Noise reduction technique for scanning tunneling microscopy

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Noise stemming from mechanical vibration, electronic noise, or low frequency ($1/f$ power spectrum) inherent in the tunneling process, often limits the resolution, speed, or range of application of scanning tunneling microscopy (STM). We demonstrate a technique for minimizing the effect of these noise sources on the STM image. In our method, the tunneling tip is vibrated parallel to the sample surface at a frequency f_0, above that of the feedback response frequency. Two signals are obtained simultaneously: the conventional topography, and a differential image corresponding to the amplitude of current modulation at f_0. The resultant ac signal can be simply related to the normal STM topographic image, with significant improvement in the signal-to-noise ratio.

In the conventional mode of operation, scanning tunneling microscope (STM) images are maps of the measured tip height $z(x,y)$ in the laboratory frame of reference for a fixed tunneling current and tip-sample bias voltage. In the absence of current noise stemming from mechanical vibration, variation in the tunnel gap properties or from the measurement apparatus, this measurement is equivalent to a "topographic" image of the surface. In the presence of noise sources, on the other hand, for frequencies below the rolloff of the feedback loop the tunneling current noise is reduced by the action of the loop, and appears as noise in the topographic image.

A typical current noise spectrum for a tungsten tunneling tip and a graphite sample taken in air is shown in Fig. 1. The contribution from the electronic elements of the feedback loop is expected to be primarily Johnson noise from the preamplifier feedback resistor, which, for a resistance of 1 MΩ at room temperature amounts to 0.13 pA/$\sqrt{\text{Hz}}$. This source of noise is not found to be significant for frequencies below 100 kHz. In the frequency band 10 Hz to 100 kHz, the tunnel current power spectrum is proportional to $1/f$, swamping individual peaks arising from mechanical vibration.

Previous efforts at avoiding the effects of noise in STM images have concentrated on post-filtering of conventional topographic data,[1,2] a technique which removes signal as well as noise. We show here that, by measuring the differential image by ac methods, it is possible to actually improve the signal-to-noise ratio. The basic principle behind differential imaging is the transfer of topographic information from low frequency (or baseband) to a higher frequency band by placing a small lateral dither on a tip as it is scanned across the sample, and measuring the resultant ac signal, as shown in Fig. 2. This ac signal represents a differentiation of the topographic signal, and is proportional to the gradient of the topographic signal averaged over the range of the dither. Since the feedback loop always acts to maintain the tunnel current constant, the dither must be generated at a frequency outside the response of the loop. In the presence of a nonzero local surface gradient, a lateral dither will generate a modulation of the tunnel current at the dither frequency. This modulated tunnel current can be measured independently, while the average tunnel current is maintained constant by the servo loop. Thus, the STM topography and differential images can be simultaneously measured and recorded.

The dither or differentiation can be done at an arbitrary frequency. In the present case, it is advantageous to dither at a relatively high frequency, to allow detection of the ac signal at a high frequency, where excess noise is low (see Fig. 1). Since the dither itself need not introduce any further noise into the system, it simply provides a means for transferring the topographic information from baseband to a higher frequency range.

Once the information has been transferred to a high frequency, it can be filtered to any bandwidth, usually determined by the desired data rate. The dither size is optimally chosen to be something comparable to the resolution of the instrument.

To demonstrate the utility of this method, we have obtained images of two surfaces, in both cases simultaneously obtaining topographic and differential images. In each case we verified that the x dither did not affect the topographic image.

In the first experiment, we imaged graphite using a commercial instrument,[3] chosen because of the relatively high feedback response frequency, as high as 8 kHz. This allows clear separation of the characteristic frequencies associated

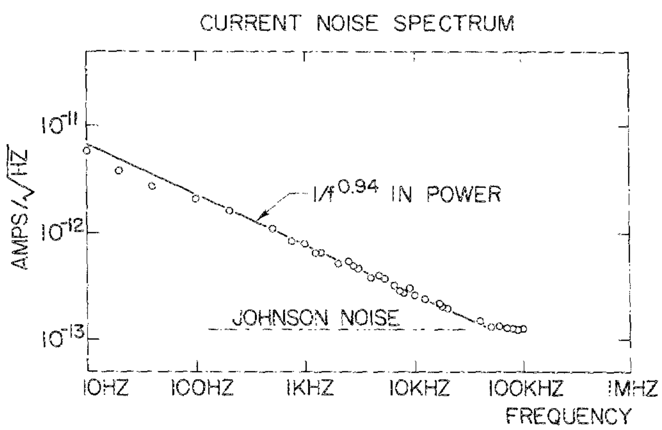

FIG. 1. Tunnel current noise spectrum for tungsten tip and graphite sample, taken in air, with feedback bandwidth deliberately adjusted to be less than 10 Hz. Bias voltage was 20 mV.

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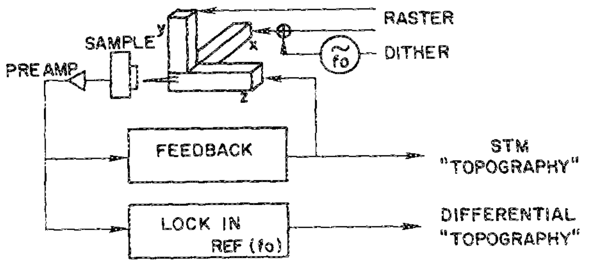

FIG. 2. Block diagram of system. Conventional STM feedback loop was used with addition of small amplitude dither signal to x piezo. Lock-in detection of tunnel current variation provided new differential image.

with data rate (180 Hz), feedback response frequency, and lateral vibration frequency (12 kHz). Graphite was chosen because of the ease with which atomic resolution images can be obtained, and because it provides a suitable test bed for applicability to experiments where atomic resolution is important.

We show in Fig. 3 two images obtained using a mechanically formed platinum tip on a freshly cleaved graphite sample. Images were obtained in roughly 15 s. During the scan the x axis (horizontal in the images) was driven with a 15 Å sawtooth waveform at a frequency of approximately 7 Hz, upon which was superimposed a sinusoidal excitation 1 Å in amplitude at a frequency of 12 kHz.

The normal topographic image appears in Fig. 3(a) and is somewhat degraded compared to the best quality images available because of poor tip quality and concomitant increase in tunneling noise. The differential image is shown in Fig. 3(b). Several features should be noted. First, substantial improvement in the image quality is apparent, due to the separation in frequency of signal and noise sources as discussed above. Second, the differential image is truly a derivative of the topograph, as is evident upon comparison of the two images. Finally, the differential technique is quite resistant to the influence of external noise. In the middle of acquisition of the images a loudspeaker was turned on near the STM providing an acoustic disturbance at a frequency of 133 Hz, well below the feedback rolloff frequency of 8 kHz and of sufficient amplitude to noticeably distort the topographic image. The effect on the differential image is barely noticeable, thus demonstrating the effective rejection of noise sources within the bandwidth of the feedback system. The bandwidth for both images was set at 180 Hz by electronic filtering. Atomic resolution was observed in the differential image with the dither amplitude reduced to as little as 0.01 Å.

Similar reduction in noise has been observed when imaging highly oriented pyrolytic graphite by rapidly scanning the tip at a speed such that the feedback loop cannot respond to variations on the atomic scale,[4] and monitoring variations in tunnel current. However, this "fast scan" method requires that the surface have variations in height of no more than one or two monolayers. For studies involving adsorbed layers thicker than this,[5] profiling of nanometer-scale structures,[6] measurement of surface roughness, or indeed any surface with topographic variation greater than a single atomic step in height, the differential method offers significant advantage. This is particularly true for a STM designed for large scan area, since this requirement generally leads to increased sensitivity to vibration.

To demonstrate the applicability of our technique to rough samples we have imaged the surface of a Au film, which had a characteristic grain size of order 60 Å and heights as measured by the STM of order 30–50 Å. The sample was a 300-Å-thick sputtered Au film on glass, and the tunneling tip was a chemically etched W tip.

Figures 4(a) and 4(b) show a typical pair of topographic and differential images, respectively, of an area 250 Å square. The reduction in noise is clearly visible, as is the differentiated form of the image.

The differential image is a map of $\partial I(x,y)/\partial x$ for fixed average tunnel current and bias voltage. The relation between this image and the conventional topography can be written as

$$z(x,y) = \left(\frac{1}{2\pi}\right)^2 \iint \frac{dk_x dk_y i e^{-i\mathbf{k}\cdot\mathbf{r}}}{k_x} \iint \frac{\partial I/\partial x}{\partial I/\partial z} e^{i\mathbf{k}\cdot\mathbf{r}} \, dx \, dy . \quad (1)$$

In the approximation that the variation of tunnel current with the gap spacing $\partial I/\partial z$ is exponential with a decay con-

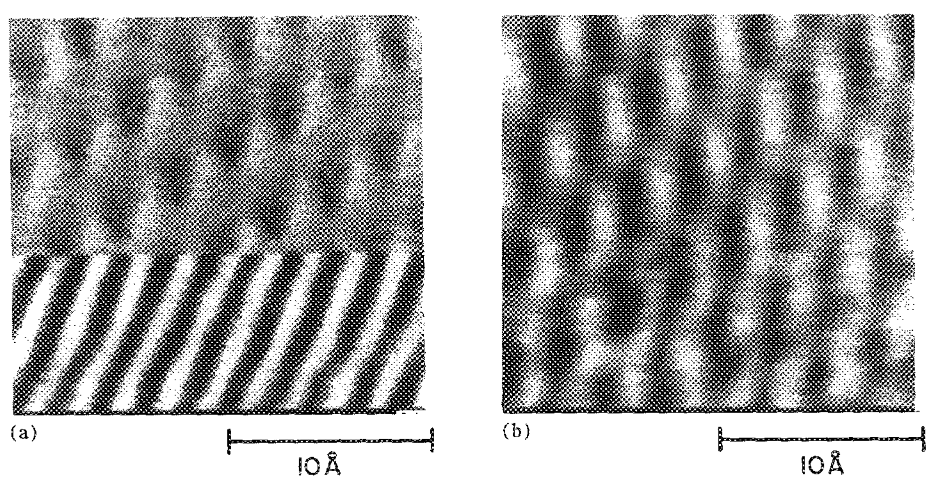

FIG. 3. (a) Topographic and (b) differential images of graphite. Dither amplitude was 1 Å, and bandwidth for both images was 180 Hz. Loudspeaker was turned on midway through the images at a frequency of 133 Hz, with disturbance noticed only in (a).

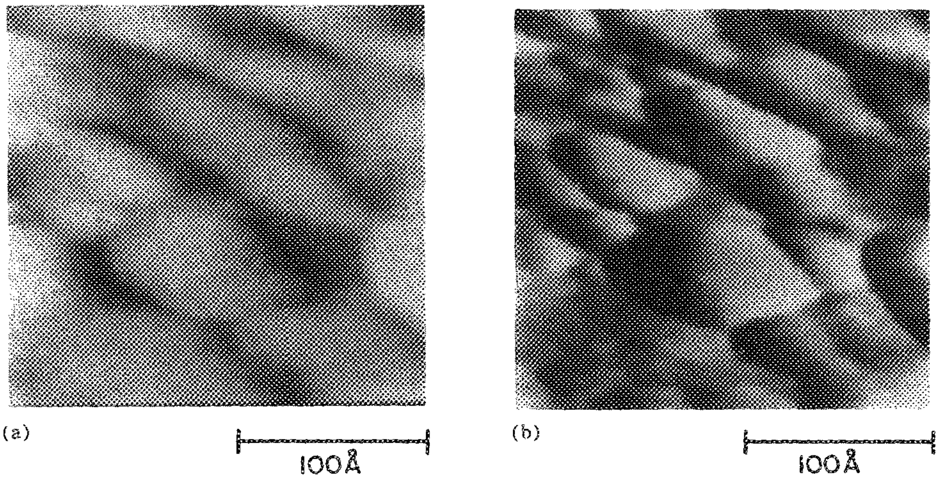

FIG. 4. (a) Topographic and (b) differential images of evaporated Au thin film. Scan area is 225 Å square. Dither was of order 5 Å amplitude at a frequency of 6.9 kHz.

stant determined by the tunnel barrier height,[7] we write $\partial I/\partial z = -\phi^{1/2}\bar{I}$, where ϕ is the electronic work function characterizing the surface and $\bar{I}$ is the average tunnel current. Thus, the conventional STM image is written in (1) as a Fourier-domain integration of the differential image.

Since the tunneling current has an exponential (nonlinear) dependence upon the spacing between tip and sample, some mixing of low-frequency noise to the higher frequencies occurs with dither. The amount of this noise depends upon the dither size, the size of the noise, and local surface gradient. When the current modulation is small compared to the average current, however, the process approaches linearity, and little low-frequency noise is transferred to the high frequencies. These effects are further reduced by the action of the loop to maintain the current constant at the low frequencies.

A more complete experiment would include an additional ac measure of $\partial I/\partial z$, which can vary due to changes in the electronic work function or the amount of contamination present on the sample surface.[8,9] In addition to allowing a complete recovery of topographic information, the acquisition of differential information simultaneously in x and z allows further immunity to noise. Since both $\partial I/\partial z$ and $\partial I/\partial x$ scale with current magnitude I, remnant current noise within the feedback loop bandwidth will be canceled by taking the ratio of the two signals in the deconvolution in (1).

Improvement in image quality with differential acquisition can be expected if the tunnel current noise is due to changes in separation or barrier height while the tip and sample geometry each are unchanged. These experiments provide some insight into the source of the $1/f$ spectrum tunneling noise, which is commonly seen in STM data obtained in air. Since we are able to reduce noise by dithering at high frequency and obtain high quality atomic resolution images of graphite, we can surmise that the tunnel current flows from a single, fixed atom or set of atoms, and not to a succession of atoms migrating over the end of the tip. The variation in current may be due to modification of the effective barrier by a mobile adsorbed contaminant,[8,9] or to a distribution of electron traps on the oxidized surface.[10]

The general method of differential data acquisition has applicability in a wide range of microscopies. Conceptually similar schemes have proven useful in scanned optical,[11] force,[12] and thermal[13] microscopy. We have shown here that differential techniques can also be used in the STM, both for studies of atomically resolved surfaces as well as for the technologically important case where significant topographic variation requires a slower raster scan speed. The enhanced signal-to-noise ratio available with this method allows the experimenter to obtain images at a faster rate, or alternatively to reduce the requirements for vibration resistance of the microscope itself, thus permitting large scan areas and operation in less than ideal operating environments.

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