Nishina Memorial Lecture

THE NANOMETER AGE:

CHALLENGE AND CHANCE

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June 1994

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The new players in the emerging nano-world are individual, selected objects of the size of some 50 nm down to molecules and atoms. The new aspect of science and technology on the nanometer scale is that these objects are treated as individuals, not as ensemble members. To a great extent, this requires real-space methods. Local probe methods, such as scanning tunneling microscopy and its derivates, are therefore a key to the nano-world. Major challenges of the new nanometer world are to exploit the new possibilities that arise from nanometer dimensions, to interface the macroscopic world to nano-individuals, to establish new concepts for working with very large numbers of nano-individuals and large sets of control parameters, to create the basis for broad interdisciplinarity, and to prepare society for the tremendous changes anticipated in a nanometer world.

I. INTRODUCTION

Miniaturization is one of the key driving forces for science and technology on the nanometer scale. Figure 1a shows the progress of miniaturization for two examples from the data processing industry. In the past two decades, miniaturization has progressed exponentially. The challenge in the coming decade, Period 1 in Fig. 1a, will be to find methods suitable for the mass production of Gbit chips from those present-day elements that can already be miniaturized sufficiently and assembled in small quantities. In Period 2, say, 10 to 20 years from now, the challenge will be to develop new types of elements. In both periods the investment into new technologies versus anticipated possible return will be a central problem. Eventually miniaturization, the division into ever smaller blocks, will come to an end in Period 3. Regarding storage, we do not know at present of any way involving less than, say, 1000 atoms in solid-state technology and some hundred in DNA. Whether it will ever be possible to store information in nuclear degrees of freedom — who knows. For data processing, heat dissipation per logic operation of least the thermal energy, kT, is a principal limit for any practical computation.

While solid-state science and technology have moved down from the millimeter to the nanometer scale, chemistry has simultaneously and independently progressed from the level of small, few-atom molecules to macromolecules of biological size (see Fig. 1b). Supramolecular chemistry might eventually provide the functional elements for the assembly scenario in the post-miniaturization period. Biological elements in general might be impractical, but biological concepts will guide us to new ways of thinking and doing things.

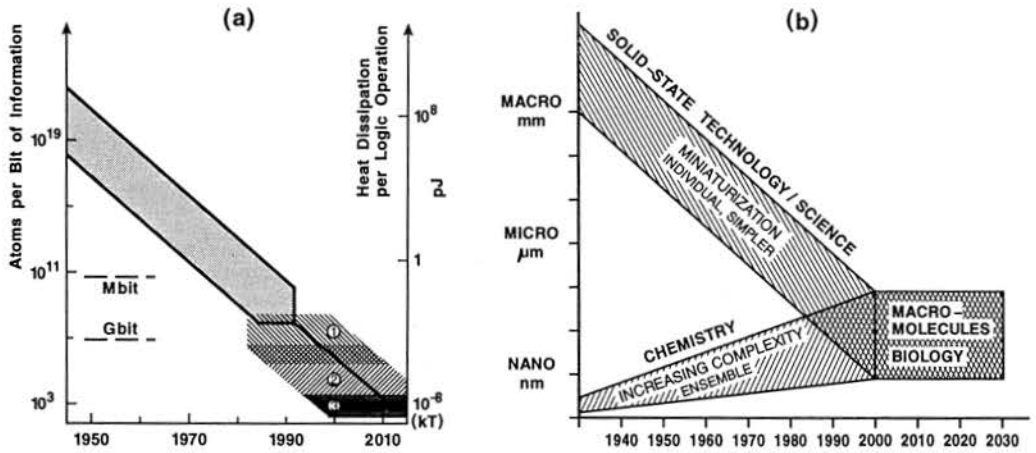

FIG. 1. *(a) Progress of miniaturization in information technology. [From H. Rohrer, Il Nuovo Cimento* **107A**, *989 (1994)* © *Società Italiana di Fisica] (b) Developments in solid-state technology and chemistry: Miniaturization builds on ever smaller individuals; increased complexity of ensemble members distinguishes macro-molecular chemistry. [From H. Rohrer, Ultramicroscopy* **42-44**, *1 (1992)]*

Numerical approaches have taken a similar development like that of chemistry, from atoms and small molecules to ever larger nano-objects. They will be of great importance in understanding properties, functions and processes on the nanometer scale because on the one hand theory has little symmetry and no fixed dimensionality to build on and on the other hand functions and processes of nanometer-sized elements depend critically on their immediate environment.

II. THE NEW NANOMETER WORLD

The nanometer age can thus be considered as a continuation of an ongoing development: for example, miniaturization in solid-state technology, increasing complexity in chemistry and numerically intensive computation. However, the new possibilities and novel aspects when working with nanometer dimensions go far beyond that — beyond, e.g., "smaller, faster, cheaper" in information technology. Dealing with chemical bonds rather than bulk mechanical properties leads to a new nano-mechanics with, for example, strains for the onset of plastic deformation an order of magnitude larger than those in the bulk. Mechanical resonance frequencies in the MHz to GHz range and thermal and diffusion response times below nanoseconds should very well complement fast electronics. Moreover, these fast relaxation times allow the creation of new materials and new structures. Local electric fields of up to several volts per angstrom, which are attainable in a scanning tunneling microscope (STM) configuration, and chemical interaction forces at angstrom distances are the basis for manipulation and modification on the atomic and the molecular level. Forces on the nano-scale are therefore a key to the nano-world. In addition, the extremely high electric fields provide convenient access to local nonlinear phenomena might also revive applications of thin ferroelectrical films. Other interesting and challenging aspects of nano-scale

dimensions are: Quantum effects will become important; we have to deal with tera and peta individuals; we often will think in terms of single electrons rather than currents; the immediate environment is a vital part of the nano-individual and not just a linear, minor perturbation; parallel operation will become the norm, and assembly and self-organization will replace miniaturization procedures.

Progress after miniaturization will be based on increased complexity. A promising route could be the assembly of molecular-sized functional elements into complex functional units. A primary task of science is to find appropriate self-assembling techniques and ways to interface the macroscopic world with molecular-sized functional elements for communication and control or modification of their functions. This will lead to an extremely fruitful, interdisciplinary effort that is expected to add new dimensions to biology as well as to supramolecular chemistry. The coming nanometer age can, therefore, also be called the age of interdisciplinarity.

Major tools for the nanometer world comprise beam methods (microscopy and lithography with beams of electrons, ions, photons, atoms, maybe sometime even with neutrons and positrons), local probe methods (STM and its derivates), computational methods and new nano-materials. The beam methods are the chief fabrication methods of current microtechnology, which they will carry deep into the nanometer age. In the nano-world, these methods might be the key for producing the patterns necessary for self-assembly and self-organization of and for communication with nano-individuals. The computational methods will be central for theory, as mentioned above, both in terms of understanding properties and processes on the nanometer scale as well as in context with new concepts of handling very large numbers of nano-individuals and many degrees of freedom in systems of nano-individuals. New nano-materials are required for machining on the nanometer scale as well as for providing appropriate supports of nano-objects, be they particular biological molecules, macro molecules from supramolecular chemistry or building blocks from solid-state technology.

III. LOCAL PROBE METHODS

Local probes are the "finger tips" to interact with nano-individuals, very much in the same way as we sense and handle macroscopic materials with our fingers. The positions and the properties of objects and functions as well as of processes associated with them are sensed, conditioned or changed by interactions between the probe and the object, see Fig. 2.

The "localization" of the experiment is given by the active size of the probe and by the interaction distance, i.e., the distance between those parts of object and probe that interact. In the following, "object" is also used for part of an object, e.g., a surface area of atomic dimensions. For an exponential distance dependence of the interaction, the localization is of the order of $\sqrt{(D+R)/\kappa}$, where R is an effective probe size, D an effective interaction distance, and $1/\kappa$ the decay length of the interaction. To obtain atomic resolution R, D and $1/\kappa$ therefore have to be of atomic dimension. For tunneling between two bare metal surfaces, $1/\kappa$ is about 0.4 Å, thus most of the tunneling current flows between atomic-sized regions of tip and sample as indicated in Fig. 2.

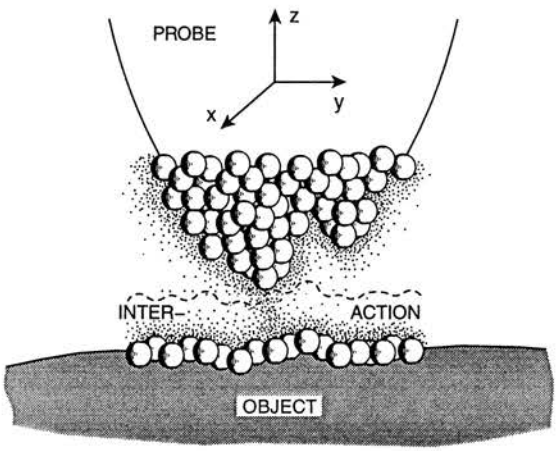

FIG. 2. *Schematic of local probe methods. The circles represent atoms of the parts of probe and object, respectively, closest to each other. The probe is moved in the x, y and z-direction. A possible y-scan trace is indicated by the dashed line. [From H. Rohrer, Jpn. J. Appl. Phys.* **32**, *1335 (1993)]*

In principle, it is very easy to produce an atomically sharp probe. Any tip, pointed or not, usually has a rough apex — unless great care is taken to produce a flat tip — of which one atom can be brought closest to the nano-object. However, at the beginning it was not so easy to keep this very last atom in place during the experiment, but now everybody has a recipe for doing so, and stability of the tip apex no longer is a serious problem.

The distance dependence of the interaction is the key to the sample topography. Scanning at constant interaction gives a constant-interaction contour that reflects the sample topography, provided the interaction is laterally homogeneous. However, the ability of gaining access to inhomogeneities down to the atomic scale is one of the unique and attractive features of the local approach and of atomic-scale imaging. The more inhomogeneous the objects of interest are, i.e., for the truly "colorful" and interesting objects, the more important it becomes that the probe–object distance can be controlled independently of the experiment to be performed. Also, a local probe measurement usually includes different interactions. In tunneling, for example, the interactions are the overlaps of tip and sample electronic wave functions at equal energy — inelastic processes are smaller by several orders of magnitude — thus different electronic states with different wave-function overlaps contribute to the total tunnel current. The art of local probe methods is then to find one interaction to control the probe-object distance and one to perform the experiment, and to separate either interaction from all the others, i.e., separation into a control and a working interaction, respectively. Ideally, the control interaction should be monotonous and, for imaging, laterally homogeneous. It is, therefore, the appropriate interaction for imaging the topography.

For most of the classical surface-science-type STM experiments, the interaction separation can be handled to a great extent by tunneling spectroscopy. The preparation methods yield compositionally well-defined surfaces of long-range homogeneity. Short-range inhomogeneities are periodic or easily recognizable, such as steps and defects — yet by no means does this imply "easy" experiments. In most other cases, however, interaction separation is

essential for understanding images. In general, separation requires simultaneous measurement of two or more quantities. In magnetic force imaging, for example, the separation of the magnetic forces and their lateral variation from the other forces and topographic effects can be achieved by introducing a well-defined Coulomb force. For ambient imaging, a procedure to separate the topography from electronic and elastic effects has recently been proposed that requires the simultaneous measuring of force and compliance on a constant tunnel current contour. Artifacts can arise when the various interactions involved yield different image resolution. Then the interaction with least resolution — or the least inhomogeneous interaction from the imaging point of view — is the most suitable one to be used as control interaction.

It should be noted that "topography" is not a clear-cut notion. Topography as the smoothed average position of surface atoms, although probe-independent, is of limited practical value for surfaces with different atoms of different sizes. A best compromise for the topography and thus also for the probe–object distance might be the point of zero force or point of contact between object and probe apex atom, although this topography can be tip dependent. The corresponding control interaction is then the total force between object and probe apex atom. Unfortunately this force is not accessible in a force measurement, which yields only forces between the object and the entire probe. Working in a liquid eliminates or substantially reduces some of the less local forces, however, molecules squeezed between probe and sample can complicate matters. Nevertheless, determining the point of contact by, for example, an abrupt change in damping or effective lever compliance appears at present to be a truly meaningful way to define within some tenths of an angstrom and control the probe–object distance.

Subsurface sensitivity is achieved when the interaction extends into the object, e.g., the electrostatic interaction of a conducting or polarizable probe with an electronic charge in an insulating layer. This, however, results in a loss of resolution, since physically the probe cannot come closer than the object surface. Other subsurface methods include ballistic electron emission microscopy (BEEM), in which ballistic electrons injected by a tunnel tip probe electronic properties at buried interfaces, and local luminescence of quantum-well structures, where the emitted light from the recombination of injected electrons is characteristic of both the surface band bending and the band gap in the interior.

A first set of applications of local probe methods deals with measurements, i.e., to monitor displacements, to determine when contact occurs, to measure local properties and to perform imaging (see Figs. 3a-c). The interactions should of course not affect the properties under consideration, although they might change others. A second set uses special aspects of the probe–object configuration. In Fig. 3d, the nonlinearity of the tunnel junction mixes different light frequencies. This can be used to image a property via the nonlinearity of the junction or to use a particularly strong local nonlinearity for frequency mixing per se. In Fig. 3e, a local plasmon mode characteristic of the tip–sample system is excited by the tunneling electron, which on decay emits a photon. In Fig. 3f, the injected electrons are used to probe a buried interface by BEEM or to investigate surface and bulk semiconductor band edges, for example, in quantum-well structures. Finally, the local probe can serve as manipulator or as machining tool. Rearranging adsorbed atoms and molecules on surfaces has resulted in most remarkable structures such as atom corrals. In Fig. 3g an atom is switched back and forth between tip and surface — the atom switch. Extraction (Fig. 3h) and deposition of

clusters and even of individual atoms have opened an exciting area of surface modification. Finally, control of processes and functions (Fig. 3i) is one of the ultimate aims of science and technology on the nanometer scale.

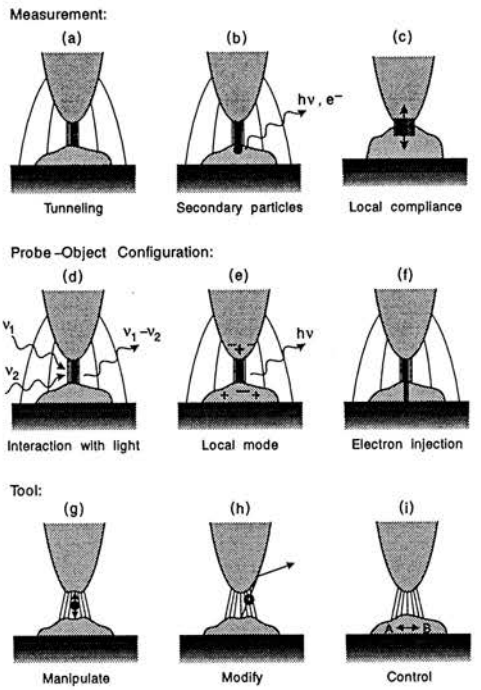

FIG. 3. *Local probe methods for imaging (a–c), as part of a specific experimental configuration on the nanometer scale (d–f), and as a tool (g–i). [From H. Rohrer, Surface Sci.* **299/300**, *956 (1994)]*

IV. COMPETENCE AND CHALLENGES

Let me now give some examples that illustrate the competence we have already achieved with local probe methods and the challenges lying ahead.

A. Measuring and Imaging

We have already acquired considerable competence with simple model systems. Atomic resolution imaging of structural, electronic and mechanical properties and of the growth and diffusion phenomena under various conditions, ranging from ultra-high vacuum to electrochemical environments, has become standard.

The first example, Fig. 4, shows a scanning tunneling microscope image of C_{60} or "bucky balls" adsorbed on Au(110), the case sketched in Fig. 3a. For convenience, I take an example from our Laboratory that illustrates various approaches to imaging. Excellent results of C_{60} imaging have been obtained at many different places, in Japan in particularly by the group at

the Tohoku University. On the left-hand side of Fig. 4, regions of uncovered gold with mostly individual gold rows 8 Å apart, which are the (1×2) reconstruction of the bare gold surface can be seen. The zigzag structure on the right-hand side is due to a monolayer of adsorbed C_{60}, which forms a (5×6) reconstruction, i.e., a five and six times larger periodicity than unreconstructed Au(110). The C_{60} molecules at the boundary zones appear much larger. Remember that STM just images electronic states. Why the electronic states at the energy of the present tunneling experiments of the isolated or edge molecules appear more extended is not known at present.

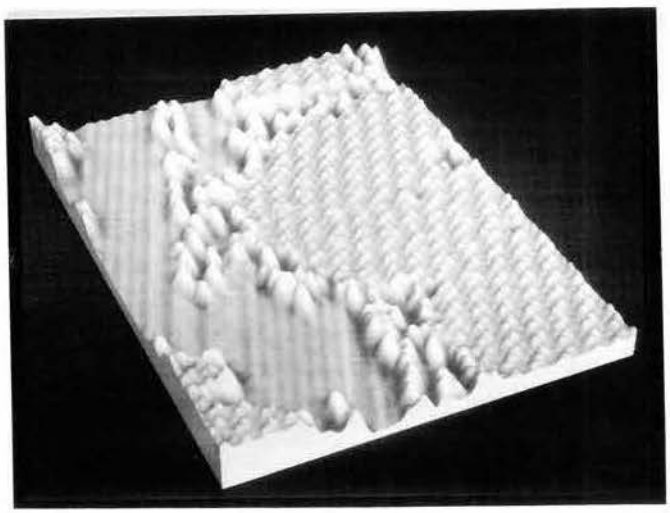

FIG. 4. *STM image of a monolayer of C_{60} molecules on Au(110), courtesy of J.K. Gimzewski, S. Modesti and R.R. Schlittler, IBM Rüschlikon.*

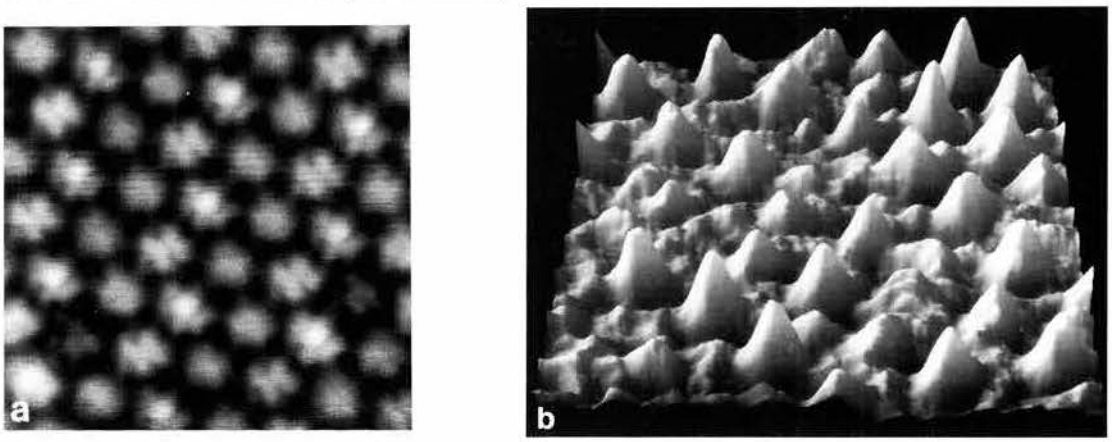

FIG. 5. *(a) STM image of "frozen-in" C_{60} molecules on Au(110), displaying three characteristic shapes, courtesy of J.K. Gimzewski, IBM Rüschlikon. (b) Photon map of an Au(110) surface covered with an annealed monolayer of C_{60}. The area is 60 Å×60 Å. [From R. Berndt, R. Gaisch, W.D. Schneider, J.K. Gimzewski, B. Reihl, R.R. Schlittler and M. Tschudy, "Photon Emission from Adsorbed C_{60} Molecules with Sub-Nanometer Lateral Resolution," Appl. Phys. A* **57**, *513 (1993) Fig. 3b,* © *Springer-Verlag 1993]*

At room temperature, the bucky balls rotate rapidly and no internal structure can be observed by STM. At 50 K, the rotation is frozen in and three types of structures associated with different frozen-in states of the molecule on the substrate can be observed, as shown in Fig. 5a. This example demonstrates the difficulty of interpreting STM images of more complex systems. The imaged electronic states reflect those of the molecules, of the substrate and, to some extent, even of the tip, and cannot be related in a straightforward way to the icosahedron shape of the C_{60}. Figure 5b shows the light emitted from the adsorbed C_{60} molecules. The tunneling electron excites a local plasmon due to the particular tip–sample configuration (example for Fig. 3e). The plasmon, on decay, emits a photon, thus making a "bucky bulb" out of a bucky ball.

The second example shows the cross-sectional STM view (Fig. 6) of a sequence of alternating thin layers of GaAs and AlGaAs. The larger band gap of AlGaAs provides the potential that confines the electrons into two, one or zero dimension, called quantum wells (for alternating thin layers), quantum wires and quantum dots, respectively. Questions of interest to be answered by an STM experiment concern the structural and electronic width of the GaAs–AlGaAs interface, the distribution of dopants and of Al, the band gaps and band bending. The GaAs appears bright because tunneling into it is easy, while the AlGaAs appears dark owing to the smaller number of electric states at the given energy of the tunnel electrons. Thus, bright and dark indicate high and low electron state densities rather than topographic features. Likewise, the apparent roughness of AlGaAs is of electronic rather than topographic nature.

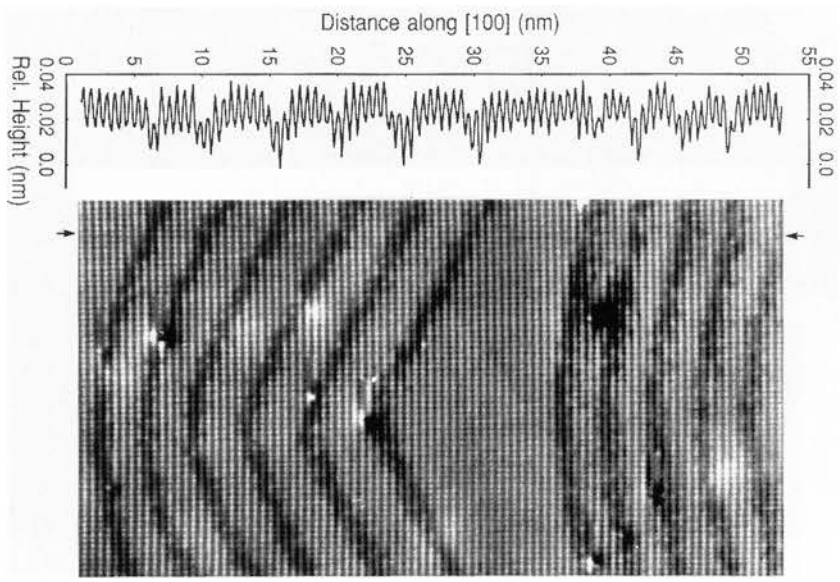

FIG. 6. *STM view of a cleaved quantum well structure with a constant tunnel current trace between the two arrows at the top. The fine mesh of bright spots corresponds to the As atoms. The overall bright areas are GaAs, the dark ones AlGaAs regions. Image courtesy of M. Pfister, M.B. Johnson, S.F. Alvarado and H.W.M. Salemink, IBM Rüschlikon.*

The blow-up (Fig. 7a) shows that the compositional transition from the GaAs layer to the AlGaAs is very sharp, the band gap, however, varies much more smoothly (Fig. 7b).

Figures 4 to 7 were examples of scanning tunneling microscopy, which requires conducting probes and objects. In force microscopy, the probe–sample interaction is a force. Resolution in force microscopy is generally a little bit less than in scanning tunneling microscopy, e.g., atomic resolution so far is the exception rather than the standard. However, its ease and breadth of application, in particular for nonconducting objects, make it the most widely applied method at the time being. Figure 8 shows a force image of magnetic tracks.

For less simple systems, however, separation and individual control of the interactions involved in a local experiment are crucial for understanding the imaging process and interpreting the image. Images can be beautiful and interesting, but then so is a sphinx. Force measurements are expected to play a central role for further progress in local characterization methods. Further challenging issues concern magnetic properties and chemical specifity on a nanometer scale, and the combination of nano in space and time.

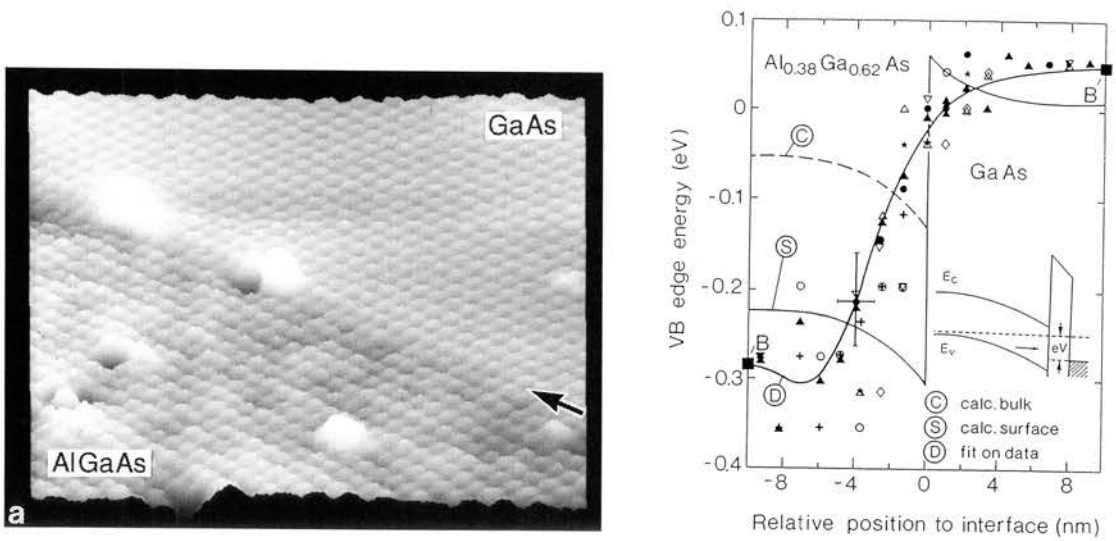

FIG. 7. *(a) The interface between the AlGaAs in the lower left and the GaAs in the upper right is "atomically" sharp. The apparent roughness of the AlGaAs is the roughness of the electronic states due to the statistically distributed Al; the large bright features are associated with the electrons of adsorbed oxygen atoms. Image courtesy of H.W.M. Salemink, IBM Rüschlikon. (b) Current onset related to the valence band across a AlGaAs/GaAs interface. The valence edge energy was derived from tunneling spectroscopic curves taken simultaneously with an atomic resolution image similar to that in (a). The drawn curve (S) refers to the value as calculated for this particular surface. Note that the transition takes place over a length of scale of 3.5 nm (about six atom rows). [From H.W.M. Salemink et al., Phys. Rev. B* **45**, *6946 (1992)]*

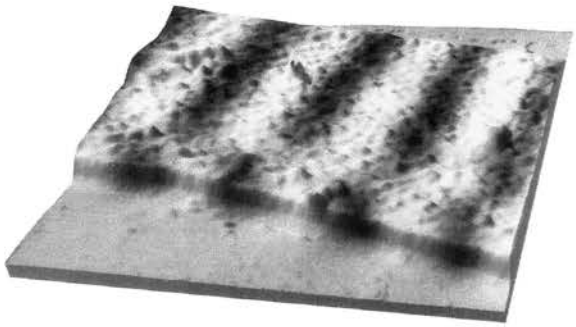

FIG. 8. *Force image of a magnetic track. In bright and dark stripes, the magnetization points in opposite directions. The magnetic pattern was imaged by magnetic forces, the topography of the track by electrostatic forces. Image area:* $6 \times 6\,\mu m$. *Image courtesy of Ch. Schönenberger and S.F. Alvarado, IBM Rüschlikon.*

B. The Solid–Liquid Interface

Local probe methods can be performed in nearly any environment in which the local probe can be moved with respect to the object and which does not screen the interaction between probe and object. They have brought a quantum leap for *in situ* characterization in ambient or liquid environments not accessible to electron and ion microscopies and have laid the foundation for nano-electrochemistry. The electrode–electrolyte interface is tremendously rich, with all its reconstructions and other structural and compositional phenomena of no lesser variety than those of the solid–vacuum interface in classical surface science. Moreover, the composition of the electrolyte brings an additional degree of freedom, reflected, for example, in the electrolyte-dependent reconstructions. Thus nanoelectrochemistry has pioneered the nanoscopic approach to the solid–liquid interface in general. The central importance of understanding and controlling the solid–liquid interface on a nanoscopic scale, however, extends far beyond the classical topic of electrochemistry.

Liquids provide new ways to treat and control surfaces. Capillary and van der Waal's forces acting on cantilever force sensors in force microscopy are best controlled in liquids. We can also think of surface control through passivation with a liquid and simultaneous local surface modification using, for example, specific molecules in the liquid.

A new surface science will emerge that can deal with "real" surfaces at ambient conditions and in liquids, and which is based on the extremely high resolution of local probe methods and their adaptability to different environments. This could open the present surface science of homogenized, well-prepared, well-controlled and reasonably well-defined surfaces to a large variety of "real" surfaces and interfaces that can be inhomogeneous on the smallest possible scale.

Important for such a new type of surface science, however, is a much improved chemical analysis capability of local probe methods. Characterization of "real" surfaces and interfaces will involve different types of experiments, since initially much less is known about the state of such surfaces and interfaces than about that of well-prepared and controlled surfaces. For interaction separation, the experiments have to be performed simultaneously, especially

because "real" interfaces can neither be reproduced on a local scale nor sufficiently controlled for sequential local experiments. The local approach will also produce very large data sets for representative surface samples, calling for increased speed and parallel operation as well as for new ways of handling and analyzing such volumes of data.

Local probe methods give us the ability to interact with individual functional molecular units, be it to study or to control their functions and the processes associated with them. The functionality of most of them, such as those of biological molecules, depends critically on an appropriate liquid environment. Therefore, mastering the solid–liquid interface on a nano-scale is crucial to the application of local probe methods to *in vivo* biology.

Lastly, the liquid provides the third dimension for efficient self-assembly and self-organization of large molecules on surfaces. Such "selfprocedures" will play a central role in the emerging nano-age, where we will have to build and interact with tera and peta nanometer-sized objects on an individual or at least on a distinctly selective basis.

The liquid–solid interface, quite generally, is a crucial element for interfacing the macroscopic world to nano-individuals — one of the primary objectives and challenges of science and technology on the nanometer scale.

C. Manipulation and Modification

Manipulation and modification on the nanometer or even atomic scale have made tremendous progress in the past couple of years. They aim at creating new types of nanometer-sized structures and functional units for scientific and practical purposes. In Fig. 9, 48 Fe atoms adsorbed on a Ni(110) surface have been arranged to form a "quantum corral." The electronic surface waves are reflected at the Fe atoms, giving rise to a standing-wave pattern, which modulates the tunneling current accordingly.

This example might not have much practical value, but is a beautiful illustration of what can be done by controlled manipulation of atoms. The more practical efforts are viewed by some mainly as a road leading to large-scale integrated systems, e.g., petabyte memories. Whether simple scratching with storage densities of Gbits/cm^2, see Fig. 10 atom extraction or deposition at 100 Tbits/cm^2, see Fig. 11, or other methods with performances somewhere in between will ever lead to viable large-scale storage application is an open issue. This will depend crucially on the possibility of producing miniaturized nano-tools suitable for parallel operation, for example of thousands to millions of tips as reading and writing heads, as well as on the progress in current technologies. However, even more exciting might be the prospects of creating sophisticated and complex nano-structures and nano-machines by manipulation and modification. Such nano-machines would be used for specific experiments or could perform specific tasks that cannot be reasonably executed or are even impossible by other means. The simplest nano-machine — although it is far from being simple — could be a functionalized tip with a specific test molecule attached that is used for recognition of other molecules (see also below, in Subsection E). Mbit to Gbit memories of micro- to millimeter dimension, everything included, could have many applications for "local" tasks. Finally, the multibillion-dollar human genome project could essentially be miniaturized, in a first step, to a local-probe DNA imaging station and in a second step to a biological DNA reading unit with an appropriate interface to the human world. We have again "smaller,

faster, cheaper", but applied to complex tasks not to individual elements. For instance, the cost of memory bits in a nano-machine plays a lesser role than for mass storage. Local probe methods appear indispensable in the exploratory stage of the nano-world. Once standard, however, fabrication of nano-machines and their control might be achieved by other means.

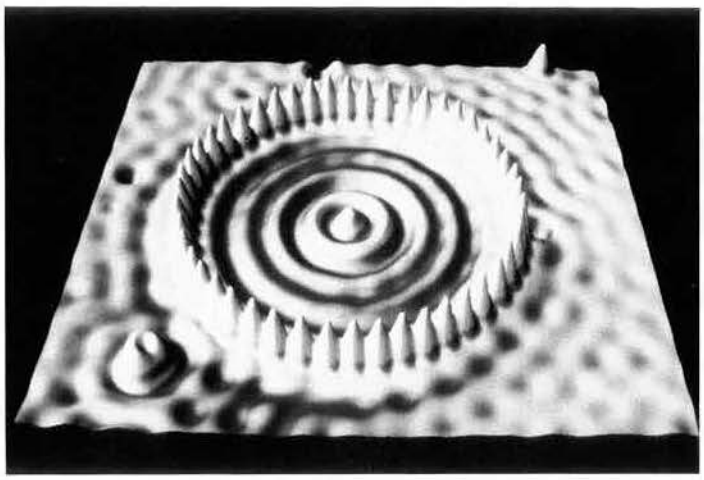

FIG. 9. *A circular quantum corral. This STM image shows 48 iron atoms that were positioned into a 124-Å-diameter ring on a copper (111) surface. The iron atoms scatter the surface-state electrons of the copper surface, resulting in the quantum confinement of the electrons to the corral. The wave structure in the interior of the corral is due to the density distribution of three of the eigenstates of the corral that happen to lie very close to the Fermi energy. Image courtesy of D. Eigler, IBM Research Division, Almaden.*

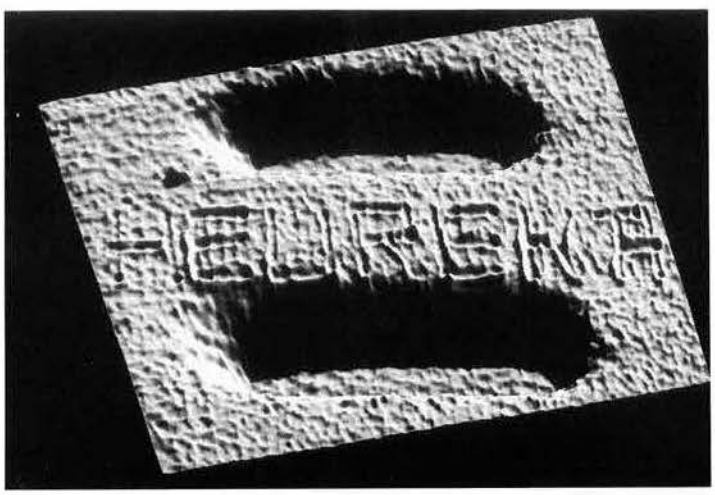

FIG. 10. *"HEUREKA" scratched with the dynamical ploughing technique ("Woody Woodpecker" approach) into a compact disc. The holes are information pits in the compact disc. The letter size is 700 nm, and the indentation depth is 10 nm, corresponding to approx. 100 Gbits/cm^2. [From T.A. Jung et al., Ultramicroscopy* **42-44**, *1446 (1992)]*

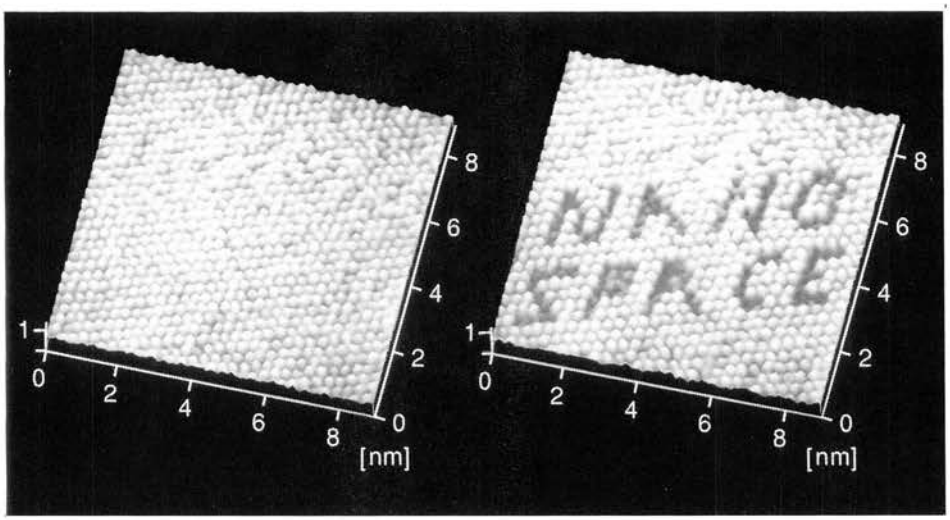

FIG. 11. *STM image of a MoS_2 surface: (a) Pristine and (b) after extraction of individual atoms to form the word NANO SPACE. This corresponds to a storage density of 100 Tbits/cm^2. Image courtesy of S. Hosaka, Central Research Laboratory, Hitachi Ltd., Tokyo.*

D. Nanotools and a New Standard

Miniaturized sensors and actuators requiring nano- to picometer precision and control are another rewarding challenge. They will serve as local measuring and control stations and as sensory organs, hands and feet of nano-robots, i.e., small robots working with nm-to-pm precision. An example is the micro-calorimeter, which measures pJoules of reaction heat in msec, and we can readily envisage the ability to measure fJoules in μsec.

Quite generally, the nanometer will become the new standard of precision. Micrometer precision was a crucial element for the later part of industrialization and for the beginning of the technology age. The notion of a nanometer world, however, still encounters considerable reservation in the western industrial world at large, although already accepted as the new standard for microtechnology of the near future, To change that is indeed a challenge. It might help to remember that the micrometer had no significance for a farmer plowing his field with an ox and plow 150 years ago — nor for the ox or the plow. Nevertheless, the micrometer changed plowing — it is the precision standard for the tractor.

E. Interfacing Molecules

Interfacing the macro-world with nano-individuals is one of the great challenges. Figure 12 sketches a program for the case of functional biological macromolecules. In the first step shown in Fig. 12a, neither the substrate nor the probe are activated; the molecule is physisorbed directly onto the substrate. This step is used for qualitative imaging and for exploring communication with the molecule. In Fig. 12b, object and probe are immersed into an appropriate liquid environment. Of interest here is the immobilization in a liquid

environment for imaging the "true" shape of the molecule and for communication. In Fig. 12c, the molecule is immobilized on a self-assembled monolayer — a problem currently of interest. The next steps include immobilization in the proper environment on a chemically activated substrate (Fig. 12d) and finally activation of the probe (Fig. 12e and f).

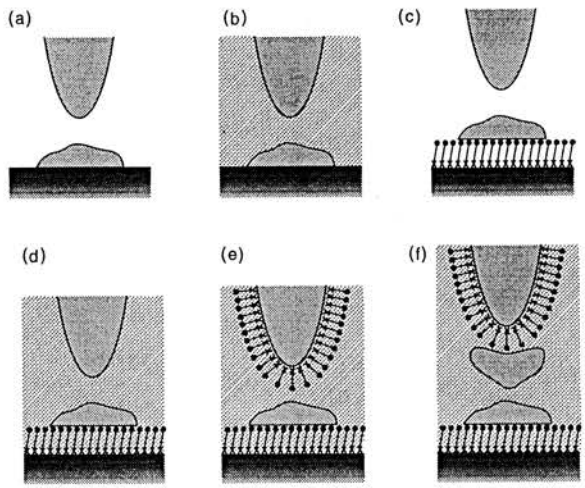

FIG. 12. *Program for "interfacing molecules" by chemical activation (functionalizing) of probe and substrate. (a) "Bare" configuration, (b) "functional" environment, (c) activation of substrate, here by a self-assembled monolayer, (d) configuration (c) in proper environment, (e) configuration (d) with activated probe. Steps (a) to (e) connect a functional object via the functional probe with the outside world. In (f) a functional molecule is the new probe. [From H. Rohrer, Surface Sci.* **299/300**, *956 (1994)]*

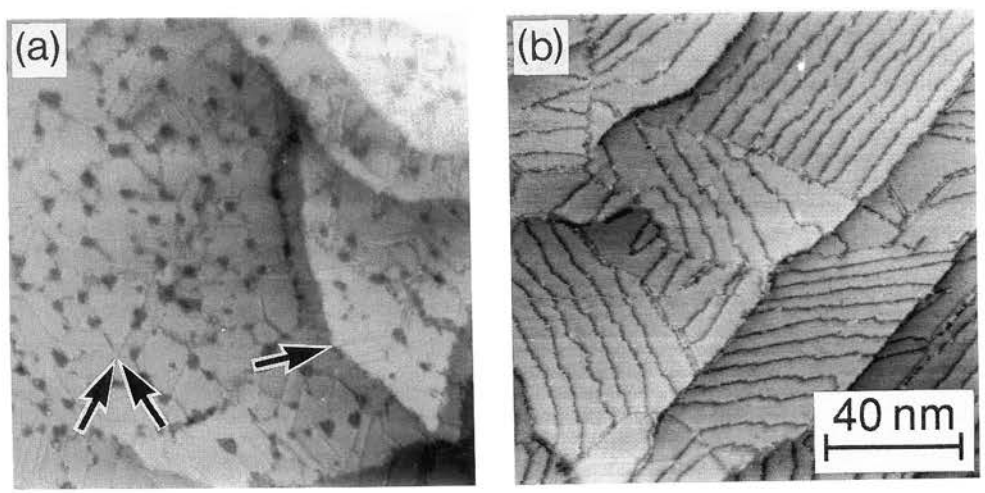

FIG. 13. *STM image of a monolayer self-assembled from dodecanethiol on Au(111), (a) as assembled and (b) annealed. Monomolecular channels form spontaneously during annealing and might be useful for directed immobilization of functional molecules (process sketched in Fig. 12c). [Reprinted with permission from E. Delamarche, B. Michel, H. Kang and Ch. Gerber, Langmuir (1994, in press). Copyright 1994 American Chemical Society.]*

F. Other Challenges

Progress into the nanometer age depends critically on improved interdisciplinary thinking and acting, both within science and between science and engineering. The thinking starts in the heads of scientists and in those of open-minded money agencies, the acting begins in formulating interdisciplinary projects and subsequent cooperation between scientists who are well trained in their disciplines. Interdisciplinarity is mainly a matter of the attitude of the scientific community — not of science politics.

Being able to handle and control condensed matter — "dead" or living — on an atom-by-atom or molecule-by-molecule basis and on a time scale of individual processes opens tremendous perspectives, but also fears. Both engender the wish for controlling science, whatever the motivation may be. The destiny of society, however, lies in the proper use of science, not in its control.