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Measurement of energy dissipation between tungsten tip and Si(1 0 0)-(2 × 1) using sub-Ångström oscillation amplitude non-contact atomic force microscope

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Abstract

Energy dissipation plays an important role in non-contact atomic force microscopy (nc-AFM), atomic manipulation and friction. In this work, we studied atomic scale energy dissipation between a tungsten tip and Si(1 0 0)-(2 × 1) surface. Dissipation measurements are performed with a high sensitivity nc-AFM using sub-Ångström oscillation amplitudes below resonance. We observed an increase in the dissipation as the tip is approached closer to the surface, followed by an unexpected decrease as we pass the inflection point in the energy–distance curve. This dissipation is most probably due to transformation of the kinetic energy of the tip into phonons and heat.

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1. Introduction

During the last few years, non-contact atomic force microscopy (nc-AFM) has improved dramatically and it is now possible to obtain atomic resolution images [1] of a large range of surfaces; semiconductors [2], metals [3], and pure insulators [4] in ultrahigh vacuum (UHV) conditions. Measurement of tip–sample forces and dissipation of energy as a function of separation [5–7] is also possible and will probably shed light into a number of interesting problems like atomic manipulation, atomic scale friction, etc. We have recently built a highly sensitive nc-AFM using small oscillation amplitudes (0.25 Å) [8] for imaging [9–11] and force/dissipation–distance spectroscopy [12]. Employment of sub-Ångström oscillation amplitudes has a number of advantages over large oscillation amplitudes used by most of other groups and simplifies the analysis considerably.

In this work, we present measurements of energy dissipation in atomic scale between a tungsten tip and Si(1 0 0) surface as a function of tip–sample separations with a nc-AFM using small oscillation amplitude, 0.25 Å.

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2. Experimental

The nc-AFM/STM operating in UHV, which is described elsewhere [8] in detail is used in our experiments. In short, the microscope employs a fiber interferometer with a noise floor of 5×10^{-4} Å/$\sqrt{\text{Hz}}$ and uses sub-Ångström oscillation amplitudes below the resonance frequency of the cantilever. Home-made tungsten levers with typical stiffness of about 150 N/m are used in the experiments. The sample were cut from 525 μm thick, P-doped, n-type wafers with 1–10 MΩ resistivity, oriented to within 0.5° of (0 0 1) plane. The samples are cleaned by Shiraki etch prior to introduction into the UHV system. Standard in situ heat treatment is employed to have an atomically clean Si(1 0 0)-(2 × 1) surface.

The lever is driven at sub-Ångström oscillation amplitude at 7 kHz, which is far below the first natural resonance frequency (typically around 23 kHz) and the change in the oscillation amplitude and phase are recorded by using a lock-in amplifier. In case of small amplitude, far below the first resonance frequency, the measured interaction stiffness (negative of the force gradient between tip and sample), k_{int}, is given by [12]

$$k_{\text{int}} = -\frac{\mathrm{d}F}{\mathrm{d}z} = k_0\left(\frac{A_0}{A}\cos\varphi - 1\right) \tag{1}$$

where k_0 is the lever stiffness, A_0 the free oscillation amplitude, A the measured amplitude, F the force, z the tip–sample separation and φ is the phase difference between the dither signal and the actual motion of the lever which is the indicator of energy dissipation. Here we assume that there is no phase difference between the dither signal applied to the lever and the free oscillations of the lever. In the real experimental setup, however, there is a phase difference, but this is corrected by nulling the lock-in phase, prior to the measurement.

The relation of the change in the phase and energy dissipation per cycle as the sample approaches to the tip can be given by [12]

$$E_{\text{diss}} = \frac{2\pi P_{\text{loss}}}{\omega} = \pi k_0 A_0 A \sin\varphi \tag{2}$$

where the P_{loss} is the power loss due to tip–sample interaction and ω is the dither frequency. The maximum damping force can be written as

$$F_{\text{damp}} = \frac{E_{\text{diss}}}{\pi A} \tag{3}$$

3. Results and discussion

We first imaged the Si(1 0 0)-(2 × 1) surface with atomic resolution with a W lever which has a resonance frequency of 23.2 kHz and a stiffness of about 157 N/m [10]. Fig. 1 shows simultaneous STM and force gradient images of the Si(1 0 0)-(2 × 1) surface obtained with our nc-AFM/STM. The free oscillation amplitude was set to 2.4 Å at a dither frequency of 7.9 kHz in this run. Tip bias voltage and tunnel current were set −1.5 V and 1 nA, respectively. Dimer rows can be recognized in both images of Si(1 0 0) surface. Some large area defects such as missing dimmer groups are also visible in the images. In the force gradient images, darker regions correspond to higher attractive force gradients. The dimer corrugation in force gradient images is 2.3 N/m along the dimers.

Fig. 2 shows the interaction stiffness, k_{int} and the tunneling current as a function of tip–sample distance measured simultaneously. The free oscillation ampli-

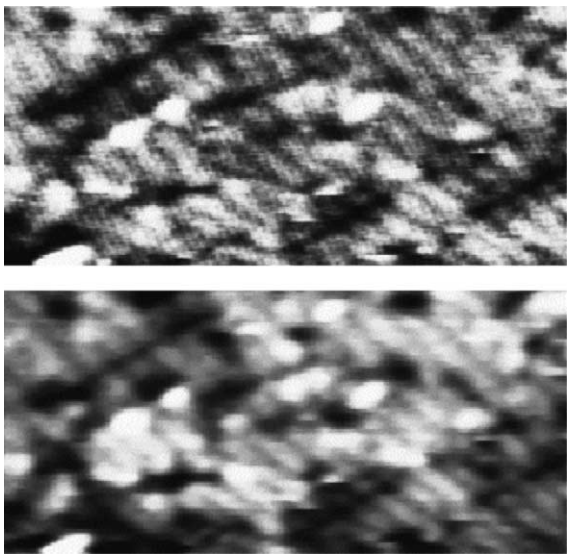

Fig. 1. Simultaneous STM (top) and force gradient (bottom) images of Si(1 0 0)-(2 × 1). Image size is 154 Å × 77 Å. $V_{\text{bias}} = -1.5$ V, $I_t = 1$ nA, $A_0 = 2.3$ Å, and $k_0 = 157$ N/m.

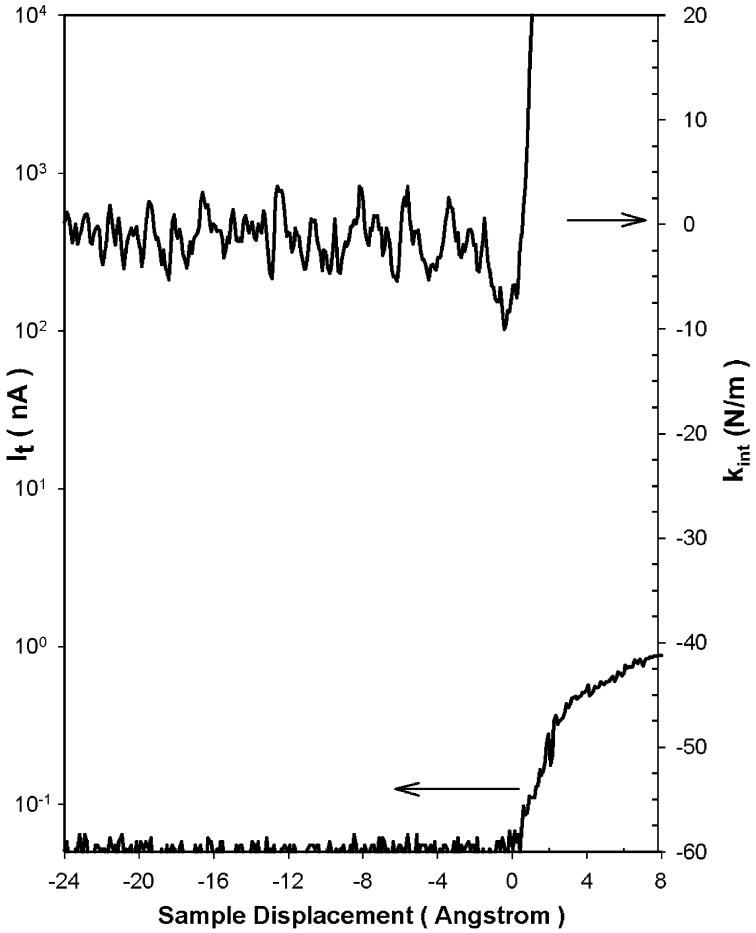

Fig. 2. Interaction stiffness and tunnel current vs. tip–sample separation. $A_0 = 0.25$ Å and $k_0 = 110$ N/m.

tude of the lever, A_0, was 0.25 Å and the interaction stiffness was calculated using Eq. (1). In our force gradient–distance, $f'-d$, curve the maximum interaction stiffness (maximum attractive force gradient) reaches 15 N/m and the corresponding binding energy is calculated to be ≈3.3 eV. The force gradient–distance measurement shows the onset of tunneling current is almost at the point where a considerable change in force gradient starts. The fitted interaction length is 3 Å which suggests the short-range interaction is dominant [10].

Fig. 3 shows the measured interaction stiffness, phase, and calculated energy loss per cycle as a function of tip–sample distance. The experiment is performed with a stiff W lever (150 N/m), which was dithered at a frequency of 7.9 kHz (the lever's first resonance frequency was 23.4 kHz) and free oscillation amplitude of $A_0 = 0.25$ Å. The interaction stiffness starts from zero at large separations and then decreases as we bring the sample closer to the tip. It reaches a minimum and starts to increase back to zero and then becomes positive as the separation is reduced further. The energy loss per cycle as well, starts from zero while the separation is large and only changes once the tip enters into the short-range interaction region. It reaches a maximum value of 68 meV/cycle, *just* after the minimum point of the interaction stiffness. The dissipation starts to decrease after reaching the maximum. The decrease in the dissipation is much slower than the increase in the stiffness and there is a considerable dissipation (68% of maximum value) when the stiffness value reaches back to zero. The

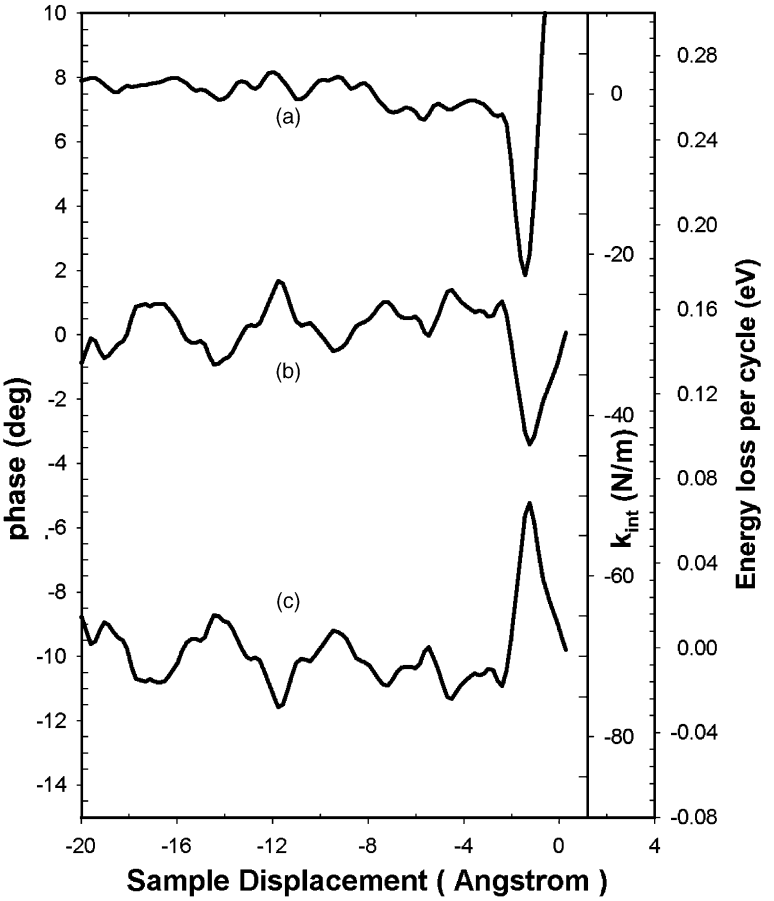

Fig. 3. Energy loss vs. distance: measured interaction stiffness (a); measured phase (b); calculated energy loss per cycle (c). $A_0 = 0.25$ Å, $k_0 = 110$ N/m, and maximum dissipated energy is 68 meV/cycle.

dissipation surprisingly drops back to zero only when the interaction stiffness plunges deeply into the positive region, where the tip–sample is most probably in contact.

Fig. 4 shows a different measurement with the same tip and a different region on the sample. The behavior is very similar to the one in Fig. 3, however, the maximum dissipation reaches a value of 116 meV/cycle this time. The maximum damping forces are calculated to be 4.4×10^{-10} and 7.4×10^{-10} N for Figs. 3 and 4, respectively.

The measured dissipation behavior is surprisingly very different and the values are significantly lower than the values reported using large amplitude nc-AFM measurements, but is much closer to theoretical predictions [13]. Our dissipation values on Si(1 0 0)-(2 × 1) are similar to the ones we reported earlier on Cu [12]. However, the overall behavior, the drop of dissipation back to zero after reaching a maximum has *never* been observed before. The short-range behavior of the energy dissipation indicates that losses between the tip and sample are highly localized, and are not due to some mechanism affecting the macroscopic tip structure. In Ref. [12] we suggested a simple mechanism which successfully describes the observed behavior of the energy dissipation in the interacting tip–sample system. The results imply the energy dissipation is probably due to the motion of a bistable atomic defect in the tip surface region. The atomic motion is rapid compared to the motion of the lever, as

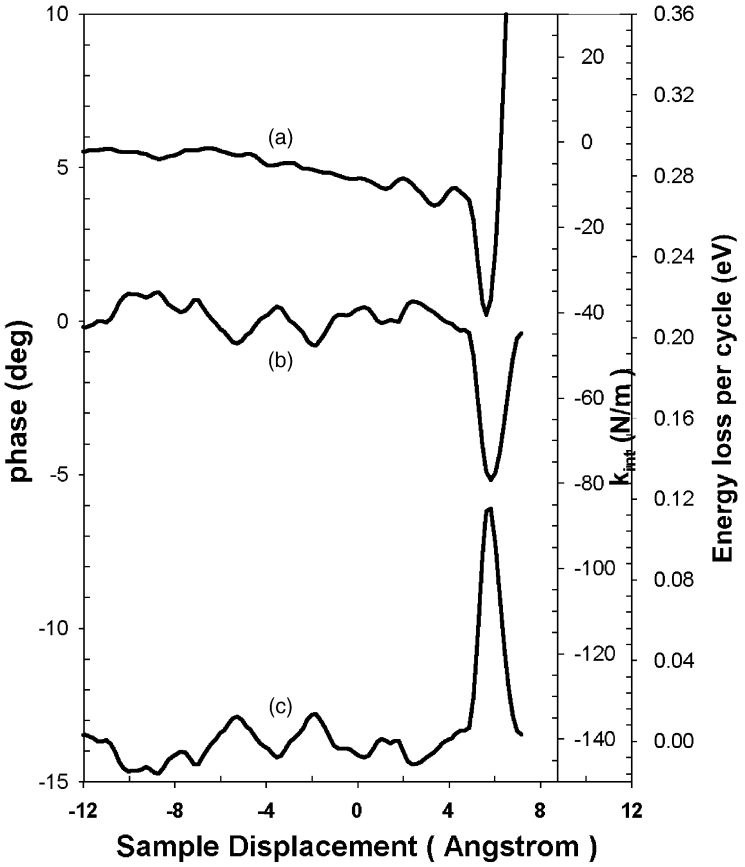

Fig. 4. Energy loss vs. distance: measured interaction stiffness (a); measured phase (b); calculated loss per cycle (c). $A_0 = 0.25$ Å, $k_0 = 110$ N/m, and maximum dissipated energy is 116 meV/cycle.

a consequence of which the relaxation energy goes almost entirely into phonons rather than back to the lever kinetic energy. Hence, energy is ultimately removed from the kinetic energy of the lever and dissipated into phonons and heat.

4. Conclusion

In summary, we measured the dissipation energy between a W tip and Si(1 0 0)-(2 × 1) sample with a nc-AFM/STM using sub-Ångström oscillation amplitude for the first time. We have shown that energy dissipation starts from zero for large separations, starts to increase as the sample is approached closer to the tip, reaches a maximum *just* after the minimum of force gradient. The dissipation drops back to zero with a rate much slower than the rate of change of interaction stiffness. When the dissipation drops back to zero, the stiffness reaches a significantly high positive value.

Acknowledgements

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