Atom Selective Imaging and Mechanical Atom Manipulation based on Noncontact Atomic Force Microscope Method *

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We investigated performances and functions of the noncontact atomic force microscope (NC-AFM) method. As a result, we found that the NC-AFM functions not only as the atomic resolution microscope but also novel atomic tools based on a mechanical method as follows; a three-dimensional mapping tool of atomic force between the tip and sample atoms, a discrimination tool of atomic force mechanisms and atom species of the sample surface, a control tool of atomic force and atom position on the sample surface, and an atom manipulation tool.

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I. INTRODUCTION

The scanning tunneling microscope (STM) invented in 1982 [1] is an atomic tool based on an electronic method that measures the tunneling current between a conductive tip and a conductive surface. It can electronically observe individual atoms/molecules. It can characterize or analyze electronic nature around surface atoms/molecules. Besides, it can manipulate individual atoms/molecules [2]. Hence, the STM is the first generation of atom/molecule technology. On the other hand, the atomic force microscope (AFM) [3] is a unique atomic tool based on a mechanical method that can deal with even the insulator surface. Since the invention of noncontact Atomic Force Microscope (NC-AFM) in 1995 [4-6], the NC-AFM and the NC-AFM based method have rapidly developed into a powerful surface tool on atomic/molecular scales, because the NC-AFM has the following characteristics: (1) It has true atomic resolution, (2) it can measure atomic force (so-called atomic force spectroscopy), (3) it can observe even insulators, and (4) it can measure mechanical responses such as elastic deformation. Thus, the NC-AFM is the second generation of atom/molecule technology. The scanning probe microscopy (SPM) such as the STM and the NC-AFM is the key technology for the nanotechnology and also for the future bottom-up process.

In this review paper, principles of NC-AFM and applications to semiconductors will be introduced. It should be noted that the NC-AFM and NC-AFM based method enable us atom selective imaging and mechanical atom manipulation. This review paper is essential to understand the status of the art and the future possibility of the NC-AFM.

II. EXPERIMENTAL

We used home-built UHV-AFM systems with a preparation chamber to observe clean semiconductor surfaces. Noncontact UHV-AFM measurements were performed at room temperature (RT) [7] or at low temperature (LT) [8] of 9.3 K and 78 K at a pressure lower than 2 × 10⁻¹⁰ Pa. The small deflection of the cantilever was detected by an optical-fiber interferometer [9] or an optical beam deflection detection system [10]. Furthermore, as shown in Fig.1, the frequency modulation (FM) detection method [11] was used to measure a small change of the frequency shift Δν in Fig.2 of the mechanical resonance of a cantilever due to an attractive force interaction between the cantilever tip and the sample surface. A positive feedback system with an automatic gain control (AGC) shown in Fig.1 was used to maintain a constant oscillation amplitude (switch 1 in Fig.1) or constant excitation voltage (switch 2 in Fig.2) [12]. As a force sensor, a clean silicon cantilever was used. As shown in Fig.1, we measured (variable) frequency shift image or (NC-AFM) to-

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FIG. 1: Schematic diagram of the NC-AFM using the FM detection method. This system has three feedback loops.

FIG. 2: Oscillation amplitude $A$ as a function of mechanical oscillation frequency of the cantilever. $v_0$, $\nu$, $\Delta\nu$ and $A_0$ are the mechanically free oscillation frequency, the mechanical oscillation frequency of the cantilever under weak attractive force, frequency shift, and oscillation amplitude, respectively.

III. RESULTS AND DISCUSSIONS

A. Contact Point, Noncontact Region and Imaging Distance

As shown in Fig. 3 [13], at first, to determine the contact point between the tip and $p$-GaAs(110) cleaved sample surface, we investigated oscillation amplitude and frequency shift of the cantilever as a function of tip-sample surface distance under the constant-excitation (voltage) mode. Figure 3 shows that the oscillation amplitude of the cantilever was almost constant down to $Z \sim 0$ nm and then decreased almost linearly with decreasing tip-sample surface distance. A decrease in the oscillation amplitude means an increase in the energy transfer from the cantilever to the sample because of the cyclic repulsive contact between the tip and sample surface. Therefore, $Z \sim 0$ nm at which oscillation amplitude starts to decrease is defined as the contact point. Hence, the region of $Z > 0$ nm is the noncontact region, while the region of $Z < 0$ nm is the contact region. It should be noted that the absolute value of the frequency shift gradually increased due to the increase of attractive force, and that its curvature attained the maximum value just before the contact point.

Then, as shown in the frequency shift images of Fig. 4 [13], distance dependence was investigated by imaging at the distance of $Z \sim 0.4$ nm, 0.10 nm and 0.08 nm from the contact point as indicated in Fig. 3. Here, the distance was determined from the averaged frequency shift of $<\Delta\nu> \sim -31$ Hz for $Z \sim 0.4$ nm, -62Hz for 0.10 nm and -70Hz for 0.08 nm as shown in Fig. 3. At $Z \sim 0.4$ nm, Fig. 4 (a) showed only vague contrast and small change of frequency shift, which might be induced by point defects. By decreasing tip-sample surface distance down to $Z \sim 0.10$ nm, as shown in Fig. 4 (b), the periodic lattice structure and atomic point defects appeared, although contrast is still vague. By decreasing the tip-sample surface distance further down to $Z \sim 0.08$ nm, as shown in Fig. 4 (c), the periodic lattice structure as well
as atomic point defects became very clear. Thus, the optimal distance to image the periodic lattice structure and the atomic point defects is just before the contact point where the distance dependence of the frequency shift becomes strongest. These results qualitatively agree with the guidelines for the achievement of true atomic resolution predicted by a simple model [14]. Figures 4 (b) and (c) clearly show that 8 Hz change of the frequency shift occurs for 0.02 nm (=20 pm) change of the tip-sample distance. Therefore, if we can measure 0.1 Hz change of the frequency shift, we can measure 0.25 pm (=250 fm) change of the tip-sample distance.

2. Lateral Resolution of High Performance NC-AFM

As shown in Fig. 6 (a), Si(100)2×1 clean surface has Si dimers with tilted dangling bonds and is reactive. Each Si dimer buckles and hence becomes asymmetric to decrease electron energy further. But each asymmetric Si dimer flip-flops between equivalent two buckled structures at RT. Therefore, slow imaging methods such as STM and NC-AFM will give time-averaged image of asymmetric dimer structure, i.e., symmetric dimer at RT. On the other hand, as shown in Fig. 7 (a), Si(100)2×1:H monohydride surface is terminated by hydrogen atoms and inactive. Besides, hydrogen terminated surface is stable and buckling will not be induced.

Figure 6 (b) shows the frequency shift image of Si(100)2×1 surface measured at $<\Delta \nu> = -30$ Hz [16]. The paired bright spots (imaged dimer) constituting rows with a 2×1 symmetry was clearly observed. Further, the distance between paired bright spots was 0.32±0.01 nm. Thus, the NC-AFM can measure the length of imaged dimer as 0.32 nm within the experimental error of 0.01 nm (=10 pm). Therefore, our home-built NC-AFM has nearly 1 pm lateral resolution.
This result suggests that the chemical bonding interaction strongly works between the tilted dangling bond out of the silicon dimer and the dangling bond out of silicon tip apex, and that, as a result, the dimer structure with a larger length than that between Si dimer was imaged.

Figure 7 (b) shows the atomic resolution image of hydrogen terminated silicon monohydride [Si(100)2×1:H] surface measured at $<\Delta \nu >= -1$ Hz. The paired bright spots (imaged dimer) constituting rows with a 2×1 symmetry was observed even in hydrogen terminated Si(100)2×1:H surface. Further, the distance between paired bright spots was 0.35±0.01nm. Thus, our NC-AFM can detect 0.03 nm (=30 pm) change of imaged dimer due to hydrogen termination. The bright spots of Fig. 7 (b) seem to be located at hydrogen atom sites on Si(100) 2×1:H surface, because the distance between bright spots 0.35±0.01nm forming dimer structure approximately agrees with the distance between paired hydrogen atoms, i.e., 0.352nm. Thus, our home built NC-AFM can image tilted dangling bonds and individual hydrogen atom.

3. NC-AFM Imaging of Atomic Surface Strain Around Missing Dimer

In case of the Si(100)2×1-clean surface, macroscopic stress measurement can measure only asymmetry of the surface stress, because of the alternating 2×1 and 1×2 structures [17]. To our knowledge, no direct measurement of atomic surface strain or stress in specific directions has been reported before our experiment [18]. Using frequency shift images of the Si(100) 2×1-clean surface such as that in Fig. 6 (b), we carefully investigated the lateral position of imaged dimers around the missing dimers. White broken lines in Fig. 8 show the centerlines of imaged dimers along the dimer bond and also across the dimer row. Around the missing dimers such as ‘A’ in Fig. 8, we found clear lateral shift of the imaged dimer toward the missing dimer along the dimer row. By averaging the measured lateral shift, we found 0.08 nm and 0.04 nm lateral shifts for the nearest (N = 1) and the second nearest (N = 2) dimers toward the missing dimer, respectively, as shown in Fig. 9. For N larger than 3, averaged lateral shift was less than the experimental error of ±0.01 nm. Similarly, using frequency shift images of the Si(100)2×1:H-monohydride surface such as that in Fig. 7 (b), we carefully investigated the lateral position of imaged dimers around missing dimers. In contrast to the result for the Si(100) 2×1-clean surface, as shown in Fig. 9, we did not observe lateral shift of dimers around missing dimers on the Si(100) 2×1:H-monohydride surface within the experimental error of ±0.01 nm. This result indicates that the hydrogen termination removes the atomic surface stress and strain, even around missing dimers. Thus, our home-built NC-AFM can measure the mechanical response of the dimers due to surface stress and can directly measure atomic surface strain in specific directions with an accuracy of ±0.01 nm (=10 pm).

In the case of the Si(100)2×1-clean surface, each missing dimer results in four dangling bonds at the second Si layer because the missing dimer defect cuts four covalent bonds between an upper dimer and four Si backbond atoms at the second layer. Then, four dangling bonds produce two lower dimers at the second layer as shown in (1) of Fig. 10 (a) [18]. These lower dimers oriented in the direction normal to the upper dimer and along the dimer row in the first layer. Under this condition, attractive force acts between paired Si atoms constituting the lower dimer. Hence, that stress pulls the upper dimer (2)
in Fig. 10 (a) toward the missing dimer along the upper dimer row. If the length of the lower dimer is 0.230 nm, which is the same as that of the upper asymmetric dimer, the nearest upper dimer will move about \((0.384\text{ nm}-0.230\text{ nm})/2=0.077\text{ nm}\) toward the missing dimer. Here, 0.384 nm is the lattice constant of the Si(100)\(1\times1\)-ideal structure and is the original spacing between dimers along the dimer row. This roughly estimated value nearly agrees with the experimentally observed value of 0.08 nm, although this simple method cannot estimate the lateral shift of the second nearest dimer (3) in Fig. 10 (a). On the other hand, in the case of the Si(100)\(2\times1\):H-monohydride surface, four dangling bonds in the second Si layer due to each missing dimer defect are terminated by hydrogen atoms one by one as shown in Fig. 10 (b). Such termination will remove the stress and hence strain around the missing dimer defects. Thus, schematic models of Figs. 10 (a) and (b) can roughly explain the experimentally observed atomic surface strain around missing dimer defects.

C. Three Dimensional (3D) Mapping of Atomic Force

Our NC-AFM can map atomic force three-dimensionally. There are two methods for three-dimensional mapping of atomic force [19]. One method measures the tip-sample \(Z\) distance dependence of the NC-AFM \((X, Y)\) images. This kind of three-dimensional (3D) mapping of atomic force on an atomic scale was achieved on Si(111)\(\sqrt{3}\times\sqrt{3}\)-Ag surface [20] and on oxygen adsorbed Si(111)\(7\times7\) surface [21]. The other method measures the \((X, Y)\) site dependence of frequency shift curves \((Z)\). This kind of three-dimensional mapping of atomic force on an atomic scale was achieved on Si(111)\(7\times7\) surface [22].

On the Si(111)\(\sqrt{3}\times\sqrt{3}\)-Ag region, we investigated the tip-sample distance dependence of the NC-AFM topogra-
D. Discrimination of Atomic Force Mechanisms and Atom Species

Figure 12 shows another example of three-dimensional mapping of atomic force obtained by measuring the tip-sample distance dependence of the NC-AFM topography on oxygen adsorbed Si(111)7×7 surface [21]. At relatively far distance, only several bright spots enclosed by yellow open circles can be seen clearly as shown in Fig. 12 (a). It should be noted that at this distance, Si adatoms, i.e., the 7×7 structure, cannot be observed clearly. On the other hand, at near distance, the 7×7 structure can be clearly seen as bright spots in the 7×7 unit cell shown by a rhombus in Fig. 12 (b). From three-dimensional mapping of atomic force such as Figs. 12 (a) and (b), we can conclude that two force mechanisms work between the Si tip and oxygen adsorbed Si(111)7×7 surface. One is a kind of localized but rather long-range force, which works well even at relatively far distance. The other is a kind of short-range force, which works strongly only at near distance. The short-range force contributes to NC-AFM imaging of the 7×7 structure, that is, Si adatoms, as shown in Fig. 12 (b). Hence the short-range force is the covalent bonding force between dangling bonds of Si adatoms and the tip apex Si atom, and has a critical distance d_c, below which the covalent bonding force works strongly as shown in Figs. 12 (a) and (b). On the other hand, at relatively far distance, different atoms from Si adatoms seem to be imaged by the rather long-range force. Oxygen adsorbed Si(111)7×7 surface has only two kinds of atoms, that is, Si atoms and oxygen atoms. Therefore, we conjectured that, at relatively far distance, oxygen atoms (or molecules) were imaged by the long-range force. Oxygen atoms will be easily charged negatively, because of its high electronegativity and n-type silicon substrate. Therefore, the origin of the long-range force may be electrostatic force between negatively charged O atom (or O₂ molecule) and Si tip. Thus using three-dimensional mapping of atomic force, we can discriminate mechanisms of atomic forces between the tip and the sample surface, and also we can discriminate atom species on the sample.
E. Control of Atomic Force and Atom Position

There are two methods to control atomic force between the tip and sample surface. One method controls atomic force by placing a suitable atom on the tip apex instead of a conventional Si atom, while the other method controls atomic force by regulating the tip-sample surface distance. Here, we will introduce examples of these two methods that will control atomic force and atom position on the sample surface.

1. Atomic Force Control by Placing a Suitable Atom on Tip Apex

At first, we will introduce one interesting example of atomic force control that compared an Ag adsorbed Si tip with a clean Si tip by investigating the tip-sample distance dependence of the NC-AFM image on Si(111)√3 × √3-Ag surface [20, 25]. To fabricate an Ag adsorbed Si tip, we transferred an Ag atom to the Si tip apex from the Si(111)√3 × √3-Ag sample surface by the soft mechanical contact of the Si tip with the Si(111)√3 × √3-Ag sample surface. After that, different type of the NC-AFM image was reproducibly obtained on the Si(111)√3 × √3-Ag sample surface, and then the tip-sample distance dependence of the NC-AFM image pattern disappeared as shown in Figs. 11 (d)-(f) [25]. Before the contact, the topmost atom of the tip apex was a Si atom, because the Si tip was cleaned by in situ Ar ion sputtering before the NC-AFM imaging and maintained under the UHV better than 2 × 10⁻⁸ Pa. On the other hand, there are only two atom species (Si and Ag) on the Si(111)√3 × √3-Ag sample surface. If an Ag atom was picked up on the Si tip apex, the NC-AFM image may change drastically. However, if a Si atom was picked up on the Si tip apex or dropped off to the Si(111)√3 × √3-Ag sample surface, the NC-AFM image will not so much change. Thus, we concluded that an Ag atom was picked up on the Si tip apex. Figures 11 (d)-(f) show the typical atomic-resolution images obtained after the Ag atom picking up from the Si(111)√3 × √3-Ag surface [20, 25].
FIG. 12: NC-AFM images of oxygen adsorbed Si(111)7 × 7 at (a) relatively far distance and at (b) near distance [21]. Scan areas are 15 nm × 15 nm.

sample surface. Here, these NC-AFM images were obtained at the frequency-shift of (d) $\Delta \nu = -4.4$ Hz, (e) $\Delta \nu = -6.9$ Hz and (f) $\Delta \nu = -9.4$ Hz, respectively. Corresponding tip-sample distances are roughly estimated to be $z = 0.19$ nm, 0.06 nm and $\sim 0$ nm from the contact point [25], respectively. As shown in Figs. 11 (d)-(f), when the tip approached the surface, the NC-AFM image pattern did not change, and only the image contrast improved. We can observe zigzag triangular pattern as shown in Figs. 11 (d)-(f). Here, each triangle was composed of three bright spots located in the $\sqrt{3} \times \sqrt{3}$ unit cell. The distance between the bright spots is 0.35 ± 0.02 nm. Directions of the apexes of all triangles are tilted a little around the [121] direction. Tentatively, we conjectured that the most appropriate site for the triangle pattern observed using the Ag adsorbed tip is the site of individual Ag atom forming the Ag trimer [25], although a theoretical research is necessary. Present results on the Si(111)$\sqrt{3} \times \sqrt{3}$-Ag sample surface with two atom species of Ag and Si atoms suggest that the NC-AFM can control the interaction force between the tip and the surface on an atomic scale by placing a suitable atom on the tip apex such as the clean Si tip, the oxidized Si tip, the Ag adsorbed Si tip, the H terminated tip and the chemically modified tip.

2. Control of Atomic Force and Atom Position by Regulating Tip-Sample Distance

We also investigated the Si(100)1 × 1:2H-dihydride and Si(100) 1 × 1:2D-dideuteride surfaces at RT, respectively. On this surface, repulsive force acts between adjacent hydrogen (or deuterium) atoms and produces the 1 × 1 canted structure in order to increase the distance between adjacent hydrogen (or deuterium) atoms, i.e., to reduce the stress due to repulsive force. As shown in Fig. 13, we were able to clearly observe the 1 × 1 structure using the NC-AFM [26].

Next, we investigated the tip-sample distance dependence of NC-AFM image of Si(100) 1 × 1:2D-dideuteride surface. By decreasing the tip-sample distance, we obtained NC-AFM images as shown in Figs. 14 (a), (b) and (c). At a relatively far distance ($d = 0.12$ nm), we observed a 1 × 1 structure as shown in Fig. 14 (a). It seems that this 1 × 1 structure is the original 1 × 1 canted structure. Then, at a near distance ($d = 0.09$ nm), we

FIG. 13: NC-AFM images of (a) Si(100)1 × 1:2H-dihydride [26] and (b) Si(100) 1 × 1:2D-dideuteride surfaces at room temperature. Scan areas are 5.7 nm × 5.7 nm. Open squares formed by white solid lines show 1 × 1 unit cells.
observed a nearly 2 × 1 structure as shown in Fig. 14 (b). However, at a close distance (d = 0.07 nm), we again observed a 1 × 1 structure as shown in Fig. 14 (c). Thus the Si(100) 1 × 1:2D dideuteride surface showed a pattern change in the NC-AFM images similar to those observed for the Si(100) 1 × 1:2H-dihydride surface [26]. Then, we increased tip-sample distance. As a result, we confirmed the reproducible pattern change from the 1 × 1 structure at the close distance to the 2 × 1 structure at the near distance, but we could not observe the reproducible change from the 2 × 1 structure at the near distance to the 1 × 1 structure at the relatively far distance within the distance capable of atomic resolution imaging. These results obtained for the Si(100) 1 × 1:2D-dideuteride surface are consistent with those obtained for the Si(100) 1 × 1:2H-dihydride surface [26]. These experimental results suggest that the original 1 × 1-canted structure induced by repulsive force between adjacent deuterium (or hydrogen) atoms seems to be somewhat unstable.

To explain these tip-sample distance dependences of the NC-AFM images, we considered the effect of attractive force between the tip apex atom and the nearest deuterium (or hydrogen) atom on the sample surface. At relatively far distance, the magnitude of the attractive force between the tip apex atom and the nearest deuterium (or hydrogen) atom is smaller than that of the repulsive force between adjacent deuterium (or hydrogen) atoms. In this case, the original 1 × 1-canted structure is stable even under NC-AFM measurement. Thus the NC-AFM image shows the original 1 × 1-canted structure at relatively far distance. However, at near distance, the magnitude of the attractive force seems to become nearly equivalent to that of the repulsive force. As a result, the attractive force pulls up the nearest deuterium (or hydrogen) atom, and acts as a trigger to induce novel self-organized 2 × 1 structure [26]. Thus the NC-AFM image shows the tip-induced novel self-organized 2 × 1 structure. At close distance, the magnitude of the attractive force seems to become larger than that of the repulsive force. As a result, the attractive force pulls up the nearest deuterium (or hydrogen) atoms one by one. Tip-induced vertical displacement of each deuterium (or hydrogen) atom due to pulling up appears to be sufficiently large compared with the corrugation of the novel self-organized 2 × 1 structure, and hence the tip-induced novel 1 × 1 structure is imaged by the NC-AFM. Thus using the NC-AFM we can control atomic force and the positions of atoms by approaching the tip apex atom close to the sample surface atoms.

F. Atom Manipulation by Near-Contact Atomic Force Microscope

The NC-AFM succeeded in a kind of atom manipulation at RT such as extraction of single Ag atom from Si(111)\(\sqrt{3} \times \sqrt{3}\)-Ag sample surface [25], and Sb atoms from Si(111) 5\(\sqrt{3}\) \(\times\) 5\(\sqrt{3}\)-Sb sample surface [27]. In these experiments, the extracted Ag or Sb atom attached to the tip apex, and hence played a role as a novel tip apex atom to control atomic force. We also tried extraction of a selected single Si atom from Si(111)\(7 \times 7\) sample surface using LT-NC-AFM at low temperature as shown in Fig. 15. Here, both the tip and sample surface were electrically grounded to suppress the effect due to the electric field. After NC-AFM imaging as shown in Fig. 15 (a), by applying a square voltage to the z-piezo, we mechanically
indented a selected Si adatom on Si(111) 7 × 7 sample surface toward the tip apex Si atom up to some distance $Z$ as shown in Fig. 15 (b). Then by retracting the sample surface down to the initial distance, we again imaged the sample surface using NC-AFM as shown in Fig. 15 (c). When we cannot observe signs of atom extraction, we again indented the selected Si adatom on the sample surface toward the tip apex Si atom up to a little deeper distance $Z$. By repeating such procedure, we succeeded in extraction of a single Si adatom on Si(111) 7 × 7 surface mechanically at 9.3 K. Figures 16 (a) and (b) are NC-AFM images before extraction and after extraction, respectively. By comparing Fig. 16 (b) with Fig. 16 (a), it is clear that a selected single corner Si adatom was mechanically extracted at low temperature of 9.3 K. By the slow indentation method using a slowly increasing voltage applied to $z$-piezo, we also succeeded in extraction of a selected Si adatom as shown in Figs. 17 (a) and (b) even at 78 K [28]. Furthermore, by indenting the Si tip apex to the created Si adatom vacancy, we succeeded in repair of the created Si adatom vacancy by Si atom deposition as shown in Figs. 17 (b) and (c) at 78 K [28].

In case of Ag extraction [25], the tip apex Si atom with a dangling bond will cut an Ag-Si covalent bond and will pick up the Ag atom from Si(111) $\sqrt{3} \times \sqrt{3}$-Ag sample surface. This is a kind of rearrangement of Ag-Si covalent bond. On the other hand, in case of Sb extraction from Si(111) $5\sqrt{3} \times 5\sqrt{3}$-Sb sample surface [27], the tip apex Si atom with a dangling bond will cut three Sb-Si covalent bonds and will pick up the Sb adatom. Thus such extraction process will increase the number of dangling bond on the sample surface. Besides it seems that Sb adsorbed Si
tip works as an Sb tip with a lone pair and three Sb-Si back-bonds on the Si tip apex [27]. Thus the Sb extraction process seems to be complicated. Similarly, in case of Si extraction shown in Fig. 18 (a), the tip apex Si atom with a dangling bond will cut three Si-Si covalent bonds and will pick up the Si adatom from Si(111)-7 × 7 sample surface. Thus extraction process such as Fig. 18 (a) will also increase the number of dangling bond on the sample surface. In these discussions, we assumed atom extraction due to pull-up process indicated by Fig. 18 (b). But there is another possibility that is atom extraction due to push-out process indicated by Fig. 18 (b). In this process, mechanical energy due to atomic indentation under weak repulsive force will increase atom potential and may finally cut three covalent bonds and then push out a single atom. We explored such near-contact (or close-contact) phenomena in more detail by the slow indentation method using a slowly increasing voltage applied to z-piezo. As a result, we found slow decrease of the oscillation amplitude and nonlinear variation of the frequency shift as a function of the sample displacement towards the tip apex as shown in Fig. 19 [28]. Slow decrease of the oscillation amplitude clarifies that the repulsive force works between the tip and sample surface, and that the push-out process contributes to the Si adatom extraction. Further, we found that the extraction due to indentation occurred at the position where a discontinuity of the frequency shift was observed. Plateaus like stage and steeper slope stage may correspond to surface phenomena such as elastic and plastic deformation on an atomic scale, and/or destruction of Si-Si covalent bonds.

IV. CONCLUSIONS

The STM is the first generation of the atom manipulation tool [2]. However, the STM is the microscope based on the electronic method that measures the tunneling cur-
FIG. 19: Plot showing the evolution of the oscillation amplitude of the cantilever (open symbols) and the variation, respect to the initial value, of the normalized frequency shift (solid symbols) when approaching the sample towards the tip during the removal process of a Si corner adatom (squares) and a Si central adatom (circles) of the Si(111)-7 × 7 reconstruction due to soft nanoindentation processes [28].

rent between the tip apex atom and surface atom. Therefore the STM has inherent limitations as follows: The STM cannot observe insulator surface, cannot manipulate atoms and molecules on insulator surface, and cannot measure atomic force or force related information. On the other hand, the AFM is the microscope based on the mechanical method that measures the atomic force or force related information between the tip apex atom and the surface atom, and has potentials for insulator surface observation with atomic resolution, manipulation of atoms and molecules on insulator surface, and measurement of atomic force or force related information on an atomic scale. Until now, the NC-AFM has achieved true atomic resolution on various kinds of surfaces such as metal [7, 15, 29], semiconductor and insulator [30, 31] surfaces. Besides NC-AFM has succeeded in three-dimensional mapping of atomic force, control of atomic force and atom position, measurement of surface strain with subatomic resolution, discrimination (or identification) of atomic force mechanisms and atom species, and imaging of point charge and charge distribution with atomic resolution [27, 32-33]. Further, the NC-AFM based method succeeded in a kind of atom manipulation even at RT such as extraction of single Ag atom from Si(111)√3 × √3-Ag sample surface and Sb atoms from Si(111)5√3 × 5√3-Sb sample surface. The NC-AFM based method also achieved in extraction of a selected single Si adatom from Si(111)7 × 7 and then achieved in repair of the created Si adatom vacancy at low temperature. Thus, this review paper summarizes the status of the art and the future possibility of the NC-AFM [34].

Acknowledgments

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