

Computer automation for scanning tunneling microscopy

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Computer automation has become a necessary part of the scanning tunneling microscope (STM). We have designed a comprehensive data acquisition and image processing IBM PC/AT workstation to complement the STM. The computer is used to control the raster scans, to acquire multichannel analog data, and to store the data for later analysis both at the workstation and on a host computer. New features include the use of PC/AT extended memory, large backup storage, and image processing at the workstation. Real-time gray-scale imaging provides quick and comprehensive information to scientists and engineers. The system is flexible enough to interface with many microscope designs and with other laboratory automation projects. A mainframe host computer system is loosely coupled with the workstation to provide off-line processing, hard copy, and mass storage.

Introduction

In scanning tunneling microscopy (STM), information about the topography of surfaces or surface electronic states can be obtained by scanning a fine tip along the surface and

monitoring the tunneling current and/or the tip displacements required to maintain a constant feedback current [1]. This method is developing rapidly in a wide range of fields for a variety of applications. To make the microscope a more efficient, accurate, and productive instrument in the laboratory, computer automation is necessary.

We have developed a second-generation STM automation system based on an initial STM data acquisition system developed by Schroer, Welland, and Demuth at the IBM Thomas J. Watson Research Center. This system and the work done with it [2] have defined several necessary and desirable features for a more fully integrated data acquisition and display system. The new automated workstation provides, among other functions, real-time background subtraction, gray-scale image presentation, user-interactive functions in real time, and multiple-channel image acquisition [3].

There were two design goals for the new computer STM workstation. First, the microscopist should be able to control all data acquisition, image display, and data processing from one workstation, preferably from within one application program. The second goal was to move toward a standard workstation that could be applied to other laboratory imaging projects. Scanning electron microscopy, thermal imaging, and the mapping of the bulk electrical properties of semiconductor wafers are examples of other applications which can benefit from the workstation described here.

The core of the workstation is an IBM PC/AT. **Figure 1** is a diagram of the PC/AT workstation components, which are discussed in full detail in the Appendix.

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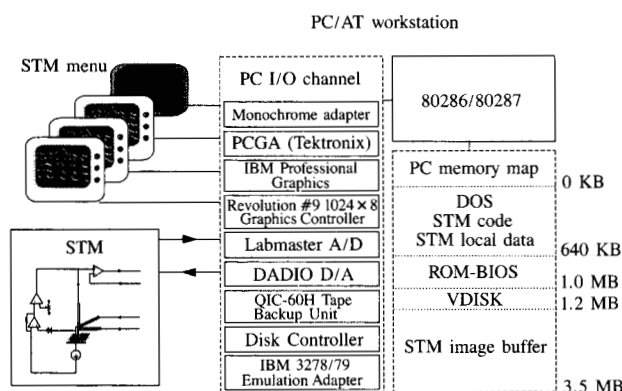


Figure 1

PC/AT workstation configuration for automated scanning tunneling microscopy.

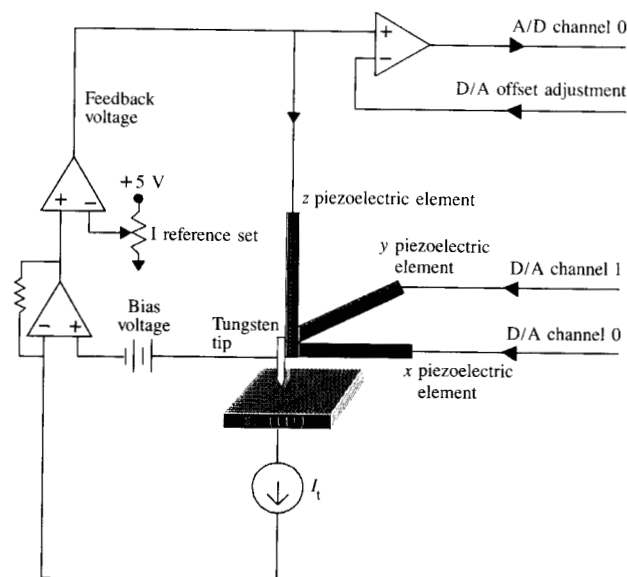


Figure 2

Scanning tunneling microscope tungsten tip, piezoelectric-element tripod, and feedback control circuit.

The PC/AT workstation

There are several unique components of the PC/AT workstation to be discussed. The STM analog-to-digital interface hardware is used to control the microscope directly and to acquire images on up to 48 channels simultaneously. The 80287 math co-processor chip is programmed to optimize the performance and accuracy of all arithmetic computation for image processing. Software has been developed to access up to 16 MB of PC/AT extended

memory to store image data. An advanced graphics system provides 1024 × 1024-pixel resolution, as well as intelligent hardware functions for image manipulations. Software for real-time interactive microscope control has been provided, as well as workstation image processing software for background subtraction, image contrast adjustment, and image filtering.

STM analog interface

The interface between the STM and the PC/AT workstation consists of several analog interconnections. Digital-to-analog (D/A) converters are used to drive the microscope piezoelectric translators. Analog-to-digital converters (A/D) are used to digitize the STM feedback voltage and other analog signals of interest for real-space spectroscopic imaging. The 12-bit A/D converters can resolve 5-mV differences in a ±10-V range, while acquiring 80000 samples per second. Figure 2 illustrates the piezoelectric element tripod, tungsten probe tip, and feedback control circuit that comprise our scanning tunneling microscope and the PC/AT interface (A/D-D/A).

To ensure that the acquired data are associated with an absolute x and y surface coordinate, the workstation uses D/A converters under synchronous control to produce the raster scanning. Each 12-bit D/A converter provides a voltage in the range of ±10 V. Two D/A converters construct the ramp voltages to drive the x - y piezoelectric elements using discrete steps. Our STM has a lateral scanning range between 20 and 1000 Å. These limits are due to the ranges of our D/A converters, the amplifiers driving the piezoelectric element tripod, and the composition of the piezoelectric element material. The resolution of the D/A converter is 5 mV per step. A consideration here is that relatively large steps in voltage between discrete levels contain high-frequency components. These can cause oscillations in the piezoelectric element tripod. Low-pass analog filters are used to filter the D/A output to prevent this.

Arithmetic/signal processor hardware

STM requires both real-time and post-image-acquisition processing that can make use of arithmetic computation hardware at the workstation. Real-time background subtraction, contrast enhancement, and image filtering all require precise floating-point or integer arithmetic. The 80287 math co-processor that plugs into the PC/AT system unit board can be used to speed up floating-point computations or increase the numerical precision of integer and floating-point arithmetic. Most PC/AT arithmetic is performed using 16-bit (integer) or 32-bit (floating-point) precision. All variables passed to the 80287 math co-processor are expanded to an 80-bit precision format called temporary real. This provides 19 significant digits with a possible magnitude representation [4] of $3.4 \times 10^{-4932} \leq |x| \leq 1.2 \times 10^{+4932}$.

Real-time digital filtering is performed in software on each STM line scan. There are sources of acoustic and vibrational noise that can be filtered very efficiently by using a finite impulse response (FIR) [5] filter equation of the form

$$x(I) = ax(I) + bx(I - 1) + cx(I - 2) \\ + dx(I - 3) + ex(I - 4),$$

where a , b , c , d , and e represent the coefficients of a 5-tap FIR filter. The real-time filter windows over each data point in the line scan range from $4 < I < N$ pixels per line. Software signal averaging is also used to improve the signal-to-noise ratio (SNR) of acquired images.

PC/AT extended memory

Without sufficient random access memory (RAM), large images would have to be stored on disk or transmitted to another computer in real time. Post-acquisition image analysis operations often require complete images buffered in RAM as well as storage for intermediate values generated during complex arithmetic. We are currently using the IBM DOS 3.1 operating system on our PC/AT. The IBM PC DOS operating system uses 20-bit memory addressing, allowing access to 1 MB of RAM. The operating system, however, reserves nearly half of this for its own use. The remaining memory is then shared between the automation program code and data. The automation program requires approximately 250 KB of storage, leaving a data buffer of 250 KB. This limitation is further complicated by new tunneling techniques that sample multiple image channels simultaneously. The need for image data memory can be 50 times that for the single-channel case.

New STM software solved this problem and allowed large images to be completely stored in RAM in real time. As an example, consider a 500×500 -pixel image. The analog inputs are acquired as 12-bit digital words and stored as 16-bit integers. A single 500×500 -pixel image requires 500 KB of random access memory ($500 \times 500 \times 2$ bytes per pixel = 500 KB).

A memory management algorithm was designed which utilizes the full 16-MB extended memory address space of the PC/AT for data storage while running the DOS 3.1 operating system. In terms of image storage, we can acquire and buffer one 2500×2500 -pixel image, or 750 images of 100×100 pixels each. The algorithm makes use of interrupts provided by the PC/AT ROM-BIOS (Basic Input/Output System) [6]. Using our memory management scheme, we can achieve a sustained data transfer rate of 2.3 MB/s from DOS addressable memory to the extended memory space. During typical multichannel image acquisition, as many as 48 images (each 150×150 pixels with 16 bits per pixel) are stored in memory and retrieved.

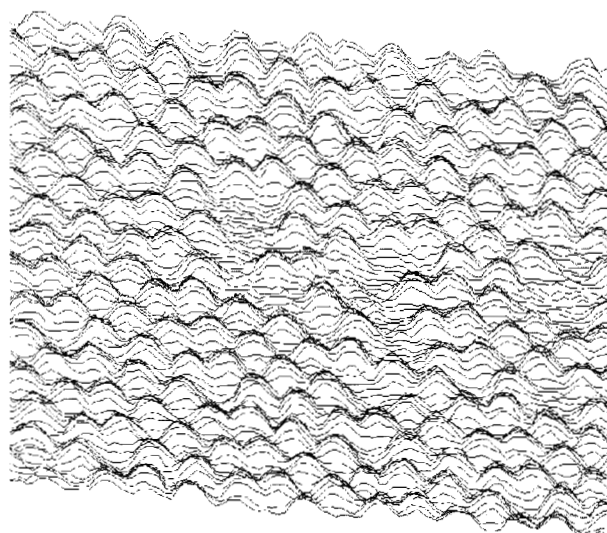


Figure 3

Line scans produced by the STM system showing topographic features of a Si(111) 7×7 semiconductor surface.

High-resolution graphics

Many existing scanning tunneling microscopes use x - y mechanical pen plotters or low-resolution (one-bit-per-pixel) computer displays to graphically represent the modulation of the z piezoelectric element (feedback voltage) [7]. These line scans separated by a fixed distance provide an illusion of three-dimensional surface topography. An example of this is shown in **Figure 3**. In defense of this technique, the line scan gives detailed information about noise statistics and irregular surface features. However, to fully analyze the scanned image data and resolve spatial information, gray-scale or *top-view* images must be generated. **Figure 4** shows the gray-scale or *top-view* image of the Si(111) surface line scan shown in **Figure 3**. In the past, these gray-scale images could be achieved only via post-acquisition image processing on a large mainframe computer. Utilizing recent advances in graphics hardware [8] and internally developed software, we can display gray-scale images in 256 levels of gray, or 256 colors from a palette of 16.8 million. The gray-scale images are displayed as the data are collected, adding only 200 ns per pixel to the total $N \times N$ pixel scan time. The graphics controller board (see Appendix) is used to buffer up to 1024×1024 pixels (1 MB), of which 1024 horizontal and 768 vertical pixels can be displayed on a monitor. The graphics controller card (see Appendix) has software-programmable zoom (pixel replication), scroll, pan, and color lookup tables.

False-color lookup tables have been designed which can be switched instantly among any of four preloaded tables on the graphics controller. False-color analysis of STM images is used to expand the perceived dynamic range of certain

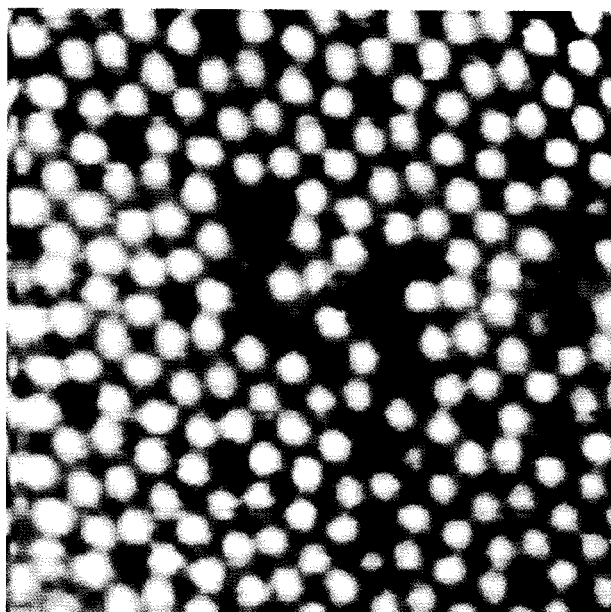


Figure 4

Gray-scale (top-view) image corresponding to the raw line-scan data of the Si(111) surface shown in Figure 3.

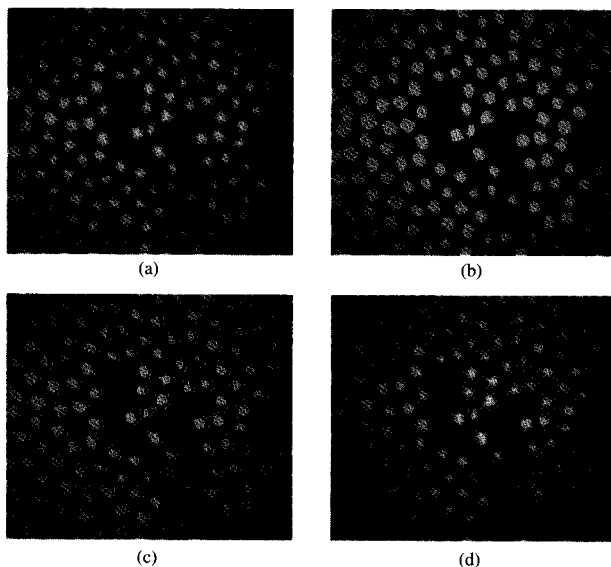


Figure 5

Using color lookup tables to provide false colors for a Si(111) image. The Si(111) image is duplicated four times (a, b, c, and d), each duplicate using a different color lookup table.

intensity regions of interest. Features which are indistinguishable in gray scale can be highlighted with false coloring. Figure 5 illustrates a Si(111) image that is

duplicated four times, each duplication using a different color lookup table.

Image zoom by interpolation

The graphics controller zoom works by replicating pixels. This results in a magnified image that suffers from pixel quantization noise. Our software zoom works by stretching and averaging the image. The image is first stretched vertically in the y dimension by inserting a blank line between each of the line scans. The blank lines are filled with new pixels representing the average value of the pixel from the line scan directly above and below the blank line. This process is also used to stretch each line scan horizontally.

Real-time plane subtraction

The STM sample is rarely flat on the atomic scale. There is usually an increasing or decreasing slope that the STM probe tip must traverse as it tracks the surface topography. In order to correct the microscope image that results due to this sample tilt, a plane must be fit and subtracted from the image.

A background plane subtraction algorithm that works on a single line scan at a time without requiring a complete image is used [3] so that data can be displayed as they are acquired. An iterative subroutine uses a window (usually of ten previously acquired line scans) to compute a plane that can be written as

$$z_{\text{PLANE}} = ax + by + c,$$

where a , b , and c are computed coefficients. By using the computed plane, scalar slope and offset values are computed to correct the current line scan for sample tilt. Line scans are displayed in gray-scale format after background plane subtraction is applied in real time. It is important to note that the updated plane coefficients are applied to the display of the current line scan, leaving past lines as they were originally plotted.

The length of the plane subtraction window is menu-selectable from 4 to 20 lines. A reasonable background approximation for the Si(111) surfaces studied uses a history of ten line scans to accurately track slopes in x and y , without reacting too strongly to unusual surface features where the slope can change several times. Figure 6 shows two STM images, one without plane subtraction applied (a) and one with plane subtraction (b).

The background plane subtraction subroutine is *re-entrant*, so that it can operate concurrently on multiple image channels in real time.

Histogram equalization

Image contrast enhancement has been coded in 80286 assembly language. A gray-scale image is displayed with 256 levels of intensity. It is desirable for all surface features to be displayed within the 256 gray levels while scanning. The

plane subtraction algorithm described earlier approximates this condition during real-time image acquisition. During post-acquisition image analysis, the microscopist can expand the dynamic range of the image by performing histogram equalization. A single keystroke will plot a histogram of the gray-scale pixel distribution corresponding to the active image. The program then prompts the user for new minimum and maximum pixel values in the range (0–255) to adjust the contrast of the image. The image pixels are then adjusted in the following manner:

All pixels < minimum are set = 0;

All pixels > maximum are set = 255;

Remaining pixels

$$= \left(\frac{(\text{old pixel value} - \text{minimum}) \times (\text{maximum})}{(\text{maximum} - \text{minimum})} \right),$$

where maximum and minimum are the gray-scale limits specified by the user.

This algorithm can adjust the contrast on a 300×300 pixel image in two seconds. The image buffer pixel values are modified in place without the use of extra storage.

Convolution filters

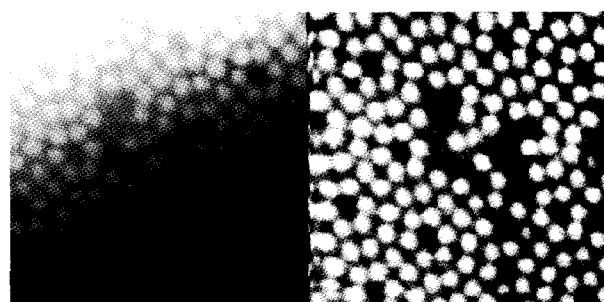
STM images typically contain noise. A rapid filtering technique has been implemented which convolutes the image as displayed, with a 3×3 window of integer filter coefficients. Although not an ideal frequency filter, convolutions are often used as low-pass or high-pass filters. The time required to convolute a 3×3 window with a 300×300 -pixel image is roughly four seconds.

A 3×3 matrix of integer values is displayed which can be convoluted with the active image. The default values in the window shown below will implement a low-pass filter. These window values can be modified by the user to implement other filter types. The convolution algorithm requires nine multiplications, nine additions, and one division for each pixel in the image [3]. The following algorithm describes the convolution of image pixels:

$$\text{Updated pixel value}_{(x,y)} = \frac{\sum_{i=x-1}^{x+1} \sum_{j=y-1}^{y+1} W_{(i+x+2, j+y+2)} \times z_{(i,j)}}{\sum_{i=1}^3 \sum_{j=1}^3 |W_{(i,j)}|},$$

where $z_{(i,j)}$ are pixel values, and the $W_{(i,j)}$ are the window coefficients. This process is repeated for each pixel in the $N \times N$ image. The edges of the image are handled as a special case since there are no data at the edges to perform the convolution.

This convolution technique can also be used for high-pass filtering, edge detection, and differentiation of the image by choosing the appropriate window coefficients. Figure 7 is a comparison of a Si(100) STM image (a) before and (b) after low-pass filtering with a 3×3 convolution window, using the coefficients shown in Figure 8.

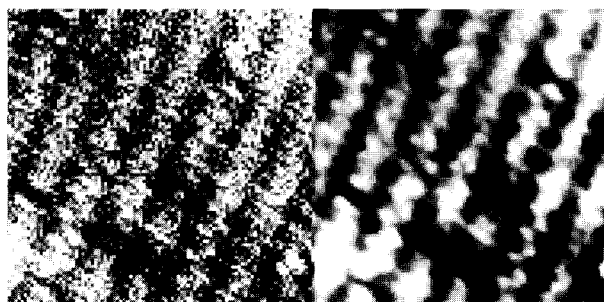


(a)

(b)

Figure 6

(a) Si(111) surface without using plane subtraction. (b) The same surface using the plane subtraction algorithm.



(a)

(b)

Figure 7

(a) Si(100) surface before low-pass filtering. (b) Same surface after low-pass filtering with a 3×3 convolution window.

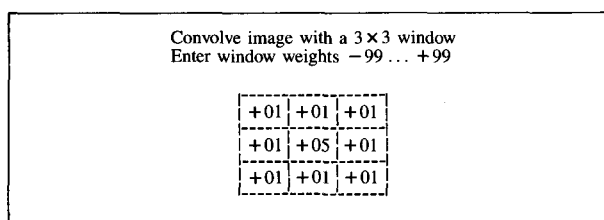


Figure 8

Program user interface for 3×3 convolution window.

• PC/AT software environment

The majority of the microscope control, data acquisition, and image display functions are coded in 80286 and 80287 assembly language [9]. All of the assembly language subroutines are called from compiled BASIC [10], running

STM User Interface									
Go	Lines	Pixels	Samples	Area	Resolution	Channel	Display	Mode	Disk Quit
Store current parameters and start scanning									
Current scan parameters									
Lines	Pixels	Area	Vertical resolution		Samples to average				
100	100	100 square Å	+ 2.000 Å/Division + 1.000 V/Division		1 Topography 1 Tunneling current				
Display				Channels	Disk	Mode			
Source	Type	Plane-sub	Device						
#1 0	Gray	10	9RT	Total	C:	Piezo-delay			
#2 0	Line	0	TEK	1		100 µs			
#3 -1	Off	0	OFF						
#4 -1	Off	0	OFF						

Figure 9

The STM program menu used to enter all parameters.

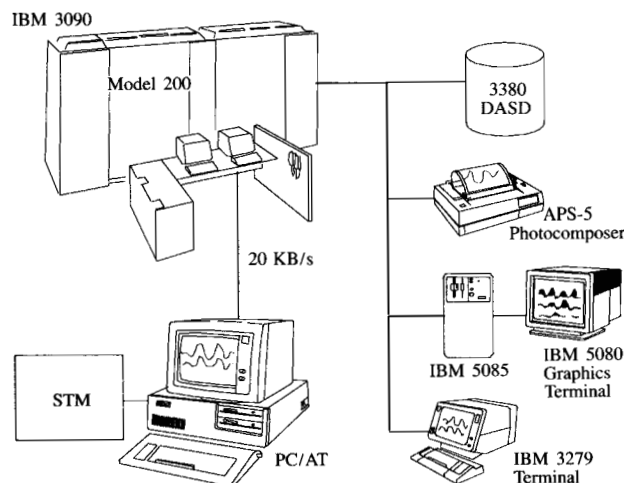


Figure 10

Host computer configuration and the STM workstation interface.

under the IBM DOS 3.1 operating system [11]. BASIC is used for all menus, user interfaces, and low-memory data storage.

All data acquisition and image processing functions are accessible from within a single program. The immediate image analysis allows the microscopist to select new scanning and control parameters to rescan an area of interest before drift or other dynamic events disturb the sample.

• STM program operation

The STM program user interface has been given careful consideration to ensure that all features of the program are

accessible from menus. **Figure 9** illustrates the most commonly used STM user interface.

A convenient feature of the user interface is that all input parameters are in real STM engineering units. The range of the scan area and the display resolution sensitivity are both specified in Å. The program converts the input scan parameters into appropriate analog input and output units transparent to the user. The conversion factors are stored in an ASCII configuration file. This allows the experiment to be changed without the need to recompile or assemble any code.

The STM menu allows the user to specify the x and y pixel resolution, and the area in Å scanned by the STM. The menu is also used to dictate the number of samples to average together per pixel, and the total number of image channels to record. Up to four image channels can be displayed in gray-scale or line-scan format in real time. A vertical resolution parameter sets the contrast of displayed gray-scale images. A programmable piezoelectric element delay in the range $1 < \text{Delay} < 32000$ microseconds for each step of the x and y piezoelectric elements is set for both the forward and reverse scan directions.

• Real-time interactive image scan control

Additional screens are presented during image scanning in real time. Keyboard interrupts may be used to alter some scan parameters without interrupting the STM scan control and image acquisition. These include scan abort, scan restart, zoom (expand) the graphics display, and switch color lookup tables. One of the keyboard interrupts will immediately load and execute an alternate set of scan parameters that have been stored in a text file. Some of these features are implemented by using the graphics controller firmware, so that they can be selected in microseconds without appreciably interfering with the STM scanning process.

Another feature for generating real-time gray-scale images graphically selects the next scan area with a computer cursor. A window is drawn around the acquired image and the microscopist can center the window around the area of interest for a higher-resolution scan. Modifying the window adjusts the area mapped out by the raster scan, automatically updating all of the scan parameters and control constants for a subsequent scan.

The real-time features discussed in this section improve STM operation to the point where dynamic events can be recorded on an atomic scale.

Host computer facilities

Mainframe computing facilities are used for several post-image-acquisition activities. Image processing, photographic-quality image hard copy, and image data file storage are accomplished by an IBM 3090 Model 200 computer with a Vector Processor attachment running the VM operating

system. **Figure 10** illustrates our host computer system configuration and interface to the STM workstation.

Host computer communications

Our PC/AT workstation is equipped with an IBM 3278/79 Terminal Emulation Adapter. Software is used for two modes of communication [12]. The first mode is terminal emulation, and the second is bidirectional file transfer. A keyboard sequence allows the user to switch the PC/AT from DOS (PC mode) to VM (System 370 mode) and back. Terminal emulation runs concurrently with PC-DOS so that host messages can be displayed on a PC monitor while the STM program is running in PC-DOS. Files can be transferred from the PC/AT fixed disk to a host disk file (IBM 3380 DASD) at a sustained data transfer of 20 KB/s.

IAX image processing system

IAX is an image processing interpretive language [13]. Built-in functions include image enhancement and image analysis. Graphic output is directed to an IBM 5080 Graphics Terminal which provides two 1024×1024 -pixel buffers with eight bit planes ($2^8 = 256$ levels of intensity). Color lookup tables can be loaded from IAX to provide 256 false colors from a possible 4096.

All image processing operations are implemented through IAX interpreter commands. Ideal filtering can be performed with Fourier transform operations from within IAX. This is particularly useful when the noise sources are well characterized. Images can be added to or subtracted from one another, as well as expanded or compressed by pixel interpolation.

Publication-quality hard copy

Processed image files can be integrated with text and included in documents as they have been in this paper. A photocomposer (APS-5) device produces black and white gray-scale images with a resolution of 720 picture elements (pels) per inch. For rapid replication, images can be printed on an IBM 4250 Electroerosion Printer, which provides high-resolution hard copy in one to three minutes.

Host computer mass storage

The images which are stored on DASD disk files are typically retained for a few weeks before they are archived on magnetic tape cartridges. IBM 3480 tape drives are used to download 200 MB of image data from DASD disk files to 3480 tape cartridges at a data transfer rate of 23 KB/s.

Applications and capabilities

Our STM has been used to study the structure of silicon surfaces. A new technique that can separate geometric (topographic) from real-space electronic structure has been developed [14]. This technique, current imaging tunneling spectroscopy (CITS), requires simultaneous measurement of

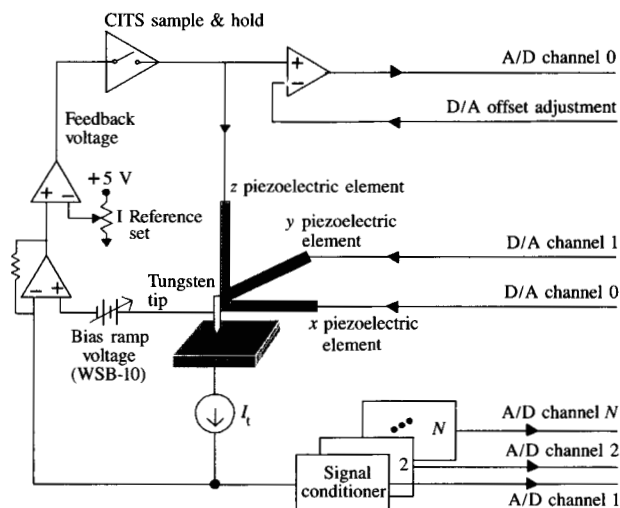


Figure 11

The STM configuration for CITS (current imaging tunneling spectroscopy).

up to 48 images, thereby taking full advantage of the multiple-channel image acquisition capabilities of our workstation. This technique has permitted direct identification of the atomic locations and geometric origin of the Si(111) 7×7 surface states. This then allows those surface states to be mapped out in real space with a lateral resolution of $3 \text{ \AA}$.

The CITS technique involves measuring a topographic channel at a fixed bias voltage, then breaking the feedback loop to measure the tunneling current at several bias voltages, while the tip is held at a fixed location. While the feedback loop is broken (90% of the time), a sample-and-hold circuit is used to maintain the piezoelectric element tripod in a fixed position. By repeating the sequence at a 2.2-kHz rate, while slowly raster scanning, tunneling current images can be obtained at sample bias voltages in the range $-2.5 < V < +2.5$. This technique allows probing within the energy band gap of the specimen. Other approaches to this problem have been hampered by experimental difficulties [15].

Our analog input board has 16 channels (see Appendix). We currently use 12 of these channels, which are multiplexed into signal conditioners to provide 48 channels of image data. A PC/AT waveform synthesizer board (see Appendix) is used to ramp the bias voltage while the feedback loop is broken. The analog signal conditioners are used to measure each of the separate tunneling currents at the respective bias voltages. **Figure 11** shows the STM configuration for the CITS technique. **Figure 12(a)** is an example of Si(111) topography and **Figure 12(b)** shows the corresponding energy states ($I_t - V$).

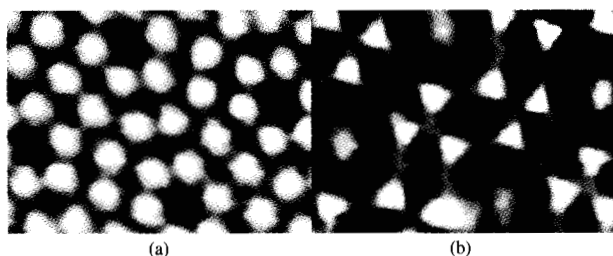


Figure 12

(a) Topography of Si(111) 7×7 surface. (b) Spectroscopic image of Si(111) 7×7 in real space ($I_t - V$).

The STM workstation has been applied to an experiment that has yielded strong evidence to verify the *dimer-adatom-stacking (DAS) fault* model of the reconstructed Si(111) 7×7 surface proposed by Takayanagi et al. [16]. The term *reconstructed* refers to the fact that the silicon surface atoms take on a different arrangement from that of the interior bulk atoms. The rearrangement minimizes the energy due to broken bonds at the surface [17]. Other evidence confirming the DAS model includes grazing-angle X-ray diffraction and medium-energy ion scattering data [18]. The same technique used to study the reconstruction of the Si(111) surface has been used to study the reconstruction of the Si(100) surface [19].

Future improvements

There are still several improvements to the computer-automated workstation to be implemented in the near future. All multichannel data acquisition is to be performed with 16-bit A/D converters. Since most STM samples are not flat, the dynamic range required of an A/D converter can be quite large. It may be necessary to resolve 0.1-Å atomic corrugations on top of a 20–30-Å slope. A sampling rate of 100000 samples per second can be sustained for the applications which require a faster scanning rate.

The application program we are now using is written in compiled BASIC and PC assembler. We plan to recode the main portion of the application program from compiled BASIC into the C language to provide better performance and portability to other workstation types such as the RT/PC.

We are currently developing software that will dump gray-scale or line-scan images to a laser printer attached to the PC/AT. Images may be up to 300×300 pixels with six bits (64 levels) of gray-scale intensity. At present we must upload image data to a host processor to obtain hard copy on the IBM 4250 Electroerosion Printer or the APS-5 Photocomposer.

The integration of higher-performance arithmetic processing hardware will allow ideal image filtering by

two-dimensional Fourier transform techniques. High-performance arithmetic processors are available that transform the PC/AT into a computer which can perform 20 million 32-bit floating-point operations per second [20]. Filtering of 60-Hz noise or other low-frequency acoustic noise in large images can be performed in milliseconds.

The IAX host computer image processing software currently in use does not make use of the available IBM 3090 Vector Processor attachment. An application program will be written for the Vector Processor Fortran compiler that will do STM-specific image enhancement and analysis. Operations such as pattern recognition, line and edge enhancement, and image deconvolution will be developed for STM applications.

The IBM 3278/79 Emulation Adapter hardware which we are currently using for host-PC/AT computer communications has limited bandwidth and does not perform workstation-to-workstation communications. The IBM Token Ring local area network is to be substituted for the 3278/3279 Emulation Adapter, and this will improve our host computer file transfer rate from 20 KB/s to 110 KB/s. STM image data can then be shared with other PC-based workstations that are configured for image acquisition or image reduction.

Conclusion

The STM microscope has demonstrated new and significant advantages over many surface imaging methods. We have developed and demonstrated an STM workstation with capabilities for real-time gray-scale imaging, multichannel data acquisition, and image processing at the workstation. These features allow the study of dynamic events on an atomic scale that has previously been virtually impossible. The advantage of immediate image analysis allows the microscopist to select new scanning and control parameters to rescan an area of interest before drift or other dynamic events disturb the sample. The computer controls allow scientists and engineers to utilize fully STM capabilities that otherwise might have been missed.

Appendix: PC/AT computer workstation hardware

The PC/AT computer workstation hardware (see Figure 1) includes the following:

1. *IBM PC/AT Computer* currently operates at 12 MHz, although we have designed the system to operate at any clock frequency so that we can easily migrate to the 16-MHz PC/AT workstation. The system unit mother board contains 512 KB of random access memory, six PC/AT expansion slots, and two PC/XT expansion slots.
2. *5 1/4" 1.2-MB Diskette Drive* provides a 500-KB/s maximum transfer rate. It has an average seek time of 83 ms.

3. *30-MB Internal Fixed Disk* provides an average seek time of 40 ms. This is the primary local image data storage medium.
4. *80287 Math Co-processor* This chip plugs into the PC/AT mother board next to the 80286 CPU chip. When programmed correctly, this co-processor can significantly accelerate floating-point computations. The 80287 provides roughly 100000 floating-point operations per second with 80 bits of precision. The 80287 instructions will execute concurrently with 80286 instructions.
5. *AST Advantage Memory Expansion Board with the Piggyback Option [21]* This card increases our PC/AT system random access memory to 3.5 MB. Multiple cards may co-reside in the PC/AT to provide 16 MB total system memory.
6. *IBM Monochrome Display Adapter and Display* is used for menu display and is the primary user interface.
7. *Revolution #9 1024 × 8 Graphics Controller [22]* accommodates 1024 × 1024 pixels with eight bits of resolution per pixel. This card plugs into the PC/AT I/O channel and provides 1 MB of graphics memory. The Graphics Controller card provides separate RGB analog signals to drive a high-resolution display.
8. *Mitsubishi 6749 Color Display [23]* is driven by the high-resolution 1024 × 8 Graphics Controller. The inputs are three separate analog signals (RGB).
9. *Labmaster Analog Input Peripheral [24]* provides 16 channels of single-ended analog input, each with 12-bit resolution. This corresponds to a voltage resolution of 5 mV in a ± 10 -V range. A single analog input channel can be used to sample the *z* piezoelectric element feedback voltage at 80000 samples per second.
10. *DADIO Analog Output Peripheral [25]* provides four channels of analog output with 12 bits of resolution. This corresponds to a resolution of 5 mV per step in a ± 10 -V range. The analog output voltage can be updated 200000 times per second. Two of these analog signals are used to drive the piezoelectric element tripod (*x-y* axis) amplifiers. A third channel is used to subtract the *z* piezoelectric element dc offset voltage from the A/D analog input to increase the A/D dynamic range.
11. *IBM 3278/79 Emulation Adapter* This card provides communications between the PC/AT workstation and an IBM System 370 host processor through a coaxial-cable-connected IBM 3274 Control Unit. Modes of communication include emulation of a VM 3270 terminal as well as bidirectional image file transfer.
12. *Qua Tech WSB-10 Waveform Synthesizer Board [26]* is an arbitrary waveform generator. A periodic waveform of up to 2048 points can be programmed into a static memory buffer that drives a D/A converter. A waveform can be clocked at rates ranging from 429 seconds per point to 200 nanoseconds per point (5 MHz). Each point consists of a 12-bit integer (0–4095). The D/A resolution is 5 mV per step in a ± 10 -V range, or 2.5 mV in a ± 5 -V range. At present we are using the WSB-10 to ramp the probe tip bias voltage during the current imaging tunneling spectroscopy (CITS) mode of operation.
13. *PC/AT Expansion Chassis [27]* provides expansion of the PC/AT I/O channel to accommodate up to 15 extra PC/AT-type plug-in cards. This is very important since the PC/AT system unit only provides for eight plug-in peripherals to the I/O channel. This is not sufficient for the scanning tunneling microscope workstation, which requires graphics, memory, and analog I/O peripherals in addition to the standard monochrome monitor and disk drive controller cards. There are certain restrictions associated with the expansion chassis. Any peripherals using dynamic memory cannot be used in the expansion chassis. We are currently using the expansion chassis to house the DADIO D/A card, the Labmaster Analog Input card, and the QIC-60H Tape Backup Unit.
14. *QIC-60H Tape Backup Unit [28]* provides 60 MB of data backup capability with a 90-KB/s data transfer rate. This is used to back up image data that have been recorded on the PC/AT 30-MB fixed disk.

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 25. The DADIO is manufactured by Scientific Solutions Inc., 6225 Cochran Rd., Solon, OH 44139.
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 28. The QIC-60H Tape Backup Unit is manufactured by Tecmar Inc., 6225 Cochran Rd., Solon, OH 44139.

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