Mechanical resonance behavior of near-field optical microscope probes

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The mechanical resonance behavior of near-field optical microscope probes is examined with a simple experiment on a flat pyrex sample. While our tapered-fiber probe is locked on the second resonance for servo control, the vibration characteristics around the first resonance are investigated. We find that the overwhelming cause of decreased vibration amplitude as the tip approaches the sample is an increase in damping presumably due to a fluidlike layer on the sample. A small additional effect is also observed that could be due to force derivatives. © *1997 American Institute of Physics.* [S0003-6951(97)02312-7]

Near-field scanning optical microscopy (NSOM) probes are usually tapered optical fibers with very small tips, as shown in Fig. 1. The most popular technique to regulate the probe-to-sample distance is to vibrate the probe parallel to the sample surface and sense a decrease in the vibration amplitude from beam diffraction as the tip approaches the sample.[1] The origin of the decrease in vibration amplitude is not well understood and is the subject of much qualitative speculation in the literature. In this letter, we quantify the force interaction and suggest that the primary cause of the decrease in vibration amplitude is due to an increase in damping from a fluidlike layer between the surface and the probe.

The vibrating probe cantilever can be modeled as a classical driven harmonic oscillator with an equation of motion given by[2]

$$ma(t)+\gamma\nu(t)+kx(t)=F_a\sin(\omega t), \qquad (1)$$

where the terms on the left hand side are the inertial, damping, and restoring forces, and the right hand side is the driving force. The quantity m is the effective mass, γ is the damping coefficient, and k is the spring constant of the cantilever. F_a is the driving force amplitude applied by the piezo actuator, and ω is the driving frequency. The probe vibration amplitude (referred to the aperture end of the probe) is $x(t)=X\sin(\omega t+\phi)$ where ϕ is the phase shift between the driving function and the probe response. The velocity and acceleration of the probe are $\nu(t)$ and $a(t)$, respectively. The response amplitude is derived by substitution of $x(t)$ in Eq. (1) to obtain

$$X(\omega)=\frac{F_a/k}{\sqrt{\left(1-\frac{\omega^2}{\omega_0^2}\right)^2+\left(\frac{\omega}{Q\omega_0}\right)^2}}, \qquad (2)$$

where ω_0 is the undamped natural frequency and $Q=h/\gamma\omega_0=\omega_0/\Delta\omega$ is the quality of the resonance. $\Delta\omega$ is the width of the resonance at $1/\sqrt{2}$ of the maximum amplitude.

The vibration amplitude X decreases as the probe approaches the sample surface, as shown in Fig. 2. The shear force servo locks when the amplitude reaches the set point, which is some fraction of the full scale probe vibration amplitude. The approach curve is obtained by driving the probe at its second modal resonance. The sample is a flat polished Pyrex substrate. The solid curve is a polynomial fit to the five data points.

The decrease in amplitude X results from a modification of the probe cantilever resonance do to the shear force interaction between probe and sample. Examination of Eq. (2) reveals that the modification can be either a decrease in Q and/or a shift in ω_0. A decrease in Q (increase in γ) would result from dissipative frictional forces that are proportional to the instantaneous velocity of the probe. A shift in ω_0 would result from a spatially varying force in the direction of the probe dither motion. The frequency shift is approximately $\delta\omega_0\equiv\omega_0F_x'(x)/2k$.

Normal force derivatives of the form $\partial F_z(z)/\partial z$ are observed in noncontact atomic force microscopy in which the cantilever is oriented nearly parallel to, and vibrated normally to, the sample surface.[3,4] Servo operation is based on the decrease in X caused by the normal force derivative. An example of such a force is the attractive van der Waals force that decays with increasing distance from the surface.[5] The force interaction in that case is more easily understood than for the case of an NSOM probe because the AFM cantilever is vibrating in z through a known force field.

There are numerous speculative explanations in the lit-

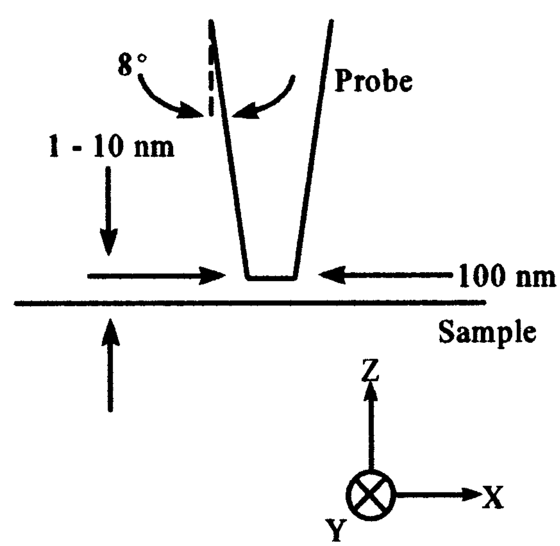

FIG. 1. Geometry of an NSOM probe tip. Dimensions shown are typical values.

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