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I–V curve oscillation observed by atomic force microscopy

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Abstract

Oscillation on the current–voltage curve measured by atomic force microscopy is observed when the distance between the tip and sample is large enough and beyond a critical value. The appearance of the oscillation is attributed to the excitation of electron standing waves between the tip and sample. From the first peak position and the voltage difference between the first two peaks on the current–voltage curve, the value of the work function at the detected point on silver film surface and the distance between the tip and the detected point can be calculated.

Keywords: Oscillation on current–voltage curve; Atomic force microscopy; Electron standing wave; Work function

1. Introduction

Since the invention of scanning tunneling microscope (STM), there have been many studies on the electron standing wave through observation of the oscillation of the differential conductance spectra versus the applied bias voltage under constant tunneling current between the tip and sample [1–6]. Kubby and Greene discussed coupled quantum wells, which were formed within thin-film adlayer [4]. Suganuma and Tomitori evaluated electric field intensities over sample surfaces from peak intervals of differential conductance oscillation due to electron standing waves [6]. But all these works did not study the electron standing wave through observation of the oscillation of *I–V* curve.

In atomic force microscopy (AFM), the same as in scanning tunneling microscopy, by changing the bias voltage between the tip and sample there is a field emission regime when a bias voltage exceeds the work function of the sample. In this regime, the tunneling electron can have a positive kinetic energy within the gap between the tip and sample, leading to the formation of electron standing waves at biases close to the bound states of an electron in a triangular potential well [7–10]. The standing waves result from constructive interference between incident and reflected electrons in the positive kinetic-energy region of the gap, between the classical turning point, Z_T, and the sample surface at $Z = 0$ in the potential

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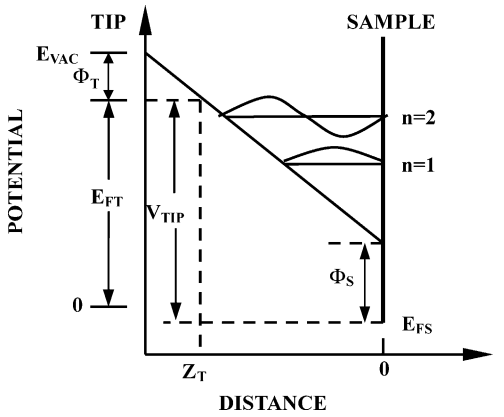

Fig. 1. Potential energy diagram between the tip and sample. E_{FT}, the Fermi level of the tip, is displaced from E_{FS}, the Fermi level of the sample, by the applied bias V_{TIP}. The work function of the tip and sample are φ_T and φ_S, respectively. The electron has a positive kinetic energy in the triangular potential well formed between the classical turning point, Z_T, and the sample surface at $Z = 0$, when $V_{TIP} > \varphi_S$. Under these conditions, standing wave states form within the well, and have been labeled as $n = 1$ and 2.

energy diagram, as clearly depicted by Kubby and Greene, as shown in Fig. 1 [4]. The first two standing wave states, labeled as $n = 1, 2$, have been shown in the figure. The eigenstates E_n in eV of the asymmetric triangle potential is expressed as [11]:

$$E_n = \left(\frac{\hbar^2}{2m}\right)^{1/3} \left[\frac{3\pi F}{2}\left(n - \frac{1}{4}\right)\right]^{2/3}, \quad n = 1, 2, \ldots \tag{1}$$

where F in eV/Å is the electric field of the declined potential and m is the electron mass.

In this paper, the oscillation of I–V curve due to the electron standing wave was observed by atomic force microscopy, and the value of work function of the sample was calculated.

2. Experimental

The experiment was conducted in air with Solver P47 AFM made by NT-MDT Co. of Russia. The conductive probe used is less than 35 nm in the radius of curvature of the tip, less than 20° in full tip cone angle, and 25 nm in thickness for W_2C coating. The resonant frequency and the force constant of the probe are 315 kHz and 48 N/m, respectively.

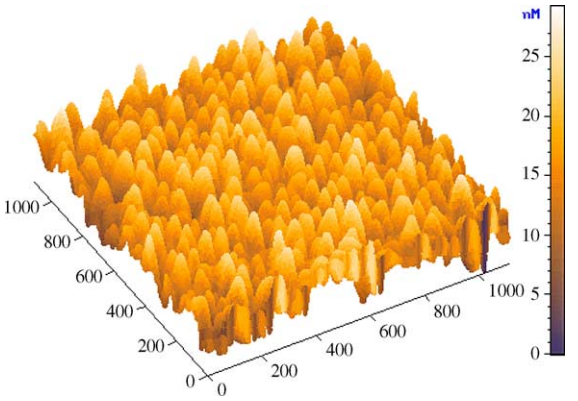

Fig. 2. Topography of Ag film scanned by tapping mode of AFM.

Silver thin film, the sample to be detected, was prepared by magnetron sputtering deposition on a silicon substrate, which was cleaned in alcohol and acetone for 10 min, respectively. Before deposition, the silver target was cleaned by sputtering for 10 min in order to remove oxides and any other contamination. The parameters used during deposition were as following: base pressure 6.0×10^{-4} Pa, Ar flow 30 sccm, working pressure 2.0 Pa, dc power 45 W, and sputtering time 25 min. The substrate was rotating during deposition to guarantee a uniform film thickness. The average thickness of the film is 150 nm. After the deposition just finished, the Ag thin film was mounted onto the platform of AFM as quickly as possible to prevent contaminants and/or water. And a certain area was scanned with tapping mode obtaining the topography as shown in Fig. 2. Then the AFM was switched to the contact mode to measure the I–V curve between the tip and the sample. The requiring time for measuring one curve was 88 ms.

3. Results and discussion

When the AFM is operated in a contact mode, the tip normally touches the surface of the sample with a constant force controlled by a feedback loop. As a result, the distance between the tip and the sample remains constant, and smaller than the value of the Van der Waals radius of about 4 Å. In this case, the I–V curve obtained is shown in Fig. 3a. It should be curve abd, but it is changed into abc curve due to the

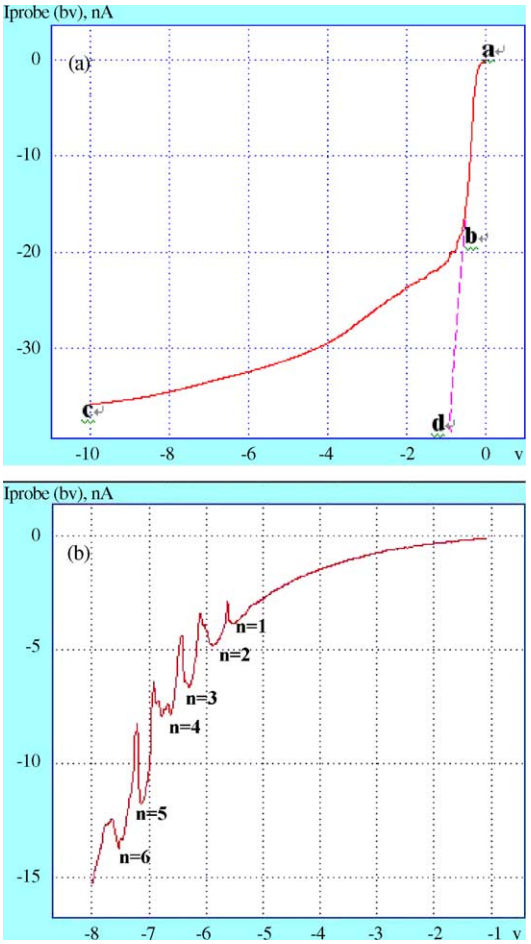

Fig. 3. *I–V* curve under constant height mode of AFM. (a) Under normal contact operation mode. Notice that curve abc should be curve abd due to bd is changed to bc caused by the nonlinearity of the preamplifier beyond 20 nA. (b) Under special operation mode with the feedback loop cut off, oscillation is observed as a result of a larger distance between the tip and sample.

nonlinearity of preamplifier when the electric current is more than 20 nA.

When the feedback loop is cut off, the gap, which is the distance between the tip and sample, will change with respect to the sample surface undulation at different detected points. In case the gap is large enough, bigger than the Van der Waals radius, oscillations of *I–V* curve will occur, as observed in Fig. 3b.

In our experiments, hundreds of points on the surface of the silver film were detected, which indicate the reproducibility of the measurement. It is found that at different points the oscillations are almost the same, but with small changes of the position where the first peak appears and the peak intervals. The first oscillation peak position is in the range from −4 to −6 V, and the interval is from 0.3 to 0.4 V, depending on the surface state of the detected point and the gap. From the measured values of the first peak position and the voltage interval between the first and second peaks, one can calculate the work function value of the detected point of the sample and the working distance between the tip and the detected point.

According to Eq. (1), there is a following expression between the first and second peaks

$$E_{21} \equiv E_2 - E_1 = \left(\frac{\hbar^2}{2m}\right)^{1/3} \left(\frac{3\pi F_2}{2 \times 4}\right)^{2/3} (7^{2/3} - 3^{2/3}) \tag{2}$$

where E_1 and E_2 are the eigenstates corresponding to the first and second peaks respectively, and with $E_2 - E_1$ equal to $V_2 - V_1$. For simplicity of calculation, assume that the difference between the electric field F_1 at V_1 and F_2 at V_2 is small and can be neglected because $V_2 - V_1$ is much smaller than V_1. Thus the electric field F can be calculated from Eq. (2). For instance, when the first and second peak positions are −5.0 and −5.4 eV respectively, which are the average values in the experiment, the calculated F is 0.055 eV/Å. Using the value of F_1 at $n = 1$, the first eigenstate, E_1 is calculated to be 0.52 eV from Eq. (1). Then the zero energy level E_0 of the potential well with respect to a sample bias voltage is determined by $E_0 = V_1 - E_1 = 4.48$ eV. It can be seen that the zero energy level E_0 is approximately equal to the reported value of the work function of silver, 4.26 eV. As we known that the work function is an extremely sensitive indicator of surface condition and is affected by absorbed or evaporated layers, surface reconstruction, crystalline orientation on the sample surface, surface charging, oxide layer imperfections, surface and bulk contamination, etc. In our experiment, the value of the work function calculated is different from place to place around the standard value of about 4.26 eV, which means the surface condition is different from place to place.

As the radius of curvature of tip is about 35 nm, which is much greater than the gap, the field between

the tip and sample is essentially constant and is given by the ratio of the applied voltage V to the gap distance d

$$F \cong \frac{V}{d} \tag{3}$$

as in a parallel plate capacitor. Accordingly, the distance between tip and sample is: $d \cong V_1/F_1 = 5/0.055 \cong 91$ Å, a very large distance between the tip and sample in AFM.

The normally required electric field is around 0.1–1 eV/Å for field emission. Thus, the electric field of 0.055 eV/Å, corresponding to the detected point and calculated in the present case, is a little bit smaller than the required value due to the large distance between the tip and sample. In fact, field emission can occur when the applied voltage is higher than the work function, even though the electric field is smaller than the required electric field. It was reported that there is an intermediate stage before the field emission regime [12], which is the beginning stage of field emission and where field emission is possible. Carefully examining the I–V curve of Fig. 3 in reference [12], one can also find the oscillation though it is very weak.

According to Simmons [13], for the low-voltage range (eV $\ll \varphi$) for the metal–vacuum–metal system:

$$J = \frac{\sqrt{2m_e}}{\Delta S}\left(\frac{e}{h}\right)^2 \bar{\varphi}^{1/2} V \exp(-A\bar{\varphi}^{1/2}) \tag{4}$$

where

$$A = \frac{4\pi\beta\,\Delta S\sqrt{2m_e}}{h}, \quad \beta \approx 1, \quad \bar{\varphi} = \frac{1}{\Delta S}\int_{S_1}^{S_2} \varphi(x)\,\mathrm{d}x$$

$\varphi(x)$ is the potential energy of electron between the two electrodes, S_1 and S_2 are the distance from the first surface to the place where the potential energy equals the Fermi energy near surfaces 1 and 2, respectively, $\Delta S = S_1 - S_2$ is the distance between the tip and the sample approximately, m_e is the electron mass, V the potential between the two electrodes, and J the current density. According to Eq. (4), J is extremely dependent on electron spacing, ΔS, which gives the explanation of the fact that the current in Fig. 3b is much smaller than the current in Fig. 3a because the gap between the tip and sample in Fig. 3b is much greater than the one in Fig. 3a. Also, according to Eq. (4), when eV $\ll \varphi$, current density is linearly dependent on applied voltage V.

But when eV $> \varphi$, the I–V characteristics in the high-bias regime is described by Fowler–Nordheim equation as [4]:

$$I(V) = \alpha A_0 F^2(V)\frac{(\mu/\varphi)^{1/2}}{\mu+\varphi}\exp\left\{\frac{-\beta\varphi^{3/2}}{F(V)}\right\} \tag{5}$$

where A_0 is the effective tunneling area, $F(V) = V/d$ the field, and φ and μ are the work function and Fermi energy of the tip, respectively. So the I–V curve is nonlinear as shown in Fig. 3b.

It should be noticed that there is a difference between the differential conductance spectra oscillation under constant tunneling current in STM and I–V curve oscillation under constant height in AFM. In STM, when the bias voltage is increased, the tip is withdrawn from the sample surface by the feedback loop to maintain the constant tunneling current, and the distance between the tip and sample is increased too. So the electric field F remains almost constant according to Eq. (3) and the E_n almost do not change with bias voltage according to Eq. (1). On the other hand, in AFM, the distance between the tip and sample remains constant at certain detected point. As the bias voltage increased, the electric field F increases too. And also the eigenvalue E_n increases. So under constant height mode in AFM, eigenvalue E_n is a function of V:

$$E_n \cong \left(\frac{\hbar^2}{2m}\right)^{1/3}\left[\frac{3\pi}{2}\frac{V}{d}\left(n-\frac{1}{4}\right)\right]^{2/3} \tag{6}$$

where V is the bias voltage, and d the distance between the tip and sample. From Eq. (6) it can be seen that the greater the value d, the smaller the eigenvalue E_n and the interval between two neighboring oscillatory peaks, so the easier to obtain the oscillation of I–V curve. Thus it is expected that there is a critical value d_c for observation of oscillation under certain sample work function and measuring limit of the oscilloscope of AFM. When $d < d_c$, it would be impossible to observe the oscillation phenomenon in AFM.

Assuming that the nth oscillation appears when $V = 8$ V (8 V is the measuring range of the oscilloscope). So $V = V_n = 8$ V and $E_n = V_n - E_0$, where E_0 equals the average value of the work function of silver, 4.26 eV, and it can be calculated according to Eq. (6)

Table 1
Number of the peaks that can be observed within the measuring range of 8 V and the demanded critical distance between the tip and sample, d (Å)

	Number of peaks										
	1	2	3	4	5	6	7	8	9	10	18
d (Å)	7.6	17.7	27.9	37.9	48.0	58.3	68.4	78.5	88.7	98.8	179.8

that if one oscillation peak can be observed within the measuring range the gap needed should be larger than 7.6 Å. And if more peaks wanted to be observed, the d values are calculated as shown in Table 1. So the oscillation cannot be observed due to the smaller distance between the tip and sample and experimental limitation (8 V) of the cantilever bias voltage under normal contact operation mode. But when the distance is large enough the oscillation would be observed.

In the present experiment, the maximum number of peaks observed is 18 corresponding to the distance of about 18 nm between the tip and detected surface, which is just in the range of surface undulation as shown in Fig. 2. So the calculation result is reasonable.

4. Summary

Oscillation of I–V curve due to electron standing wave under special operation condition is observed by AFM. From the experiment and calculation, it can be seen that observation of oscillation under a certain measuring range of oscilloscope demands that the distance between the tip and sample must be large enough. Also from the voltage of the first oscillation peak position and the peak interval, the value of work function at a certain point on the sample surface and the distance between the tip and the detected point can be calculated.

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