**Overview**

Scanning Probe Microscopes (SPMs) are a family of instruments that are used to measure properties of surfaces, including Atomic Force Microscopes (AFMs) and Scanning Tunneling Microscopes (STMs). In their first applications, SPMs were used solely for measuring 3D surface topography and, although they can now be used to measure many other surface properties, that is still their primary application. SPMs are the most powerful tools for surface metrology of our time, measuring surface features whose dimensions are in the range from interatomic spacing to a tenth of a millimeter.

The main feature that all SPMs have in common is that the measurements are performed with a sharp probe operating in the near field, that is, scanning over the surface while maintaining a very close spacing to the surface. These instruments, specifically STMs, were the first to produce real space images of atomic arrangements on flat surfaces. SPMs are now most commonly used to perform very precise, three-dimensional measurements on the nanometer-to-micron scale.

Until the 1990s, researchers had relied upon other instruments for imaging and measuring the morphology of surfaces. Now in existence for over a decade, SPMs are the newest entry into the surface metrology field. As opposed to optical microscopes and Scanning Electron Microscopes (SEMs, TEMs), SPMs measure surfaces in all three dimensions: x, y, and z. Like SEMs, SPMs image and measure the surface of the sample. X and y topographic resolution for most SPM scanning techniques, including AFM, is typically 2 to 10 nanometers (STM resolution 0.01 nm).
can be as good as 0.1nm). $Z$ resolution is typically better than 0.1nm.

The comparison in Table 1 shows that optical microscopes and SPMs are the easiest to use, with little or no sample preparation and no vacuum required. Optical microscopes and SEMs can have larger fields of view, but SPMs provide the highest magnifications and resolution. Furthermore, only SPMs work on most samples with minimal sample preparation.

**Brief History**

The scanning tunneling microscope (STM) was the first SPM technology and was recognized as having atomic resolution capability in 1981. STM, in fact, still provides the best resolution available (Figure 1). The ability of STM to measure surface morphology is clearly outstanding. Unfortunately, there are some limitations, the most significant of which is that the surface of both the tip and sample must be good conductors. This severely limits the materials that can be studied.

This limitation led to the invention in 1986 of the first atomic force microscope. The first commercially-available AFM, the NanoScope® AFM (Digital Instruments) was introduced in 1989. Like the STM, the AFM also uses a very sharp tip to probe and map the morphology of a surface. However, in AFM there is no requirement to measure a current between tip and sample. In this case, the tip is positioned on the end of a long cantilever with a low spring constant (of the order of 1 Newton/m). In contact mode AFM, the first AFM scanning technique, the tip-sample force is held fixed by maintaining a constant and very low deflection of the cantilever, pushing the tip against the sample. This force can be in the range of interatomic forces in solids (about $10^{-9}$ Newton), thus, the name “atomic force” microscopy.

Next, we describe the basic parts of an AFM system, including how the vertical motion of the tip is detected and transformed into topographic data.
Basic AFM Components

The basic AFM is relatively simple in concept (Figure 2). Its closest predecessor is the stylus profilometer, which has been used extensively in the semiconductor and optics industries, among others. AFM technology uses sharper probes and lower forces to provide higher resolution information without sample damage. A generic AFM comprises the following components:

Scanning System

The most fundamental component of the AFM and the heart of the microscope is the scanner. Depending on the individual design, the scanner may scan (move) the sample (Figure 2b, MultiMode™ SPM) if it is small enough, or it may scan the probe over a larger sample (Figure 2c, Dimension™ 3100 SPM). To accomplish the precision required, a piezoelectric tube scanner is typically used and can be controlled to provide subangstrom motion increments.

Probe

Another key component in the system is the probe, or tip. As mentioned above, the probe can be scanned over the sample or it can be stationary and the sample can be scanned under it. With today’s sophisticated technology, tip/cantilever assemblies (Figure 3) can be mass-produced with consistently-shaped, very sharp tips. These tips are secured on the end of cantilevers which have a wide range of properties designed for a variety of scanning technologies.

Probe Motion Sensor

This unit senses the force between the probe and the sample and provides a correction signal to the piezoelectric scanner to keep the force constant. The most common design for this function is called an optical lever, or beam deflection system, which is the lowest noise, most stable and most versatile system available. This design uses a laser shining onto and reflecting off the back of the cantilever and onto a segmented photodiode to measure the probe motion.

Controller Electronics

This unit provides interfacing between the computer, the scanning system, and the probe motion sensor. It supplies the voltages that control the piezoelectric scanner, accepts the signal from the probe motion sensor, and contains the feedback control system for keeping the force between sample and tip constant.

Vibration/Noise Isolation

To achieve the highest resolution, the microscope must be vibrationally isolated from its surroundings. There are very effective, yet simple systems for isolating AFMs from floor vibrations and from acoustic vibration sources.

Computer

Finally, scanning probe microscopy would not be feasible without the availability of powerful, high speed PCs to drive the system and to process, display, and analyze the wealth of data produced.

Figure 3. SEM micrograph of an etched single-crystal silicon tip and tip/cantilever assembly.

Figure 4. Detailed topography of three defects – two protrusions and a depression – in a phase-shift photolithography mask. A cross section measures the smaller of the two protrusions (A) ~140nm across in the plane of the image. The depression defect (B) measures less than 6nm deep. 1.5µm scan.
Applications/Scanning Techniques

In its short lifetime, SPM has already added many variations to the fundamental scanning tunneling theme. Once the AFM overcame the severe application limit of STM, the varieties of techniques and the range of applications began to mushroom. Although topographic mapping is still the dominant application for AFM (Figure 4), commercially available SPMs now provide some or all of the following scanning techniques:

- Scanning Tunneling Microscopy (STM): Measures topography using the tunneling current between the probe tip and a conductive sample surface.
- Contact Mode AFM: Measures topography by sliding probe tip across sample surface.
- TappingModeTM AFM (patented): Measures topography by lightly tapping the surface with an oscillating probe tip; eliminates shear forces (present in contact mode); TappingMode is now the scanning mode of choice for most applications, particularly for soft surfaces like polymers.
- Non-contact Mode AFM: Measures topography by sensing Van der Waals attraction between surface and probe tip; provides lower resolution and is less stable than either contact or TappingMode.
- LiftMode™ (patented): Two-pass technique that separately measures topography and another selected property (magnetic force, electric force, etc.) using topographical information to track the probe tip at a constant distance above the surface; provides the best resolution and minimizes cross-talk with topographic data.
- PhaseImaging™ (patented): Maps surface composition based on differences in local mechanical or adhesive properties of the sample.
- Lateral Force Microscopy (LFM): Measures frictional forces between the probe tip and the sample surface. Tip can be functionalized with chemical species for Chemical Force Microscopy.
- Magnetic Force Microscopy (MFM): Measures magnetic force gradient and distribution above the sample surface using LiftMode (Figure 5).
- High Frequency MFM (HFMFM): Measures magnetic field strength and gradient of devices operating at high frequencies (e.g. magnetic write element of a hard disk read/write head).
- Magnetoresistive Sensitivity Mapping (MSM): Measures the response of a transducer (e.g. hard disk read head) to a localized magnetic field.

Figure 5. AFM (top) and LiftMode MFM (bottom) images of pole tip region on magneto-resistive (MR) read/write head used in computer hard drives. MFM image shows domain structure and MR sensor that cannot be seen in the AFM topography. 12µm scan.

Figure 6. Condensed deoxyribonucleic acid (DNA) has been proposed as a gene delivery mechanism for biotechnology applications. Here, unfixed molecules were imaged in salt solution. 20µm scan.
• Electric Force Microscopy (EFM): Measures electric field gradient and distribution above the sample surface using LiftMode.

• Electrochemical Microscopy: Measures topographical changes in situ as induced by electrochemical reactions in electrolyte solutions. Can be performed with AFM or STM.

• Scanning Capacitance Microscopy (SCM) and Scanning Spreading Resistance Microscopy (SSRM): Measure 2D carrier (dopant) concentration profiles in semiconductor materials.

• Scanning Thermal Microscopy (SThM): Maps surface temperature distribution.

• Tunneling AFM and Conductive AFM: Measures current for electrical characterization of electrical conductivity and evaluation of thin film integrity.

• Nanoindenting: Measures mechanical properties and wear characteristics (hardness, adhesion, durability) of thin films, polymers, etc. (e.g. dielectrics)

These techniques are being applied to a wide array of application areas, from biology to semiconductors, from data storage devices to polymers, and from integrated optics to measurement of forces between particles and surfaces. Other applications include MEMS fabrication, paints and coatings, metals/alloys/platings, plastics/

In addition, AFM systems have already been developed for highly-specific applications, including automated robotic systems for handling semiconductor wafers (Figure 2d), and with analysis routines designed for specific applications such as CD and DVD bump/pit measurements, laser texturing measurements for hard disk production, and pole tip recession measurements for data storage read/write head manufacturing. These applications continue to expand.

Environments and Controls

AFM applications are carried out in a variety of environments. AFMs can be operated in ambient air, in vacuum, and in liquids (Figure 6). Biological measurements, in particular, are often carried out in vivo in biological fluids. Electrochemical experiments are performed in liquid cells, allowing atomic scale observation of electrochemical processes. Film deposition, nucleation and growth are studied in the vacuum environment of the deposition system. In some cases, surface cleaning studies are done at atmospheric pressure in the controlled environment of a dry glove box.

Figure 7. Successive phase images of poly(hexacyclodimethyl)siloxane at (a) 85°C and (b) 90°C. Heating induces formation of liquid islands within the amorphous polymers (a), which convert into arrays of small dots on additional heating (b). 10µm scans.
Recent new products include heating systems for biological and polymer applications up to 250°C (Figure 7), complete with sophisticated sample and environmental sensing. Systems are also now available for controlling the gaseous environment of the sample under study (Figure 8).

Recent Technology Advances

New controllers and electronics, for example, the NanoScope IV SPM Controller (Digital Instruments, Veeco Metrology), have been designed to enhance performance relative to traditional designs. Some of the recent developments in AFM technology include:

Faster scanning for increased throughput

Scanning at up to ten times the speed of traditional systems has opened doors to new applications that require faster turn-around at the rate of seconds – rather than minutes – per scan (Figure 9). Future expectations are that near-video rates may be possible over the next few years.

Higher lateral resolution

The newest AFM systems provide higher data density to allow zooming into the finest details, even on large scans (Figure 10). This provides the resolution required to characterize sidewalls on such samples as DVD bumps/pits and semiconductors. It also allows observation and measurement of nano-scale details on large scans – without the need to spend additional time re-scanning the sample with a smaller scan area.

Enhanced electronics

New technologies allow improved sensitivity and quantification of the probe’s phase response/interaction, opening doors for understanding nano-scale properties of materials.

“Q”-control

Controlling the quality factor, or Q, of the probe allows better control of the forces between tip and sample and improves the sensitivity of measurements such as with PhaseImaging and MFM (Figure 11).

Summary

Development of atomic force microscopes has allowed scientists and engineers to see structure and detail with unprecedented resolution and without the need for rigorous sample preparation. Scanning tunneling microscopy produced dramatic images of atomic lattices and atomic force microscopy broadened the technology to non-conductive surfaces. Several advances have further extended this technique’s utility to a wide range of applications. Tapping-Mode now permits imaging of soft materials without damage to the sample and LiftMode allows separate but simultaneous imaging of topography and other parameters, such as magnetic or electric forces, without cross-contamination. PhaseImaging has opened up the capability for mapping of surface compositional variations. New scanning and measurement
technologies permit measurement of a new range of parameters that have further increased the utility of AFM for a wide variety of applications. In the few short years of its existence, these developments have taken AFM from laboratory curiosity to one of the most powerful, flexible, and widely used technologies for surface characterization.

Readers of this article are welcomed to learn more about AFM technology and applications by visiting www.di.com. Application notes on most of the scanning technologies presented here are available on the web site or in hard copy on request.

Figure 10. TappingMode+ height image and zoom of a copolymer. The square image is a zoom into the boxed area in the original rectangular image. This detail is revealed by simply zooming in with software and without the need for time-consuming, repetitive smaller scans. Without this higher resolution scanning, the zoomed image would not have the pixel resolution required to view nanoscale details. 10µm x 1.24µm scan and 1µm x 1µm zoom.

Figure 11. Images of the same area on magnetic recording tape scanned with and without Q-control. Phase detection MFM images and average cross-section measurements of the probe phase shift illustrate the nearly 4x enhanced sensitivity of the Q-controlled image. 15µm scans.