Development of a Convenient in situ UHV Scanning Tunneling Potentiometry System Using a Tip Holder Equipped with Current-Injection Wires

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Scanning tunneling potentiometry (STP) is one of the advanced variations of scanning tunneling microscopy (STM). By combining STM and STP, the local structures and potential distribution on conducting samples with a lateral current flowing along the sample surface can be measured simultaneously with a high spatial resolution. However, additional electrodes are necessary to make the current flow along the sample surface, which can sometimes be difficult to handle. We developed a new type of STM tip holder that makes it easier to perform in situ STM/STP measurements in ultrahigh vacuum (UHV), prepare a sample and transfer the sample/tip. Using this tip holder, a Si(111)-√3×√3-Ag surface and Bi(111) films grown on Si(111) were measured using STP. For the Si(111)-√3×√3-Ag surface, abrupt potential drops at the atomic steps in the topographic images are observed. On the other hand, for the Bi film, a nearly homogeneous potential gradient is observed along the direction of the electric current without potential drops at the steps on the surface. By combining numerical simulation and atomic-scale resolved STM images, it is shown that the current distribution is not homogeneous at all, even at nanometer scales. This is due to a wide range of scatter in the resistances across steps, irrespective of the step height. This originates from difference in the ratio of the conductivity at the steps to that on the terraces between the two material systems.

I. INTRODUCTION

Scanning tunneling potentiometry (STP) is one of the advanced variations of the scanning tunneling microscopy (STM) technique. The STP function in STM measurements enables us to map the local electrochemical potential distribution as a current flows along the surface. In combination with the STM capability of imaging local geometric/electronic structures at an atomic resolution [1, 2], STP reveals the atomic-scale causes of the electrical resistance, such as the atomic steps and domain boundaries on surfaces.

STP was invented in 1986 by Muralt and Pohl [3]. They measured the potential distribution along the surface of a Au film deposited onto a SiO₂ substrate while a current flowed through the film. Then, other researchers have performed STP measurements of various samples [4–14]. STP measurements at a low temperature were also performed [15, 16]. In 2008, Bannani et al. obtained high-resolution potential maps of a Si(111)-√3×√3-Ag surface by STP using a multiprobe STM [17]. They fixed two of the four STM tips on the sample surface as the current-injection electrodes and scanned the third tip in between them for STM/STP imaging. In 2012, Hamada and Hasegawa(Y) developed an extended STP system enabling the stable measurement of semiconductor samples [18]. Recently, STP measurements of the topological insulator Bi₂Se₃ were performed to reveal the possible effect of suppression of the backscattering of carriers on the resistance at the atomic steps on the surface [19].

In order to add the STP function to STM measurements, two modifications should be made. First, a DC current must flow laterally along the sample surface during STM measurements. Second, to distinguish the electrochemical potential information from the topographic information, the tunneling current should be measured by the STM tip with a bias voltage having an AC component as well as the usual DC component. The DC component of the tunneling current is used to measure the electrochemical potential, and the AC component is used to measure the topography of the sample surface.

As for the first modification, stable electrical contacts are necessary to ensure that the DC current flows along the sample surface. In the case of samples on semiconductor substrates, such as superstructures on Si substrates, this can sometimes be difficult. Using clamps that physically fix the substrate as electrodes is a common method, and they were used in some STP measurements for thin metal films [3, 18]. However, the clamps contact the film in air after film deposition, meaning that this is done ex situ. Although this may cause no problems for thin films, it will cause difficulty for surface measurements since surfaces are easily contaminated in the atmosphere. This problem has been overcome, and in situ four-point-probe measurements using clamps have been performed on surface structures in ultrahigh vacuum (UHV) [20, 21]. How-
ever, it was restricted to room temperature (RT) measurements since the contact resistance became too high at low temperatures owing to carrier freeze-out in the semiconductor substrate.

Another way to prepare the electrodes for current flow is using layered substrates that have contact layers. The electrodes are attached to the contact layers and an ohmic contact between the electrodes and the substrate can be made. In this case, when we restrict the measurement to the cleavage plane that is perpendicular to the layered direction, STP measurements can be performed after making the desired sample with metal deposition. This has been demonstrated in Ref. 9. A similar method has been employed for more sophisticated magnetotransport studies [22]. However the number of repeated measurements is restricted to the number of times that a sample can be cleaved nicely, which is sometimes difficult to perform. Furthermore, if a more complex surface cleaning technique such as annealing or sputtering is needed, it is impossible to use this method as there will be intermixing between the contact and sample layers.

Therefore, to perform surface STP measurements using one substrate repeatedly under extreme conditions and to be able to clean the surface by various methods, the sample and current-flowing electrodes need to be separated. The electrodes should contact the sample in UHV after sample preparation for in situ STP measurements, and the measurement system should be cooled to a low temperature. A multiprobe STM is a flexible system that has this capability [17]. However the operation of a multiprobe STM is not easy, especially when stably contacting the sample surface with the current-injection wires. Furthermore, it is difficult to perform STP measurements at low temperatures using a multiprobe STM because the sample stage is usually susceptible to thermal radiation. It is also difficult to perform measurements in the presence of a high magnetic field because a scanning electron microscope is used in many cases and the machine itself becomes too complicated.

Thus, in the present study, we have developed an STM/STP measurement system in which the STP measurements can be conducted more easily. We have developed a new tip holder equipped with two wires on both sides of the STM tip to apply the electric current through the sample. This allows the troubles associated with mounting the current-injection electrodes on the sample surface to be avoided after the sample preparation procedures in UHV or any ex situ contrivance for creating electrodes on the sample before transferring the sample into UHV. Furthermore, in this system, STP measurements could be performed at a low temperature and in the presence of a high magnetic field in principle. We show the details of our STP system and demonstrate the simultaneous measurements of the topography and potential at RT for a Si(111)-$\sqrt{3}\times\sqrt{3}$-Ag surface and a Bi(111) ultrathin film.

II. INSTRUMENTAL DETAILS

The experimental system consists of a commercially available low-temperature and high-magnetic-field UHV STM (USM1500, UNISOKU Co., Ltd.), an STM controller (RHK Technology, Inc.), and a custom-made STP feedback circuit. Figure 1(a) shows a picture of the entire system. It has three UHV chambers, the measurement chamber, preparation chamber, and load-lock chamber, which are all connected to each other through gate valves. In the preparation chamber, the sample is heated by a direct current and material deposition is performed by molecular beam epitaxy under in situ reflection high-energy electron diffraction (RHEED) observation. The prepared sample is transferred to the measurement chamber for STM/STP measurements. At the STM stage, the sample, STM tip, and current-injection wires can be cooled to ~5 K by filling the cryostat with liquid helium. By pumping He, we can reach ~2 K. The sample temperature is ~78 K with only liquid nitrogen cooling. Furthermore, a magnetic field up to 8 T can be applied to the sample in the surface-normal direction with a superconducting magnet (although the magnetic field was not used in the present study). Figure 1(b) shows a magnified picture of the STM head (surrounded by the blue dashed
The distance between the two current-injection wires is up on both sides of the STM tip (Fig. 1(c)). The distance sensor is attached to the sample holder receiver. The temperature approaches the sample by moving it upwards. The temperature in Fig. 1(a)). The STM tip faces upwards and the current-injection wires. The blue curve corresponds to the ordinary tip holder without the current-injection wires.

A special STM tip holder was developed for STP measurement, in which two current-injection wires are set up on both sides of the STM tip (Fig. 1(c)). The distance between the two current-injection wires is \( \sim 7 \) mm. They are BeCu wires having a spring property, allowing the STM tip to approach the sample surface after the current-injection wires are directly pressed against and contact the sample. The contact area of the sample may be damaged by the wires, but the damaged area is far from the scan area owing to the large spacing between the two electrodes. Metal cylinders covering the current-injection wires are electrically connected to the STM signal guard lines to protect the STM tip from electrical noise due to the current-injection wires. This special tip holder enables in situ STM/STP measurements without mounting current-injection electrodes on the sample before/after sample preparation. The contact area of the current injection electrodes of this tip holder is larger than that in multiprobe STM. This results in a reduction of contact resistances of current injection terminal. Accordingly, the 1/f noise which is caused by contact resistance is reduced.

Figure 1(d) shows a schematic of the electric circuit in our STM/STP system, which has been custom-made by referring to previous reports [17, 18]. A DC voltage is applied between the current-injection wires to make a constant current flow (\( I_{\text{sample}} \)) along the surface. An AC bias voltage (\( V_{\text{AC}} \)) is applied between the STM tip and the sample. The amplitude should be sufficiently small to avoid artifacts (which will be discussed later). Its frequency is determined by the stray capacitance of the STM measurement system. The tunnel current, however, has both DC and AC components because the DC component in the tunnel bias voltage appears owing to the voltage drop caused by the lateral current along the sample surface. The DC component in the tunneling current is used to measure the electrochemical potential of a point under the tip. Namely, the STP feedback loop (Fig. 1(d), lower part drawn by red lines) changes the applied DC voltage of the entire sample while maintaining a constant DC voltage between the current-injection wires until the DC component of the tunneling current becomes zero. Therefore, this applied voltage from the feedback loop corresponds to the local potential at the tip position. The variation in the electrochemical potential through tip scanning results in a potential map of the sample surface. The AC component is used to control the tip–sample distance by keeping the average value of the tunnel current constant; the tunneling current due to the AC bias voltage is rectified to prevent the tunnel current from becoming zero on average. The averaged value (\( I_{\text{set}} \)) is equivalent to the set current in typical STM measurements. Thus, the averaged value of the rectified AC component of the tunneling current is used to record the surface topography. When an STP measurement is performed, the DC bias voltage applied between the sample and the tip (\( V_{\text{set}} \)) is around zero.

The STM tip was prepared by the electrochemical etching of tungsten wires with a diameter of 0.3 mm in a 1.5 normality KOH aqueous solution. Before the measurements, the etched STM tips were heated by electron bombardment to remove the oxide layers in the preparation chamber.

Figures 2(a) and (b) show the noise power spectra of the topography (a) and tunneling current (b), which were measured when the STM feedback was turned on. In these two graphs, the red curves correspond to a spectrum using the tip holder with the current-injection wires, and the blue curves correspond to the ordinary tip holder without the current-injection wires. The noise levels of the tip holder with current-injection wires and that without them are almost the same, and the contact wires do not influence the STM performance. In fact, the topography noise is smaller for the tip holder with current-injection probes in Fig. 2 (a). This probably originates from the difference in the actual tunneling contact at the W tip apex, which is not relevant to the presence of the current-injection wires.

III. RESULTS AND DISCUSSION

A. Si(111)-\( \sqrt{3} \times \sqrt{3} \)-Ag surface

First, we performed STM/STP measurements of a Si(111)-\( \sqrt{3} \times \sqrt{3} \)-Ag surface, which is known to be conductive owing to a free-electron-like surface-state band [23]. The substrate was cut from an n-type Si(111) wafer hav-
Fig. 3: (a) Topographic image of Si(111)-$\sqrt{3} \times \sqrt{3}$-Ag at RT for the lateral current $I_{\text{sample}}=1.2$ mA. The applied AC voltage is $V_{AC}=0.3$ mV, and its frequency is 593.1 Hz. The set current for STM feedback is $I_{\text{set}}=10$ pA. An STP measurement is performed at RT. The inset of (a) shows atomic-scale resolution image at 77.8 K. The sample bias is $V_{\text{set}}=1.5$ V, and the set current is $I_{\text{set}}=350$ pA. (b) Electrochemical potential image simultaneously acquired with (a). (c) Topographic image of the same place as (a) under a reversed lateral electric current. (c) appears different from (a) because of thermal drift. (d) Electrochemical potential image simultaneously acquired with (c). The yellow arrows indicate the macroscopic direction of the applied lateral current.

Fig. 4: (a), (d) Topographic images of a Si(111)-$\sqrt{3} \times \sqrt{3}$-Ag surface at RT with a lateral current flowing along the surface. These two images are acquired at different places. The black arrows indicate the direction of the current. $V_{AC}=0.3$ mV at 593.1 Hz. $I_{\text{set}}=10$ pA. (b), (e) Electrochemical potential images simultaneously acquired with (a) and (d), respectively. (c), (f) Line profiles along the white lines in the topographic and potential images. (c) corresponds to (a) and (b), and (f) corresponds to (d) and (e). The red lines show the topography (left axis), and the blue lines show the potential profiles (right axis).
The continuity of the electric current density distribution inside the area is calculated to satisfy the boundary condition for the simulation area. The potential at the boundary of an image is taken as the potential values. The experimentally measured electrochemical law for the conductivity (\(\sigma\)).

The conductors belonging to a step have a single value depending on the location—on terraces or at steps. All the conductors placed on the sides of each element of the matrix; the conductivity of each conductor is different. The current densities overlaid on the potential maps. The direction of the arrows indicates the direction of the current, and the color of the arrows indicates the magnitude of the current density.

FIG. 5: (a), (e) Experimental potential images at different places of the Si(111)-\(\sqrt{3} \times \sqrt{3}\)-Ag surface measured at RT. The measurement parameters are similar to those for Fig. 2(b). (f) Simulated potential images corresponding to (a) and (e), respectively. (c), (g) Line profiles of the experimental and calculated potential distributions along the red lines in (a), (b) and (e), (f), respectively. The blue lines are the experimental data, and red ones the simulation. (d), (h) Calculated local current densities overlaid on the potential maps. The direction of the arrows indicates the direction of the current, and the color of the arrows indicates the magnitude of the current density.

FIG. 6: Conductivity across a step on the Si(111)-\(\sqrt{3} \times \sqrt{3}\)-Ag surface as a function of the step height. The step height is in units of a single Si(111) step.

In order to quantitatively analyze the conductivity across steps, a numerical simulation was performed on the basis of the experimental data. The observed area is divided into an \(N \times M\) matrix (typically \(1024 \times 128\)) to regard the surface as a two-dimensional (2D) network of many conductors placed on the sides of each element of the matrix; the conductivity of each conductor is different depending on the location—on terraces or at steps. All conductors on terraces have the same conductivity (\(\sigma_{trc}\)). The conductors belonging to a step have a single value for the conductivity (\(\sigma_{stp}\)), but different steps have different values. The experimentally measured electrochemical potential at the boundary of an image is taken as the boundary condition for the simulation area. The potential distribution inside the area is calculated to satisfy the continuity of the electric current density \(\nabla j = 0\) and Ohm’s law \(j = -\sigma \nabla V\) at each point in the area, where \(j\), \(\sigma\), and \(V\) are the current density, conductivity, and potential, respectively. The conductivity of the conductors at each step (\(\sigma_{stp}\)) is changed until the residual between the experimental potential distribution and the calculated one becomes sufficiently small. As the conductivity of the terrace conductors (\(\sigma_{trc}\)) is assumed to be constant and a reference for the conductivity value, this self-consistent calculation only provides the ratios \(\sigma_{stp}/\sigma_{trc}\) for each step. We first assumed the same step conductivity for steps with the same height, but different values are used for different step heights. However, such a constraint in the simulation was not able to reproduce the experimental potential distributions correctly. Therefore, we next assigned different conductance to the respective steps irrespective of the step height, which resulted in a reasonable reproduction of the experimental data.

Figures 5(a) and (e) show the experimental potential distributions in the different places, and Figs. 5(b) and (f) show the simulated potential distributions corresponding to Figs. 5(a) and (e), respectively. The entire potential distributions are reproduced well by the simulation for the entire areas of both cases. Figures 5(c) and (g) show the line profiles along the red lines in the experimental and simulated potential maps in Figs. 5(b) and (f). The line profiles in the potential distribution are also reproduced reasonably well by the simulation.

The simulation also reveals the local current distribution. In Figs. 5(d) and (h), the calculated distributions of the current density (color scale) with arrows indicating the current direction are overlaid on the images in Figs. 5(b) and (f). This is obtained by using the equation \(j = -\sigma \nabla V\). The value of \(\nabla V\) at each point in the image can be calculated from Figs. 5(b) and (f). The value of \(\sigma\) on the terraces is set to be \(3.3 \times 10^{-3} \Omega^{-1}/\square\) according to the literature (Ref. [26]). The unit of 2D conductivity is the same as the conductance (\(\Omega^{-1}\)). To distinguish sheet conductivity from conductance, ohms inverse per square (\(\Omega^{-1}/\square\)) is commonly used. In Fig. 5(d), we see that the electric current flows uniformly through steps and that the direction of the calculated current in the central part of area is nearly parallel to the macroscopic direction of the applied current. Furthermore, the value of \(j\) is on the same order as the macroscopic current density calculated by dividing the net current by the sample width (~0.6 A/m). However, in Fig. 5(h), where the potentials on adjacent terraces do not change monotonically, the flow of the electric current is not uniform; the current directions are almost opposite to each other on adjacent terraces. Moreover, the current density is...
The conductivity at a step where the potential is reversed between neighboring terraces is nearly zero in the simulation, which means that the current does not flow at all across the step.

We carried out a simulation as described above for several STP images obtained from the Si(111)-√3 × √3-Ag surface and obtained the resistances of many steps. Figure 6 summarizes the step conductivity as a function of the step height (the step height divided by the height of a single atomic step which is 0.31 nm for the Si(111) surface) obtained from the topographic images. We have not plotted the data for the infinite and zero conductivity at some steps (some steps do not show the abrupt potential drop at all). Figure 6 indicates that the step conductivity is independent of the step height and is scattered in the range of (1–100) × 10³ Ω⁻¹ m⁻¹. According to previous reports, the step conductivity including the multiple steps of this surface was estimated to be in the range of 0.1–1 × 10⁵ Ω⁻¹ m⁻¹ [25, 27], which corresponds to the lower limit in our results; most values of the step conductivity deduced from the present study are larger than this range of values.

Since the conductivity across a step is modeled as a tunnelling process through the potential barrier at the step [27], the conductivity is proportional to the transmission coefficient of the electron wave function through the barrier; thus, it should depend on the height and width of the potential barrier. Therefore, our present result of the absence of a systematic dependence of the step conductivity on the step height may be attributed to some type of deformation of the potential barrier, which is different for each step to another irrespective of the step height. As one of the possibilities of this deformation, defects near the steps (such as extra Ag atoms attached to step edges) can be considered. Extra Ag atoms move on the terrace of Si(111)-√3 × √3-Ag when there is a small number of these atoms. However, when the number of extra Ag atoms becomes larger than the critical coverage, extra Ag atoms start to form three-dimensional (3D) nuclei [23]. These 3D nuclei could exist on terraces or near steps. Actually, in the atomic-scale resolved topographic images, we find some step decoration by adsorbates, as shown in Fig. 7. The degree of this decoration differs among steps (compare Figs. 7(a) and (b)), even for steps with the same height. Thus, this conjecture may be plausible. The selection of a clean steps that have no adsorbates in the scan area is not very important during the STP measurement because the applied current flows through a large area of the sample and adsorbates on the clean step could exist outside the scan area. Therefore, all results are plotted in Fig. 6, except for the infinite and zero conductance.

Another possibility is that our assumption in the simulation does not correspond to the actual experimental conditions; we assumed that the terrace conductivity σₜₑᵣₑ for Si(111)-√3 × √3-Ag was constant for all terraces. Since the carrier density and Fermi wavenumber of the surface-state band (called the S₁ state) depend on the small number of extra Ag atoms that remains on the terraces of the Si(111)-√3 × √3-Ag surface, as revealed by angle-resolved photoemission spectroscopy (ARPES) [28, 29], it is possible that the terrace conductivity is different among different terraces. Actually, in Fig. 5(g), a noticeable potential gradient is observed on a wide terrace in the experimental data (blue line), whereas the other terraces do not show such a large potential gradient. Therefore, we may need more sophisticated simulations to understand the details of the potential distributions.

B. Bi(111) ultrathin film on Si(111)

Next, we performed STM/STP measurements of ultrathin Bi films grown on a Si(111) substrate. The substrate was cut from an n-type Si(111) wafer having a resistivity 0.005–0.01 Ω·cm. The Si substrate was heated to 1500 K by a direct current in UHV for cleaning to obtain a 7×7 surface structure. After cooling to RT, approximately nine bilayers (BLs) of Bi (1 BL = 1.14 × 10¹⁵ atoms/cm²) were deposited to form a high-quality Bi(111) film showing a clear 1 × 1 RHEED pattern [30]. It is expected that an ohmic contact is formed between the current-injection wires and the Bi film because the Bi film is metallic.

Figure 8(a) shows a topographic (STM) image, and Fig. 8(b) shows the potential (STP) image simultaneously

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**FIG. 7:** Topographic images near steps on a Si(111)-√3 × √3-Ag surface showing (a) nearly no adsorbates and (b) many adsorbates at the step.

**FIG. 8:** STM/STP images taken for a 9-BL thick Bi(111) film. The lateral current is Iₗₛₑₑₑₑₑₑ = 2.5 mA. The applied AC voltage is Vᵣₑₑₑₑₑₑ = 0.5 mV, and its frequency is 593.1 Hz. The set current for STM feedback is Iₑₑₑₑₑₑₑ = 20 pA. (a) A topographic image and (b) an STP image simultaneously acquired. (c) Line profiles of the potential images in the vertical direction.
FIG. 9: (a) and (b), (c) and (d), and (e) and (f) show the simultaneously measured topographic and potential images of a 9-BL Bi(111) film in the same place for different amplitudes of the AC component $V_{AC}$ of the bias voltage at RT. (a) and (b) were acquired at $V_{AC} = 0.5$ mV. (c) and (d) were acquired at $V_{AC} = 0.9$ mV. (e) and (f) were taken at $V_{AC} = 1.3$ mV. (g) shows the same potential image as (f) with white dashed lines overlaid along the dip structure for clarity. (h) Line profiles along the white lines in the topographic images. The upper three lines are for the potential distributions, and the lower three lines are for the topographic images. The red, blue, and green lines correspond to $V_{AC} = 0.5$ mV, 0.9 mV, and 1.3 mV, respectively. (i) Schematic of the effect of the symmetric LDOS near $E_F$. The tunneling current also has a symmetric amplitude with an AC bias voltage. (j) Schematic of the effect of the asymmetric LDOS near $E_F$. If the LDOS has asymmetric structures between the positive and negative sides with respect to the $E_F$, the measured tunneling current by AC bias voltage also could be asymmetric, and it causes the artifacts in the potential variation in our method.

obtained at RT, in which a lateral DC current (2.5 mA) flows along the surface. The applied AC voltage at the tunneling gap was 0.5 mV at a frequency of 593.1 Hz. The set current for the STM measurement was 20 pA. Figure 8(c) shows the line profiles of the potential images in Fig. 8(b). The line profile is measured along the direction of the lateral current.

In Fig. 8(b), no special structures such as abrupt potential drops at steps are observed, whereas the topographic images clearly show BL steps on the Bi(111) surface. This is in contrast to the case of the Si(111)-$\sqrt{3}\times\sqrt{3}$-Ag surface and means that the resistances of the steps and terraces for the Bi(111) surface are nearly the same. This Bi surface seems to be special since the steps are known to play a crucial role in surface transport phenomena in general. Other than the Si(111)-$\sqrt{3}\times\sqrt{3}$-Ag surface, the supercurrent on the Si(111)-$\sqrt{7}\times\sqrt{7}$-In surface is also known to be affected by the atomic steps [31, 32]. But in this rare case, the local electrical field ($E$), which is the gradient of the electrochemical potential, can be calculated from the potential images directly. Namely, the local electrical field ($E$), which is the gradient of the electrochemical
potential, can be calculated from the potential images directly. The 2D current density \( J_{2D} \) injected through the current-injection wires can be estimated from the applied DC current divided by the sample width by assuming a uniform current distribution throughout the sample. As a result, the 2D conductivity \( \sigma_{2D} \) can be calculated from \( J_{2D} = \sigma_{2D} \cdot E \). In Fig. 8(b), \( E \approx 370 \text{ V/m} \), and \( J_{2D} \) is calculated as 1.3 A/m. Thus, the calculated 2D conductivity is \( \sigma_{2D,\text{STP}} = (3.4 \pm 0.9) \times 10^{-3} \Omega^{-1} \cdot \text{m}^{-1} \) for a thickness of \( \approx 9 \text{ BLs} \). Another work using STP reported a similar value [17]. Our result is consistent with the previous reports.

Figures 9(a), (c), and (e) show topographic (STM) images acquired in the same place, and Figs. 9(b), (d), and (f) show the corresponding potential (STP) images, respectively, measured at larger AC amplitudes. The amplitude was changed from 0.5 mV (Figs. 9(a) and (b)) to 0.9 mV (Figs. 9(c) and (d)) and finally to 1.3 mV (Figs. 9(e) and (f)). There are no remarkable differences in the topographic images (Figs. 9(a), (c), and (e)), whereas in the potential images, there are the dip structures at the positions that correspond to steps in the topographic images. Voltage feedback delay could cause shifts between the dip structures in STP images and steps in STM images. Figure 9(g) shows the same image as Fig. 9(f) with guidelines placed along the dip structures for clarity. Figure 9(h) shows the line profiles along the white lines indicated in the topography images. The upper three lines are the line profiles of the potential images, and the lower three lines are the line profiles of the topographic images. The red, blue, and green lines correspond to the AC voltages of 0.5 mV, 0.9 mV, and 1.3 mV, respectively. The dip structures in the potential images are more prominent as the AC amplitude becomes larger. If these potential dips originate from the real charge localization at the step edges, they should be observed at any AC amplitude, which is, however, contrary to the present case. Furthermore, they do not disappear when the scan speed becomes slower and are equally observed when the tip ascends the steps as well as when the tip descends them. Thus they should be neither real potential changes caused by charge localization nor a result of the tip feedback. They are also not a result of the flowing lateral current since we observe them even when no current is flowing. Instead, they are explained by difference of asymmetry in the local density of states (LDOS) near the Fermi energy \( E_F \) between the terraces and the step edges, as shown below.

Figures 9(j) and (j) show schematics of the possible effect of a symmetric and asymmetric LDOS near \( E_F \) on the tunneling current for an AC+DC tunneling bias voltage. Assuming that the LDOS of the tip is constant near \( E_F \), a sample with a symmetric LDOS provides a tunneling current with a symmetric amplitude having positive and negative polarities (Fig. 9(j)). However, a sample with an asymmetric LDOS provides a tunneling current with an asymmetric amplitude by the AC bias voltage (Fig. 9(j)). Because our STP circuit averages the tunneling current for an AC+DC tunneling bias voltage, the asymmetry of the AC component of the tunneling current can be transformed into a finite additional DC voltage in the STP circuit. This variation in the DC component depends on the degree of asymmetry of the LDOS and the amplitude of the applied AC component of the bias voltage (see the red and blue curves in Figs. 9(i) and (j)). If the degree of asymmetry of the LDOS on the terraces and that at the steps are different, the averaged electrochemical potential can also be apparently different. In previous reports, scanning tunneling spectroscopy spectra at terraces and steps have been measured for the Bi(111) surface [34, 35]. According to these works, the LDOS of the Bi surface seems to have an asymmetrical gradient with respect to \( E_F \), and this asymmetry is larger in the LDOS at the step edges compared to that on the terraces. This can cause a difference in the average value of the tunneling current, which becomes an artifact in the electrochemical potential near the step edges, as indicated by the dark lines in the STP maps.

IV. CONCLUSIONS

We have developed a new STM tip holder in which two current-injection wires for direct contact to the sample are installed on both sides of the STM tip. This makes it easy to perform in situ STM/STP measurements in UHV, transfer the sample/tip, and prepare the sample. Using this tip holder, we have succeeded in simultaneously obtaining topography and potential images for the Si(111)-\( \sqrt{3} \times \sqrt{3} \)-Ag surface and Bi(111) films grown on Si(111).

STP measurements for the Si(111)-\( \sqrt{3} \times \sqrt{3} \)-Ag surface superstructure have revealed that the electrochemical potential drastically changes at steps and only gradually at terraces. This suggests that the main source of the resistance for this surface is the steps. The potential images were simulated on the basis of self-consistent calculations. The simulation results show that the current distribution on the surface is very inhomogeneous, even at nanometer scales. This is because the conductivity across steps is very different among the steps. There are insulating steps at which the current does not flow across them or very conductive steps at which no potential drops are observed. The conductivity across a step is in many cases on the order of \((1-100) \times 10^2 \Omega^{-1} \text{m}^{-1}\). The values are not correlated with the step height, probably owing to variations in local step decoration.

The potential distribution on the Bi(111) film showed an overall potential gradient that was almost constant, and there were no local structures due to atomic steps on the surface in the potential images, in contrast to the Si(111)-\( \sqrt{3} \times \sqrt{3} \)-Ag surface. This suggests that the conductivity across BL steps on the Bi(111) surface is not much lower than the conductivity on the terraces. The conductivity of the Bi film calculated from the potential images is consistent with previous reports. When the AC amplitude of the tunneling bias voltage was high, artifacts in the potential variation were observed at the step edges. This likely originates from the asymmetry in the LDOS at the step edges between the negative and positive sides around \( E_F \).

The developed STP system can be extended for further sophisticated measurements. For example, Hall measure-

http://www.ssj.org/ejssnt (J-Stage: http://www.jstage.jst.go.jp/browse/ejssnt/)

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ments at nanometer scales can be performed in the presence of an applied magnetic field at low temperatures. By using spin-polarized STM tips, it should be possible to detect spin-dependent transport phenomena. Although many Rashba-split surface states have been found from spin-resolved ARPES [36], their spin transport phenomena have not been fully investigated [37]. This STP system can be useful in performing such studies.

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