MAD CITY LABS INC.

Building A Do-It-Yourself Atomic Force Microscope

Homemade AFMs are low-cost and high-performance and provide flexibility and customization.

Atomic force microscopes (AFMs) are versatile tools for characterizing surfaces down to the subnanometer scale. Researchers wanting to, say, map out the optical antennas they've inscribed on a chip, or measure the quantum dots they've created, can image objects at resolutions down to the picometer level by scanning an AFM over the surface.

Useful as they are, AFMs seem out of reach to many academic scientists, graduate students, and researchers at small companies because of their high cost, which runs in the range of $200,000. Fortunately, researchers can build their own AFMs for as little as $30,000 using off-the-shelf components such as nanopositioning stages.

Pick Your Probe

An AFM works by tracing a probe across a surface in an X-Y raster pattern. Variations in the height of the surface exert a force on the probe, causing it to move up and down in the Z direction. Recording those motions provides a topographical map of the surface, giving the dimensions of surface structures. The probe itself can be any of a number of devices — a popular one is a micromachined cantilever tip, which moves up and down as it is dragged across the surface. Laser deflection measures the position of the probe, and a photodetector within the microscope records the how much laser beam is offset.

For a simpler and more cost-effective alternative, those building their own AFM can turn to a resonant probe. Resonant probe microscopy was one of the early forms of AFM, but it was mostly superseded in the early 1990s when micromachined cantilevers became more available. Resonant probe microscopy relies on what is essentially a “tuning fork,” a quartz crystal oscillator that oscillates at a fixed frequency, often about 50 Hz.

To build the probe, all that is required is to attach a tip of some sort to the end of the tuning fork. The tip can be set to move in the Z axis by

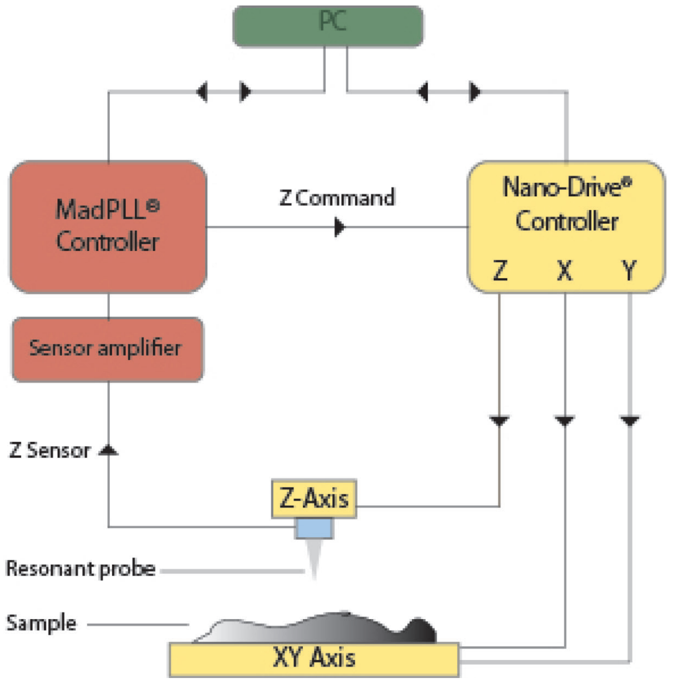

Figure 1. A schematic representation of an atomic force microscope, showing the phase lock loop controller, motion control hardware and resonant probe.

10 or 20 nm. As illustrated in Figure 1, a feedback loop controls the height of the probe over the surface so it maintains a constant force. The tip touches the surface intermittently as it moves along, essentially "bouncing" across the surface. As the tip moves closer to or farther from the surface, the frequency of the oscillation changes, so to maintain a constant frequency the controller moves the crystal up and down. By measuring how much and in which direction the probe must be moved to maintain the frequency — "constant frequency mode" — the user can determine the height of every part of the surface.

Whereas micromachined probes can cost from \$20 to \$60 each, the resonant probe is much more affordable and can even be built by the user. The tuning fork crystal can be purchased from a standard electronics component supplier for around a dollar. The tip can be a short length of optical fiber if researchers desire to look at light on their surface. It could be an etched tungsten wire, as illustrated in Figure 2. It could even be a shard of silicon from a broken silicon wafer, which would not require any special alignment.Even though a wafer might cost \$50, breaking it into hundreds of tiny pieces to attach to tuning forks would provide plenty of inexpensive probes.

Another possibility is to use an Akiyama probe. In an Akiyama probe, a micromachined cantilever is attached to the tuning fork. That combines the advantages of both — the crystal's extremely stable oscillation and the cantilever's reasonable spring constant, which provides an accurate measure of distance. The resulting probe is robust and easy to use, even for people with little training. It requires neither careful alignment nor a highly skilled operator.

To make use of whatever probe they choose, users can attach it to a phase lock loop controller (PLL), such as Mad City Labs' MadPLL®. This instrument includes the digital PLL controller, software to run the scans, a sensor amplifier, a probe board mount, and a mounting board on which to attach the resonant probe, which can be done without alignment.

Select Your Travel Range

The PLL works in concert with piezo nanopositioning stages. Nanopositioners, of course, have various ranges of motion. In the case of an AFM, a short travel range is probably best. For the probe itself, vertical motion of 15 to 30 μm will provide subnanometer resolution of the surface. Though three-axis positioners are available, it is usually better to separate the Z axis from the X-Y raster scan due to the different performance characteristics required for the z-axis motion compared to the raster scanning.

In the X and Y directions, typical scanning ranges are only 1 or 2 microns. Many applications can benefit from scanning an area of 1 μm by

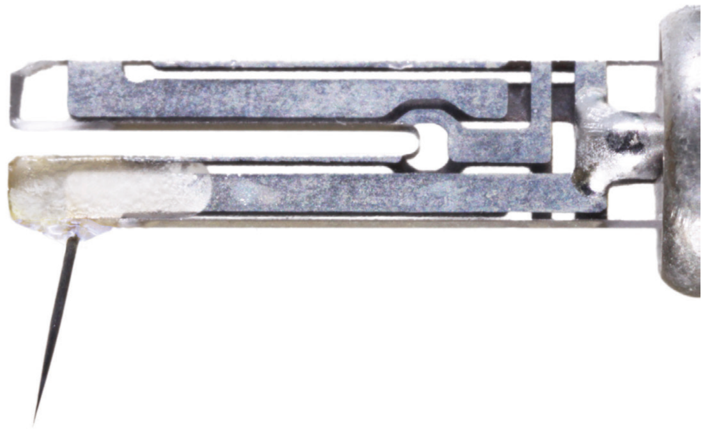

Figure 2. A quartz tuning fork with an etched tungsten tip.

1 μm with resolution of 100 pm. For those, a nanopositioner with a travel range of 100 μm is more than sufficient. Users can view a 100 μm surface area through a microscope, pick the spot they wish to scan, then move the probe to that location. It is also possible to move the probe over distances of 25 to 50 mm with a motorized positioner to select particular scanning areas on a large surface.

The X-Y scanners can have a wider range of motion than the Z scanner because they are not as sensitive to noise. It is important, however, that they do not move out of plane, so it is best to choose a scanner that uses flexure-guided motion, which will provide a smooth, repeatable scan without out-of-plane movement.

Selection of the step size is provided by the digital-to-analog converters (DACs) and analog-to-digital converters (ADCs) that control the motion of the stages. On a 100 μm stage, the smallest step size provided by a 16-bit DAC is 1.6 nanometer. That may be sufficient for some applications, particularly industrial ones. If, however, the test calls for X-Y scans to be performed in steps below 1 nm, users should choose a 20-bit DAC, which provides steps down to 0.1 nm.

The homemade AFM should be mounted on an optical table that provides vibration isolation to prevent noise from overwhelming the scanning signal. It may also be advisable to place the AFM in some sort of enclosure to prevent air currents from interfering with the scan. A simple enclosure — even just an overturned plastic box — will do.

Buy Software Or Build Your Own

The imaging process should be software controlled. The MadPLL® comes with software, called AFMView, which operates the microscope, scans the stages, and controls the motorized stages, with an executable program that works at the click of a mouse. Because the executable program is written in LabVIEW, it's also possible for the user to write their own scanning program in LabVIEW to customize the MadPLL® operation to their particular experiments.

AFMView can also provide self-calibration of the tuning fork, which can be used in different modes with fixed amplitude or fixed frequency. The user can perform a coarse scan of the surface, use that to automate calibration of the probe, and be ready to run a finer scan within a couple of minutes. The software takes feedback from the probe, which provides a control signal that allows it to run the system.

Versatile Applications

With the inexpensive AFM built, researchers have a powerful imaging tool for studying surface morphology. Figure 3 illustrates the measurement of individual atomic steps in silicon. These measurements were done with a tungsten tip. These atomic steps in silicon, are 312 pm high.

By attaching a small length of optical fiber to a tuning fork, researchers can create a near-field scanning optical microscope (NSOM) to characterize the optical properties of structures on the surface at the same time they measure the morphology. They could also perform nano-Raman spectroscopy.

Perhaps the user is creating optical antennas to interact with surface plasmon polaritons. Those polaritons are waves of electromagnetic oscillations that arise at the interface of metal and air or metal and a dielectric, which can enhance optical signals. A resonant probe equipped with an optical fiber could detect the output of the antennas.

One test some researchers may want to perform involves placing biological probes on an optically active surface. In order to study the interaction of, say, a protein with some aspect of surface morphology, they use surface plasmon polaritons to excite the biological probe, then detect the optical signal with the NSOM. For such experiments, stray light from the AFM could create headaches.

In fact, where the resonant probe has a major advantage over optical deflection AFMs is in

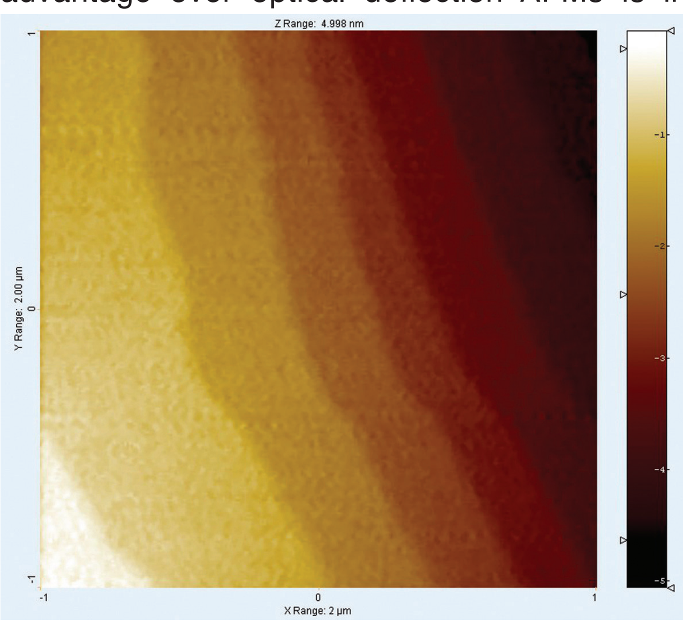

Figure 3. A two dimensional representation of Si (111) atomic steps measured by AFM. Each color shift represents a different atomic layer measurement. The average step height was calculated as 311pm with a standard deviation of 3pm in agreement with the accepted value of 312pm +/- 12pm.

just such situations, when using light to read the probe's motion would drown out other measurements. In optical deflection, a laser beam shining on the cantilever tells the system how much the cantilever is moving. Unfortunately, the beam also sprays light all over the surface, and the stray light adds noise to any optical signal, making the signal difficult to detect. The resonant probe is just as capable as the optical deflection system of mapping the topography of the surface, but it requires no light and thus allows additional optical measurements to be made.

AFMs are often seen as out of reach for many scientists with limited budgets. But they are such useful and versatile tools for characterizing surfaces, mapping out morphology, and studying the behavior of tiny structures that they should not be dismissed as unaffordable. It is entirely possible for researchers to create their own inexpensive, homemade AFMs to perform whatever sort of surface testing fits their needs and to customize the travel range, select the right probe, and tune the performance to best suit their requirements.

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