Vol 10 Suppl., July 2001
1009-1963/2001/10(Suppl.)/0S19-08
Chinese Physics
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and IOP Publishing Ltd

FOURIER ANALYSIS OF TEMPORAL AND SPATIAL OSCILLATIONS OF TUNNELING CURRENT IN SCANNING TUNNELING MICROSCOPY*

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(Received 4 April 2001; revised manuscript received 16 May 2001)

Partially oxidized Si(111) surfaces and surfaces of highly oriented pyrolytic graphite (HOPG) were studied by two different ultrahigh vacuum scanning tunneling microscope (UHV-STM) systems and by an STM system working under ambient conditions, respectively. The STM current images of partially oxidized Si(111) surfaces and HOPG surfaces were analyzed by one/two-dimensional fast Fourier transformation (1D-FFT/2D-FFT). The phenomenon of temporal oscillations of tunneling current on the partially oxidized Si(111) surfaces was detected with both UHV-STM systems. Temporal as well as spatial oscillations of tunneling current appeared in highly resolved STM current images of the Si(111) surfaces simultaneously, but both kinds of oscillations could be discriminated according to their different influence on the 2D-FFT spectra of the current images, while varying the scanning range and rate. On clean HOPG surfaces only spatial oscillations of tunneling current induced by the surface structure were observed.

Keywords: scanning tunneling microscopy, pyrolythic graphite surface, silicon(111) surface
PACC: 0779, 6800, 7300

I. INTRODUCTION

Since its invention by Binnig, Rohrer and their coworkers in 1981,[1] scanning tunneling microscopy (STM) has developed to an invaluable surface analytical technique, allowing the investigation of surface structures on the atomic scale and the local measurement of *I-V* curves. Many measures have been taken to isolate STM systems from vibrations at the environment.[2] Very sensitive and stable electronic circuits have been designed for the detection of weak tunneling current from nA to fA. However, characteristic fluctuations of the tunneling current have nevertheless been observed on surfaces of some conductive materials. These fluctuations may in principle result from an imperfect isolation from external vibrations, from the residual electronic noise in the circuits, or from particular electronic properties of the sample surfaces. Although the former two factors have been excluded, random as well as periodic time-dependent fluctuations have been detected at certain surfaces.

Koch and Hamers *et al.* observed the fluctuations of tunneling currents on in-situ oxidized Si(100) surfaces by STM.[3,4] Large current spikes appeared over a background of smaller fluctuations in STM current images. The frequency spectrum of the weak fluctuations was flat with sharp lines at frequencies of 60Hz and its harmonics. Wider lines were associated with resonance's in the microscope system. These studies demonstrated that the spike-like tunneling current which digitally switches between two characteristic values undoubtedly is a source of the low-frequency 1/f noise that is seen in all metal-oxide semiconductor field-effect transistors (MOSFETs).[5]

Xie and von Blanckenhagen observed temporal oscillations of tunneling current on partially oxidized Si(111) surfaces by STM.[6] It was demonstrated that current oscillations on partially oxidized Si(111) and Si(100) surfaces, appearing in scanning tunneling spectroscopy(STS) spectra and in STM current images, come from the same source.[7] External sources, such as mechanical vibrations or periodic noise generated in electronic circuits of the STM, could be excluded as cause for these current oscillations.[8] These

*Project supported in part by the National Foundation for Natural Sciences and by the Ministry of Education of China as well as by the International Office of the German Ministry of Education and Research.
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oscillations are clearly related to the partial oxidation of the Si surfaces. They also appear when the tunneling current flows through Au nanoclusters deposited on partially oxidized Si surfaces.[6−8] Hence this phenomenon is not only a matter of principle but as well relevant to the development of nanometer-scale electronic systems.

It is an open question why the current fluctuations are periodic in these cases, and not random as in MOSFETs and on entirely oxidized Si surfaces. On the other hand, periodic conductivity oscillations have been measured at several bulk semiconductors,[9] which may as well be caused by intrinsic surface or interface properties. In all cases, current fluctuations seem to be, in some way, related to the existence of electron traps by which the oscillation frequencies could be determined in the case of partially oxidized Si surfaces. Tunneling current oscillations were observed on Au clusters deposited on the surfaces of highly oriented pyrolythic graphite (HOPG)[10] and directly on the HOPG surfaces by other authors.[11]

In this paper the STM current images of clean and partially oxidized Si(111) surfaces, as well as of surfaces of HOPG, are analyzed by one/two dimensional fast Fourier transformation (1D/2D-FFT) methods. The images are measured by three different STM systems. In particular, the occurrence of temporal and spatial oscillations of tunneling current and possibilities of their separation are discussed.

Ⅱ. EXPERIMENTAL

Experiments were conducted with two different ultrahigh vacuum scanning tunneling microscopes (UHV-STM) systems (from Perkin-Elmer and Omicron, respectively) and with an STM system operated at ambient conditions (from Digital Instruments, A-STM). The base pressures in the UHV-STM systems were $< 2 \times 10^{-8}$Pa. The Si(111) samples were cut from commercial wafers, clamped to the sample holder by two Mo plates and heated directly by DC current. The samples were degassed at $\sim$600°C for about 10 hours, and then flashed several times up to 1250°C while maintaining the background pressure $< 1 \times 10^{-7}$Pa. The native oxide layers were removed by this procedure after which the (7×7) reconstruction of the Si(111) surface could be detected by the UHV-STM systems at room temperature. Clean and homogeneous graphite surfaces were prepared by cleaving the HOPG sample several times. Tungsten tips were used in the Omicron UHV-STM, gold tips in the Perkin-Elmer UHV-STM, and Pt-Ir tips in the Digital Instruments A-STM. After application of the flashing procedure, the Si samples were transported to the STM sample stages and oxidized *in situ* by direct doping with oxygen or by keeping the sample in UHV for at least 12 hours. The long-term contamination and oxidation of Si surfaces in UHV were studied by high-resolution electron energy loss spectroscopy (HREELS) and Auger electron spectroscopy (AES). Those results will be published elsewhere. All measurements were done at room temperature. The STM images shown in this paper are not treated by frequency filtering.

Ⅲ. RUSULTS AND DISCUSSIONS

Partially oxidized Si(111) surfaces were first investigated with the Perkin-Elmer UHV-STM system. Figure 1 shows two STM current images and their analysis by 1D-FFT and 2D-FFT. The two images were taken at the same location with a scanning area of 0.01nm×0.01nm and with scanning rates of 3.052Hz and 6.104Hz, while keeping all other scanning parameters unchanged. The scanning range was small in comparison to the lattice parameters of the atomic structure of the surface, so that no current oscillations would be induced by the spatial structure. Figure 1(a) and 1(c) depict STM current images, the distribution of the tunneling currents at the cross-sections, the positions of which are marked by black lines on the images, and the 1D-FFT spectra of the current distribution at the cross-sections. The positions of the cross-sections at the Y-axis of the images are arbitrarily selected, but the cross-sections are strictly parallel to the X-axis, in order to keep them in one scan trace. The 1D-FFT spectra show few high sharp peaks. Because the scan range is so small, the peaks can only be due to temporal current fluctuations. This conclusion is confirmed by the fact that the frequencies of the highest peaks in Figs.1(a) and 1(c) are the same (723.4Hz), although the scan rates were different by a factor of two. The "DC" labels in the 1D-FFT and 2D-FFT spectra refer to "direct current" and indicate the longest space period. The 2D-FFT power spectral display is scaled according to the scan size of the original image. Because the scan size of these images is only 0.01nm, and the minimum space period in the 1D-FFT/2D-FFT spectra is 0.01×2/512 (image pixels 512×512), hence 0.000039 nm are the minimum displayable space period in the 2D-FFT. The 1D-FFT spectra (Figs.1(a) and 1(c)), and the 2D-FFT spectra

(Figs.1(b) and 1(d)) are aligned to each other according to the direct current point DC. For each sharp peak in the 1D-FFT spectra, a corresponding dark straight line parallel to the Y-axis is found in the 2D-FFT spectra. There is no periodic feature along the Y-axis.

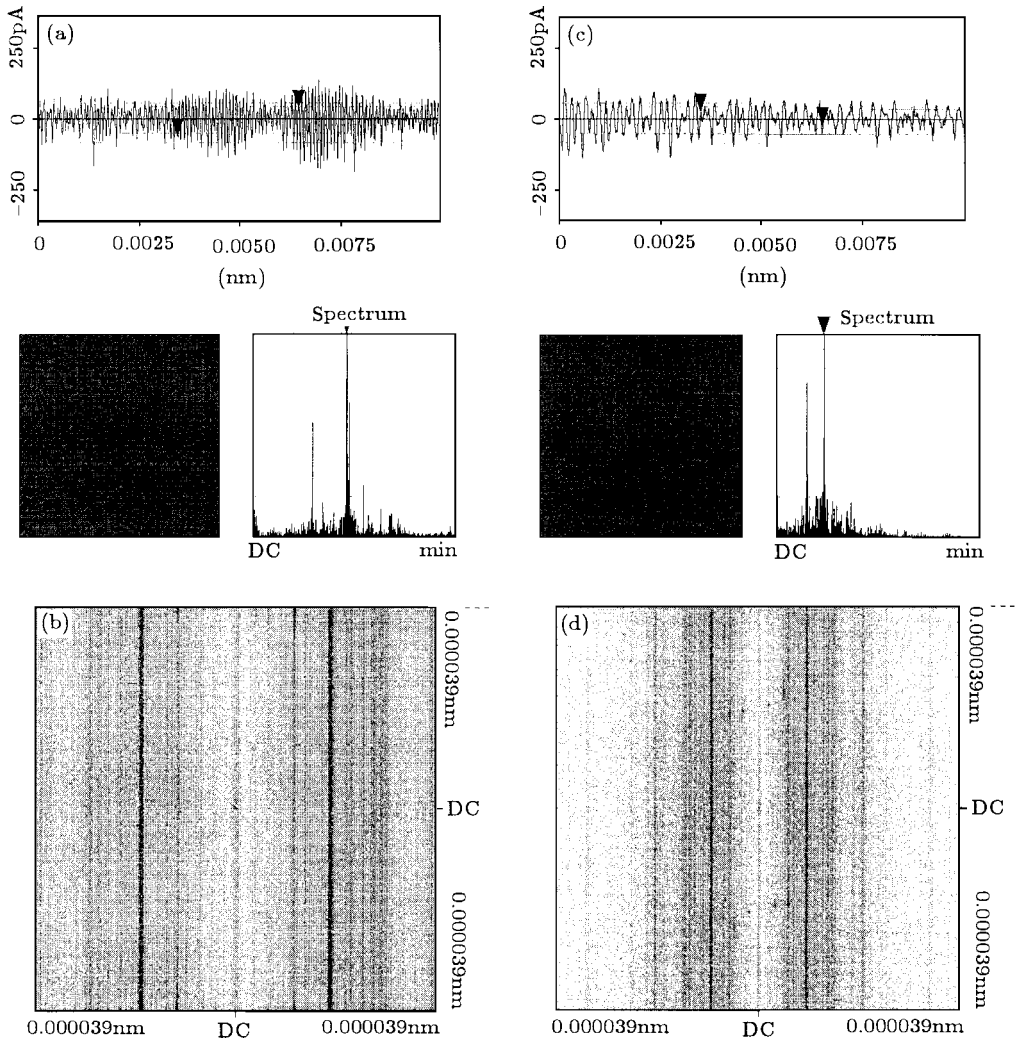


Fig.1. Influence of the STM scanning rate on the behavior of one/two-dimensional fast Fourier transformation (1D/2D-FFT) of the STM current image. The STM current images of a partially oxidized Si(111) surface were measured with two different scanning rates and analyzed by 1D/ 2D-FFT spectra. In Figs.1(a) and 1(c), STM current images measured with 0.01nm scan range are shown together with the traces of tunneling current distribution (top) taken at the cross sections marked on each STM image by the black lines, and the 1D-FFT spectra of the current distribution along the lines (right). In Figs.1(b) and 1(d), the 2D-FFT spectra of the STM current images are presented. The scanning rates were 3.052Hz (a) and 6.104Hz (c). The other parameters were the same for both images: bias 2.00V, set point 288.6pA, scan range 0.01nm.

Figures 2(a) and 2(b) illustrate two atomically resolved STM height images taken at the same location, but with scan areas of 200nm×200nm and 100nm×100nm, respectively. The images were taken with the Perkin-Elmer UHV-STM after the sample had been kept in UHV for at least ∼12 h after final flashing. The scan parameters except for the scan ranges were the same for both images. In this case the surfaces were partially covered with adsorbates, and hence the contrast of the images was weak. The 2D-FFT power spectra of the corresponding current images are shown in Figs.2(c) and 2(d), respectively. The pattern of the dark points represent the (7×7) reconstruction of the Si(111) surface. The (7×7) patterns in the 2D-FFT spectra are displayed on different scales, since the scan range was different for both im-

ages. Besides the point patterns corresponding to the reciprocal lattice of the (7×7) reconstruction, there are some single straight lines, and some pairs of lines parallel to the Y-axis. The two 2D-FFT spectra are arranged according to the locations of the "DC" position. The darkest lines in both 2D-FFT spectra are equidistant, although the scan ranges are different for both measurements. This result demonstrates clearly again the existence of temporal tunneling current oscillations. 1D-FFT spectra of these two current images yield a frequency of 723.4Hz for both darkest lines.

When the scanning range is larger than two unit cells of the surface structure, tunneling current oscillations could be induced by the periodical structure due to the incomplete decoupling of the height and current signals by the STM during scanning. Sharp peaks in the 1D-FFT spectra would appear and be related to the spatial periods and the scan rate. The frequency f[Hz] of such spatially induced current oscillation is given by

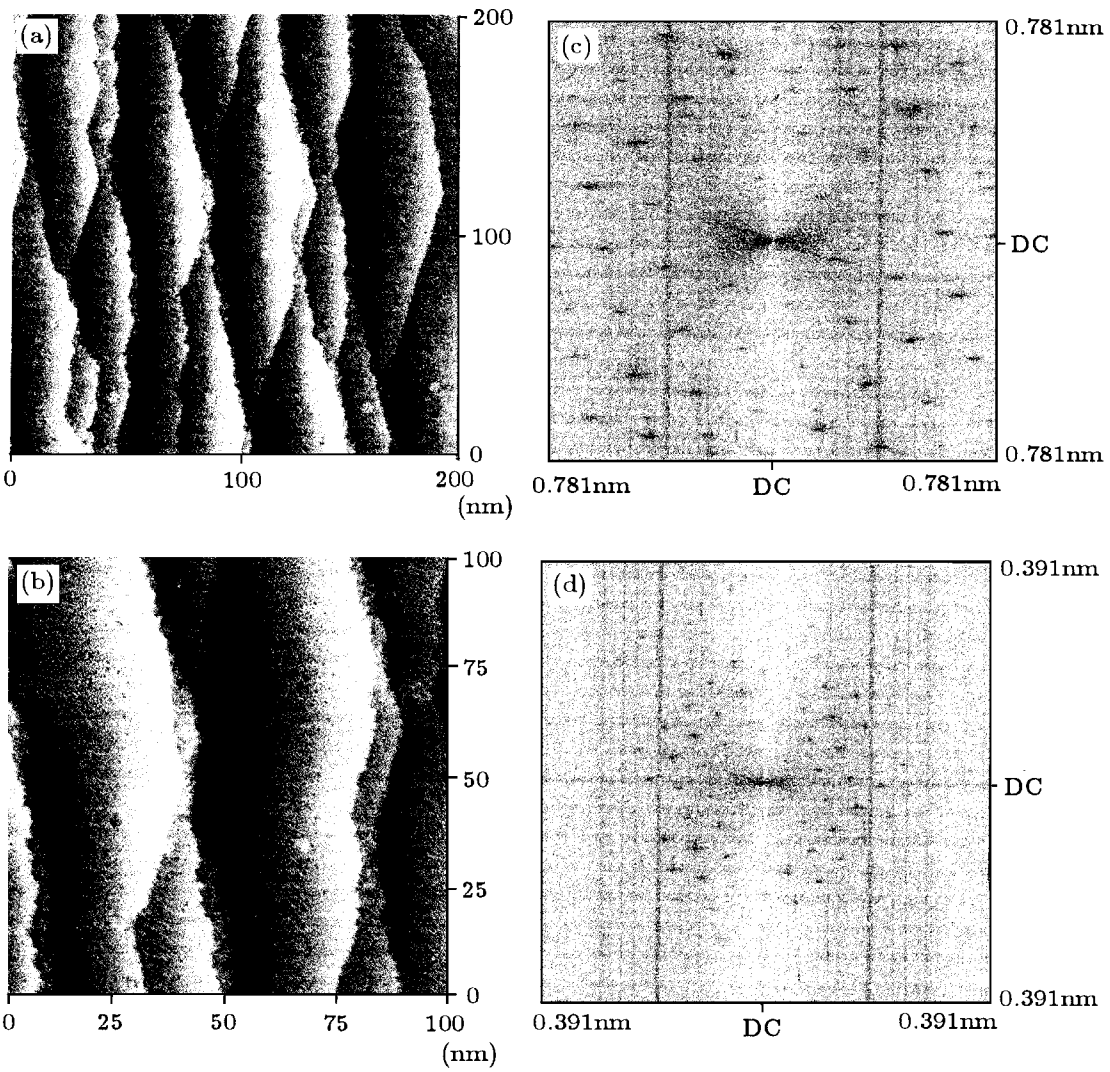


Fig.2. Comparison of two STM height images of a partially oxidized Si(111) surface measured at the same location with different scanning ranges ((a) 200nm and (b) 100nm), and 2D-FFT spectra of the corresponding current images ((c) and (d)). Scanning parameters are bias 2.00V, set point 192.8pA, scanning rate 3.052Hz.

$$f = 2d_{\mathrm{x}}r/d_{\mathrm{p}}$$

where d_{x} [nm] represents the scanning range, r[Hz] the scanning rate, and d_{p} [nm] the spatial period. If the lateral resolution of the STM is sufficient, the FFT spectra of the current images will show peaks at the frequency f and its harmonics as shown below.

Comparative 2D-FFT spectral analyses were per-

formed for the STM current images of HOPG surfaces in order to show the different behavior of real temporal and induced spatial tunneling current oscillations. Figures 3(a) and 3(b) represent two STM current images of the HOPG surface scanned with the A-STM in an area of 10nm×10nm with rates of 3.052Hz and 1.969Hz, respectively. Because the STM tip was not at optimal condition adequate for detecting atomically resolved images, the current images did not show atomic resolution, however clear oscillations of the tunneling current were present. The 2D-FFT spectra of these two current images are depicted in Figs.3(c) and 3(d), showing features due to current oscillations induced by the surface structure. The two 2D-FFT spectra are aligned to each other at the position of "DC". Two pairs of straight lines appear in each 2D-FFT spectrum. Each line in either 2D-FFT spectrum corresponds to a line in the spectrum. Although the scan rates when measuring these two images were different, the positions of the pairs of lines in the two spectra did not change. As already explained in connection with Fig.1, the 2D-FFT spectral display is scaled according to the scan range of the corresponding image. But as expected, the spatially induced periods of the current oscillation did not vary after the scan rate was changed. The oscillations of tunneling current in this case are directly related to the periodic structures of the HOPG surface, although the structure is not clearly resolved.

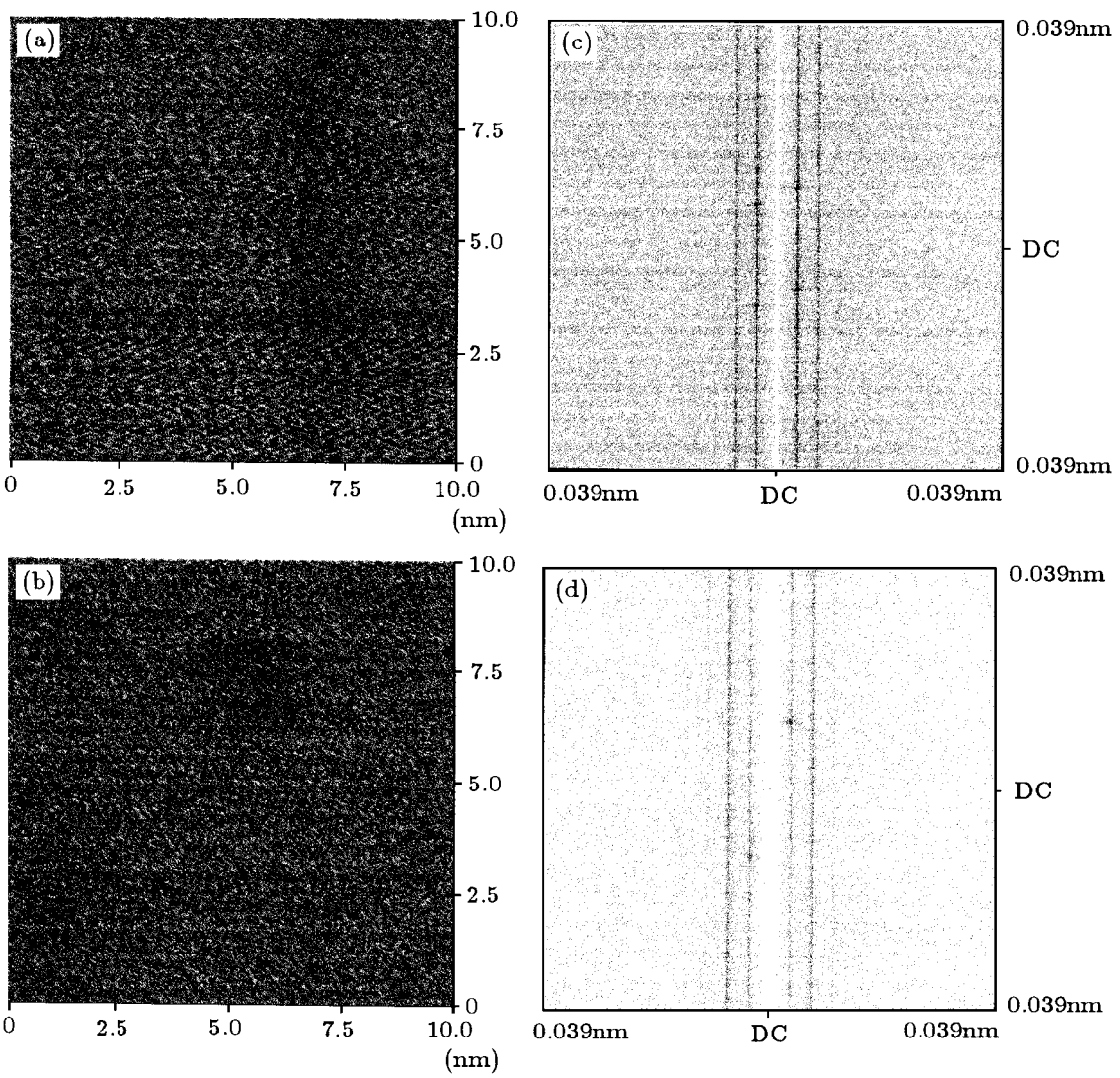


Fig.3. Demonstration of spatial oscillations of tunneling current on the cleaved surface of HOPG. The STM current images were taken on an HOPG surface with different scanning rates (3.052Hz (a) and 1.969Hz (b)) under ambient conditions. They share the other scanning parameters: bias 121.5mV, set point 242.0pA, scanning range 10.0nm. The corresponding 2D-FFT spectra are illustrated in Figs.3(c) and 3(d).

The relation of the spatial oscillations in STM current images to the surface structure can also be demonstrated by changing the scan range. Figures 4(a) and 4(b) show two atomically resolved current images of HOPG taken in scan areas of 10nm×10nm and 20nm×20nm. All other scanning parameters were kept constant for these two images, whose 2D-FFT spectra are shown in Figs.4(c) and 4(d), respectively. The two spectra are aligned as mentioned above. The surface periodic structure of HOPG is reflected by the pattern of the black points in these two 2D-FFT images. In this experiment one main symmetry axis of the graphite surface structure was parallel to the Y-axis. Besides the black points, a few pairs of straight lines crossing through the black points in the spectra are found. The pattern of the black points and the distances between the straight lines expand with the increase in the scan area. The 1D-FFT spectral analysis of the current images indicates that the spatial period of each corresponding pair of straight lines in the 2D-FFT spectra is the same for both current images. Obviously, the straight lines in the 2D-FFT spectra represent oscillations of the tunneling current, which in this case result from the periodic structure of the HOPG surface. The lines appear in the current images because of the coupling between height and current signals by the STM feedback system during scanning. Because fast scanning occurs along the X-axis and slow scanning along the Y-axis the diffuse lines among the points of the 2D-FFT spectra appear

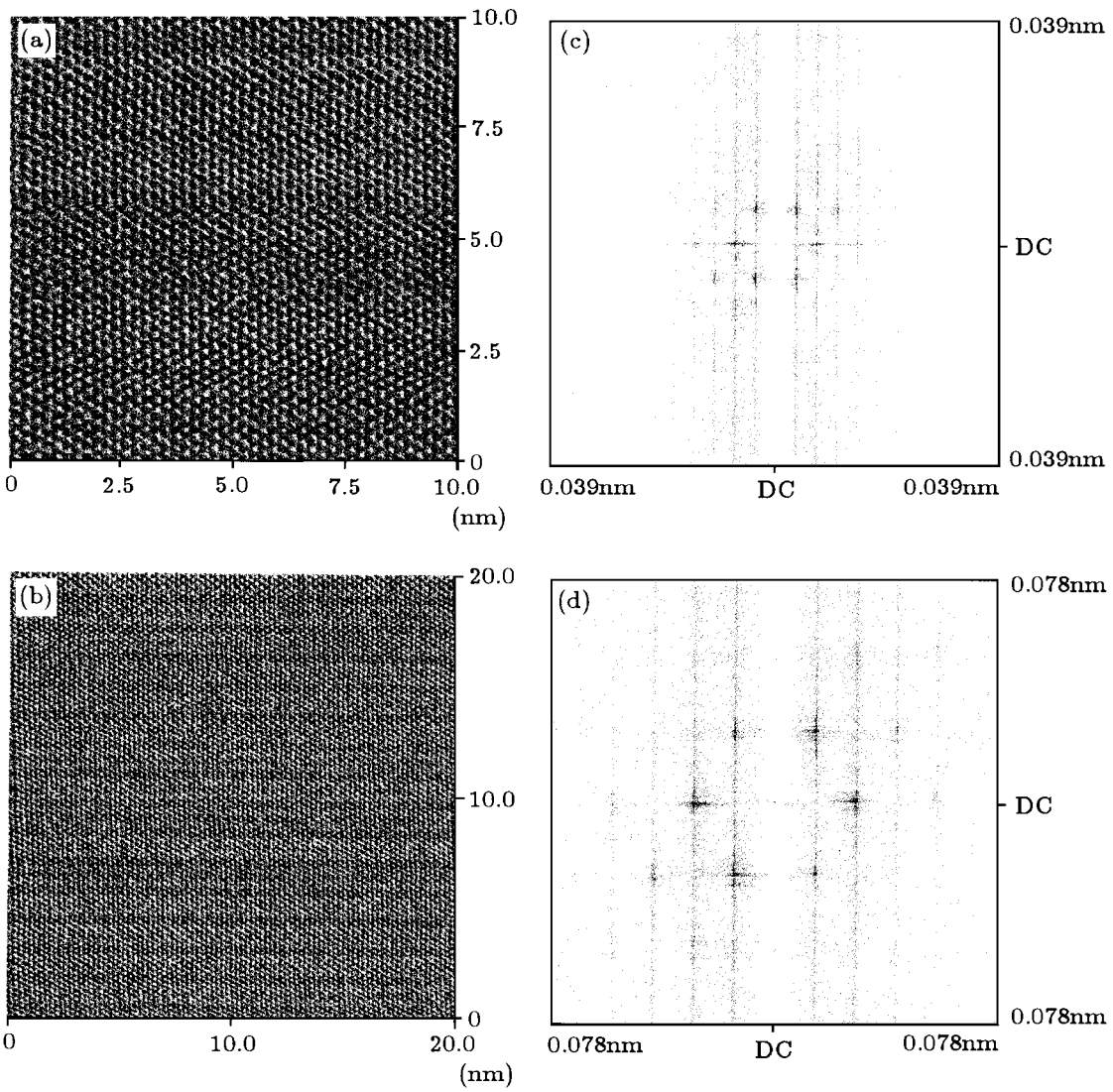


Fig.4. Display of the relation between the periodic structure of the real surface of HOPG and the spatial oscillations of tunneling current. Atomically resolved current images of an HOPG surface were measured at different scanning areas ((a) 10nm×10nm, (b) 20nm×20nm). Their 2D-FFT spectra are presented in Figs.4(c) and 4(d). Scanning parameters were: bias 121.5mV, set point 240.0pA, scanning rate 3.052Hz.

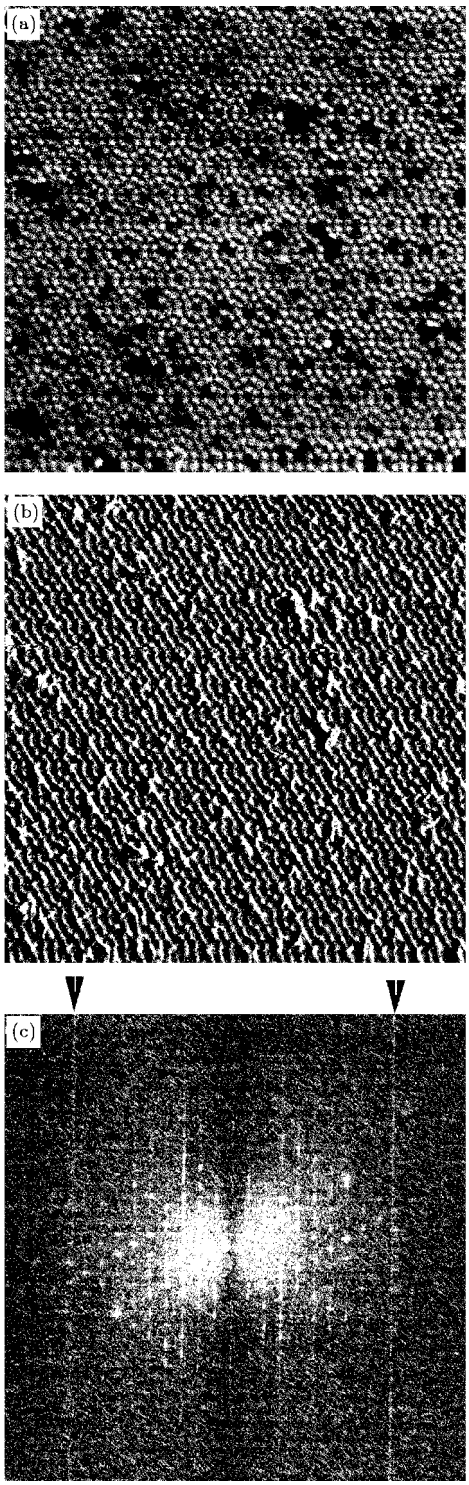


Fig.5. Concurrence of the temporal and spatial oscillations of tunneling current in one STM current image of a partially oxidized Si(111) surface. Figs.5(a), 5(b), and 5(c) show the STM height image, the corresponding current image, and the 2D-FFT spectra of the current image, respectively. Scanning parameters were: bias 1.545V, set point 299pA, scanning speed 568.8nm/s, and scanning area 50nm×50nm.

preferentially in the direction of the Y-axis. These kinds of 2D-FFT spectra have obvious features, which are different from those derived from the partially oxidized Si surfaces mentioned above. The distances between neighboring straight lines are constant, i.e. there is an exact harmonic relation for the frequencies from the strong central pair of lines to the weak outer lines, and there are no lines which are not determined by the point lattice.

The oscillations of tunneling current on partially oxidized Si(111) surfaces were also observed by the Omicron UHV-STM system. The experiment was done after keeping the flashed sample in UHV for about 12h. Figure 5 displays the STM height image of the Si(111)-(7×7) surface structure (a), its corresponding current image (b), and the 2D-FFT spectrum of the current image (c). Lines again preferentially appear in the direction of the Y-axis connecting the bright points of the reciprocal lattice. These lines have the same features as those of the 2D-FFT spectra of HOPG discussed above in Fig.4. But one pair of strong lines, indicated by two black arrows in Fig.5(c) does not cross the lattice points and, hence does not result from the surface structure. These lines are obviously due to real temporal current oscillations in accordance with the results obtained with the Perkin-Elmer STM (Fig.2(c)). Both the temporal and spatial oscillations of tunneling current appear in this 2D-FFT spectrum. In the 2D-FFT spectrum of Fig.2(c) the structure features are not so clear as in the spectrum of Fig.5(c), because the contrast of the STM images was weaker in that experiment.

IV. CONCLUSION

Temporal oscillations of tunneling current on partially oxidized Si(111) surfaces have been observed by two different UHV-STM systems. By measurements with three different STM systems and studies of partially oxidized Si surfaces as well as of HOPG surfaces it was demonstrated that the phenomenon of temporal tunneling current oscillations is not an artificial effect. It is related to intrinsic properties of partially oxidized Si surfaces. Spatial oscillations of tunneling current resulting from the periodic structure of surfaces have been detected on Si(111) and HOPG surfaces. The straight lines appearing in the 2D-FFT spectra of the HOPG current images are due to the periodic structure of the surface only. Temporal and spatial oscillations of tunneling current appear simultaneously in highly resolved STM current images taken at partially oxidized Si(111) surfaces, but they can be dis-

criminated according to the change of their 2D-FFT spectra, while varying the scanning rate and range. In the case of temporal oscillations, the 1D-FFT analysis of the STM current images indicates that the frequencies of the corresponding straight lines in the 2D-FFT spectra do not vary when the scanning rate and/or the scanning size are changed. However, in the case of spatial oscillations, the spatial periods of the peaks in the 1D-FFT spectra are not influenced by a variation of the scanning size and/or rate.

ACKNOWLEDGEMENTS

The authors would like to thank Professor W. Y. Lai, Professor D. H. Shen, and Professor Q. K. Xue for discussions, Mr M. Barczewski and Ms A. Berlinger for support during the preparation of the paper, and Mr. R. Gröger for review of the manuscript as well as Omicron for instrumental support.

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