Investigation of the Probe-Sample Interaction in the Ultrasonic/Shear-Force Microscope: The Phononic Friction Mechanism

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Investigation of the probe-sample interaction in the ultrasonic/shear-force microscope: The phononic friction mechanism

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The dissipative and conservative interactions between a sharp probe and a flat Si sample in the ultrasonic/shear-force microscope are investigated. It is shown that, when working in the ambient condition, there are two distinct probe-sample interaction regions: the pure dissipative interaction region in the relatively far probe-sample distance, and the highly correlated dissipative and conservative interaction region in the close probe-sample distance. The ultrasonic data suggest that the phonon generation is a dissipative channel for the probe-sample interaction in the shear force microscope. A shaking potential model is proposed to explain the phononic friction mechanism.


The shear force is widely used for controlling the probe-sample distance in the near field scanning optical microscope (NSOM). In 1995, the quartz tuning fork (TF), was introduced in the shear force microscope. Because of its high Q, high stiffness, simple implementation of the detection system, and no hazard to photon sensitive material, the TF is widely used as a force sensor in a variety of dynamic force microscopes. But the origin of the shear force interaction is still not well understood.

On the other hand, in recent years, due to the development of new interfacial friction tools, significant experimental and theoretical progresses have been made in the area of nanotribology. The new phononic friction model shows that when the wear is negligible in the friction process the phonon generation accounts for the dissipation. But, to the best of our knowledge, no experiment has been implemented to prove the mechanism of phononic friction directly. Here, we incorporate an ultrasonic sensor in the tuning-fork based shear-force microscope to obtain extra information about the probe-sample interaction. The data presented in this manuscript suggest that the phonon generation is a dissipative channel for the wear-free probe-sample shear force interaction.

A more detailed description of the ultrasonic/shear force microscope experimental setup has been provided elsewhere. Very succinctly (see also the inset in Fig. 1), the sample is a piece of polished Si wafer, and the probe is a tapered optical fiber with a tip radius of around 30 nm. The resonant frequency of the TF shifts to a lower frequency 31 283 Hz when the probe is attached to it, and its Q decreases to ~10^3. To evaluate the probe-sample interaction at different separation distances, the frequency spectrum of the TF admittance is measured by the lock-in amplifier No. 1; additional information is provided by the ultrasonic transducer placed in intimate contact with the sample, whose output signal is processed by the lock-in amplifier No. 2.

The motion of the TF can be described by the Newton’s equation

\[ M \ddot{x} = F_{\text{drive}} + F_{\text{damp}} + F_{\text{restore}} = F_{\text{drive}} - M \gamma_0 \dot{x} - k_0 x, \]

where \( x \) is the displacement of the TF vibration, \( F_{\text{damp}} \) is the damping force, \( F_{\text{restore}} \) is the restoring force due to the TFs elastic deformation, \( M \) is the effective mass, \( \gamma_0 \) is the damping rate of the free TF in the air, and \( k_0 \) is the effective spring constant of the TF.

The dissipative and conservative probe-sample interaction, \( F_{\text{dissipate}} \) and \( F_{\text{conserve}} \), will contribute to the TF motion as follows:

\[ M \ddot{x} = F_{\text{drive}} + F_{\text{damp}} + F_{\text{dissipate}} + F_{\text{restore}} + F_{\text{conserve}} \]

where \( \gamma' \) is the effective damping rate due to the dissipative interaction, \( k' \) is the force gradient due to the conservative interaction, \( \gamma \) is the total damping rate, and \( k \) is the total restoring force gradient.

The electrical response of the TF can be linked to the mechanical response by the piezoelectromechanical coupling constant \( \alpha \), and \( LQ + RQ + (1 + C)Q = V_d \), where \( Q = 2Q_0, L = M/2\alpha^2, R = M\gamma/2\alpha^2, 1/C = k/2\alpha^2 \), and \( V_d = F_{\text{drive}}/\alpha \). Due to the parallel capacitance \( C_p \) of the TF, the electrical admittance of the TF is

![Image](87, 231907-1)
where the dielectric power has a peak at the resonant frequency. The dissipation gives the conservative interaction, responsible for the damping of the admittance spectrum, increases monotonically. The conservative interaction, responsible for the frictional probe-sample interaction in the form of phonons, which will either survive and propagate away or dissipate in the form of heat. Maybe there are some other dissipation channels involved, like the excitation of electron-hole pairs, or interactions mediated by the contamination layer. But the ultrasonic data support that the phonon generation is a dissipation channel in the shear force interaction.

The inset in Fig. 2 shows the increase of the ultrasonic signal peak with the TF dissipative power at the resonant frequency during the probe approaching process under 60 mV driving voltage. Notice the two distinct regions for the ultrasonic data support that the phonon generation is a dissipation channel in the shear force interaction. These two distinct ultrasound generation regions suggest that there are two different types of probe-sample interactions. The observed experimental linear relationship between the ultrasonic signal and the TF dissipative power confirms further their direct correlation.

Figure 3 shows the effective damping rate, the force gradient, and the ultrasonic signal change with respect to the probe-sample distance under 60 mV driving voltage. The changes in the probe-sample distance are obtained from the piezoelectric voltage measurements. When the probe is at several hundred nanometers away from the sample, the damping rate linearly increases as the probe-sample distance decreases. But neither the force gradient nor the ultrasonic signal change significantly. It means that the probe-sample interaction in this region is mainly dissipative; the contamination layer (water or hydrocarbon compound layer) could be accounted for the viscous dissipation.

When the probe-sample distance is less than 1 nm, the damping rate of the TF, the force gradient and the ultrasonic signal increase dramatically. What kind of forces account for the close probe-sample interaction? It could be atomic force. According to Ref. 4, the Coulomb force and the capillary force are also plausible candidates. The contamination layer could be the reason too, if it could change its viscosity and shear modulus in depth as proposed in Refs. 8 and 11. But the fingerprint of the shear probe-sample interaction in this
But in fact the probe-sample interaction is considered stationary and conservative. The dissipative probe-sample interaction region is that the dissipative and conservative probe-sample interactions are correlated to each other. The stronger the conservative probe-sample interaction is, the stronger the dissipative probe-sample interaction will be.

Based on the latter observation, we propose a shaking potential model for the phononic friction mechanism of the shear force probe-sample interaction. When the probe-sample interaction is weak, the probe-sample interaction potential \( U(x) \) is approximately quadratic, where \( x \) is the lateral probe-sample interaction distance. The second derivative of the interaction potential \( k = \frac{\partial^2 U}{\partial x^2} \) causes the resonant frequency change of the TF, and \( M \ddot{x} + M \gamma \dot{x} + k_0 x = F_{\text{drive}} + F_{\text{probe-sample}} = F_{\text{drive}} - k x \). In previous studies the probe-sample interaction is considered stationary and conservative. But in fact the probe-sample interaction is a dynamic process, because the sample is plucked by the probe-sample interaction (as confirmed by our ultrasound recording). If the displacement of the sample is \( u \), the motion of TF can be expressed as \( M \ddot{x} + M \gamma \dot{x} + k_0 x = F_{\text{drive}} + F_{\text{probe-sample}} = F_{\text{drive}} - k(x - u) \). Since the displacement of the sample is induced by the motion of TF, it is reasonable to assume \( u = \Delta x = |\tilde{A}| e^{i\phi} x \), where \( \tilde{A} \) is a complex factor describing the coupling between the probe and sample motion. Thus the last equation can be rewritten as

\[
M \ddot{x} + M \gamma \dot{x} + k_0 x = F_{\text{drive}} - k(1 - |\tilde{A}| \cos \phi) x + \frac{|\tilde{A}| \sin \phi}{\omega} \dot{x}.
\]

According to Eq. (1), \( \gamma' = -|\tilde{A}| \sin \phi / M \omega k \). This shows that the dissipative probe-sample interaction increases with respect to the conservative probe-sample interaction, which is supported by our experimental data. So in the close probe-sample interaction region, because of the phase lag of the probe-sample interaction, the conservative interaction is always accompanied by the dissipative interaction, and the dissipative power of TF is released in the form of phonons.

All in all, the ultrasonic/shear-force microscope has many advantages in nanotribology. By using the mechanical resonator model, a wealth of information about the probe-sample interaction can be retrieved from the TF and the ultrasound data. When working in the ambient environment, which is very common in NSOM applications, two distinct probe-sample interaction regions are identified. In the closer to the surface region, the shaking potential model, introduced here, provides a new way to explain the correlation between the dissipative and conservative probe-sample interaction, and the phononic dissipation of the shear force interaction.

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