Up close & personal with atoms & molecules

Nature is the best example of a system functioning on the nanometer scale, where the involved materials, energy consumption and data handling are optimized. Opening the doors to the nanoworld the emergence of the scanning tunneling microscope in 1982 and the atomic force microscope in 1986 led to a shift of paradigm in the understanding and perception of matter at its most fundamental level. As a consequence new revolutionary concepts stimulated already a number of new technologies in meeting the somewhat still mechanistic top down approach with the bottom-up approach of self-assembly and self-organisation that has been so successfully implemented in the natural world. However to keep this worldwide effort alive the interdisciplinary structure of Nano requires a new breed of scientists educated in all science disciplines with no language barriers ready to make an impact on all the global challenges ahead where Nanotechnology can be applied.*

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At around 460 B.C. based on thoughts of his mentor, Leucipus, did a Greek philosopher, Democritus, elaborate on the idea of atoms extensively. He was contemplating whether it would be possible to break matter again and again down to a level where it is 'uncuttable'. He coined the term 'Atomos' (Greek), the smallest indivisible particle of matter. Unfortunately, the atomic ideas of Democritus, however, had no lasting effects since Aristotle dismissed the atomic idea as worthless and established his own view describing matter which persisted well into the renaissance. Indeed, it took mankind 2,000 years until John Dalton, an English natural philosopher, in 1803 performed a series of experiments with various chemicals to show that matter seems to consist of elementary particles. Again, more than 100 years later when a fairly good understanding of the properties of the atom existed, it was Erwin Schroedinger in 1926, in the course of getting the grips on to quantum mechanics, to propose that atoms behave

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to an extent like waves and described the electrons as a three-dimensional waveform, rather than just firm particles. As a consequence, when two conductive surfaces are brought into close proximity, where the electron wavefunctions of the atoms overlap and, when a voltage is applied, electrons start to ‚tunnel' causing a current to flow. It is this quantum phenomena that 50 years later in 1981 led to a new type of microscope enabling to image individual atoms for the first time in a three dimensional representation with unprecedented resolution.

Scanning tunneling microscope

The scanning tunneling microscope (STM), was introduced to the scientific community in 1982[1] (Fig. 1a). This new type of microscope does not use optics to image surfaces, but a sharp biased metal tip is brought into a distance of a few angstroms to a conductive surface. The tiny gap between tip and surface is maintained by keeping the flow of quantum mechanical tunneling current constant. The exponential dependency of the tunneling current gives the device its perpendicular sensitivity, moving the tip just by one atomic diameter, the current changes by a factor of thousand[2] (Fig. 1b). Lateral resolution stems from the fact that the tunnel current is confined to the foremost atom of the tip and its counterpart of the surface under investigation. Scanning the device in two dimensions over the surface a three dimensional representation of the surface is achieved on the atomic scale. Soon after its invention, a technically refined version of the STM (Fig. 1c) proved its capability to clarify one of the most intriguing surface-science-related problems at that time, namely the arrangement of silicon atoms on the Si(111)7x7 surface[3] (Fig. 1d). These images provided solid experimental evidence in direct space for one of the theoretically suggested models.

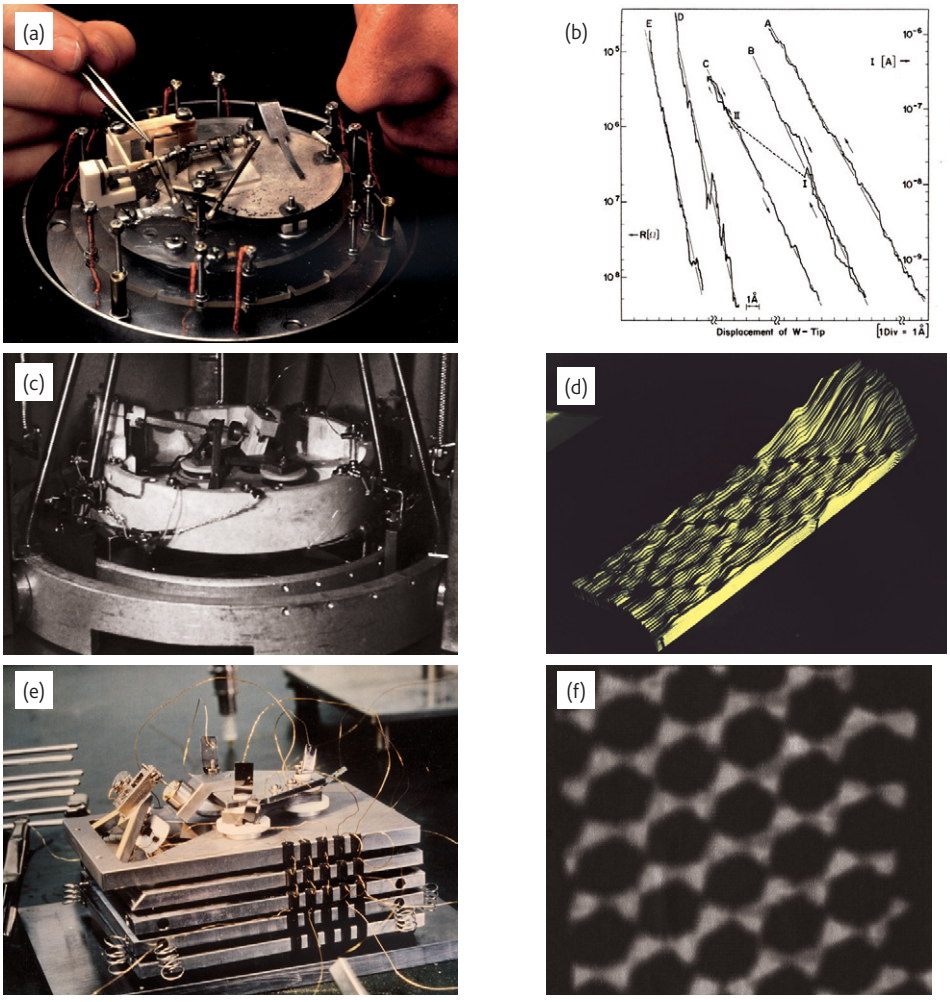


Fig. 1 Three generations of STMs. For coarse adjustment a piezo-driven positioning stage called 'louse' has been used. (a) 1st generation STM with magnetic levitation damping using a superconducting lead bowl. (b) With this instrument the exponential dependence of the tunneling current on distance was measured in 1981. (c) 2nd generation STM with eddy-current damping system using SmCo magnets. (d) With this microscope the Si(111) 7x7 surface was first imaged in 1982. (e) STM for operation in a scanning electron microscope to allow gradual magnification of the sample from the millimeter range to the atomic scale. The design concept of this STM was aimed at maximized rigidity, using a stack of alternating viton and stainless steel plates. (f) With this microscope, the sixfold symmetry of highly-oriented pyrolytic graphite (HOPG) was imaged for the first time in 1986 (courtesy of Christoph Gerber).

It took the scientific community a while to verify these results obtained at the IBM Research Laboratory in Zurich in 1983. The confirmation by other groups[4,5] came roughly two years later at a workshop in Oberlech in the Austrian alps in 1985, generating great excitement among the participants. During the years the device went through a series of improved alterations and it was in 1986 that with a newer type (Fig. 1e) the sixfold symmetry of the atomic arrangement of graphite could be shown for the first time[6] (Fig. 1f), indicating the enormous potential of the instrument. In the same year, Gerd Binnig and Heinrich Rohrer shared the Nobel Prize in Physics "for their design of the scanning tunneling microscope".

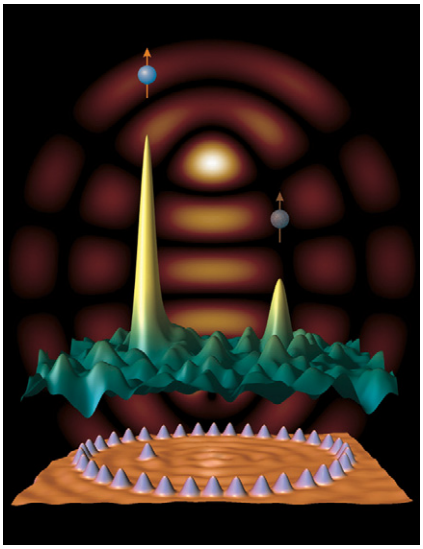


Fig. 2 Elliptical ring of 36 cobalt atoms creating a quantum mirage that may lead to an efficient way of moving information within future atom-scale circuits and computers. When a single cobalt atom (protrusion on the left) is placed at one of the two focus points of the elliptical ring, some of its properties suddenly appear at the other focus (protrusion on the right), where no atom exists (courtesy of IBM Research Almaden).

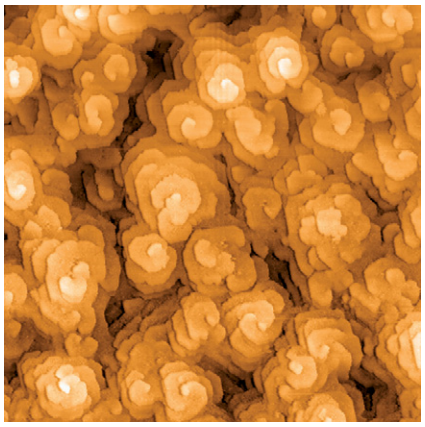


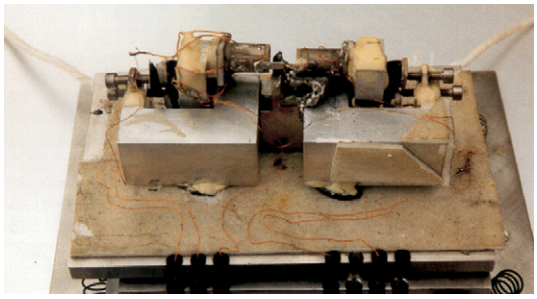
Fig. 3 Scanning tunneling microscopy image of a high T_c superconductor thin film of $YBa_2Cu_3O_{7-x}$ grown by pulsed-laser deposition (image size 1 μm^2). The screw dislocations defects were discussed as possible pinning centers for vortices (courtesy of Hans Peter Lang).

Moving beyond the fledgling state of the device, Scanning Tunneling Spectroscopy (STS) was introduced[7,8]. A powerful technique probing the local density of electronic states (LDOS) and band gap of surfaces and materials on surfaces at the atomic scale. Generally, STS involves observation of changes in constant-current topographs with tip-sample bias, local measurement of the tunneling current versus tip-sample bias (I-V) curve, measurement of the tunneling conductance, dI / dV, or more than one of these. Furthermore, imaging individual molecules on surfaces were shown for the first time[9]. At the same time ballistic electron emission microscopy (BEEM) was proposed as one of the first applications of the scanning tunneling microscope[10,11].

Leaving adolescence of the technique definitely behind happened when researchers at the IBM Research Lab in Almaden, California, used the instrument to write the IBM logo with 35 xenon atoms on a nickel surface[12], and later moving iron atoms on a copper surface to make a quantum corral[13] (Fig. 2), and visualizing the quantum mechanical effect of standing waves in a two dimensional electron gas[14]. Inelastic Electron Tunneling Spectroscopy (IETS) was the next important step reaching the limit of sensitivity with vibrational spectroscopy[15], that of addressing a single bond. The ability to measure spatially resolved vibrational intensity with sub-Angstrom resolution in single molecules makes it possible to directly determine quantitatively a number of fundamentally important physical and chemical processes.

Ever since the initial decade the STM has changed surface science to a great extent and so far led to a much more comprehensive understanding of the fundamental aspects of matter. The impact of this fact is shown in many fields, e.g. high temperature superconductivity[16-19] (Fig. 3), spin polarisation[20],

(a)



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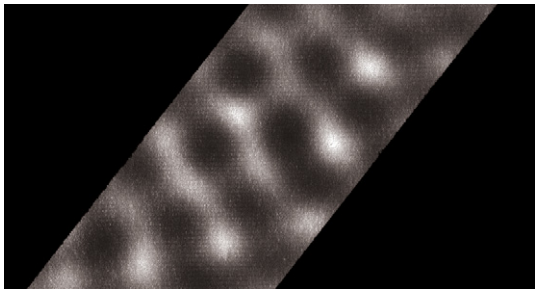

Fig. 4 (a) 1st AFM. The approach was done using a STM for distance control. The original instrument is on permanent exhibition at the Science Museum, London (UK). (b) First atomic resolution with AFM on highly oriented pyrolytic graphite (HOPG) (courtesy of Christoph Gerber).

quantum information[21], self-assembly and adsorption of organic and biomolecules at surfaces[22,23], nanocatalysis[24,25], molecular electronics[26,27], imaging defect atoms beneath the surface[28] and reading the genetic code of a DNA sample with a new sequencing technique[29].

Atomic force microscope

The Atomic Force Microscope (AFM) made its entrance in 1986[30] (Fig. 4a), as a consequence that its predecessor the STM lacked the ability of imaging nonconductive surfaces and outright insulators. Since its invention in 1986, the AFM has to a certain extent surpassed the STM and proved its suitability in various fields of application. As with the STM, the AFM relies on a sharp tip that is scanned over a surface. This tip is part of a cantilever that can measure forces down to the lower piconewton range. In a sense the AFM resembles a record player — the forces between the surface and the tip cause the cantilever to bend in the vertical direction, and by measuring this deflection, it is possible to produce an image of the surface with atomic resolution[31] (Fig. 4b). The forces, which can be attractive or repulsive, depend on the nature of the interaction between the tip and the surface being investigated. First designed as an instrument to image the surfaces of nonconductive materials[32,33] with high lateral and vertical resolution, the technique has been adapted for various environments, such as vacuum, fluidics, ambient, low temperatures and magnetic fields, as well as for chemistry and biology applications[34]. The capability to investigate surfaces with unprecedented resolution using this technology introduced a wealth of related techniques using probes with local interaction. The interaction force may be the interatomic forces between the atoms of the AFM

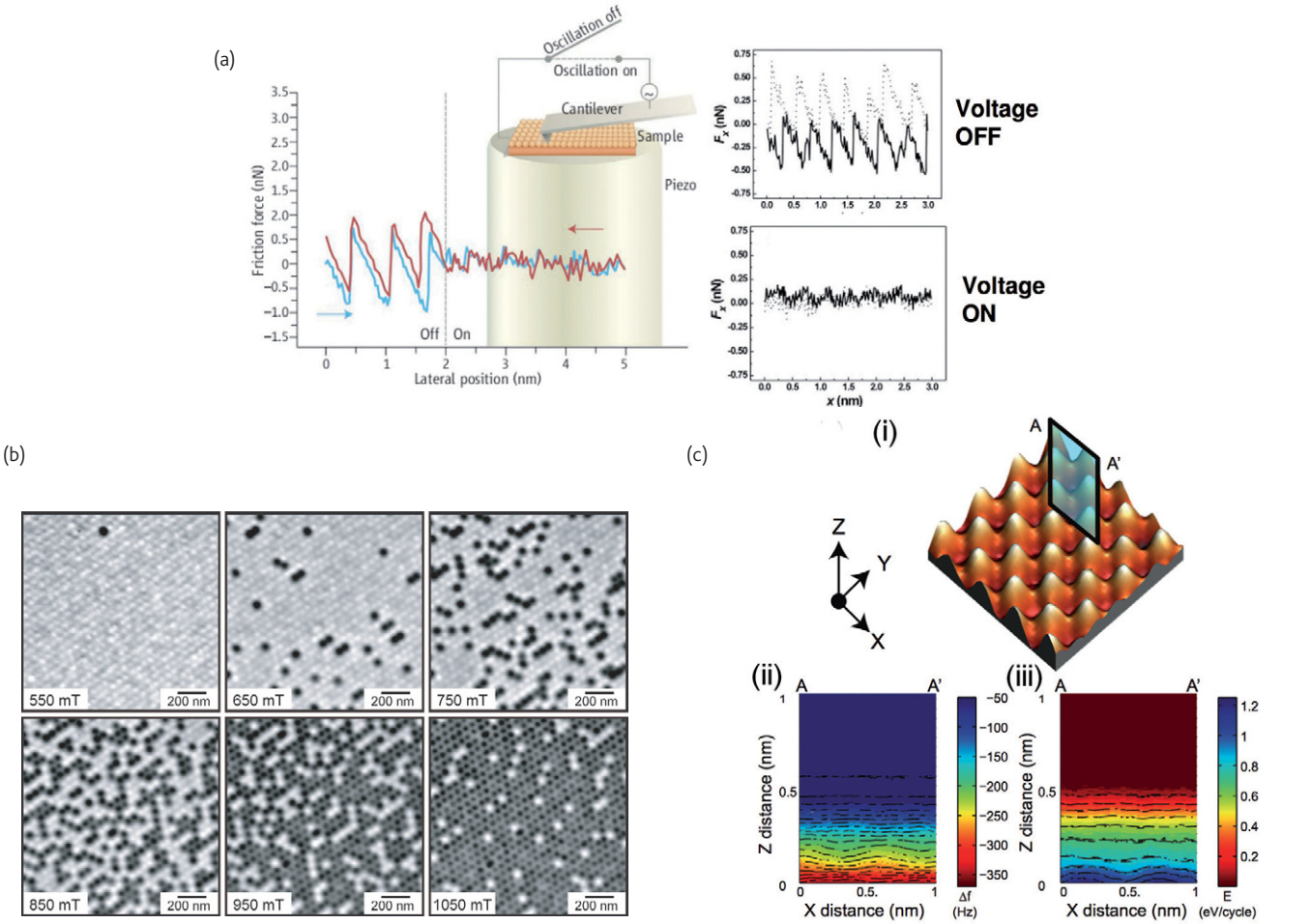

Fig. 5: (a) Friction on the atomic scale can be switched on/off by electrostatic actuation differentiating between stick-slip and the superlubricity regime (courtesy of Ernst Meyer, University of Basel). (b) Magnetic force microscopy images of Bit Patterned Media with 50 nm center-to-center spacing supplied by J. Ahner, Seagate Freemont. Taken at 17 K, the images show the same area after magnetic fields are incrementally applied perpendicular to the plane of the sample. Bright (dark) dots are magnetised in the direction opposite (parallel) to the tip magnetisation. The images were taken in constant height MFM mode on the Nanoscan PPMS-AFM by T. V. Ashworth, Nanoscan AG, Dübendorf, Switzerland. Nanoscan AG (www.nanoscan.ch) produces the PPMS-AFM, a variable temperature, variable magnetic field SPM designed to fit the Quantum Design PPMS ® (San Diego, CA 92121-3733, USA). The PPMS-AFM was designed in collaboration with Empa, Swiss Federal Laboratories for Materials Testing and Research, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland (courtesy of T. V. Ashworth, NanoScan AG, Dübendorf, Switzerland). (c) Three-dimensional noncontact AFM spectroscopy above the insulating surface of KBr(001): (i) topography, (ii) Z-distance dependence of the conservative and (iii) dissipative force across the direction leading towards atomic tomography (courtesy of S. Kawai, University of Basel).

tip and those of a surface, short-range van der Waals forces or long-range capillary forces. Investigation of friction forces and stick–slip processes[35] has led to major advances in tribology[36,37] (Fig. 5a). Modifying the AFM tip chemically allows various properties of the sample surface to be measured[38,39]. The AFM tip can be driven in an oscillating mode to probe the elastic properties of a surface (elastic modulus spectroscopy[40]). Local charges on the tip or surface lead to electrostatic forces between tip and sample, which allow a sample surface to be mapped, i.e. local differences in the distribution of electric charge on a surface (electrostatic force microscopy[41]) to be visualized. In a similar way magnetic forces can be imaged if the tip is coated with a magnetic material, e.g. iron, that has been magnetized along the tip axis (magnetic force microscopy[42], see Fig. 5b). The tip probes the stray field of the sample and allows the magnetic structure of the sample to be determined. A strong dependence of the resolution on the tip–sample distance is observed. Information on force gradients can be obtained by cantilever oscillation techniques. At high oscillation frequencies (cantilevers with high resonance frequency), further information on interatomic forces between tip and sample can be obtained. Depending on the oscillation amplitude the terms 'tapping mode' or 'dynamic force microscopy' are used[30,43]. Dynamic force microscopy is able to provide true atomic resolution on various surfaces under ultrahigh vacuum conditions[44] and allows force spectroscopy on specific sites[45] leading to atomic scale tomography[46,47] (Fig. 5c). Material properties can be locally discerned using ultrasonic force microscopy[48]. Various other quantities can be measured if the tip is functionalized as a local measurement tool, e.g. as a very small thermocouple to measure temperature differences in scanning thermal microscopy[49]. Locally resolved measurement of the chemical potential is the goal of Kelvin probe microscopy[50], whereas the capacity change between tip and sample is evaluated in scanning capacitance microscopy[51]. In very recent developments by introducing damping non-conductive dynamic force microscopy[52] and nanomechanical holography[53] it became possible to visualize and monitor molecules or nanoparticles beneath the surfaces in a non-invasive manner (Fig. 6).

Another offspring of the STM is the scanning ion-conductance microscope[54] (SICM). It consists of an electrically charged glass micro- or nanopipette probe filled with electrolyte lowered toward the surface of the sample (which is non-conducting for ions) in an oppositely charged bath of electrolyte. As the tip of the micropipette approaches the sample, the ion conductance and therefore current decreases since the gap through which ions can flow, is reduced in size. Variations in the ion current are measured by an amplifier, and are used as a feedback signal by a scanner control unit to keep the distance between pipette tip and sample constant by applying corresponding voltages to the Z-piezo drive during the scanning procedure. Therefore, the path of the tip follows the contours of the surface.

In addition to imaging surfaces, AFM can also be used to modify surfaces and perform molecular manipulation down to the level of

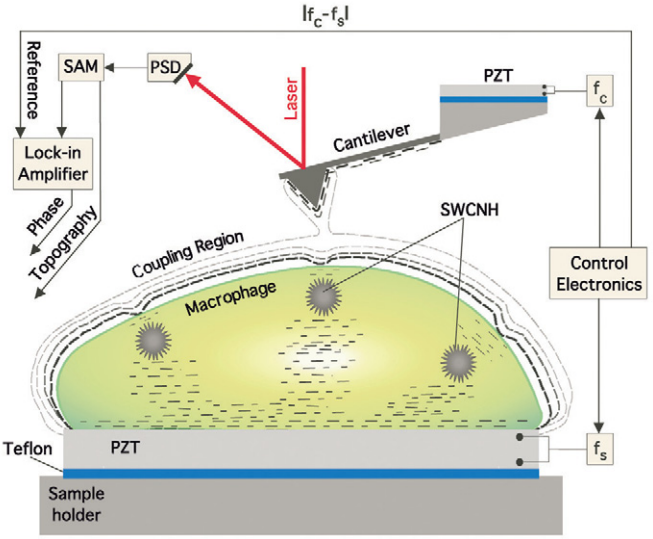

Fig. 6 Intracellular imaging of aspirated nanoparticles using ultrasonic holography. The signal access module (SAM) provides the instantaneous location of the reflected laser beam as monitored by a position-sensitive detector (PSD). The dynamics of the cantilever is presented at the input of a lock-in amplifier. The local perturbation in the coupled oscillations of the ultrasonic-driven microcantilever – macrophage system is monitored with the lock-in using the difference frequency $f_c - f_s$ as reference. By mapping the strength of the coupling in a scanned area of the cell, a phase image emerges that contains information on the buried single walled carbon nanohorns (SWCNHs). PZT: actuation piezo (courtesy of Thomas Thundat, Oak Ridge National Laboratory).

individual molecules or atoms[55]. By depositing, removing material from the tip and/or sample surface, a surface can be modified locally for the storage, retrieval and erasing of information[56], switching or direct patterning of non-volatile memory nanostructures in doped $SrTiO_3$ single crystals[57-60] (Fig. 7). Dip-Pen Nanolithography[61,62] (DPN) is a scanning probe nanopatterning technique in which an AFM tip is used to deliver molecules to a surface via a solvent meniscus, which naturally forms in the ambient atmosphere (Fig. 8). This direct-write technique offers high-resolution patterning capabilities for a number of molecular and biomolecular 'inks' on a variety of substrates, such as metals, semiconductors, and monolayer functionalized surfaces. The operation mode of acquiring force distance curves (measurement of forces as a function of tip–sample separation) allows to draw conclusions regarding the material characteristics of surfaces and their chemical properties[63]. With bonds established between the tip of a scanning force microscope and a molecule tethered to a surface, force can be exerted very locally on a single molecule and thus the strength of bonds and the forces required to break individual bonds can be investigated (force distance spectroscopy and single-molecule spectroscopy[64,65]). Mechanical analysis regarding stiffness of live metastatic cancer cells using AFM allows local diagnosis of the health condition of cells[66].

The mechanical detection of electron or nuclear magnetic resonance (magnetic resonance force microscopy, MRFM[67]) has shown improved sensitivity compared to induction-based techniques

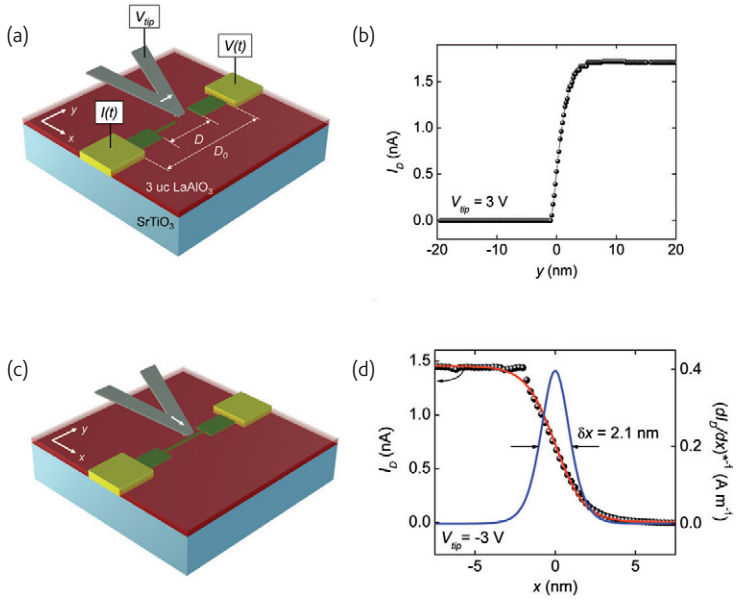

Fig. 7 Writing and erasing nanowires at the $LaAlO_3/SrTiO_3$ interface. (a) Schematic diagram of the experimental set-up for writing a conducting wire. A voltage-biased AFM tip is scanned from one electrode towards a second one in contact mode. The tip generates an electric field that causes a metallic q-2DEG to form locally at the interface under the route of the tip. (b) Conductance between the two electrodes measured with a lock-in amplifier as a function of the tip position while writing a conducting wire with 3V bias applied to the tip. A steep increase in conductance occurs when the tip reaches the second electrode. (c) Schematic diagram of the experimental set-up for cutting a conducting wire. The negatively biased AFM tip moves in contact mode across the conducting wire. The tip erases the metallic q-2DEG locally when it crosses the conducting wire. The conductance between two electrodes is monitored as the tip scans over the wire. (d) Conductance between the two electrodes measured as a function of the tip position across the wire, while cutting the wire with the tip biased at –3V. A sharp drop in conductance occurs when the tip passes the wire (courtesy of Jeremy Levy, University of Pittsburgh, U.S.A., and Jochen Mannhart, University of Augsburg, Germany).

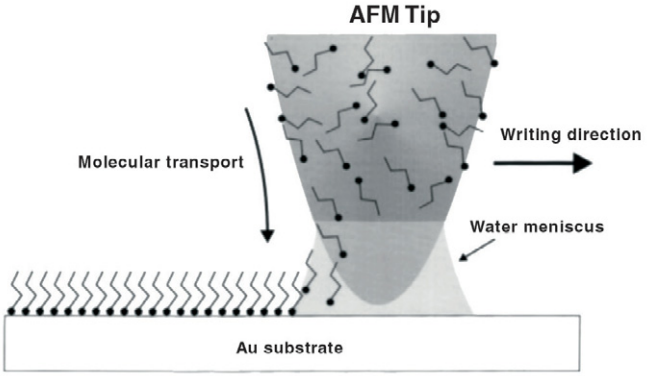

Fig. 8 Schematic representation of DPN. A water meniscus forms between the AFM tip coated with octadecane thiol (ODT) and the Au substrate. The size of the meniscus, which is controlled by relative humidity, affects the ODT transport rate, the effective tip-substrate contact area, and DPN resolution (reprinted with permission from[61].

(Fig. 9). This technology has gained some 15 orders of magnitude since its introduction[68] and its lateral resolution has entered the nanoscale[69]. The current spatial resolution of the device is 4 nm allowing the detection of 35 nuclear spins as compared with current magnetic resonance imaging (MRI) technologies still operating in the millimeter or micrometer scale. As a result a three-dimensional image of a tobacco virus could be shown for the first time[70]. Single nuclear spin detection seems to be achievable in a foreseeable time which undoubtedly will have great impact, e.g in structural biology in locally

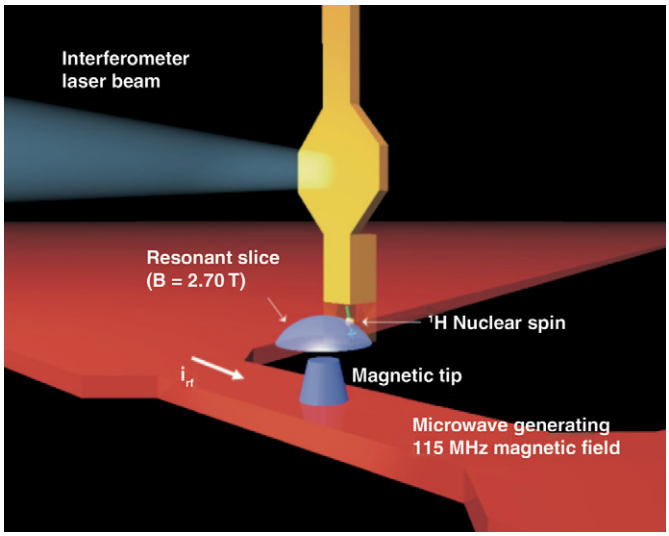

Fig. 9 A representation of a state of the art magnetic resonance force microscopy (MRFM) apparatus. A sample – shown here schematically as a ^{1}H spin – is attached to the end of an ultrasensitive cantilever and positioned close to a magnetic tip. A rf current i_{rf} passing through a copper microwire generates an alternating magnetic field. We modulate i_{rf} to induce periodic ^{1}H spin-flips. The resonant slice represents those points in space where the total field B matches the magnetic resonance condition for the ^{1}H spin. When the ^{1}H spin is scanned through the resonant slice, it undergoes periodic inversion. These spin-flips result in a small alternating force between the ^{1}H spin and the magnetic tip, causing the cantilever deflect periodically. In this way, we can image the three-dimensional ^{1}H density in an sample (courtesy of Martino Poggio, University of Basel, Switzerland).

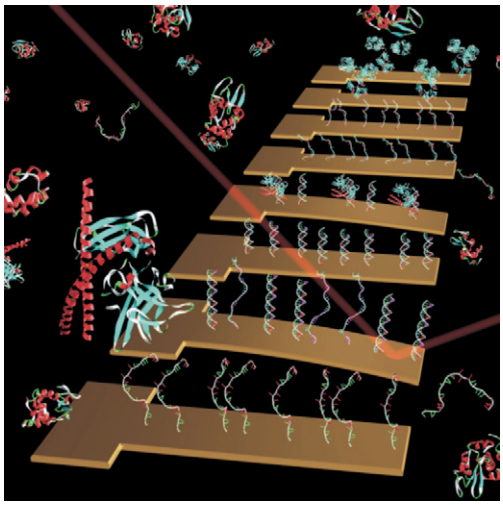

Fig. 10 Schematic representation of a combined DNA and protein microcantilever array sensor (COMBIOSENS). Cantilevers 1, 2, 5 and 6 are functionalized with single stranded DNA molecules for detection of hybridization with the complementary strand, but only the sequence on cantilever 2 matches the complement present in the liquid environment, and therefore some DNA double-strand molecules have already formed on the surface of the cantilever. Microcantilever 3 is functionalized with double-stranded DNA for detection of transcription factors that bind to specific DNA sections. Cantilevers 7 and 8 are functionalized with proteins and antibodies, respectively. These sensors can specifically detect other proteins and antigens (courtesy of H.R. Hidber, University of Basel).

mapping a surface with chemical resolution. The development of a technique that might be able to provide a chemically resolved image of a sample surface (chemical force microscopy) has revealed that the cantilever itself is a very sensitive tool for observing chemical reactions and processes.

Nanomechanical sensing

Another broad area of application is chemical and biological sensing[71,72] (Fig. 10). In this approach the absorption of molecules onto the cantilever allows them to be detected because they change the mass, and hence the resonance frequency of the cantilever[73]. However, in physiological environments, the absorption of biomolecules (such as DNA[74-76], proteins, peptides and antibodies[77]) is detected by changes in surface stress in a way that could have advantages over standard biomolecular techniques. In general, the possibilities offered by coating the individual cantilevers in an array with layers to which only particular types of biomolecules can attach are enormous[78-80].

Extraterrestrial, scientific and economic impact

Indeed, even the sky is not the limit for AFM technology. The Rosetta mission to comet 67P launched by the European Space Agency in 2004 includes an AFM in its MIDAS (Micro-Imaging Dust Analysis System) instrument. The goal of this mission, which is expected to touch down on 67P in 2014, is to analyze particle size distributions in cometary material. NASA's Phoenix mission to Mars in 2008 included an AFM for similar studies (Collaboration between the Universities of Neuchâtel and Basel, as well as with Nanosurf GmbH). Today these methods are still making a tremendous impact on many disciplines that range from fundamental physics and chemistry through information technology, spintronics, quantum computing, and molecular electronics, all the way to life sciences. Indeed, over 6,000 AFM-related papers were published last year alone, bringing the total to more than 70,000 since it was invented, according to the web of science, and the STM has inspired a total of 20,000 papers. There are also at least 500 patents related to the various forms of scanning probe microscopes. Commercialization of the technology started in earnest at the end of the 1980s, and approximately 11,000 commercial systems have been sold so far to customers in areas as diverse as fundamental research, the car industry and even the fashion industry. There are also a significant number of home-built systems in operation. Some 40–50 companies are involved in manufacturing SPM and related instruments, with an annual worldwide turnover of $350 million.

Nanotechnology quo vadis

What does the future hold? Nanotechnology is still dominated to a certain extent by the top down approach where miniaturization plays a crucial role. However, there is a worldwide effort of meeting the bottom-up approach of self-assembly and self-organisation that has been so successfully implemented in the natural world trying to unravel nature's secrets on a nanometer scale to create a new generation of materials, devices and systems that will spectacularly outperform those we have today in information technology, medicine and biology, environmental technologies, the energy industry and beyond. As we understand better how nature is doing ‚things' on a fundamental level, achievements like clean chemistry or clean processing[81,82] will emerge along with it how to handle the waste problems, not polluting the environment. New smart materials, hybrid or heterostructured, as well as carbon nanotubes[83], a variety of nanowires[84] or graphene[85,86] could be ingredients for novel energy saving devices. In order to understand the whole functionality of a cell Systems Biology Institutes have been established with the hope of artificially synthesizing a cell in a bottom-up approach[87]. Nanomedicine including non-invasive diagnostics[88] will be more and more on the agenda fighting diseases on the molecular level, e.g. new kind of drug delivery systems based on peptides[89,90] or block co-polymer nanocontainers[91] are investigated as possible carriers to target carcinogenic cells[92]. Biology is driven by chemistry however the scaffold, the gears, the knots and bolts, e.g in cell membranes is nanomechanics, a template orchestrated by nature worthwhile trying to copy and implementing in novel nano devices. Scanning Probe Microscopy and related methods will still play an important role in many of these investigations helping to capitalize on this fundamental knowledge, beneficial for future technologies and to mankind.

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