Study of Probe-Surface Interaction in Shear-Force Microscopy: Effects of Humidity and Lateral Spring Constant

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The shear force between a glass probe and a mica surface has been investigated as a function of the relative humidity, $H$, and the lateral spring constant of the probe, $K$. It was found that the interaction length $D_0$ decreases with increasing $H$ and exhibits a sharp drop around $H=40\%$. With increase in $K$ from 5 to 40 N/m, $D_0$ gradually increases, although this feature was absent when a probe with a softer tip-end was used. The latter result indicates that the shear force in an atmospheric condition is not a remote force but results from some contact between the tip and the surface. Our results that $D_0$ is independent of the oscillating amplitude and that the resonance curve of the probe is almost symmetric except in close vicinity to the surface are not in accord with the force model proposed recently, i.e., the knocking mechanism. It is proposed that the probe can vibrate even if the probe touches the surface, and that the resonance frequency increases steeply as the contact tightens. Theoretical estimation of the contribution of noncontact forces is also described.

Key words: near-field optics, shear-force microscopy, tip-surface interaction, relative humidity, lateral spring constant

1. Introduction

The shear force microscope (SFM) utilizes a dynamical force, i.e., “shear force,” depending on the probe-sample distance as the laterally vibrating probe approaches in close proximity to the surface. In SFM, sensing of the resonance characteristics of the probe modulated by this force can be used to obtain the surface topography. The same mechanism has also been used to regulate the probe-sample distance in scanning near-field optical microscopy (SNOM).1,2) Recent progress in SFM techniques pushed the spatial resolution up to a value close to that of the atomic force microscope (AFM) under particular conditions, e.g., in liquid3) or in biomaterial being observed.4)

Detailed knowledge of the shear force is indispensable for a quantitative understanding of an observed image and to develop further the performance of SFM. Especially, the nature of the surface force in an atmospheric condition must be solved because most applications of SFM are made in this condition. Several researchers have pursued the origin of the shear force, and several possible mechanisms underlying the probe-surface interaction have been proposed, including viscosity force, van der Waals forces, capillary force, and a mechanical contact between the tip and the surface.4–10) In spite of these observations under laboratory conditions, no general consensus about the nature of the shear force has yet been reached.

It is known that the resonance characteristics of the probe depend sensitively on ambient conditions such as humidity.5) If an atmospheric condition influences the shear force, the condition must be controlled to obtain quantitative observations, which will give us information about the nature of that force. In fact, many scanning probe microscopic studies have shown that humidity not only changes the magnitude of interactions, but also affects the topographic images.11–14) We recently investigated the effect of humidity on the shear force between a glass probe and a mica surface, and found that the interaction length exhibited a humidity-dependent behavior.15)

In this paper we present a detailed account of our study of the shear force on a mica surface under controlled humidity. We first describe the resonance characteristics and the effect of humidity on the shear force, a brief account of which has been published recently.15) Second, in order to estimate the shear force more quantitatively, we describe how the lateral spring constant of the probe influences the interaction length. Knowledge of these factors affecting the shear force will lead us to a better understanding of its nature in an atmospheric condition.

Experimental methods are given in Sect. 2 and the results of the measurements are described in Sect. 3. In Sect. 4, the results of the measurements are discussed on theoretical grounds, and contributions from possible noncontact forces are estimated.

2. Experiments

2.1 Shear Force Microscope with a Humidity Control

Figure 1 shows the construction of the SFM used in the present study. This apparatus employs the conventional optical method16,17) for detecting the shear force and is similar to that of the distance-regulation apparatus incorporated in SNOM, except the part for controlling the
humidity. A transparent air-tight chamber (45×30×15 cm³) made of acrylic plate encloses the whole SFM. The humidity was controlled by such means as filling the chamber with dry nitrogen gas, evaporating water, and putting a desiccant into the chamber, depending on the desired humidity. The accuracy of the humidity control was better than ±4%.

We used a multi-functional ceramic piezoelectric tube (10 mm in diameter, and 35 mm in height) that served to scan, position, and dither the tip. A laser beam was focused onto a position located about 1 mm from the lower end of the tip. The light scattered from the tip was detected by a photodiode placed in the far-field region. Both the separation between the laser and the probe, and that between the photodiode and the probe were about 8 cm. The output of the photodiode was amplified and filtered, and its ac component was fed into a dual phase lock-in amplifier (model 7260, EG&G Instruments Co.). The signal amplitude was proportional to the amplitude of the tip oscillation and hence included information about the tip-surface interaction. With this construction, we were able to obtain a shear-force image of the sample in an atmospheric condition. An example of the observed images is illustrated in Fig. 1(b).

To measure the change in resonance characteristics as the tip approached the surface, the dither frequency was swept around the resonance frequency of the tip. The sweeping speed controlled by the computer was less than 100 Hz/s. The signal amplitude and the phase were monitored simultaneously during the approach of the probe to the surface. The vibration amplitude was estimated by a modified beam diffraction method. In the experiment with a number of different probes, the dither voltage was adjusted so that the amplitudes of the probes were equal in all cases.

2.2 Glass-Pipette Probe

We used a glass micropipette probe, which was fabricated with a commercial puller (PB-7, NARISHIGE Co.). Various shapes of the probe can be easily fabricated by controlling the heat power and the pulling force of the puller, and one of them observed by an optical microscope is shown in Fig. 2(a). The profile of the tapered region more than a few hundred μm from the tip end, which is
referred to as the primary tapered region, is approximately of the exponential form, which agrees with the previous theoretical result.\textsuperscript{20} The profile near the end of the tip, which is referred to as the secondary taper,\textsuperscript{21} differs from the exponential form (Fig. 2(b)). The shapes of this region can be approximately fitted to a function of \( x^n \), the origin of \( x \) is the end of the probe, and one shape can be fitted with \( n<1 \) and another with \( n>1 \). We refer to the former shape as "parabolic shape" and to the latter as "cusp shape."

The vibration of the probe is the conjugated motion of the primary and the secondary tapered regions. Since the mass of the former is much larger than that of the latter, however, the resonance characteristics of the probe are mainly determined by the form of the primary tapered region. In fact, we can fabricate the probe with a resonance frequency from several kHz to one hundred kHz by changing the shape of the primary tapered region. Thus, we defined the spring constant of the probe, \( K \), as that of the primary tapered region.

The value of \( K \) was calculated using the classical elasticity theory.\textsuperscript{21} When the probe end is laterally bent by a small displacement, \( u \), from its equilibrium position, then the shearing force, \( F \), induced in the probe at the position, \( z \), is given by

\[
F = -E \frac{d}{dz} \left( I(z) \frac{d^2 u}{dz^2} \right),
\]

where the origin of \( z \) is the end of the primary tapered region, and \( E \) and \( I(z) \) are Young's modulus and moment of inertia of the probe, respectively. The value of \( E \) is 6.3×10\(^{10} \) N/m. The radius \( r(z) \) of the sectional area of the probe is represented by a functional form \( r_0exp(\alpha z) \), where \( r \) is the radius at \( z=0 \) and \( \alpha \) is a parameter characterizing the profile of the primary taper. Thus, the moment of inertia \( I(z) \), as a function of \( z \), is given by

\[
I(z) = I_0exp(4\alpha z),
\]

where \( I_0 = \pi (r_0^4 - r_i^4)/4 \), and \( r_i \) and \( r_o \) are the inner and the outer radius at \( z=0 \), respectively. We consider that the probe is clamped at one end (\( z=L \)) and free at the other end (\( z=0 \)), to which a constant force \( f \) is applied. Then, solving the differential equation which is obtained by substituting Eq. (2) into Eq. (1), and using proper boundary conditions, i.e., \( u(L) = u'(L) = 0 \) and \( u'(0) = 0 \), we finally obtain, using the definition of \( K \), i.e., \( K = f/u(0) \),

\[
K = \frac{32\pi^3 E l_0}{1 - e^{-4\alpha L}(8\alpha^4 L^4 + 4\alpha L + 1)}.
\]

We measured the shape of the fabricated probe using an optical microscope and calculated \( K \) using Eq. (3).

2.3 Sample

A cleaved mica has been widely employed to investigate such surface features as tip-surface interactions,\textsuperscript{11,12} surface forces,\textsuperscript{22} and formations of a water layer.\textsuperscript{23} The mica we used was cleaved in laboratory air of ambient humidity, and the mica sheet was glued to a glass substrate. As soon as the sample was set on an SPM stage, the relative humidity was reduced below 15% by injecting dry \( N_2 \) gas into the chamber. This was the initial condition for all the measurements described below.

3. Results

3.1 Resonance Characteristics

Figure 3 shows the frequency and the amplitude at resonance of a freely vibrating probe as a function of ambient humidity, \( H \). The quality factor, \( Q \), was \( \sim 200 \), and was almost the same for all the probes used.\textsuperscript{4} The scatters of data were \( \pm 20\% \) for the amplitude and \( \pm 2 \) Hz for the frequency, and were independent of \( H \). No difference between the increasing and the decreasing processes of \( H \) were observed. When \( H \) exceeded 70%, on the other hand, the resonance characteristics often changed drastically and the signal to noise ratio was inadequate to measure the resonance profile. However, we could not determine whether this change was attributable to the intrinsic features of the probe as has been indicated in the previous work.\textsuperscript{10} One possibility is that water droplets condensed on the surface of the tip as well as on the transparent window of the photodiode and laserdiode, and they disturbed the laser alignment. Thus, we carried out the following measurements under the condition of \( H \) below \( \sim 50\% \).

Figure 4 shows the frequency and the amplitude at resonance at \( H=15\% \) as a function of distance, \( D \), the origin of which was defined as the position where the vibration became unstable and its amplitude almost damped to zero. With decreasing \( D \), the resonance frequency increases significantly, whereas the amplitude at the reso-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{resonance_frequency.png}
\caption{Resonance frequency, \( \omega_r \), and the amplitude at the resonance, \( A_r \), of a freely vibrated probe as a function of relative humidity, \( H \). For the decreasing process of \( H \), \( \omega_r \) (open circles) and \( A_r \) (open squares). For the increasing process of \( H \), \( \omega_r \) (closed circles) and \( A_r \) (closed squares).}
\end{figure}

\textsuperscript{4} The quality factor, \( Q \), is defined as \( \omega / \Delta \omega \), where \( \Delta \omega \) is the width of the resonance at \( 2^{-1} \) of the maximum amplitude. This definition is the same as Ref. 5, in which \( Q \) is about 204. In contrast, \( Q \) defined in Ref. 8 is \( \omega / 2\Delta \omega \) where \( \Delta \omega \) is the full-width of half maximum of the resonance. In this definition, \( Q \) of our probe is \( \sim 74 \), which is almost the same as that of Ref. 8, i.e., 68.
nance decreases slightly.* Although we found that qualitative features of the resonance curve are independent of $H$, a quantitative difference was observed. The difference was in the position where the resonance frequency begins to shift upward from its eigenfrequency. We refer to this position as the effective interaction length, $D_{0}$, because the tip-surface interaction is so strong for $D < D_{0}$ as to change the resonance characteristics appreciably. Later, we will focus on $D_{0}$ to investigate the nature of the shear force.

The resonance curves at values of $D$ #1-#4 shown in Fig. 4 are depicted in Fig. 5. Shapes are almost symmetric even though the tip feels the shear force, and the asymmetry becomes significant only in the close vicinity of $D=0$. Also, as shown in the inset of Fig. 4, we found that $D_{0}$ is independent of the dither voltage, i.e., the amplitude of the probe. These two results are not in accord with the previous report.8

Here, it is worth comparing the approach curve at resonance (Fig. 4) with that fixed at its eigenfrequency, i.e., shear force curve, which is employed as a feedback signal in conventional SFM. The latter is plotted in Fig. 6. The phase change of the shear force curve starts at further separation than that of the amplitude, which steeply decreases in close proximity to $D=0$. Such behaviors were pointed out in the previous study.9 According to general features of the forced resonator, the phase responds sensitively to the initial shift from the eigenfrequency because, with respect to the shift of the eigenfrequency of the resonator, the deviation of the phase is maximum whereas that of amplitude is minimum, i.e., zero. Therefore, we can say that the primary shift of the resonance frequency causes the phase shift of shear force curve, and further shift of the resonance frequency including the change of the amplitude at resonance causes a steep increase in the phase as well as reduction of the amplitude of the shear force curve. In fact, the resonance frequency and the phase begin to change at the same distance, i.e., $D_{0}$.

**3.2 Effect of Humidity**

In Fig. 7, $D_{0}$ normalized with the value in the low-humidity region ($H<20\%$) is shown as a function of $H$. It is seen that $D_{0}$ decreases slowly with increasing $H$ below $H=30\%$, and more sharply around $H=40\%$, above which $D_{0}$ becomes almost constant. We measured $D_{0}$ versus $H$ curve with a number of tips, and found that the qualitative

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*Although the quantities of the frequency shift and the amplitude reduction varied with a given tip-sample combination, the former was always the most dominant in other characteristics in $H=15-50\%$. 

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![Fig. 5. Resonance profile of the tip at several values of the tip-surface distance. The numbers 1-4 correspond to those in Fig. 4.](image_url)

![Fig. 6. Approach curves of the amplitude (closed circles) and the phase (open circles) fixed at the eigenfrequency of the probe.](image_url)
feature obtained with different tips was essentially the same as that shown in Fig. 7, although the absolute value of $D_h$ differed from tip to tip. We also carried out similar measurements for both processes of increasing and decreasing of $H$, but found no difference between the two. This result indicates that a water layer relates to the shear force because the thickness of the water layer on a mica increases with increase in the ambient humidity.$^{22-24}$

3.3 Effect of Shape of Probe

To get further information on the shear force, we measured $D_h$ as a function of $K$. Using the probe with the secondary tapered region of a parabolic shape, we observed the relation of $D_h$ versus $K$ in which $D_h$ gradually increased with increasing $K$ (Fig. 8). If the detected shear force were only a noncontact force, $D_h$ should decrease with increasing $K$, because the smaller the spring constant of the probe, the more sensitively noncontact forces should be detected. Thus, this result indicates that the observed shear force strongly relates to a contact force between the tip and the surface.

As shown in the inset of Fig. 8, the result obtained using the probe with a cusp shape was independent of $K$ even though the ambient conditions were the same. This indicates that the shape of the secondary tapered region influences $D_h$. It is noted that Lantz et al.$^{25}$ recently reported observations that the difference of the spring constant of the tip conjugated on the cantilever has significant influence on the apparent lateral force; the apparent magnitude of the force detected by cantilever with soft tip varies from the true magnitude of the lateral force by means of the slight bending of the tip-end. Comparing a tapered probe for SFM with a cantilever for AFM, we can say that the primary tapered and the secondary tapered regions correspond to the cantilever and its tip, respectively, because the interaction is detected at the position of the former, and is sensed at the end of the latter. Thus, a tapered probe with much larger the spring constant of the secondary tapered region than $K$ is needed to detect the shear force. We roughly estimated the spring constant of the secondary tapered region from Fig. 2(b), and found the spring constant of the parabolic shape to be about ten times that of the cusp shape, which is comparable to $K$ of the primary region. An explanation of the result shown in the inset of Fig. 8, then, is that the shear force induced at the tip end was not transferred to the primary tapered region, and thus the apparent shear force varied widely even when the same $K$ was used.

4. Discussion

As stated, the result shown in Fig. 8 suggests strongly that the force probed by the tip results from some sort of contact between the tip and the surface. What is the mechanism of this contact force? Gregor et al. proposed a nonlinear oscillator model which considers an asymmetric contact (knocking) between the tip and the surface.$^{25}$ These authors showed that the mechanism showed the resonance profile to become extremely asymmetric as soon as the tip felt the shear force, and the apparent interaction length was proportional to the amplitude of the probe. However, we observed that resonance profiles are almost symmetric even though the tip feels the shear force, and the asymmetry of the resonance curve becomes significant only in the close vicinity of $D=0$. Also, as shown in the inset of Fig. 4, we found that $D_h$ is independent of the dither voltage, i.e., the amplitude of the probe. These results contradict what can be predicted by their model. Thus, the shear force cannot be explained only by the knocking mechanism alone. Here, we assume that the probe can vibrate even if it touches the surface, and the resonance frequency increases steeply as the contact tightens. The oscillating energy as well as the restoring force of the probe oscillating at a constant amplitude should be propor-
tional to $K$. Thus, the probe with large $K$ may still oscillate even when the tip end touches the surface so that $D_e$ increases with increasing $K$. An instability of the probe vibration may induce a sudden damp of the probe.

This effect should be further noted for an optical fiber probe for SNOM, the shape of which consists of cylindrical, primary and secondary tapered regions.\textsuperscript{2,30} The spring constant of the cylindrical region is very high in comparison with the other two regions. Thus, when the motion of the probe is attributed to the cylindrical region, and the tip end touches the surface, the oscillation may not damp, and the primary and secondary regions may be bent.

The instability may be the main effect on the shear force when the tilting angle between the probe and the surface is large, because the asymmetric force is increasing owing to the tilting angle. In such a case, the knocking mechanism may explain the features of the shear force.

If we admit that the main origin of the shear force is a contact force, a question can be raised as to why a contact force exhibits humidity dependence. It is known that capillary force is quite operative in the near-field region under atmospheric conditions,\textsuperscript{20,36} and thus it is natural that the adhesion force including van der Waals forces as well as capillary force plays an important role in the humidity dependence of shear force. The previous studies on AFM showed that the adhesion force remains almost constant in the range of $H=15-30\%$ and increases steeply above $30\%$.\textsuperscript{13,14} Comparing our result shown in Fig. 7 with these results, we see that the increase of adhesion force induced the decrease of $D_e$. In general, it is impossible to make the tilting angle zero.\textsuperscript{6} Thus, the position at which the tip first touches the surface does not equal that of the tip axis. If the adhesion force were smaller than the restoring force of the probe toward its equilibrium position, the probe that touched the surface slightly could be away from the surface so that the forced tip would oscillate until the oscillation encountered the unstable condition. On the contrary, if the adhesion force were larger than the restoring force of the probe, then the tip end would be trapped on the surface, and the oscillation of the tip would immediately be unstable because the vibrating axis would deviate from the tip axis.

In spite of the simple considerations mentioned above, many problems to quantitatively estimate the shear force have been raised. These include lack of an analytical method to determine the instability of the oscillation as the tilting angle exists in SFM, and quantification of the adhesion force between the end of the glass tip and the mica surface. We are thus unable to discuss these phenomena further at this stage.

The friction force, which is another force induced at the time the tip touches the surface, decreases with increasing $H$.\textsuperscript{11,10} If so, this force should cause that $D_e$ increases with increasing $H$, which is contrary to our result shown in Fig. 7. Therefore, we believe that the friction force between the end of tip and the surface has little effect on shear force.

Although the present results suggest strongly that the main contribution to the tip-surface interaction comes from a contact force, they do not allow us to rule out completely the contribution from noncontact forces. Below, we will estimate theoretically how large the contribution from the noncontact tip-surface interaction can be under an atmospheric condition.

A vibrating probe for SFM as well as a vibrating cantilever for AFM can be modeled as a forced harmonic oscillator $m_e\ddot{x}+\gamma \dot{x}+Kx=Asin\omega t$, where $m_e$ is the effective mass, $\gamma$ is the damping coefficient of the freely vibrating probe, and $\omega$ is the dither frequency.\textsuperscript{5,6,10} The effective mass, $m_e$, which cannot be measured directly, can be equal to $K/\omega^2$, where $\omega_b$ is the eigenfrequency of the probe. We can also make $\gamma$ equal to $m_e\omega_b/Q$. Order of $\gamma$ was estimated as $\sim 10^{-7}$-$10^{-5}$, since $K$ is $1$-$50$ N/m, $\omega_b$ is $\sim 10$-$100$ kHz, and $Q$ is $\sim 200$. When the noncontact force is induced between the probe and the surface, the oscillator model should be modulated to $m_e\ddot{x}+(\gamma+\gamma_1)\dot{x}+(K+K_1)x=Asin\omega t$, where the terms containing $\gamma_1$ and $K_1$ represent viscosity force and van der Waals forces, respectively, both forces being a function of the tip-surface distance.

First, we consider the viscosity force, which was recently estimated for non-tapered probe.\textsuperscript{24} The result calculated from Eq. (6) in Ref. 7 shows that even with 1 nm of tip-surface distance, $\gamma_1$ is less than $1\%$ of $\gamma$ for 1 $\mu$m of the probe diameter, which is approximately the maximum diameter of the tip we used. Therefore, the viscosity force can be detected only within sub nm of the tip-surface distance using conventional SFM apparatus, which employs a tapered probe, the diameter of which is on a submicron order.

Next, we consider the van der Waals forces taking a tilting angle into account (Fig. 9). When the shape of the tip end is assumed to be a sphere with a radius $R$, the van der Waals forces are expressed as

$$F(x)=\frac{AR}{6(D\cos\alpha-x\sin\alpha)^2},$$

(4)

where, $A$ is the Hamaker constant between mica and glass, the value of which is $7.9 \times 10^{-20}$ J.\textsuperscript{22} Accordingly, $K_1$ is obtained as

\textsuperscript{*}According to 254 of L.D. Landau and E.M. Lifshitz: Fluid Mechanics (Pergamon Press, Oxford, 1988), alternative conditions are required to eliminate the nonlinear term of the Navier-Stokes equation; either (1) the depth of penetration of the wave in a viscous fluid, $\delta$, which is defined as $(v/\omega)^{1/2}$ is much smaller than the order of magnitude of this dimension, $l$, and the Reynolds number is small, or (2) $\delta$ is much larger than $l$ and the amplitude of the oscillations is small in comparison with the dimensions of the body. In SFM using a tapered probe, $l$ which corresponds to the diameter of the tip end is the order of $10^{-7}$ m and velocity $U$ is the order of $10^{-5}$ m/s because the amplitude and the angular frequency are the orders of $10^{-4}$ m and $10^{-5}$ rad/s, respectively. Then, the Reynolds number, $Ul/\nu$, in an atmospheric condition is the order of $10^{11}$-$10^{15}$, which is very small, where kinematic viscosity, $\nu$, of the air is the order of $10^{-5}$ m$^2$/s. Furthermore, $\delta$ is the order of $10^{-4}$. Thus, the first condition (1) is satisfied, and the nonlinear term of the Navier-Stokes equation also vanishes.
where the first term is due to the force directed to the positive \( x \), giving a negative contribution to the spring constant, while the second term is due to a so-called simple pendulum, and give a positive contribution. According to this model, the resonance frequency decreases with increasing tilting angle. Substituting Eq. (5) into Eq. (4), we obtain for the van der Waals forces as

\[
K_i = -\frac{dF(x)}{dx} \bigg|_{x=0} \sin\alpha + F(0) \frac{\cos\alpha}{L},
\]

(5)

From Eq. (6), we obtain \( \alpha < \arctan \sqrt{D/2L} \) as the condition for the increase of the resonance frequency with the decrease of \( D \). For \( D \approx 10^{-2} - 10^{-4} \) m and \( L \approx 10^{-3} \) m, the condition reduces to \( \alpha < 0.4 - 0.1 \), restricting \( \alpha \) to a very small value. Now, let us assume that \( \alpha \) is equal to zero, at which the value of \( K_i \) is maximum. Then, for \( R \approx 10^{-3} - 10^{-4} \) m and \( L \approx 10^{-3} \) m, \( K_i \) becomes on the order of \( 10^{-8} - 10^{-9} \) N/m, which is very small compared with \( K \) and hence van der Waals force cannot be detected by SFM with a small tilting angle.

Since the viscosity force and van der Waals forces in the separation above 1 nm are too small to be detected by SFM, the main contribution of the shear force may be the contact force. Of course, noncontact capillary force, which is induced as the tip contacts the surface through the water layer, and electrostatic force, which often has an important role in the interaction between a mica and an insulating material at low humidity,\(^{29}\) might be operative. We believe, however, that the operation of SFM corresponds to contact mode because the feedback position of SFM is that at which the resonance frequency increases steeply, the feature of which relates to that of the contact mechanism as shown in Fig. 8.

5. Conclusions

The shear force between a glass probe and a mica surface was investigated as a function of the relative humidity, \( H \), and the lateral spring constant of the probe, \( K \). The latter result indicates that the observed shear force strongly relates to the contact force between the tip and the surface. We proposed that the mechanism of the contact force is that the probe still oscillates even when the tip end touches the surface, so that the resonance frequency increases steeply.

Comparing the observed humidity-dependent behavior of the shear force with the past studies on AFM, we see that the increase of adhesion force induced the decrease of \( D_0 \), and thus we proposed that in higher humidity, the tip end is trapped by the adhesion force and the oscillation becomes unstable immediately owing to the tilting angle.

Theoretical estimation of noncontact forces indicated that the viscosity force as well as the van der Waals forces in a separation more than 1 nm from the surface is too small to be detected by SFM. Thus, the operation of SFM corresponds to a contact mode.

References