The Topografiner: An Instrument for Measuring Surface Microtopography

Russell Young, John Ward, and Fredric Scire published their paper on the topografiner in 1972 [1]. Nearly 30 years later, it is tempting to say that scanning probe microscopy (SPM) needs no introduction. The number of papers concerning this technique is now approaching 5000 per year (Fig. 1), so that hardly any technical professional with an interest in microscopy can have escaped acquaintance with one or more of its variants. The explosion of SPM activity began after publication of atomic resolution images of silicon [2] in 1983 and the award of the Nobel Prize in Physics to Binnig and Rohrer in 1986 made scanning tunneling microscopy (STM) famous. Today, SPM has found applications in physics (e.g., crystal and surface electronic structure of metals and semiconductors, superconductivity, liquid crystals), chemistry (e.g., catalysis, electrochemistry, Langmuir-Blodgett films, polymer morphology), biology (structure of nucleic acids, cells, proteins, lipids, etc.) and other fields. A recent chemistry-oriented review [3] referenced 33 other SPM-related reviews and books published in the preceding 2-year period alone!

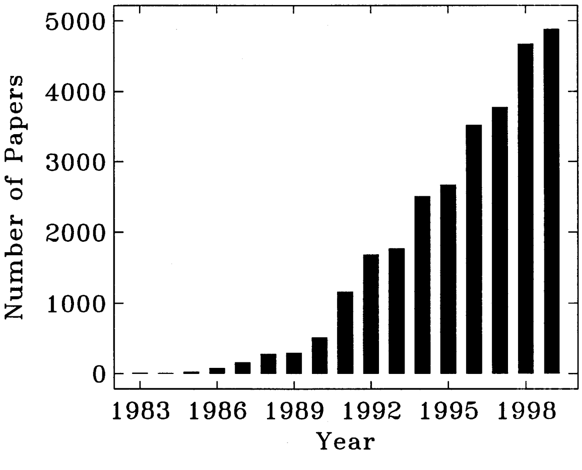

Fig. 1. Growth of publications in scanning probe microscopy, as determined by searching the ISI Science Citation Index.

There are four essential elements of a scanning probe microscope that distinguish it from other microscopes: 1) a very sharp mechanical probe, the tip of which is maintained in close proximity to the sample surface; 2) detection of a surface property (e.g., a tunneling current) that changes rapidly in the vicinity of the surface and therefore provides a very sensitive indicator of the tip-sample distance; 3) use of an electronic feedback system to control the tip-sample distance or to maintain a controlled low-force contact—essential to prevent damage to the sharp tip; and 4) the ability to position the tip with respect to the sample in three dimensions with sub-nanometer resolution, as for example through the use of piezoelectric devices. In the earliest implementations, a voltage was applied between the tip and a conducting sample. The feedback system maintained the resulting field emission or tunneling current at a constant value by adjusting the tip height as needed. The tip was then raster-scanned laterally across the surface (Fig. 2). The feedback loop responded by moving the tip normal to the surface, thereby tracing the surface topography at constant current and therefore approximately constant tip-sample separation. The resulting adjustments to the tip position were monitored, and they formed a record, to first approximation, of the surface topography. Other scanning probe microscopies use other near-surface properties, for example tip-sample force (AFM) or capacitance (SCM). Sometimes one property is monitored for feedback purposes while the image is formed from another, as in NSOM (near-field scanning optical microscopy).

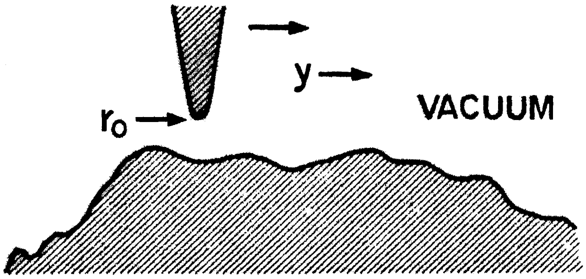

Fig. 2. Scanning the tip across a surface. This figure is from Ref. 4, where the concept of what eventually became the topografiner was first described.

The first successful scanning probe microscope was Russell Young's topografiner [1]. In this instrument, a field emission current between the tip and sample was employed for feedback control. The Royal Swedish

Academy of Sciences' press release announcing Binnig and Rohrer's Nobel prize for the scanning tunneling microscope gave substantial attention to Young's work: "The first to succeed in doing this [building an instrument that operated on the principle of maintaining a small constant distance between the sample surface and a sharp mechanical stylus] was the American physicist Russell Young at the National Bureau of Standards in the USA. He used the phenomenon known as field emission . . . However, Young realized, that it should be possible to achieve better resolution by using the so-called tunnel effect." [5]

A schematic of the topografiner is shown in Fig. 3. The specimen was mounted between spring- loaded copper clamps. This permitted thin specimens, for example replicas, to be held taut. An electrical current through the specimen could heat it for cleaning. A tungsten tip was attached to molybdenum bridges between two molybdenum rods. The emitter could be heated for cleaning by passing current through the bridges to which it was attached. The emitter assembly was mounted on a vertical "piezo." Piezoelectric ceramic materials expand and contract with applied voltage, producing continuously controllable motion with subnanometer resolution and a typical range of a few micrometers. The sample was brought into range of this device using a differential screw, which itself had a range of a bit more than 250 μm. The sample and tip were originally placed within this distance of each other manually, using an optical microscope to view the tip-sample separation and making coarse adjustments using the threaded connection in the tube that joined the tip assembly to the specimen assembly. The *X* and *Y* scan piezos deflected the rod supporting the emitter, thereby producing motion of the tip in the plane of the specimen.

The tip-sample separation was maintained by a feedback controller that adjusted the voltage on the vertical piezo to maintain a constant current through the tip-specimen junction. To form the images, the voltage applied to this piezo was recorded with either an *x-y* recorder or a storage oscilloscope during scanning. Unlike later STMs, the topografiner was rigidly attached to its vacuum chamber. Vibration isolation was all external. The chamber was mounted on a vibration isolation table and enclosed by an acoustical shield. Inside, a pressure of about 5×10^{-8} Pa (4×10^{-10} Torr) was maintained.

Young et al. discussed several tip-sample interactions. Two of these, field emission and metal-vacuum-metal tunneling, were explored in some detail. When the electric field in the vicinity of the tip is high enough, electrons may tunnel from the metal tip through the work-function barrier into nearby vacuum states. The amount of current is governed by the Fowler-Nordheim equation. This form of tunneling can work even at large tip-sample distances, provided the potential difference is kept high enough to create a large enough field. In metal-vacuum-metal (MVM) tunneling, the tip and sample are sufficiently close that electrons can tunnel directly from one to the other. It was with this form of tunneling that STMs later resolved individual atoms on surfaces. Young et al. calculated that for the field and work function expected for their operating conditions and tip, MVM tunnel current became an important contribution for tip-sample separations less than 2 nm and completely dominated the measured current by 1 nm.

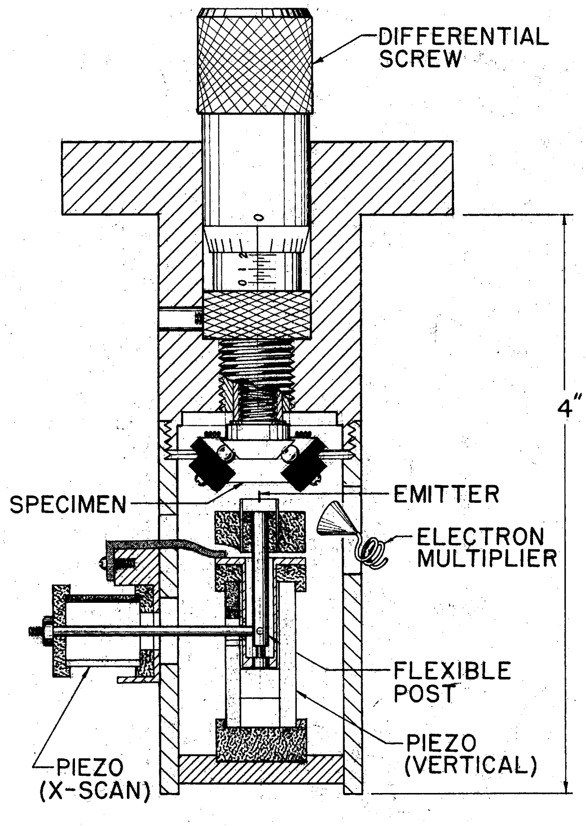

Fig. 3. Schematic of the topografiner (from Ref. [1]).

With the servo loop inactive, Young et al. measured current-voltage (*I-V*) curves at a variety of tip- sample separations, which they estimated ranged from 1.2 nm to 2.7 nm. At the lowest separation, they were measuring currents of up to 5 nA at voltages below 0.5 V. These conditions would be widely regarded in light of present-day experience with STMs as being well within the MVM tunneling regime, supporting their claim [1,6] that these were the first recorded MVM *I-V* curves. They mention several applications of MVM studies, including the measurement of tunneling spectra, thus anticipating scanning tunneling spectroscopy, which was implemented by others in the early 1980s.

Despite the recognized advantages, the instrument was not operated closed loop in the MVM tunneling mode because of vibrational noise and instability in the feedback electronics in that mode. Instead, images were acquired in field emission mode. A section of the paper was devoted to demonstrating that the measurements were consistent with Fowler-Nordheim tunneling. The imaging capability was demonstrated on a 180 line/mm diffraction grating replica (Fig. 4). Young et al. estimated the resolution to be 3 nm perpendicular to the surface and 400 nm in the plane. They estimated the instrument was capable of an ultimate resolution of 0.3 nm (one atomic layer) perpendicular to the surface, limited by noise, and 20 nm in the lateral direction, limited by tip radius.

In yet another imaging mode, secondary electrons generated by the field emitted electrons upon impact with the sample were collected by a nearby electron multiplier (see Fig. 3). The secondary yield as a function of tip position produced an image of the surface analogous to that created in a scanning electron microscope. This is interesting because it implements an imaging mode in which a property of the surface other than the one being employed by the feedback system is used to create images. The detector does not need to have focusing optics in order to determine the source of the particles because the tip localizes the excitation. This mode anticipated similar strategies employed later, for example the collection of photons generated at the tunnel junction of an STM.

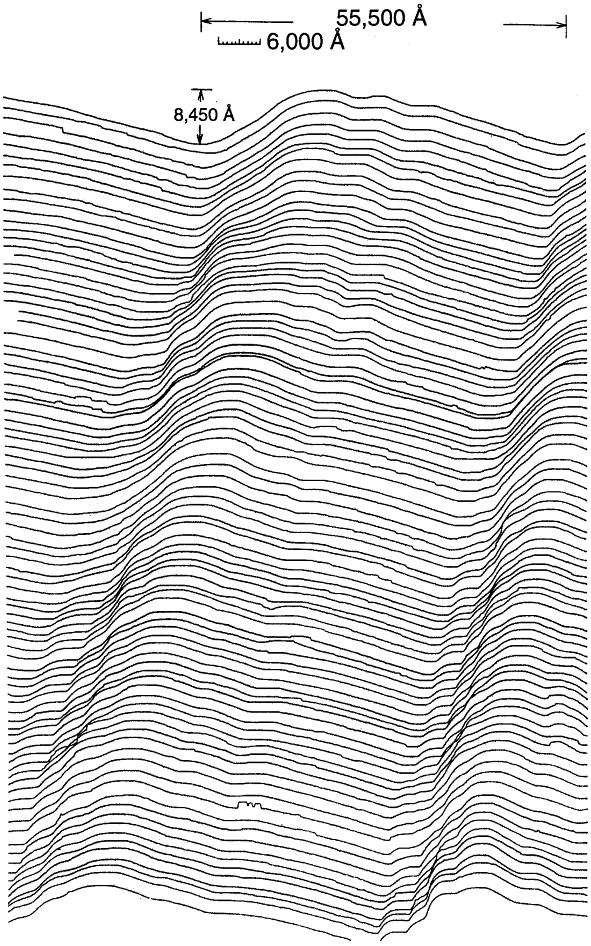

Fig. 4. Topographic map of ruled diffraction grating with the Topografiner. Labeled distances are in ångströms. 1 Å = 0.1 nm. (From Ref. [1]).

The development of the topografiner began in the context of a burst of surface studies following World War II, when many new surface analysis techniques were becoming available. In the late 1960s surface scientists sought to study single-crystal surfaces, where theory and experiment could be compared in the study of corrosion, catalysis, surface electronic properties, and other surface properties of importance to the nascent microcircuit industry.

At NBS, Young collaborated closely with other surface scientists (see the account in this volume on *Resonance Tunneling of Field Emitted Electrons through Adsorbates on Metal Surfaces*). The seeds of the ideas leading to the topografiner are discernible in Young's prior experiences. Before receiving his B.S. degree in physics, he served in the military for three years during World War II. Concerning this time, he said, "I used radar to automatically track enemy planes and simultaneously direct antiaircraft guns to intercept them. Tight servo loops were used to lock in the plane's position. I had previously studied television theory which uses a raster scan to form the picture." During and immediately after his Ph.D. studies, he was active in the study of field emission, attracting wide attention, for example, for an important paper on the energy distribution of emitted electrons as a probe of the electronic state of surfaces [7]. It was natural, given his search for a new surface characterization microscope, for Young to combine these technologies.

In 1966, Young investigated and published the performance of an instrument he called the field emission ultramicrometer [4]. This was a device for sensing surfaces with a field emission tip and measuring distances or displacements. It resembled the topografiner in its use of field emission as a probe of tip-sample separation, but did not use feedback to control the separation and did not have the capacity to scan the tip in the plane of the sample. In the final figure of that paper, part of which is reproduced here as Fig. 2, Young suggested the addition of these elements to create a microscope with extremely high vertical resolution that could record the detailed contour of a complex surface.

In 1969 a project to carry out this plan was approved by NBS management. Young was able to employ a technician, Fredric Scire. Starting with the availability of laboratory space in 1970, Scire and Young worked closely together designing, constructing, testing, and publishing the topografiner investigation. John Ward joined the project after the instrument had been substantially constructed. He developed tip preparation methods and performed early experiments on operation of a field emission probe in air. The electronic characteristics and sensitivity of the topografiner, and the observation of metal-vacuum-metal tunneling with it, were described in 1971 [6]. The instrument's first published images were included in Young's review of surface microtopography techniques for *Physics Today* [8]. In July of 1971, shortly before publication of those articles, NBS management terminated the topografiner project to concentrate effort into a program to provide calibration artifacts to the microcircuit industry. The final design of the instrument, together with the theory of its operation and its actual performance, were afterwards published in the title paper [1].

Today, we have the advantage of many years of instrument development, tens of thousands of publications by researchers all over the world, and the commercial production of SPMs, which have become a ubiquitous and relatively inexpensive tool. But Young and his coworkers were breaking new ground with the topografiner, not following any existing recipe. If first attempts teach anything, then second attempts must be better, so it is no surprise that the topografiner had deficiencies compared to current instruments. But the remarkable thing, from the perspective of a modern SPM researcher, is the soundness of judgement with which Young, Ward, and Scire analyzed the deficiencies of their own instrument and planned improvements to it.

For example, the topografiner differed from current implementations of the STM by the absence, in the topografiner, of a logarithmic or otherwise variable amplifier in the feedback control circuit. With the benefit of experience, we can say that this is most likely the reason the topografiner's feedback control became unstable in MVM tunneling mode. The exponential increase of tunnel current with decreasing tip-sample separation means the servo loop gain increases exponentially as the tip enters tunneling range. The high gain coupled with inevitable mechanical resonances results in an unstable amplifier condition. Remarkably, Young had correctly diagnosed the problem. The paper included a graph of servo loop gain for various tip-sample separations and described the resulting instability. At the time the project was cancelled Young's proposed program included a task to "Develop improved servo loop with ability to handle variable gain feature inherent in field emission devices . . . " [9]. This improvement alone might have made possible the acquisition of images in MVM tunneling mode.

The instrument also had in common with Binnig and Rohrer's first STM a rather soft mechanical loop. The resulting low resonance frequencies exacerbate feedback loop stability problems, forcing the instrument to be operated at lower scan rates. Later instruments raised the mechanical resonance frequency by reducing the amount of mass that had to be moved by the z piezo and making the mechanical loop between the sample and the tip as small as possible. Young et al. commented in their section on the servo loop that "these mechanical resonances, which must be eliminated in the next generation of the instrument, cause phase shifts and thus servo loop instabilities."

As mentioned earlier, the topografiner was rigidly attached to its vacuum chamber. Beginning with Binnig and Rohrer, vibration isolation systems for SPMs include an isolation level between the instrument and its vacuum chamber (if there is one). This greatly reduces the transmission of acoustical noise, picked up by the large vacuum chamber, to the instrument. Instead, the topografiner was surrounded by an acoustical isolation shell. Even without internal vibration isolation, the topografiner demonstrated noise levels as low as 0.3 nm. This level of noise would not have prevented scanning in MVM tunneling mode, and its reduction would have been an evolutionary improvement.

The achievements of the project are better appreciated by reflecting upon some of the difficulties with which the principals had to contend. The topografiner did not have computerized data acquisition, taken for granted in today's instruments. The first integrated circuit computers were only beginning to be available at the time of the project (The PDP 8 was introduced in 1970), so data acquisition was with x-y recorder and storage oscilloscope. Feedback circuitry was a challenge. Severe funding limitations prevented the purchase of modern electronic equipment.

Perhaps chief among their difficulties was the difficulty inherent in being the first in any exploration. One to a certain extent stumbles around in the dark, aware of some goals without knowing precisely how to reach them and perhaps completely unaware of other treasures that may lie within reach. One such was atomic resolution. The possibility of laterally resolving individual atoms by such a technique was not suspected by anyone at that time. Young et al., and later Binnig and Rohrer, at first viewed tips as "a kind of continuous matter with some radius of curvature" [10]. The lateral resolution was therefore expected to be limited to something on the order of the tip radius, at that time approximately 100 nm for state of the art field emission tips. Images of atoms were an unexpected gift, a consequence of the existence of minitips or other roughness on the tip surface, together with the strong distance dependence of tunneling, which causes the nearest minitip to dominate.

We should not let speculation about could-have-beens detract from the accomplishment that was. In the space of the two years from first funding to project termination, Young et al built a new kind of microscope which was non-contacting, non-damaging, capable of three dimensional imaging, and which compared favorably in its topographic resolution to the best instruments of the time. They demonstrated a new principle of operation, analogs of which are now making significant contributions to every area of microscopy. And they obtained the first *I-V* characteristic curves for metal-vacuum-metal tunneling.

In addition to the notice, already mentioned, in the 1986 Nobel citation, Russell Young received a Presidential Citation in 1986. In 1992 he received the Gaede-Langmuir Award from the American Vacuum Society "for his invention of the Topografiner, an instrument which led to the development of the scanning tunneling microscope." Today, the topografiner resides at the Smithsonian Institution.

Prepared by J. S. Villarrubia, with assistance from R. D. Young, F. Scire, E. C. Teague, and J. W. Gadzuk.

Bibliography

[1] R. Young, J. Ward, and F. Scire, The Topografiner: An Instrument for Measuring Surface Microtopography, *Rev. Sci. Instrum.* **43**, 999-1011 (1972).

[2] G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, 7×7 Reconstruction on Si(111) Resolved in Real Space, *Phys. Rev. Lett.* **50**, 120-123 (1983).

[3] L. A. Bottomley, Scanning Probe Microscopy, *Anal. Chem.* **70**, 425R-475R (1998).

[4] R. D. Young, Field Emission Ultramicrometer, *Rev. Sci. Instrum.* **37**, 275-278 (1966).

[5] Press release, Royal Swedish Academy of Sciences, October 15, 1986 (Text in brackets not in original).

[6] R. Young, J. Ward, and F. Scire, Observation of Metal-Vacuum-Metal Tunneling, Field Emission, and the Transition Region, *Phys. Rev. Lett.* **27**, 922-924 (1971).

[7] R. D. Young, Theoretical Total-Energy Distribution of Field-Emitted Electrons, *Phys. Rev.* **113**, 110-114 (1959).

[8] R. D. Young, Surface microtopography, *Phys. Today* **24** (11), 42-49 (1971).

[9] R. D. Young, memorandum to Dr. John Simpson, July 19, 1971.

[10] G. Binnig and H. Rohrer, Scanning Tunneling Microscopy—from Birth to Adolescence, *Rev. Mod. Phys.* **59**, 615-625 (1987).