Quantum Friction

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We investigate the van der Waals friction between graphene and an amorphous SiO_2 substrate. We find that due to this friction the electric current is saturated at a high electric field, in agreement with experiment. The saturation current depends weakly on the temperature, which we attribute to the quantum friction between the graphene carriers and the substrate optical phonons. We calculate also the frictional drag between two graphene sheets caused by van der Waals friction, and find that this drag can induce a voltage high enough to be easily measured experimentally.

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For several decades, physicists have been intrigued by the idea of quantum friction. It has recently been shown that two bodies moving relative to each other experience a friction due to quantum fluctuations inside the bodies [1–4]. However, at present there is no experimental evidence for or against this effect, because the predicted friction forces are very small and precision measurement of quantum forces are incredibly difficult with present technology. The existence of quantum friction is still debated even among theoreticians [5–9]. In this Letter we propose that quantum friction can be observed in experiments on studying of electrical transport phenomena in nonsuspended graphene on amorphous SiO_2 substrate.

Graphene, the recently isolated single-layer carbon sheet, consists of carbon atoms closely packed in a flat two-dimensional crystal lattice. The unique electronic and mechanical properties of graphene [10,11] are being actively explored both theoretically and experimentally because of its importance for fundamental physics, and for possible technological applications, in particular, for electronics and sensors [10,12].

Graphene, as is all media, is surrounded by a fluctuating electromagnetic field due to the thermal and quantum fluctuations of the current density. Outside the bodies, this fluctuating electromagnetic field exists partly in the form of propagating electromagnetic waves and partly in the form of evanescent waves. The theory of the fluctuating electromagnetic field was developed by Rytov [13–15]. A great variety of phenomena such as Casimir-Lifshitz forces [16], near-field radiative heat transfer [17], noncontact friction [2–4], and the frictional drag in low-dimensional systems [18,19] can be described using this theory.

In this Letter, we investigate the friction force on moving with drift velocity v charge carriers in graphene due to interaction with optical phonons in nearby amorphous SiO_2. The dissipated energy results in heating of the graphene, and is transferred to the SiO_2 substrate via the near-field radiative heat transfer process and direct phononic coupling. Using the theories of the van der Waals friction and the near-field radiative heat transfer we formulate a theory that describes these phenomena and allows us to predict experimentally measurable effects. In comparison with the existing microscopic theories of transport in graphene [20,21] our theory is macroscopic. The electromagnetic interaction between graphene and a substrate is described by the dielectric functions of the materials which can be accurately determined from theory and experiment.

Assume that a graphene sheet is separated from the substrate by a sufficiently wide insulator gap, which prevents particles from tunneling across it. If the charge carriers inside graphene move with velocity v relative to the substrate, a frictional stress will act on them. This frictional stress is related to an asymmetry of the reflection amplitude along the direction of motion [see Fig. 1]. If the substrate emits radiation, then in the rest reference frame of charge carriers in graphene these waves are Doppler shifted which will result in different reflection amplitudes. The same is true for radiation emitted by moving charge carriers in graphene. The exchange of "Doppler-shifted-photons" will result in momentum and energy transfer

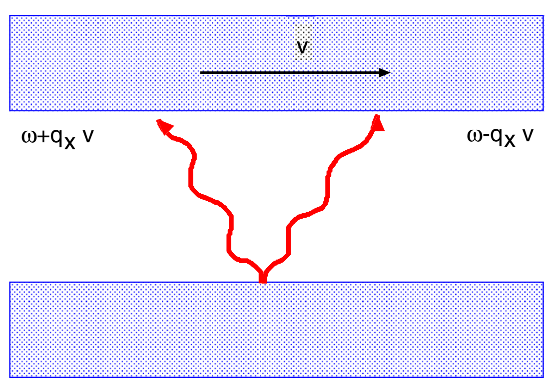

FIG. 1 (color online). Two bodies moving relative to each other will experience van der Waals friction due to the Doppler shift of the electromagnetic waves emitted by them.

between graphene and substrate, which is the origin of the van der Waals friction.

Let us consider graphene and a substrate with flat parallel surfaces at separation $d \ll \lambda_T = c\hbar/k_B T$. Assume that the free charge carriers in graphene move with the velocity $v \ll c$ (c is the light velocity) relative to the substrate. According to Refs. [2–4] the frictional stress F_x acting on charge carriers in graphene, and the radiative heat flux S_z across the surface of substrate, both mediated by a fluctuating electromagnetic field, are determined by

$$F_x = \frac{\hbar}{\pi^3}\int_0^\infty dq_y \int_0^\infty dq_x q_x e^{-2qd}\left\{\int_0^\infty d\omega\left(\frac{\mathrm{Im}R_d(\omega)\mathrm{Im}R_g(\omega^+)}{|1-e^{-2qd}R_d(\omega)R_g(\omega^+)|^2}\times[n_d(\omega)-n_g(\omega^+)] + \frac{\mathrm{Im}R_d(\omega^+)\mathrm{Im}R_g(\omega)}{|1-e^{-2qd}R_d(\omega^+)R_g(\omega)|^2}[n_g(\omega)-n_d(\omega^+)]\right) + \int_0^{q_x v} d\omega \frac{\mathrm{Im}R_d(\omega)\mathrm{Im}R_g(\omega^-)}{|1-e^{-2qd}R_d(\omega)R_g(\omega^-)|^2}[n_g(\omega^-)-n_d(\omega)]\right\}, \tag{1}$$

$$S_z = \frac{\hbar}{\pi^3}\int_0^\infty dq_y \int_0^\infty dq_x e^{-2qd}\left\{\int_0^\infty d\omega\left(-\frac{\omega\mathrm{Im}R_d(\omega)\mathrm{Im}R_g(\omega^+)}{|1-e^{-2qd}R_d(\omega)R_g(\omega^+)|^2}\times[n_d(\omega)-n_g(\omega^+)] + \frac{\omega^+\mathrm{Im}R_d(\omega^+)\mathrm{Im}R_g(\omega)}{|1-e^{-2qd}R_d(\omega^+)R_g(\omega)|^2}[n_g(\omega)-n_d(\omega^+)]\right) + \int_0^{q_x v} d\omega \frac{\omega\mathrm{Im}R_d(\omega)\mathrm{Im}R_g(\omega^-)}{|1-e^{-2qd}R_d(\omega)R_g(\omega^-)|^2}[n_g(\omega^-)-n_d(\omega)]\right\}, \tag{2}$$

where $n_i(\omega) = [\exp(\hbar\omega/k_B T_i - 1]^{-1}$ $(i = g,\ d)$, $T_{g(d)}$ is the temperature of graphene (substrate), R_i is the reflection amplitude for surface i for p-polarized electromagnetic waves, and $\omega^\pm = \omega \pm q_x v$. The reflection amplitude for graphene (substrate) is determined by [18]

$$R_{g(d)} = \frac{\epsilon_{g(d)} - 1}{\epsilon_{g(d)} + 1}, \tag{3}$$

where $\epsilon_{g(d)}$ is the dielectric function for graphene (substrate).

In the study below we used the dielectric function of graphene, which was calculated recently within the random-phase approximation (RPA) [22,23]. The small (and constant) value of the graphene Wigner-Seitz radius r_s indicates that it is a weakly interacting system for all carries densities, making the RPA an excellent approximation for graphene (RPA is asymptotically exact in the $r_s \ll 1$ limit). The dielectric function is an analytical function in the upper half-space of the complex ω plane

$$\epsilon_g(\omega, q) = 1 + \frac{4k_F e^2}{\hbar v_F q} - \frac{e^2 q}{2\hbar\sqrt{\omega^2 - v_F^2 q^2}}\left\{G\left(\frac{\omega + 2v_F k_F}{v_F q}\right) - G\left(\frac{\omega - 2v_F k_F}{v_F q}\right) - i\pi\right\}, \tag{4}$$

where

$$G(x) = x\sqrt{1-x^2} - \ln(x + \sqrt{1-x^2}), \tag{5}$$

where the Fermi wave vector $k_F = (\pi n)^{1/2}$, n is the concentration of charge carriers, the Fermi energy $\epsilon_F = \gamma k_F = \hbar v_F k_F$, $\gamma = \hbar v_F \approx 6.5$ eV Å, and v_F is the Fermi velocity. The dielectric function of amorphous SiO_2 can be described using an oscillator model [24].

The equilibrium or steady state temperature can be obtained from the condition that the heat power generated by friction must be equal to the heat transfer across the substrate surface

$$F_x(T_d, T_g)v = S_z(T_d, T_g) + \alpha_{\mathrm{ph}}(T_g - T_d), \tag{6}$$

where the second term in Eq. (6) takes into account the heat transfer through direct phononic coupling; α_{ph} is the thermal contact conductance due to phononic coupling.

Figures 2(a) and 2(b) show the dependence of the current density on the electric field at $n = 10^{12}$ cm^{-2}, and for different temperatures. In obtaining these curves we have used that $J = nev$ and $neE = F_x$, where J and E are current density and electric field, respectively. Note that the current density saturate at $E \sim 0.5$–2.0 V/μm, which

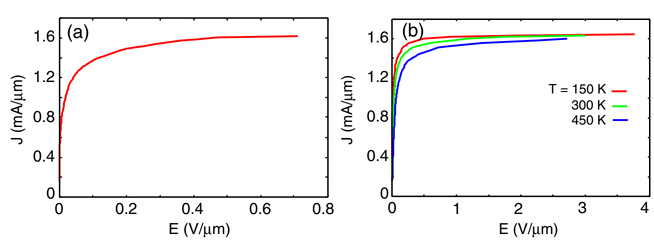

FIG. 2 (color online). The role of the interaction between phonon polaritons in SiO_2 and free carriers in graphene for graphene field-effect transistor transport. The separation between graphene and SiO_2 is $d = 3.5$ Å. (a) Current density-electric field dependence at $T = 0$ K, $n = 10^{12}$ cm^{-12}. (b) The same as in (a) but for different temperatures.

is in agreement with experiment [25]. The saturation velocity can be extracted from the I-E characteristics using $J_{\rm sat} = nev_{\rm sat}$, where 1.6 mA/$\mu$m is the saturated current density, and with the charge density concentration $n = 10^{12}$ cm^{-2}: $v_{\rm sat} \approx 10^6$ m/s. Figure 2(a) was calculated at $T_d = 0$ K. At zero temperature, the van der Waals friction is due to quantum fluctuations of charge density, and is determined by the second term in Eq. (2) [1–4]

$$F_x(T_d = T_g = 0) = -\frac{\hbar}{\pi^3}\int_0^\infty dq_y \int_0^\infty dq_x \int_0^{q_x v} d\omega q_x e^{-2qd} \times \frac{\mathrm{Im}R_d(\omega)\mathrm{Im}R_g(\omega^-)}{|1 - e^{-2qd}R_d(\omega)R_g(\omega^-)|^2}. \quad (7)$$

The existence of quantum friction is still debated in the literature [5–9]. The van der Waals friction can be studied in noncontact experiments, and in frictional drag experiments [4]. In both these experiments the solids are separated by a potential barrier thick enough to prevent electrons or other particles with a finite rest mass from tunneling across it, but allowing the interaction via the long-range electromagnetic field, which is always present in the gap between bodies. In noncontact friction experiments the damping of cantilever vibrations is typically measured, while in frictional drag experiments a current density is induced in one medium. The friction between the moving charge carriers and nearby medium gives rise to a change of I-E characteristics, which can be measured.

The friction force acting on the charge carriers in graphene for the high electric field is 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 graphene is a factor 4 larger than for the optical phonon in SiO_2. Thus, one can expect that for graphene on SiO_2 the high-field I-E characteristics will be determined by excitations of optical phonons in SiO_2. According to the theory of the van der Waals friction [4], the quantum friction, which exists even at zero temperature, is determined by the creation of excitations in each of the interacting media, the frequencies of which are connected by $vq_x = \omega_1 + \omega_2$. The relevant excitations in graphene are the electron-hole pairs whose frequencies begin from zero, while for SiO_2 the frequency of surface phonon polaritons $\omega_{\rm ph} \approx 60$ meV (9×10^{13} s^{-1}). The characteristic wave vector of graphene is determined by Fermi wave vector k_F. Thus the friction force is strongly enhanced when $v > v_{\rm sat} = \omega_{\rm ph}/k_F \sim 10^6$ m/s, in accordance with numerical calculations. Thus measurements of the current density-electric field relation of graphene adsorbed on SiO_2 give the possibility to detect quantum friction.

An alternative method of studying of the van der Waals friction consists of driving an electric current in one metallic layer and studying the effect of the frictional drag on the electrons in a second (parallel) metallic layer. Such experiments were first suggested by Pogrebinskii [26] and Price [27], and were performed for 2D-quantum wells [28,29].

Similar to 2D-quantum wells in semiconductors, frictional drag experiments can be performed (even more easily) between graphene sheets. Such experiments can be performed in a vacuum where the contribution from the phonon exchange can be excluded. To exclude noise

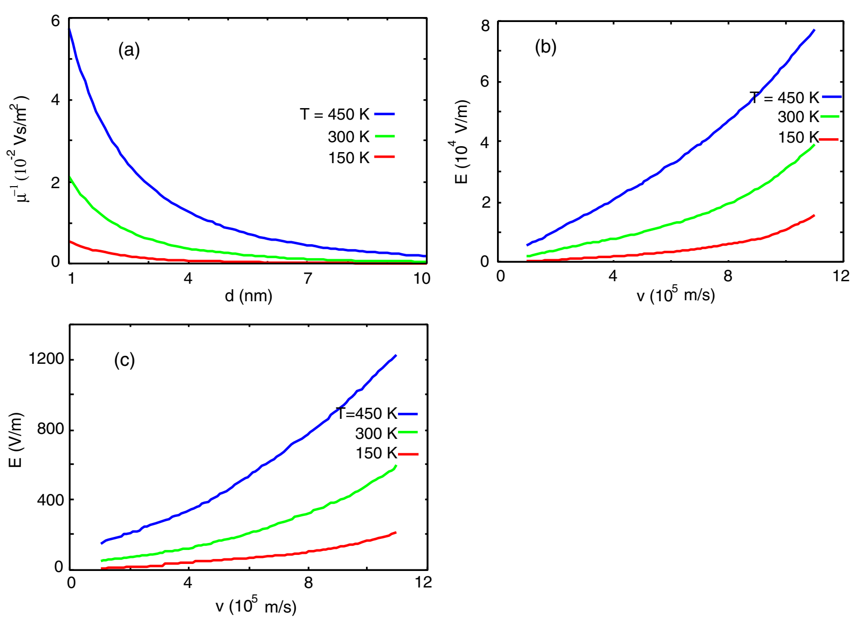

FIG. 3 (color online). Frictional drag between two graphene sheets at the carrier concentration $n = 10^{12}$ cm^{-2}. (a) Dependence of friction coefficient per unit charge, $\mu^{-1} = \Gamma/ne$, on the separation between graphene sheets d. (b) Dependence of the electric field induced in graphene on drift velocity of charge carriers in other graphene sheets at the layer separation $d = 1$ nm. (c) The same as in (b) but at $d = 10$ nm.

(due to presence of dielectric) the frictional drag experiments between quantum wells were performed at very low temperature ($T \approx 3$ K) [28]. For suspended graphene sheets there is no such problem and the experiment can be performed at room temperature. In addition, 2D-quantum wells in semiconductors have very low Fermi energy $\epsilon_F \approx 4.8 \times 10^{-3}$ eV [28]. Thus electrons in these quantum wells are degenerate only for very low temperatures $T < T_F = 57$ K. For graphene the Fermi energy $\epsilon_F = 0.11$ eV at $n = 10^{12}$ cm^{-2}, and the electron gas remains degenerate for $T < 1335$ K.

At small velocities the electric field induced by frictional drag depends linearly on the velocity, $E = (\Gamma/ne)v = \mu^{-1}v$, where μ is the low-field mobility. For $\hbar\omega \ll \epsilon_F$ and $q \ll k_F$ the reflection amplitude for graphene is given by the same expression as for a 2D-quantum well [4] and from Eq. (3) we get

$$\Gamma = 0.018\,78 \frac{\hbar}{d^4}\left(\frac{k_B T}{k_F e^2}\right)^2 \tag{8}$$

Figure 3(a) shows the dependence of the friction coefficient (per unit charge) μ^{-1} on the separation d between the sheets. For example, $E = 5 \times 10^{-4} v$ for $T = 300$ K and $d = 10$ nm. For a graphene sheet of length 1 μm, and with $v = 100$ m/s this electric field will induce the voltage $V = 10$ nV. Figures 3(b) and 3(c) show the induced electric field-velocity relation for high velocity, with $d = 1$ nm (b) and $d = 10$ nm (c).

Concluding remarks.—We have used theories of the van der Waals friction and near-field radiative heat transfer to study transport in graphene due to the interaction with phonon-polaritons in an (amorphous) SiO_2 substrate. High-field transport exhibits a weak temperature dependence, which can be considered as a manifestation of quantum fluctuations. Thus the study of transport properties in graphene gives the possibility of detecting quantum friction, the existence of which is still debated in the literature. We have calculated the frictional drag between graphene sheets mediated by the van der Waals friction, and found that it can induce large enough voltage to be easily measured.

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