

Scanning Probe Microscopy in Materials Science

Ernst Meyer, Suzanne P. Jarvis, and
Nicholas D. Spencer, Guest Editors

Abstract

This brief article introduces the July 2004 issue of *MRS Bulletin*, focusing on Scanning Probe Microscopy in Materials Science. Those application areas of scanning probe microscopy (SPM) in which the most impact has been made in recent years are covered in the articles in this theme. They include polymers and semiconductors, where scanning force microscopy is now virtually a standard characterization method; magnetism, where magnetic force microscopy has served both as a routine analytical approach and a method for fundamental studies; tribology, where friction force microscopy has opened entirely new vistas of investigation; biological materials, where atomic force microscopy in an aqueous environment allows biosystems to be imaged and measured in a native (or near-native) state; and nanostructured materials, where SPM has often been the only approach capable of elucidating nanostructures.

Keywords: atomic force microscopy, biological materials, magnetism, nanostructured materials, polymers, scanning probe microscopy, scanning tunneling microscopy, semiconductors, tribology.

Scanning probe microscopy (SPM) has become a useful tool for characterizing the topography of material surfaces down to the nanometer scale. In that sense, it is a natural—albeit wide-ranging and multifaceted—extension of optical microscopy,^{1,2} and in just a few decades, it has developed into an extremely useful family of techniques (see Table I, on next page). The field of scanning probe microscopy started in 1981 with the invention of scanning tunneling microscopy (STM) by Binnig and Rohrer.^{3,4} The basic components of scanning probe microscopy are shown for the case of STM in Figure 1. The ability to achieve atomic resolution on the surfaces of metals and semiconductors has turned STM in a short period into an invaluable surface science tool. Together with techniques such as secondary-ion mass spectrometry and Auger spectroscopy, STM is a powerful technique for characterizing thin-film growth in molecular-beam epitaxy. Examples include the elucidation of Si-Ge heterostructures, which are discussed in the article by Tomitori and Arai in this issue. STM also offers the possibility of scanning tunneling spectroscopy (STS),

where valuable information about the local density of states can be gained with far greater spatial resolution than previous ap-

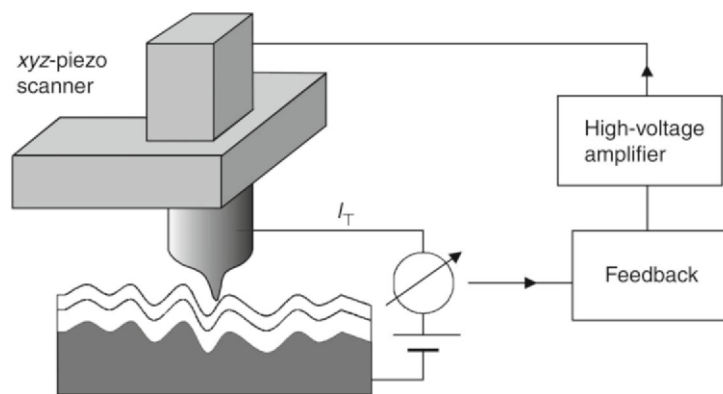


Figure 1. The basic components of scanning probe microscopy (SPM) are shown for the case of scanning tunneling microscopy (STM): xyz-piezo scanners move the probing tip across the sample surface. The tunneling current, I_T , is used, in the case of STM, as the input signal to the feedback loop. The output signal of the feedback is amplified and then fed to the z-piezo to control the distance between the probe tip and the sample. Other scanning probe microscopes send different signals to the feedback loop, derived from interactions such as force (scanning force microscopy, magnetic force microscopy) or light (scanning near-field optical microscopy).

proaches using normal and inverse photoemission. Examples include the ability to determine the surface states of semiconductors and the bandgap in superconductors.

One limitation of STM is the necessity for electrical conductivity of the samples. The invention of scanning force microscopy (SFM, or, atomic force microscopy, AFM) by Binnig, Quate, and Gerber in 1986 overcame this limitation,⁵ bringing about a revolution in materials science. The standard resolution of SFM in the repulsive contact mode is in the nanometer range. With the extension of SFM to dynamic force microscopy, it became possible by the mid-1990s to achieve true atomic resolution.⁶ Insulators such as ionic crystals⁷ or oxides⁸ could be imaged on the atomic scale for the first time.

Apart from its impressive performance in high-resolution imaging of insulators, SFM/AFM has the advantage of being applicable in almost any environment, such as air, dry nitrogen, high vacuum, high pressures, or liquids. The last is of critical importance for applications in biology, as the technique allows cells and membranes to be studied in their functional native (wet) environments. AFM of biological samples will be covered by Frederix et al. in this issue.

SFM not only yields maps of sample topography, but also provides information about local properties such as elasticity, charge distributions, magnetization, and chemical reactivity. This distinguishes SFM from other microscopies and makes it an invaluable tool in materials science. Chemical force microscopy⁹ has been used to image the surface chemical state of oxides¹⁰ and polymers,¹¹ and it is now possible to probe chemical forces between a single dangling

Table I: Various Scanning Probe Microscopy (SPM) Techniques.

Name(s) of Technique	Acronym(s)	Mode of Operation	What is Measured?
Scanning tunneling microscopy	STM	Tunneling current controls z-regulating feedback loop.	Atomic-scale imaging of morphology (indirectly), or location of orbitals at particular energy levels. When tunneling voltage is varied, the measured current yields a spectrum. This variation of the technique is called scanning tunneling spectroscopy (STS) and yields information on both filled and empty states of the sample's band structure.
Atomic force microscopy or Scanning force microscopy	AFM, SFM	Cantilever-spring deflection controls z-regulating feedback loop.	Nanoscale measurements of surface morphology, materials properties, and forces between tip (which may be functionalized) and surface.
Friction force microscopy or Lateral force microscopy	FFM, LFM	Cantilever-spring deflection controls z-regulating feedback loop while torsional deflection of spring is displayed.	Friction can be measured and differentiated on a nanometer scale. When this is related to the surface chemistry, this is often referred to as chemical force microscopy (CFM), and tips are often surface-treated in order to enhance contrast.
Magnetic force microscopy	MFM	Deflection of cantilever spring caused by magnetic forces between magnetized tip and surface controls z-regulating feedback loop.	Magnetic field gradient above a sample.
Electric force microscopy	EFM	Deflection of cantilever spring caused by electrostatic forces between tip and surface controls z-regulating feedback loop.	Electric field gradient or surface potential above a sample.
Scanning Kelvin probe microscopy	SKPM	Capacitive force is measured between oscillating tip and surfaces while the sample voltage is varied until the electrostatic field is compensated.	Map of surface contact potential difference.
Scanning capacitance microscopy	SCM	Capacitance is measured between oscillating tip and surfaces while scanning a biased tip above the sample surface.	Map of surface capacitance.
Near-field scanning optical microscopy or Scanning near-field optical microscopy	NSOM, SNOM	An optical fiber with a small aperture is scanned in very close proximity to the sample, and the transmitted or reflected light is detected and/or analyzed spectroscopically.	Optical images of a surface with resolution of ~100 nm; optical images of smaller emitting species, such as single fluorescent molecules.

bond and atoms in a silicon surface.¹² Therefore, maps of chemical reactivity can be prepared, opening new perspectives for materials synthesis and catalysis studies. The use of SFM to measure the mechanical, structural, and thermal properties of polymers has also become widespread and is now facilitated by the ability to heat samples *in situ* in the microscope. The wide range of approaches used in industrial polymer characterization is discussed in the article by Bar and Meyers.

SFM can also be modified to measure the normal and lateral forces between the probe

tip and sample simultaneously. This approach is known as friction force microscopy (FFM), or lateral force microscopy (LFM), and it has opened a new window onto the entire field of nanotribology. In 1986, Mate et al. demonstrated atomic-scale stick-slip between a tungsten tip and a graphite surface.¹³ Further experiments helped to increase our understanding of the origins of friction.¹⁴ Recently, the transition from stick-slip to an ultralow friction state has been observed in the laboratory.¹⁵ Measurements of friction using SPM are described in the article by Perry.

Many important material properties, such as structural anisotropy, can be elucidated by dynamic modes of AFM. These modes, including dynamic lateral force microscopy, are discussed in the article by Carpick and Eriksson. Magnetic force microscopy (MFM) is an extension of SFM, where magnetic tips are scanned over ferromagnetic samples. This has become an important tool for quality control in magnetic media and is also a key approach to a number of fundamental studies of magnetism, such as imaging magnetic vortices in superconductors and investigating colossal magnetoresistance in

materials. The characterization of nanomagnets by MFM is discussed by Zhu and Grütter.

In just a few decades, scanning probe microscopy has become a ubiquitous and essential tool in materials imaging and characterization. We hope that the accompanying articles in this issue provide both food for thought and serve as inspiration for further applications of this extraordinarily useful family of techniques.

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such as x-ray photoelectron spectroscopy and time-of-flight secondary ion mass spectroscopy. Recent projects include the preparation of chemical gradients, biomimetic lubrication, and high-throughput methods of materials evaluation.

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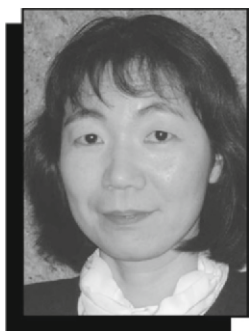
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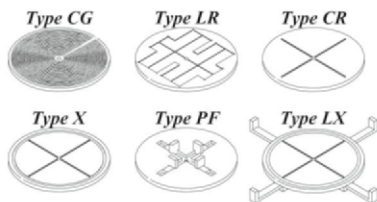
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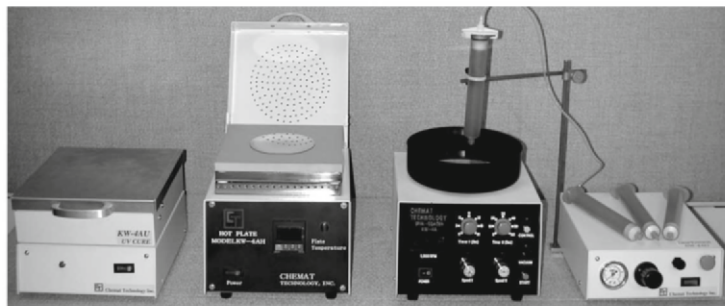
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