Noncontact Friction and Force Fluctuations between Closely Spaced Bodies

B. C. Stipe,[1] H. J. Mamin,[1] T. D. Stowe,[2] T. W. Kenny,[2] and D. Rugar[1]

[1]*IBM Research Division, Almaden Research Center, 650 Harry Road, San Jose, California 95120-6099*

[2]*Departments of Applied Physics and Mechanical Engineering, Stanford University, Stanford, California 94305-4021*

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Noncontact friction between a Au(111) surface and an ultrasensitive gold-coated cantilever was measured as a function of tip-sample spacing, temperature, and bias voltage using observations of cantilever damping and Brownian motion. The importance of the inhomogeneous contact potential is discussed and comparison is made to measurements over dielectric surfaces. Using the fluctuation-dissipation theorem, the force fluctuations are interpreted in terms of near-surface fluctuating electric fields interacting with static surface charge.

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The microfabricated cantilever has become a remarkably sensitive tool for the study of forces at small length scales and serves as the heart of the atomic force microscope (AFM). In addition to measuring static forces, microfabricated cantilevers can also be used to reveal ultrasmall dissipative interactions [1–5]. In a recent Letter, Dorofeyev *et al.* [6] studied noncontact friction between a gold-coated tip and a gold surface under ultrahigh vacuum conditions at room temperature. They observed a noncontact friction effect that they claim is mediated by thermal near-field radiation [7] present near the metal surfaces. This result is controversial [8], however, since this "vacuum" friction effect (sometimes called "van der Waals friction") has been previously calculated [9–11] to be 11 orders of magnitude smaller than that observed by Dorofeyev *et al.*

It is worthwhile to try to resolve this disagreement since noncontact friction effects are of practical importance for many proposed ultrasensitive force detection experiments. This is because the ability to detect small forces is inextricably linked to friction via the fluctuation-dissipation theorem. For example, the detection of single spins by magnetic resonance force microscopy (MRFM), which has been proposed for three-dimensional atomic imaging [12] and quantum computation [13], will require force fluctuations to be reduced to unprecedented levels. In addition, the search for quantum gravitational effects at short length scales [14] and future measurements of Casimir forces [15] may eventually be limited by noncontact friction effects.

In order to improve the basic understanding of noncontact friction effects, we present measurements of noncontact friction between closely spaced gold surfaces at various temperatures. As shown in Fig. 1, our experiments were performed using a gold-coated single-crystal silicon cantilever that was oriented perpendicular to a Au(111) sample. With the perpendicular cantilever orientation, the tip's vibrational motion was parallel to the sample surface to within an orientation accuracy better than 1°. The measurement apparatus was mounted inside a turbopumped vacuum can that was placed in a superinsulated Dewar. The 250-nm-thick Au(111) sample was epitaxially grown at 300 °C by evaporation of gold onto a mica substrate. The freshly prepared sample was transferred to the measurement apparatus and introduced into vacuum within a few hours. AFM imaging of typical samples showed large (>100 nm) atomically flat terraces separated by monatomic step bunches.

The custom-fabricated cantilever [16,17] had dimensions of 250 μm × 7 μm × 250 nm with spring constant $k_0 = 3.3 \times 10^{-4}$ N/m and fundamental mode resonance frequency $\omega_0/2\pi = 3.86$ kHz. The low spring constant and inherently low dissipation of this cantilever allows much smaller dissipation levels to be probed than is possible with conventional AFM cantilevers. To enhance the frictional effects, the cantilever's in-plane tip was designed to be relatively blunt, with a radius of curvature of approximately 1 μm. To provide electrical contact to the tip, the entire cantilever was sputter coated with 1 nm titanium followed by 10 nm platinum. Because of the very low spring

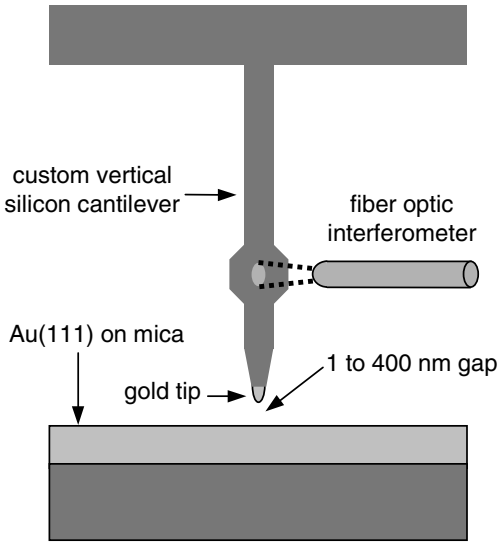

FIG. 1. Schematic diagram of the experimental setup. The cantilever's motion was detected with a fiber optic interferometer while the tip-sample spacing was controlled by piezoelectric actuators. The entire cantilever was metallized so that the tip-sample bias voltage could be varied.

constant, care was taken to coat the cantilever evenly to prevent curling. Finally, the tip of the cantilever was coated with 200 nm of gold by evaporation. It was found that the coatings reduced the intrinsic cantilever quality factor Q_0 by approximately a factor of 6 relative to uncoated cantilevers. The resulting cantilever quality factors were 5200 at 295 K, 8100 at 77 K, and 17 200 at 4 K. The high longitudinal stiffness of the perpendicular-oriented cantilever (>1000 N/m) allowed us to position the cantilever tip to within 2 nm of the surface without snap-in. The cantilever's vibrational motion was detected with a fiber-optic interferometer operating at 1310 nm wavelength with less than 10 nW optical power incident on the cantilever [18]. The noise level of all measurements was limited only by cantilever Brownian motion [16,19].

We model the cantilever as a simple harmonic oscillator with a Langevin-type thermal excitation term $F(t)$ [20]: $m(d^2x/dt^2) + \Gamma(dx/dt) + kx = F(t)$, where x is the cantilever tip displacement, $m = k_0/\omega_0^2$ is the cantilever effective mass, and $\Gamma = m\omega/Q$ characterizes the friction. The stochastic driving term $F(t)$ has the (single-sided) power spectral density $S_F = 4\Gamma k_B T$, which ensures that the thermal equilibrium vibration amplitude satisfies the equipartition theorem: $\frac{1}{2}k\langle x^2\rangle = \frac{1}{2}k_B T$. In general, we can write the friction coefficient as $\Gamma = \Gamma_0 + \Gamma_s$, where Γ_0 is the intrinsic cantilever friction coefficient and Γ_s represents the noncontact tip-sample friction. Γ_s is the main quantity of interest and is determined experimentally according to $\Gamma_s(d) = \Gamma(d) - \Gamma_0 = m[\omega(d)/Q(d) - \omega_0/Q_0]$, where $\omega(d)$ and $Q(d)$ are the cantilever frequency and quality factor measured at a tip-sample distance d.

Three different methods for determining Q are demonstrated in Fig. 2. In the "ringdown" method, the cantilever is oscillated at its natural resonance frequency with a preset rms amplitude X_0 (typically 10 to 20 nm) using a piezoelectric disk and a gain-controlled positive feedback loop [19]. The drive circuit is then abruptly grounded and the cantilever rings down until thermal equilibrium is established. If $X(t)$ represents the rms amplitude of the cantilever oscillation, then $X^2(t)$ is simply an exponential decay toward $k_B T/k$ with decay time constant Q/ω [21]. If the tip vibration direction is accurately parallel to the sample surface, Q determined from the ringdown time (Fig. 2a) should be accurate even when $d \leq X_0$.

To verify the accuracy of the ringdown method for small d, we used a second method that is based on the Brownian (thermal) motion of the cantilever. This method has the advantage that the tip vibration amplitude is much smaller than in the ringdown method (<4 nm rms). We record the envelope of the thermal vibration $X(t)$ for a period of several minutes and numerically compute the autocorrelation of the energy $\langle X^2(t)X^2(t+\tau)\rangle$. For a high Q harmonic oscillator driven by Gaussian thermal noise, it can be shown that $\langle X^2(t)X^2(t+\tau)\rangle$ exponentially decays with a time constant Q/ω [22]. Figure 2b shows the decaying portion of the energy autocorrelation taken for the same two tip-sample spacings as shown in Fig. 2a for the ringdown method. Q values determined by fitting the autocorrelation data agreed with the ringdown measurements to better than 20%. Both the ringdown method and the energy autocorrelation method are insensitive to small anharmonic effects.

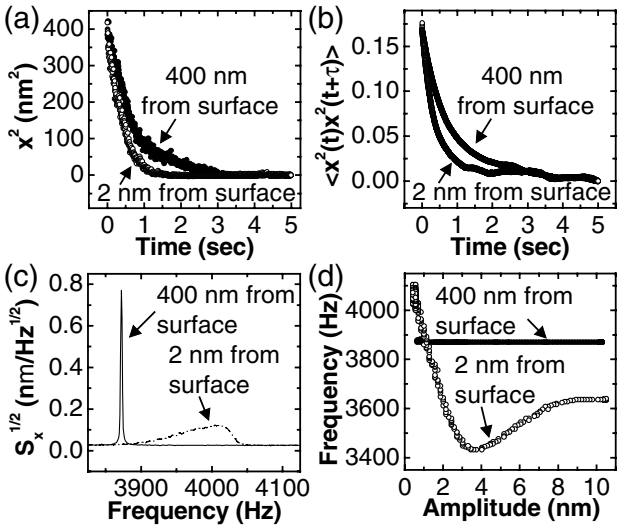

FIG. 2. Three methods for determining tip-sample friction. (a) Cantilever ringdown after excitation to an rms amplitude of 20 nm gives $Q = 17\,250$ for $d = 400$ nm and $Q = 8270$ for $d = 2$ nm. (b) Autocorrelation of the thermal energy $X^2(t)$ gives $Q = 20\,300$ for $d = 400$ nm and $Q = 8200$ for $d = 2$ nm (offset has been substracted). (c) Spectral width of cantilever thermal vibrations gives $Q = 17\,000$ for $d = 400$ nm and $Q = 30$ for $d = 2$ nm assuming a harmonic potential. Notice, however, that the lineshape at 2 nm is not Lorentzian. (d) Cantilever frequency vs cantilever amplitude during free ringdown shows anharmonic behavior at $d = 2$ nm. All measurements were performed at 4.2 K.

We also tested the method used in Ref. [6]. In this method, the power spectral density of the cantilever's thermal vibration S_x is measured, and the spectral width of the resonance peak is used to determine Q (Fig. 2c). At large tip-sample separation, Q values obtained from the peak width agreed with the previous two methods. However, at smaller tip-sample separation, the line shape broadened and eventually became non-Lorentzian. For $d = 2$ nm, the inferred Q value was 600 times smaller than that obtained using the other two methods (Fig. 2c). The distortion and broadening of the spectral density for small d is due to the combination of oscillator anharmonicity and naturally occurring fluctuations of the thermal vibration amplitude. The presence of anharmonicity was verified by measuring the dependence of cantilever frequency on amplitude (Fig. 2d). At $d = 2$ nm, the frequency shift was as large as 100 Hz for a 1 nm change in vibration amplitude. Since only a small degree of anharmonicity is required to significantly broaden the spectral peak, we consider this method to be unreliable for measuring tip-sample friction.

Figure 3a shows tip-sample friction measured as a function of distance at 295 and 77 K using the ringdown method. The friction at 295 K for a spacing of 10 nm was 1.5×10^{-13} kg/s, which is ~4000 times smaller than that reported in Ref. [6] at the same distance using a parallel cantilever configuration. The friction at 77 K decreased by about a factor of 6 relative to room temperature. For both temperatures, the distance dependence was found to roughly follow the power law $1/d^n$, where $n = 1.3 \pm 0.2$. We note that this contrasts with $n \approx 3$ found in a recent Letter using the parallel cantilever configuration [23].

Experiments were also performed as a function of tip-sample bias voltage V. Figure 3b shows typical results obtained for three different combinations of tip-sample spacing and temperature. In each case, the dissipation increased quadratically with bias voltage. The minimum dissipation occurred very close to $V = 0$, indicating that the average contact potential difference between tip and sample was negligible. Interestingly, the dissipation at nonzero bias voltage was observed to have the same temperature dependence as the dissipation at zero bias. For example, at 77 K the dissipation with nonzero bias was reduced by the same factor of 6 as observed for the zero-bias dissipation. This fact strongly suggests that the friction at zero and nonzero bias have a common origin that is electrical in nature. The overall behavior of our data is closely approximated by $\Gamma_s = \alpha(T)(V^2 + V_0^2)/d^n$, where $\alpha(T)$ characterizes the temperature dependence and $V_0 \sim 0.2$ V characterizes the friction at zero bias. V_0 was found to be nearly independent of T and d.

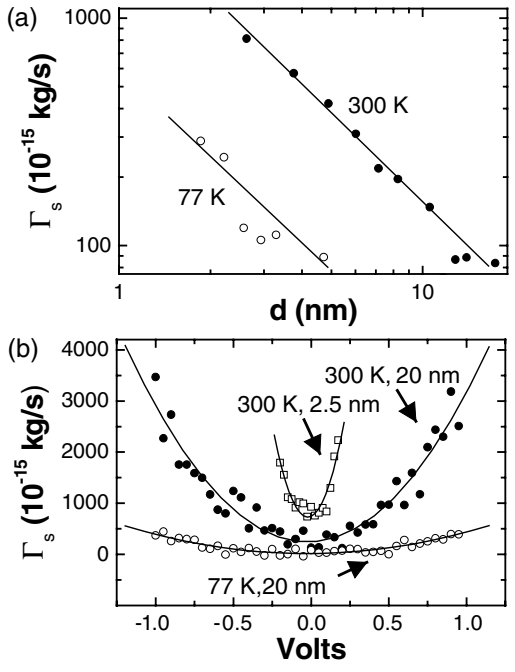

FIG. 3. (a) Zero-bias tip-sample friction as a function of distance for $T = 300$ and 77 K. Data were taken by the ringdown method with an initial amplitude of 10 nm. (b) Friction as a function of bias voltage. Note that friction at 300 K for $d = 20$ nm is approximately 6 times larger than at 77 K regardless of voltage.

The above results suggest that there is substantial tip-sample electric field present even when the external bias voltage is zero. Since our gold tip is polycrystalline, this zero-bias electric field is likely to be the result of local variations in tip work function, resulting in a spatially inhomogeneous contact potential [24]. In gold, work functions for the (111) and (100) surfaces differ by 0.16 eV [25], roughly matching the observed value for V_0.

The presence of inhomogeneous tip-sample electric fields is difficult to avoid, even under the best experimental conditions. For example, even if both the tip and the sample were metallic single crystals, the tip would still have corners present and more than one crystallographic plane exposed. The presence of atomic steps, adsorbates, and other defects will also contribute to the inhomogeneous electric field. The ubiquity of this field and its effect on both conservative and dissipative interactions for closely spaced bodies may impose significant limitations on a number of sensitive experiments, including Casimir force measurements, single-spin force detection, and attempts to observe van der Waals friction.

To further illustrate the importance of inhomogeneous tip-sample electric fields, we have also measured noncontact friction for fused silica samples at 4.2 K. Since silica is a good insulator, one may expect much larger static electric fields to exist near its surface compared to gold. As shown in Fig. 4, the friction near the silica surface was found to be an order of magnitude larger than in the gold sample. The same tip was then used to measure a second silica sample that had been irradiated with ^{60}Co γ rays (4.4×10^8 rad) to produce E' centers (Si dangling bonds) at a density of 7×10^{17} cm^{-3}. Although the sample is electrically neutral overall, the E' centers are known to be positively charged [26], creating enhanced field inhomogeneity and causing the noncontact friction to rise another order of magnitude (Fig. 4).

Although the dissipation is electrical in origin, the detailed mechanism is not totally clear. The most straightforward mechanism for dissipation is to assume that inhomogeneous fields emanating from the tip and the sample induce image charges in the opposing surface. When the tip moves, currents are induced, causing Ohmic dissipation [1,4]. However, in metals with good electrical conductivity, Ohmic dissipation is insufficient to account for the observed effect [8,27]. Thus, the tip-sample electric field must have an additional effect, such as driving the motion of adsorbates and surface defects. Further studies with cleaner surfaces will be required to fully elucidate the dissipation mechanism.

Just as damping in liquids is intimately connected with the random impacts which give rise to Brownian motion of small particles [28], the noncontact friction effect considered here is necessarily connected with the random forces that drive the cantilever Brownian motion. For example,

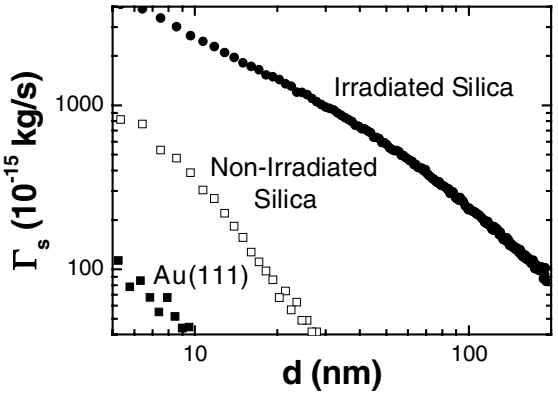

FIG. 4. Noncontact friction for three samples measured at 4.2 K. The gamma-irradiated silica and nonirradiated silica samples exhibit much larger friction effects than the gold sample.

in Fig. 2b we show the influence of force fluctuations on the cantilever's Brownian motion. In the present case, the force fluctuations originate in electric field fluctuations near the surface of the tip or the sample that interact via the Coulomb field with the static charge induced by the applied voltage (if any) and the inhomogeneous contact potential. Since measurements of the mean square amplitude of the cantilever Brownian motion were always found to agree with the amplitude predicted by the equipartition theorem, we conclude that the system is generally well behaved and in thermal equilibrium. Accordingly, the fluctuation-dissipation theorem applies and the spectral density of the force fluctuations at the cantilever resonance frequency is given by $S_F = 4\Gamma_s k_B T$.

From this spectral density and its voltage dependence via $\Gamma_s(V)$, we can now make a rough estimate of the spectral density of the electric field fluctuations that drive the cantilever Brownian motion (averaged with appropriate weighting over the spatial extent of the tip charge). We assume $V \gg V_0$ so that the tip charge due to the inhomogeneous contact potential can be ignored and assume that the field fluctuations are small compared to the static tip-sample field. For a voltage V applied between tip and sample, the induced tip charge is $q = CV$, where C is the tip-sample capacitance. Since the x components of force and field are related via $F_x = qE_x$,we can write $S_F = q^2 S_E$, where S_E is the power spectral density of E_x. Therefore, $\Gamma_s = (C^2 V^2/4k_B T)S_E$. Note that this predicts the observed V^2 dependence of the voltage-induced friction, indicating that S_E is a constant independent of applied voltage.

As a specific example, consider the middle curve in Fig. 3b taken at 300 K with $d = 20$ nm. An applied voltage of 1 V resulted in a friction increase of $\Gamma_s = 3 \times 10^{-12}$ kg/s. From a rough estimate of the tip-sample capacitance ($C \sim 10^{-16}$ F), one finds $S_E^{1/2} \sim 2\mathrm{Vm}^{-1}\,\mathrm{Hz}^{-1/2}$. To put this magnitude of field fluctuation into perspective, we now estimate the charge fluctuation in the sample that would give rise to this electric field fluctuation. If we assume that the fluctuations are the result of a single fluctuator located on the sample surface just under one edge of the cantilever (i.e., offset by 125 nm from the cantilever axis), then the corresponding charge spectral density is $\sim 2 \times 10^{-5} e\ \mathrm{Hz}^{-1/2}$. Although this is only a rough analysis, we note that this level of charge fluctuation noise is comparable to that commonly observed in single-electron transistor experiments [29], perhaps indicating a common origin.

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