secondary school chemistry section

edited by
Hal Harris
University of Missouri–St. Louis
St. Louis, MO 63121

Getting Close with the Instructional Scanning Tunneling Microscope

Carl Steven Rapp
University School, East Tennessee State University, Box 70632, Johnson City, TN 37614

Scanning tunneling electron microscopy (STEM) is a powerful technique that provides magnification of conducting surfaces to the atomic level. It is unfortunate that it is usually thought of as a tool only of the research laboratory, because the world of nanochemistry can greatly enhance teaching at the secondary level. My recent experience as a member of a group of twenty teachers selected to work for eight summer weeks with scientists at Xerox Corporation and professors at the University of Rochester has opened new vistas for me and my high school students. We learned to use the Burleigh Instructional Scanning Tunneling Microscope (ISTM), an instrument designed for educational use by the University of Rochester, Xerox Corporation, and Burleigh Instrument Inc. The images we can produce are not of the same quality as are often seen in the research literature. However, care in making a sharp, uncontaminated scanning tip and data collection in a vibration-free area can result in pictures that are more than adequate for the introduction of “atomic eyes” to my classroom.

The ISTM is useful in the study of the effect of acids and bases on metals and the surfaces of semiconductors (some experiments are described below). Cutting the platinum–iridium tip or preparing the tungsten tip and mounting the sample are hands-on activities that give students a glimpse of the technological nanoworld. This state-of-the-art instrumentation is making it possible for students to actually view atoms in their own classroom. What is truly amazing, however, is that the ISTM can be set up and atomic resolution images obtained in about an hour.

Background

Interest in an X-ray based microscope developed after it was recognized that electromagnetic waves of shorter wavelength provide better resolution. Electrons were first used in microscopy to take advantage of the wave nature of electrons, based on the de Broglie hypothesis, $\lambda = h/p$, where λ is the particle wavelength, p is its momentum, and h is Planck’s constant. Accelerated electrons, controlled by magnetic and electromagnetic fields, are used in the transmission electron microscope (TEM), which can resolve particles in the 2-Å range, in a manner not dissimilar in principle from optical microscopy. The scanning tunneling microscope (STM), invented by Gerd Binning and Heinrich Rohrer in 1981, works in a different way. It uses a sharp electrode that is moved very close to the surface of study, and the current between the surface and the probe is measured as a function of position. Binning and Rohrer won the Nobel prize in physics in 1986 for their work (*1*).

Figure 1 shows a photograph of the Burleigh instructional scanning tunneling microscope. The critical component of this ISTM is the head, which contains a sharp metallic scanning tip and the piezoelectric controller. The tip consists of a piece of platinum–iridium wire or tungsten wire about one centimeter in length. The platinum–iridium tip is prepared by cutting the wire at an angle of about 45 degrees, ideally terminating in a single atom. As an alternative, since platinum–iridium wire is very expensive, tungsten wire can be used. Cutting the tungsten, however, does not produce a sharp enough probe. The tungsten tip is prepared by treating the tungsten wire electrolytically in a 3–6 M solution of KOH at 35 V (under a fume hood). The exact method of preparation is described in the *Instructional Scanning Tunneling Microscope Workbook* (*2*); the workbook is highly recommended for high school teachers.

Operation of the ISTM requires that the sharp electrode tip be positioned extremely close to the surface to be imaged. This is achieved by using a sensitive stepping motor and piezoelectric transducers fitted in the head. The electronics of the system can position the tip within a nanometer from the sample surface. At this distance, the electron orbitals of the sample and the tip nearly overlap. A small bias voltage is applied between the tip and the sample and it is possible to measure the small current (on the order of nanoamperes) that results from quantum mechanical tunneling between them. Variations of approximately 1 Å in the tunneling gap between the tip and the sample surface results in an order-of-magnitude change in the tunneling current. This sensitivity provides ISTM with its high resolution power (*2–4*). Readers interested in learning more about the tunneling of electrons should consult other references (*5–8*).

To obtain the image of the sample, the tip is rastered across the sample surface using a piezoelectric crystal. One of the best explanations of what is meant by the term “rastered” is found in an article written by Kurt Wagner (*1*).

Figure 1. Image of the Burleigh ISTM set up in my classroom. Notice the head sitting on the cinder block (which is sitting on two small inner tubes) to dampen vibration.

He explains it this way: “Think of a blind man walking along with his white cane. He scans back and forth rapidly (the *x* axis) as he walks forward (the *y* axis). He senses bumps and depressions with his cane (the *z* axis).” The probe of the ISTM is analogous to the white cane moving back and forth (rastering).

The ISTM can obtain images in either of two modes. In constant-height imaging, the tip of the ISTM scans a relatively flat surface and the electron tunneling current is measured. Because the current is a strong function of the distance between the electrode and the surface, a graph of current as a function of position reproduces the surface morphology. In the topographic mode, the tip scans along the surface, in the *x*- and *y*- directions, following the surface shape, in order to maintain a constant current. The positions are stored in the computer as the *z*-component of position, and this is usually displayed on the monitor as a variation in brightness.

Electronic Data Collection

The result of using the ISTM must be an image. To get from quantum mechanical tunneling to a picture requires the use of a computer to interpret a collection of currents measured at the ISTM tip. The image is acquired one point at a time. A bias voltage is applied to the tip to produce a tunneling current between the tip and the sample, as the tip moves back and forth across the sample. The computer also generates signals that are amplified by the control unit to the piezoelectric transducer needed to move the tip in the *x*- and *y*-directions. In the topographic mode, the control electronics uses negative feedback to control the height of the tip so that a constant tunneling height is maintained above the sample surface (*2*).

The computer supplies voltages corresponding to the *x*- and *y*-directions and receives a current corresponding to the *z*-direction. The *x*- and *y*-voltages correspond to the lateral position, while the *z*-current corresponds to the height of the sample. The computer can plot this information of height versus lateral position. The *x*, *y* positions are the coordinates of a point on the computer’s display screen; the *z* value corresponds to the gray level of the display. High areas of the sample will appear brighter and low areas will appear darker (*2*).

ISTM Activities Suitable for the High School Chemistry Laboratory

A piece of copper was placed on the sample carrier and imaged at a bias voltage of −100 mV, a reference current of 2.00 nanoamperes, and a scan range of 30,000 by 30,000 Å (1 Å = 10^{-8} cm) in the topographic mode. This image (Fig. 2) shows a relatively smooth surface. Figure 3 shows the results of reaction (reaction time of 30 s) between the copper sample and concentrated nitric acid (15.8 M). Note the dark areas in this image; this shows where chemical etching has occurred on a nanometer scale. Using the True-Image Software supplied with the Burleigh ISTM, students can measure the depth of the pits formed by the etching action of nitric acid. This gives them a new perspective and realization of chemical reactions at the atomic level. Students are able to look at reactions and make measurements on a level previously only imagined.

Figure 4 shows the electron clouds of graphite atoms; notice the nice orderly arrangement of the atoms. Students notice this immediately. It gives them a sense of atomic structure never attained before. Using the software to produce a three-dimensional view of the image (Fig. 5) gives

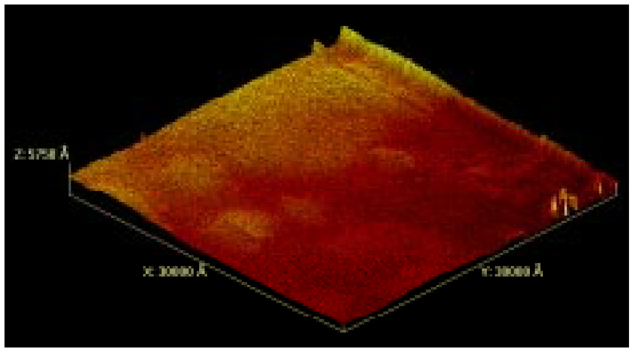

Figure 2. Image of untreated surface of the copper sample.

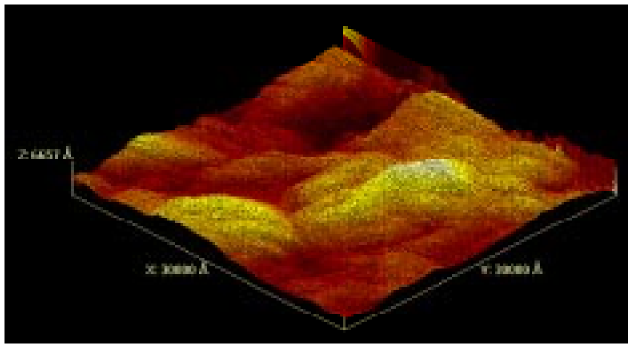

Figure 3. Copper sample treated with concentrated nitric acid (15.6 M).

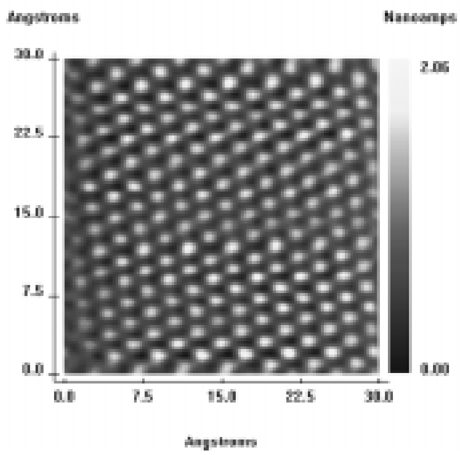

Figure 4. Individual graphite atoms.

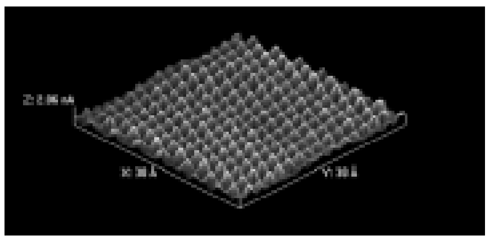

Figure 5. Three-dimensional view of graphite atoms (from Fig. 4).

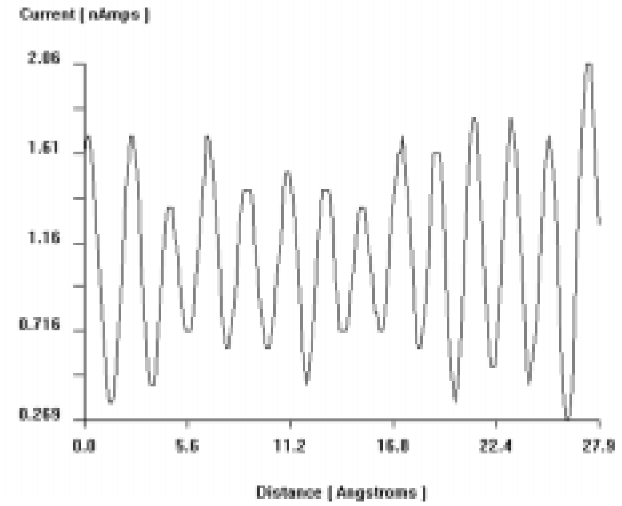

Figure 6. A cross-sectional view of graphite atoms (from Fig. 4).

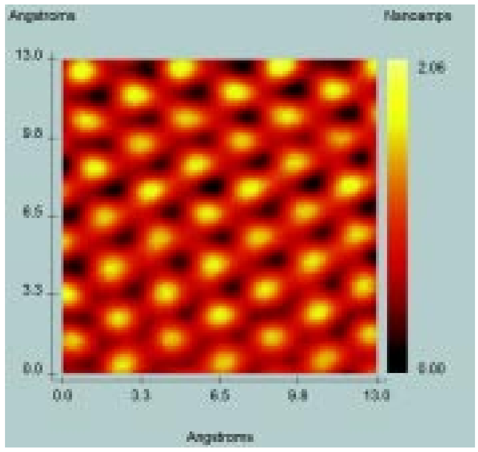

Figure 7. Magnified view of graphite atoms (from Fig. 4).

them another amazing view of the nanoworld. Here, they can measure the height of the atoms (the atom's atomic cloud). By making a cross-section view (Fig. 6) students can estimate the distances between the graphite atoms. By using Figure 7 (a magnified view of Figure 4), the diameter of the graphite atom was determined by my students to be about 2 Å. Students gain a sense of accomplishment by making measurements like this, using an atom-size "ruler".

This is the second year the ISTM has been in my classroom and it has created enthusiasm in our students, parents, administrators, and teachers in the study of science, using cutting-edge technology. More and more universities are developing programs such as the University of Rochester has with this project. Check with your local university to see if they might have an ISTM training and loan program. Readers interested in the University of Rochester STM program should contact Debbie Shannon, NSF Center for Photoinduced Charge Transfer, Department of Chemistry, Hutchinson Hall, Room 200, University of Rochester, Rochester, NY 14627; (716) 275-8286 or (716) 275-4231 or fax (716) 473-6889. You will be amazed at the possibilities of the ISTM, and your students will come to a new understanding of atomic structure.

Acknowledgments

I wish to thank William Herkstroeter, Dwayne Miller, Jack Kampmeier, Debbie Shannon, Mary Gilman, and Julia Rehm at the University of Rochester for their assistance and guidance in this project. Special thanks to Ravinder Rana for his help.

Literature Cited

1. Wagner, K. *Sci. Teach.* **1994,** *61*(3), 24–27.
2. Miller, R. J. D.; Mizes, H. A.; Samsavar A. *Instructional Scanning Tunneling Microscope Workbook*; Burleigh Instruments, Inc.: Fishers, NY, 1992.
3. Hansma, P. K.; Tersoff, J. *J. Appl. Phys.* **1987,** *61*, R1–R23.
4. Kuk, Y.; Silverman, P. J. *Rev. Sci. Instrum.* **1989,** *60*, 165–180.
5. Braun, R. D. *J. Chem. Educ.* **1992,** *69*, A90.
6. Coury, L. A., Jr.; Johnson, M.; Murphy, T. J. *J. Chem. Educ.* **1995,** *72*, 1088.
7. Reimschuessel, A. C. *J. Chem. Educ.* **1972,** *49*, A413.
8. Reimschuessel, A. C. *J. Chem. Educ.* **1972,** *49*, A449.