ICTP/FANAS Conference on trends in Nanotribology

19 - 24 October 2009

Near-field radiative heat transfer and non-contact friction

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- Introduction
- Theory of the fluctuating electromagnetic field
- 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?

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

<table>
<thead>
<tr>
<th>$T$(K)</th>
<th>$\lambda_T$(μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2298.8</td>
</tr>
<tr>
<td>4.2</td>
<td>545.2</td>
</tr>
<tr>
<td>100</td>
<td>22.9</td>
</tr>
<tr>
<td>273</td>
<td>8.4</td>
</tr>
<tr>
<td>1000</td>
<td>2.3</td>
</tr>
</tbody>
</table>
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

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

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

\[ \left\langle j^f_i (\mathbf{r}) j^f_k (\mathbf{r}') \right\rangle \omega = \frac{\hbar}{(2\pi)^2} \left( \frac{1}{2} + n(\omega) \right) \omega^2 \text{Im} \varepsilon_{ik}(\mathbf{r}, \mathbf{r}', \omega) \]

\[ n(\omega) = \frac{1}{e^{\hbar \omega/k_B T} - 1} \]
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
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 $d = 10 \, \text{Å}$. 
The heat flux between two semi-infinite silver bodies coated with $10$ Å high resistivity ($\rho = 0.14$ Ω 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 Transfer

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.
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 the free carries of charge (electrons or ions) is induced in the upper medium.
Frictional Drag in 2D-electron systems

Frictional drag between 2D-electron system

**Left** - Low density 2D electron systems: \( n_S = 1.5 \times 10^{15} \text{m}^{-2} \), \( T = 3 \text{ K}, \ d = 175 \text{ Å} \),

**Right** - High density 2D electron systems: \( n_S = 1.5 \times 10^{19} \text{m}^{-2}, \ T = 300 \text{ K}, \ d = 175 \text{ Å} \)
Frictional Drag induced by liquid flow.

M. B. Ghost, A. K. Sood, S. Ramaswamy, and N. Kumar
2004
Frictional Drag induced by Brownian motion.

![Graph 1](image1)

![Graph 2](image2)
**Electrostatic friction**

\[ F_x = QE_x = CV E_x \]

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

\[ \Gamma = 2C^2(V^2 + V_0^2)w \int_0^\infty dq q e^{-2q\sqrt{2dR}} \frac{\text{Im} R_p(\omega_0, q)}{\omega_0} \]
Noncontact friction experiment.

\[ F_{\text{friction}} = \Gamma V \]

\[ \Gamma \sim 10^{-13} - 10^{-12} \text{kg/s} \text{ at the separation } 1 - 100 \text{ nm Stipe et.al. 2001.} \]

\[ \Gamma \approx d^{-n} \text{ with } n = 1.3 \pm 0.3 \]
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 \( \Gamma = 2.4 \times 10^{-20} \text{kg/s} \) which is eight orders of magnitude smaller than experimental value \( 3 \times 10^{-12} \text{kg/s}. \)
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

$$\Gamma_{ad}^c = \frac{w\eta MR^{0.5}(V^2 + V_0^2)}{24.5d^{1.5}\pi n_ae^*2}$$

For Cs/Cu(100) system we obtain agreement with experiment at $d = 20\text{nm}$ with $\eta = 10^{11}\text{s}^{-1}$, $n_a = 10^{18}\text{m}^{-2}$, $R = 1\mu\text{m}$, $w = 7\mu\text{m}$ 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