

Micromanipulation Based on AFM: Probe Tip Selection

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Abstract — Micromanipulation based on AFM (atomic force microscope) has become popular in recent years. Since the AFM probe tip can have several shapes, how to select tip shape is discussed for micromanipulation in this paper. Based on the Hamaker hypotheses and the Lennard-Jones potential, interactions between probe and substrate surface are analyzed for three typical shape probe tips, namely, quadrilateral pyramid, cone, and paraboloid. Simulations are presented, and conclusion is obtained: a quadrilateral pyramid probe tip with small inclination between edge and axis is the best choice for micromanipulation based on AFM.

Keywords — AFM, Micromanipulation, quadrilateral pyramid probe tip.

I. INTRODUCTION

Recently, micromanipulation based on AFM (atomic force microscope) is an active research direction. Micromanipulation is such a manipulation that the end-effectors process in a small workspace (e.g. centimeter scale) while the system's precision reaches from sub-micrometer to nanometer [1]. Research on micromanipulation is becoming important and popular, because of the expected wide range of applications and also for many theoretical and technological problems that it poses, such as, the assembly of small parts to obtain micro or miniature systems, surgery and research in biology, and biotechnology [2-4], which will be a most promising research field in this century.

The atomic force microscope (AFM) is one of a family of scanning probe microscopes which has grown steadily since the invention of the scanning tunnelling microscope by Binnig and Rohrer in the early eighties for which they received the Nobel Prize for Physics in 1986 [5]. It is an atomic resolution microscope which measures the interatomic force between the probe tip and substrate surface to obtain the substrate topology images. Besides imaging, it has become popular as a simple manipulation tool [6-10].

The AFM has three main components, namely, a piezoelectric tube scanner, a cantilever beam-mounted probe, and a cantilever deflection sensor consisting of a laser source and a position sensitive diode (PSD) as shown in Fig. 1. Information on sample topography or local properties is obtained based on probe-sample interactions. When the tip is brought into proximity of a sample surface, forces between the tip and the sample lead to a deflection of the cantilever according to Hooke's law. Probe position is determined by

measuring the change in the slope at the cantilever free-end using the cantilever deflection sensor.

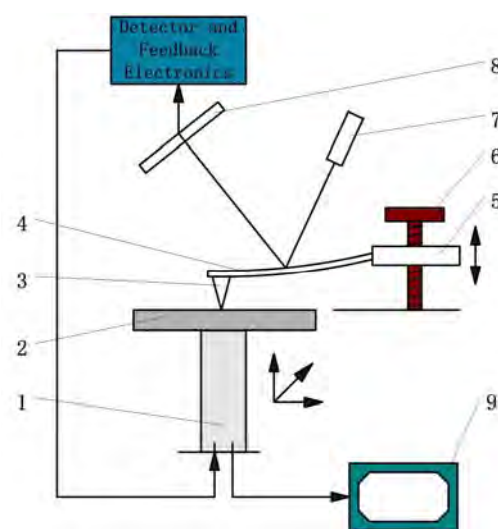


Figure 1. The components of AFM: 1 Piezoelectric scanner; 2 Sample; 3 Probe tip; 4 Cantilever; 5 Chip; 6 Coarse positioning system; 7 Laser source; 8 Position sensitive diode (PSD); 9 Computer system.

There are two main designs for AFM. In one design, the probe is attached to the scanner that moves it relative to a stationary sample. Thus it is named probe-scanning. It is flexible, but it is hard to track the laser. While in the other design, the cantilever is fixed and a sample is placed on the scanner which moves it relative to the cantilever. Oppositely, this is called sample-scanning.

The primary modes of AFM operation are static (contact) mode and dynamic (tapping) mode. In contact mode, the probe presses against a sample, exerting a vertical force proportional to the cantilever deflection. The probe is then dragged against the sample along each scan line in a raster fashion. The slope at the cantilever free-end is measured and fed back. During scanning, a control system is used to maintain a constant slope, by adjusting the vertical deflection of the piezo scanner. Changes in the piezo deflection are therefore, related to changes in the sample topography. Thus the sample topography can be recorded by the changes of piezo deflection. In the dynamic mode, the cantilever is externally oscillated at or close to its resonance frequency. The oscillation amplitude, phase and resonance frequency are modified by tip-sample

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interaction forces; these changes in oscillation with respect to the external reference oscillation provide information about the sample's characteristics. This mode is gentler compared to the contact mode, since the tip is tapped along the surface instead scrapped along it. Thus it is also called tapping mode. Tapping mode is usually used for imaging really soft, fragile or very lightly bound material.

Manipulation of nano particles is very important, since it is fundamental for assembly of nano structures. Thus we try to develop micromanipulation based on a sample-scanning AFM to manipulate nano particles on substrate surface. Contact mode is utilized to manipulate the particles, while tapping mode is utilized to image the particles in order to affect them minimally.

The AFM using cantilever is usually made from silicon or silicon nitride with a very low spring constant, on the end of which a sharp tip is fabricated using semiconductor processing techniques. To manipulate micro particles, a silicon probe is usually used. But the probe tip can have several shapes, such as, quadrilateral pyramid, cone, and paraboloid, etc. Which is the best choice for micromanipulation? To our best knowledge, few works have been done on this aspect. In our opinion, there are two basic criterions to select the probe tip: 1) it is suitable to use as a manipulation tool, 2) it is easy to manufacture. In this paper, we show our interest at the first point. Ideally, a tip has no interaction with the substrate can affect the manipulation process minimally, since there is no extra resistance except the friction force between particle and substrate. Therefore a small interaction tip is preferred.

Actually, an interaction force model was established by Li in 2003 [11] with the common method used in macro world. But he just presented the relationship of the interaction forces with the common method used in macro world. In this paper, we utilized the Hamaker hypotheses which are used popular in the micro world and the Lennard-Jones potential to analyze the interaction force.

In section 2, we analyze the interactions of probe-substrate for three tips with different shapes. Simulations are presented in section 3. And conclusion is given in section 4.

II. PROBE-SUBSTRATE INTERACTION

In this section, the interactions between three typical tips and substrate surface are analyzed using the Hamaker hypothesis and Lennard-Jones potential. Fig. 2 shows three typical shapes of AFM probe tip: quadrilateral pyramid, cone, and paraboloid.

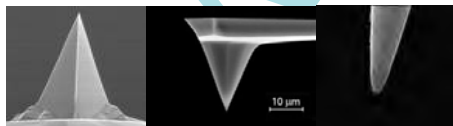


Figure 2. Three different shape probe tips: quadrilateral pyramid, cone, and paraboloid.

A. Interaction of two arbitrary shaped bodies

In macro world, material shows its continuity. But it is discrete in micro world, since it is composed of molecular, atom, and ion. The routine continuous methods don't work any more to study the interaction in micro world. In 1937, Hamaker [12] published three famous hypotheses which laid the foundation for using continuous methods solving the problems in micro world. The three hypotheses proposed by Hamaker were:

1) *Additivity*: The total interaction can be obtained by the pairwise summation of the individual contributions;

2) *Continuous medium*: The summation can be replaced by integration over the volumes of the interaction bodies assuming that each "molecule" occupies a volume dV with a density ρ ;

3) *Constant material properties*: The number density ρ and the interaction coefficient are constant over the volume of the bodies.

Currently, the Hamaker hypothesis is the most popular method used in the micro world.

The tip and sample are both constituted with single atoms. According to the solid physics, two arbitrary atoms, of tip and sample surface respectively, with distance l have the inter atom force obtained from Lennard-Jones potential [13]:

$$f(l) = 12A/l^3 - 6B/l^7 = f_1 + f_2 \quad (1)$$

where A and B are exclusive constant and attractive constant respectively. And f_1 term describes exclusive force, while f_2 term describes attractive force.

Based on the Hamaker hypothesis and (1), the interaction force between two arbitrary shaped bodies is given by:

$$F = \rho_1 \rho_2 \int_2 \int_1 f(l) dV_1 dV_2 \quad (2)$$

where $\rho_1, \rho_2, dV_1, dV_2$ are the number density and infinitesimal volume of bodies 1 and 2 respectively.

B. Atom-plane interaction

Fig. 3(a) shows the interaction of an atom D and a sphere. Atom E is an arbitrary atom of the sphere, d is the distance between the atom D and the sphere surface, and R_1 is the radius of the sphere. We want to compute the vertical component of the atom-sphere interaction force, all other components being zero due to the symmetry of the problem. According to the Hamaker hypotheses, the interaction force between atom D and sphere is obtained by integrating f over the sphere volume:

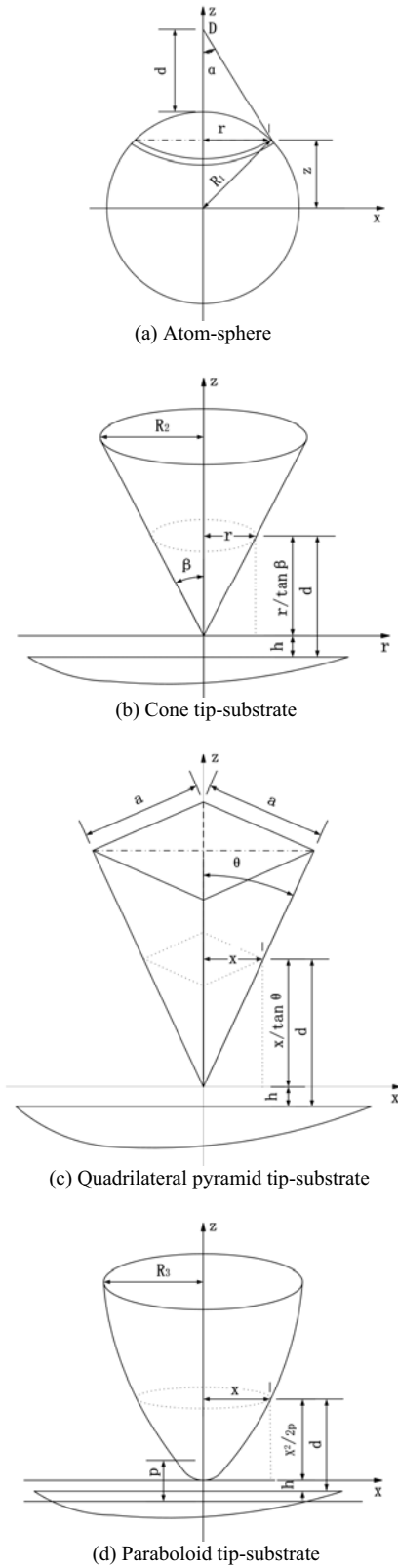


Figure 3. Interaction

$$F_{A-S} = \rho_1 \int_V f dv = -\frac{8B\pi\rho_1 R_1^3 (d + R_1)}{d^4 (d + 2R_1)^4} + \frac{16A\pi\rho_1 R_1^3 (d + R_1) [d^2 + 2R_1 (d + R_1)]}{5d^{10} (d + 2R_1)^{10}} \times [5d^4 + 4R_1 (d + R_1) (5d^2 + 8R_1 (d + R_1))]. \quad (3)$$

When $R_1 \rightarrow \infty$, (3) yields the atom-plane interaction force:

$$F_{A-P} = \frac{A\pi\rho_1}{5d^{10}} - \frac{B\pi\rho_1}{2d^4}. \quad (4)$$

C. Probe tip-substrate surface interaction

Let us assume that body 1 in (2) is the substrate surface plane and body 2 is the probe tip.

Fig. 3(b-d) show the interaction between a cone shape tip, a quadrilateral pyramid tip, and a paraboloid tip with substrate surface respectively. In these models, h denotes the separation between the tip apex and the substrate surface, β denotes the half cone angle of the cone, θ denotes the inclination between edge and axis of the pyramid, and p denotes the foci of the paraboloid. According to the Hamaker hypotheses, the interaction force between cone tip and substrate surface is obtained by integrating F_{A-P} over the volume of the cone tip:

$$F_{C-P} = \rho_2 \int_V F_{A-P} dv = \frac{A\pi^2 \rho_1 \rho_2}{1260} \left[\frac{\tan^2 \beta}{h^7} - \frac{36R_2^2 + 9R_2 h \tan \beta + h^2 \tan^2 \beta}{\left(\frac{R_2}{\tan \beta} + h\right)^9} \right] - \frac{B\pi^2 \rho_1 \rho_2}{6} \left[\frac{\tan^2 \beta}{h^3} - \frac{3R_2^2 + 3R_2 h \tan \beta + h^2 \tan^2 \beta}{\left(\frac{R_2}{\tan \beta} + h\right)^3} \right]. \quad (5)$$

Equation (5) is very complicated. Since in the actual situation of a AFM, $R_2 \gg h$, it is reduced to:

$$F_{C-P} = \frac{A\pi^2 \rho_1 \rho_2 \tan^2 \beta}{1260h^7} - \frac{B\pi^2 \rho_1 \rho_2 \tan^2 \beta}{6h} \quad (6)$$

The first term describes the exclusive force, while the second one describes the attractive force.

With the same method, we obtain the probe-substrate interaction force for the tips of quadrilateral pyramid shape and paraboloid shape.

Quadrilateral pyramid tip-substrate surface plane:

$$F_{Q-P} = \rho_2 \int_V F_{A-P} dv$$

$$= \frac{A\pi\rho_1\rho_2}{630} \left[\frac{\tan^2 \theta}{h^7} - \frac{18a^2 + \frac{9\sqrt{2}}{2} ah \tan \theta + h^2 \tan^2 \theta}{\left(\frac{\sqrt{2}a}{2 \tan \theta} + h\right)^9} \right]$$

$$- \frac{B\pi\rho_1\rho_2}{3} \left[\frac{\tan^2 \theta}{h} - \frac{\frac{3}{2}a^2 + \frac{3\sqrt{2}}{2} ah \tan \theta + h^2 \tan^2 \theta}{\left(\frac{\sqrt{2}a}{2 \tan \theta} + h\right)^3} \right]$$

Since $a \gg h$, the above equation is reduced to:

$$F_{Q-P} = \frac{A\pi\rho_1\rho_2 \tan^2 \theta}{630h^7} - \frac{B\pi\rho_1\rho_2 \tan^2 \theta}{3h} \quad (7)$$

Paraboloid tip-substrate surface plane:

$$F_{P-P} = \rho_2 \int_V F_{A-P} dv$$

$$= \frac{A\pi^2 \rho_1 \rho_2 p}{180} \left[\frac{1}{h^8} - \frac{9R_3^2 + 2ph}{2p\left(\frac{R_3^2}{2p} + h\right)^9} \right]$$

$$- \frac{B\pi^2 \rho_1 \rho_2 p}{6} \left[\frac{1}{h^2} - \frac{3R_3^2 + 2ph}{2p\left(\frac{R_3^2}{2p} + h\right)^3} \right]$$

Since $R_3 \gg h$, the above expression is reduced to:

$$F_{P-P} = \frac{A\pi^2 \rho_1 \rho_2 p}{180h^8} - \frac{B\pi^2 \rho_1 \rho_2 p}{6h^2} \quad (8)$$

III. SIMULATIONS

In this section, simulations of the probe-substrate interaction are presented to analyze which shape is the best choice for micromanipulation based on AFM.

The Hamaker constant is defined as $H = \pi^2 \rho_1 \rho_2 C$ [14], where C is the interaction constant. Then we

have $\rho_1 \rho_2 = H / (\pi^2 C)$. And equations (6-8) can be rewritten as:

$$\frac{CF_{Z-P}}{H} = \frac{A \tan^2 \beta}{1260h^7} - \frac{B \tan^2 \beta}{6h} \quad (9)$$

$$\frac{CF_{S-P}}{H} = \frac{A \tan^2 \theta}{630\pi h^7} - \frac{B \tan^2 \theta}{3\pi h} \quad (10)$$

$$\frac{CF_{P-P}}{H} = \frac{Ap}{180h^8} - \frac{Bp}{6h^2} \quad (11)$$

Simulations of FC/H on condition of $A=B=1$ are shown in Fig. 4. From the simulation results, we can see that under the same condition the interaction between the quadrilateral pyramid tip and sample surface is smallest, while the one for paraboloid is the largest. Actually, the manufacture of quadrilateral pyramid shape tip is easier, and the AFM probes with pyramid tip are used most popular. Therefore, the quadrilateral pyramid tip is the best choice without doubt.

In addition, we notice that the interaction is smaller when the inclination between edge and axis is smaller. Thus, we conclude that the quadrilateral pyramid probe tip with a small inclination between edge and axis is preferred for the micromanipulation based on AFM.

IV. CONCLUSION

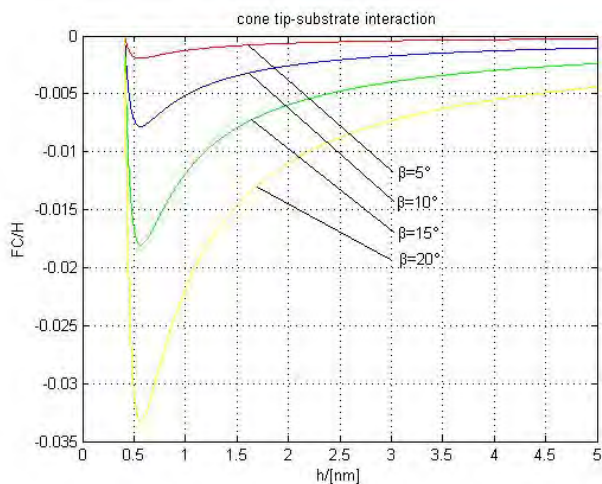
Micromanipulation based on AFM is a very hot research topic in recent years. To develop micromanipulation based on AFM, we have to select a proper AFM probe tip. Among all the shape of AFM probe tips, the tip-substrate interaction force is smallest for the pyramid tip, which affects the micromanipulation minimally. And the manufacture of pyramid tip probes is the easiest one. Thus, a probe with pyramid tip is best choice for the micromanipulation based on AFM.

Probe-substrate interaction forces are given for three typical shape tips. From the simulations, we conclude that a pyramid tip with small inclination between edge and axis is preferred for manipulation.

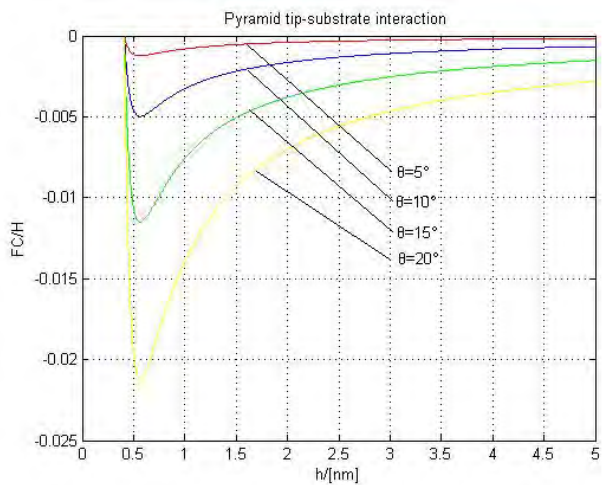
For our future work, the micromanipulation ability of AFM will be analyzed according to the probe tip geometry, the force that the cantilever can endure when approaching the substrate, the interaction force between the tip and the object, etc.

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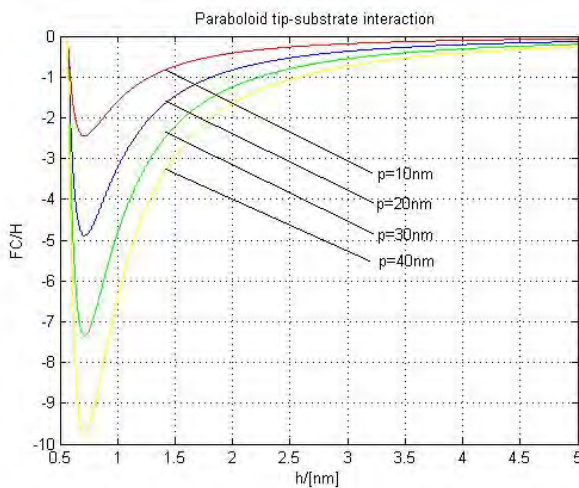
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(a) Cone tip-substrate



(b) Quadrilateral pyramid tip-substrate



(c) Paraboloid tip-substrate

Figure 4. Simulation results

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