研 究 速 報

Micro/Nano Manipulation Using Atomic Force Microscope

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1. Introduction

In the field of mechatronics, one of the main directions of research is the miniaturization of robots, machines and devices more and more where this new branch is called as *micro/nano mechatronics*. Recent advances in this field enabled milli-robots inside of nuclear plants, milli-surgical robots for minimal invasive surgery, Scanning Probe Microscopy such as Atomic Force Microscopy (AFM) and Scanning Tunneling Microscopy where the geometrical, electrical, magnetic, and etc. kind of properties of materials can be measured down to atomic scale in 3-D. However, still the total sizes of these robots and machines are limited to millimeter or centimeter sizes, and one of the major reasons is the lack of the manipulation and fabrication technologies for the objects with the sizes less than 10μm.

By manipulation we mean using an external force for positioning or assembling objects in 2-D or 3-D, cutting, drilling, twisting, bending, pick-and-place, or push and pull kind of tasks. For manipulating micro/nano scale objects different approaches are utilized. They can be classified into two parts as *non-contact* and *contact* manipulation systems. At the former, laser trapping (optical tweezers) or electrostatic or magnetic field forces are utilized. Yamomoto et al. [1] can cut DNA using restriction enzymes on a laser trapped bead, and Stroscio et al. [2] utilized electrical force between STM probe tip and surface atoms for manipulating Xe or Ni atoms. As the contact manipulation, AFM probe tip is utilized for positioning particles on a substrate by contact pushing or pulling operations [3, 4].

2. AFM as the Micro/Nano Manipulator and Sensor

Basic structure of a conventional AFM is given in Figure 1. A microfabricated silicon cantilever with a very sharp tip at the end, and known stiffness and geometrical properties can be deflected due to the interatomic forces if the probe tip is positioned very close to a material surface in the order of few nm or Angstrom (A°) where a standard nano force-distance relation during the tip-surface approach and retraction is shown in Figure 2. When approaching there is a nonlinear attractive force due to the long range van der Waals forces and sometimes capillary forces, and after a maximum peak (small peak), the tip begins to contact around the interatomic distance, i.e. 1.69 A°. After contact, the cantilever is elastically deformed, and the interatomic force is repulsive and almost linear until to the plastic deformation region.

Using XYZ piezolelectric actuators with the resolution down to 0.01 nm, very precise positioning is possible. The cantilever deflection Δz can be measured using a laser beam and a photo detector system down to 0.01 nm resolution, or other methods such as piezoresistance or capacitance measurement, and etc. Since the stiffness of the probe k_c is known, the normal force on the tip can be computed as $F_s=k_c\ \Delta z$ assuming quasi-static motion. Controlling the z-motion such that force reaches a reference

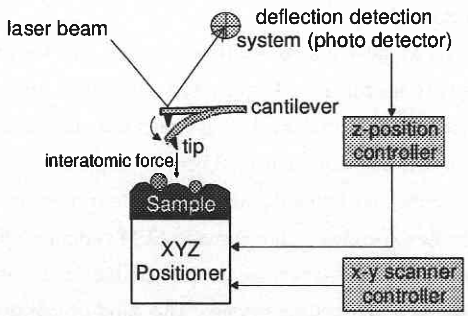

Fig. 1 Structure of a normal and lateral force measuring conventional AFM.

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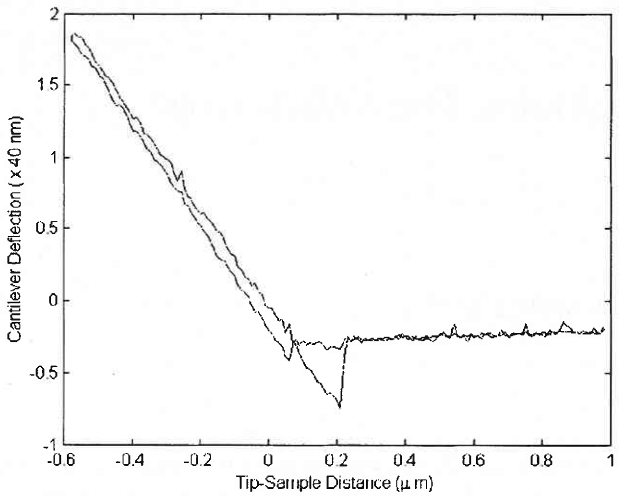

Fig. 2 Interatomic force and distance relation during Si tip and Si surface approach and retraction (experimental).

value in the contact region, the relative motion corresponds to the height at that (x,y) point. Scanning all (x,y) points in a rectangular region, topology data can be held. This method is called *contact* imaging. However, for the manipulation applications, the nano objects to be manipulated are designed not to be fixed on the substrate, and contact-type of scanning can move the objects. Therefore, during imaging, *non-contact* AFM imaging is required. As the non-contact imaging type, tapping mode imaging is preferable where soft samples can be scanned with few deformation, and instabilities due to the water layer on the surface are reduced. In the tapping mode, the cantilever tip is set to several 10s of nm above the substrate, and it is vibrated externally around its resonance frequency f_r by an amplitude equal to its separation distance. Thus, the tip taps to the substrate, and the interatomic forces change the vibration amplitude and frequency. Detecting these changes and controlling the sample/cantilever z-position during scanning, surface topology image is held. Thus, our strategy is *imaging in the tapping mode and manipulation in the contact-mode.*

Using AFM also lateral frictional forces can be measured which is very useful for 2-D push and pull object manipulation where friction plays a major role. Frictional force can be measured by detecting the cantilever torsional bending angle using a four-cell photo detector, and knowing the torsional stiffness of the cantilever. In the experiments, home-made AFM system is utilized [5, 6]. Piezoresistive cantilevers are used where the deflection is measured through a Wheastone bridge. This kind of cantilevers are advantageous for manipulation applications where laser detection systems limit the mechanical design, and motion capabilities of the probe while these cantilevers do not. However, the deflection resolution is almost ten times worse than laser detection one.

3. Micro/Nano Forces

During the manipulation of a micro/nano object using an AFM probe, the interacting forces are shown in Figure 3. All of these forces should be modeled, and the dynamical analysis of the manipulation should be conducted for improving general design rules and strategies. Modeling of these forces in the spherical particle pushing case is given in [7, 8]. From these models, the conditions for a reliable contact pushing of any object are driven as follows:

1. Objects should be precisely movable by contact pushing on the substrate reducing friction between particle and substrate.
    1.1. Depositing lubricant monolayer on the substrate, i.e. for a Au object, Silane monolayer on a Si substrate, and Polylysine layer on a Mica [4],
    1.2. Minimizing the particle-substrate adhesion (friction is function of external load plus adhesive force at the nano scale [8]):
        1.2.1. Selecting proper material types (minimal surface energies),
        1.2.2. Reducing the adhesive forces such as capillary force by reducing the humidity level or coating the tip by teflon, or electrostatic force by grounding the tip and substrate, etc.,
    1.3. Proper cantilever selection:
        1.3.1. high stiffness (10s of N/m) for pushing stability (applying enough load for pushing and breaking the adhesion force during separation from the object after manipulation),
        1.3.2. hard tip (Si or Si_3N_4),
    1.4. Contact point/angle selection (for applying maximum shearing force such that the horizontal line passing through the object center in spherical particle case),
    1.5. High motion accuracy (for precise positioning during pushing):
        1.5.1. closed-loop positioners for reducing hystheresis and drift effects,
        1.5.2. reducing environmental noise sources (vibration, thermal changes, etc.),
        1.5.3. selecting low thermal conductivity materials on the mechanical parts for reducing the thermal drift,
2. Objects should not stick to the tip while retracting the probe after manipulation: (tip-particle adhesion) < (particle-sub-

strate adhesion)

2.1. small tip radius (few 10s of nm) with hard material: small contact area,
2.2. manipulation in liquid (reduces capillary and electrostatic forces),
2.3. tip or particle coating for reducing adhesion forces (latex particles are coated with Au for reducing adhesion due to triboelectrification [7]).

However, some of conditions have trade-offs. Conditions 1.2 and 2 are opposite, then a between optimum particle-substrate adhesion should be designed. Secondly, Condition 1.3.1 results in reduction of force measurement sensitivity such that smaller stiffness means higher force resolution. These trade-offs can be solved depending on the priority in a specific application.

4. Experiments

1 μm diameter gold-coated latex particles are positioned on a silicon substrate by pushing in ambient conditions with 50% humidity level. In Figure 4, a particle in front of the end of the cantilever is pushed approximately 15μm downward successfully. Coating the latex particles with gold, reduced the tribo-electrification forces. Cantilever parameters are $k_c=8$ N/m and *25nm* tip radius. Top-view Optical Microscope images are utilized for real-time monitoring with *95 nm/pixel* resolution. Modeling of forces and their evaluation with the experimental results are given in [7, 8].

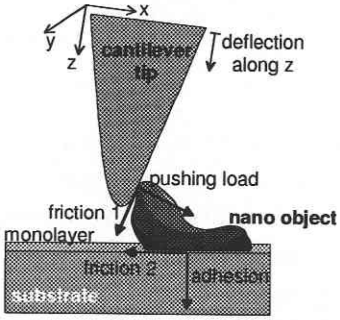

Fig. 3 Interaction forces during pushing nano objects by AFM probe tip.

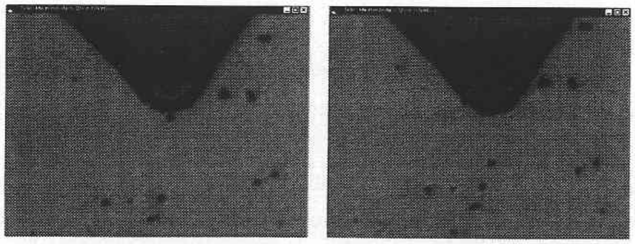

Fig. 4 2-D positioning of a 1 μm gold-coated latex particle by contact pushing where the initial configuration (left) and last one (right) are shown.

5. Conclusion

In this paper, a micro/nano manipulation system using home-made AFM as the nano manipulator and sensor is introduced. Preliminary experiments on 1μm latex particle positioning show that the system can be utilized for micro/nano manipulation experiments. As the future work, the sizes of the manipulated objects will be decreased to few 10s of nanometer, and types of manipulated objects will be increased.

(Manuscript received, June 28, 1999)

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