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Atomic Force Microscopy manipulation with ultrasonic excitation

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Abstract. The exposure of nanostructures to ultrasound renders the opportunity to explore novel methods to control their assembly. In the presence of surface ultrasonic vibration, large Sb nanoparticles on MoS_2 substrates can be laterally displaced using the tip of a compliant AFM cantilever by just increasing the ultrasonic excitation amplitude. Magnetic nanoparticles of about 10-20 nm in diameter are swept by the tip when scanning in contact mode in the absence of ultrasound, but remain undisturbed in the presence of low amplitude ultrasonic vibration. In Atomic Force Microscopy-assisted manipulation of nanoparticles, ultrasonic vibration affects both tip-particle and particle-surface frictional properties.

1. Introduction

Recently, we discussed the advantages of using ultrasound in Atomic Force Microscopy (AFM)-based nanofabrication procedures [1]. Since ultrasonic vibration reduces or eliminates nanoscale friction [2], the excitation of ultrasound at a sample surface may allow us to control the motion of nanoparticles (NP) at surfaces. Effects such as sonolubrication and acoustic levitation have been studied at the microscale [3-5]. As illustrated in Fig. 1, on the nanoscale, ultrasonic excitation can introduce novel mechanisms to induce the displacement of NP on surfaces with an AFM cantilever tip. Surface ultrasonic vibration will modify both tip-particle and particle-surface frictional properties. In addition, the excitation of internal vibrations in the NP may also modify the NP dynamic response.

Here, we present data from AFM manipulation experiments with ultrasonic excitation of Sb NPs deposited on MoS_2 [6, 7], and magnetic NPs (MNPs) adsorbed on silicon. Large Sb NPs (of ~ 400-600 nm in diameter) were laterally displaced using the tip of a compliant AFM cantilever by increasing the amplitude of surface ultrasonic vibration. The MNPs (of ~ 10-20 nm in diameter) were swept by the tip when scanning in contact mode in the absence of ultrasound, but remained undisturbed in the presence of low amplitude surface ultrasonic vibration; by increasing the ultrasonic amplitude, a tip-induced motion of the MNPs was again observed. The results unequivocally demonstrate that the modification of the surface ultrasonic excitation amplitude allows us to control the dynamic response of the NPs upon tip actuation.

2. Experimental

The AFM with ultrasonic excitation equipment has been set up in our lab by appropriately modifying a commercial AFM (Nanotec), in which the techniques of Ultrasonic Force Microscopy (UFM) [8, 2]

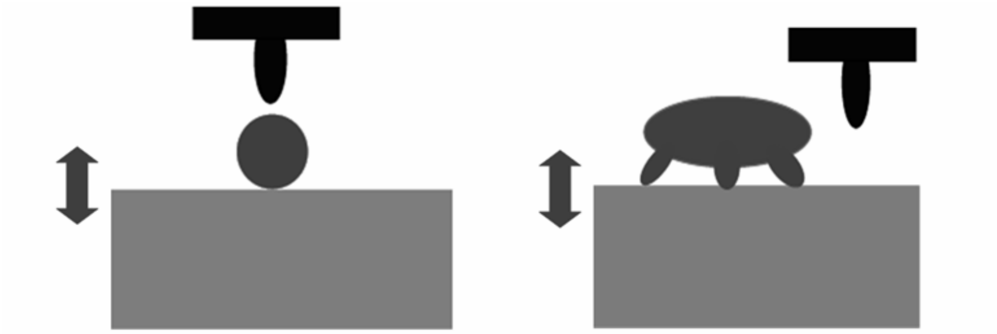

Figure 1. The excitation of ultrasonic vibration at a sample surface may introduce novel mechanism to induce the displacement of NP on surfaces with an AFM cantilever tip (see text).

and Mechanical-Diode Ultrasonic Friction Force Microscopy (MD-UFFM) [9] have been implemented. A schematic drawing of the equipment for UFM measurements is provided in ref. [10]. The UFM mode allows us to excite ultrasonic vibration at the tip-surface contact and monitor the ultrasonic-induced cantilever displacement while simultaneously recording contact-mode AFM and LFM images over the same surface region. Information about the preparation procedure and properties of the samples of Sb nanoparticles can be found in ref. [10]. The MNP were obtained from a ferrofluid solution. A drop of the ferrofluid was dissolved in benzene and pipetted onto a Si(111) surface, which had been previously rinsed in alcohol and blown dry under N_2 flux. A thin layer of poly-l-lysine was deposited onto the MNP covered silicon surface. Olympus rectangular Silicon Nitride cantilevers with a pyramid-like tip shape and spring constant of 0.06 Nm-1 were used in contact-mode AFM, UFM, and manipulation experiments.

3. Results and Discussion.

Studies of AFM manipulation of Sb NPs using dynamic AFM have been previously reported in the literature [11, 12]. Results from the experiments of AFM manipulation of Sb NPs with ultrasonic excitation are shown in Fig. 2. Displacing the AFM cantilever tip along the arrow in Fig. 2(a) [13] induces a displacement of the Sb NP when the ultrasonic amplitude is sufficiently high. Fig. 2 (b) and Fig. 2(c) show topographic signals (z-piezo signals) and lateral force signals when the tip is displaced along the arrow in (a) without inducing a NP motion. No ultrasound was excited while recording the data in Fig. 2(b). Low amplitude surface ultrasonic vibration was excited while recording the data in Fig. 2 (c). Comparison of the lateral force signals in Fig. 2(b) and Fig. 2(c) reveals that the excitation of ultrasonic vibration while recording the data in Fig.2(c) suffices to eliminate friction between the tip and the NP surface. Increasing the surface ultrasonic excitation amplitude, the Sb NP can eventually be displaced by the AFM cantilever tip to a new position, as shown in Fig. 2(d). Once the NP has been displaced for a first time, imaging in the presence of ultrasound induces the NP displacement even with low ultrasonic amplitudes. Fig. 2(e) was recorded immediately after Fig. 2(d), in the presence of low-amplitude surface ultrasonic vibration. As it is noticeable from the image, the previously displaced Sb NP moves downwards while the tip is recording the image. Fig. 2(e) and Fig. 2(f) are simultaneously recorded UFM and LFM (forward scan) images showing the tip-induced motion of Sb NPs in the presence of ultrasonic vibration. The traces left by the NP in these images provide information of the ultrasonic forces (UFM signal, Fig. 2 (e)) and the lateral forces (Fig. 2(f)) exerted by the tip while the NPs are being displaced. Due to its inertia, the cantilever does not vibrate at ultrasonic frequencies and hence, in principle it is possible to measure the lateral friction force in the presence of surface ultrasonic vibration during the NP displacement, which should provide a wealth of information about the required forces and the dissipated energy [15].

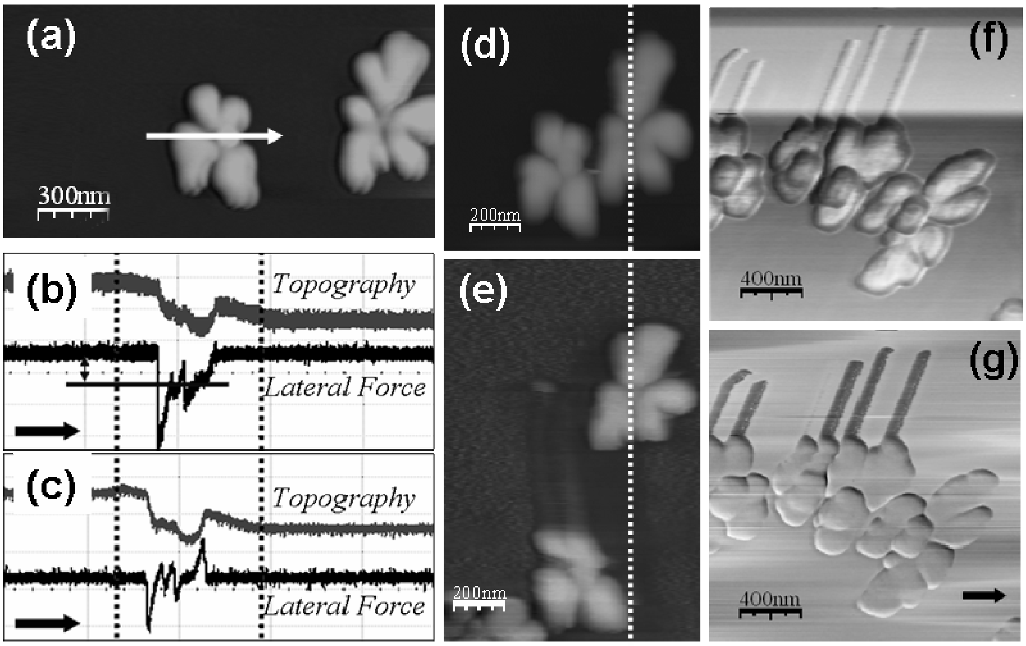

Figure 2. AFM manipulation of Sb NP with ultrasonic excitation. **(a)** Topographic contact-mode AFM image without ultrasound; set-point force F_o = 0.8 nN. **(b)** Topographic and lateral force signals recorded with an oscilloscope as the tip is displaced along the arrow in (a) without ultrasound; F_o = 1 nN; the procedure does not displace the NP. **(c)** As in (b), in the presence of surface ultrasonic vibration; F_o = 1 nN; ultrasonic frequency: f = 2.1 MHz, ultrasonic amplitude: A=2 V; the procedure does not displace the NP. **(d)** Topographic contact-mode AFM image without ultrasound over the same surface region as (a), recorded after displacing the AFM tip along the arrow in (a) in the presence of ultrasonic vibration: f = 2.1 MHz, A = 8 V **(e)** Topographic contact-mode AFM image recorded in the presence of surface ultrasonic vibration: f = 2.1 MHz, A = 2 V; the previously displaced NP moves as the tip scans downwards. **(f, g)** Simultaneously recorded UFM (f) and LFM (g) images of Sb NPs; the NPs move as the tip scans downwards; set-point force: Fo = 0.32 nN, f = 2.1 MHz, A_m = 6V, f_m= 2.4 KHz.

The UFM signal originates from the nonlinear the tip-nanoparticle-surface interaction forces, and hence UFM data recorded while the particle is in motion should render information about the nanoparticle dynamics at the tip-surface gap with a time resolution in the ultrasonic time scale.

Results from the experiments of AFM manipulation of MNPs with ultrasonic excitation are shown in Fig. 3. Fig. 3(a) and Fig. 3(b) show simultaneously recorded a contact-mode AFM topography (Fig. 3(a)) and UFM image (Fig. 3(b)) of the MNPs recorded in non-manipulation conditions. The MNPs exhibit a darker (softer) contrast, and are clearly distinguished in the UFM image. Fig. 3(c) and Fig. 3(d) show again simultaneously recorded contact-mode AFM (Fig. 3(c)) and UFM (Fig. 3(d)) images. The central region in Fig. 3(c) and Fig. 3(d) was first imaged in contact-mode AFM with the same AFM parameters, but in the absence of ultrasound, and the MNP were swept away by the tip. In the presence of low-amplitude surface ultrasonic vibration, the MNP remained undisturbed. A further increase of the ultrasonic amplitude caused again a NP movement. .

4. Summary & Outlook

We have presented experimental results on AFM manipulation of Sb NP and MNP that demonstrate that the dynamic response of the NPs upon tip actuation is modified in the presence of surface ultrasonic vibration, and can be controlled by varying the ultrasonic excitation amplitude.

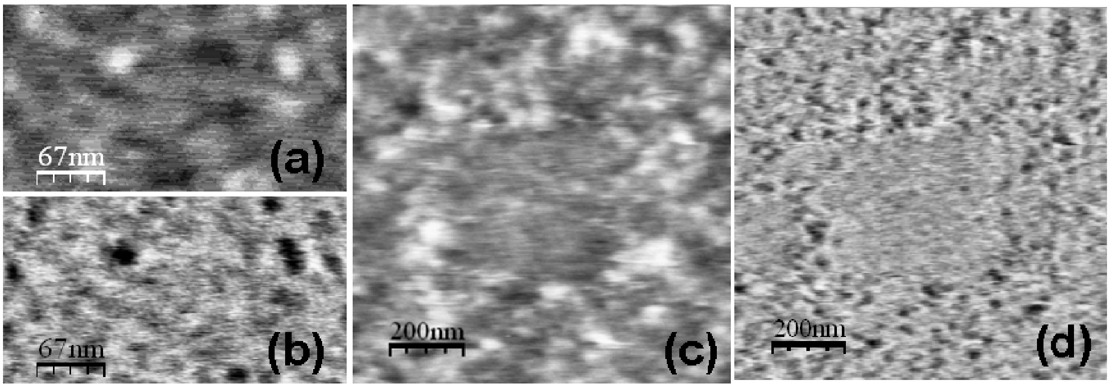

Figure 3. AFM manipulation of MNP with ultrasonic excitation. **(a, b)** Simultaneously recorded contact-mode AFM topography (a) and UFM (b) images; the MNP are distinguished from their darker (softer) UFM contrast. **(c, d)** Simultaneously recorded contact-mode AFM topography (c) and UFM image (d). The central region in (c, d) was first imaged in contact mode without ultrasonic vibration, and the MNP were swept away. $F_o = 0.3$ nN, $f = 2.8$ MHz, $A_m = 0.8$V, $f_m = 2.4$ KHz.

Ultrasonic excitation might facilitate new mechanisms for energy dissipation in the repositioning of nanoscale particles and lead to novel technological procedures in the fabrication of nanostructures.

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