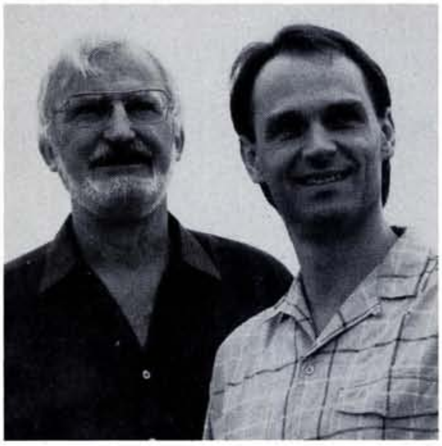

1986 Nobel Prizes
Development of Scanning Tunnelling Microscopy

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Heinrich Rohrer (left) and Gerd Binnig (also winners of the 1984 EPS Hewlett-Packard Europhysics Prize).

On October 15, 1986 the world learned about the award of the Nobel Prize in Physics to Ernst Ruska for his fundamental investigations in electron optics and the construction of the first electron microscope, and to Gerd Binnig and Heinrich Rohrer for designing the scanning tunnelling microscope.

Ruska, now 79, obtained satisfactory images with his two-stage instrument in 1931 and surpassed the resolution and magnification of light microscopes two years later while working at the Technical University in Berlin [1]). Since then electron microscopes with their different imaging modes and modifications, have slowly matured and gained acceptance as indispensable tools in physics, materials science, microelectronics, biology and medicine that enable structural analysis and selective manipulation on a scale of few μm down to a few Å (under special conditions). It is therefore gratifying that the Prize Committee decided to honour Ruska's pioneering work, thus recognizing what *The New York Times* referred to as a "microscopic oversight".

By contrast, the Scanning Tunnelling Microscope (STM), first successfully operated only five years ago, soon proved able to resolve atomic-scale features on the surfaces of even poorly conducting materials. Although it is only beginning to have an impact beyond fundamental science, the tremendous potential of STM (depending on the context, M means either microscope or microscopy) has been realized by the Prize Committee at a relatively early stage.

Both instruments rely on electrons and are limited by quantum properties of the latter, but have otherwise little in common. The present contribution focusses on the development of STM by its inventors. A similar article on electron microscopy will appear later. Before reviewing the main stages in the evolution of the STM (see also Ref. 2), let me describe the physics and operation of that conceptually simple instrument. The state of the art, including complete references, is covered in two recent Proceedings [3, 4]).

Basic Principles

The key to STM is to approach a probing tip, made of a refractory hard metal like tungsten, within a few Å of the sample to be investigated so that a measurable current I_T (typically 1 nA) flows in response to a fixed voltage V_T ranging from a few mV for metals to several volts for poor conductors. The tip is then scanned along the surface at a constant distance *s* (to zero order) by means of a feedback control unit that maintains I_T constant. As sketched in Fig. 1, both fine approach and scanning are effected by calibrated piezoceramic rods producing displacements of several Å/V. The *z*-displacement (proportional to V_z recorded along successive scans yields a nondestructive topographic profile (dotted line) provided the tip neither accidentally touches the surface nor induces local fields causing atoms to jump.

In contrast to experiments with solid (e.g. oxide) barriers, initiated by Giaever in 1960, the new technique relies on tunnelling through vacuum or an inert medium, like liquid He, thus permitting *in situ* investigations of local surface changes induced by external means, or by the tip itself. Recently STM images of relatively inert surfaces like gold and graphite have been obtained in air and water [3, 4]).

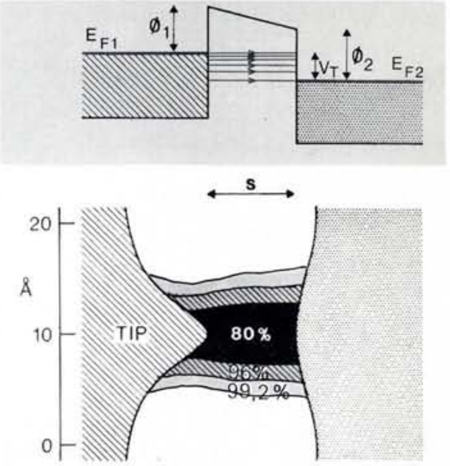

Fig. 2 — Distribution of tunnelling current density in energy (top) and space (bottom). (Ref. 3), Copyright 1986, IBM.

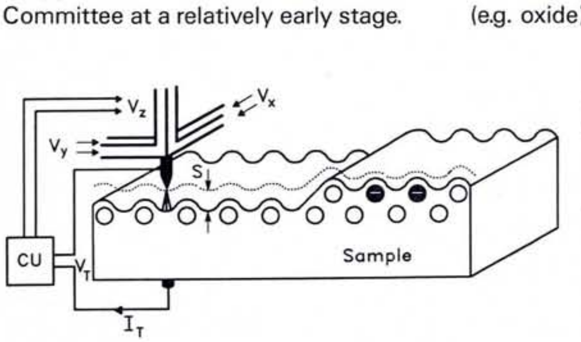

Fig. 1 — Principle of STM: The probing tip (black) is actuated by voltages independently applied to three mutually orthogonal piezodrives. While the tip is scanned along the sample by V_x, V_y, the control unit, CU, records and supplies the voltage V_z required to keep the tunnelling current I_T (V_T) constant.

To obtain stable images, differing only by small drifts, required much ingenuity and perseverance. Mechanical vibrations and noise had to be suppressed. In the 1970's a few groups tried, but none could reach the goal of controlled approach, vacuum tunnelling and scanning. The specific designs discussed below all rely on an isolation and damping system against external disturbances and on a coarse approach mechanism that brings the sample within the working range (100 Å to several μm) of the piezodrives. The influence of internal vibrations generated by the motion of the tip is avoided by setting the cutoff frequency of the feedback well below the lowest mechanical eigenfrequency of the tip-scanning unit.

Parameters determining the tunnelling current distribution, and hence the sensitivity and resolution of STM, are illustrated in Fig. 2. Assume for simplicity that the barrier is vacuum and that both sample and tip are good conductors. The applied voltage V_T then appears across the separating potential barrier, and the height of the latter is approximately the average $\phi = (\phi_1 + \phi_2)/2$ of the tip and sample work functions. Its thickness *s* is the distance between the turning points of electrons at a given energy within the window defined by the corresponding Fermi levels E_{F1}, E_{F2} (assuming rapid equilibration within each electrode and negligible thermal excitation above the barrier). If $V_T << \phi_1, \phi_2$, the distance dependence of I_T is dominated by the exponential decay of the transmission coefficient at $E_{F1} \approx E_{F2}$. For free electrons tunnelling between parallel electrodes, the current density would be

$$j \approx (e^2/h\pi)\,(\kappa/s)\,V_T \exp(-2\kappa s), \quad (1)$$

where $h/e^2 = 25.8\ \mathrm{k\Omega}$ and $2\kappa(\text{Å}^{-1}) = 1.025\sqrt{[\phi(\mathrm{eV})]}$.

For a curved tip I_T is approximately obtained by integrating (1) laterally about the closest separation *s*, thus giving an effective tunnelling area of $2\sqrt{(r/\kappa)}$ diameter for a tip of radius *r* at its apex. This estimate of the lateral resolution *L*, *e.g.* 50 Å for even a smooth tungsten field emission tip with $r = 1000$ Å and $\phi = 4.5$ eV, looked promising enough and motivated Binnig and Rohrer to build their first STM [5, 6]. Their ability to observe monoatomic steps with apparent widths < 10 Å led them to conjecture that the ground tungsten wires they used for tips supported small clusters of atoms. The extreme sensitivity of I_T to *s* naturally selects the "minitip" closest to the sample [6]: the dream of resolving single surface atoms (schematically indicated by circles in Fig. 1) suddenly seemed within reach! Subsequent theories demonstrated that *L* is of order $1.6\sqrt{[(r+s)/\kappa]}$, but can also be smaller if, for instance, a host or a foreign atom with an outwards-directed orbital sits at the apex of the tip.

The two future laureates also proposed extensions of STM, namely local tunnelling spectroscopy and barrier-height profiling [6]. In the former one records the response dI_T/dV_T to a small rapid modulation as V_T is slowly swept to bring specific electronic states into energy coincidence with, for instance, the Fermi level of the tip. Such density-of-states effects modify the prefactor, but not the exponential in (1), at least for small V_T. A measurement of dI_T/ds *via* modulation of V_z therefore reveals local variations in ϕ due, *e.g.* to adsorbates (black circles in Fig. 1). Such variations cause changes in the apparent topography that are difficult to recognize unless ϕ is simultaneously recorded.

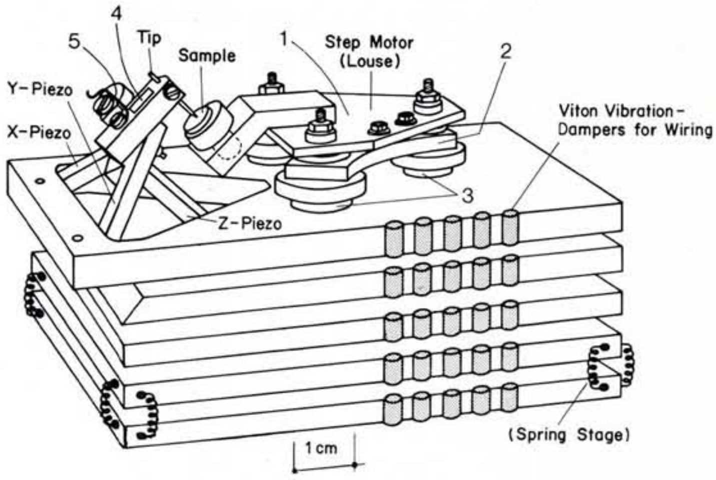

Fig. 3 — Schematic diagram of "pocket-size" STM. (Ref. 9), Copyright 1986, the American Institute of Physics.

Experimental Aspects: Early Work

The idea of STM arose in 1978 during a visit by Binnig to discuss research plans with Rohrer while he was writing up his doctoral dissertation. After settling in Zürich in the fall, Binnig started designing and testing various components with his uncanny ability to see the essential. He was helped by Rohrer's former experienced technician, Christoph Gerber, who has since then instructed hundreds of visitors and newcomers to the field. Binnig and Rohrer still pursued their previous research interests, but the situation changed in autumn 1981 when a working STM design took shape and an eager young technician, Edmund Weibel, joined the group.

Initially magnetic levitation above a superconducting lead bowl coated with aluminium provided vibration isolation and eddy-current damping. A linear decay of log I_T *vs. s* was observed after a heuristic cleaning procedure, with ϕ as high as 3.2 eV excluding tunnelling through an oxide or other contamination layer [5]. Preliminary STM scans of Au and Pt surfaces were shown together with that evidence at LT16 in August 1981. An expert in junction tunnelling sitting next to me exclaimed "my God, I have dreamed of doing this for the last twenty years!".

The second STM enabled careful surface preparation in UHV and revealed the above-mentioned narrow steps on Au(110) [6] and, later, Si(111), as well as correlated topographic and ϕ scans for Au clusters on that surface [7]. Vibration isolation *via* a two-stage spring system with Viton connectors kept noise in *s* below 0.2 Å. (This was reduced to 0.05 Å in the third STM [8]) which also included LEED and Auger surface diagnostics.) As in later designs, including the compact one sketched in Fig. 3 [9]), a "louse" consisting of a piezoplate (2) on three metal feet (3) separated from a ground plate by high dielectric constant insulators ensured coarse approach in steps of 100 Å to 1 μm *via* sequential clamping of the feet in harmony with contractions and elongations of the body (2). Better procedures for obtaining stable minitips *in situ* were developed, *e.g.* applying up to 100 V for a certain time.

At his first invited talk at the German Physical Society meeting in April 1982 Binnig claimed that ≃ 3 Å wide features occasionally appearing in adjacent scans were single adsorbates. Soon afterwards individual close-packed [001] atomic rows on the reconstructed Au(110) surface could be imaged. This observation prompted theorists to get to work and provided a basis for testing estimates of the resolution.

But it was the first STM image of the puzzling 7×7 reconstruction of annealed Si(111) that generated the most excitement. The features in the rhombohedral unit cell apparent in Fig. 4 (deep minima at the corners, 12 maxima associated with host adatoms, lower half on the $[\bar{2}11]$ side [10]) was confirmed in differently doped samples [11]), and later by groups at AT&T Bell Laboratories [12]), IBM Yorktown Heights [3, 4]) and elsewhere.

New Developments

Rohrer received his first informal award for STM at a workshop in January 1983 for the relief shown in Fig. 4 (top) that was quickly assembled by cutting and glueing x-y recorder traces on cardboard. Soon afterwards he energetically pushed computer-assisted STM data

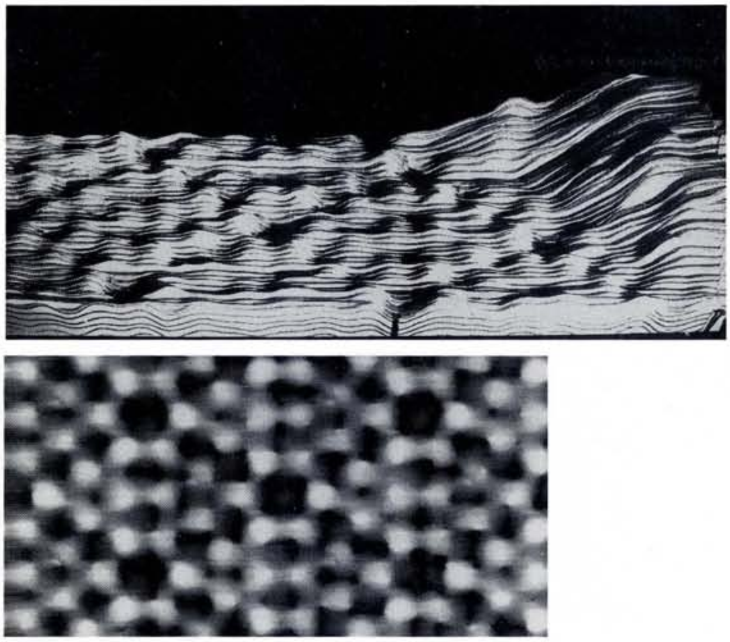

Fig. 4 — First STM image of 7×7 reconstructed Si(111) surface: original traces (top) and averaged grey-tone image (bottom); the closest-lying maxima are 6.65 Å apart. (Ref. 10), Copyright 1983, the American Physical Society.

handling and image processing, as well as the application of STM to materials science, electrochemistry and biology *via* collaborative efforts. Some of us at the IBM Zürich Laboratory switched to STM-related research. Numerous visitors came by and profited from the experience already acquired, while other groups started building STM's on their own. Joint projects financed by IBM Europe and the institutions concerned were established with universities in Madrid (Autonoma), Marseilles (Luminy), Berne and Zürich (ETH). Sessions and symposia on STM started being regular features at scientific meetings.

The fruits of the first collaborations obtained with the third STM are summarized in several reviews [11 8]). They include observations of single adsorbed oxygen atoms on Ni(110), of the subtle large-scale reconstruction of Au(100), of the spiral structure of DNA and of the neck of a virus. Somewhat later local tunnelling spectroscopy confirmed the existence of both occupied and unoccupied states (depending on the sign of V_T) confined in front of or close to various surfaces, while scanning revealed that some of the latter were also localized laterally, *e.g.* where unsaturated bonds are expected between adatoms on 7×7 Si(111). These results were reported at a workshop in Oberlech in July 1985 where about twenty different groups or investigators working in STM reviewed their progress [3]). Subsequent V_T-dependent studies by two groups at IBM Yorktown Heights clarified the nature of such surface states for the 7×7 and for the metastable 2×1 reconstruction of that surface. They were highlights at the first international conference on STM in Santiago de Compostella last summer [4]).

Other highlights originated from the atomic force microscope invented during Binnig's sabbatical at Stanford [13])

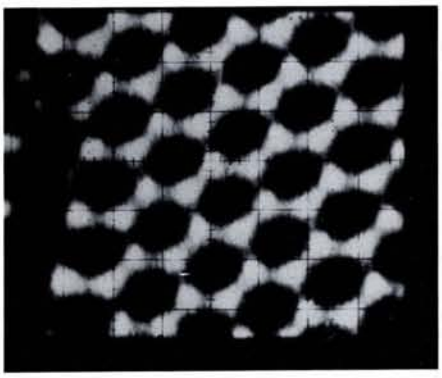

Fig. 5 — Real-time STM image of cleaved graphite. Minima are only 2.42 Å apart.

and the atomic resolution studies of cleaved graphite performed before his departure with the STM shown in Fig. 3. A stack of stainless-steel plates separated by Viton dampers provided enough vibration isolation for stable operation in air. When placed into the UHV chamber of a scanning electron microscope, this compact instrument could produce traces of excellent clarity [9]) and the corresponding image clearly shows minima with the expected spacing. Although only every second surrounding carbon atom appears as a slightly shifted maximum in that picture, Binnig and coworkers very recently managed to image all six, albeit in a narrow range of current, as shown in Fig. 5. This photograph was taken in a few seconds direct from an oscilloscope driven by a fast-scanning STM operating in liquid He similar to one that was built in one day in Stanford [4]).

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