

Wide-range, low-operating-voltage, bimorph STM: Application as potentiometer

by P. Muralt
D. W. Pohl
W. Denk

An STM is described which operates at voltages ≤ 120 V. Its 3D scanner offers a wide range of displacements, has low drift and hysteresis, and exhibits good resolution. These features make it interesting for technical applications. In addition, its use as a potentiometer is described.

1. Introduction

Scanning tunneling microscopy (STM) is a novel surface-analytical method for real-space imaging of surface structure and chemistry on an atomic or near-atomic scale [1, 2]. The surface properties are sensed by the tunneling current flowing from or to a fine metal tip scanned over the surface. The three main components of the STM are the 3D fine ($< 1 \mu\text{m}$) and coarse ($> 1 \mu\text{m}$) controls of the position of the tunneling tip and the vibration-isolation and damping stages.

In most of the instruments currently in use, the fine as well as the coarse controls are fabricated from piezoceramic plates, typically about 3 mm thick [1, 3]. As a consequence, high voltages are needed for the micrometer displacements required, typically 2 kV/ μm . The maximum displacement with such an arrangement is restricted to 1 to 3 μm in view

of the maximum permissible voltage of about 2 kV and a length of a few centimeters. The latter condition is derived from the stringent stiffness requirements as discussed, for instance, by D. W. Pohl [4].

A 1- μm range is completely sufficient when homogeneous surfaces without macroscopic structures are studied. If, however, certain localized features on the surface have to be found, it is important to have at one's disposal a larger range of displacements, for example, 10 to 20 μm . STMs with such a scanning capability are needed for the investigation of integrated circuits and other small technological ("man-made") structures, as well as for "low-end" applications aiming at low-resolution, large-field-of-view tunneling micrographs. It is also frequently desirable to avoid high voltages in the application of an STM, be it for reasons of safety, cost, or electrical perturbation.

In the present paper, a tunneling microscope with a large scanning range is described. The scanner is built with piezoelectric bimorph elements which provide very large displacements as compared to massive elements, even when the operating voltages are kept in the 100- to 200-volt range.

For coarse positioning, a step motor of the "louse" type [1] was constructed from piezoelectric tubes. Such tubes also provide increased displacement when compared to massive material of similar stiffness. This allowed a reduction of the operating voltage to the 100–200-V range, too. The present STM—which we call the "bender STM"—therefore avoids completely high voltages. This is of particular interest for operation at ambient pressure or in manufacturing environments.

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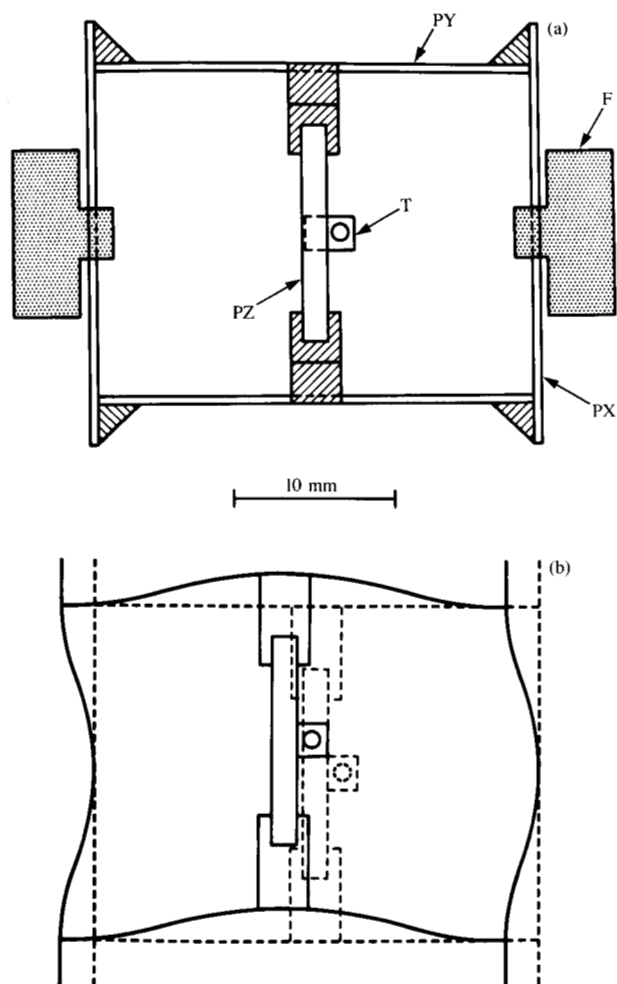


Figure 1

(a) Drawing of the scanner as seen from the top (looking in the z-direction). PX, PY, PZ: piezoelectric bimorphs producing displacements in the x-, y-, z-directions, respectively; T: tip holder; F: fixation to base plate; shaded pieces: macor. (b) Schematic showing the displacement mode of the x- and y-bimorphs.

The instrument was first tested under ambient conditions using a gold crystal as sample material. Next, the bender STM was used to explore a new application, potentiometry with STM resolution. Potentiometric micrographs were obtained from a planar metal-insulator-metal (MIM) structure.

2. Instrument description

The bimorphs used for the scanner consist of pairs of thin parallel-polarized piezoceramic sheets attached to a common center electrode. The outer electrodes are connected. A voltage applied between inner and outer electrodes creates fields of opposite directions within the layers. One layer

shrinks, the other one expands, producing a bending motion. The resulting transverse displacement is larger than the longitudinal expansion of a single sheet by a factor of ℓ/s (ℓ = length, s = separation of the centers of the layers). It is hence equal to $(\ell^2/sd)d_{31}V$ (d = thickness of piezoelectric layer, d_{31} = relevant piezoelectric coefficient, V = applied voltage) in the case of the usual mount with one end clamped, the other one free. Owing to small values of $d \approx s$ of commercial bimorphs, the ratio of displacement versus applied field is several hundred times larger than for the above-mentioned plates. One cannot fully exploit the large sensitivity, though, since the small thickness implies reduced stiffness of bimorphs as compared to massive plates. When the bimorph is adjusted to the same stiffness by reducing length and load, there remains a net gain in sensitivity of about 10 to 30 times, allowing the above-mentioned low-voltage operation [4].

Schematic drawings of the three-dimensional scanner are shown in Figure 1. Four bimorphs arranged to form a square [Figure 1(a)] provide lateral displacements in the x- and y-directions. The center parts of the x-bimorph pair are connected to the STM frame, while the centers of the y-pair are connected to each other by two shorter bimorphs. The latter produce displacements in the z-direction normal to the sample. They are needed for tunnel-distance regulation.

The electrodes of the bimorphs are cut and connected in such a way that the outer quarters bend opposite to the inner halves. Thus, the ends stay parallel with the centers [Figure 1(b)]. Tip and tip holder are mounted between the centers of the z-pair. Macor pieces and vacuum epoxy glue were used for the relative fixation of the piezoelectric elements. The piezoelectric elements are clamped to stainless-steel plates screwed to a macor block (Figure 2). The various wires connected to the electrodes of the piezoelectric elements are fixed and interconnected at the upper side of the macor block (not visible in Figure 2) to reduce the number of electrical connections.

The high symmetry of the scanner arrangement with the tip at its center provides a large degree of thermal stability: Upon temperature change, thermal expansion moves the corners of the square while leaving the center quite unaffected. As a result, in conjunction with a similarly stable sample mount described below, drift of the tip-to-sample position is very small in the bender STM.

The bimorphs used in the present setup are types R102P and R050P from Piezoelectric Products Inc. [5] for the x, y-pairs and the z-pair, respectively. Their dimensions are 25.4 mm $\times$ 6.4 mm $\times$ 0.5 mm (R102P) and 13.5 mm $\times$ 1.6 mm $\times$ 0.5 mm (R050P). When used in the mode described above, the displacement is twice the value of the quarter length, i.e., $1/2$ of the full excursion of an unmodified element. The piezoelectric element's responsivity calculated from specifications [5] yields 105 nm/V for the x- and y-bimorphs. In reality, this number is smaller than that

calculated owing to the need for fixation space. The measured number is 65 nm/V. For the z-bimorphs, a value of 6.4 nm/V was measured. Operating with a maximum voltage of ± 120 V results in a total range of ± 7.8 μm laterally and ± 770 nm in the direction of the tip. These numbers were determined with the help of an inductive transducer with a resolution of 10 nm.

The lowest eigenfrequencies of the scanner were obtained as 1.3 kHz for the x- and the y-motion, and 5.0 kHz for the z-element. They were measured by means of a Fourier analyzer. One bimorph was excited with a frequency-swept ac voltage. The electrical response of the parallel bimorph was detected. Alternatively, a signal could also be picked up from a neighboring bimorph—say, from one of the y-bimorphs while exciting the z-pair—because of a small, but finite, amount of coupling between the different modes. **Figure 3** shows a spectrum obtained with the latter configuration. The 5-kHz resonance of the z-element can be clearly recognized, while the resonance of the y-bimorphs at 1.3 kHz is only weakly excited.

One of the most delicate problems was mounting of the tip holder. In order to keep the load on the scanner system sufficiently small, the tip holder has to be as tiny as possible. The dimensions of the present holder are $2 \times 2 \times 2.5$ mm³. It is made of stainless steel, and has a hole of 1-mm diameter for mounting the tip. The holder is glued between the z-bimorphs together with two electrodes connected to signal ground which shield the tip from leakage currents from the z-bimorphs. The wire to the tip and the tip itself are clamped into the hole by means of the wedge-like shape given to the shaft of the tip.

For coarse movements, a "louse" was built from piezoelectric tubes as driving elements. The louse is a triangularly shaped device with three feet at the corners connected by piezoelectric elements which allow the relative position of the feet to be changed [1]. With an appropriate sequence of pulses applied to the piezoelectric elements and electrostatically clamped feet, the louse transports a sample in a stepwise manner to the tip. In our design, tubes one inch long (EBL No. 2 [6]) occupy the sides of the triangle. They are glued to three macor edge elements, to which the feet are fixed.

The sample holder, inclined 60° with respect to the horizontal, is screwed to one of the edge elements and thus stays above one of the feet. This feature ensures minimum lateral drift of the sample with respect to the base plate. The feet are made of aluminum and have an anodized oxide layer as isolation. The relative positioning of louse and scanner can be seen in the photograph of **Figure 4**, showing the STM from the side.

The performance of the louse was tested with an inductive transducer the head of which was mounted on the sample holder. Good reproducibility of the motion was observed. In a typical mode of operation, we measured regular steps of

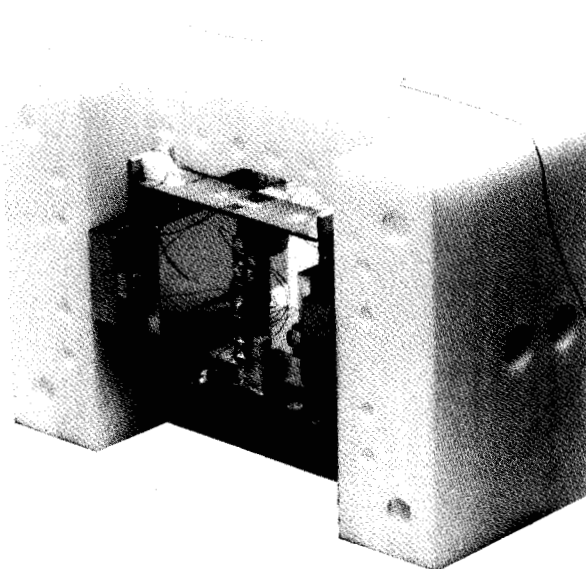


Figure 2

Three-dimensional bimorph scanner as seen from below.

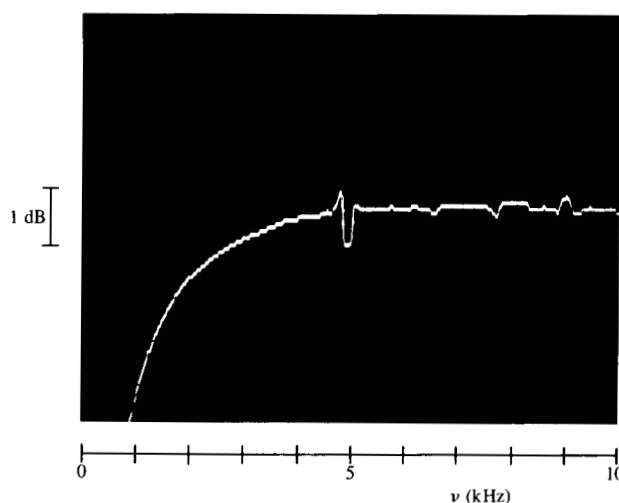


Figure 3

Excitation spectrum of the z-bimorphs measured with the y-bimorphs.

0.5 μm at a rate of two steps per second with 120-V and 70-V pulses applied to tubes and feet, respectively.

For vibration isolation, a stack of metal plates with rubber dampers between each pair of plates was used, as was first applied by Gerber et al. [3]. The cutoff frequency of the stack is about 40 Hz. The instrument was placed on an optical table with an eigenfrequency of 5 Hz to shield it from

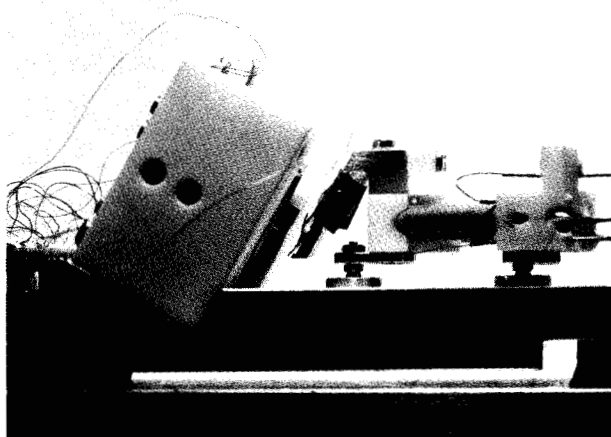


Figure 4

Side view of the bender STM.

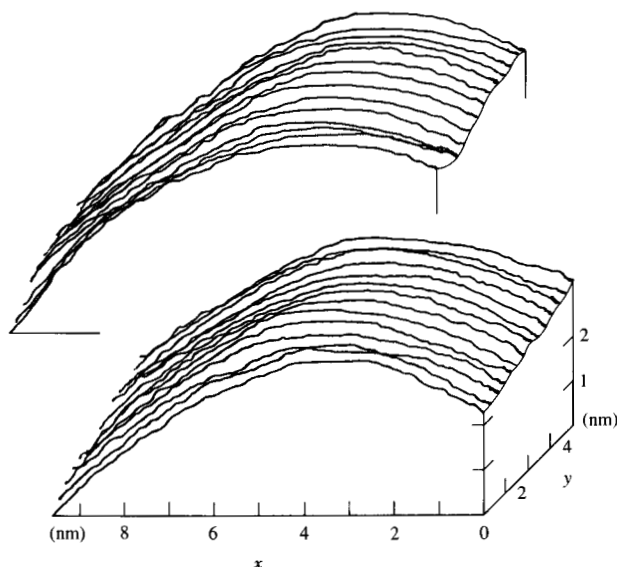


Figure 5

Two sequentially scanned images of a gold (110) surface ($U_T = 80$ mV, $I_T = 1$ nA).

building vibrations of 17 Hz. It was also possible, however, to operate the instrument on a desk top with decent resolution. The residual influence of temperature changes was reduced by packing the instrument into a heavy brass box. The latter also helps to keep away low-frequency sound waves, for instance from pumps and voices in the laboratory.

The electronic part of the instrument is built in a compact manner. All 120-V parts are gathered in one unit with three

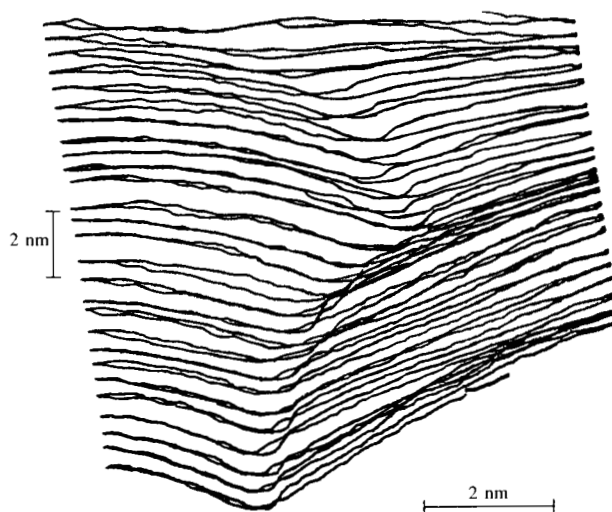


Figure 6

Forward/backward scans performed immediately after approach. Changes in y - and z -directions are due to drift. Same sample as in Figure 5.

operational amplifiers (Burr-Brown 3582 or 3584, 145-V maximum output signal). The layout allows the selection of gain in several steps between 1 and 10. The voltages for tubes and feet of the louse are taken from the same unit (140-V supply).

The rest of the electronics is standard design except for the x/y -scanner control signals, which are produced by a self-made ramp and step generator housed in the same frame as the tip-to-sample separation feedback circuitry. The scanning area can be chosen continuously, and the number of lines within this area is selectable. The outputs for the recorder are normalized and produce a pseudo-perspective view of the line scans.

Test images were mostly made on a gold (110) surface. The stability of the feedback signal corresponds to residual fluctuations of the tip-to-sample separation within less than $0.5 \text{ \AA}$. Some results are shown in Figures 5 and 6.

The two images in Figure 5 demonstrate drift and resolution. They were scanned with the same x - and y -offsets, the second one two minutes after the first. The drift amounts to about $10 \text{ \AA}$ in both directions, thus yielding a drift speed of about $5 \text{ \AA/min}$. Monoatomic steps at the slope of the hill are well resolved.

Figure 6 shows scans measured with forward and backward scanning on the same line (no change of y -offset) shortly after the tip had approached the sample. The lateral position of steps is reproduced within a range of 1 to $2 \text{ \AA}$, irrelevant of scanning direction. The drift to lower z -values is mainly due to thermal nonequilibrium after the optical

microscope lamp is switched off. The figure demonstrates the small hysteresis and temperature sensitivity of our scanner system.

3. Scanning tunneling potentiometry (STP)

When a voltage is applied across a sample specimen as sketched in **Figure 7(a)**, the tunneling voltage becomes a function of tip position. This effect can be exploited to map the potential distribution on the sample surface together with its topography [7].

In order to differentiate between topographic and potentiometric variations, we applied an ac tunneling voltage $U_{T1} = \hat{U}_{T1} \cdot \sin \omega t$ to both sample electrodes while maintaining a dc voltage difference ΔU between the electrodes. The tip was held on ground potential via a current-to-voltage converter; i.e., $U_{TIP} = 0$. The ac part of the tunneling current was used for tip-to-sample distance control. The dc part of the tunneling current was regulated to zero by shifting potential of the sample by the amount U_{REGL} . Hence, U_{REGL} is a direct measure of the local potential at the site of the tip. The two electrode potentials read as

$$U_1 = U_{REGL} + \hat{U}_{T1} \cdot \sin \omega t, \quad (1)$$

$$U_2 = U_{REGL} + \hat{U}_{T1} \cdot \sin \omega t + \Delta U. \quad (2)$$

No steady current between tip and sample is needed for the measurement of the local potential. Thus, the method works similarly to an impedance bridge with the advantage of zero-current detection. Potentiometric measurements can therefore be performed even on highly resistive samples.

The tip-to-sample separation is somewhat sensitive to ohmic effects when the resistance between the site of the tip and both electrodes becomes of the order of the tunneling resistance or larger. It has to be kept in mind, however, that the separation depends only on the logarithm of the actual tunneling voltage.

The control system is shown schematically in **Figure 7(b)**. The distance is regulated for constant ac tunneling current by means of a lock-in amplifier (LI) in addition to the usual logarithmic amplifier (LG) and control circuitry (PI). The distance regulation can be operated between 0.5 and 3 kHz in our present setup. The potential is adjusted with the help of integrator I. Its output is equal to U_{REGL} in the feedback loop.

Tests were performed with a planar metal-insulator-metal (MIM) structure. The latter was obtained from a gold-island film after electroforming in the presence of organic material. The preparation and properties of such structures are described in a number of papers [8-11]. A micro-slit about 1 μm in diameter is formed between two interconnected gold films, as illustrated in **Figure 7(b)**.

In **Figure 8**, STM scanning images of the interconnected, $\approx 1\text{-}\mu\text{m}$ -thick gold film are shown. Nearer to the slit (**Figure**

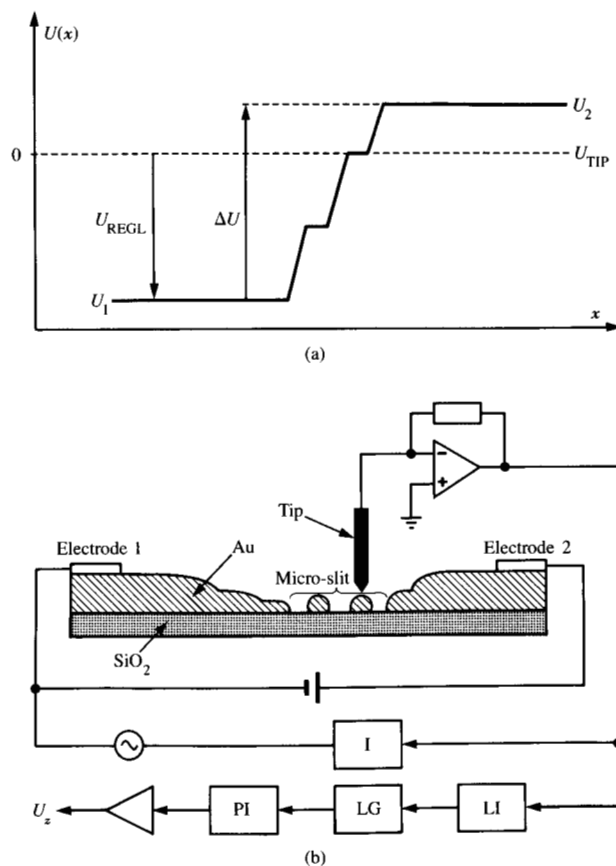


Figure 7

(a) Schematic of potential distribution. The local potential $U(x)$ at the site of the tip is shifted to ground potential by potential regulation. (b) Schematic of sample and feedback circuitry. LI: lock-in amplifier, LG: logarithmic amplifier, PI: control circuitry. U_z is the voltage applied to the z-piezoelectric element.

9), the film gets thinner and the typical granular structure shows up. Various experiments showed that the apparently isolated gold islands inside the slit are connected by some kind of conducting filaments containing mainly carbon [11]. The conduction mechanism across the slit is not yet well understood, but is of considerable interest because of intriguing switching, memory, and other effects. The voltage across the slit does not drop uniformly, but changes abruptly at certain "hot spots." Photoemission indicates field strengths of up to 10^9 V/m in these areas [10]. Direct detection of such localized voltage drops, however, has so far been impossible with conventional methods.

Figure 10(a) shows a potentiometric image, and **Figure 10(b)** its corresponding topographic scanning image. The signals for potential and distance were recorded simultaneously on a two-channel x-y recorder. The pictures demonstrate the signal stability when almost no voltage drop

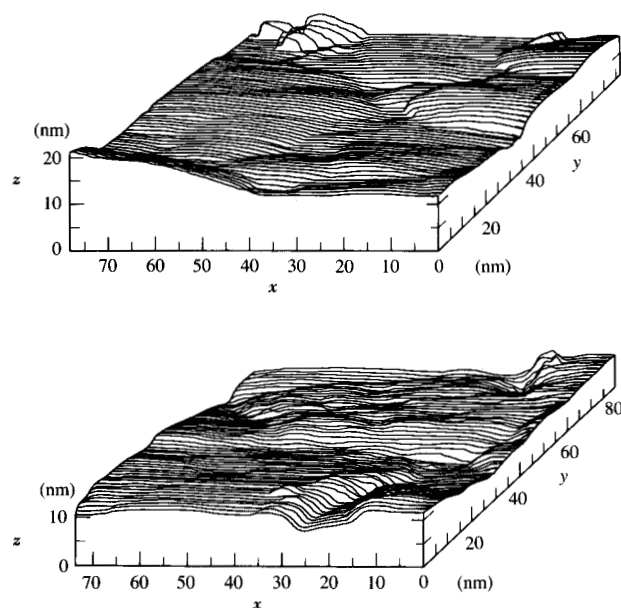


Figure 8

Two STM scanning images of a 1- μm -thick gold film evaporated on quartz.

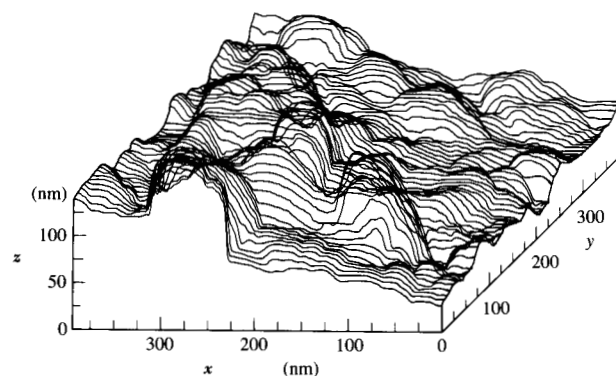


Figure 9

STM scanning image of thin, granular, but still interconnected gold film evaporated on quartz.

is encountered. The potential is nearly flat, indicating a relatively good electric connection between gold islands situated on the same side of the line at which the voltage drops. The smooth areas result from tunneling on gold surface areas, which is obvious from comparison with scans outside the micro-slit. Hence, noisy scanning sections must be ascribed to the ill-defined areas between the gold islands.

A scanning image of the voltage drop is depicted in the upper portion of **Figure 11**. The area scanned was $800 \text{ nm} \times$

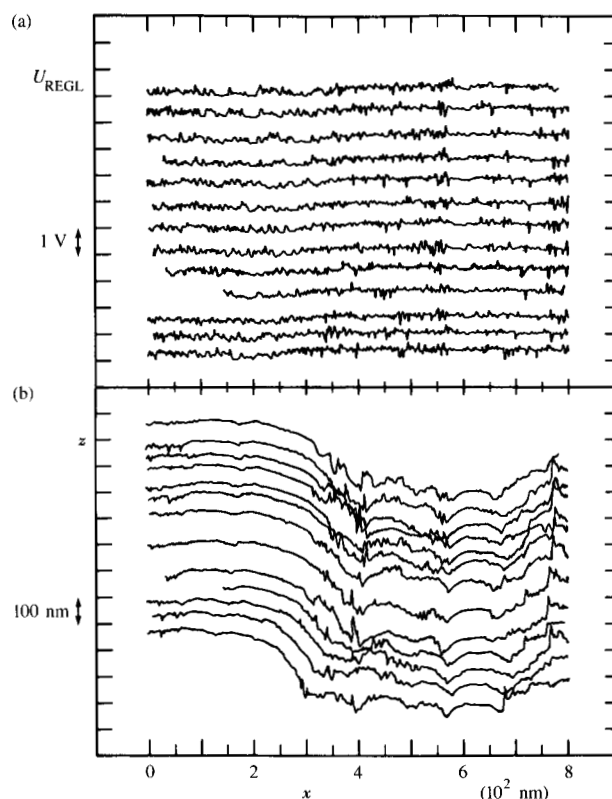


Figure 10

(a) Potentiometric image and (b) corresponding topographic plot in the island region of an electroformed sample with y-offset at fixed value. $\Delta U = 10 \text{ V}$.

25 nm. The applied voltage across the sample was 5.2 V. One recognizes that almost the entire voltage drop occurs within an extremely narrow gap of about 10 nm width. The residual potentiometric plot is practically flat except for two ridges of intermediate potential. They are possibly due to charged islands occurring in this MIM structure [9]. Other scanning images reveal regions where the whole voltage dropped in one step (**Figure 12**). The field strength deduced from the scans typically ranges from 10^8 to 10^9 V/m , in agreement with the results from photoemission [10].

The measurements show that some conducting material is present between the gold islands, since tunneling is possible there. An approximate filament resistance of the order of 10^4 – $10^5 \Omega$ has been derived [8] from fluctuations in the current interpreted as filament rupturing. This value is well below the tunneling resistance (10^6 – $10^7 \Omega$) and ohmic effects are therefore negligible.

Care has to be taken, however, with regard to the quantitative interpretation of the potential step: The conductive zone is probably ruptured at this line, creating a small area of very high resistance. Furthermore, hot

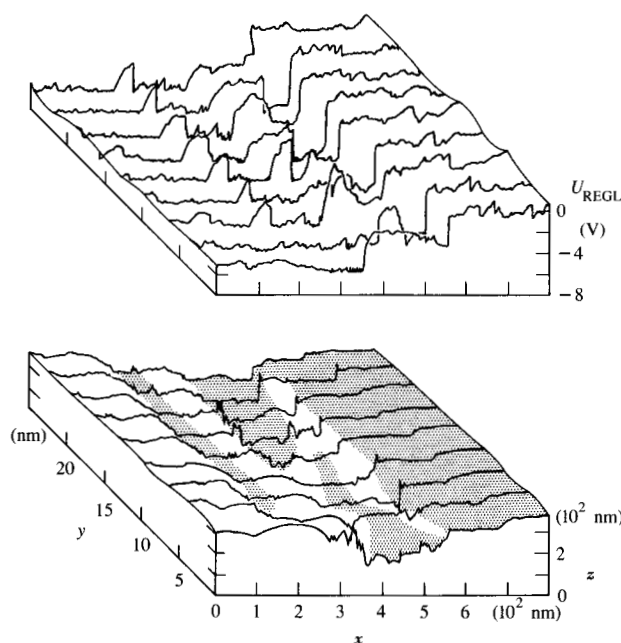


Figure 11

Resistive barrier of an MIM structure (STP mode). y-axis elongated; area = 800 nm × 25 nm. Dotted areas: regions with increased values of U_{REGL} . Experimental parameters: $\Delta U = 5.2$ V, $U_{\text{TI}} = 0.4$ V, $\omega/2\pi = 1$ kHz, tunneling current $I_{\text{T,eff}} = 5.6$ nA.

electrons might be created at the negative border of the gap, as was observed by means of photoemission electron microscopy at voltages between 2 and 6 V across the sample [9]. They might contribute to or even dominate the current between sample and tip while the latter flies over the gap. In fact, the tip sometimes retracted completely from the sample while scanning over the micro-slit. This is exactly the response to be expected from a tip passing a hot electron cloud. Thus, aside from pure potentiometry, STP might provide information on a number of other interesting phenomena related to electronic transport.

The various scans show that the noise of the distance-regulation signal is site-dependent. In Figure 11, the left-hand-side intermediate region with a higher electric energy eU has a less noisy distance signal, and hence must be ascribed to gold surface areas. The combination of these features would be expected for the negatively charged gold islands previously discussed.

It is also interesting to apply STP to the investigation of semiconductors. In this case, however, a rectifier IV characteristic in the tunneling current usually exists, and a pure ac tunneling voltage gives rise to a dc part of the tunneling current. The effect of the potential regulation in such a case is demonstrated in Figure 13 with n-Si as sample material. In the example shown, the potential offset is

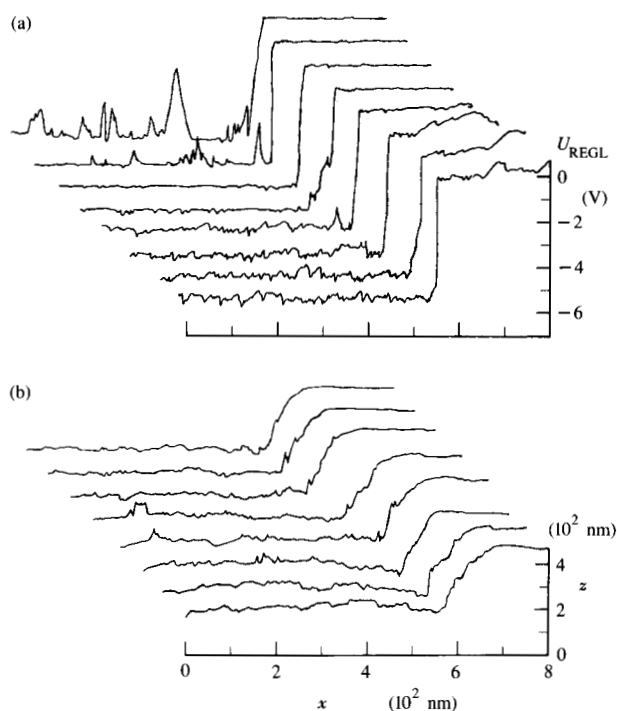


Figure 12

(a) Potentiometric image and (b) corresponding topographic plot across the line of the potential drop (y-offset constant).

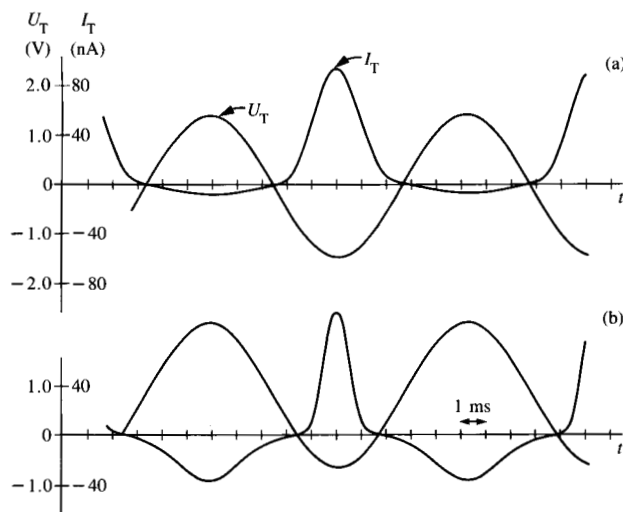


Figure 13

n-type silicon: Tunneling voltage U_T applied to the sample and current I_T vs time showing rectifier characteristic (ambient conditions, $I_{\text{T,eff}} = 14$ nA, signal averaged over 1000 cycles for noise suppression). (a) No potential regulation, zero dc offset of the tunneling voltage. (b) With potential regulation, i.e., with zero dc component of tunneling current.

positive. Analogously, a p-type material produces a negative offset. Application of an ac tunneling voltage and recording the potential offset (or equivalently, the average current) thus provides a simple way to characterize type of conductivity, which of course may also vary from site to site.

In order to discriminate potential and rectifier effects, it is necessary to scan the same area twice, once with applied field and once without field. As an alternative, the tunneling current can be gated when the ac tunneling voltage goes through zero; then potentiometric studies can be performed in the same way as on metals previously described.

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Paul Muralt *Institute for Atomic and Solid State Physics, Free University of Berlin, Arnimallee 14, D1000 Berlin 33, Federal Republic of Germany.* Dr. Muralt received his Ph.D. in 1984 from the Eidgenössische Technische Hochschule in Zurich, Switzerland. From 1984 to 1986 he held a postdoctoral position at the IBM Research Laboratory at Zurich, where he studied electrical interfaces using scanning tunneling microscopy. Most recently, Dr. Muralt has joined the Free University of Berlin, where he is commencing a new STM activity.

Dieter W. Pohl *IBM Zurich Research Laboratory, Säumerstrasse 4, 8803 Rüschlikon, Switzerland.* Dr. Pohl joined IBM in 1968 after receiving a Ph.D. with first-class honors from the Technical University of Munich, Federal Republic of Germany. In 1962, he operated one of the first lasers in Europe during the investigations for his diploma thesis. At IBM, he worked on problems of nonlinear optics and light scattering for several years. In 1982, he joined the IBM Zurich effort on STM and related techniques. Dr. Pohl is now heading a project oriented towards the study of materials of technological interest. He is the inventor of the near-field optical microscope, which exploits micromechanical principles developed for scanning tunneling microscopy to obtain optical images with near-electron-microscopical resolution. Dr. Pohl is a member of the European, Swiss, and German physical societies.

Winfried Denk *Cornell University, Department of Physics, Ithaca, New York 14853.* Mr. Denk, who is currently a graduate student in the Physics Department of Cornell University, studied physics at Ludwigs-Maximilians University in Munich from 1978 to 1981. After that, he received a Diplom degree in physics from the Eidgenössische Technische Hochschule, Zurich, Switzerland, with a thesis in two-dimensional NMR spectroscopy of biological macromolecules. During this time he also worked at the IBM Research Laboratory in Rüschlikon on the near-field optical scanning microscope and piezoelectric scanner problems. In 1984 Mr. Denk entered Cornell University; he is studying mechanical fluctuations in biological systems.