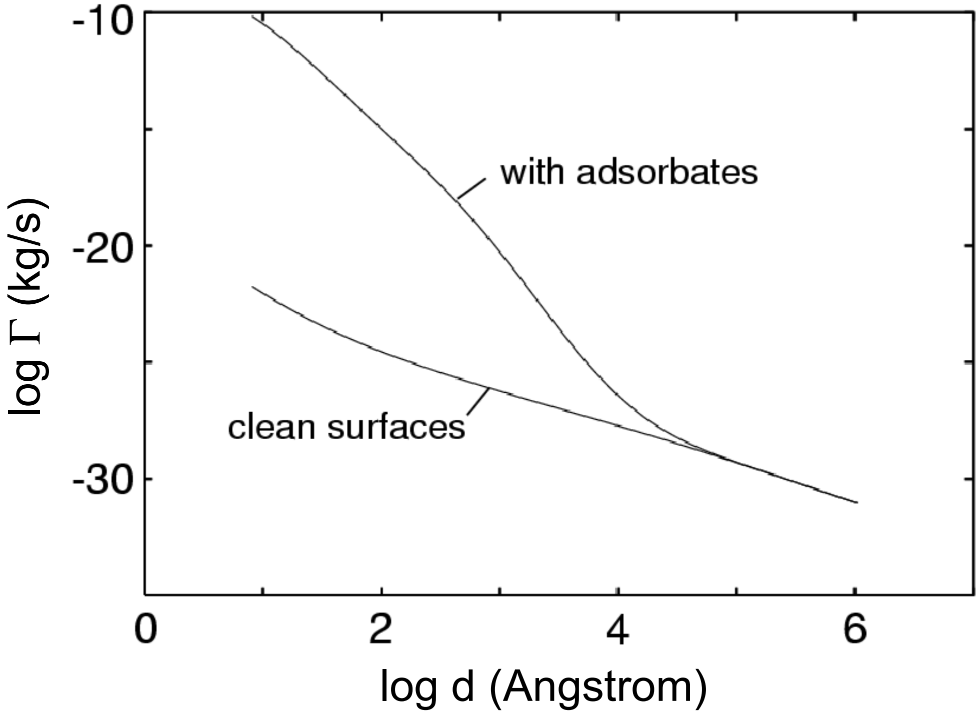
Rousseau E. *et al* 2009; Shen S. *et al* 2009

Van der Waals friction between two metal surfaces



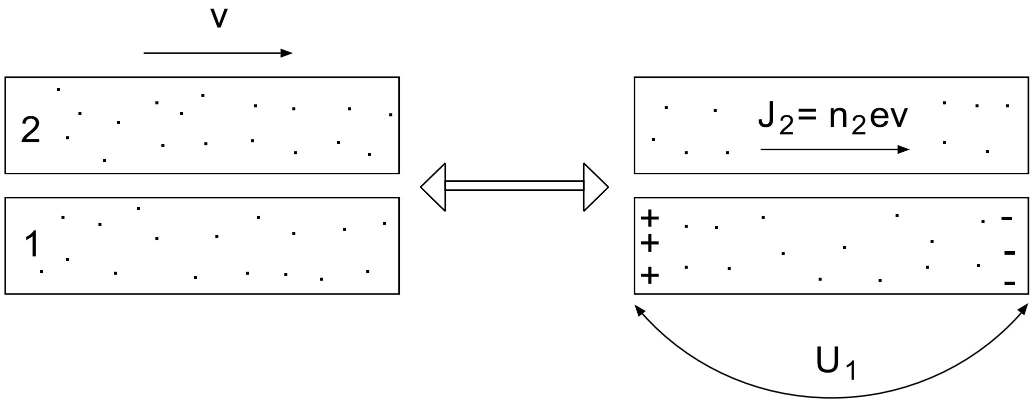
Left-The friction coefficient for two flat surfaces in parallel relative motion as a function of separation d at $T = 273$ K with parameters chosen to correspond to copper.
Right- The same as left figure but for normal relative motion.

Adsorbate enhancement of van der Waals friction



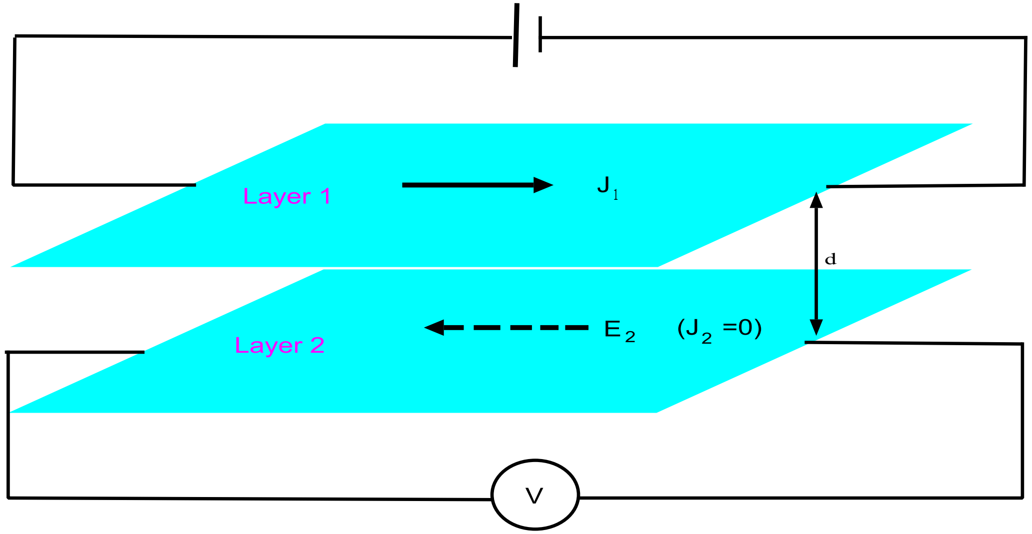
The friction coefficient between the copper tip and copper substrate the surfaces of which are covered by low concentration of cesium atoms $\theta \approx 0.1$, as a function of the separation d. The radius of curvature of the cylindrical tip $R = 1\,\mu$m and the width $w = 7\,\mu$m.

Two ways to study Van der Waals friction



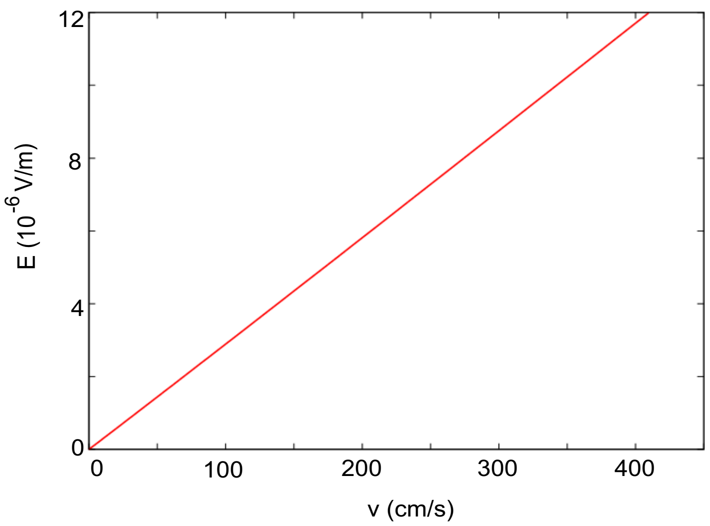
Left:a metallic block is sliding relative to the metallic substrate with velocity v.
Right: A drift motion of t he free carries of charge (electrons or ions) is induced in the upper medium.

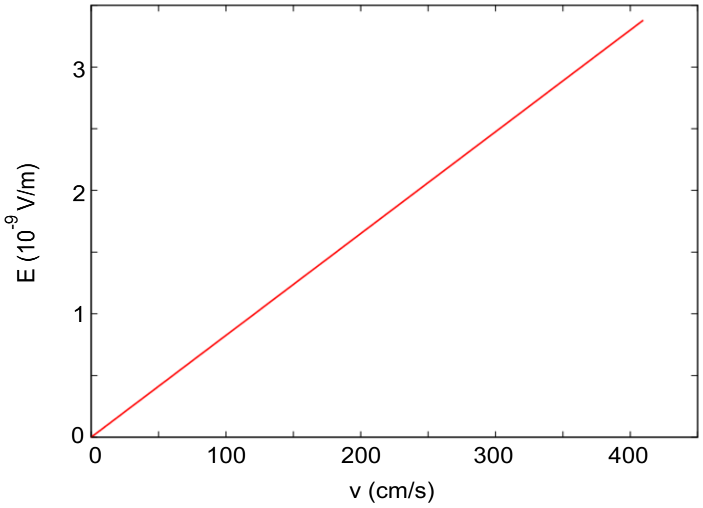
Frictional Drag in 2D-electron systems



Theory. M. B. Pogrebenskii 1977, P. J. Rice 1983
Experiment. T. J. Gramila *et.al* 1991, U. Sivan *et.al* 1992

Frictional drag between 2D-electron system

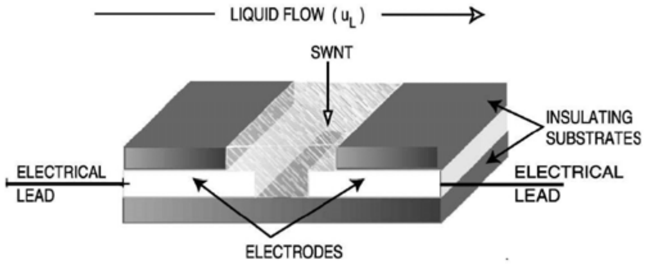


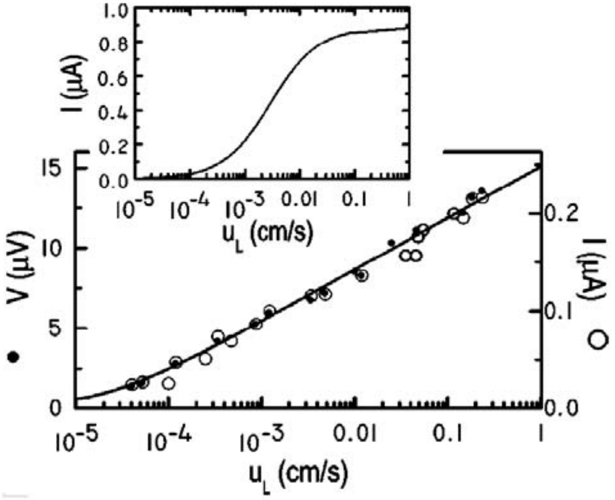


Left-Low density 2D electron systems: $n_s = 1.5 \times 10^{15}$m^{-2}, $T = 3$ K, $d = 175$ Å ,

Right-High density 2D electron systems: $n_s = 1.5 \times 10^{19}$m^{-2}, $T = 300$ K, $d = 175$ Å

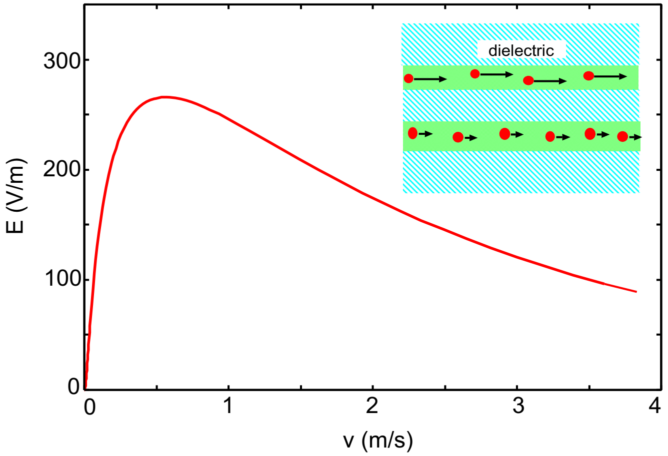
Frictional Drag induced by liquid flow.

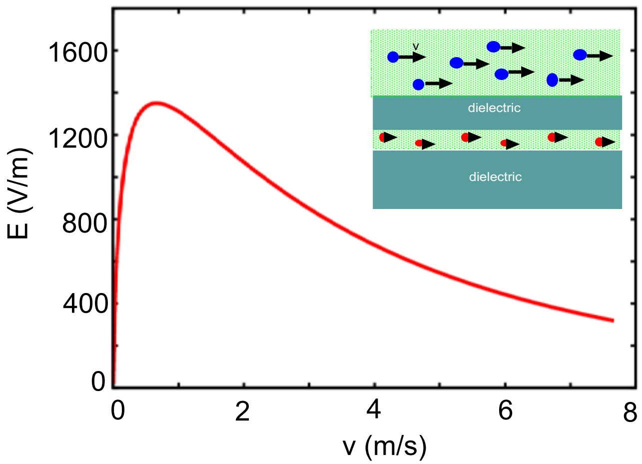




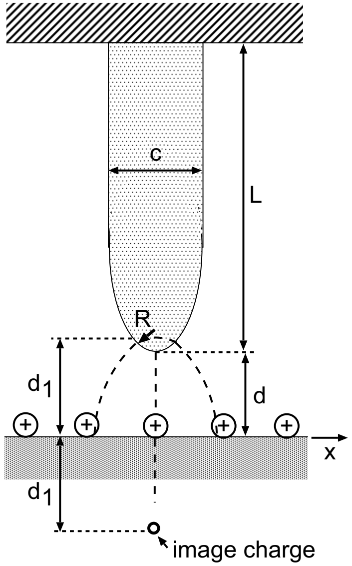
M. B. Ghost, A. K. Sood, S. Ramaswamy, and N. Kumar
2004

Frictional Drag induced by Brownian motion.





Electrostatic friction

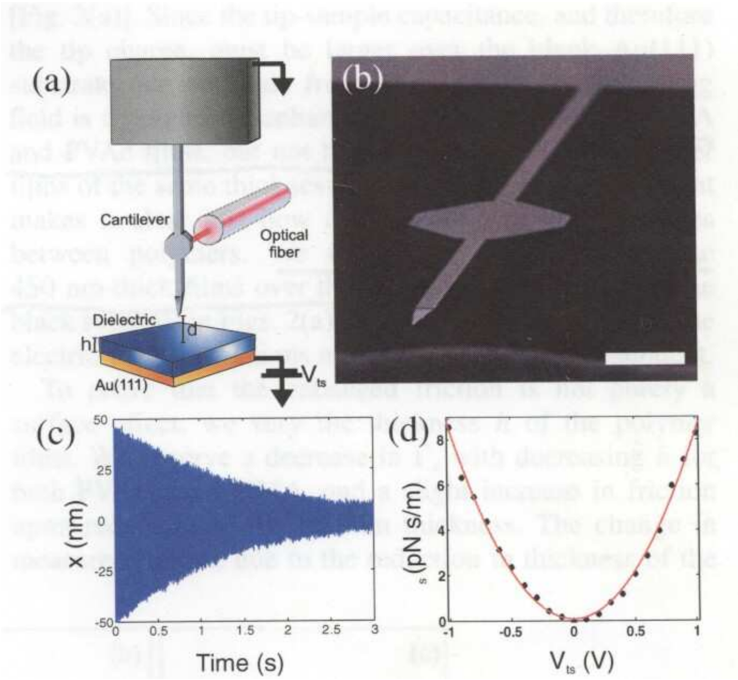


$$F_x = QE_x = CVE_x$$

$$\Gamma = \frac{C^2V^2}{k_BT}\int_0^\infty \langle E_x(t)E_x(0)\rangle dt$$

$$\Gamma = 2C^2(V^2+V_0^2)w\int_0^\infty dqqe^{-2q\sqrt{2dR}}\frac{\mathrm{Im}R_p(\omega_0,q)}{\omega_0}$$

Noncontact friction experiment.



$$F_{friction} = \Gamma V$$

$\Gamma \sim 10^{-13} - 10^{-12}\mathrm{kg/s}$ at the separation $1 - 100$ nm Stipe *et.al.* 2001. $\Gamma \approx d^{-n}$ with $n = 1.3 \pm 0.3$

Clean surface

$$\Gamma_{cl}^{c} = \frac{w(V^2 + V_0^2)}{2^6 \pi \sigma d^2}$$

For gold tip and gold sample this equation gives $\Gamma = 2.4 \times 10^{-20}\mathrm{kg/s}$ which is eight orders of magnitude smaller than experimental value $3 \times 10^{-12}\mathrm{kg/s}$.

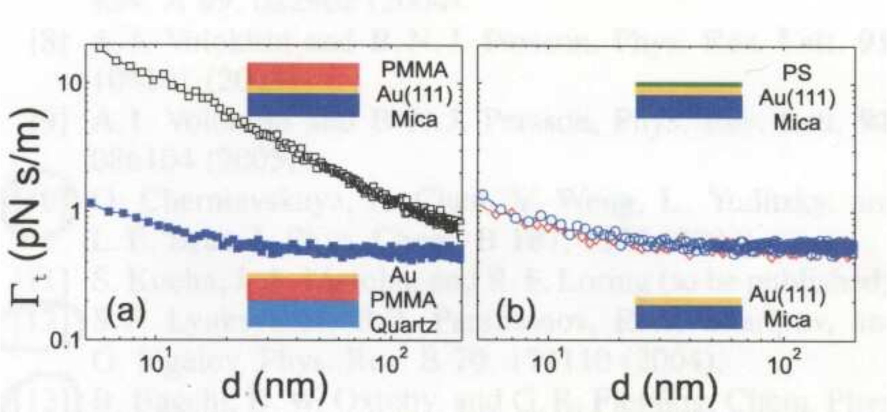
Adsorbate noncontact friction

For the Cs/Cu(100) system experiment suggest the existance of an acoustic film mode, even for the dilute phase ($\theta \approx 0.1$). In this case

$$\Gamma_{ad}^{c} = \frac{w\eta M R^{0.5}(V^2 + V_0^2)}{2^{4.5} d^{1.5} \pi n_a e^{*2}}$$

For Cs/Cu(100) system we obtain agreement with experiment at $d = 20\mathrm{nm}$ with $\eta = 10^{11}\mathrm{s}^{-1}$, $n_a = 10^{18}\mathrm{m}^{-2}$, $R = 1\mu\mathrm{m}$, $w = 7\mu\mathrm{m}$ and with the electric charge of the Cs ions $e^* = 0.28e$.

Dielectric fluctuations and noncontact friction



S.Kuehn, J.A.Marohn, and R.F.Loring 2006