

APPLIED PHYSICS

High-Speed Atomic Force Microscopy

Paul K. Hansma, Georg Schitter, Georg E. Fantner, Craig Prater

A graduate student was recently heard lamenting, “I feel like my life is passing me by!” as he waited for an atomic force microscope (AFM) image to form line-by-painstaking-line. In AFM, a sharp tip at the end of a tiny cantilever is scanned across a sample to image its topography and material properties. The images can be obtained for samples in air, water, or vacuum with typical resolution on the order of 10 nm. Despite the enormous success and widespread use of AFM, however, most users want higher speed imaging. Conventional AFMs typically take 1 to 100 min to obtain a high-quality image. The productivity and use of AFMs would increase dramatically if the speed could match the millisecond to minute image times of other scanning microscopes such as confocal and scanning electron microscopes. Moreover, there are many experiments, such as watching biological processes in liquids, that simply cannot be done without faster imaging.

The first paper on high-speed AFM was published 15 years ago (1). So why are faster AFMs generally not available? Just as a chain is only as strong as its weakest link, AFM speed is limited by the slowest component in its entire control loop. The achievement of high-speed scanning has required innovations in cantilevers, deflection measurement, scanners, and controllers. These innovations have pushed the state of the art in micromachining, electromechanical engineering, and control engineering.

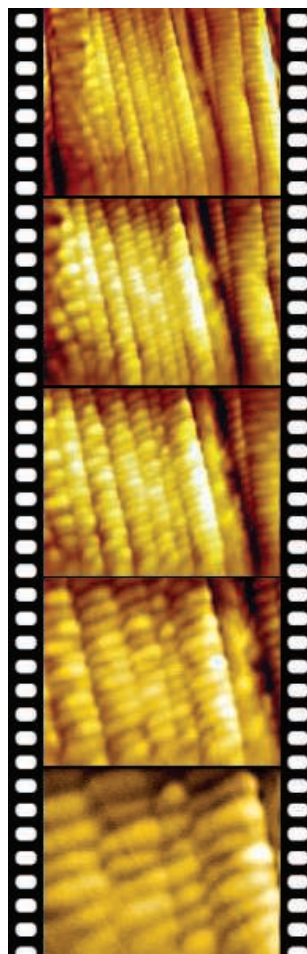
About 10 years ago, small cantilevers (2) and heads for small cantilevers (3) were first reported. These small cantilevers can have much higher resonant frequencies at the same spring constant because their mass is much smaller. Typically the mass is smaller by a factor of 1000, making the resonant frequency higher by a factor of the square root of 1000, or about 30. The problem has been that, although individual research groups have made limited quantities (4–7), there has been no commercial source. And it has

been a sort of “chicken or egg” problem: Major cantilever manufacturers have been reluctant to invest in small cantilevers because there were no commercial AFMs that could use them; AFM manufacturers have been reluctant to make small-cantilever AFMs because there were no commercially available small cantilevers. One of us (G.F.) has founded a start-up company, SCL-Sensor Tech., to produce small cantilevers with integrated tips for this purpose.

Faster scanners are also required to take full advantage of the higher speed possible with small cantilevers. Here too, there has been substantial progress beginning with pioneering work by Ando *et al.* (7) and the work of Humphris *et al.* on resonant scanners (8). A recently reported scanner (9) based on finite element analysis of optimally constrained designs (10) achieves the necessary factor of ~30 improvement in scanner resonant frequencies in a scanner with a practical range of 13 μm in the x and y (horizontal) directions and 4.3 μm in the z (vertical) direction.

This leaves the control system. Here as well, substantial progress has been made both in electronics (7, 11) and in control algorithms (12, 13) and high-speed data acquisition (14, 15). For fully functional high-speed AFM imaging, it is also necessary to increase the speed of the feedback loop that controls the height of the AFM tip by a factor of 30 to maintain minimal imaging force and high image accuracy. Fortunately, this appears within reach with emerging developments in high-speed digital electronics. For now, most of the detail in high-speed images is in the so-called error mode, such as those shown in the

Innovations in engineering, miniaturization, and control-system design have the potential to allow faster imaging by atomic force microscopes.



Fast imaging. This series of images of rat tail collagen illustrates how high-speed AFM allows zooming in on areas of interest rapidly. This entire zoom series from an image width of 2 μm to a width of 470 nm was taken in 0.56 s and shows every fourth image in the series. Collagen's characteristic 67-nm banding pattern is clearly resolved in the raw data and enhanced with image processing for easy visibility. A conventional AFM would need about 15 min of imaging to obtain a comparable series of images.

figure. The feedback is simply not fast enough to maintain constant cantilever deflection and accurately track the subtle details in sample topography. The information about these subtle details, such as the bands on the collagen fibrils, comes from measuring the subtle changes in cantilever deflection, which the feedback electronics are not fast enough to keep constant. The resulting images are called error mode images because they display the errors in maintaining constant cantilever deflection. As the speed of

feedback increases, users increasingly will move from error mode images to quantitative topography images. Also, the imaging will be gentler because the force, which is proportional to cantilever deflection, will be kept constant.

In addition to relieving the tedium of waiting for images, commercial high-speed AFMs will also enable researchers to study fast processes such as protein motion (7, 16) and crystal growth (4) and to do faster force spectroscopy (5) that has only been possible in a few labs with homebuilt equipment. High-speed AFM also offers enormous promise to increase the use of AFM for industrial measurements, where metrology is often monitored by the cost per measurement site. In the case where an AFM can

P. Hansma, G. Schitter, and G. Fantner are in the Department of Physics, University of California, Santa Barbara, CA 93106, USA. C. Prater is at Veeco Instruments Inc., Santa Barbara, CA 93117, USA. E-mail: prasant@physics.ucsb.edu