AIP | Review of Scientific Instruments

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Citation: Rev. Sci. Instrum. **82**, 083704 (2011); doi: 10.1063/1.3624691

View online: http://dx.doi.org/10.1063/1.3624691

View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v82/i8

Published by the American Institute of Physics.

Angle dependence of the interaction distance in the shear force technique

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(Received 1 April 2011; accepted 21 July 2011; published online 16 August 2011)

We study the interaction distance in the lateral force detection, using a standard quartz tuning fork as a force transducer. That is the distance at which the interaction sample-probe starts to be detected. We study in particular the dependence on the approaching angle. For angles smaller than 0.366 radians, we found an exponential behavior of the interaction distance as a function of the approaching angle. We show an equation that adjusts well with the experimental data, and discuss the possible phenomena. © *2011 American Institute of Physics*. [doi:10.1063/1.3624691]

I. INTRODUCTION

Many works have been devoted to the study of the lateral force detection, generally called shear force technique,[1–3] where a resonantly vibrating fiber tip is approached to the sample. The amplitude of vibration decreases drastically near to the sample surface, this is due to the tip-sample interaction forces, which are essentially Van der Walls forces.[4] This is used as a common way to control the probe-sample distance in the scanning near-field optical microscopes (SNOM's). In the last years, standard quartz tuning forks (QTFs) have become the main tool for the lateral and normal forces detection,[5,6] getting resolutions in the range of several nanometers for lateral case and fractions of nanometer for the normal case.[7,8] Even more, Giessibl *et al*. have reported that it is possible to obtain atomic resolutions using lateral force detection.[9] In all those cases, a vertical interaction between probe and sample is considered, that means, the normal direction to the sample surface is parallel to the displacement of such a probe, but there are interesting effects when the angle takes a different value than zero, because the interaction area increases as the angle too, in this way, we present this work, devoted to explore the relationship between the approaching angle and the interaction distance. It is important to say that we have called the interaction distance to the maximum distance at which the probe senses the sample, i.e., the distance at which the interaction becomes big enough to be measured with our detection system. In Sec. II we describe the experimental setup, in Sec. III we show the obtained results, and finally in Sec. IV we discuss and conclude the present work.

II. EXPERIMENT

The experiment was realized with a standard QTF, at a resonance frequency of 32.565 kHz, and externally dithered[10] by a common piezoelectric element. The probe was fabricated with a monomodal optical fiber, by chemical etching method,[11] with a 100 nm tip radius, measured by scanning electron microscopy. The sample is a clean and flat glass surface, mounted on a NPS XYZ-15A nanopositioner (NPS). All the head, i.e., QTF, dither piezo and probe, is fixed at a common mount and the movement in the Z direction is realized with the NPS, with a step size of 1 nm in all the cases.

We mounted the head of the microscope in a goniometer base, with resolution of 1.7×10^{-3} rad, for the control of approaching angle, θ_i. All the components were carefully positioned and fixed in the base, to get an error in angle as small as possible. We estimated a total error in the approaching angle of $\pm3.4 \times 10^{-3}$ rad, due to observation factors and imprecision of goniometer, then we chose an angle variation of 0.017 rad (1°), which is five times the estimated error, big enough that does not affect the results. In order to make clearer the geometry of our setup, we consider a Cartesian coordinate system, where Y-axis coincides with the rotation axis of the goniometer, Z-axis is parallel to the normal sample, with the positive direction pointing from the tip to the sample and X-axis having a positive direction according to the right hand rule, as is shown in Figures 1 and 2. In Figure 1, we show a schematic representation of our instrument, where the dither direction is parallel to the Y-axis, it is important because there is no possibility of contact between probe and sample due to the probe's oscillation.

III. RESULTS

In Figure 2, an isometric view of the probe-sample system is shown. It is clear that the approaching angle (θ_i) is the angle formed between the Z-axis and the axis of the probe (line formed by OA), and lies in the X-Z plane. As it was mentioned before, the variations of such angle will affect the probe-sample interaction.

Figure 3 shows a common approach plot for the shear force interaction, we have set the approaching angle as $0 \pm 3.4\times10^{-3}$ rad and it is clear that the interaction distance,

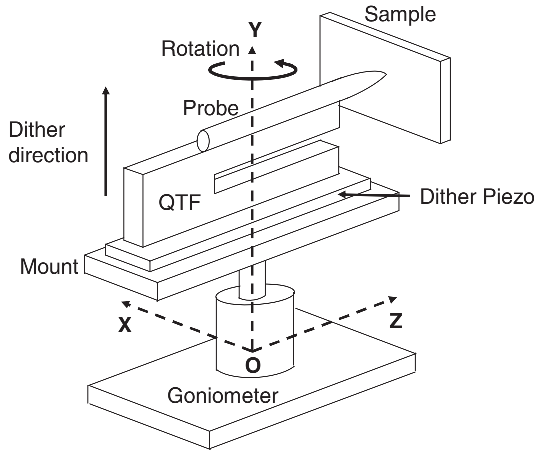

FIG. 1. Schematic diagram of the system for approaching angle adjust.

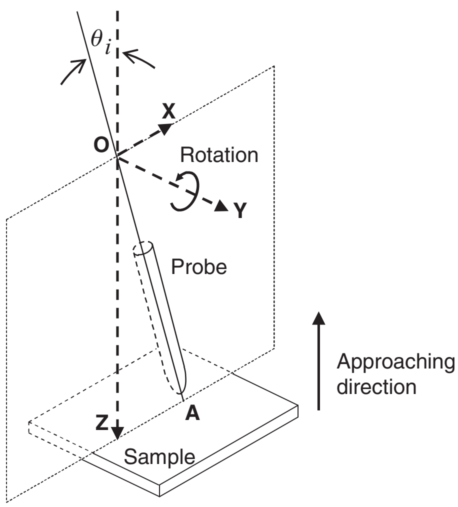

FIG. 2. Isometric view of the system, showing the approaching angle, θ_{i}.

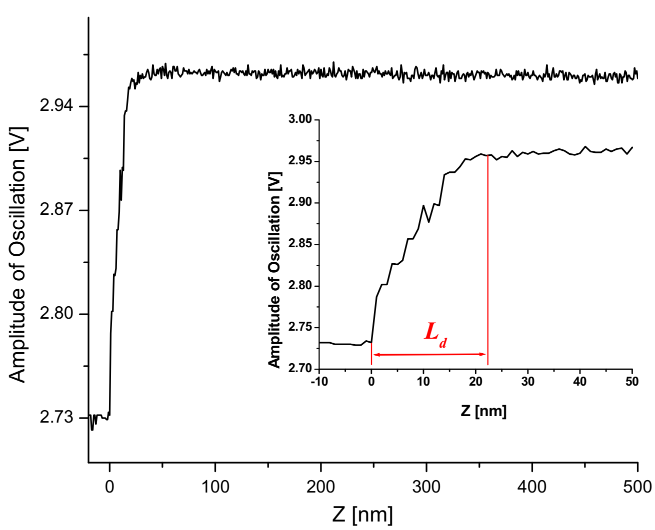

FIG. 3. (Color online) Typical approach in the shear force technique with 1 nm step and a sine drive voltage of 20 mV. The inset shows 60 nm in the vicinity of the sample surface. We can see an interaction distance of about 22 nm.

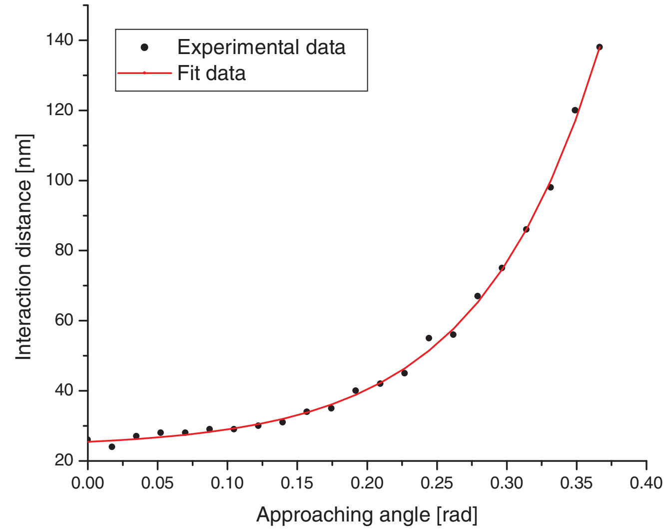

FIG. 4. (Color online) Experimental and fitting, dot and continuous line respectively, obtained in the experiment.

L_d, is about 22 nm as previously reported,[12] see the red arrows in the inset.

After several realizations of the experiment, we found a collection of points, enough to fit a curve described by the Eq. (1) and shown in Figure 4 as a red line.

$$L_d\,(\theta_i) = 23.83 + 1.62 \exp\left(\frac{\theta_i}{0.086}\right), \tag{1}$$

where L_d is the interaction distance and θ_i the approaching angle. The constants 23.83 and 1.62 have units of distance in nm.

Using a simple geometrical model, we found that the interaction distance is a function of $\cos(\theta_i)$, thus the Eq. (1) is an interesting approximation because the behavior is certainly unexpected. The possible explanation is due to the quasi-pyramidal shape of the probe, then, when the approaching angle changes, the interaction area becomes bigger and grows very fast. It is clear that Eq. (1) recovers the value of the interaction distance for the case $\theta_i = 0$ rad, reported in Figure 3, with a difference of approximately 2 nm.

IV. DISCUSSION AND CONCLUSION

It is well known that the control distance system in a SNOM tries to keep an input signal, amplitude of oscillation, phase, or frequency shift constant by approaching and retracting the probe to the sample. It means that in the exploration of a sample, there will not be just one approximation; actually the process will be repeated at each point of the scanning process in the experiment. Even more, in a controlled experiment, Hecht *et al*. have demonstrated the influence of a 0.1 nm gap-width variation in shear force image system and, even atomic size variations in gap width topographic motion can fake an optical structure which does not exist,[13] then, our results are totally applicable in such height changes, for the angles in the studied range.

Based in our experimental results, it is possible to describe the behavior of another variable that determines the resolution of the force microscope used in scanning near-field optical microscope as control distance system, this is the approaching angle. We have found an exponential dependence of the interaction distance with that angle, at least in the range of 0 to 0.366 rad. For bigger angles, we did not find a regular behavior, however we think it is necessary a further experimental study in order to propose a suitable relationship. It is important to note that in the present work we did not discuss the effect of the approaching angle in the near field and topographical images, but we expect to study those effects and report them in a future work.

ACKNOWLEDGMENTS

One of the authors (J. M. Merlo) wants to acknowledge CONACyT for supporting this investigation with a Ph.D. scholarship whose registration number is 206757.

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