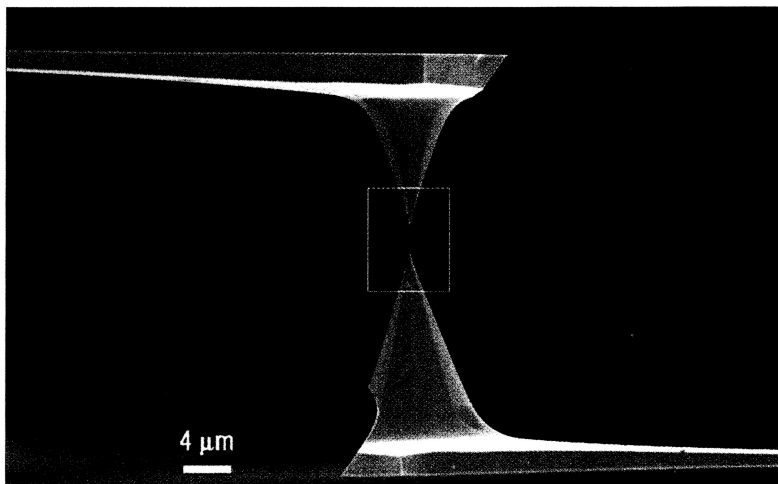


Vacuum experiments reveal the nanoworld

Atomic force microscopy in vacuum is providing new insights into the structural, frictional and mechanical properties of materials at the atomic scale. Robert Carpick surveys the latest advances that have been enabled by this versatile tool



Amazing grace – a multiwalled carbon nanotube held between two AFM tips inside a scanning electron microscope

The atomic force microscope has revolutionized surface imaging since its invention in 1986 by Gerd Binnig and Christophe Gerber at IBM's Zurich Research Laboratory in Switzerland and Calvin Quate at Stanford University in the US. The atomic force microscope (AFM) has been used to study an array of materials with resolution at the atomic scale, and is compatible with almost any environment, including air, gases, liquids and ultrahigh vacuum. This flexibility allows all types of materials to be studied, ranging from insulators through to semiconductors, metals and organic materials.

The AFM has acquired stunning images of crystal surface lattices, measured forces between individual DNA strands, imaged the deposition of atoms in real-time, and allowed scientists to manipulate and position individual molecules. It has provided insights into problems that have vexed scientists for years, and has enabled discoveries of phenomena that were previously unimagined.

The AFM is now firmly established as a critical tool in the rapidly expanding field of nanotechnology. Structures with a size approaching the scale of their atomic constituents have novel optical, electronic and mechanical properties. These can be exploited in a range of applications, including ultrahigh density data storage, ultrafast nanoscale transistors, photonic materials that steer light just as semiconductors guide electrons, and assembled molecules and structures that are otherwise impossible to create.

With these new opportunities come new challenges. As devices get smaller it becomes essential to control surface properties on the atomic scale. This is a difficult challenge, however, as our understanding of surface atomic properties is far from complete. And an interface between two materials is even more complicated than two separate surfaces.

Materials at the atomic scale

An ultrahigh vacuum environment is essential for studying surfaces at the atomic scale. After several years of progress AFM vacuum applications have matured to the point where they can provide quantitative information on material properties. One area of interest has been the frictional, structural and mechanical properties of materials at the atomic scale. Recent experiments in this field show that vacuum AFM is uniquely capable of discovering the knowledge needed to enable nanotechnology.

At the heart of an AFM is a sensor that measures atomic scale forces and displacements. A number of sensor configurations can be used, but the most popular is the cantilever sensor. It is composed of a tip, 10–100 nm wide, that is integrated with a compliant cantilever beam (figure 1). Various vendors produce microfabricated cantilevers with different force constants, sizes and tip materials.

Forces acting on the tip cause the cantilever to move, with the resulting deflections usually recorded by optical means. This approach routinely measures forces in the 10^{-10} N range or better, although Dan Rugar from IBM's Almaden Research Center in the US has recently used ultra-sensitive cantilevers in vacuum to measure forces approaching 10^{-18} N.

The relative positions of the sample and cantilever must be precisely controlled in all three directions to acquire data in terms of both applied force and position. This is achieved by using scanning elements made from piezoelectric materials, which deform

