Intrinsic reconstruction of ice-I surfaces

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Understanding the precise atomic structure of ice surfaces is critical for revealing the mechanisms of physical and chemical phenomena at the surfaces, such as ice growth, melting, and chemical reactions. Nevertheless, no conclusive structure has been established. In this study, noncontact atomic force microscopy was used to address the characterization of the atomic structures of ice Ih(0001) and Ic(111) surfaces. The topmost hydrogen atoms are arranged with a short-range (2 × 2) order, independent of the ice thickness and growth substrates used. The electrostatic repulsion between non–hydrogen-bonded water molecules at the surface causes a reduction in the number of the topmost hydrogen atoms together with a distortion of the ideal honeycomb arrangement of water molecules, leading to a short-range–ordered surface reconstruction.

INTRODUCTION

The atomic structure of the surface of a crystal solid is difficult to determine, even if the bulk structure is perfectly identifiable. The lack of adjacent atoms or molecules at a truncated surface destabilizes the atomic structure of the ideal (bulk-like) surface, which can cause surface reconstruction (i.e., modification of the atomic position, periodicity, and chemical composition of the surface). Identifying the surface structure at subnanoscale is the first step in understanding the characteristic chemical and physical properties exhibited at the surface. However, the surface structures of ice—a ubiquitous solid—are still not well-understood.

The presence or absence of the surface reconstruction of ice Ih, which is a representative phase of crystalline ice that appears below the normal pressure (1), is still controversial. In the ideal surface of ice Ih(0001), the O atoms of water molecules form a buckling hexagonal lattice, namely, a bilayer (BL). In bulk ice Ih, H atoms have various possible arrangements, even under the “Bernal-Fowler rules” (2). At the ideal surface, non–H-bonded H atoms directed toward the vacuum (dangling H atoms) are not perfectly ordered but rather are randomly distributed over the top position of 50% of the topmost O atoms (Fig. 1, A and B). Previous diffraction studies showed (1 × 1) patterns and proposed that the ideal structure was preserved (3, 4), whereas several spectroscopic experiments indicated the existence of surface reconstruction (5–8). The atomic structure of the ice surface has not been identified despite intensive surface-sensitive experimental measurements (9–11).

To resolve this serious discrepancy, scanning probe microscopy can provide complementary information to the above-mentioned studies. Although scanning tunneling microscopy (STM) is widely used for the atomic-scale imaging of thin water films (12, 13), it cannot be applied to insulating thick ice. Alternatively, noncontact atomic force microscopy (ncAFM) should be suitable because it can probe insulating materials with atomic resolution (14), and it is advantageously sensitive to dangling H atoms at surfaces (15–17). Although constant-height ncAFM imaging with a carbon monoxide–functionalized tip (18) helps visualize individual water molecules in ultrathin water films on metal surfaces (19–21), thick ice layers fully covered in a substrate disable the tip apex from well-controlled functionalization. A previous ncAFM study with a quartz tuning-fork sensor did not report atomic resolution for thick ice layers grown on Pt(111) (22). Therefore, an optimal force sensor is required to visualize the atomic structures of ice surfaces. Using a Si cantilever with an optical interferometer (23–25), which has greater sensitivity in its interatomic force detectability, is one of the best solutions. Using this force detection method, we conducted ncAFM at 85 K and realized atomic-resolution imaging of ice-I surfaces (Fig. 1C).

RESULTS

Visualization of ice-I surfaces

To grow single-crystalline ice layers, we used two types of typical substrates: single-crystalline Rh(111) and Pt(111) (figs. S1 and S2).
On Rh(111), ice layers were grown like hexagonal pillars with a difference in height (Fig. 2A), whereas ice layers homogenously covered the Pt substrate (Fig. 2D) in good agreement with the literature (26–29). In contrast to the morphological difference, ncAFM images of the terraces for both ice layers show a rather similar appearance (Fig. 2B for Rh and Fig. 2E for Pt). The protrusions in the topographic images reflect an attractive interaction between the tip and sample; thus, they correspond to the positions of the atoms protruded toward the vacuum, i.e., dangling H atoms (15–17). The H atoms appear to be randomly distributed, just as on the ideal surface (Fig. 1B); however, careful analysis of the AFM images shows the following characteristics and reveals that the surface was reconstructed.

1) Reduction in the number of dangling H atoms. According to the atomic-resolution images shown in Fig. 2 (B and E), the densities of dangling H atoms were calculated to be 1.2 and 1.5 atoms/nm², respectively, and their values are approximately half of the density for the ideal surface (2.8 atoms/nm²). The dangling H atoms at these surfaces are more sparsely distributed than those at the ideal surface (Fig. 1B).

2) Short-range (2 × 2) order of dangling H atoms. Although the protrusions in the AFM images seem disordered, the corresponding self-correlation (SC) images exhibit a blunt hexagonal pattern (Fig. 2, C and F). This indicates a short-range order of dangling H atoms. The hexagonal arrangement of the spots suggests that single-crystalline ice was grown in accordance with the substrate atomic lattice (4, 30). The distance of the spots from the center is 0.9 nm for both samples, which is twice that of the O lattice of the ideal ice-Ih(0001) surface (0.446 nm). The (2 × 2) order reasonably explains half the H-atom density relative to the ideal surface. A weak (2 × 2) pattern was previously observed in a diffraction study (4), which is likely ascribed to this H-atom order at the surface (see the Supplementary material).

3) Distortion of the O lattice. The protrusions in the images cannot overlap the ideal honeycomb mesh of the O atoms, implying that the ideal lattice of honeycomb O atoms at the surface was distorted. The blunt hexagonal pattern in the SC images was reproduced by a slightly displaced array of spots rather than the perfect (2 × 2)–arranged spots (fig. S7). Note that the (1 × 1) diffraction patterns in the previous diffraction studies (3, 4) probably reflect the distorted O lattice (see the Supplementary material).

As shown in Fig. 2, we confirmed that the atomic structure of ice-Ih surfaces is independent of the growth substrates. Furthermore, we observed ice surfaces with various thicknesses on both substrates (Fig. 3) to clarify the effect of the BL stacking manner (i.e., in the comparison between ice Ih and Ic) and H-atom orientation in the bulk (the comparison between para- and ferroelectricity) on the surface reconstruction. In general, ice-Ih exhibits paraelectricity because of the disorder of the H-atom orientation (Fig. 1A). Ice on Rh(111) retains its intrinsic property (7, 26, 27); however, at the ice-Pt(111) interface, H atoms tend to point toward the substrate, causing ferroelectricity (9, 29). The polarization of the H-atom orientation...
decays with the ice BL distance from the interface (9, 29). Moreover, the crystalline phase of ice grown on Pt(111) can change, depending on the thickness (22, 31); ice-Ic layers form at medium thicknesses (10 to 50 BLs), whereas ice-Ih layers dominate at other thicknesses (the top panel of Fig. 3; see also fig. S3). Despite the difference in the properties of the bulk, the image appearance is quite similar at any thickness of the ice layer grown on either Rh or Pt substrate, and the corresponding SC image exhibits a (2 × 2) order (figs. S4 to S6). The density of dangling H atoms that was calculated from the topographic ncAFM images (Fig. 3) is independent of the ice thickness and substrate (~1.4 atoms/nm²). This result indicates that surface reconstruction is common between ice-Ih(0001) and Ic(111) and robust against changes in the H-atom orientation in the bulk and all interface effects.

Plausible structural models
The three characteristics mentioned above are not fulfilled by the existing structural models of ice Ih(0001) (32–34). The information from the ncAFM images is not sufficient to fully determine the molecular geometries and coordinates at the surface because the O lattice is invisible. Nevertheless, we proposed new structural models for future validation via theoretical calculations. On the basis of the positions of dangling H atoms in an ncAFM image of ice Ih (Fig. 4A), we simulated the displacement of O atoms from the ideal honeycomb lattice (Fig. 4B, green) and constructed two possible models (see Materials and Methods): distorted O lattices without and with heptagonal and pentagonal rings (Fig. 4, C and D, respectively). In these models, we assume that several of the topmost O atoms are located beneath the dangling H atoms (Fig. 4, C and D, red), while the other O atoms are separated from the three neighboring O atoms with proper interatomic distances and angles (Fig. 4, C and D, blue). In the former model (Fig. 4C), the hexagonal network is maintained to the greatest degree possible, which enables the layer to be effectively matched with the underlying layer. However, the origin of the lattice distortion cannot be interpreted from this model. Pedersen et al. (35) theoretically proposed that water molecules at an ice-Ih(0001) surface rotate exothermically to eliminate the dangling H atoms, and this process causes the distorted O lattice with heptagonal and pentagonal rings near the rotated water molecule. The observed surfaces can be interpreted as the result of such a reordering process dominating throughout the surface, causing the number of H atoms to be reduced by half. Therefore, the latter model (Fig. 4D) is more plausible; the hexagonal lattice is mostly maintained, while the rearrangement of the water molecules to reduce dangling H atoms creates a limited number of defects.

DISCUSSION
We conclude that the reconstruction of the ice-I surfaces originates from the electrostatic repulsion between the dangling H atoms. Several theoretical studies (32–35) proposed that the electrostatic repulsion between partially charged H atoms plays an important role in the surface structure. The repulsion can be eliminated either by removing of the dangling H atoms (34, 35) or by sparsely distributing the residual dangling H atoms (33). Both effects are responsible for the formation of the (2 × 2) H-atom order. The independence of the atomic structure from ice thickness and growth substrate implies that this structure is universal for crystalline-ice surfaces. The reconstruction of the molecular arrangement would play a crucial role in the chemical and physical phenomena occurring at the surfaces, such as melting, ice growth, and chemical reactions (10, 36, 37).

MATERIALS AND METHODS
Materials
We used single-crystalline Pt(111) and Rh(111) substrates (MaTeCk) to grow crystalline ice under ultrahigh vacuum (UHV) conditions. The Pt (Rh) substrate was cleaned by several cycles of annealing at 1200 K and Ar⁺ sputtering at 850 (800) K, followed by annealing at 950 (900) K under O₂ pressure to remove contaminant C atoms from the surface. The growth of crystalline ice was performed by dosing H₂O gas onto the clean substrate. Ultrapure H₂O was purified via freeze-and-pump cycles, and the gas was injected into the UHV chamber through a tube nozzle, which is separated from the substrate by 10 cm. For ice on the Pt (Rh) surface, the deposition rate was 3 (2) BL/min, and the substrate temperature was maintained at 145 (141) K. In addition, the samples were postannealed. Although we observed several samples under different postannealing parameters (temperature of 110 to 120 K and duration of 10 min to 10 hours), the results were identical.

Experimental methods
All the experiments were performed in a UHV chamber under a pressure of 5.0 × 10⁻¹⁰ torr at 85 K (UNISOKU-based custom-built ncAFM/STM). The details of the system were described elsewhere (38). The STM observation was performed with a PtIr tip (UNISOKU)
in constant current mode. The ncAFM measurements were conducted in frequency modulation mode using Si cantilevers (BudgetSensors). Typical values of the stiffness $k$, eigenfrequency $f_0$, and $Q$ factor for the cantilevers were 30 N/m, $3 \times 10^6$ Hz, and $1 \times 10^3$, respectively. The oscillation of the cantilever was measured by an optical interferometer. We note that the signal-to-noise ratio in our Si cantilever-based ncAFM is larger than that in the quartz tuning fork sensor (qPlus)–based ncAFM by two orders of magnitude (23). Oscillation amplitude $A$ of the cantilever was kept at 10 nm during the measurement. The ncAFM images were obtained in constant frequency-shift mode. The set point for each image was described as the normalized frequency shift

$$\gamma = \frac{kA^3}{f_0} \Delta f$$

where $\Delta f$ denotes the frequency shift. To minimize the long-range electrostatic force, the average contact potential difference was compensated by applying a bias voltage to the sample during the ncAFM measurement.

**Method for obtaining the atomic structural models of the ice-Ih(0001) surface**

The structure models shown in Fig. 4 (C and D) were constructed by the following procedure:

1) An ideal honeycomb O-atom lattice was superimposed on the ncAFM image (Fig. 4B, green).

2) The positions of dangling H atoms were determined from the protrusions in the ncAFM image (Fig. 4, A and B, red).

3) We assumed that a dangling H atom was located just above the nearest neighboring O atom (O$_{NN}$) on the surface BL. Then, O$_{NN}$ for each dangling H was uniquely assigned.

4) This process was skipped for the model without heptagonal and pentagonal rings (Fig. 4C) but was considered for the model with heptagonal and pentagonal rings (Fig. 4D). A Stone-Wales defect (fused 5–7–7–5–membered rings) in the ideal honeycomb lattice was assumed to be located near a dangling H atom. This defect was adopted only when the position of O$_{NN}$ became closer to the dangling H atom than in the absence of the defect.

5) The next-nearest neighboring O atoms for each dangling H (O$_{NNN}$, i.e., three O atoms directly bonded to O$_{NN}$ via hydrogen bonding) were placed around an O$_{NN}$ atom with the ideal O–O length and bonding angle.

6) The positions of O$_{NN}$ and O$_{NNN}$ were fixed. The other O atoms were displaced from the original positions so that each O atom was located at the weight center of its three neighboring O atoms. We repeated this process 10 times.

7) The positions of O$_{NN}$ were fixed. The other O atoms (including O$_{NNN}$) were displaced from the original positions so that each O atom was located at the weight center of its three neighboring O atoms. This operation resolved the large distortion of the bonding between O$_{NNN}$ and its neighboring atoms. We repeated this process until the position of all the O atoms become stable.

We varied the lateral positions of the initial honeycomb structure over the ncAFM image (Fig. 4B) and executed the model calculations. As the most reasonable result, we adopted the atomic structures with the smallest dispersion of bonding angles between O atoms (Fig. 4C).

Processes 5 and 6 ensure that oxygen atoms near dangling H atoms (i.e., O$_{NN}$ and O$_{NNN}$) are as undistorted as possible. We imposed these conditions to express that the distortion was increased in regions where dangling H atoms disappeared due to the rotation of the water molecules (35).

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/37/eabb7986/DC1

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