by Lisa E. Benatar and Sung I. Park

SPMs Step from Laboratory to Industry

Since 1982, when Gerd Binnig and Heinrich Rohrer published the first paper on scanning tunneling microscopy, the field of scanning probe microscopy has undergone enormous growth in both scientific and commercial applications (see, for example, Figure 1). The number of scanning probe microscopes (SPMs) in use will soon reach as many as 10,000.

Although most SPMs sold commercially serve as analytical instruments, more specialized and dedicated forms of SPMs are starting to reach the market. Of particular interest to industrial physicists are the instruments targeted for advanced manufacturing processes in integrated circuits, data storage, and medical devices.

A scanning tunneling microscope (STM) brings a sharp conducting tip into close proximity with a conducting sample, and then moves the tip across the sample surface one line at a time. Although the tip and the sample do not touch, a small but measurable current flows between them. When the tip is more negatively charged than the sample, electrons from tip atoms tunnel across the gap to the closest atoms on the sample surface. The tunneling current depends exponentially on the gap distance, and this gives STMs their extraordinary sensitivity. STMs can image a sample with subangstrom resolution vertically and atomic resolution laterally.

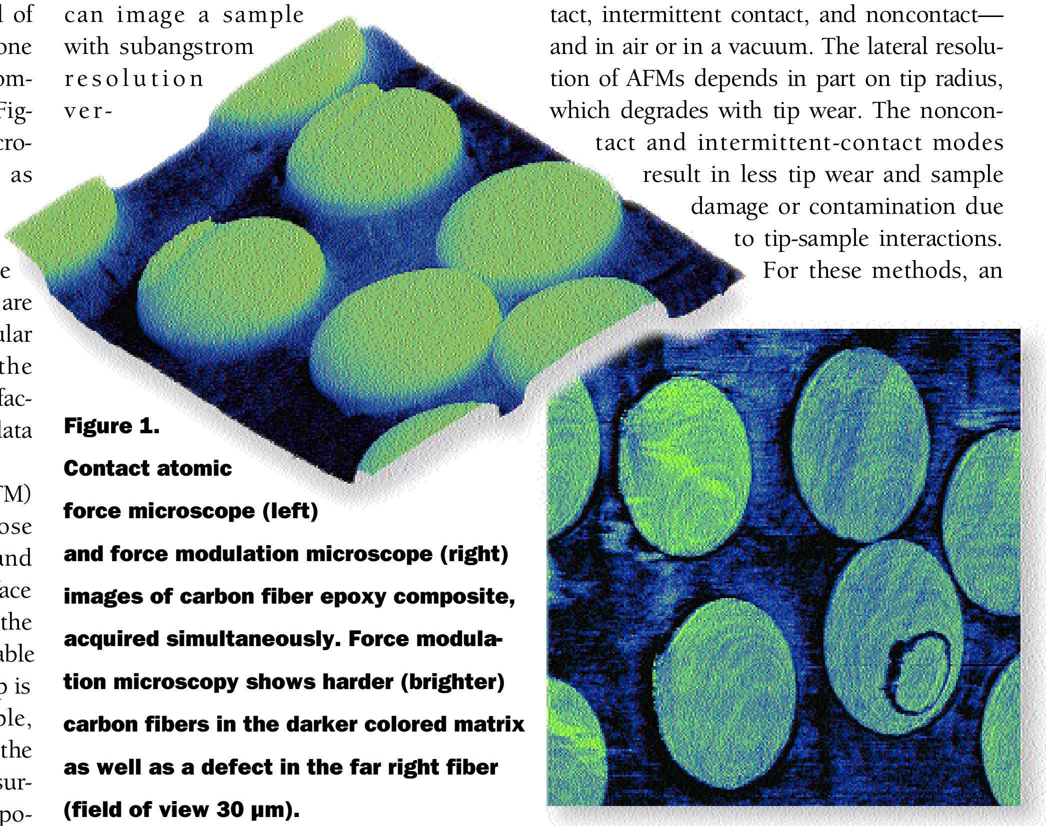


Figure 1. Contact atomic force microscope (left) and force modulation microscope (right) images of carbon fiber epoxy composite, acquired simultaneously. Force modulation microscopy shows harder (brighter) carbon fibers in the darker colored matrix as well as a defect in the far right fiber (field of view 30 µm).

STMs, however, can only be used to image conducting samples. The introduction of the atomic force microscope (AFM) in 1986 opened the SPM field to insulating and semiconducting materials as well. An AFM images a sample's topography by moving a sharp tip at the end of a cantilever across the sample's surface, one line at a time. The micromachined cantilever, roughly 200 μm long and 1 μm thick, deflects as the interatomic force between tip and sample atoms varies because of changes in sample topography. Figure 2 shows a diagram of AFM hardware and signal pathways.

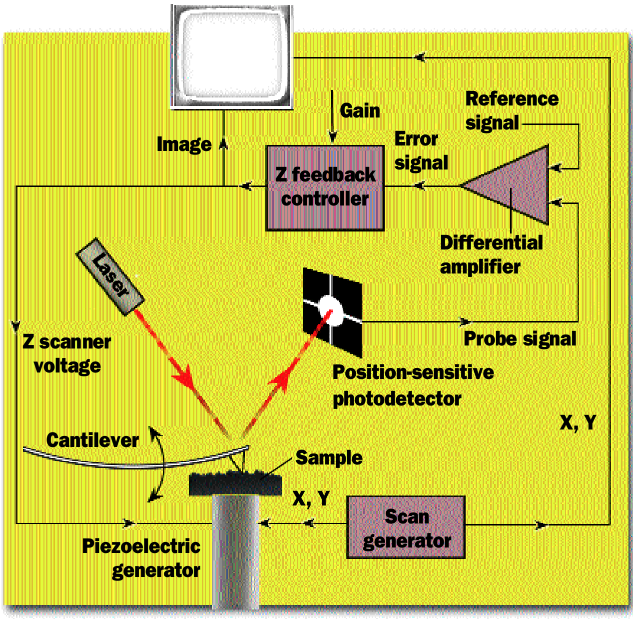


Figure 2. Diagram of hardware components and signal pathways for AFM operation.

AFMs can operate in three modes—contact, intermittent contact, and noncontact—and in air or in a vacuum. The lateral resolution of AFMs depends in part on tip radius, which degrades with tip wear. The noncontact and intermittent-contact modes result in less tip wear and sample damage or contamination due to tip-sample interactions. For these methods, an oscillating cantilever is held tens to hundreds of angstroms above the sample surface. The cantilever tip either does not come into contact with the sample surface (noncontact) or it comes into contact only at the lowest point in its oscillation cycle (intermittent contact). While contact AFMs measure strong repulsive forces between atoms in contact, noncontact AFMs measure changes in attractive forces by monitoring changes in the cantilever's mechanical resonant frequency. Magnetic or electrostatic forces can be detected by noncontact AFM techniques that serve as the basis for magnetic force microscopy and electrostatic force microscopy.

By measuring signals other than those originating from vertical deflection or vibration of the cantilever, one can gain additional information about a sample's material properties. For example, an instrument operating in the contact AFM mode can be used to determine variations in the frictional coefficient of a topographically flat sample by mea-

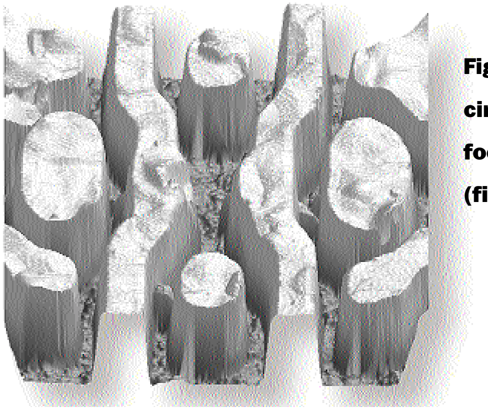


Figure 3. An integrated circuit imaged with a focused-ion-beam tip (field of view 4 µm).

suring the lateral twisting of the cantilever that occurs when it encounters areas of greater friction. This technique is called lateral force microscopy.

The resolution of an SPM image depends on the tip radius and the range and rate of change of the tip-to-sample interaction force. These factors influence the degree to which the interaction is confined to atoms at the very end of the tip. The more isolated this interaction, the greater the effective sharpness of the tip. For contact AFM operation, the interaction force is the steep, short-range repulsive force, but tip wear and deformation act to lower the lateral resolution, The lateral resolution for contact AFM is on the order of nanometers for sharp tips.

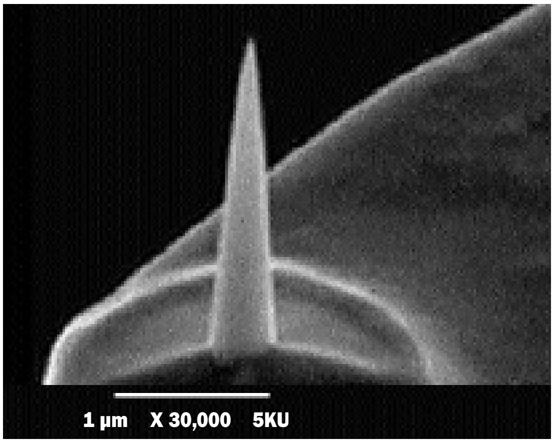
For noncontact AFM operation in air, the interaction force is at slightly longer range and its gradient is less, but tip wear is reduced or eliminated. Lateral resolution is again on the order of nanometers. A noncontact AFM operating in a vacuum eliminates the effects of air damping and significantly sharpens the sensitivity of the cantilever to changes in the force gradient. When sharp tips are used in an ultrahigh vacuum environment, noncontact AFMs can achieve atomic resolution. For magnetic force microscopy, the relatively long-range magnetic force provides the interaction force, and lateral resolution is tens of nanometers.

Industrial applications

To decrease feature sizes and to improve production techniques, the integrated-circuit (IC) industry relies on the high-resolution capabilities of SPMs, which contribute to reducing feature sizes by acting as high-resolution, nondestructive imaging tools that monitor the microroughness of bare substrates and deposited layers. They measure the registration of masks layered over one another; determine linewidth dimensions; characterize dopant levels of deposited layers, including amounts, depth, and distribution; and calibrate production tools. The cost per instrument can run anywhere from \$100,000 to \$500,000.

To shrink gate lengths while preserving a transistor's electronic properties, manufacturers must reduce the length and thickness of doped features. Surface microroughness must be minimized to prevent the presence of physical holes in a thin doped layer, a condition known as punch through. AFMs can provide extremely sensitive measurements of microroughness, which helps improve quality by indicating when to adjust processing.

A second critical process in IC manufacturing is mask overlay registration. AFMs are used to examine mask patterns for imperfections, ensuring the reproducibility of a pattern on a substrate. Also, once a pattern is etched on a chip, AFMs using specially shaped tips can measure semiconductor linewidths and accurately image deep, narrow features such as trenches. Figure 3 shows an image of an IC metal test pattern taken with a focused-ion-beam tip. Figure 4 shows the tip.



North Carolina State University

Figure 4. Scanning electron microscope image of a focused-ion-beam tip. These tips are made by milling the circumference of a silicon tip with a focused ion beam.

Another example of the importance of SPMs to the IC industry is a mode called scanning capacitance microscopy (SCM), which can be used to demonstrate dopant-depth profiles. SCM works by operating in the contact AFM mode, and both an alternating current (ac) and a direct current (dc) bias is applied between the tip and the sample. A sample-surface layer of silicon dioxide between the tip and the doped regions acts as a thin dielectric. The dc bias moves charge either toward or away from the tip, creating the equivalent of a parallel-plate capacitor, and the ac bias varies the voltage across the "plates." The resulting image scales with capacitance and can be used to infer the spatial distribution of dopant concentrations.

Hard disks and soft cells

The hard-disk industry uses magnetic force microscopes to image the magnetic domains of storage disks and thin-film heads, assessing the effects on these domains of varying processing conditions and providing side-by-side topographic and magnetic information (Figure 5).

Today, the hard-disk industry's struggle to meet the ever-increasing demand for storage density has led disk manufacturers to shift to laser texturing. This process of intentionally roughening disks provides a practical way to reduce stiction between the head and the disk when the disk begins to move. In standard mechanical texturing, the entire disk is roughened by abrasives. In laser texturing, a ring-shaped, textured landing zone for the head is created near the inner radius of a disk by directing powerful laser pulses onto a rotating disk. The laser pulses create helical rows of crater-shaped bumps. Because the rest of the disk (the data zone) is kept at minimal roughness, a laser-textured disk can sustain the integrity of thinner magnetic films, making smaller bit patterns possible.

Laser bumps need to be imaged quickly and accurately. Typically, laser bumps vary in height by about 20 nm over several micrometers of lateral dimension. Because AFMs can operate at high speeds, they become a powerful tool for laser-bump characterization.

In addition to topographic, capacitance, and magnetic information, one can map the mechanical properties of a sample's surface using an SPM operating in force modulation microscopy mode (Figure 1). High image

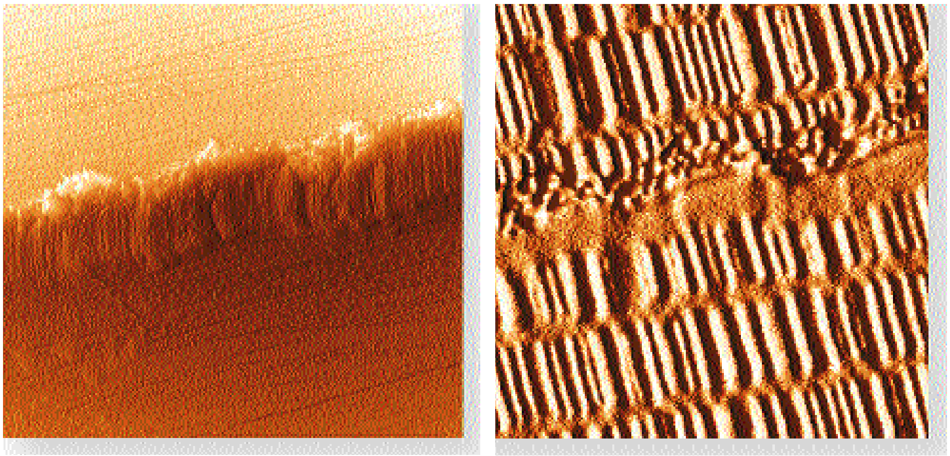


Figure 5. Effects of a head/disk crash on topography (left) and magnetic domains (right) of a disk imaged with a magnetic probe microscope.

resolution and simultaneous complementary information are key contributions of AFM technology to industries using microscopic structuring of materials to obtain desired macroscopic mechanical properties.

The biomedical industry takes advantage of the SPM's ability to produce high-resolution images of surfaces immersed in fluids. Combination scanning probe and optical microscopes allow researchers to examine cells using traditional optical techniques and SPM techniques with one system. Areas that can be studied with SPMs include cell-surface structure, tissue-wound repair, membrane-surface mechanics, and the response of cells to drugs.

Obstacles and trends

In spite of its image-resolution capabilities and breadth of applications, three major factors hamper the greater application of SPM technology in industry: poor user-friendliness, convolution of the tip shape with surface features in images, and slow speeds.

User-friendliness poses a significant obstacle because acquiring the best-quality SPM images can require a high level of technical expertise by the user. The variety of samples and imaging conditions that one may encounter makes automation of many SPM modes difficult. Improving the software interface to make SPMs easier to use and standardizing imaging techniques remain key industry goals.

Tip-convolution effects are being addressed by ever-improving techniques for micromachining silicon cantilevers and tips into controlled and known shapes. Software-based routines are now in development to counter tip-convolution problems, making image interpretation more straightforward. Diamond-coated tips have reduced tip wear.

Finally, researchers aim to improve operational speed with new software. "Smarter" systems now in development include features such as variable scan rates, which allow the system to speed up while scanning topologically flat regions.

In the IC industry, speed and throughput issues are being addressed by work on multiple-cantilever-based AFMs. Such instruments, equipped with hundreds or thousands of cantilevers scanning in tandem, could increase the throughput of SPMs used for high-resolution measurements and material characterization. Moreover, research indicates that multiple-cantilever AFMs offer the potential to increase throughput when used as a lithography tool. Ω

BIOGRAPHY

Lisa E. Benatar is a materials scientist and technical marketing specialist at Park Scientific Instruments in Sunnyvale, California (lbenatar@park.com). Sung I. Park (sipark@appliedprobes.com) is a cofounder of, and a consultant to, Park Scientific, now a subsidiary of ThermoSpectra Corp., a Thermo Electron company.