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Load dependence of the frictional-force microscopy image pattern of the graphite surface

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We find a remarkable transition of the frictional-force microscopy image pattern of a graphite surface depending on the load. This transition is observed in both simulations and experiments. Based on the Tomlinson mechanism, the image transition can be explained as the change of the size and shape of the stable region of the cantilever basal position. [S0163-1829(98)03704-7]

Frictional-force microscopy (FFM)[1] has proved its usefulness in understanding the basic friction mechanism between a single asperity and an atomically flat surface. So far many theoretical studies discussed the mechanism of atomic-scale friction appearing during the scan process of FFM.[2–6] Recently many theoretical simulations[7–17] based on the Tomlinson model[18] have been performed in order to study the two-dimensional feature of the scan process of FFM, and to interpret the FFM image pattern. The effects of the cantilever stiffness, scan direction, and anisotropy of the cantilever on FFM image pattern have been investigated. However, the load dependence of FFM image patterns has not yet been discussed. Therefore, the aim of this paper is to compare the load dependent simulations with the experimental data, and to clarify that the Tomlinson model can describe reasonably the load dependence of friction in an atomic scale.

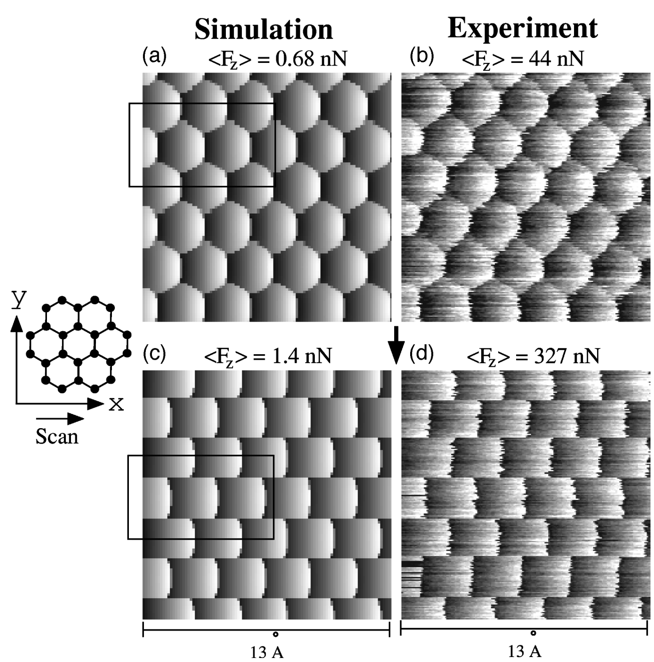

FIG. 1. FFM images of F_x/k_x obtained by (a), (c) theoretical simulations and by (b), (d) experiments with a cantilever scanned in the x direction.

Figures 1(a)–1(d) show the comparison between the simulated and the experimental FFM images of F_x/k_x under the constant-height and the repulsive-force modes. The atomistic model of FFM is represented by a single-atom tip connected to a cantilever and a rigid monolayer graphite surface. The detailed condition of the simulation is described in Refs. 13 and 14. Figs. 1(b) and 1(d) are obtained by experiment whose detailed setup is described in Refs. 19 and 20.

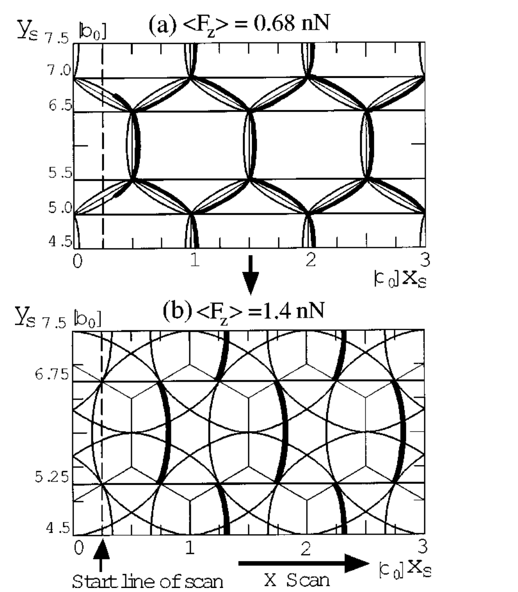

FIG. 2. Thick curves represent analytically predicted fringes of FFM image patterns for $\langle F_z \rangle =$(a) 0.68 nN and (b) 1.4 nN. Solid lines represent C-C bonds of the graphite surface. The start line of scan ($x=0.25c_0$) is also shown by broken lines.

Here (x,y) and (x_s,y_s) are lateral components of the tip atom and the cantilever basal positions, respectively. Both simulated and experimental images are obtained for two different loads $\langle F_z\rangle$. As the cantilever basal position approaches the surface, the average value of F_z, $\langle F_z\rangle$, increases.

It can be clearly seen that simulated image patterns, Figs. 1(a) and 1(c), reproduce fairly well the experimental ones, Figs. 1(b) and 1(d), respectively. In Figs. 1(a) and 1(b), if we emphasize the boundary between the region where F_x/k_x changes from the minimum to the maximum, or from the maximum to the minimum, the zig-zag patterns along the x direction, corresponding to the C-C bond of the graphite lattice, appear. However, as the load increases, this zig-zag pattern perfectly vanishes and only the straight pattern parallel to the scan direction appears as shown in Figs. 1(c) and 1(d). Thus the feature of the simulated image transition reproduces excellently that of the experimental ones. Here, the load of simulation is by two orders of magnitude smaller than that of the experiment. Figures 1(a) and 1(c) of simulated images correspond to the load $\langle F_z\rangle=$(a) 0.675 and (c) 1.4 nN, respectively. On the other hand, Figs. 1(b) and 1(d) of the experimental images correspond to the load $\langle F_z\rangle=$(b) 44 and (d) 327 nN, respectively. The difference of $\langle F_z\rangle$ between the simulation and the experiment is due to the fact that we adopt a single-atom tip model in the simulation.

The physical meaning of these image patterns can be understood by using an analytical method whose idea was first presented by Gyalog *et al.*[9] This method uses a stable equilibrium condition based on Tomlinson model. Figures 2(a) and 2(b) show the boundaries of the stable region of the cantilever basal position. Especially thick curves denote analytically predicted fringes of FFM image patterns between the bright and the dark area. These thick curves are exactly some sections of the boundaries of the stable regions. It is clarified that zig-zag patterns in Fig. 2(a) perfectly vanish in Fig. 2(b) because the shape and the size of the stable regions of the cantilever basal position changes depending on the load.

In this work, by using both numerical simulation and experiment, we find the load dependence of the FFM image pattern and interpret it by a stable equilibrium condition. This analysis gives a clear explanation to the load dependence of both simulated and experimental FFM images.

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