STM Atom Manipulation with Different Material Tips

D.H.Huang[a,*] and M. Aono[a,b,c]

[a]*Aono Atomcraft Project, ERATO, JST,*
Tohkohdai, Tsukuba-shi, Ibaraki 300-2635 , Japan
[b]*Surface and Interface Laboratory,*
The Institute of Physical and Chemical Research (RIKEN),
Hirosawa, Wako-shi, Saitama 351-0106, Japan
[c]*Department of Precision Science and Technology,*
Osaka University, Suita, Osaka 565-0871, Japan

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Abstract

Voltage pulses applied between an STM tip and a surface can modify the surface on the nanometer scale due to electric-field-induced evaporation. However, for different material tips, the different threshold biases have been observed for achieving such surface modification. In this paper, we measure the tip displacement for the W and Pt tips during a pulse at constant tunneling current, and deduce that the electric field produced by the pulse depends on tip material or tip workfunction.

1. Introduction

The invention of the scanning tunneling microscope (STM) has provided a promising method for manipulating single atoms and processing materials on the nanometer scale [1-10]. During the study of Si extraction, we have found that the extraction probability depends not only on amplitude of the bias applied between the tip and the sample but also on tip material for a given bias. Figure 1 and Figure 2 shows two examples of Si extraction by using a W tip and a Pt tip, respectively. After placing a W tip above a pre-selected Si atom, indicated by an arrow in Fig. 1(a), on the Si(111)-7x7 surface and applying voltage pulses of -5.5 V to the sample for 30 ms at tunneling current 0.6 nA, this Si atom has been extracted through field evaporation as shown in Fig. 1(b). The -5.5 V amplitude of the sample pulse is almost a critical value for a W tip to modify the Si surface [5]. For a Pt tip, however, such Si extraction can be obtained with a considerably lower bias. By scanning a Pt tip at -3.5 V sample bias and 50 nA tunneling current along the direction connecting corner adatoms of the 7x7 structure, Si atoms can continuously be extracted from the Si(111)-7x7 surface, as shown in Fig. 2, in which two parallel single atom grooves with a separation of a half 7x7 unit cell have been created. The Si(111)-7x7 surface can be modified routinely by a Pt tip for a bias of amplitude 3.5 V, whereas with W tips, pulses at such a voltage almost never result in modification. This indicates that a Pt tip can produce higher electric field at a given bias.

In a previous study, we have shown the dependence of electric field on STM tip preparation and found that the cleanness of an STM tip is one of the major source of irreproducibility for STM surface modification [11]. In this paper, we study the dependence of the electric field produced by a voltage pulse on tip materials (W and Pt) by measuring the variation of the tip displacement during the pulse. The experimental results can explain why the threshold voltage for Si extraction with a Pt tip (about 3.5 V) is lower than that with a W tip (about 5.5 V).

2. Experimental

Experiments were performed using a commercial ultra-high vacuum (UHV) STM (JSTM-4000 XV). Base pressure in the chamber was 1.0×10^{-8} Pa. The sample was a n-type P-doped Si(111) wafer which was outgassed at 550℃ for over ten hours prior to removal of the surface oxide. The clean Si(111)-7x7 surface was then prepared by repeated flash heating of the sample to 1200℃ for 20 s. During this procedure the chamber

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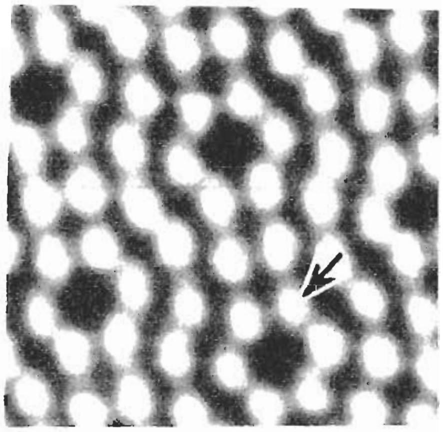
* Corresponding author. Present address: Yamamoto Quantum Fluctuation Project, ERATO, JST, 3-9-11 Midoricho, Musashino, Tokyo 180-0012, Japan.
Tel: +81-422-36-2594, fax: +81-422-36-1867, e-mail: dehuan@yqfp.jst.go.jp

pressure remained below 5.0x10^{-8} Pa. The W tips were a 0.3 mm single crystal tungsten wire, sharpened by electrolytic etching using a 0.5 N solution of KOH, and the Pt tips were then sharpened by mechanical cutting. Therefore, the initial apex of a Pt tip may not be as sharp as that of the W tip. By following processes, however, both tips can be cleaned and sharpened. The W and Pt tips were cleaned by electron-bombardment heating to above 1200℃ in the UHV chamber, followed by field evaporation by applying 5-10 V voltage pulses in both polarities repeatedly (>100 times) between the tip and the sample. Both tips (W or Pt) processed in this way will be not only well cleaned but also sharpened presumably with a single atom well protruded from the tip apex due to field evaporation and field emission [12, 13], as both tips can be used to manipulate single atoms on the silicon surface, as shown in Fig. 1 and Fig. 2.


(a)

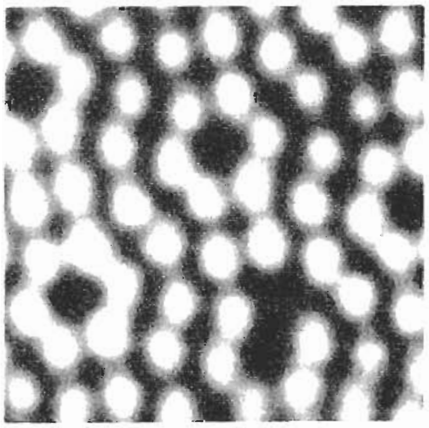

(b)

Fig. 1 STM images showing the extraction of a single Si atom from the Si(111)-7x7 surface using a W tip. A Si atom indicated by an arrow in (a) was extracted as shown in (b), three voltage pulses of -5.5 V for 30 ms were applied to the sample to extract the Si atom. These STM images (5.0 Åx5.0 Å) were taken at a sample voltage of +2 V and a tunneling current of 0.6 nA.

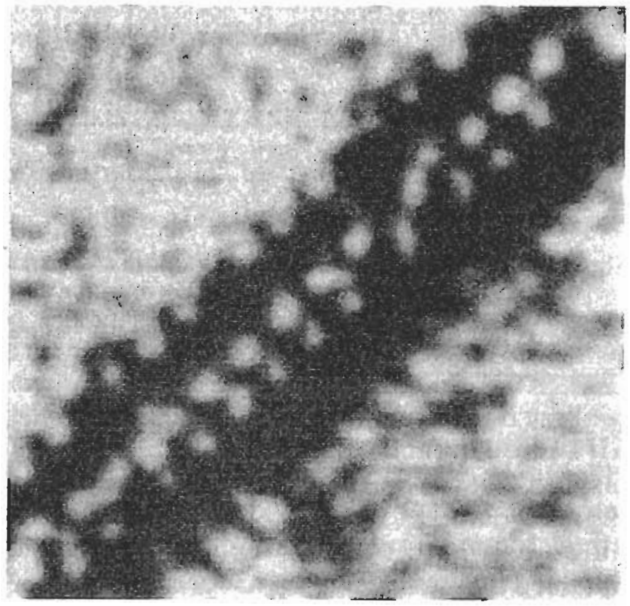


Fig. 2 Empty-state image of an Si(111)-7x7 surface having two parallel single atom grooves with a separation of a half 7x7 unit cell created by using a Pt tip at -3.5 V sample bias and 50 nA along the direction of corner adatoms of 7x7 unit cell.

The voltage pulses were monitored dynamically by recording the z-piezo voltage and the tunneling current signals on a two-channel digital storage oscilloscope (Phillips PM3323) which was interfaced to a PC. The sample bias served as an external trigger.

3. Results and discussion

In this study we are concerned specifically with those cases where no modification occurs during the applied voltage pulse. In such cases the tip, which is stationary in the lateral directions, moves a fixed distance away from the surface during the pulse, in order to increase the tunnel junction resistance and thus maintain a constant current at the higher pulse bias. After the pulse, if no modification has occurred, the tip returns to its original height above the surface, as shown in Fig. 3 [14]. Concerning the calibration of the height scale in Fig. 3, the relative displacement can be

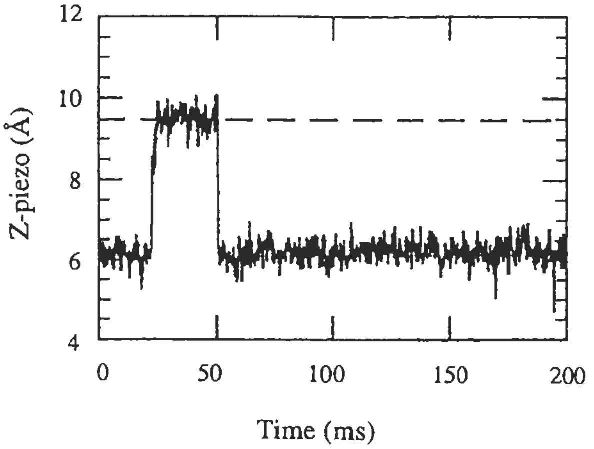
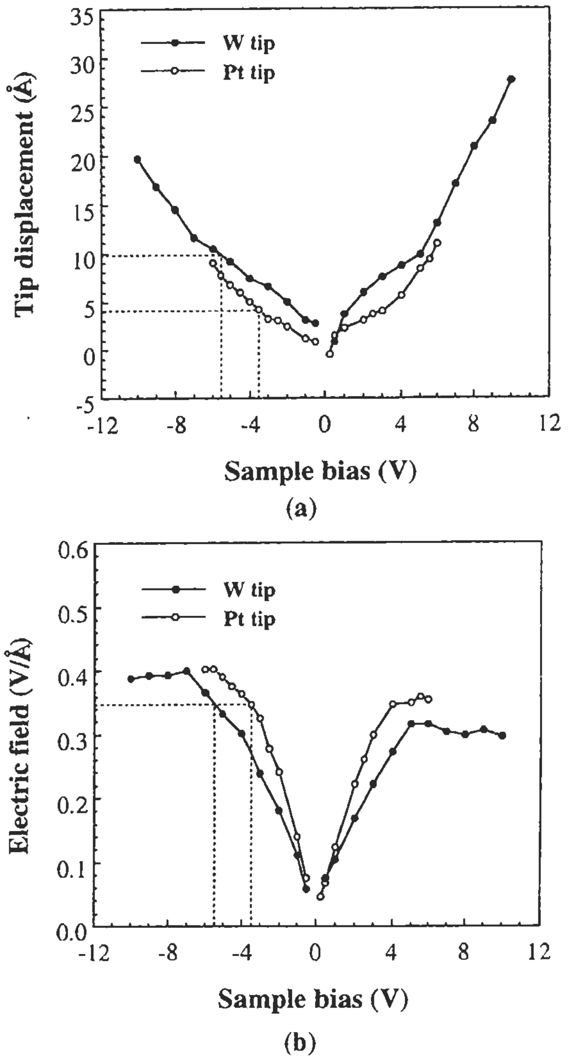


Fig. 3 Tip displacement during 30 ms sample voltage pulse of amplitude -5.5 V at 0.6 nA. The tip is at rest at +2 V and 0.6 nA before and after the pulse.

calibrated by scanning over a single step on the Si(111) surface. The absolute zero of displacement is not known accurately, and in Fig. 3 is chosen to be 6 Å. This value is based on an estimate of the origin of this scale obtained by moving the tip towards the surface until instabilities in the displacement are observed, indicative of contact.

We emphasize that the main reason for using a pulse technique in this study, rather than continuously varying the bias, is to effectively eliminate spurious fluctuations in the tip displacement due to modification occurring on the surface or the tip at high voltages.

Measurements of the tip displacement were made for voltage pulses of amplitude 0.5 V to 10 V in both polarities for a W tip, and 0.25 V to 6 V in both polarities for a Pt tip, the voltage applied before and after the pulse being + 2 V at tunneling current 0.6 nA. All biases refer to the sample.



(a)

(b)

Fig. 4 (a) tip displacement curves as a function of sample bias for a W tip and a Pt tip, (b) estimated electric field applied by these tips, with $S_0 = 6$ Å.

The typical curves for the displacement of a W tip or a Pt tip versus sample bias are shown in Fig. 4(a). The tip displacement at each bias is averaged over at least five measurements at different positions on the surface in order to remove systematic effects. As one can see in Fig. 4(a), the displacement of the Pt tip is smaller than that of the W tip at all bias. In the previous study, it has been observed that tip geometry does not play a significant role in determining the tip displacement during pulses [11], therefore, the smaller tip displacement for a Pt tip may be due to its higher workfunction. It is well known that the radius of curvature of an STM tip apex is normally much larger than the tip-sample separation, so the electric field, F, can be approximated by $F=V/s$, with $s=s_0+\Delta s$, where s is the tip-sample separation, s_0 an absolute position under a reference bias voltage, and Δs the tip displacement during the applied voltage, V. We estimate the applied field by the simple calculation with the formula $F=V/s$ for both tips with s_0 equal to 6 Å. Figure 4(b) shows the variation of the estimated electric field for both tips, in which one can find that the electric field for the Pt tip at -3.5 V is as high as that for the W tip at -5.5 V. This can provide an explanation for Si surface modification, shown in Fig. 1 and Fig. 2, with different biases for a W tip and a Pt tip. We note that our estimate of F ignores tip curvature, which in practice will reduce the field strength at the sample surface and increase the field strength at the tip surface, relative to the parallel plate value used here. This effect becomes more important as s increases, so the decrease of the electric field for a W tip, having a larger displacement of about 10 Å at large V of -5.5 V, may in practice be more pronounced than that for a Pt tip, having a smaller displacement at small V of -3.5 V, as shown in Fig. 4(a).

In the case of fabrication of two parallel single atom grooves by a Pt tip shown in Fig. 2, since a large tunneling current of 50 nA has been applied during fabrication by scanning the Pt tip at -3.5 V sample bias, so the absolute position s_0 for the field estimate must be reduced, and therefore the applied field for fabrication shown in Fig. 2 should be larger than that shown in Fig 4(b) at -3.5 V.

4. Conclusion

We have measured variations of the STM tip displacement at constant current for voltage pulses of amplitude 0.5-10 V in either polarity for a W tip and 0.25-6 V for a Pt tip. From these measurements we have estimated the dependence of the electric field applied at the surface on tip material and found that a higher workfunction material tip will have a lower threshold bias for surface modification due to its smaller displacement relative to the surface during the application of pulses.

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