Evolution of surface to bulk tunneling spectrum by scanning tunneling microscopy

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By decreasing tip-to-surface separation on the Si(111)−7×7 surface, we have observed symmetry change in topographic images and evolution from surfacelike to bulklike energy spectra. Because the tunneling is via Si adatoms interfacing to the bulk, the barrier heights at Si atoms of different dangling bonds are inhomogeneous. The observed phenomena can be numerically explained by a model of shifting chemical potential of the surface electrons due to the competing coupling strengths between the states of the tip, the surface, and the bulk. It leads to the conclusion that we have probed the interfacial coupling between electronic states of surface atoms and the bulk with atomic resolution.

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I. INTRODUCTION

Since the invention of scanning tunneling microscopy (STM) by Binnig et al., 1 it has become a prevailing tool to study surface states down to atomic scale. 2 Bulk states such as superconducting order parameter can also be measured using this technique. 2 However, it has not been used to explore the bulk-surface interface with atomic resolution. Early research on the bulk-surface interface typically focused on surface scattering at structures of impurity atoms 4 or monatomic step. 5 Studies of the intermediate layer between the surface and the bulk are relatively few. Some researchers have observed indirectly the effect of the magnetic exchange couplings of bulk electrons on surface states, which resulted in phenomena such as quantum mirage 4 and the magnetization of a single adatom. 6 To our knowledge, the use of ballistic-electron-emission microscopy 7 to resolve the subsurface Schottky barrier between a metal film and a semiconductor substrate with nanometer resolution is the only direct study of the interface. Because of increased interest in both theoretical and experimental studies of the conducting oxide interface, 8–10 the understanding of subsurfaces with atomic resolution becomes crucial. Our discovery of a new methodology to explore the interfacial coupling on Si(111)−7×7 might also be very useful for studying other materials in the future.

The distinctive surface layer of the 7×7 reconstruction naturally provides us with a perfect subsurface to study. According to the Dimer-Adatom-Stackingfault (DAS) model, 11 the surface [Fig. 1(a)] shows a different two-dimensional (2D) symmetry to that of unperturbed Si(111) plane. As indicated in a theoretical calculation, 12 this surface is of a metallic phase, but close to a metal-insulator transition. Its low conductivity 13 and the Si semiconducting gap make it easier to investigate the spectral evolution from surface states to bulk states probed by using scanning tunneling spectroscopy (STS).

In this paper, we present our studies on the tip-height dependence of topographic image, spectra of differential conductance, and tunneling currents. The idea is based on that decrease of the tip-surface separation reduces tunneling barrier between the STM tip and sample. 14–17 The evolution of density of states (DOS) from surface states to bulk states is measured as the tip approaches the sample surface. It is important that the surface-bulk interface remains pristine during the experiment. We describe experimental details in Sec. II. In Sec. III, the experimental data and analyses are presented. Based on the experimental observations, we develop a numerical model to explain the results, which is shown in Sec. IV. Finally, Sec. V contains a conclusion of this study.

II. EXPERIMENT

A three-chamber (loading chamber, sample preparation chamber, low-temperature chamber) UHV system is used for this study. The Si(111)−7×7 surface is prepared by repeatedly annealing a p-type Si(111) substrate (boron doped, resistivity of 0.05 to 0.1 Ω cm) in the UHV (about 1 × 10−10 torr) sample preparation chamber. The processed sample is then transferred to the STM stage at 4.3 K. We use a Pt-Ir tip to measure the STM and STS of the surface. The advantage of using this tip and p-type Si is the smaller contact potential, 0.15 eV, compared to the typical value of about 0.5 eV between a W tip and n-type Si. Our Pt-Ir tip is cleaned in situ by touching the surface gently and then is refined by repetitively scanning over Si steps. The sample bias is fixed at +2 V for taking topographic images and for measuring the tip-height dependence of tunneling currents I(z). During image scanning, at some chosen sites, the scanning is halted and the feedback loop is opened and then the spectra of I(v) and I(z) are measured. This procedure ensures the spectra are measured at the specific atomic site. The relative tip displacement z is controlled by piezovoltage and is calibrated against a single atomic step on Si(111) surface. We obtain the spectra of differential conductance (dI/dV) by differentiating the I-V curves numerically.

III. RESULTS AND DISCUSSION

The first hint of detecting the subsurface is provided by a series of topographic images taken at different tip heights at
The tip is elevated back to a higher position more, the image of the unit cell returns to its pristine form as equal. The topographic images of the same surface become increasingly asymmetrical across the short diagonal as the tip height reduces. Note that the rest atoms do not appear in empty-state images, a unit cell and its short diagonal are marked with white lines. It shows that the approximate symmetry between the unfaulted half cell and the faulted half cells diminishes as the tip height reduces. Note that the rest atoms do not appear in empty-state images and the long diagonal of a unit cell is about 5 nm.

The spectra of $I(V)$ curves at six atomic sites along the long diagonal of the unit cell and at different tip heights set by $I_s$ are shown in Fig. 2. The spectra are increasingly shifted vertically for clarity and they demonstrate the individual spectral features of each atom. However, the spectra at all atomic sites resemble the bulk DOS, i.e., $\propto \sqrt{E-E_C}$. The notation $E_C$ denotes the magnitude of bulk Si semiconductor gap.

To elucidate the evolution of the DOS, we measure the $I(V)$ curves at six atomic sites along the long diagonal of the unit cell at 4.3 K. (a) Spectra taken at tip height defined by $I_s=50$ pA indicate that each atom has its own features despite the common energy gap. The positive gap edge is similar to the bulk conduction-band edge $E_g=0.52$ eV relative to the chemical potential, shown in the inset. However, the negative gap edge is less well defined and has a value about 0.9 eV, which is larger than the valence-band edge $E_v =0.65$ eV. Additional band bending due to reverse bias may be the reason for the discrepancy. (b) Spectra taken at a lower tip height defined by $I_s=500$ pA show convergence at all atomic sites. The common empty-state spectrum at positive bias resembles the bulk DOS, i.e., $\propto \sqrt{E-E_C}$. The notation $E_C$ denotes the magnitude of bulk Si semiconductor gap.

We further reveal the effect of bulk electronic states on tunneling spectrum by showing the normalized spectra $(dI/dV) / (I/V)_{\text{average}}$ of the surface-atom sites in the faulted half cell at 4.3 K for three different tip heights (Fig. 3). The spectra for the unfaulted-half cell are not shown because the respective atoms in the both faulted-half and unfaulted-half cells have similar spectral features except different peak heights. The $(I/V)_{\text{average}}$ is calculated according to Eq. (1), a scheme proposed by Mårtensson and Feenstra,18.
The spectra are measured by $I_s = 10$, 50, and 100 pA at (a) center adatom, (b) rest atom, and (c) corner adatom sites. In addition to the surface states identified in the spectra at 20 K, the spectra at 4.3 K possess an extra feature of energy gap. This energy gap is attributed to the bulk Si semiconductor gap, as shown in our numerical calculation. The parameters of $a$ and $\Delta V$ in $(dI/dV)/(I/V)_{\text{average}}$ are 2 and 1.3, respectively. The value of energy state is insensitive to the choice of these two parameters. For clarity, the spectra are shifted vertically.

The normalization by $(dI/dV)/(I/V)_{\text{average}}$ reduces the influence of the tip-sample separation set by $I_s$ and removes the divergence of normalized differential conductance $(dI/dV)/(I/V)$ in the regime of very low tunneling currents. Some surface states are evident, but their energy positions are clearly upshifted by an apparent gap. To understand the origin of the energy shift, we repeat the same measurements at a higher temperature, $T = 20$ K, and the results are in Fig. 4. Now the surface states corresponding to center adatom ($U'_1, U'_0$), rest atom ($S_2$), and corner adatom ($S'_1, S_1, U_1$) can be clearly identified (Fig. 4). The spectra at 20 K clearly display the gapless states, indicative of a metallic surface. However, even without the gap in the spectra, the surface-state features still shift up in energy with lowering tip height. In comparison to the spectra at 20 K, we tentatively assigned the surface states as shown in Fig. 3.

We summarize the dependence of energy values of surface states on $I_s$ at 20 and 4.3 K in Fig. 5. The energy values of all six states are linearly dependent with $I_s$ for both temperatures. By extrapolating the energy of each state to zero $I_s$, we can obtain the unperturbed energy positions of these surface states. At 20 K, the energy values of states $S_2, S'_1, S_1, U'_1, U_1$, and $U'_0$ are $-0.84, -0.44, -0.08, 0.17, 0.29$, and 0.42 eV respectively, while they are $-1.66, -1.35, -0.95, 0.64, 0.75$, and 0.92 eV, respectively, at 4.3 K. Since there is no energy deviation in the values obtained at 20 K, we suppose that these values at 20 K represent the correct energy values of the surface states. In Fig. 6, we show the extrapolation energy values of the surface states at 20 and 4.3 K. Interestingly, the energy difference between the empty states at 20 and 4.3 K is about 0.5 eV, close to the conduction-band edge of bulk Si (inset of Fig. 2(a)]. The corresponding difference in the filled states is about 0.9 eV, which is larger than the expected 0.65 eV of the bulk valence-band edge suggested by surface band bending. This larger shift and deviation from the typical form of semiconductor energy gap may be attributed to the enlargement of the Schottky barrier in the reverse bias. Despite the absence of a bulklike gap in the spectra of 20 K, the influence of bulk states likely causes the deformation around 0.5 eV in the spectrum of $I_s = 100$ pA. The effects of both temperature and current on the energy shift of the surface states strongly suggest that the chemical potential of the surface states is deviated from the chemical potential of the substrate.

To understand the evolution with tip height clearly, we measured the tip-height dependence of tunneling current at different sites (Fig. 7). If the tunneling resistance is dominated by a vacuum barrier, the tunneling current is expected to increase with decreasing tip height. However, the tunneling current decreases with decreasing tip height, which indicates that the chemical potential of the surface states is deviated from the chemical potential of the substrate.
FIG. 5. (Color online) Current dependence of energy shift of surface states. Data points are obtained from Figs. 4 and 3 at (a) 20 K and (b) 4.3 K, respectively. Lines are drawn according to linear fits. The error bars are estimated by respective spectral widths. By extrapolating the energy of each state to zero \( I_0 \), we can obtain the energy values of states \( S_2, S_1', S_1, U_1', U_1, \) and \( U_0' \) at 20 K are −0.84, −0.44, −0.08, 0.17, 0.29, and 0.42 eV respectively, while they are −1.66, −1.35, −0.95, 0.64, 0.75, and 0.92 eV, respectively, at 4.3 K. This figure shows that the major difference between the spectra at 20 and 4.3 K is the extra energy gap presented in the spectra at 4.3 K. Based on our model, this is the bulk Si semiconductor gap.

\[
\phi_d (\text{eV}) = 0.952 \left( \frac{d \ln I}{dz (\text{Å})} \right)^2, \tag{2}
\]

all data points should fall on a universal line in this \( I(z) \) plot. Indeed, this is the case for a span of 0.2 nm near \( z=0 \) defined by \( I_z=10 \text{ pA} \). A barrier \( \phi_d \) of 2.8 eV is thus derived, which is close to the value of 3.1 eV reported on a \( p \)-type Si substrate.\(^\text{24} \) However, \( I(z) \) becomes site dependent for \( z \) less than −0.1 nm. Since the difference in \( I(z) \) is insignificant between the corresponding atoms in the two halves, we focus our discussion on the unfaulted half [Fig. 7(a)]. The slope of \( \ln[I(z)] \) decreases monotonically below \( z=0.1 \) nm at the rest atom site. At the adatom sites, there is a deviation in the range of \( z=0.15 \) to −0.2 nm, where the tunneling current for the center adatom site increases more rapidly. A similar phenomenon has been observed as the tip approaches some metal surface, which has been attributed to the tip-surface relaxation.\(^\text{15-17} \) No relaxation is observed at the corner adatom, suggesting that its bonding with substrate atoms is stronger. In fact, we have observed that the center adatom can be displaced by high tunneling currents at temperatures higher than 10 K, while no displacement of the corner adatom is induced under the same condition. The previous report of manipulation of Si center adatoms is consistent with our result.\(^\text{22} \) Below \( z=0.2 \) nm, the apparent barrier heights at both adatom sites reduce to 0.2 eV or less, indicative of tunneling-barrier collapse. Thus we conclude that the overlapping of the electron wave functions between the tip and the surface is significantly enhanced at \( I_z=500 \text{ pA} (z=0.23 \text{ nm}) \), but not enough to push the surface atoms out of their equilibrium positions. The fact that the magnitude of \( \phi_d \) reduction is different at different sites and yet \( I(V) \) becomes universal at \( I_z=500 \text{ pA} \) strongly suggests that the mechanism is not due to surface or tip atom alterations, multiple tunneling-scattering effect, or any other effect involving only the tip and the surface layer.

The inhomogeneous \( \phi_d \) in the regime of high tunneling current could be attributed to interactions between the tip atom and surface atoms. Hofer and Fisher found that tunneling conductance is proportional to the tip-surface interaction energy.\(^\text{23} \) They proposed that the current flow between individual atoms is a measure for their interaction. Since the dangling bonds of the three atoms have different filling factors,\(^\text{2} \) the interactions with the tip atom would vary at the three atom sites. Therefore, the \( I(z) \) curves behave differently.

The above discussion leads us to contemplate the possibility that the chemical potential of bulk electrons (\( \mu_B \)) and surface electrons (\( \mu_S \)) may actually be separated from each other by the tunneling current. The dangling bonds on the \( 7 \times 7 \) surface usually enable the pinning of \( \mu_B \) and \( \mu_S \), which results in band bending as illustrated in the inset of Fig. 2(a). If the bulk-surface coupling is so strong that the two levels are tied together even at high current, then the tunneling...
importantly, it can explain the universally bulklike energy of 4 meV. Thus it is plausible that the large resistance of shows a thermally activated resistance with an activation energy of 2.8 eV is derived. The difference of the latter two is the biased voltage. Ignoring thermal excitation, the tunneling current, \( I_1 \), between the tip and the surface states can be approximately written as the following equation:

\[
I_1 = A \int_{\mu_S}^{eV} \rho_s(e - \mu_S) T(e, eV) de. \tag{3}
\]

Here, \( T(e, eV) \) is the tunneling matrix element, \( \mu_S \) is the chemical potential of the surface electrons (or expressed as \( eV_2 \)), and \( \rho_s \) is the density of the silicon surface states. The current, \( I_2 \), between the surface and bulk states, is assumed to take the tunneling form because of the relatively weak coupling between the two states

\[
I_2 = \int_0^{\mu_S} \left[ C \left( \frac{e}{E_C} - 1 \right) + D \frac{\gamma^2}{\pi(e^2 + \gamma^2)} \right] \times \rho_B(e - \mu_B) T(e, eV) de, \tag{4}
\]

where the density of the bulk states is modeled by a gapped DOS with a conduction-band edge at \( E_C = 0.52 \text{ eV} \) and a density of dopant states of Lorentzian form with an energy width of \( \gamma = 0.1 \text{ eV} \). We also assume that the functional form of \( T(e, eV) \) is similar in both tip-to-surface and surface to bulk tunnelings. Although the spectrum of \( \langle dl/dV \rangle / \langle I/V \rangle \text{average} \) is proportional to DOS, the tunneling matrix element still contains an exponential factor of voltage bias according to the WKB approximation. It is better to choose \( \rho_2(e - \mu_B) T(e, eV) \) to be the measured \( \langle dl/dV \rangle / \langle I/V \rangle \text{average} \) of the specified tunneling site at 20 K at the tip height fixed by \( I_z = 10 \text{ pA} \). The reason why we divided \( dl/dV \) by \( \langle I/V \rangle \text{average} \) is to let the unit of \( \rho(e - \mu_B) T(e, eV) \) become dimensionless and choosing 1.85 V is arbitrary as long as \( I/V \) is not too small.

The constants \( A, C, \) and \( D \) are fitting parameters to be determined. The continuity of current requires the equality of \( I_1 \) and \( I_2 \). Solving this equation, \( I_1 = I_2 \), gives us the value of \( \mu_S \) in terms of the three fitting parameters. Thus we obtain the \( I(V) \) curve in the chosen range of the external biased voltage \( V \). The value of \( A \) dictates the strength of the tip-surface coupling. Therefore, it should become larger when the tip is closer to the surface. Meanwhile, the strength of the surface-bulk coupling near the Fermi level is related to the value of \( D \). We first determine these three values at 4.3 K and \( I_z = 10 \text{ pA} \). From Eq. (4), we know that the value of \( D \) dominates the tunneling current in voltage range from 0 to 0.52 eV. Because the measured tunneling current in this range is down to the noise level, we can only determine an upper

FIG. 7. (Color online) \( I(z) \) curves of the center adatom, corner adatom, and rest atom. The \( I(z) \) curves of these atoms in the unfaulnd half cell are shown in (a) and the respective data in the faulted half cell are shown in (b). The current is measured with a fixed sample bias voltage of +2 V at 4.3 K. The zero point of \( z \) is arbitrarily chosen to be the tip height defined by \( I_z = 10 \text{ pA} \) at all six atomic sites along the long diagonal of a unit cell. Smaller value of \( z \) represents closer tip to surface separation. For each set of \( I \)-vs-\( z \) measurement, after releasing the \( z \)-control feedback with \( I_z = 10 \text{ pA} \), the tip is first retracted back by about 0.2 nm. Then the \( z \) dependence of the tunneling current is measured by using the tunneling form because of the relatively weak coupling between the two states.

The tunneling matrix element still contains an exponential factor of voltage bias according to the WKB approximation. It is better to choose \( \rho_2(e - \mu_B) T(e, eV) \) to be the measured \( \langle dl/dV \rangle / \langle I/V \rangle \text{average} \) of the specified tunneling site at 20 K at the tip height fixed by \( I_z = 10 \text{ pA} \). The reason why we divided \( dl/dV \) by \( \langle I/V \rangle \text{average} \) is to let the unit of \( \rho(e - \mu_B) T(e, eV) \) become dimensionless and choosing 1.85 V is arbitrary as long as \( I/V \) is not too small.

The constants \( A, C, \) and \( D \) are fitting parameters to be determined. The continuity of current requires the equality of \( I_1 \) and \( I_2 \). Solving this equation, \( I_1 = I_2 \), gives us the value of \( \mu_S \) in terms of the three fitting parameters. Thus we obtain the \( I(V) \) curve in the chosen range of the external biased voltage \( V \). The value of \( A \) dictates the strength of the tip-surface coupling. Therefore, it should become larger when the tip is closer to the surface. Meanwhile, the strength of the surface-bulk coupling near the Fermi level is related to the value of \( D \). We first determine these three values at 4.3 K and \( I_z = 10 \text{ pA} \). From Eq. (4), we know that the value of \( D \) dominates the tunneling current in voltage range from 0 to 0.52 eV. Because the measured tunneling current in this range is down to the noise level, we can only determine an upper
bound of $D$ which we choose for all fittings at 4.3 K. Then, we choose a fixed point in our experimental data and demand all calculated $I$-$V$ curves to go through this point. Through this fixed-point procedure, the parameters $A$ and $C$ are no longer independent. By changing $C$, we can have different sets of $A$, $C$, and $D$. The set that can fit the experimental data best in the entire range of $V$ is the best fitting parameters.

The coupling strength does not vary with different setting current, so the values of $C$ and $D$ should remain unchanged at the same temperature. Because of this reason, we just need to change $A$ to fit the fixed point in the case of $I_s=500$ pA. At 20 K, we also work on $I_s=10$ pA first. Since the value of $C$ indicates the contribution of Si conduction band to the tunneling current, it should be insensitive to temperature. Therefore, the value of $C$ at 20 K is chosen to be the same as that at 4.3 K. The method we use to find the remaining $A$ and $D$ is the same as that we find $A$ and $C$ at 4.3 K. Through fitting the $I$-$V$ curves at 4.3 K, we obtain a fixed value of $C$ and setting current-dependent $A$ with a negligible $D$. Then with the same fixed $C$, we again obtain a fixed value of $D$ and values of $A$ which are dependent on the setting current through fitting $I$-$V$ curve at 20 K.

Figure 8 shows a series of raw data and simulated results at failed corner adatom site at 4.3 and 20 K. The left axis is referred to current and the right axis is referred to voltage ($V_2$) indicating the relative shift of $\mu_S$ to $\mu_B$ at different external biased voltages. According to the simulated result of $\mu_S$, we schematically illustrate the modeling situation of tunneling in the respective inset of the subfigure. At 4.3 K, the small value of $D$ leads to a negligible current below the minimum of conduction-band edge and thus $V_2$ is equal to $V$. The increase of biased current, thus the value of $A$, farther shifts $\mu_S$ to $\mu_T$, which is shown in the evolution of $\mu_S$ curves from Fig. 8(a) ($I_s=10$ pA) to Fig. 8(b) ($I_s=500$ pA). For small $I_s$ such as 10 pA, $\mu_S$ is raised to the conduction-band edge and keeps to this energy value so that observed tunneling spectra reveal shifted surface states. On the other hand, for large $I_s$ such as 500 pA, $\mu_S$ is nearly leveled to $\mu_T$. There is hardly a voltage drop between the chemical potentials of the tip ($\mu_T$) and the surface states ($\mu_S$) so that a universal bulk DOS is revealed in the spectra of STS. This is consistent with the results of $I(z)$ indicating the collapsed barrier of vacuum tunneling at 500 pA (Fig. 7).

At 20 K, the coupling strength ($D$) of surface states to the dopant band is stronger, which is $10^3$ times larger than the coupling strength at 4.3 K. For low setting currents at 20 K, $\mu_S$ is practically pinned to the dopant level $\mu_B$. In Fig. 8(c) ($I_s=10$ pA), current appears in the gap region of bulk Si and the value of $V_2$ is negligible small. Thus the observed spectra show the typical surface states. The larger voltage shift observed at $I_s=100$ pA, shown in Fig. 8(d), can explain the deformation around 0.5 eV in the spectra of $I_s=100$ pA in Figs. 4(b) and 4(c). The simulation not only quantitatively explains the experimental data but also accounts for the constant energy difference of 0.5 eV between the empty surface states at 4.3 and 20 K as well. The energy shift of surface
states due to the semiconductor gap is eliminated by increasing the value of $D$, thus enhancing the surface-bulk coupling. The good agreement between the simulations and data suggests that we have unraveled the interfacial coupling between the surface states and the bulk states. In Fig. 1(e), which is scanned as vacuum tunneling barrier collapses, the image contrast in addition to the arrangement of the surface atoms could be attributed to the different surface to bulk conductivity in the two half cells. The surface to bulk conductivity in the faulted half cell is higher than that in the unfaulted half cell, thus the faulted half appears brighter in Fig. 1(e). Theoretical study of the surface to bulk conduction in the system of the Si(111)–7 × 7 surface is needed to compare with our experimental data.

V. CONCLUSION

Using a UHV low-temperature STM system, we have observed the evolution of topography on the Si(111)–7 × 7 surface with decreasing STM tip height at $T=4.3$ K. Our result shows a sharper contrast between the faulted and unfaulted halves of the 7 × 7 unit cell as the tip is closer to the surface. Since the surface layers of adatoms and rest atoms in the two halves are symmetrical, this contrast implies that the tunneling tip can sense the subsurface layer. Furthermore, the tunneling spectra taken at individual atomic sites also evolve from $I(V)$ curves showing features characterizing individual atoms to a universal $I(V)$ curve resembling the bulk silicon gap. At 20 K, this energy gap disappears and surface states of Si atoms are observed at all tip heights used. However, the surface features do shift up in energy as the tip becomes closer to the surface. To reveal the underline mechanism of these evolutions, the tip-height dependence of tunneling current for different atomic site is measured at 4.3 K. The result shows that apparent barrier heights $(\phi_b)$ of the surface atoms correspond to a universal value, typical of vacuum tunneling, at relative large tip-surface separation and become inhomogeneous showing different degree of tunneling-barrier collapse. Only the center adatoms show the evidence of the tip-surface relaxation. Thus the fact that all tunneling $I(V)$ curves, taken at the smallest separation, become universal cannot be explained by the mechanism of the tip-surface relaxation, the multiple tunneling effect, or any other effect related to individual surface atoms.

In order to explain the observed phenomena, we have developed a model allowing the surface chemical potential to be shifted away from that of the bulk state due to high tunneling currents. Normally, the surface chemical potential is pinned to that of the bulk, thus the surface density of state is obtained by ramping the tunneling potential difference between the tip and the surface in tunneling experiment. However, in the extreme case when the surface chemical potential is shifted and pinned to that of the tip, then it would be natural to observe the bulklike tunneling $I(V)$ curve. In order to show this simple model can quantitatively explain the $I(V)$ curves, we have performed numerical calculations for various tip heights defined by the setting currents. With only three fitting parameters, the simulated $I$-$V$ curves are in reasonably good agreement with the measured ones. By virtue of the good fitting, we can obtain the relative coupling strength of between surface states and the bulk states with atomic resolution. We believe this is a methodology to explore the subsurfaces of Si and can be applied to other interesting materials as well.

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