ATOMIC MANIPULATION AND IDENTIFICATION USING NONCONTACT ATOMIC FORCE MICROSCOPE

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ABSTRACT
A noncontact atomic force microscope operated at low-temperature is used for vertical manipulation of selected single atoms from the Si(111)7×7 surface. The strong repulsive short-range chemical force interaction between the closest atoms of both tip apex and surface during a soft nanoindentation leads to the removal of a selected silicon atom from its equilibrium position at the surface without additional perturbation of the 7×7 unit cell. Deposition of a single atom on a created vacancy at the surface is achieved. These manipulation processes are purely mechanical, since neither bias voltage nor voltage pulse is applied between probe and sample.

1. INTRODUCTION
In Nanotechnology, the fascinating capability of manipulating single atoms and molecules with atomic scale precision is the very important function. So far, as a tool, only the STM has been used, and various techniques have been developed for nanostructuring: vertical manipulations and lateral manipulations with different mechanisms of pushing, pulling, and sliding. However, there is a technical limit in ability of the atom manipulation using the scanning tunneling microscope (STM), because it uses the tunneling current and hence can’t observe the insulators. Furthermore, the STM can’t measure the force, which is the very useful information acting between the tip and the surface. On the other hand, noncontact atomic force microscope (NC-AFM) has the capability for resolving the atomic features on surfaces including insulators, because it uses the force. So, NC-AFM is required to most effectively apply as a powerful science tool in the manipulations of atoms and molecules. However, there is no report of the atom manipulation using NC-AFM.

In the present experiment, we succeed in removing the adatoms from the surface and depositing the atoms onto Si(111)7×7 surface using NC-AFM. Further, we discuss the mechanism of the atom manipulation.

2. EXPERIMENTAL
The experiments were performed using a home-built low-temperature (LT) ultrahigh vacuum (UHV) NC-AFM [1]. NC-AFM was operated in the frequency modulation detection scheme, and constant excitation mode was used for oscillating low resistivity commercial n-doped silicon cantilevers with a typical spring constant of 48 N/m and first harmonic mechanical resonant frequency of 160 kHz. Before cooling down to LT and starting the experiments, both cantilever tip apex and sample surface were prepared in situ. Clean Si(111)7×7 surface was obtained from a n-type As doped single crystal Si wafer by direct current heating. The Si tip apex was carefully cleaned up by argon-ion bombardment. The experiments were conducted at 78 K tip and sample temperature. During the experiments, both tip and sample were always electrically grounded.

For the mechanical vertical manipulation of selected single atoms, the following sequence of steps was applied. After taking an atomically resolved image over a region centered on one terrace of the surface, a specific atom of the imaged area was selected for being manipulated. The tip was positioned directly above it and a soft nanoindentation was applied. The nanoindentation was performed with the feedback loop disconnected ramping the sample towards the oscillating tip at a typical rate value of 0.3 Å/sec from the tip-sample distance at which the initial image was acquired. Since the cantilever was
oscillating at its first resonant frequency, multiple nanoindentation processes were taking place during the sample approach, one per oscillation cycle. The nanoindentation process was carefully controlled by monitoring simultaneously both the variations of the cantilever oscillation amplitude and the cantilever frequency shift. Upon further indentation, a sudden jump in the frequency shift was normally detected. At this point, the ramp applied for moving the sample was stopped, the sample was retracted to the initial position, and the feedback was reactivated at the same frequency shift set point value used for the initial image acquisition. Finally, the surface was imaged again with the same parameters used for taking the initial image.

3. RESULTS AND DISCUSSIONS

An example of the result of applying this experimental procedure to Si adatoms of the Si(111)7×7 reconstruction is shown in Fig. 1. The selected Si corner adatom marked with a circle in Fig. 1(a) was removed from its initial position at the surface and a vacancy was created without additional perturbation of the Si(111)7×7 unit cell [Fig. 1(b)]. This fact implies that at least three strong covalent bonds that fixed the Si adatom to the surface were broken during the nanoindentation. Successive mechanical manipulations can be performed over nearby adatom positions as shown in Fig. 1(c), where the corner adatom placed in the neighbor 7×7 unit cell, and marked with a circle in Fig. 1(b), was successively removed.

Previous STM works on manipulation of the bare Si(111)7×7 surface pointed to a thermally activated field ion emission due to a high electric field between tip and sample during the application of a voltage pulse [2] as the mechanism for removing single Si adatoms at RT. This could be also the mechanism for the modification of the Si(111)7×7 surface performed with LT NC-AFM by applying a voltage pulse between probe and sample recently reported by Sugawara et al. [3]. An alternative mechanism was proposed by Stipe et al. for the LT lateral displacement manipulation experiments of single Si adatoms performed by STM, where tunneling electrons from the STM tip occupying temporarily a surface resonance state could play a fundamental role. Nevertheless, the experiments presented in this work suggest that a completely different mechanism for manipulating Si adatoms is involved since neither bias voltage nor voltage pulse was applied between probe and sample during the manipulation process.

4. CONCLUSION

NC-AFM allows enough precision for performing controlled soft nanoindentations involving the outermost atomic layers of the tip-surface system, that can be used for obtaining information of the local mechanical properties of the atomic bonds and local stress of a surface at atomic level. As a result of these carefully controlled soft nanoindentation processes, a method for vertical manipulation of selected single atoms with NC-AFM is proposed. This method is based only on short-range chemical interaction forces since neither bias voltage nor voltage pulse is applied between probe and sample.

FIG. 1. Sequence of topographic images showing two mechanical single atom vertical manipulation processes performed successively over the selected atomic positions of the Si(111)7×7 surface marked with a circle in (a) and (b), respectively, by using NC-AFM. As a result, two vacancies were created at the selected atomic positions (c). Image size is 66×66 Å². Cantilever oscillation amplitude was 665 Å and frequency shift reference value was -1 Hz for all the images.

REFERENCES