An AFM Learning Module Employing Diffraction Gratings

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Note: The Department of Physics and Astronomy at Appalachian State University recently acquired an Atomic Force Microscope (AFM) system for education and outreach activities. We developed a new learning module about diffraction gratings that uses the AFM, which we are sharing with other educators who wish to introduce AFM in the classroom. Empirically, it appears that AFM excites students, in addition to giving them hands-on experience with an important tool used in physics and nanoscience research.

Introduction

The Physics and Astronomy Department of Appalachian State University acquired a Nanosurf Easyscan 2 system [1] in the Fall of 2008 with funds from an NSF MRI award (DMR 0821124). We have used this AFM in over a dozen outreach activities for middle and high school students. We also have incorporated the AFM into several of our college courses, including an overview course on microscopy, a first-year seminar course on nanotechnology, and a senior-level lab course for physics students. We have learned from our outreach and teaching experience that introducing AFM to students excites them about nanoscience and nanotechnology and provides an important opportunity for implementing experiential learning in the classroom. Several principles are reinforced by having the students learn to operate the microscope and acquire images themselves. When students take ownership of acquiring AFM data during sample analysis and are able to take with them a digital file or print out the imaging results, it allows them to share what they learned with their peers and family. This learning cycle, from abstract conceptualization to concrete experience, has proven to be an effective pedagogy for students of all ages. To improve our outreach and teaching activities, we have developed several new learning modules for AFM, and we share one physics-based module here.

DIFFRACTION GRATING LEARNING MODULE

Below we show the diffraction grating learning module in its entirety. This module was written for facilitators of the outreach or teaching activity.

Purpose of Activity

This activity draws on students' knowledge of diffraction gratings and the physics of electromagnetic radiation in the visible range interacting with a grating. This experiment teaches students how diffraction gratings work and introduces them to an atomic force microscope (AFM). With this experiment, the students will learn how to use an AFM and see that it can be used to scan and image objects at a very small scale. At the same time, the students learn about the concept of the diffraction of light.

Materials Needed

- Diffraction gratings
- Lasers (The wavelength of light coming from the laser should be known. We used a He-Ne laser, which has a wavelength of 632.8 nm.)
- Goggles (rated for specific wavelength of light coming from the laser)
- Meter sticks
- Calculators
- Atomic Force Microscope

Information to Know Before the Experiment

Diffraction gratings. Diffraction gratings are made up of a large number of equally spaced, parallel slits. The slits cause diffraction when light passes through them. Once the light is diffracted, the light waves interfere with one another and produce a pattern. For a monochromatic light source, which will be used in this experiment, the pattern will consist of bright and dark spots of light. The following grating equation defines the path of the most intense beams of light:

$$n\lambda = d(\sin\varphi + \sin\theta)$$

where n is the diffraction order, λ is a specific wavelength of light, d is the distance between the slits or grooves of the diffraction grating, φ is the angle of incidence, and θ is the angle of diffraction.

Atomic force microscopes (AFMs). Most AFMs use a combination of a tiny cantilever, a laser, and a photodiode to image a region at the micro or nanoscale. As the cantilever moves across the surface, the laser beam shines down onto the back of the cantilever and reflects back to the photodiode as shown in Figure 1. The information from the photodiode is then sent to the control electronics. The feedback loop in the control electronics adjusts the vertical position of the tip to try

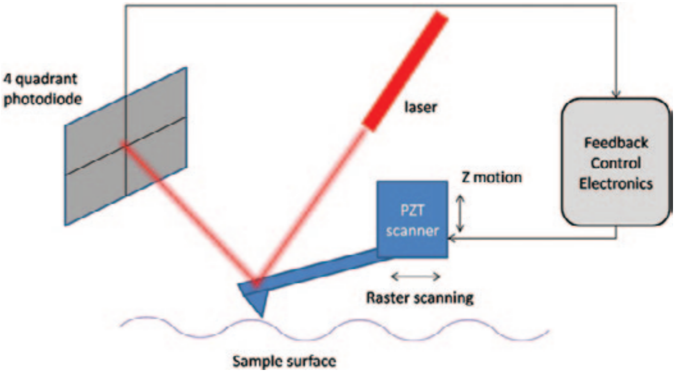
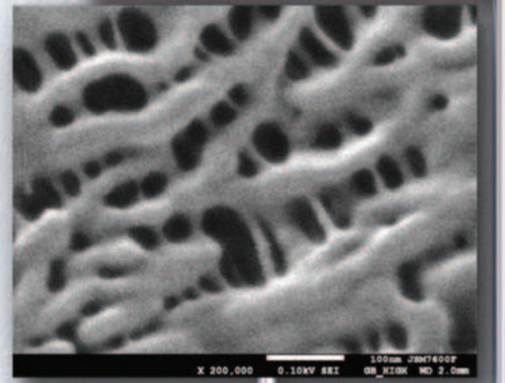


Figure 1: Schematic diagram showing how the atomic force microscope signal is generated and collected.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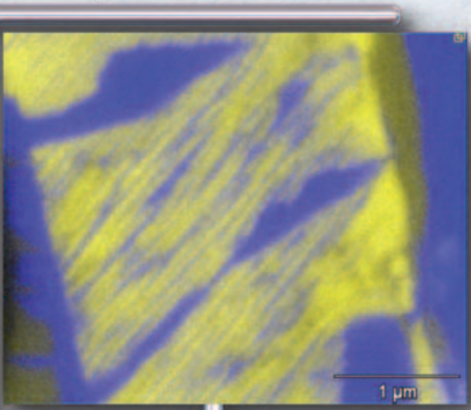
X 200,000 0.10kV SEI GB_HIGH WD 2.0mm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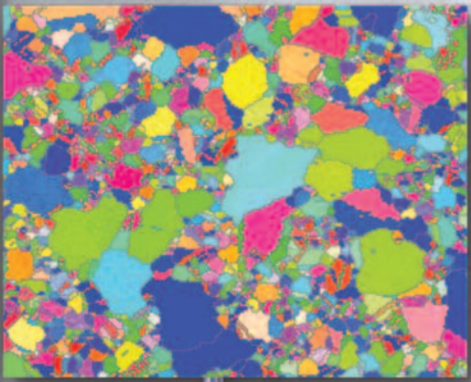

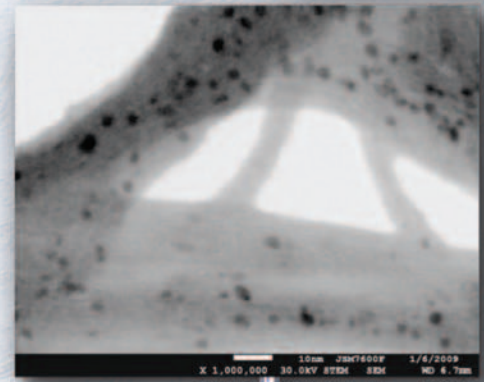
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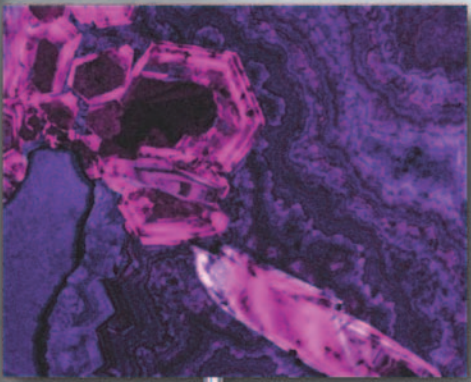
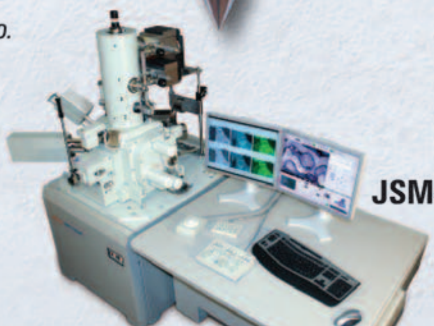




to keep the laser in the same position on the photodiode, and this maintains the same tip-sample distance while the sample is scanned. By knowing the distance the tip must move to maintain the constant tip-sample distance, the AFM software can produce an image of the topography of the surface.

The atomic force microscope can be operated in many different modes. The most common ones are contact mode and tapping mode. Tapping mode will be used in this experiment. When an AFM is set for tapping mode, the cantilever oscillates very quickly up and down (the resonance frequencies of most cantilevers range from 10–100 kHz). The tip on the cantilever literally “taps” the surface gently. The feedback loop will adjust the position of the tip to maintain a constant amplitude of oscillation. We do not present an in-depth explanation of AFM here. There are many websites and books devoted to this topic [2, 3].

Procedures

Diffraction grating measurements. This set of instructions will allow students to calculate the distance between the parallel slits on the diffraction grating using simple measuring tools.

1. Set up separate stations with a laser, laser goggles, meter stick, calculator, and diffraction grating. Obtain the wavelength of the light the laser produces, if it isn’t known already.
2. Separate the class into groups of three or four and allow them to look at the equipment at their station.
3. Ask the students questions to introduce the diffraction grating. Examples:
    What is the transparent film placed at your station?
    Is the film completely smooth?
    Did you know that there are thousands of parallel slits in the film?
    Can you see tiny lines on the film?

   Have the students set up the system that is shown in the Figure 2.

They must place the laser behind the diffraction grating. Then they need to turn on the laser and direct the laser beam so that it runs normal to the diffraction grating surface. (This will allow the math to be a bit easier because φ in the grating equation will equal 0°.)

4. Have the students calculate the angles θ_1 and θ_2 shown in Figure 2 by using basic trigonometry. The students should measure the distances S_1 and S_2 in the figure and also the distance from the grating to the wall. The tangent function can be used to calculate the necessary angles from these distance measurements.
5. Have the students use the grating equation to find the distance, d, between the slits of the diffraction grating.

Now that the distances have been found using “caveman tools,” the students will use an AFM to find the distances between the slits.

AFM. Set up the AFM to scan the surface of the diffraction grating. Once the images are produced by the AFM, have the students use the measuring tool in the software. Following are the steps needed to measure distances on the image.

1. Click on the image
2. Locate the Tool Bar and find the Measuring Tool.
3. Using this tool, click on one edge of the slit and then click on the next edge of the slit to find the distance between the slits. The screen should look something like Figure 3.

Notice that the line is located between equivalent upper edges of each slit. Also notice that the distance between slits can be found under the Tool Status box.

Once the lengths have been found using both techniques, the students should compare their results. The results will differ a little. The students should give some reasons for these differences.

Discussion

Progress through the module. This module has been used as an outreach activity for middle and high school students on 5 separate occasions (approximately 40 students have participated in this activity), and has been used as a short project for our university’s senior level physics students for two semesters (approximately 20 students). For the middle and high school students, the activity was closely monitored at all times, with the instructor prompting the students and helping them along with both the theory and operation of the equipment. The college students received some coaching in the operation of the AFM, and help with replacing tips and sample positioning, but were otherwise able to function independently. For all groups and levels of ability, however, we found that having students work in groups of three or fewer was optimal. Three students can work together with the laser beam and diffraction grating while three other students use the AFM. This does increase experimental error, as the two groups are not using the same diffraction gratings for their measurements. However, if the diffraction gratings are from the same manufacturer and the instructor checks the spacing of both gratings prior to the student exercise, this uncertainty is minimal.

Many of the middle and high school students were unfamiliar with the concept of diffraction and diffraction gratings. We therefore started each outreach activity for these age groups by asking them to look at white light through some

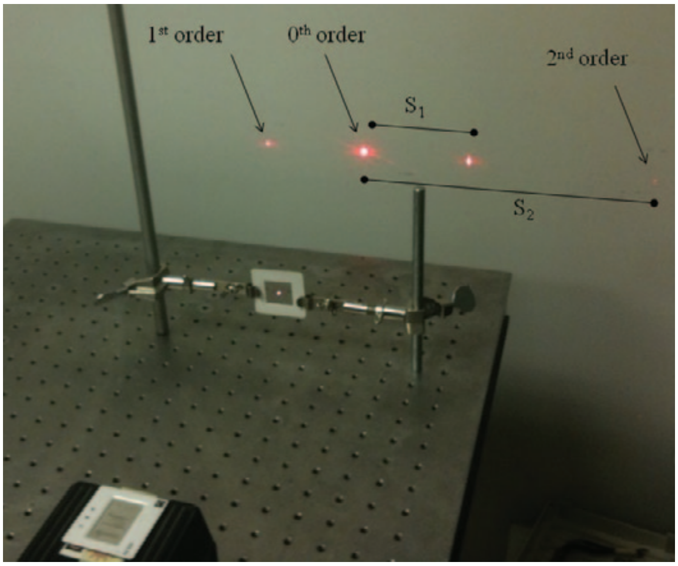
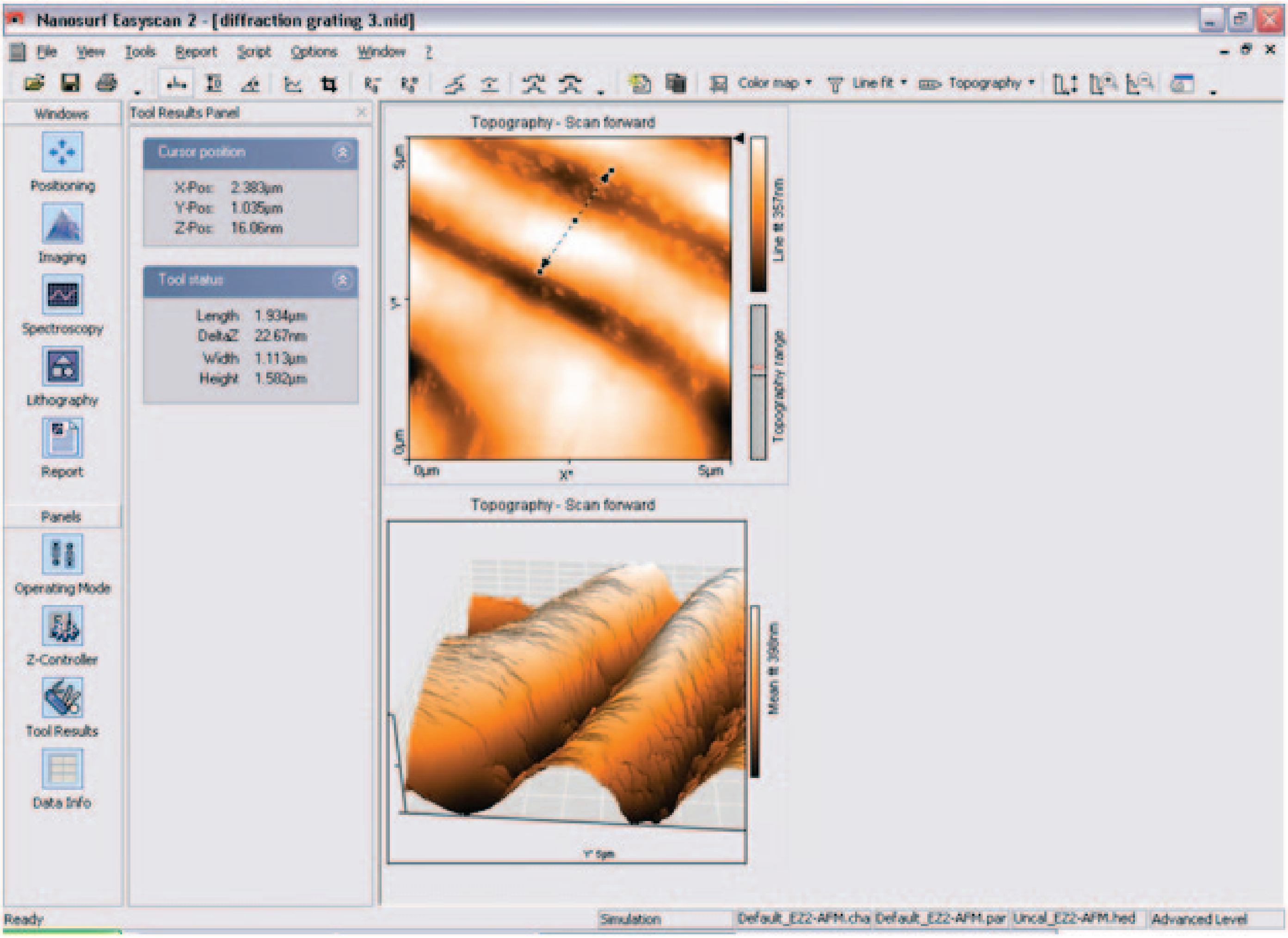


Figure 2: Top-down view of the experimental set up. A HeNe laser is pictured in the foreground, and the laser spot can be seen on the diffraction grating. The diffracted laser beams strike the wall, and the 0th, 1st, and 2nd orders of diffraction can be seen and are indicated. The distances S_1 and S_2 from the 0^{th} order spot to the 1^{st} and 2^{nd} order spots, respectively, are also indicated.

spare diffraction gratings. They then understood that the grating bends the path of light, depending upon its wavelength, similar to a prism. We began the activity for the younger students with the laser and the grating already aligned. After the students looked through the gratings at the white light, we then turned on the laser and showed them how the grating separates the monochromatic light into 0th, 1st, and 2nd orders. We then briefly explained the physics behind diffraction gratings and gave the students the diffraction equation. We asked the students what they thought they could do to find the grating spacing, given the existing experimental set up. All of the outreach groups were able to tell us that the angle could be calculated by making measurements of the distance from the grating to the wall and the distance between the laser spots on the wall. The students then made the appropriate distance measurements and calculated the angle using the inverse tangent. From the angle, they were then able to calculate the grating spacing d using the diffraction equation. For the middle and high school students, we began the second activity with the AFM already scanning the grating. We then supervised the students while they adjusted certain scan parameters, such as the scan size or position. We allowed the students to use the measuring tool in the software to determine the distance between the slits in the grating. They compared the two methods, and noted that the results were very similar for the two very different techniques.

College students in the senior level lab operated more independently. For our lab course, students work in groups of three on a single project for 2–3 weeks. They complete four projects each semester. For each project, they are required to acquire and analyze data, write a ten-page paper, and present a talk on their work. For the AFM project portion of the course, the students were required to complete two AFM learning modules, including this module and a learning module on magnification, which we do not discuss here. For this learning module, the students were required to set up the laser and diffraction grating themselves. They were also required to find the mean and standard deviation for the grating spacing using several different distances from the grating to the wall. The college students had little to no experience using AFMs prior to this lab. The main purpose of the lab for the college students was to introduce AFM, so they were required to read some literature on how AFMs work and understand the theory of the operation. After a brief orientation to the hardware and software, all the college students felt confident operating the AFM without constant supervision. They acquired all the images independently. They acquired several images of the grating at different



X-Pos: 2.383µm
Y-Pos: 1.035µm
Z-Pos: 16.06nm

Length 1.934µm
DeltaZ 22.67nm
Width 1.113µm
Height 1.582µm

Figure 3: Screen capture of the software that operates the Nanosurf Easyscan2 [1].

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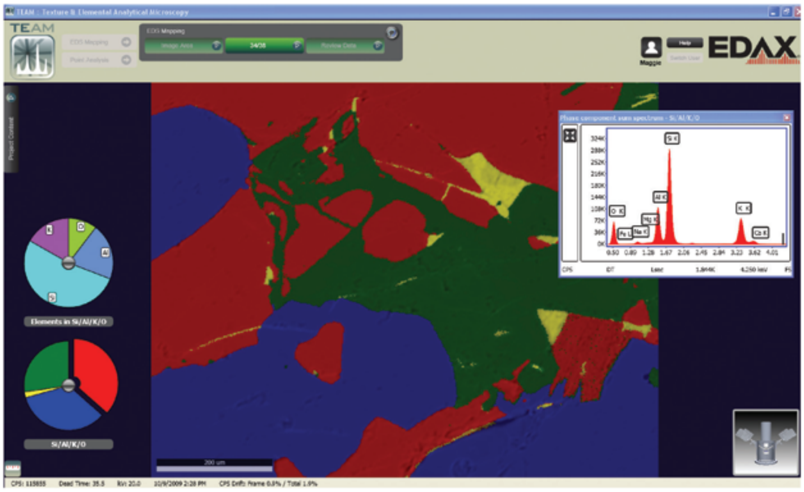

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magnifications (see Figure 4 for a sample of an image acquired by a student), and generated a mean and standard deviation for the grating spacing using the measuring tool at several different points from their various images. One group acquired 20 different measurements of the slit spacing. They estimated their uncertainty for each measurement as ± 9 nm, based on the resolution of the image acquired and their ability to position the line for the profile measurement. Because of variation of the spacings on the grating due to the manufacturing process, their calculated mean and standard deviation for the slit spacing was 1825 ± 40 nm. They then successfully showed that the values for the grating spacing obtained via the two different methods overlapped within the experimental uncertainty.

Student response. The middle and high school students, whose work with the module was not being graded and was carefully monitored and supervised, really enjoyed the project. They were excited to be working with advanced technologies such as the AFM and stayed engaged and focused for the duration of the outreach activity. After the experience was over, they had learned what diffraction gratings are and how they work. They also had a rudimentary understanding of how AFMs operate upon conclusion of the activity.

Reaction from the college students varied more. Problems included frustration that there were two sides to the grating and one side showed no spacings and some frustration with sample positioning and aligning the microscope. Others were impatient with the amount of time that it takes to acquire a single AFM image (especially those who were accustomed to working with light microscopy or scanning electron microscopy). What was most pleasing was students trying to really conceptualize what they were doing, such as why the spacings were not all exactly perfect and the same size. Other students immediately began thinking of error propagation and how to improve the measurement of the distance from the grating to the wall. Student presentations showed that there were still gaps in understanding the AFM operation, data analysis, and interpretation, but the physics of diffraction gratings was correct, showing a firm base from introductory courses.

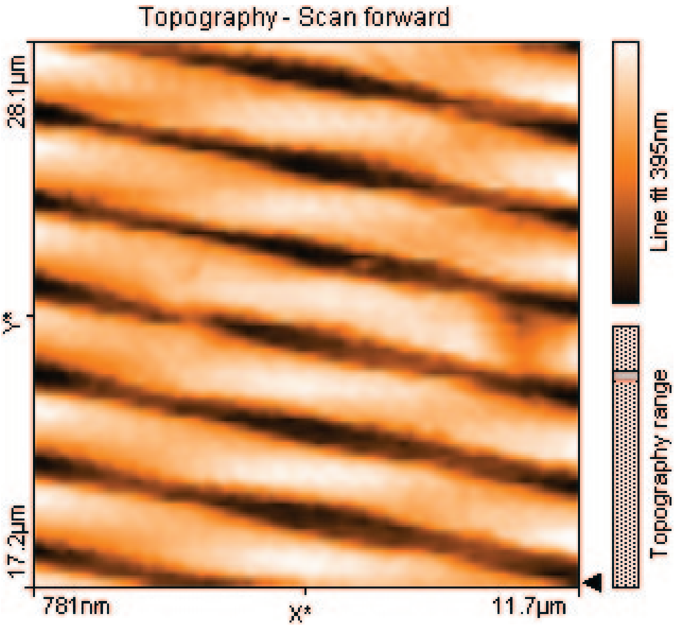

Figure 4: AFM image of a diffraction grating surface acquired by some of our students.

Future modules. We have developed and are currently testing other AFM learning modules not discussed here, including modules on magnification, roughness measurements, and phase imaging. Future modules also may be needed to address error propagation and artifact identification in the AFM.

Conclusions

This module demonstrated the diffraction of light by a grating, predictions from a well-known diffraction equation, and direct measurement of the grating slit spacing with AFM. Moreover, students learned about AFM from an experiential perspective; they will benefit from that experience in future careers.

References

[1] The system is manufactured by nanoScience Instruments, Inc. http://www.nanoscience.com/products/easyScan2/easyScan2.html

[2] See references on this topic published by nanoScience Instruments, Inc. http://www.nanoscience.com/education/AFM.html

[3] E Meyer, HJ Hug, and R Bennewitz, *Scanning Probe Microscopy: The Lab on a Tip*, Spring, Heidelberg, Germany, 2003.

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