Dielectric Fluctuations and the Origins of Noncontact Friction

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Abstract

Dielectric fluctuations underlie a wide variety of physical phenomena, from ion mobility in electrolyte solutions and decoherence in quantum systems to dynamics in glass-forming materials and conformational changes in proteins. We have shown that dielectric fluctuations also lead to noncontact friction. Using high sensitivity, custom fabricated, single crystal silicon cantilevers, we measured energy losses over poly(methyl methacrylate), poly(vinyl acetate), and polystyrene thin films. A new theoretical analysis, relating noncontact friction to the dielectric response of the film, is consistent with our experimental observations. This work constitutes the first direct, mechanical detection of noncontact friction due to dielectric fluctuations.

Summary

As part of our efforts to bring magnetic resonance imaging to the nanoscale [1], we have investigated the noncontact friction experienced when an ultrathin, highly compliant silicon cantilever is brought near the surface of a polymer film. We find, surprisingly, that the main source of friction experienced by such ultrasensitive cantilevers arises from thermal dielectric fluctuations in underlying polymer film [2, 3].

The cantilever used in this study was similar to cantilevers whose fabrication and characterization we have described previously [4]. We have used such cantilevers to detect nuclear magnetic resonance [1, 5] with record sensitivity, to detect electric spin resonance [6], and to characterize the magnetic properties of individual submicron magnetic particles [7].

The cantilevers used in the noncontact friction study can be seen in Figure 1. The cantilever has dimensions of 250 µm by 5 µm by 340 nm, a force constant of 700 µN, a resonance frequency of 7.385 kHz, and a mechanical quality factor in vacuum of approximately 31,000. The tip region of the cantilever was thinned from 340 nm to < 100 nm using a reactive ion etch. The cantilever tip had a radius of approximately 30 nm and was coated with a thin layer of platinum using a shadow mask technique [8].

We used the cantilever to probe noncontact friction at distances of 3 to 200 nm above thin polymer films, as sketched in Figure 2. The cantilever oscillates parallel to the sample, in contrast to the configuration of conventional atomic force microscopy. The sample is a polymer film of thickness 12 nm to 450 nm, spin-cast onto an epitaxial Au(111) substrate. The tip-sample voltage \( V_{ts} \) was applied to the substrate while the cantilever is grounded. This applied voltage produced a charge on the cantilever tip which interacts with local fluctuating electric fields to produce a time-random force on the cantilever that, in turn, leads to friction.
An example of our findings can be seen in Figure 3. Here we plot the friction experienced by the cantilever, as inferred from its ringdown time, as a function of height over a 450 nm thick film made from three different polymers (poly(methyl methacrylate), PMMA; poly(vinyl acetate), PVAc; and polystyrene, PS. It is clear that the friction is dramatically different over the three materials.

Details of the measurement can be found in Reference [2] and a theory for the effect can be found in References [3, 5].

References


