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**CLASSIFICATION OF SCANNING PROBE
MICROSCOPIES**
(Technical Report)

Prepared for publication by
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Classification of scanning probe microscopies (Technical Report)

TABLE OF CONTENTS

- 1 INTRODUCTION
- 2 THE CONCEPT OF SCANNING PROBE MICROSCOPY
- 3 AN OVERVIEW ON DIFFERENT SPM TECHNIQUES
 - 3.1 Scanning tunneling microscopy (STM)
 - 3.2 Scanning force microscopy (SFM)
 - 3.2.1 Contact mode scanning force microscopy (CM-SFM)
 - 3.2.1.1 Atomic force microscopy (AFM)
 - 3.2.1.2 Tapping mode atomic force microscopy (TM-AFM)
 - 3.2.2 Non-contact scanning force microscopy (NC-SFM)
 - 3.2.2.1 Electric force microscopy (EFM)
 - 3.2.2.2 Magnetic force microscopy (MFM)
 - 3.2.2.3 Van der Waals force microscopy (VDWFM)
 - 3.3 Scanning near-field optical microscopy (SNOM)
 - 3.3.1 Aperture scanning near-field optical microscopy (ASNOM)
 - 3.3.2 Non-aperture scanning near-field optical microscopy (NA-SNOM)
 - 3.3.3 Evanescent field scanning near-field optical microscopy (EF-SNOM)
 - 3.3.4 Scanning near-field plasmon microscopy (SNPM)
 - 3.4 Scanning electrochemical microscopy (SECM)
 - 3.5 Scanning capacitance microscopy (SCaM)
 - 3.6 Scanning ion conductance microscopy (SICM)
 - 3.7 Scanning thermal microscopy (SThM)
 - 3.8 Scanning near-field acoustic microscopy (SNAM)
- 4 LIST OF ACRONYMS
- 5 REFERENCES

Abstract: In the last few years scanning probe microscopy techniques have gained significant importance in a variety of different research fields in science and technology. A rapid development, stimulated by the invention of the scanning tunneling microscope in 1981 and still proceeding at a high pace, has brought about a number of new techniques belonging to this group of surface analytical methods. The large potential of scanning probe microscopes is documented by over 1000 publications per year. Due to the fact that a number of different terms and acronyms exist, which are partially used for identical techniques and which are sometimes confusing, this article is aimed at classification and at an overview on the analytically most important techniques with clarification of common terms. Emphasis will be put on analytical evaluation of scanning tunneling and scanning force microscopy, as up to now these techniques have gained the highest importance for analytical applications.

1. INTRODUCTION

An important milestone in the history of scanning probe microscopy techniques was the invention of the scanning tunneling microscope (STM) by Binnig & Rohrer in 1981 [1], although the idea of obtaining super-resolution microscopical information by scanning a sharp probe across a sample surface at a very

close distance and by utilizing near-field effects was already existing before the advent of STM. For example the concept for scanning near-field microscopy, which opens up the opportunity for exceeding the microscopical resolution given by Abbe's criterion [2], was introduced by Syngé [3] in 1928 and O'Keefe [4] in 1956. However, the technology for an instrumental implementation of the idea was not available at that time. An apparatus showing already a number of instrumental similarities as compared to the STM was the topografiner developed by Young in 1972 [5]. In this instrument scanning and positioning of a metal tip above the sample surface was performed by means of piezoelectric translators. In connection with the work on the topografiner also vibration isolation has been improved and identified as one important key towards high resolution imaging. Due to the fact that the tip-sample separation was controlled by a field emission signal, the lateral resolution was limited to about only 400 nm. However, in their publication of 1972 [5], Young *et al.* have already suggested that the resolution could be increased significantly by bringing the tip closer to the sample surface and by utilizing the tunneling effect, an idea which took until 1981 to be implemented in the first scanning tunneling microscope. In fact this microscope was the first one in the family of scanning probe microscopes to attract high interest across the whole scientific community due to its ultimate resolution power down to the atomic scale. Since the invention of the STM has strongly stimulated the development of other scanning probe microscopes, these techniques are frequently considered as offsprings of the STM.

2. THE CONCEPT OF SCANNING PROBE MICROSCOPY

Figure 1 shows the general concept of scanning probe microscopy (SPM). A sharp probe (e.g. tip, optical fiber, pipette) is raster-scanned (either probe or sample can be moved) across a sample surface by means of piezoelectric translators, while a certain signal is recorded by the probe for every single image point. Since this signal constitutes local information of the surface below the probe the term local probe technique can be found frequently. As far as the range of today's applications is concerned, the most important aspect—but not the only one—of this concept is to use the local signal for monitoring the distance between probe and surface. Thus, topographical information can be obtained in real space.

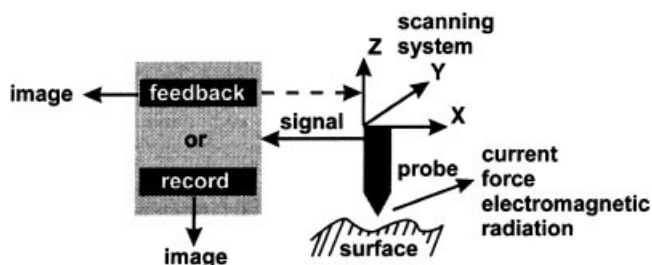


Fig. 1 General scheme of scanning probe microscopy.

We can distinguish between two different modes of operation, which we should call the constant height mode and the constant signal mode. In the constant height mode the absolute vertical position of the probe remains constant during raster-scanning. Thus, the probe–surface separation changes according to the sample topography resulting in a varying signal of the probe. This mode of operation is advantageous when small areas are to be scanned at high scan rates in order to minimize image distortion by, e.g. thermal drifts, especially when working at atomic resolution. However, the risk of probe crashes, which may result in damage of either probe or sample surface, is higher in this mode. In the constant signal mode the signal of the probe is kept constant through readjusting the vertical position of the probe (or the sample) by applying an appropriate voltage on the vertical piezoelement. This voltage can be used to trace the surface topography, if other effects that could influence the probed signal are negligible. In this mode large areas (up to more than 100 μm in square) of rough sample surfaces can be imaged with a minimum risk of destroying the sample with the probe or vice versa. However, lower scan rates are required in this mode to allow appropriate height readjustment by the feedback loop.

From this general description we can identify the following components as common features of SPMs:

- sharp probe
- piezoelectric translator to move the probe relative to the sample
- detection system for the signal delivered by the probe
- feedback system to keep the signal constant by height readjustment of the probe
- imaging system to convert the single data points into an image

A common and straightforward way to name SPM techniques is to exchange the 'P' in SPM by an appropriate abbreviation for the type of signal measured (e.g. signal: tunneling current—STM (scanning tunneling microscopy) or signal: forces—SFM (scanning force microscopy)). Therefore, also SXM is sometimes used as general abbreviation, however, it is recommended to rather use SPM, due to the more descriptive nature of the latter expression ('P' for probe).

It has already been mentioned above that topographical imaging is not the only perspective of SPM analysis. It has also been demonstrated that the possibility of positioning sharp probes above a surface with Ångström and sub-Ångström precision, opens up the exciting potential of accessing local spectroscopic information even confined to spots as small as a single atom. This approach is not always in accordance with the general concept of SPM presented above. Nevertheless the corresponding spectroscopic techniques are related to SPM, since similar or identical experimental set-ups are used.

The structure of the following overview on SPM techniques is aimed at a classification of SPMs and a clarification of common terms and abbreviations. Terms introduced in the course of the history of SPM, which do not fit exactly in the above-mentioned scheme of nomenclature, will be addressed. The continued use of such terms can be accepted or even recommended as long as they are unequivocal and correctly describe the method. It should also be noted that a detailed description of instrumental designs and a complete review on applications is beyond the scope of this article. For this purpose further literature will be referenced in an exemplary way when appropriate.

3. AN OVERVIEW ON DIFFERENT SPM TECHNIQUES

Table 1 shows an overview on the techniques described in this paper along with recommended terminology and synonyms which can be found in literature, too.

3.1 Scanning tunneling microscopy (STM)

Principle: In the STM the probe is a sharp metal tip scanned across the surface at distances in the order of typically 1 nm. A bias voltage of typically a few millivolts is applied between the tip and the sample leading to a tunneling current in the order of a few nanoamperes. Since there is an exponential relation between the tunneling current and the tip-surface separation, the tunneling current is an extremely sensitive measure to control that separation. For example a variation of the separation by 0.1 nm changes the tunneling current by a factor of approximately 10. This means that in principle variations in the separation of 0.001 nm can be monitored by keeping the current constant within a few percent. It should be pointed out however, that the tunneling current is also influenced by the electronic structure of the surface. For images taken in constant current mode at a certain bias voltage sometimes the term constant current topograph (CCT) is used. Since electrons can only tunnel from occupied states in the tip to unoccupied states in the surface or vice versa depending on the polarity of the bias, in general for small voltages the STM images represent contours of the local density of states near the Fermi level ($LDOS_{EF}$). It is not the goal of this article to review the work published on theory, instrumentation, and application of STM. Therefore, for further information only a book by Bonnell [6] and references cited therein are recommended.

Analytical figures of merit:

- A wide range of scan sizes from more than 100 μm down to the atomic level can be covered in one experiment. Thus, it is possible to first obtain an overview image of a surface and then zoom in

Table 1 Overview on SPM techniques

Technique	Common synonyms	Related techniques	Common synonyms
scanning tunneling microscopy (STM)		scanning tunneling spectroscopy (STS) scanning noise microscopy (SNM) scanning noise potentiometry (SNP) alternating current STM (ACSTM) scanning chemical potential microscopy (SCPM) scanning optical absorption microscopy (SOAM) spin polarized STM (SPSTM) ballistic electron emission microscopy (BEEM) photon emission STM (PESTM) photon assisted STM (PASTM)	scanning tunneling optical microscopy (STOM) laser assisted STM (LASTM)
scanning force microscopy (SFM) atomic force microscopy (AFM)		friction force microscopy (FFM) Young's modulus microscopy (YMM) force-distance measurements	lateral force microscopy (LFM)
tapping mode AFM (TM-AFM)	intermittent contact AFM		
electric force microscopy (EFM)	scanning Maxwell stress microscopy (SMM)	scanning surface potential microscopy (SSPM) scanning Kelvin microscopy (SKM)	
magnetic force microscopy (MFM) van der Waals force microscopy (VDWFM)			
scanning near-field optical microscopy (SNOM)	near-field scanning optical microscopy (NSOM)		
aperture SNOM (ASNOM) transmission ASNOM (T-ASNOM) collection ASNOM (C-ASNOM) emission ASNOM (E-ASNOM) nonaperture SNOM (NA-SNOM)			
evanescent field SNOM (EF-SNOM)	photon scanning tunneling microscopy (PSTM) evanescent field optical microscopy (EFOM)		
scanning near-field plasmon microscopy (SNPM) scanning electrochemical microscopy (SECM) scanning capacitance microscopy (SCaM) scanning ion conductance microscopy (SICM)			
scanning thermal microscopy (SThM)	scanning thermal profiler (SThP)		
scanning near-field acoustic microscopy (SNAM)			

certain structural features at higher resolution. This greatly enhances the potential for many topographical and metrological investigations, because allocation of the identical surface area is a severe problem or might be impossible, when samples need to be transferred between instruments accessing information on different scales and resolutions.

- Due to the fact that the information is obtained in real space, local defects (e.g. mono-atomic defects, steps, dislocations) can be investigated. This clearly is a great advantage compared to diffraction methods relying on extended periodic structures, and thus showing averaged information.
- Since the position of the tip is controlled by an electromechanical positioning device (piezo translator) in all spatial directions, three-dimensional topographical information can be extracted from the images. Of course this is only true, if local electrical effects are negligible, since correctly speaking STM produces an image of the local density of states at the Fermi level. This simplification is justified however, when surface topographies with roughnesses well above the atomic level (e.g. several nanometer or more) are considered. On the atomic scale in general interpretation is much more complicated and both experimental measures (e.g. comparison of images taken at different bias voltages and polarities) and comparisons with theoretical calculations have to be performed in order to discriminate between electronic structure and surface topography.
- Besides measurements in ultrahigh vacuum (UHV), STMs can also be operated under ambient conditions. This is a further advantage that significantly enhances the applicability of the technique. Although many fundamental studies on surfaces of solids must be carried out under well-defined vacuum conditions, imaging under liquids or in ambient atmosphere is of significant interest for analytical chemistry, since a wide variety of materials ranging from metals and semiconductors to organic and biological samples can be studied in their natural environment. In many cases sample preparation is straightforward. Sometimes samples can be used as they are, or fresh cleavage surfaces can be prepared. There is only one major restriction that must be kept in mind: in general insulators cannot be imaged. In some cases such materials can be studied by STM, when present in form of thin layers on a conductive substrate. Another perspective of imaging under ambient conditions are in-situ studies of surface processes at solid/liquid and solid/gas interfaces. Such processes can also be investigated under controlled electrochemical potential by means of special electrochemical cells. In the literature the technique is often referred to as electrochemical STM (ECSTM). It must be mentioned however, that measures (e.g. coating of the tip with an insulating polymer) have to be taken to get rid of faradaic currents between the tip and the electrolyte solution. The ECSTM has already been used successfully to study processes at electrode surfaces down to the atomic scale (see, e.g. [6], references cited therein, and [7]).
- As already mentioned in Section 2, also spectroscopic information can be revealed by SPM techniques. In case of the STM the term scanning tunneling spectroscopy (STS) is used and there are basically two options to perform spectroscopy. In the first option the tip is moved to a spot of interest and the tunneling current is recorded as a function of the bias voltage without changing the position of the tip. In this way a spectrum of the density of states can be obtained, since different occupied or unoccupied states get involved in the tunneling process, when the bias voltage is changed. Methodologically it is not absolutely correct to use the term *scanning* tunneling microscopy for this technique, since what's actually performed is point spectroscopy. Nevertheless we discuss this method in context with STM, because the same instrumentation is used as already mentioned at the end of Section 2.

The other option of obtaining spectroscopic information is simultaneous recording of STM images at various bias voltages. This can be accomplished by performing point spectroscopy at every image point or by modulating the bias voltage while scanning. In the literature simultaneous recording of images at various bias voltages is sometimes called current imaging tunneling spectroscopy (CITS). As one example for the discrimination between different chemical species (in this case Ga and As atoms on a GaAs(110) surface) in an atomically resolved STM image by simultaneously recording two images at reversed bias voltage the work of Feenstra *et al.* [8] should be referenced. The spectroscopic potential of STM has also been used in a very promising way by the group of Avouris [9–11] for studying surface chemistry on silicon surfaces. Although it is clear that such studies must be performed under optimized

and well-defined conditions in a UHV chamber, they clearly show the large potential of STM for elucidating the mechanism of chemical surface reactions (here the oxidation of silicon) at the atomic scale.

- Although there is no doubt about the fascinating potential of STM in analytical chemistry, limitations and possible sources for artefacts should be addressed as well. First of all the influence of the tip on the obtained data should be noted. In the case of STM both electronic and geometric effects must be considered. Electronic effects play a significant role when imaging with atomic resolution. Neglecting the chemical nature of the atom at the apex of the tip is only a first order approximation assuming that the surface states of the sample and the tunneling current images are unaffected from the electronic structure of the tip. For further information on the interpretation of STM images see [6] and references cited therein. Geometric effects and other sources of artefacts as vibrations and drifts will be addressed in Section 3.2.

Related techniques:

STMs have also been used to obtain information about surfaces according to signal generation schemes different from the original STM as described above. For instance, surface topography can also be mapped with an STM without applying a voltage between tip and sample. In this case the thermal noise of the current is used for signal generation [12–14]. The method has been referred to as scanning noise microscopy (SNM) and scanning noise potentiometry (SNP).

STM operated with alternating current opens up the opportunity to study insulators. The technique has been referred to as alternating current STM (ACSTM) [15].

In the scanning chemical potential microscope (SCPM) [16] the voltage across the tunneling gap is supplied by a thermal gradient between chemically different tip and sample. This allows high resolution imaging of thermoelectric variations of the chemical potential gradient with temperature. A thermal gradient can also be applied by illumination with laser light in a certain wavelength range. This technique has been referred to as scanning optical absorption microscopy (SOAM) [17].

The STM can also be used to probe surface magnetism with high resolution when spin-polarized electrons, produced by a ferromagnetic tip, are introduced [18–24]. Spin-polarized STM (SPSTM) is suggested as a term for this technique.

Ballistic electron emission microscopy (BEEM) is a modification of the STM, which can be used for studying interfacial barrier heights in layered systems [6,25,26]. The sample consists of at least two layers forming an interface (e.g. a metal layer on top of a semiconductor), which acts as a potential barrier for the charge carriers. When a bias voltage is applied between the tip and the metal layer, electrons can tunnel across the gap and are 'injected' into the metal layer. Some of these electrons can travel through the metal layer and reach the interface prior to scattering. If they have sufficient energy to enter the semiconductor (collector), a collector current can be measured. The energy of the electrons can be controlled by changing the bias voltage between tip and metal layer. In this way spectroscopy of the transport of charge carriers through buried interfaces can be performed.

Other modifications of the STM involve electromagnetic radiation [27–39]. We must distinguish between two basic concepts: measuring photons generated in the tunneling gap by inelastic tunneling effects [31,35,37,38] and generation of electrical currents by irradiation of the tunneling gap [28–30,32–34]. For the first group of methods the term photon emission scanning tunneling microscopy (PESTM) is recommended, for the second one photon assisted scanning tunneling microscopy (PASTM). For the PESTM also the term STOM (scanning tunneling optical microscopy) has been used [38]. However, the recommended terminology better accounts for the difference between emission and irradiation mode and better discriminates these techniques from near-field optical and evanescent-field probe techniques. For further specification of a method the terminology can be modified according to the type of radiation or radiation source (e.g. LASTM for laser assisted STM).

In addition to these modified STM techniques also acronyms for instruments combining STM with other techniques can be found. Specifically, the field ion STM (FI-STM), which allows in-situ investigation of the STM tip by field ion microscopy (FIM), should be mentioned [40].

Finally, it should be mentioned that the term STM has also been used in connection with techniques *not* involving tunneling of electrons. For example the term photon scanning tunneling microscopy (PSTM) has been used for a method, which should rather be assigned to scanning near-field optical microscopy and will therefore be described there.

3.2 Scanning force microscopy (SFM)

The common operation principle of scanning force microscopes is sensing of forces between a sharp tip and a sample surface while raster-scanning the tip across the surface. Such forces can be measured by mounting the tip on a cantilever beam—which acts as a spring—and sensing the deflection. The force is proportional to the deflection and depends on the spring constant of the cantilever (Hooke's law). This detection scheme can be considered as a quasi-static operation mode (sometimes also referred to as DC-mode). An other option is to drive the cantilever at a certain oscillation frequency (sometimes also referred to as AC-mode or dynamic mode). As interaction forces or force gradients are encountered, the oscillation will be damped. The change of the resonance frequency or of the vibration amplitude is a sensitive measure for the force acting on the tip. This operational mode is often referred to in literature as dynamic force microscopy (DFM) [41–43]. For an overview on instrumental designs for force sensing and for SFMs in general a book by Sarid [44] is recommended. SFMs can also be classified according to the nature of the forces (e.g. contact, noncontact, interatomic, electrical, magnetic) relevant for signal generation. Also the distinction between attractive force microscopy (SAFM [45]) and repulsive force microscopy has been made in literature, however, this terminology is less useful for a systematic classification, since it is less discriminating for the nature of signal generation and the corresponding detection techniques. In the terminology of specific SFM techniques it is common not to use the term *scanning* (e.g. atomic force microscopy (AFM) instead of scanning atomic force microscopy (SAFM) or electric force microscopy (EFM) instead of scanning electrical force microscopy (SEFM)). This is not in accordance with the general terminology for SPM suggested in the introduction. However, in view of the fact that the common shorter terminology is already well established, sufficiently descriptive and unequivocal, a change of this terminology does not seem to be appropriate.

For extracting additional information from force interactions between tip and sample (e.g. via force-distance curves (see Section 3.2.1.)) the term force spectroscopy has been used.

3.2.1 Contact mode scanning force microscopy (CM-SFM)

3.2.1.1 Atomic force microscopy (AFM)

Up to now besides STM the AFM, which has been invented by Binnig, Quate & Gerber [46] in 1985, has gained the highest importance among all scanning probe microscopes [44,47–51].

Principle: In the AFM the tip, which is mounted on a soft spring (cantilever), permanently stays in contact with the sample surface during scanning. Since neither the cantilever nor the sample is driven at an oscillation frequency, the conventional AFM can be characterized as operating in the quasi-static DC-mode. Figure 2 schematically shows the forces encountered when a sharp tip touches a surface. In the contact area of the tip apex (in the ideal case a single atom) repulsion occurs due to the overlapping electronic shells of tip and sample atom. Since these interatomic repulsive forces are short-range forces and confined to an extremely small area, they can be utilized to trace the surface topography with atomic resolution. Besides these short-range forces also long-range forces (e.g. electrical forces, magnetic forces, van der Waals forces), which can be attractive or repulsive, are observed. These forces interact across larger surface areas and are therefore not suited for atomic resolution imaging. In fact these forces are unwanted in AFM, since they increase the total force (which can be attractive or repulsive, although the interatomic force relevant for signal generation is always repulsive) acting on the cantilever, and thus contribute to possible deformation or even destruction of the sample, especially when soft and sensitive materials are investigated.

One example for such unwanted forces, which are always encountered when samples are imaged in air, are capillary condensation forces. The origin of these forces is wetting of the tip surface when the tip immerses into liquid adsorbate films present on the sample. As a consequence, the tip is pulled towards

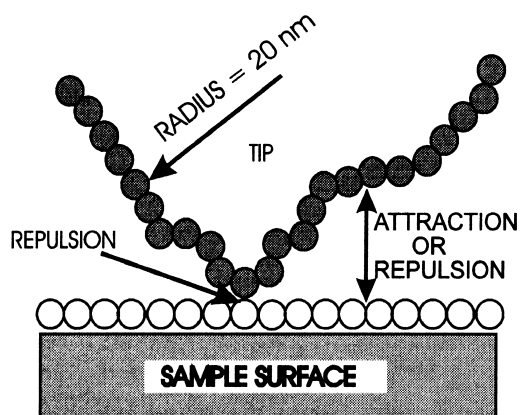


Fig. 2 Schematic view of forces encountered when the tip touches the sample surface. The circles symbolize the sample atoms and tip atoms, respectively.

the sample surface, which significantly increases the force in the contact area at the apex (by a factor of typically 100). Thus, measures have to be taken (for example imaging under liquids) to eliminate or reduce such forces in order to acquire AFM images at minimum repulsive, interatomic interaction forces.

The force-distance curve in Fig. 3 further illustrates the range of operation of the AFM. Force-distance curves show how the force changes, when the sample surface approaches the tip. At large separations there is no interaction and the observed force is zero (straight line between 1 and 2, if we assume that there are no long-range forces like, e.g. electrostatic charging forces). At position 2 the tip jumps into contact due to attractive van der Waals interaction. As the sample is further moved towards the tip the total force acting on the cantilever becomes repulsive. When the sample is retracted again, the force is reduced along the line from position 3–4. Below the zero force line in the diagram the net force acting on the cantilever becomes attractive, because the tip is held at the surface due to adhesion. In 4 the adhesion force and the cantilever load are just balanced and the tip flips off the surface when further retracting the sample. For AFM measurements the force can be set along the curve between position 3 and 4, preferably close to 4 in order to minimize the contact force. The value of the pull-off force can be reduced significantly by imaging under liquids due to elimination of capillary forces as already mentioned above. For a general overview on force interactions a book by Israelachvili is recommended [52].

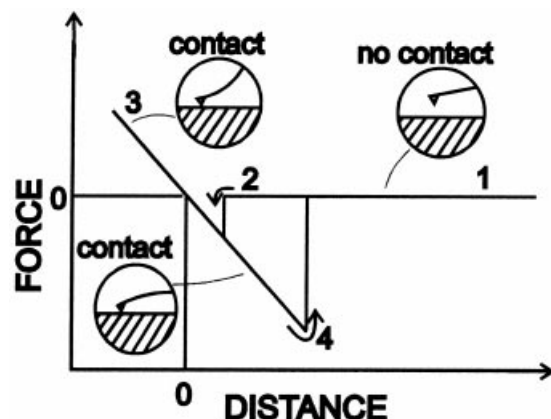


Fig. 3 Force-distance curve depicting the interaction of the AFM tip with the sample surface. For explanation refer to the text.

Although it is not the goal of this paper to review instrumentation and design, just one option to measure forces in AFMs, the optical lever deflection system [44,53], should be described, since it is widely used in commercial instruments and offers a number of analytical advantages. Figure 4 shows a

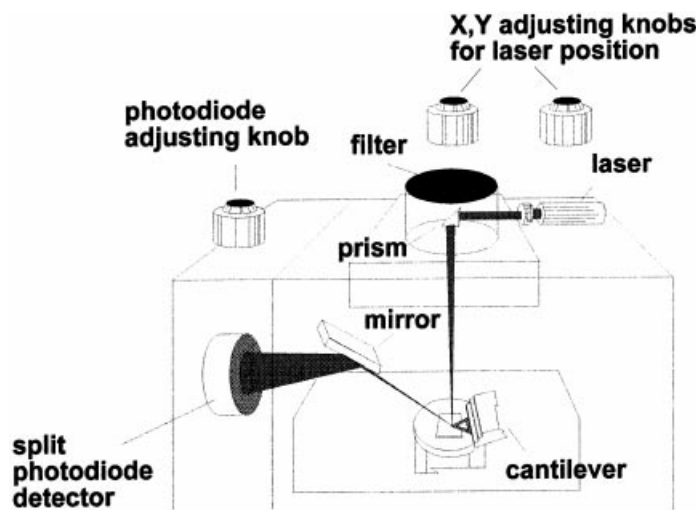


Fig. 4 Schematic view of the deflection sensing system as used in the NanoScope III AFM (Digital Instruments, Santa Barbara, USA).

scheme of this system. A laser beam is focused on the rear of the cantilever. The reflected laser beam is detected by means of a double segment photodiode. During scanning a varying deflection of the cantilever is achieved, due to the surface topography encountered. As a consequence the mirror plane for the laser beam changes, and thus its position on the photodiode. Therefore, the difference signal between the two segments of the photodiode is a sensitive measure for the deflection of the cantilever. One advantage of this system is the fact that it can be conveniently operated also under liquids, because interference of the deflection measurement with the conditions in the measurement cell can be excluded. This detection scheme is well suited to achieve atomic resolution. Today microfabricated cantilevers [54,55] (silicon nitride or single crystal silicon) with spring constants of less than 0.1 N/m and resonance frequencies of more than 100 kHz are commercially available allowing measurement at forces typically in the range from 1 nN (under liquids) to 100 nN (in air). For further information the reader is referred to the book by Sarid [44] and a number of review articles [47–51].

Analytical figures of merit:

- The wide range of scan sizes and the fact that information is being obtained in real space has already been addressed for the STM in Section 3.1. The same statements are also true for the AFM.
- As far as the information content of AFM images is concerned, the interpretation of the images as surface topography both on the large and atomic scale is justified in a good approximation. The reason is that in contrast to the STM the interatomic repulsive force ‘looks’ at the total charge density, which is distributed spherically around the atomic nuclei. Thus, in a first order approximation the influence of electronic inhomogeneities on the image features can be neglected, which facilitates interpretation. This capability makes the AFM a powerful tool for metrological purposes (e.g. determination of surface roughness or measurement of width, height and depth of individual structures), since the images contain direct depth information. This is an important advantage compared to, e.g. secondary electron microscopy.
- Since conductive samples are not necessary, also insulators can be studied with the AFM without the need to coat them. This significantly facilitates sample preparation and artefacts introduced by the coating can be avoided. That can again be seen as a further advantage compared to secondary electron microscopy when imaging a variety of samples from inorganic insulators to organic and biological specimens.
- Since AFM measurements can be performed also under liquids, the technique is a very valuable tool for in-situ investigation of surface processes like corrosion, crystal growth, or film deposition processes [56–58]. Similar to the STM in-situ measurements can also be performed under controlled

electrochemical potential (electrochemical AFM (ECAFM)) [59,60], Another promising potential of imaging and sample preparation under liquids is the protection of sensitive surfaces under inert media. In this way atmospheric influences (e.g. oxidation, humidity) can be avoided by in-situ preparation and in-situ imaging [56].

- When using the AFM and interpreting the results one must also be aware of possible artefacts caused by vibrations, convolution of surface features with the tip geometry, deformation or scratching of the surface by the force load, or drifts.

Vibrations can introduce noise or periodic structures to the images. Identification of vibrational artefacts can be accomplished by changing experimental parameters like scan rates, scan sizes, scan angles, and gains for the feedback loop. Features which significantly change upon variation of these parameters can be identified as not originating from the real surface topography of the sample. Vibrations can be eliminated or reduced by appropriate isolation stages or chambers for protection from acoustical noise.

Most tip artefacts occur when the geometric shape of the tip does not allow its very apex to perfectly follow the real sample topography, especially when looking at surfaces on the nanometer and micrometer scale. This can be the case for example when steep edges or narrow holes and trenches are imaged. Then the observed slope of the edge and the observed depth of the hole, respectively, is affected by the apex angle of the probing tip. Objects sharper than the tip (e.g. whisker crystals sticking out of the surface) produce images of the tip. If commercial silicon nitride tips with pyramidal shape [54] are used, this leads to the observation of pyramids, which are aligned parallel to the imaging tip (this is an additional hint for the identification of this artefact). Further sources of artefacts are multiple and asymmetric tips. Multiple tips produce multiple images of single features, asymmetric tips lead to different resolutions along different directions. Comparison of images taken at different scan orientations (scan angles) can give a hint to the latter artefact. Truncated tips deteriorate the imaging resolution and frequently produce characteristic repeating square-like patterns aligned parallel to each other. They reflect the stumpy apex of the tip. Whenever such unpalatable observations are made, special care has to be taken when interpreting the obtained data. Comparison of images taken under different conditions and implementation of information from other techniques is then an important measure to make sure that the images reflect the real sample topography.

Deformation and destruction of the sample has to be considered, especially when studying soft materials. Thus, minimization of the force load is important. Information on the influence of this artefact can be obtained by repeatedly scanning the same surface area and by observation of previously scanned areas in a larger imaged field. Unstable and nonreproducible images as well as scratching of craters are an alerting indicator for artefactual results. In this case, if possible, further minimization of the force load should be performed or other SFM techniques (see Section 3.2.1.2) should be used.

Lateral drifts (e.g. thermal drifts) lead to distortions in the images. They can be identified by changing scan parameters like scan rate or scan angle and by comparison of 'up'- and 'down'-scans. In high resolution imaging the influence of thermal drifts can be reduced by applying high scan rates. On the micron scale drifts are normally not a severe problem.

Related techniques:

Friction force microscopy (FFM)

Since in AFM the tip is permanently in contact with the sample surface while scanning, there are also shear forces acting on the tip which lead to torsion of the cantilever. Therefore, the term lateral force microscopy (LFM) is frequently used. These forces can be utilized to measure the friction between tip and sample. Practically, lateral forces can be measured with regular AFM instrumentation. Detection of the torsion of the cantilever can be achieved by means of a quadruple photodiode (see also principle of AFM), which allows simultaneous detection of cantilever deflection and torsion. In this way topography and lateral force images can be recorded simultaneously. This bears the potential of assigning material

specific information (friction) to single features seen in the topography images. This is of special interest for research in the field of tribology [61–64].

The principle of the FFM has also been used in a development called the chemical force microscope (CFM) [65]. In this method the tip has been chemically modified to make it sensitive towards different chemical surface compositions. That way image contrast could be achieved due to variations in adhesion (and thus also in friction) between tip and sample.

Young's modulus microscopy (YMM)

Besides AFM imaging in the conventional quasi-static DC-mode, it is also possible to extract information from measurements in the dynamic AC-mode, but still in the contact mode. This option has been introduced by Maivald *et al.* [66]. The sample is modulated at a certain amplitude Δz . This also drives the tip, which is in contact with the sample, at a certain amplitude $\Delta z'$. Due to deformation of the sample by the load of the tip, $\Delta z'$ is lower than Δz . Only if the sample was indefinitely stiff $\Delta z'$ would equal Δz . Thus, the difference of the two values is a measure for the elasticity of the sample (also the term elasticity atomic force microscopy has been used in literature). The method has been used successfully, e.g. for imaging carbon fibers in a polymer matrix [66].

Force-distance curve measurements

Force-distance curves have already been described above in order to show the range of operation of a conventional AFM (see also Fig. 3 and corresponding explanation). Here, it should be mentioned that besides optimization of the imaging force for AFM measurements, they can also be used to obtain information about the interaction between tip and sample surface [67–76]. For instance, the pull-off force observed in the curves is a measure for the adhesion between tip and sample. However, the value of that force largely depends on the medium under which measurements are performed [72] and interpretation is not straightforward. Moreover, force-distance curves usually show large deviations from the schematic shape drawn in Fig. 3 (see, e.g. [72]). Specifically, the straight line at a force equal to zero drawn for the noncontact region is only a simplification. Due to long-range interactions (e.g. van der Waals, electrostatic) experimental force-distance curves show specific features in this region. This has been utilized for, e.g. studying electrostatic interaction in electrolytes [71].

3.2.1.2 Tapping mode atomic force microscopy (TM-AFM)

It has already been addressed that sample deformation or destruction can be a problem in AFM. Here, an improvement can be achieved with the TM-AFM. In the TM-AFM the cantilever with the tip is modulated at a frequency of several hundred kilo-Hertz (dynamic AC-mode). This is performed in such a way that the tip is just slightly tapping the sample surface. Thus, the vibrational amplitude of the cantilever is damped. This effect can be used to control the distance between tip and sample surface, and thus the topography of the sample can be monitored. Although in the TM-AFM the tip is not permanently in contact with the sample while scanning, it is still suggested to consider it as a CM-SFM technique and to use the term AFM, since intermittent contact occurs during imaging. Regarding the problem of transition from noncontact to contact the reader is referred to [77–79]. Due to the fact that shear forces are eliminated and vertical forces are reduced significantly in the TM-AFM, it is especially (but not only) advantageous for investigating sensitive materials (e.g. biological surfaces) or unstable surface features (e.g. small particles) [80–86].

3.2.2 Non-contact scanning force microscopy (NC-SFM)

For a number of methods utilizing long-range forces frequently the term noncontact AFM can be found in literature. This term, which rather exists for historical reasons, is *not* recommended for methods obtaining information through operation in the pure noncontact (adhesive) regime (we have defined AFM as a technique utilizing interatomic short-range interaction forces in the repulsive mode, which implies that contact occurs). Again, for a discussion of the transition from noncontact to contact the reader is referred to [77–79].

NC-SFM introduced by Martin *et al.* [87] usually is operated in the dynamic AC-mode, since much lower forces (and force gradients) can be detected in this mode. Due to the long-range nature of the forces

involved, they are not confined to such small areas as in AFM. Therefore, the lateral resolution achievable is lower.

3.2.2.1 Electric force microscopy (EFM)

The electric force microscope utilizes electrostatic forces or force gradients between a conductive tip and a sample for signal generation. Different operation modes as bimorph-driven lever, sample-driven lever, and voltage-driven lever (since in this design the lever is driven by the modulated electric force between tip and sample and no separate mechanical oscillator is required, also the term scanning Maxwell stress microscopy (SMM) has been used) have been reported. For an overview see reference [44]. The electrostatic forces between sample and tip (charges on the tip can be introduced by applying DC or AC voltages between tip and sample) have been utilized to obtain information on surface charges [88,89] (the technique has also been referred to as localized charge force microscopy), topography, capacitance (dielectric constant), and potential (see [44] and references cited therein). Other terms that can be found in connection with EFM are scanning surface potential microscopy (SSPM) [90] and scanning Kelvin probe force microscopy (SKFM) [91] (or scanning Kelvin microscope (SKM) [92]), which are based on the design of the SMM and which are able to image surface potentials and contact potential differences (CPD).

3.2.2.2 Magnetic force microscopy (MFM)

In MFM [93] magnetostatic forces are measured by interaction of magnetic domains on a surface with a magnetized tip. The modes of operation (see also [44]) are similar to those described for the EFM. MFM is mainly interesting as a tool for applications in magnetic storage device manufacturing [94] for imaging of magnetic patterns with a resolution of approximately 50 nm.

3.2.2.3 Van der Waals force microscopy (VDWFM)

VDWFM [95] is a further option to map surface topography in the noncontact regime and also under very 'gentle' conditions. Van der Waals forces (for a good overview see [52]) are always present between atoms or molecules. They can be attractive or repulsive and are effective from interatomic spacings to long-range distances up to 10 nm and more. The resolution achievable depends on the tip-sample separation. At larger distances soft and delicate surfaces can be imaged with minimum forces, however, at lower resolution. With decreasing tip-sample separation both the force introduced to the sample and the resolution increases. When the oscillating tip just slightly touches the sample surface the regime of the TM-AFM is reached (see Section 3.2.1.2).

Since most measurements reported in literature have been performed in the attractive region, also the term scanning attractive mode force microscopy (SAFM) [45] can be found. Due to the fact that signal detection is achieved in the dynamic mode the term noncontact dynamic force microscopy (noncontact DFM) has been used too. Although in principle these terms are correct, the terminology used in this article is recommended, because it is more specific (discrimination between different types of forces) and better fits into a general systematics of SPM based on the nature of the signal.

3.3 Scanning near-field optical microscopy (SNOM)

In SNOM [96–103] the concept of SPM is used to scan a fine optical fiber across a sample surface at a short distance above the surface and near-field effects of electromagnetic radiation are used for signal generation. Although the more general term scanning optical microscopy is being used for microscopical techniques involving scanning and optical information, the term SNOM is more specific and better accounts for the fact, that in scanning probe microscopy, as we have identified and defined it here, one is mainly interested in obtaining 'super-resolution' by operating probes in the near-field. In this way it is possible to perform measurements far below the resolution limit of $\lambda/2$ (Abbe's criterion). Also the term near-field scanning optical microscopy (NSOM) can be found in literature. However, the term SNOM is more consistent with the general term scanning probe microscopy.

3.3.1 Aperture scanning near-field optical microscopy (ASNOM)

The ASNOM utilizes a narrow aperture, produced by coating a fine optical fiber with a metal film. Only the aperture opening at the apex of the fiber tip is left uncovered. The resolution is determined by the

diameter of the aperture (which can be made much smaller than the wavelength of the used radiation) and the probe-sample separation. In the most popular operation mode photons are directed onto the sample surface through the aperture and the light that passes through it and through the object is analyzed in transmission mode [96]. Therefore, the term transmission ASNOM (T-ASNOM) is recommended.

The probe with the narrow aperture can also be used to collect photons coming from the illuminated sample. Illumination can be performed from the rear in transmission mode or from the top in reflection mode. For this operation mode the term collection ASNOM (C-ASNOM) is recommended. If the collected photons are originating from emission of a self-luminous sample, the term emission ASNOM (E-ASNOM) could be used as an alternative for C-ASNOM.

3.3.2 *Non-aperture scanning near-field optical microscopy (NA-SNOM)*

The NA-SNOM works pretty much like the ASNOM described above. The major difference is the design of the probe. Instead of metal coated tapered fibers special probes (e.g. tetrahedral tips) without apertures and with geometries leading to strongly localized emission of light are used. Thus, the size limitation of apertures normally faced for metal coated fibers can be overcome opening up the possibility for extremely high resolution down to 1 nm [99,100].

3.3.3 *Evanescent field scanning near-field optical microscopy (EF-SNOM)*

In contrast to the ASNOM the EF-SNOM [101–103] uses an uncoated optical fiber tip as probe. While scanning across the surface this probe senses the evanescent field above the sample surface, which is generated by total internal reflection (TIR) through illumination of the sample from the rear. Due to the fact that the evanescent field decays exponentially with the distance from the surface, the intensity detected by the probe is a very sensitive measure for the probe-surface separation. Thus, topography is accessible with high resolution similar to STM. Therefore, the technique is mostly referred to as photon scanning tunneling microscopy (PSTM) (or analytical photon scanning tunneling microscopy (APSTM) [104,105], if it provides also spectroscopic information) to point out the analogy between electron tunneling and ‘photon tunneling’. Also the term evanescent field optical microscopy (EFOM) has been used. Nevertheless the term EF-SNOM is recommended, since it is more consistent with the general scheme for nomenclature of SPMs and also precludes confusion with STM.

3.3.4 *Scanning near-field plasmon microscopy (SNPM)*

In the SNPM [106] surface plasmons are resonantly excited by a laser beam. The resulting optical near-field at the surface is locally probed by a sharp tip. Since elastic plasmon scattering and the radiationless energy transfer from the tip to the sample strongly depends on the separation between sample and tip, the intensity of the reflected laser beam becomes distance dependent as well.

3.4 Scanning electrochemical microscopy (SECM)

In the SECM [107,108] the faradaic current flowing at the scanning tip is used for signal generation. Since the tip is covered with an insulating coating at its sides, an ionic current can only flow through the uncoated apex of the tip. If the tip is far away from the surface the current is determined by hemispheric diffusion of ions to the tip. If the tip is brought close to an insulating substrate, diffusion is hindered and a lower current is observed (depending on the tip-surface separation). If the tip is brought close to a conductive surface which is held at a potential to produce ionic products contributing to the tip current, an increased current will be measured. Thus, the method is sensitive both towards tip-sample separation and to the nature of the surface, opening up the possibility to study electrochemical processes on a wide variety of materials [109].

3.5 Scanning capacitance microscopy (SCaM)

In the SCaM [110–113] a fine electrode is scanned across the sample surface within a distance of a few nanometers. The capacitance of the probe-sample system can be utilized to control the spacing between probe and sample. Since the capacitance also depends on the dielectric constants of the sample and the medium between sample and probe, the SCaM can also be used for mapping spatial variations of

dielectric properties. It should be mentioned that SCaM has also been combined with AFM for simultaneous monitoring of the surface topography [112].

3.6 Scanning ion conductance microscopy (SICM)

In the SICM [114,115] the tip of a micropipette is scanned across the sample surface under an electrolyte solution. When a voltage is applied between the electrode inside the pipette and the electrolyte reservoir, an ionic current can flow. The current depends on the opening of the pipette, and thus also on the probe-sample separation. This principle can be used to trace the surface topography by keeping the ionic current constant. The method has also been used to image ionic currents flowing through pores of membranes.

3.7 Scanning thermal microscopy (SThM)

In the SThM [116] a small thermocouple junction at the end of a metal tip is scanned across the sample surface. In this way local temperature differences can be imaged. The term scanning thermal profiler (SThP) has been used for this technique, too.

3.8 Scanning near-field acoustic microscopy (SNAM)

In SNAM [117,118] a supersonic beam produced by a tip, which can be excited, e.g. by a piezoelectric oscillator, is transmitted to the sample surface. The transmitted amplitude can serve as a measure for the tip-surface separation, but also for material properties like, e.g. surface elasticity. SNAM can be used to image the surface topography of a variety of materials—also of soft ones like, e.g. polymers.

4 LIST OF ACRONYMS

ACSTM	alternating current scanning tunneling microscopy
AFM	atomic force microscopy
ASNOM	aperture scanning near-field optical microscopy
BEEM	ballistic electron emission microscopy
C-ASNOM	collection aperture scanning near-field optical microscopy
CCT	constant current topograph
CFM	chemical force microscopy
CITS	current imaging tunneling spectroscopy
CM-SFM	contact mode scanning force microscopy
CPD	contact potential difference
DFM	dynamic force microscopy
E-ASNOM	emission aperture scanning near-field optical microscopy
ECAFM	electrochemical atomic force microscopy
ECSTM	electrochemical scanning tunneling microscopy
EFM	electric force microscopy
EFOM	evanescent field optical microscopy
EF-SNOM	evanescent field scanning near-field optical microscopy
FFM	friction force microscopy
FIM	field ion microscopy
FI-STM	field ion scanning tunneling microscopy
LASTM	laser assisted scanning tunneling microscopy
LDOS	local density of states
LFM	lateral force microscopy
MFM	magnetic force microscopy

NA-SNOM	nonaperture scanning near-field optical microscopy
NC-SFM	noncontact scanning force microscopy
NSOM	near-field scanning optical microscopy
PASTM	photon assisted scanning tunneling microscopy
PESTM	photon emission scanning tunneling microscopy
PSTM	photon scanning tunneling microscopy
SAFM	scanning attractive force microscopy
SCaM	scanning capacitance microscopy
SCPM	scanning chemical potential microscopy
SECM	scanning electrochemical microscopy
SFM	scanning force microscopy
SICM	scanning ion conductance microscopy
SKFM	scanning Kelvin probe force microscopy
SKM	scanning Kelvin microscopy
SMM	scanning Maxwell stress microscopy
SNAM	scanning near-field acoustic microscopy
SNM	scanning noise microscopy
SNOM	scanning near-field optical microscopy
SNP	scanning noise potentiometry
SNPM	scanning near-field plasmon microscopy
SOAM	scanning optical absorption microscopy
SPM	scanning probe microscopy
SPSTM	spin polarized scanning tunneling microscopy
SSPM	scanning surface potential microscopy
SThM	scanning thermal microscopy
SThP	scanning thermal profiler
STM	scanning tunneling microscopy
STOM	scanning tunneling optical microscopy
STS	scanning tunneling spectroscopy
SXM	scanning probe microscopy
T-ASNOM	transmission aperture scanning near-field optical microscopy
TIR	total internal reflection
TM-AFM	tapping mode atomic force microscopy
UHV	ultra high vacuum
VDWFM	van der Waals force microscopy
YMM	Young's modulus microscopy

REFERENCES

- 1 G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel. Surface studies by scanning tunneling microscopy. *Phys. Rev. Lett.* **49**, 57–61 (1982).
- 2 E. Abbe. Beiträge zur Theorie des Mikroskops und der mikroskopischen Wahrnehmung. *Arch. Mikrosk. Anat.* **9**, 413–468 (1873).
- 3 E. H. Synge. A suggested method for extending microscopic resolution into the ultra-microscopic region. *Phil. Mag.* **6**, 356–362 (1928).

- 4 J. A. O'Keefe. Resolving power of visible light. *J. Opt. Soc. Am.* **46**, 359 (1956).
- 5 R. Young, J. Ward, F. Scire. The topografiner: an instrument for measuring surface microtopography. *Rev. Sci. Instrum.* **43**, 999–1011 (1972).
- 6 D. A. Bonnell. *Scanning Tunneling Microscopy and Spectroscopy, Theory, Techniques and Applications*. VCH Publishers Inc, New York (1993).
- 7 O. M. Magnussen, J. Hotlos, G. Beitel, D. M. Kolb, R. J. Behm. Atomic structure of ordered copper adlayers on single-crystalline gold electrodes. *J. Vac. Sci. Technol.* **B9**, 969–975 (1991).
- 8 R. M. Feenstra, J. A. Stroscio, J. Tersoff, A. P. Fein. Atom-selective imaging of the gallium arsenide(110) surface. *Phys. Rev. Lett.* **58**, 1192–1195 (1987).
- 9 Ph. Avouris. Atom-resolved surface chemistry using the scanning tunneling microscope. *J. Phys. Chem.* **94**, 2246–2256 (1990).
- 10 Ph. Avouris, I. W. Lyo, F. Bozso. Atom-resolved surface chemistry: The early steps of Si(111)- 7×7 oxidation. *J. Vac. Sci. Technol.* **B9**, 424–430 (1991).
- 11 Ph. Avouris, I.-W. Lyo. Probing and inducing surface chemistry on the atomic scale using the STM. *AIP Conf Proceedings* **241**, 283–297 (1992).
- 12 R. Möller, A. Esslinger, B. Koslowski. Noise in vacuum tunneling: application for a novel scanning microscope. *Appl. Phys. Lett.* **55**, 2360–2362 (1989).
- 13 R. Möller, A. Esslinger, B. Koslowski. Thermal noise in vacuum scanning tunneling microscopy at zero bias voltage. *J. Vac. Sci. Technol.* **A8**, 590–593 (1990).
- 14 R. Möller, C. Baur, A. Esslinger, P. Kürz. Scanning noise potentiometry. *J. Vac. Sci. Technol.* **B9**, 609–611 (1991).
- 15 G. P. Kochanski. Nonlinear alternating-current tunneling microscopy. *Phys. Rev. Lett.* **62**, 2285–2288 (1989).
- 16 C. C. Williams, H. K. Wickramasinghe. Scanning chemical potential microscope: a new technique for atomic scale surface investigation. *J. Vac. Sci. Technol.* **B9**, 537–540 (1991).
- 17 J. M. R. Weaver, L. M. Walpita, H. K. Wickramasinghe. Optical absorption microscopy and spectroscopy with nanometer resolution. *Nature* **342**, 783–785 (1989).
- 18 S. F. Alvarado. Surface magnetism of epitaxial thin films by polarized electron scattering. *J. Appl. Phys.* **64**, 5931 (1988).
- 19 R. Wiesendanger, H.-J. Güntherodt, G. Güntherodt, R. J. Gambino, R. Ruf. Observation of vacuum tunneling of spin-polarized electrons with the scanning tunneling microscope. *Phys. Rev. Lett.* **65**, 247–250 (1990).
- 20 R. Wiesendanger, D. Bürgler, G. Tarrach, H.-J. Güntherodt, G. Güntherodt. Tunneling of spin-polarized electrons. *AIP Conf Proceedings* **241**, 504–510 (1992).
- 21 R. Wiesendanger, D. Bürgler, G. Tarrach, A. Wadas, D. Brodbeck, H.-J. Güntherodt, G. Güntherodt, R. J. Gambino, R. Ruf. Vacuum tunneling of spin-polarized electrons detected by scanning tunneling microscopy. *J. Vac. Sci. Technol.* **B9**, 519–524 (1991).
- 22 S. F. Alvarado, P. Renaud. Observation of spin-polarized-electron tunneling from a ferromagnet into gallium arsenide. *Phys. Rev. Lett.* **68**, 1387–1390 (1992).
- 23 S. F. Alvarado. Spin polarized electron tunneling from a ferromagnet into GaAs(110). *J. Appl. Phys.* **73**, 5816 (1993).
- 24 S. F. Alvarado. Tunneling potential barrier dependence of electron spin polarization. *Phys. Rev. Lett.* **75**, 513–516 (1995).
- 25 W. J. Kaiser, L. D. Bell. Direct investigation of subsurface interface electronic structure by ballistic electron emission microscopy. *Phys. Rev. Lett.* **60**, 1406–1409 (1988).
- 26 L. D. Bell, W. J. Kaiser. Observation of interface band structure by ballistic-electron-emission microscopy. *Phys. Rev. Lett.* **61**, 2368–2371 (1988).
- 27 J. K. Gimzewski, B. Reihl, J. H. Coombs, R. R. Schlittler. Photon emission with the scanning tunneling microscope. *Z. Phys. B* **72**, 497–501 (1988).
- 28 M. Völcker, W. Krieger, T. Suzuki, H. Walther. Laser-assisted scanning tunneling microscopy. *J. Vac. Sci. Technol.* **B9**, 541–544 (1991).
- 29 Y. Kuk, R. S. Becker, P. J. Silverman, G. P. Kochanski. Photovoltage on silicon surfaces measured by scanning tunneling microscopy. *J. Vac. Sci. Technol.* **B9**, 545–550 (1991).

- 30 D. A. Bonnell, G. S. Rohrer, R. H. French. Tunneling spectroscopy analysis of optically active wide band-gap semiconductors. *J. Vac. Sci. Technol.* **B9**, 551–556 (1991).
- 31 K. Takeuchi, Y. Uehara, S. Ushioda, S. Morita. Prism-coupled light emission from a scanning tunneling microscope. *J. Vac. Sci. Technol.* **B9**, 557–560 (1991).
- 32 S. Akari, M. Ch. Lux-Steiner, M. Vögt, M. Stachel, K. Dransfeld. Photoassisted tunneling spectroscopy: Preliminary results on tungsten diselenide. *J. Vac. Sci. Technol.* **B9**, 561–563 (1991).
- 33 D. G. Cahill, R. J. Hamers. Scanning tunneling microscopy of photoexcited carriers at the silicon(100) surface. *J. Vac. Sci. Technol.* **B9**, 564–567 (1991).
- 34 S. Grafström, J. Kowalski, R. Neumann, O. Probst, M. Wörtge. Analysis and compensation of thermal effects in laser-assisted scanning tunneling microscopy. *J. Vac. Sci. Technol.* **B9**, 568–572 (1991).
- 35 R. Berndt, R. R. Schlittler, J. K. Gimzewski. Photon emission scanning tunneling microscope. *J. Vac. Sci. Technol.* **B9**, 573–577 (1991).
- 36 R. Berndt, R. R. Schlittler, J. K. Gimzewski. Photon emission processes in STM. *AIP Conf Proceedings* **241**, 328–336 (1992).
- 37 J. K. Gimzewski, R. Berndt, R. R. Schlittler. Observation of local photoemission using a scanning tunneling microscope. *Ultramicroscopy* **42–44**, 366–370 (1992).
- 38 M. Tsukada, T. Shimizu, K. Kobayashi. Microscopic theory of light emission from the scanning tunneling microscope. *Ultramicroscopy* **42–44**, 360–365 (1992).
- 39 R. Möller, S. Akari, C. Baur, B. Koslowski, K. Dransfeld. Scanning tunneling microscopy and photons. *AIP Conf Proceedings* **241**, 314–327 (1992).
- 40 T. Sakurai, T. Hashizume, Y. Hasegawa, I. Kamiya, N. Sano, K. Yokoyama, H. Tanaka, I. Sumita, S. Hyodo. New versatile room-temperature field ion scanning tunneling microscopy. *J. Vac. Sci. Technol.* **A8**, 324–326 (1990).
- 41 D. Anselmetti, M. Dreier, R. Lüthi, T. Richmond, E. Meyer, J. Frommer, H.-J. Güntherodt. Biological materials studied with dynamic force microscopy. *J. Vac. Sci. Technol.* **B12**, 1500–1503 (1994).
- 42 R. Lüthi, E. Meyer, L. Howald, H. Haefke, D. Anselmetti, M. Dreier, M. Rüetschi, T. Bonner, R. M. Overney, J. Frommer, H.-J. Güntherodt. Progress in noncontact dynamic force microscopy. *J. Vac. Sci. Technol.* **B12**, 1673–1676 (1994).
- 43 M. Dreier, D. Anselmetti, T. Richmond, U. Dammer, H.-J. Güntherodt. Dynamic force microscopy in liquids. *J. Appl. Phys.* **76**, 5095–5098 (1994).
- 44 D. Sarid. *Scanning Force Microscopy*. Oxford University Press, New York (1991).
- 45 N. Umeda, S. Ishizaki, H. Uwai. Scanning attractive force microscope using photothermal vibration. *J. Vac. Sci. Technol.* **B9**, 1318–1322 (1991).
- 46 G. Binnig, C. F. Quate, Ch. Gerber. Atomic force microscopy. *Phys. Rev. Lett.* **56**, 930–933 (1986).
- 47 D. Rugar, P. Hansma. Atomic Force Microscopy. *Phys. Today* **43**, 23–30 (1990).
- 48 S. N. Magonov. Surface characterization of materials at ambient conditions by scanning tunneling microscopy (STM) and atomic force microscopy (AFM). *Appl. Spectrosc. Rev.* **28**, 1–121 (1993).
- 49 J. Frommer. Scanning tunneling and atomic force microscopy in organic chemistry. *Angew. Chem.* **104**, 1325–1357 (1992).
- 50 H. Fuchs. Atomic force and scanning tunneling microscopy of organic surfaces. *J. Mol. Struct.* **292**, 29–47 (1993).
- 51 G. Friedbacher, T. Prohaska, M. Grasserbauer. Surface analysis with atomic force microscopy through measurement in air and under liquids. *Mikrochim. Acta* **113**, 179–202 (1994).
- 52 J. Israelachvili. *Intermolecular and Surface Forces*. Academic Press, London (1991).
- 53 G. Meyer, N. M. Amer. Optical-beam-deflection atomic force microscopy: The sodium chloride(001) surface. *Appl. Phys. Lett.* **53**, 2400–2401 (1988).
- 54 T. R. Albrecht, S. Akamine, T. E. Carver, C. F. Quate. Microfabrication of cantilever styli for the atomic force microscope. *J. Vac. Sci. Technol.* **A8**, 3386–3396 (1990).
- 55 O. Wolter, Th. Bayer, J. Greschner. Micromachined silicon sensors for scanning force microscopy. *J. Vac. Sci. Technol.* **B9**, 1353–1357 (1991).
- 56 T. Prohaska, G. Friedbacher, M. Grasserbauer, H. Nickel, R. Lösch, W. Schlapp. In situ investigation of

- aluminum gallium arsenide/gallium arsenide multilayer structures under inert and reactive media by atomic force microscopy. *Anal. Chem.* **67**, 1530–1535 (1995).
- 57 I. Schmitz, T. Prohaska, G. Friedbacher, M. Schreiner, M. Grasserbauer. Investigation of corrosion processes on cleavage edges of potash-lime-silica glasses by atomic force microscopy. *Fresenius J. Anal. Chem.* **353**, 666–669 (1995).
- 58 P. E. Hillner, A. J. Gratz, S. Manne, P. K. Hansma. Atomic-scale imaging of calcite growth and dissolution in real time. *Geology* **20**, 359–362 (1992).
- 59 S. Manne, P. K. Hansma, J. Massie, V. B. Elings, A. A. Gewirth. Atomic-resolution electrochemistry with the atomic force microscope: Copper deposition on gold. *Science* **251**, 183–186 (1991).
- 60 A. A. Gewirth. Atomic resolution electrochemistry of underpotential deposition processes. *AIP Conf Proceedings* **241**, 253–261 (1992).
- 61 C. M. Mate, G. M. McClelland, R. Erlandsson, S. Chiang. Atomic-scale friction of a tungsten tip on a graphite surface. *Phys. Rev. Lett.* **59**, 1942–1945 (1987).
- 62 T. Miyamoto, R. Kaneko, S. Miyake. Tribological characteristics of amorphous carbon films investigated by point contact microscopy. *J. Vac. Sci. Technol.* **B9**, 1336–1339 (1991).
- 63 J. Krim, R. Chiarello. Sliding friction measurements of physisorbed monolayers: a comparison of solid and liquid films. *J. Vac. Sci. Technol.* **B9**, 1343–1346 (1991).
- 64 R. M. Overney, T. Bonner, E. Meyer, M. Rüetschi, R. Lüthi, L. Howald, J. Frommer, H.-J. Güntherodt, M. Fujihira, H. Takano. Elasticity, wear, and friction properties of thin organic films observed with atomic force microscopy. *J. Vac. Sci. Technol.* **B12**, 1973–1976 (1994).
- 65 C. D. Frisbie, L. F. Rozsnyai, A. Noy, M. S. Wrighton, C. S. Lieber. Functional group imaging by chemical force microscopy. *Science* **265**, 2071–2074 (1994).
- 66 P. Maivald, H.-J. Butt, S. A. C. Gould, C. B. Prater, B. Drake, J. A. Gurley, V. B. Elings, P. K. Hansma. Using force modulation to image surface elasticities with the atomic force microscope. *Nanotechnology* **2**, 103–106 (1991).
- 67 N. A. Burnham, R. J. Colton. Measuring the nanomechanical properties and surface forces of materials using an atomic force microscope. *J. Vac. Sci. Technol.* **A7**, 2906–2913 (1989).
- 68 J. H. Hoh, J.-P. Revel, P. K. Hansma. Tip-sample interactions in atomic force microscopy: I. Modulating adhesion between silicon nitride and glass. *Nanotechnology* **2**, 119–122 (1991).
- 69 H. W. Hao, A. M. Baró, J. J. Sáenz. Electrostatic and contact forces in force microscopy. *J. Vac. Sci. Technol.* **B9**, 1323–1328 (1991).
- 70 H. A. Mizes, K.-G. Loh, R. J. D. Miller, S. K. Ahuja, E. F. Grabowski. Submicron probe of polymer adhesion with atomic force microscopy: Dependence on topography and material inhomogeneities. *Appl. Phys. Lett.* **59**, 2901–2903 (1991).
- 71 H.-J. Butt. Electrostatic interaction in atomic force microscopy. *Biophys. J.* **60**, 777–785 (1991).
- 72 A. L. Weisenhorn, P. Maivald, H.-J. Butt, P. K. Hansma. Measuring adhesion, attraction, and repulsion between surfaces in liquids with an atomic force microscope. *Phys. Rev. B* **45**, 11226–11232 (1992).
- 73 W. A. Ducker, T. J. Senden, R. M. Pashley. Measurement of forces in liquids using a force microscope. *Langmuir* **8**, 1831–1836 (1992).
- 74 J. H. Hoh, J. P. Cleveland, C. B. Prater, J.-P. Revel, P. K. Hansma. Quantized adhesion detected with the atomic force microscope. *J. Am. Chem. Soc.* **114**, 4917–4918 (1992).
- 75 A. Kawai, H. Nagata, M. Takata. Characterization of surface energetic behavior by atomic force microscopy. *Jpn. J. Appl. Phys.* **31**, L977–L979 (1992).
- 76 J. H. Hoh, A. Engel. Friction effects on force measurements with an atomic force microscope. *Langmuir* **9**, 3310–3312 (1993).
- 77 B. Anczykowski, D. Krüger, H. Fuchs. Cantilever dynamics in quasicontract force microscopy: Spectroscopic aspects. *Phys. Rev. B* **53**, 15485–15488 (1996).
- 78 B. Anczykowski, D. Krüger, K. L. Babcock, H. Fuchs. Basic properties of dynamic force spectroscopy with the scanning force microscope in experiment and simulation. *Ultramicroscopy* **66**, 251–259 (1996).
- 79 D. Krüger, B. Anczykowski, H. Fuchs. Physical properties of dynamic force microscopies in contact and noncontact operation. *Ann. Phys.* **6**, 341–363 (1997).
- 80 Q. Zhong, D. Inness, K. Kjoller, V. B. Elings. Fractured polymer/silica fiber surface studied by tapping mode atomic force microscope. *Surf. Sci. Lett.* **290**, L688–L692 (1993).

- 81 K. Umemura, H. Arakawa, A. Ikai. High resolution imaging of cell surface using a tapping-mode atomic force microscopy. *Jpn. J. Appl. Phys. Part 2* **11B**, L1711–L1714 (1993).
- 82 P. K. Hansma, J. P. Cleveland, M. Radmacher, D. A. Walters, P. E. Hillner, M. Bezanilla, M. Fritz, D. Vie, H. G. Hansma, C. B. Prater, J. Massie, L. Fukunaga, J. Gurley, V. Elings. Tapping mode atomic force microscopy in liquids. *Appl. Phys. Lett.* **64**, 1738–1740 (1994).
- 83 C. A. J. Putman, K. O. Van der Werf, B. G. De Grooth, N. F. Van Hulst, J. Greve. Tapping mode atomic force microscopy in liquid. *Appl. Phys. Lett.* **64**, 2454–2456 (1994).
- 84 T. Shibata-Seki, W. Watanabe, J. Masai. Imaging of cells with atomic force microscopy at a tapping mode. *J. Vac. Sci. Technol.* **B12**, 1530–1534 (1994).
- 85 C. A. J. Putman, K. O. van der Werf, B. G. de Grooth, N. F. van Hulst, J. Greve. Viscoelasticity of living cells allows high resolution imaging by tapping mode atomic force microscopy. *Biophys. J.* **67**, 1749–1753 (1994).
- 86 S. H. Leuba, G. Yang, C. Robert, B. Samori, K. van, Holde, J. Zlatanova, C. Bustamente. Three-dimensional structure of extended chromatin fibers as revealed by tapping-mode scanning force microscopy. *Proc. Natl. Acad. Sci. USA* **91**, 11621–11625 (1994).
- 87 Y. Martin, C. C. Williams, H. K. Wickramasinghe. Atomic force microscope—force mapping and profiling on a sub 100-Å scale. *J. Appl. Phys.* **61**, 4723–4729 (1987).
- 88 J. E. Stern, B. D. Terris, H. J. Mamin, D. Rugar. Deposition and imaging of localized charge on insulator surfaces using a force microscope. *Appl. Phys. Lett.* **53**, 2717–2719 (1988).
- 89 B. D. Terris, J. E. Stern, D. Rugar, H. J. Manin. Localized charge force microscopy. *J. Vac. Sci. Technol.* **A8**, 374–377 (1990).
- 90 M. Fujihira, H. Kawate. Structural study of Langmuir–Blodgett films by scanning surface potential microscopy. *J. Vac. Sci. Technol.* **B12**, 1604–1608 (1994).
- 91 M. Nonnenmacher, M. O’Boyle, H. K. Wickramasinghe. Surface investigations with a Kelvin probe force microscope. *Ultramicroscopy* **42–44**, 268–273 (1992).
- 92 R. Mackel, H. Baumgartner, J. Ren. The scanning Kelvin microscope. *Rev. Sci. Instrum.* **64**, 694–699 (1993).
- 93 Y. Martin, H. K. Wickramasinghe. Magnetic imaging by ‘force microscopy’ with 1000 Å resolution. *Appl. Phys. Lett.* **50**, 1455–1457 (1987).
- 94 G. Persch, H. Strecker. Applications of magnetic force microscopy in magnetic storage device manufacturing. *Ultramicroscopy* **42–44**, 1269–1274 (1992).
- 95 U. Hartmann. Theory of Van der Waals microscopy. *J. Vac. Sci. Technol.* **B9**, 465–469 (1991).
- 96 D. W. Pohl, L. Novotny. Near-field optics: Light for the world of NANO. *J. Vac. Sci. Technol.* **B12**, 1441–1446 (1994).
- 97 M. Isaacson, J. Cline, H. Barshatzky. Near-field-optical microscopy. *AIP Conf Proceedings* **241**, 23–36 (1992).
- 98 R. C. Reddick. Photon scanning tunneling microscopy. *AIP Conf Proceedings* **241**, 37–50 (1992).
- 99 U. C. Fischer, J. Koglin, H. Fuchs. The tetrahedral tip as a probe for scanning near-field optical microscopy at 30 nm resolution. *J. Microscopy*. **176**, 231–237 (1994).
- 100 J. Koglin, U. C. Fischer, H. Fuchs. Material contrast in scanning near-field optical microscopy at 1–10 nm resolution. *Phys. Rev. B* **55**, 7977–7984 (1997).
- 101 T. L. Ferrell, J. P. Goundonnet, R. C. Reddick, S. L. Sharp, R. J. Warmack. The photon scanning tunneling microscope. *J. Vac. Sci. Technol.* **B9**, 525–530 (1991).
- 102 T. L. Ferrell, S. L. Sharp, R. J. Warmack. Progress in photon scanning tunneling microscopy (PSTM). *Ultramicroscopy* **42–44**, 408–415 (1992).
- 103 N. F. van Hulst, F. B. Segerink, F. Achten, B. Böglér. Evanescent-field optical microscopy: Effects of polarization, tip shape, and radiative waves. *Ultramicroscopy* **42–44**, 416–421 (1992).
- 104 P. J. Moyer, C. L. Jahncke, M. A. Paesler, R. C. Reddick, R. J. Warmack. Spectroscopy in the evanescent field with an analytical photon scanning tunneling microscope. *Phys. Lett. A* **145**, 343–347 (1990).
- 105 M. A. Paesler, P. J. Moyer, C. J. Jahncke, C. E. Johnson, R. C. Reddick, R. J. Warmack, T. L. Ferrell. Analytical photon scanning tunneling microscopy. *Phys. Rev. B* **42**, 6750–6753 (1990).
- 106 M. Specht, J. D. Pedarnig, W. M. Heckl, T. W. Hänsch. Scanning plasmon near-field microscope. *Phys. Rev. Lett.* **68**, 476–479 (1992).

- 107 A. J. Bard, F.-R. F. Fan, J. Kwak, O. Lev. Scanning electrochemical microscopy. Introduction and principles. *Anal. Chem.* **61**, 132–138 (1989).
- 108 A. J. Bard, P. R. Unwin, D. O. Wipf, F. Zhou. Scanning electrochemical microscopy. *AIP Conf. Proceedings* **241**, 235–247 (1992).
- 109 A. J. Bard, F.-R. F. Fan, D. T. Pierce, P. R. Unwin, D. O. Wipf, F. Zhou. Chemical imaging of surfaces with the scanning electrochemical microscope. *Science* **254**, 68–74 (1991).
- 110 J. R. Matey, J. Blanc. Scanning capacitance microscopy. *J. Appl. Phys.* **57**, 1437–1444 (1985).
- 111 C. C. Williams, W. P. Hough, S. A. Rishton. Scanning capacitance microscopy on a 35 nm scale. *Appl. Phys. Lett.* **55**, 203–205 (1989).
- 112 R. C. Barrett, C. F. Quate. Charge storage in a nitride-oxide-silicon medium by scanning capacitance microscopy. *J. Appl. Phys.* **70**, 2725–2733 (1991).
- 113 D. W. Abraham, C. Williams, J. Slinkman, H. K. Wickramasinghe. Lateral dopant profiling in semiconductors by force microscopy using capacitive detection. *J. Vac. Sci. Technol.* **B9**, 703–706 (1991).
- 114 P. K. Hansma, B. Drake, O. Marti, S. A. C. Gould, C. B. Prater. The scanning ion conductance microscope. *Science* **243**, 641–643 (1989).
- 115 C. B. Prater, P. K. Hansma, M. Tortonese, C. F. Quate. Improved scanning ion-conductance microscope using microfabricated probes. *Rev. Sci. Instrum.* **62**, 2634–2638 (1991).
- 116 C. C. Williams, H. K. Wickramasinghe. Scanning thermal profiler. *Appl. Phys. Lett.* **49**, 1587–1589 (1986).
- 117 B. T. Khuri-Yakub, S. Akamine, B. Hadimioglu, H. Yamada, C. F. Quate. Near field acoustic microscopy. *Proc. SPIE* **1556**, 30–39 (1992).
- 118 A. Michels, F. Meinen, T. Murdfield, W. Göhde, U. C. Fischer, E. Beckmann, H. Fuchs. 1 MHz quartz length extension resonator as a probe for scanning near-field acoustic microscopy. *Thin Solid Films* **264**, 172–175 (1995).