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Quantum friction

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Everything in the world is surrounded by electromagnetic fields, which are caused by the quantum and thermal fluctuations of the current density inside bodies. These fluctuating fields entail few important phenomena – the van der Waals interaction, the van der Waals friction, radiative heat transfer, etc. In this paper one of the aboce-mentioned phenomena, the van der Waals friction (quantum friction), is discussed. The most important quantum friction detection experiments are described in details – quantum friction between plates in relative motion, frictional drag force measurements and the quantum friction between the cantilever and the surface. Finally, prospective applications of the quantum friction are being discussed e.g. graphene-based field-effect transistor, precise force measuring, single spin detection by magnetic resonance force microscopy. Despite the number of written papers, this topic still remains controversial and under debates.

Contents

1. Introduction

Most of the forces in nature – electric, magnetic, gravity – do not require body-body contact. Unlike those mentioned above, as is generally known, the friction force acts only between the bodies in physical contact. However, another type of friction had been recently discovered. The aforementioned one is noncontact friction, and it arises between the objects that are in close proximity, but not in contact. The problem of noncontact friction plays important role in modern science especially in ultrasensitive force detection experiments, atomic force microscopy, and detection of single spin by magnetic resonance force microscopy. Van der Waals and Casimir forces measurements may also be limited by noncontact friction. To answer to the question "How to suppress the quantum friction?" will be possible only once the friction's origin is established. Over the last decade, many attempts to explain this phenomenon theoretically and experimentally have been done, but the theory that gives all the answers still does not exist.

2. The origin of the quantum friction

The origin of the van der Waals friction (quantum friction) is closely related to the van der Waals interaction. Let us consider a smooth surface with a neutral atom in close proximity. Despite the fact that a neutral atom has a zero mean electric dipole moment, is has also a nonzero electric dipole moment caused by the fluctuating current density due to quantum and thermal fluctuations [21]. The short-lived electric dipole moment of an atom can induce another dipole moment on a surface or in an atom some distance away. The interaction between two dipole moments results in attraction or repulsion, and is called conservative van der Waals interaction. Any two electrically neutral extended bodies interact with each other in the same way. There are two different regimes that must be distinguished:

- Separation between bodies d is small compared to the wavelength $\lambda \sim {}^{c}/_{\omega_0}$, c - the speed of the light, ω_0 - a characteristic frequency of the charge fluctuation; in this regime the interactions are determined by the fluctuations in an instantaneous Coulomb field. Retardation effects are negligible.
- If $d > \lambda$ retardation effects must be taken into account.

The interaction between moving bodies is called "dissipative van der Waals interaction". Let us suppose that we have two smooth parallel surfaces in proximity but not in contact. They must be separated by a wide band gap to prevent particles from tunneling across it. The surfaces are defined by their electromagnetic reflection coefficients only. If the surfaces are in relative motion the induced charge will lag slightly behind the fluctuating charge inducing it. This is the origin of the van der Waals friction. It is important that the friction arises in the absence of any roughness. Let us take a closer look at the origin of this friction. If the first body emits electromagnetic waves parallel and antiparallel to the moving direction, then in the rest reference frame of the second body these waves are opposite Dopler-shifted. Due to the frequency

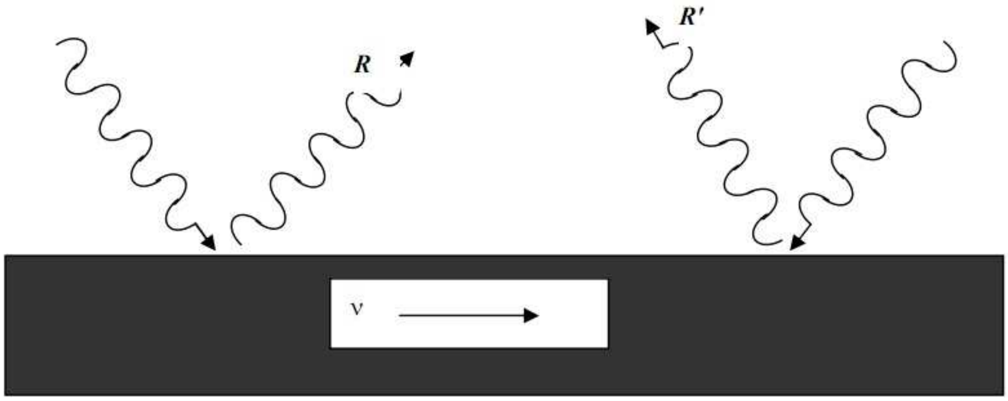


Fig.1. The electromagnetic waves emitted in opposite directions will experience an opposite Doppler shift and therefore will reflect differently.

dispersion of the reflection amplitude electromagnetic waves will reflect differently from the surface of the body. The same statement is true for waves emitted by the second body. The surface will emit radiation field due to thermal fluctuation of the current density, but even at low temperature the surface will be surrounded by radiation field created by zero-point quantum fluctuations.

Let us now attempt to describe van der Waals friction with the mechanism of the photon exchange. The forces mediated by photon can be long ranged, since there is no force preventing photon's to leave a surface. That is why a photon is the main candidate to describe quantum friction. Quantum friction originates from two types of different processes:

- The photons are created in both bodies with opposite momentum, and their frequencies obey an equation $vq = \omega_1 + \omega_2$, q - the momentum transfer
- The photon is created on one body and annihilated in another body.

The theory of van der Waals friction is controversial, that is why many theories have been created and many different experiments have been carried out, but the obtained results are in sharp contradiction with each other. For example, Volokitin and Persson [16] and Pendry [17] theoretically proved that difference between the Dopler shift of two modes can lead to a frictional force, if the reflectivities of the surfaces depend on frequency. Pendry defends his work, maintaining that he derived this result using different lines of argument. In addition, the quantum-frictional effects have been observed experimentally. However, T. Philbin and U. Leonhardt showed using Lifshitz's theory, that there is no lateral force, that is why no quantum friction between plates moving parallel. To prove their theory Philbin describe experiment that would seem to allow the extraction of unlimited energy from the quantum vacuum [17] if the lateral force exists.

3. Quantum friction experiments

While the conservative Van der Waals interaction [20] has long history and now it can be considered well-studied, the field of van der Waals friction is still controversial. Therefore many attempts to measure quantum friction were made. Among them are:

- Quantum friction measurement between two smooth parallel surfaces in relative motion;
- The measurements of the frictional drag force induced by Coulomb interaction between two 2D electron systems;
- Quantum friction measurement between the cantilever and the surface;
- Quantum friction measurement between two graphene sheets and between graphene and amorphous SiO_2 substrate.

These experiments are explained in more detail in the next chapters.

3.1. Quantum friction between two surfaces in relative motion

A straightforward calculation of the van der Waals friction based on the general theory of the fluctuating field developed by Rytov [10] and applied by Lifshitz [11] was carried out by Volokitin and Persson [14-16,18]. In their study, two semi-infinite solids having smooth parallel surfaces separated by a distance d and moving with velocity

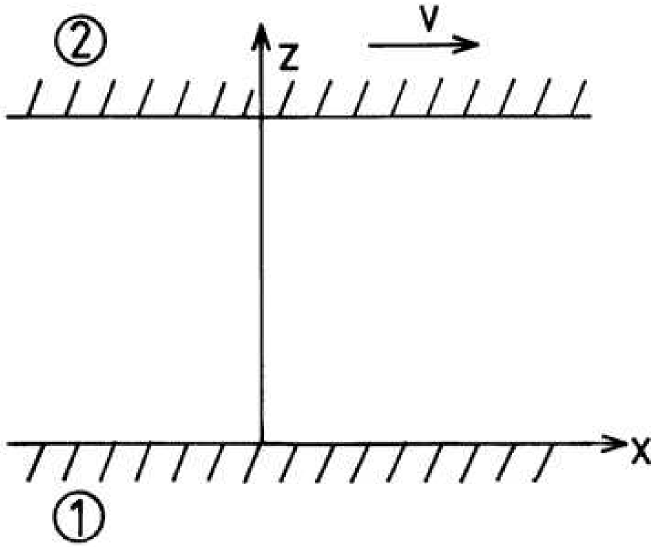


Fig.2. Two semi-infinite plates separated by distance d and moving with velocity v relative to each other

V relative to each other were observed. The two coordinate systems K and K' associated with the first and the second solids. The interaction between the bodies was mediated by the fluctuating electromagnetic field. The fluctuating field between bodies was calculated by introduction a 'random' field into the Maxwell equations and substituting the boundary conditions on the surface of bodies. The relationship between the calculated fields was then determined by Lorentz transformation. The frictional stress that acts on the surface of the body can be calculated from the xz - component of the Maxwell stress tensorσ_{ij}:

$$\sigma = \frac{1}{8\pi}\int_{-\infty}^{\infty} d\omega[\langle E_z E_x^* \rangle + \langle E_x E_z^* \rangle + \langle B_z B_x^* \rangle + \langle B_x B_z^* \rangle]_{z=0}$$

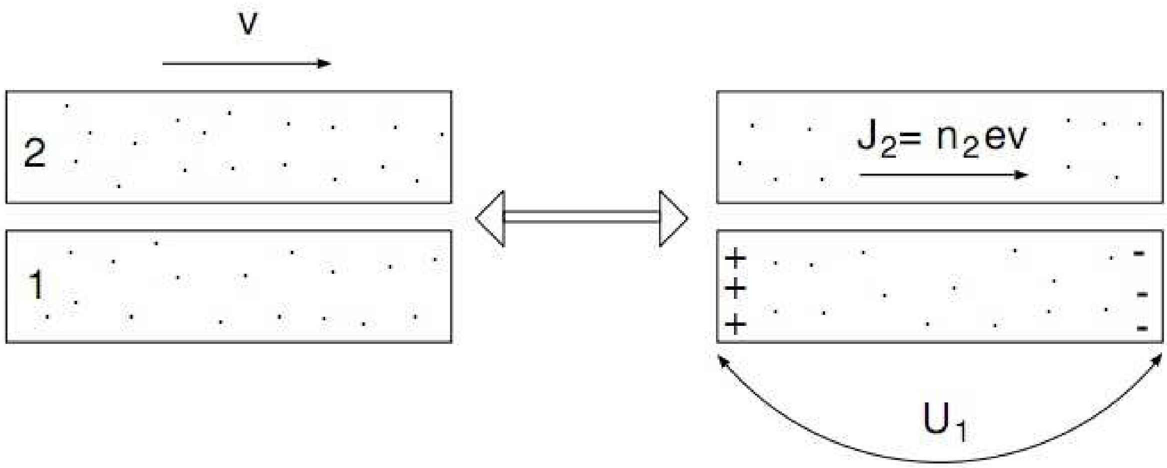
By substituting expressions for electric and magnetic field, changing the integration over ω between the limits $-\infty$ and ∞ to integration only over positive valuesω, and neglecting the terms of order $({}^{v}/{}_{c})^2$ the following results were obtained:

$$\sigma = \frac{\hbar}{8\pi^3}\int_0^\infty d\omega \int d^2 q q_x \left\{ \frac{\left(1-|R_{1p}|^2\right)\left(1-|R_{2p}^-|^2\right)}{|1-e^{2ipd}R_{1p}R_{2p}^-|^2}\left(n(\omega - q_x V) - n(\omega)\right) + \left[R_p \to R_s\right] \right\}_{q<\frac{\omega}{c}} + \frac{\hbar}{2\pi^3}\int_0^\infty d\omega \int d^2 q q_x e^{-2|p|d} \times \left\{ \frac{ImR_{1p}ImR_{2p}^-}{|1-e^{-2|p|d}R_{1p}R_{2p}^-|^2}\left(n(\omega - qV) - n(\omega)\right) + \left[R_p \to R_s\right] \right\}_{q>\omega/c}$$

This formula is general and can be easily transformed, e.g. for different distances d, temperature T, sliding velocities v etc.

3.2. The frictional drag force between 2D electron systems

Suppose we have electron 2-dimensional systems next to each other. A voltage is applied to the first system, while the second system remains open-circuit. Since no current can flow in the second system, an electric field arises that opposes the frictional drag force from the first system. The frictional drag force between two isolated 2-dimensional electron systems separated by a barrier can be considered as the dissipative Van der Waals friction. The origins of the drag force are Coulomb interaction and an exchange of phonons between the layers. By using a described system it is easy to observe the dependence of the frictional drag force on the separation d, electron density n and temperature T. The idea of such a system was first proposed by Shevchenko [1] and Lozovik and Yudson [2] and few years later Coulomb drag between separated 2D electron gases was discussed by Pogrebinskii [3] and Price [4] and other [19].



a) *b)*

Fig.3. a) electronic frictional shear stress σ is produced by relative motion of two metallic plates b) If a voltage U_2 is applied to the first metallic plate, the frictional stress will generate a voltage U_1 in the second plate.

The frictional stress $\sigma = \gamma v$ that acts on the electrons in the first metallic plate due to the current density $J = nev$ in the second plate must be calculated. Since current is not allowed to flow in the plate 1, an electric field E_1 arises and cancels the frictional stress σ:

$$\gamma = {n_1 e E_1}/{v} = {n_1 n_2 e^2 E_1}/{J_2} = n_1 n_2 e^2 \rho_{12}$$

n - carriers concentration per unit area, $\rho_{12} = {}^{E_1}/_{J_2}$ – transresistivity, the ratio of the induced electric field in the first plate to the current density in the second plate. Calculations carried out by Volokitin and Persson [5] showed, that under applied voltage $U_2 \approx 1\ V$, induced voltage in the second plate will be of the order $10^{-8}V$, therefore easily detectable by modern electronic instruments.

3.3. Quantum friction between the cantilever and the surface

In order to improve the basic understanding of noncontact friction between closely spaced gold surfaces, number of experiments were carried out by Gostmann et al.[6], Mamin et al.[7], Hoffmann et al.[8] and other[12][13]. A flat Au(111) surface and a ultrasensitive gold-coated cantilever have been used for noncontact friction measurement. Contributions of different forces can be separated from the total measured force interaction by considering their characteristic distance dependence. An experimental setup consists of metallic tip-sample system and detection system, under ultrahigh vacuum.

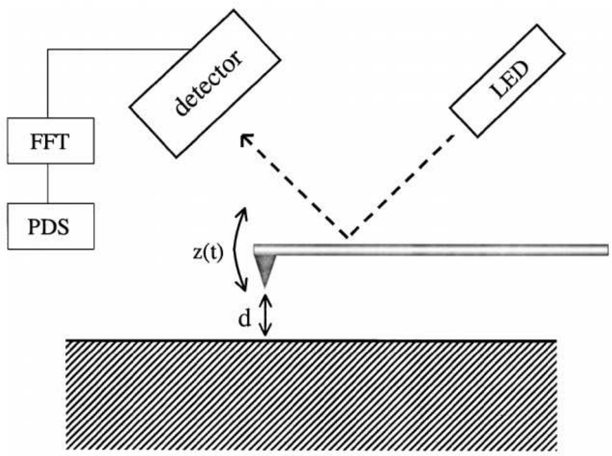


Fig.4. AFM experimental setup

When the tip is brought into proximity of a sample, forces between the tip and the sample lead to a deflection of the cantilever. The deflection is measured using a laser spot reflected from the cantilever into an array of photodiodes. This technique allows the determination of the distance dependent damping coefficient. Conservative and dissipative interactions can be analyzed in terms of their distance dependence. The theory for the conservative forces is well studied at the moment, however the origin of the long range damping forces in unclear yet. The tunneling of electrons can be excluded from the consideration because of the long range character of the interaction. Clearly, what is happening here is that Van der Waals damping (or quantum friction) is responsible for long range energy dissipation.

3.4. Quantum friction between graphene sheets.

Graphene – an allotrope of carbon, whose structure is one-atom-thick sheets of carbon atoms that are densely packed in a crystal lattice. Graphene is surrounded by a fluctuating electromagnetic field due to the thermal and quantum fluctuations of the current density. The electromagnetic field exists also outside of the body, in the form of evanescent and non-evanescent waves. Frictional drag experiments, similar to 2D-electron systems, can be performed between graphene sheets. Experiments must be performed in vacuum, to exclude contribution from the phonon exchange. At low velocities the induced electric field depends linearly on the velocity: $E = \mu^{-1}v$, μ – carrier mobility in a weak electric field.

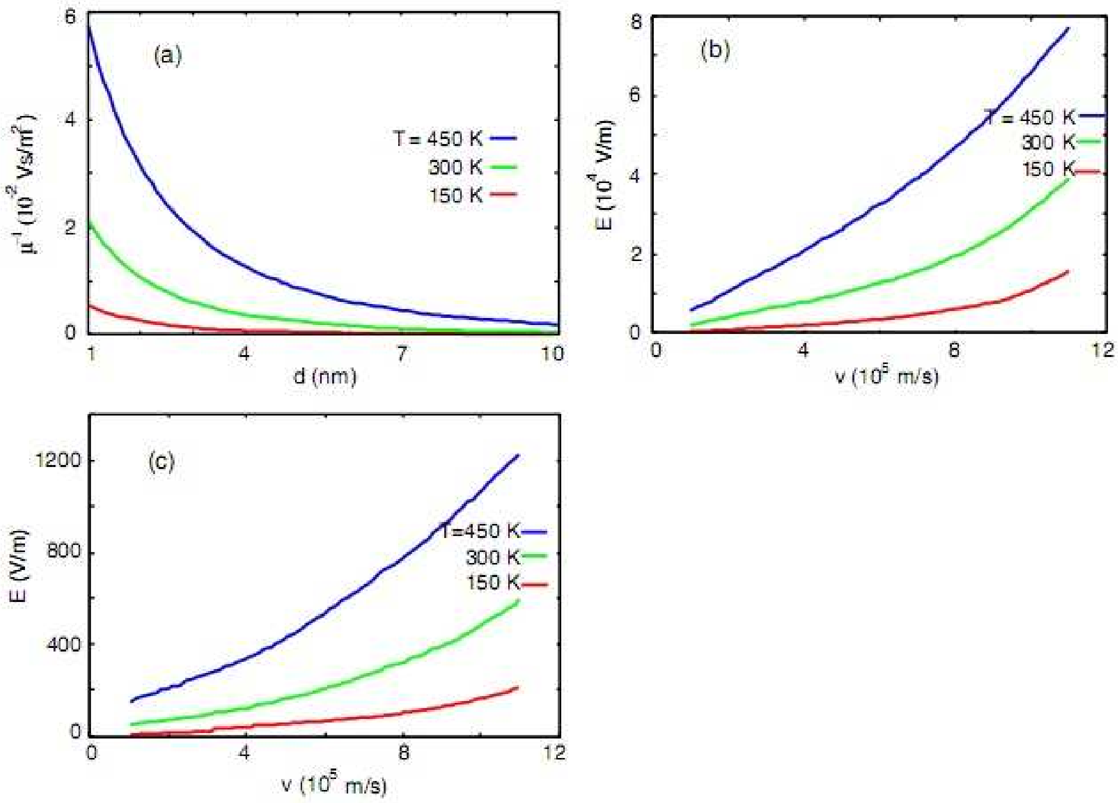


Fig.5. Frictional drag between two graphene sheets. (a) Dependence of friction coefficient per unit charge, on the separation between graphene sheets. (b),(c) Dependence of the electric field induced in graphene on drift velocity of charge carriers in another graphene sheets at the layer separation $d = 1$ nm and $d = 10$ nm.

As it was shown in [9,23], voltage $V = 10$ nV will be induced for graphene sheet of length 1 μm, and with $v = 100$ nV.

Another way to detect quantum friction is measuring I-V curves of the graphene-based field-effect transistor. Electrons in graphene are influenced by the external

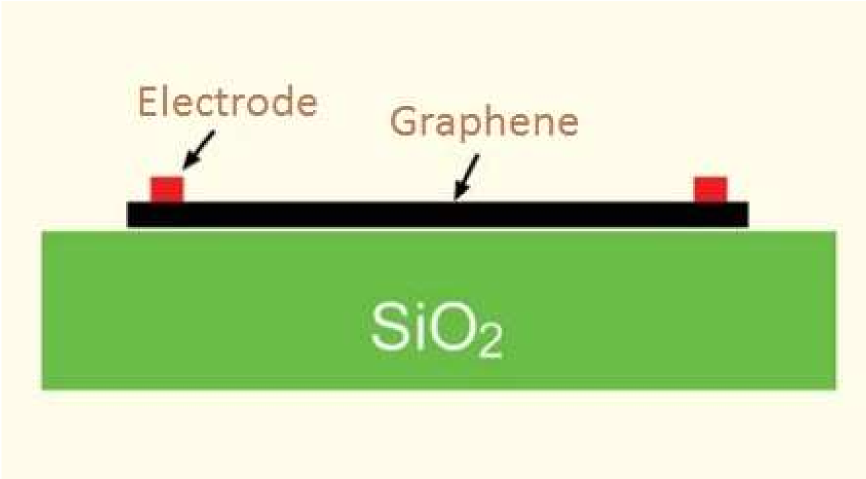


Fig.6. Graphene-based field-effect transistor.

friction forces, that is caused by interaction with SiO_2 phonons. The friction force acting on the charge carriers in graphene for high electric field is mostly determined by the interaction with the optical phonons of the graphene and with the optical phonons of the substrate. The frequency of optical phonons in SiO_2 is 4 times lower than for the optical phonons in graphene. Therefore the high-field friction force will be determined by excitations of optical phonons in SiO_2. Thus, measuring I-V curves of a graphene-based field-effect transistor makes it possible to detect quantum friction.

4. Conclusion and discussion

Quantum friction, as superconductivity and superfluidity, is a macroscopic phenomenon, the nature of which is determined by the quantum laws. Quantum friction is very important in modern applied researches. For example, the characteristics of f graphene-based field-effect transistor, that is available at the moment, may be largely determined by the quantum friction. According to the strategic concepts of nanotechnology, the graphene-based field-efect transistor should replace the silicone one during the next 10 years and will lead to further progress in nanoelectronics. Many other micro- and nanoelectromechanical systems may also depend on the quantum friction. In addition, quantum friction determines the limit for reducing the friction force, and therefore – reducing fluctuations. According to Einstein's relation, friction and fluctuations are related to each other. The same force that leads to chaotic motion of a Brownian particle is responsible for the friction when the particle moves in a medium. On the other hand, the fluctuations affect the accuracy of the force measurement. For example, single spin detection by magnetic resonance force microscopy would require reducing the fluctuating forces to an unprecedented level. Besides measuring the Casimir – Lifshitz forces could also be limited by the effects of noncontact friction. For all mentioned applications, it is necessary to learn how to manage a noncontact friction. To sum up, the origin of quantum friction has been studied in this paper. The main theories together with supporting experiments were described. Despite dozens of papers, published by different scientific groups all over the world, the quantum friction theory remains contradictory, and requires future research.

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