High Precision Profilometry

by

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ABSTRACT

Topographic features of sample surfaces can be imaged by using a wide variety of profilometry methods. Optical methods are limited in resolution to the wavelength of visible light, beyond which diffraction effects arise. Other mechanical methods cannot reach nanometric resolution due to large force interactions between probe and sample surface. Scanning Probe Microscopy offers a means of profiling a wide range of surface types, with possible atomic resolution, relying on many physical phenomena such as inter-atomic forces, tunneling currents, capacitive and magnetic fields. In this research project we survey and select a profilometry method to be used for topography assessment of high aspect ratio and complex geometry samples. Preliminary design considerations for a high precision profilometry based on Atomic Force Microscopy meant for profiling the complex samples is carried out.

Thesis Supervisor : Kamal Youcef-Toumi

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1 Introduction

To better understand the effects of manufacturing processes on product quality as well as to carry out a thorough quality control on these products, an assessment of the characteristics of the parts that compose this product must be made.

Many items rely on certain surface characteristics in order to fully comply with the quality specs. However, many of the features that must be characterized in order to render surface quality measurements have dimensions that reside in the nano and micro scale ranges.

In addition, the demands on industry to produce smaller products with higher precision components continue to increase. Growing consumer demand calls for advances in precision design and particularly in nanoscale systems. For example, within the next few years the semiconductor industry expects subnanometer precision in the mask/wafer alignment and inspection systems. In addition, the manufacturers of DRAM chips seek a 0.18 micrometer process which requires subnanometer precision over a 200mm to 300mm range of motion. Size is also of a primary concern; sensors with as small as one-fifth the size of current systems are desired.

It is clear from these facts that the characteristic size of fabricated features generated with these new technologies will be in the nanometer range. Furthermore, tolerances will probably be nano or sub-nanometric. To assess the quality of these new high precision products and small features as well as to better understand the applied fabrication techniques, new metrology systems will be necessary.

We identified six basic technology demands that are posed when the development of such systems comes to place: (1) correct selection of the metrology method that will be employed to obtain the metrology data from the presented sample, (2) research and development as well as fabrication of the nanoscale actuation systems, respecting the specification of sub-nanometric accuracy over the desired range, (3) research and development as well as fabrication of the sensing systems necessary for feedback and metrology measurement, (4) structural design that ensures minimisation of thermal effects and external vibration, tightness of structural loop and its independence from the metrology loop, self compensation of various error sources and error mapping, (5) design and implementation of control schemes for accurate motion and vibration isolation (if not passive) and finally, (6) processing and interpretation as well as presentation of the extracted data.

In this research project, a new profilometry tool was designed in order to acquire the shape of special kinds of samples. The characteristic surface feature sizes are in the nano scale range.

In addition to the six basic demands stated above, the design of the high precision profilometry tool took into account the intricate characteristics of the samples that would portray features with high aspect ratio and closed surfaces (holes).

2 Statement of the Problem

The objective of this research consists of designing and implementing a high precision profilometer whose purpose is to obtain the topography of special types of samples. The two main unusual characteristics of these samples are:

1. They portray high aspect ratio features.
2. The regions to be characterized with the profilometer might be included in closed curves (holes).

The general appearance of the sample is shown on figure 1.

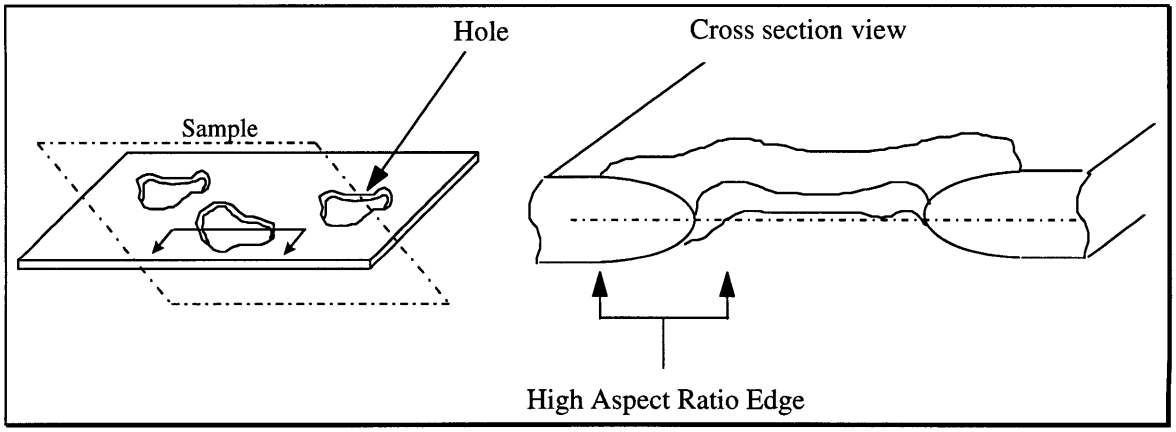

Figure 1 : Sample features.

The region to be profiled is composed of a high aspect ratio edge, pointed in figure 1, that has a curvature radius of the order of tens of nanometers. The characteristic dimension of the hole is on the order of some millimeters. The edge follows the inline of the hole (the **perimeter**). In addition, although in figure 1 the edge is depicted as

symmetric, real samples might not be symmetric along the hole diameter. From now on, in this document, we will refer to the high aspect ratio edges as simply **edges**; one **sample** might have multiple holes, in which the **edges** are located.

The profilometer will be used to determine the topography of the edge. One specific measurement is the radius of curvature of the edge tip. This characterization must be carried out in many positions along the hole perimeter . The characterization process must be non-destructive in the sense that the sample must not be broken in order to measure the profile. The aimed lateral resolution is about 10nm and the vertical resolution is on the order of 1nm. Finally, the profiling action must be fast, with a desired completion time of a few minutes to characterize each hole. A certain number of regions along the perimeter will be selected in each hole. This is particularly important to ensure that the inspection data is retrieved from many parts of the sample.

3 Profilometry Methods

The selection of the suitable profilometry method is based on the profilometry requirements. The requirements are: (1) non-destructive method, (2) lateral resolution, (3) vertical resolution, (4) lateral range, (5) vertical range, (6) repeatability, (7) time to characterize each sample and (8) cost. Note also that the conductivity characteristic of the sample will also drive the choice of the method. Since samples can be conductive or not, the chosen profilometry method must be applicable to either type. These samples are conductive but they can be coated with some type of non-conductive material.

Many technologies were investigated in order to select the appropriate profiling technique. In the conventional stylus method, a stylus with a sharp tip is mechanically dragged along the surface. The deflection of the hinged stylus arm is measured and recorded as the surface profile. The use of a hinged stylus arm allows measurement of very rough surfaces (peak-to-peak heights > 1 mm) [4, 6, 15]. On the other hand, since the hinged stylus arm is partially supported by the stylus itself, physical rigidity limits the minimum stylus tip radius and hence the lateral resolution to about 0.1μm [4]. Probe-to-surface contact forces range from 10^{-3} to 10^{-6} [27].

In optical profilometry, many different optical phenomena (such as interference and internal reflection) can be utilized. The most popular technique is based on phase-measuring interferometry, in which a light beam reflecting off the sample surface is interfered with a phase-varied reference beam. The surface profile is deduced from the fringe patterns produced. With a collimated light beam (i.e. the light is made to travel in

parallel lines) and a large photodetector array, the entire surface can be profiled simultaneously. This and other conventional optical methods are limited in lateral resolution by the minimum focusing spot size of about 0.5μm (for visible light) [4]. In addition, measurement values are dependent on the surface reflectivity of the material being profiled. For lateral resolution requirements of 10 nm, it should be obvious that the conventional methods described above are not suitable profiling solutions. Currently, only the recently developed *scanning probe* microscopes can meet the 10 nm lateral resolution requirement. In these microscopes, an atomically sharp (or nearly so) tip at a very close spacing to the surface is moved over the surface using a piezoactuator. *Scanning probe* microscopes investigated were the contact atomic force microscope (AFM), the scanning tunneling microscope (STM), scanning near-field optical microscope (SNOM), scanning capacitance microscope, scanning thermal microscope, and other variations of atomic force microscope, such as non-contact (long range) atomic force, magnetic and electrostatic force microscopes.

In the contact mode atomic force microscope, a cantilever beam mounted microstylus is moved relative to the sample surface using piezoactuators, the deflection of the cantilever is taken to be a measure of the surface topography. Atomic force microscopy offers ultrahigh lateral and vertical resolution (< 1nm possible), however, the maximum surface roughness that can be profiled is much less than that of the conventional stylus due to the limited deflection of the stylus cantilever. Probe-to-surface contact forces range from 10^{-8} N to 10^{-11} N [27].

For the scanning tunneling microscope (STM), the quantum tunneling current between the probe tip and sample is measured. The STM is attractive because it is a non-contact device (i.e. no surface damage, potential for high speed profiling) with the highest resolution of all the scanning probe microscopes, however, it can only be used on electrically conducting surfaces.

In scanning near-field optical microscope (SNOM), the focusing limit of conventional far-field optics is bypassed by bringing a 20nm diameter light aperture approximately 5nm from the surface; the resulting transmitted or reflected light is collected to form an image. SNOM technology is still very much in the research stage -

the minimum achievable lateral resolution so far (12 nm) has been limited by the ability to form the light apertures reproducibly [3, 29].

In the non-contact atomic force microscope, long range van der Waals forces are measured by vibrating the cantilever (on which the probe tip is mounted) near its resonance frequency and detecting the change in the vibrational amplitude of the beam due to a change in the force gradient (i.e. because of changes in the surface profile) [14]. The non-contact atomic force microscope offers non-invasiveness profiling, however, the technique has several disadvantages when compared to contact atomic force microscopy. First, van der Waals forces are hard-to-measure weak forces, hence the microscope is more susceptible to noise. Secondly, the probe tip must be servoed to a fixed height above the sample (typically a few nanometers) - this must be done slowly to avoid crashing the tip. Thirdly, since the tip is always floating above the surface, the effective tip radius is increased and hence the achievable lateral resolution is decreased [18, 19, 24, 30].

In the scanning thermal microscope, the measured temperature of an AC current heated tip is a function of gap spacing [1]. The magnetic and electrostatic force microscope measure the force due to a magnetic and electrostatic potential field, respectively [31]. The electrostatic force microscope is different from the scanning capacitance microscope [2], which measures the capacitance between the probe tip and the sample. These methods do not measure topography directly - the sensed quantity is actually a function of both the surface topography and other quantities (e.g. local dielectric constant).

The surface sample properties will also drive the selection of the method. For example, the AFM can be used to profile both conductive and non-conductive surfaces; thin film characterization is one field in which AFMs are actively being used [32]. The surface roughness that can be measured is dependent on the overall size of the stylus (this is a problem common to all scanning probe microscopes) - high height-to-width aspect ratio micromachined tips are available [33].

4 Method Selection

The result of our literature review (see *Appendix A*) on SEM, Stylus, Optical interferometry, SNOM, AFM, Tunneling and Probe microscopes in general revealed that the only destructive method would be the SEM. This happens because in order to expose the inner area of the hole (i.e. the edge itself), the sample must be split. However, sample modifications are not acceptable.

If the samples were not coated, it would allow us to employ probe microscopy methods that use the conductivity and reflectivity attributes of the sample (scanning magnetic force microscopy, scanning capacitance microscopy). The other methods as AFM, tunneling, interferometry and stylus are also applicable. The SNOM method is not a potential choice since translucent samples are required.

The lateral and vertical resolutions as well as the ranges are the most important requirements. The following requirements must be observed:

Ranges:

profiling up to 2µm back from the edge tip

Resolutions:

lateral resolution of 10nm

vertical resolution of 1nm

Surface qualities:

conductive or non-conductive

For these requirement, the potential profilometry methods are: (a) AFM, (b) STM. Note that only probe microscopy complies with the profilometry requirements.

As far as cost is concerned, it would be reasonable to think that probe scanners are at the same price range including training and maintenance. With regards to the profiling time per sample, this will be a direct function of the number of profile scans needed to correctly assess the edge topography. In other words, the profiling time per sample is a direct function of the number of independent regions to be scanned on each edge. Also, there are two possible different profiling procedures: profiling a single edge per sample or profiling several (or even all) edges per sample.

The number of scanned regions per edge depends on the amount of data, comprehensiveness of data and purpose of the data. It is reasonable to state that the more comprehensive the scanning (in terms of covered area) the larger the number of scanned regions per edge will be needed.

The Atomic Force Microscope operating in contact mode is the most indicated methodology. Its vertical range is sufficient for this application. The scanning probe must be able to reach at least 2μm back from the edge tip. The lateral resolution is a function of the probe tip radius and sub-10nm resolution can be achieved with commercially available probes. Because the samples might be coated or not, the STM is not suitable for the profile measurement.

5 Atomic Force Microscopy

The Atomic Force Microscope (AFM) measures the topography of a surface with a probe that has a very sharp tip. The tip is a couple of micrometers long and it is mounted at the free end of a cantilever that is typically 100 to 200 micrometers long. The probe tip radius is typically less than 0.1 micrometers [36]. The contact forces between surface and probe bends the cantilever. Sensors pick up the amount of bending as a measure of the surface topography. Since it relies on contact forces rather than on magnetic or electric surface effects, the AFM can be used to profile conductive and non-conductive samples.

The force that causes the cantilever bending is an inter-atomic interaction called van der Waals forces. The AFM can operate in two different regimes, **contact** and **non-contact** [36], according to the spacing kept between probe and sample. In the contact regime, the probe is kept some angstroms from the surface and the interactions are mainly repulsive. In the non-contact regime, the spacing is from tens to hundreds of angstroms and the interactions are attractive, mainly due to the long range van der Waals forces [8, 36].

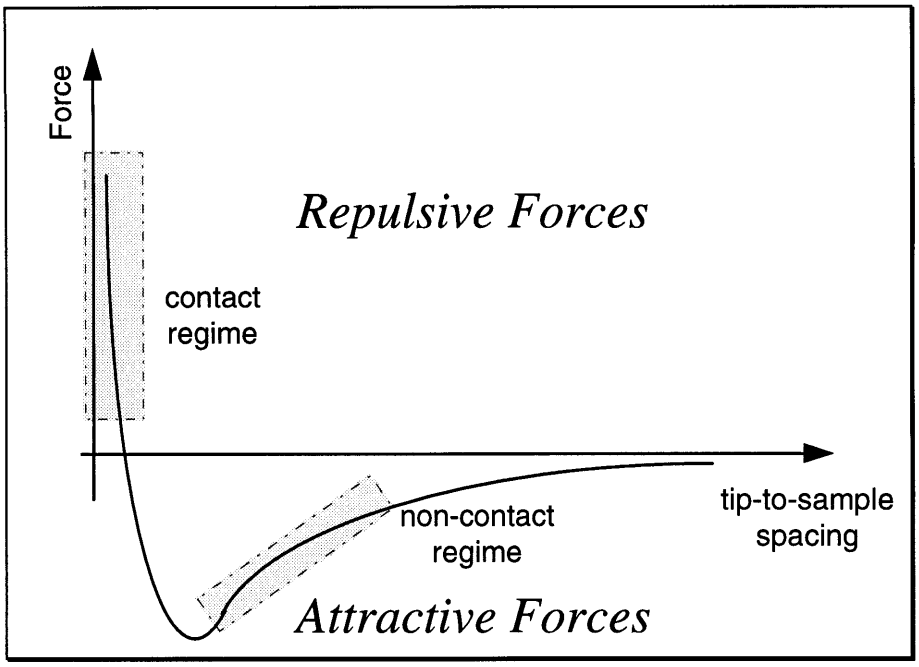

Figure 2 : Contact and non-contact regimes in AFM.

5.1 Contact Regime

In the contact regime, the tip is brought into physical contact with the sample. Since the cantilever is very compliant, contact forces are typically on the nano-Newton range. The cantilever bends because of small repulsive forces generated by the interactions between the clouds of electrons on the tip of the probe and on the sample. The closer the tip comes together with the sample, the higher the repulsive interactions as seen in figure 2.

Other forces might come into play in contact AFM. For instance, capillary forces might be generated by layers of water often present in the sample surface. The water creates a strong attractive force between probe and sample (in the range of 10^{-8} Newtons typically) [8]. The total force exerted by the tip on the sample is the sum of the cantilever spring force and the capillary forces. These forces are balanced by the repulsive van der Waals forces. Also, as long as the tip is contact with the sample, the capillary forces should remain mostly constant. The AFMs normally use a position sensitive photodetector to measure the deflection of the cantilever. A laser beam bounces on the

back of the cantilever and "lands" on an array of detectors. This method has two advantages. The first one is that, being an optical lever technique, it does not introduce any mechanical loading in the measurement. Secondly, the ratio between the path length between cantilever and detector with the length of the cantilever itself produces a mechanical amplification, meaning that even very small defections of the cantilever (some angstroms) can be monitored. Piezo-resistive cantilevers can also be used. They rely on resistance changes in the cantilever generated by the deflection. Finally, it is also possible to adapt a Scanning Tunneling Microscope at the end of the cantilever to measure its deflection as it scans the sample.

The contact AFM imaging can be carried out in two ways: constant height or constant force. In the constant height mode, the piezo scanner is stationary and the ever changing deflection of the cantilever is taken to be a measurement of the profile. In the constant force imaging mode, the deflection of the cantilever is taken as a reference input to a feed back regulator that keeps the deflection constant. The scanner moves the probe up and down in the Z direction so as to keep the deflection at the set point. In this case, the Z height of the scanner is taken to be a measurement of the surface topography. In the constant force mode, the scanning speed is limited by the ability of the feed back loop to respond to surface changes. That is, the highest speed is limited by the servo bandwidth. For excessively high speeds, the probe "flies over the sample" and topographical details are lost. In order to retrieve the same depth of details in a faster scan, the proportional feed back gain must be increased, enhancing tracking ability, however, this might excite the natural vibrational frequencies of the cantilever and image glitches might be created. Constant height imaging is less used than constant force. It is normally applied to atomically flat samples where deflections are assumed to be small.

5.2 Non-contact regime

In the non-contact regime, a piezoelectric actuator vibrates the cantilever near its resonant frequency (typically 100 to 400kHz) with an amplitude of some tens to hundreds

of angstroms. The AFM detects the changes in the resonant frequency or vibration amplitude caused by the proximity with the sample.

The non-contact technique is indicated when the sample is very soft and elastic since the contact forces are a lot smaller (pico Newtons) [8] than those associated to contact imaging. Risk of sample damaging is thus reduced. Because of these small forces, measurements are more difficult and more prone to noise contamination. The cantilevers are stiffer than those used in contact imaging because soft cantilevers might be pulled into contact with the sample.

The resonant frequency of the cantilever changes with the square root of the effective spring constant of the cantilever. The spring constant varies with the force gradient experienced by the cantilever which is in turn a function of the tip sample separation as shown in figure 2. For this reason, changes in resonant frequency can be traced to changes in sample topography.

Image artifacts can be caused when water contaminates the surface. This is not a problem in contact imaging where the probe penetrates the water layers. Finally, to keep either the vibration amplitude or the resonant frequency constant, a feedback loop moves the scanner up and down, changing the force gradient. A constant resonant frequency and constant vibration amplitude will imply that a constant average tip-sample separation is kept.

6 Geometric Aspects

Because of the high aspect ratio of the edge and because of the fact that this edge runs inside a hole placed in the sample, the orientation of the probe with respect the edge region to be scanned is a very important design aspect.

AFMs are normally used to profile mostly flat samples. In our case, the closed characteristic of the edge and the sharpness of the target areas will generate two problems: image convolution will occur between the probe shape and the edge itself. Secondly, the probe will have to be re-oriented with respect to the edge, for each different region along the perimeter.

We investigated two ways of scanning the tip of the edge. In one case, the sample is **horizontal**. In the other case, the sample is in the **vertical** position. In both cases, the probe cantilever is aligned with the edge normal direction.

6.1 Horizontal Scanning

To perform the horizontal profilometry, the closed edge must be correctly oriented and positioned with respect to the measurement frame. Firstly, the area to be scanned must be positioned horizontally. Then, for each sector of the edge, the sample must be re-oriented (rotated w.r.t. the hole center line) so that the profiling is orthogonal to the edge. Because the edges are two sided, the whole sample must be flipped to allow the scanning

of the opposite face. Finally, the sample may contain many holes with edges meaning that the positioning system must be capable of correctly placing each edge under the probe, in the correct position and orientation.

The closed edge must be in the horizontal plane (or near) to be scanned. If the sample is in the horizontal position, the following configuration is observed:

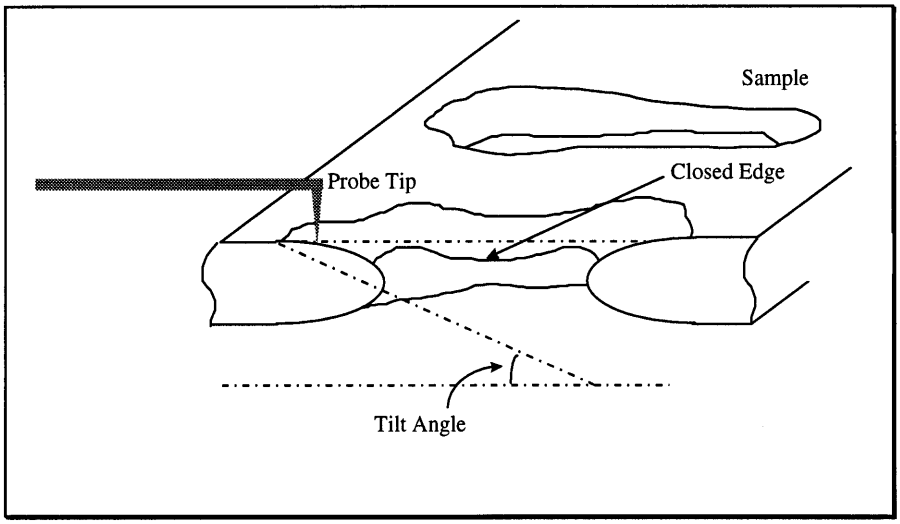

Figure 3 : Horizontal Scanning.

The scanned surface must be parallel to the scanning lines. Therefore, the desirable arrangement is achieved if the sample is tilted so as to make the relative position between the base surface of the edge and the AFM cantilever parallel.

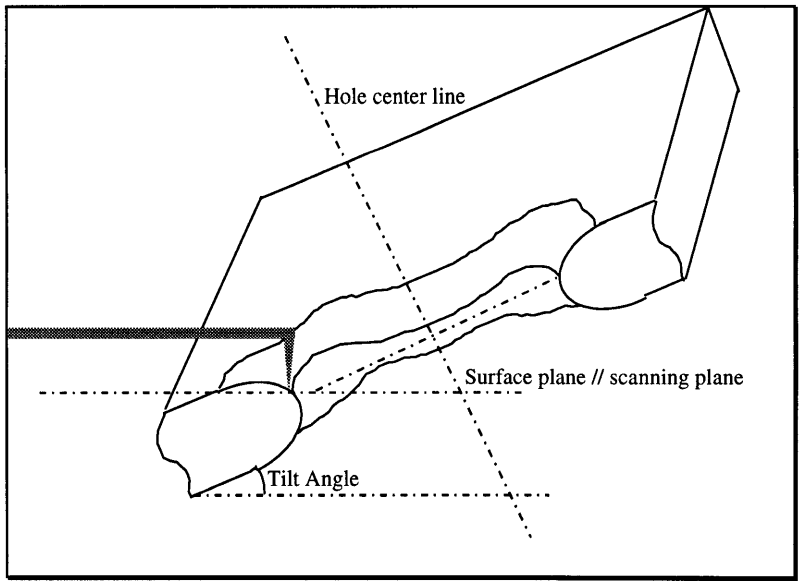

Figure 4 : Horizontal Scanning with tilted sample.

In some cases, the profiling can be done without the tilting. If the area to be scanned is very small, then even for a very inclined base plane, a large enough vertical range would allow the scanning.

For the scanning to be orthogonal to the edge. The scanning lines must be parallel or perpendicular to the ultimate edge.

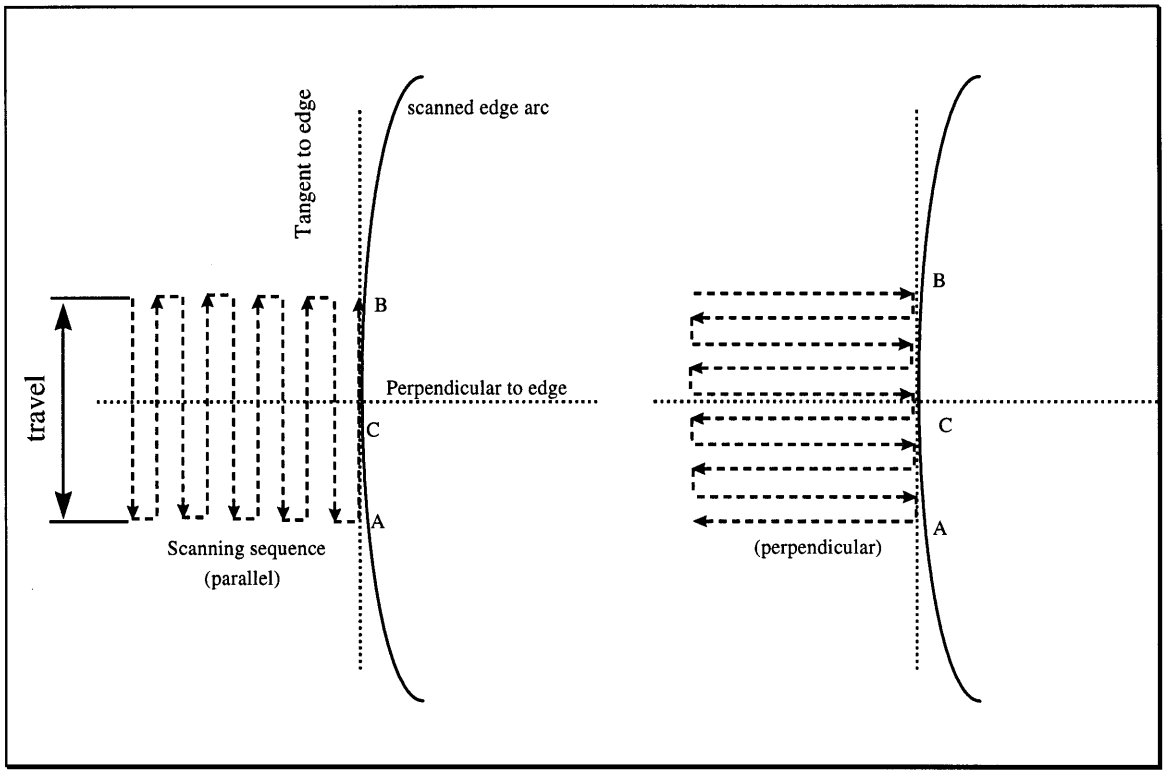

Figure 5 : Parallel and perpendicular directions for the scanning in orthogonal mode.

Both parallel and perpendicular orthogonal scanning have the same drawback: near the extremity the probe tip will fall into the hole. In the first case, the probe will abandon the sample near the center of the scanned edge arc. In the second case, the probe is likely to leave the surface near A or B. One clear way to overcome this problem is to scan, each time, a single line "perpendicular" to the edge until the probe falls; then retract the probe to a reference datum where the scan is resumed. The scanning, however, will take at least twice as long. It is important to notice, however, that if the travel is sufficiently smaller than the internal edge radius, then this scanning procedure is very similar to any other AFM scanning in mostly flat surfaces, as long as the edge base surface is on the horizontal.

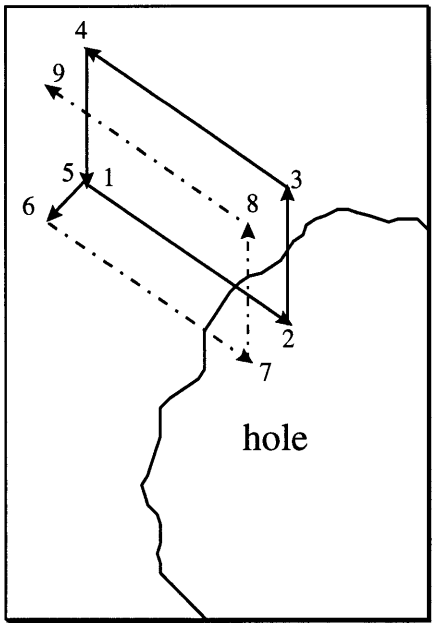

Figure 6 : Retract procedure.

The samples are two sided and this means that the sample has got to be flipped so as to allow the scanning of the opposite face [5]. The flip motion can be done sequentially and the sketch below shows some of the possible concepts:

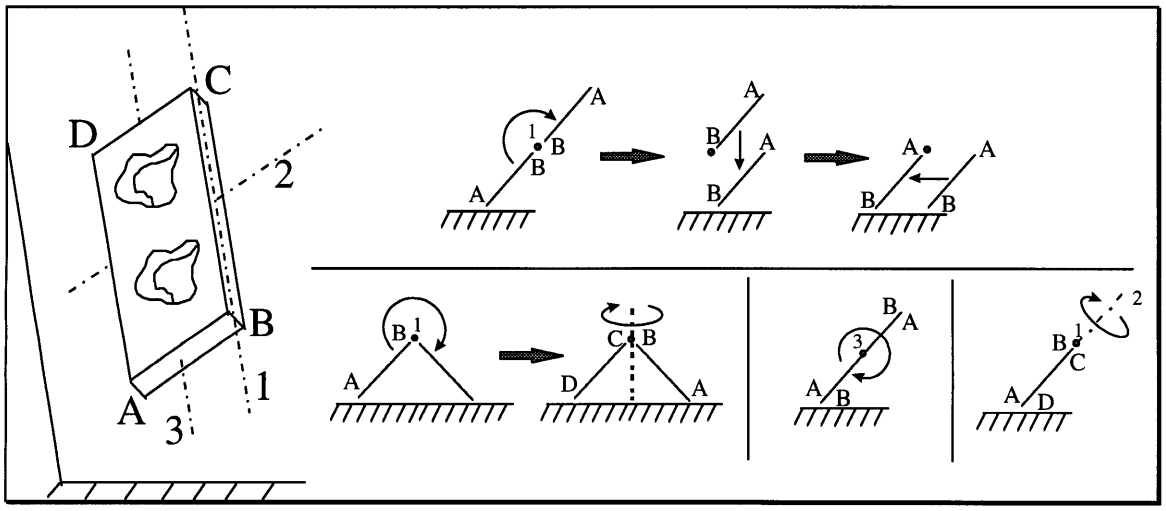

Figure 7 : Flipping the sample.

As mentioned before, the profiling will be carried out in some regions along the perimeter of the hole, that is, the edge. The higher the number of scanned areas, the more comprehensive the data and the longer the time for completion of the profiling task. The scanning must be orthogonal to the ultimate edge (the tip) as stated before. Therefore, for

different regions in the same edge, the sample will have to be re-oriented so that the edge tip remains orthogonal to the scanning lines. Because the profiled area must continue in the horizontal, the rotation must keep the tilt and just change the angular position of the edge with respect to its center line. See configuration 1.in figure 8.

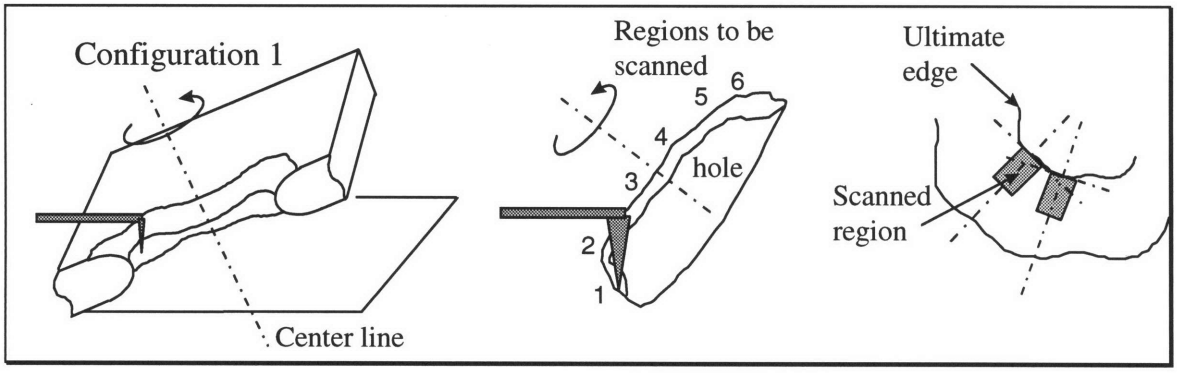

Figure 8 : Keeping all scanned areas in the horizontal plane.

We must remember that if the vertical range of the profilometer is larger than the vertical displacement between the edge tip and the initial datum line, (where the scanning begins) than no tilt is necessary. The point is illustrated in configuration 2.

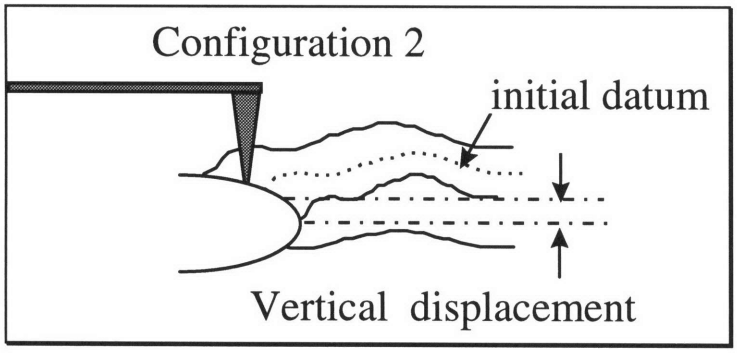

Figure 9 : Scanning without tilting the sample.

In the same sample there maybe multiple holes. Each edge must have its profile taken. Therefore, the positioning system must be able to re-locate the sample for a sequence of edges.

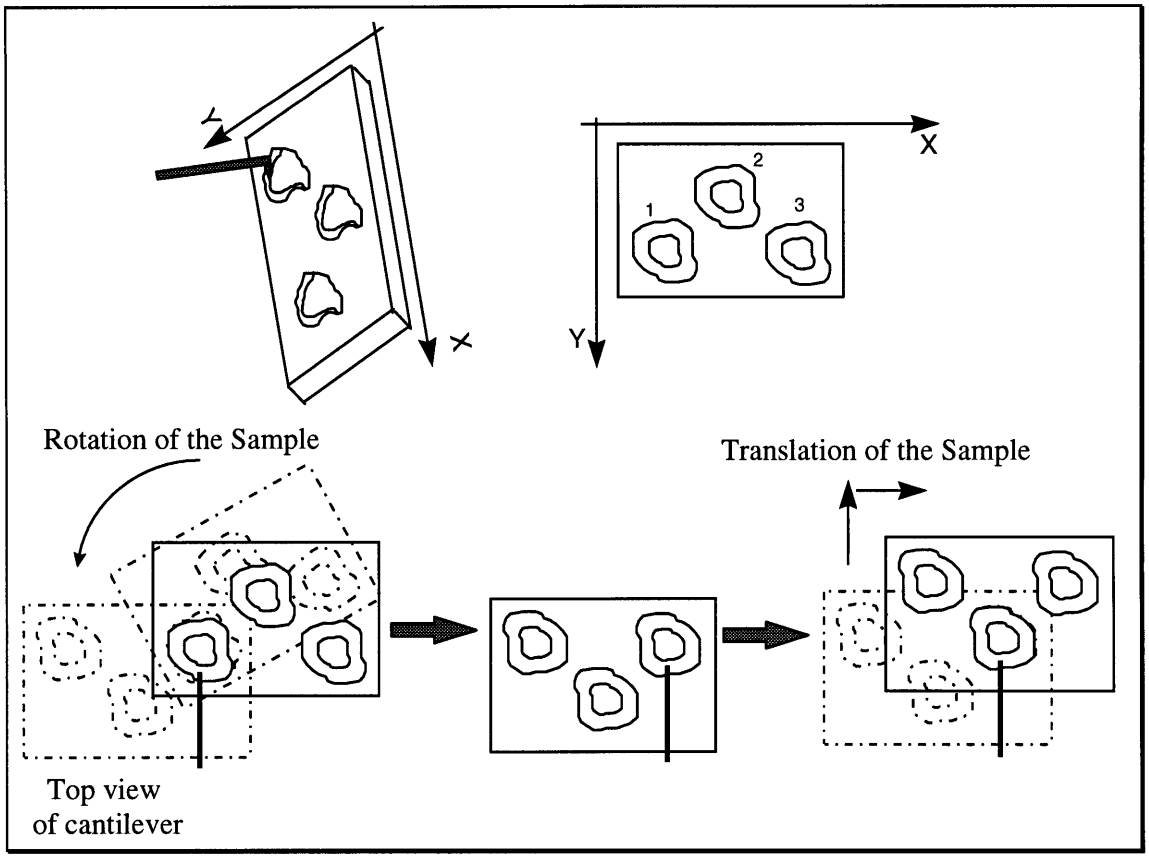

Figure 10 : Re-orientation of the sample.

One important factor to be considered is that, at the very tip of the edge, the AFM probe tip will not touch the edge. Instead, the sides of the probe will contact the sample. This might generate distortions in the image collected at the very tip. This distortion is known as image convolution. For the **horizontal** scanning procedure, the convolution errors are maximum at the tip.

6.2 Vertical Scanning

Another way to obtain the edge geometry is to have the probe and the sample aligned, i.e. both in the vertical as shown in figure 11.

The geometry to be probed is a complicating factor . The closed edges pose two extra demands on the measurement system: (1) probes must be able to access regions enclosed by the perimeter thus limiting the size of the probe up to the diameter of the hole

and (2) the probe must be normal to the edge for data extraction creating the need for a realignment action along the probed edge (fig 11).

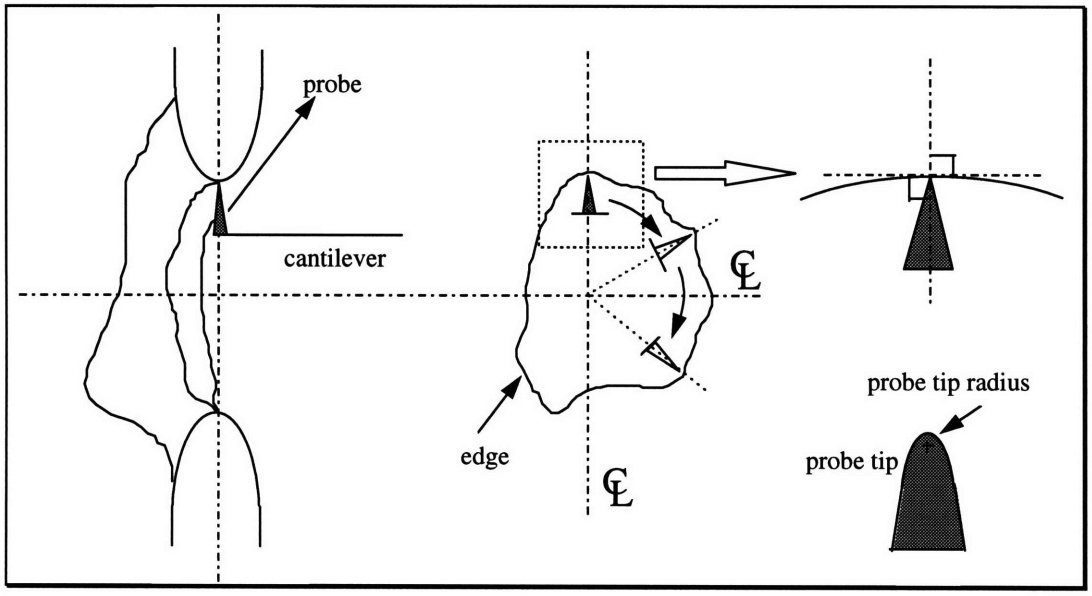

Figure 11 : Orthogonality requirements for data extraction.

Note that with this configuration, on the very tip of the edge, the tip of the probe will be in contact with the sample. This makes convolution errors minimal at the region of interest, which is the ultimate edge. The probe tip is normal to the edge. This is done by keeping the probe in the same line of the hole diameter and by re-orienting the probe along the scanned surface in order to have it always normal to the scanned surface.

If it were possible to scan always normal to the edge surface, the convolution errors would vanish (fig. 12).

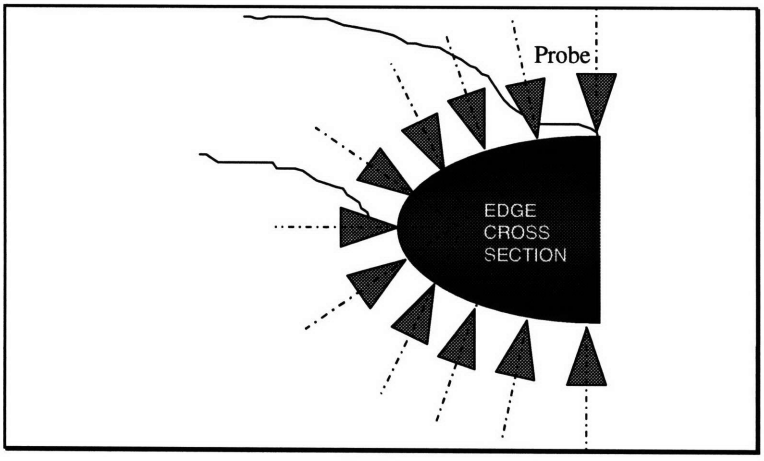

Figure 12 : Scanning in the direction normal to the edge surface.

This, however, adds extra complexity to the system. To be always normal to the scanned surface, 3 DOF's would be necessary: one for lateral motion, one for vertical motion and one for rotational motion. All of them with nanometric resolution.

The characteristic dimension of the hole is in the millimeter range One must ensure that available probes can fit inside the closed edge for the profile measurement. Some AFM probe typical dimensions are shown in figure 13.

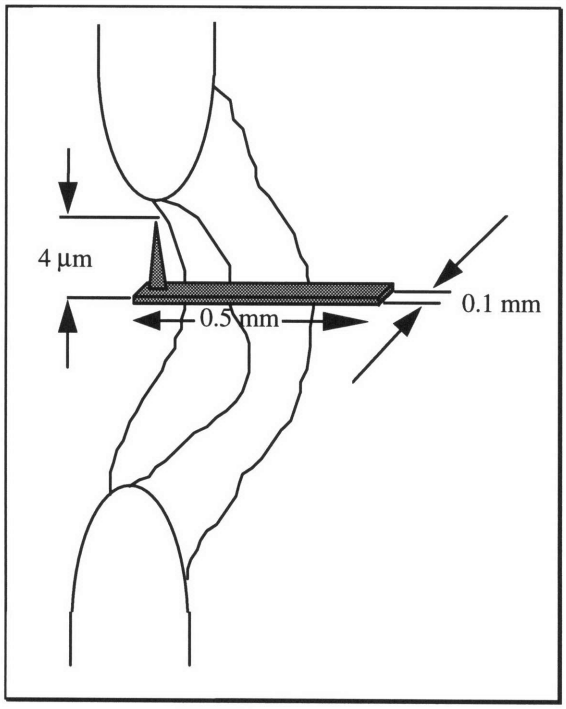

Figure 13 : Geometric constraints on the probe dimensions.

Note that the cantilever has to be long enough to reach the two sides of the edge. However, it cannot be too wide or thick, otherwise it will not fit inside the hole. The AFM probes surveyed are all suitable for this application in terms of dimensions. Vertical range is typically 2µm.

The geometry poses an extra demand on the sensing system. In common AFMs, the deflection of the cantilever (dictated by the shape of the sample) is measured with a laser beam that is reflected on the back of the cantilever. The reflected beam is picked up in a photosensitive array as shown in figure 14.

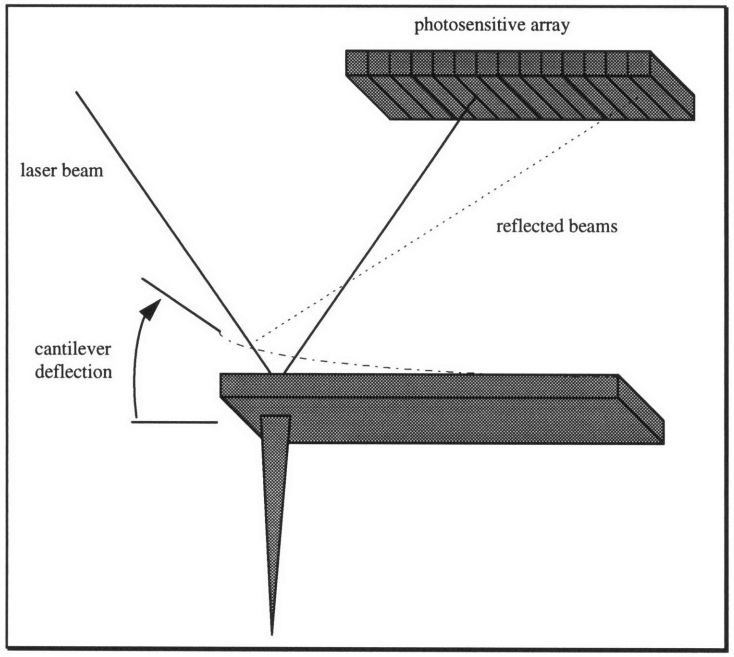

Figure 14 : Laser reflection method for deflection measurement.

For this application, a sensing system like that is not suitable since the sample would block the beam (the edge is a closed curve). To overcome this problem, self-sensing or locally sensing cantilevers might be used. A self-sensing cantilever is made of piezo-resistive material. The deflection of the cantilever causes a change in resistance that can be measured by applying a constant current and measuring the voltage change. Self sensing cantilevers are commercially available. Locally sensing probes are those that integrate a sensor near the cantilever. These deflection sensors are normally capacitors [12, 13, 16] . Examples are provided in figure 15.

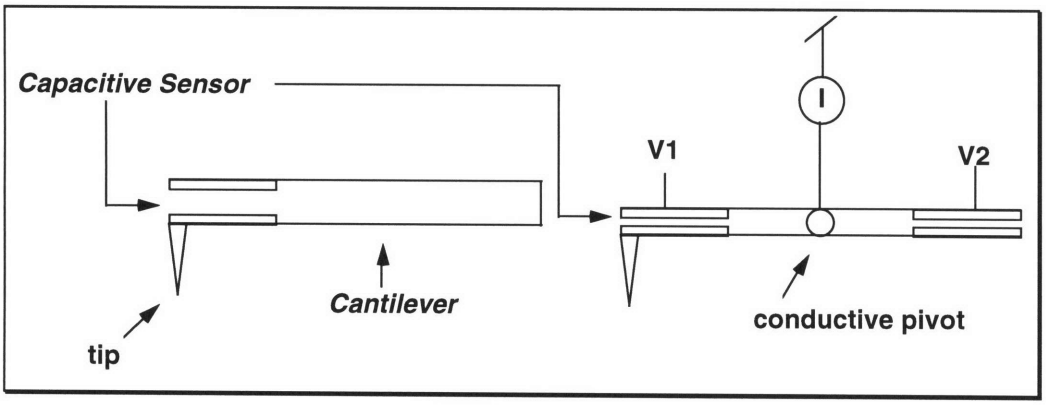

Figure 15 : Locally sensing AFM probes.

Currently available self-sensing probes like the piezo-resistive probes commercialized by Park Instruments are actually capable of rendering the same resolution as the laser triangulation method. The laser triangulation method, however, requires a very careful alignment of probe and sensing array.

The analysis show that, in order to minimize convolution errors in the region of interest, namely the extremity of the edge, the **vertical** scanning is the most indicated one.

6.3 Scanned Regions

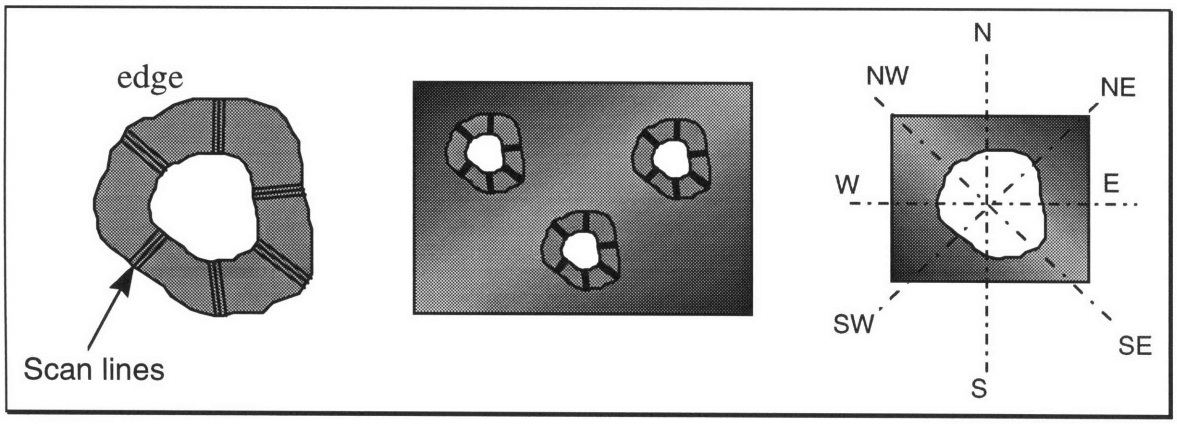

Figure 16 : Direction and region consistency throughout characterization.

As seen in figure 16, the scanned regions on different edges must be correlated. To ensure the consistency of measurements, the same areas must be profiled in the same directions. The design target is to characterize eight different regions per edge.

7 Tip Size and Image Formation - Convolution

The lateral resolution of atomic force microscopes is dictated by the size of the probe tip, the slopes of the surface irregularities and the included angle of the probe. The effects of finite tip size in the profile measurement can be seen in figure 17. The real profile is mixed with the probe shape. The final image incorporates information from both surface geometries (probe and scanned object). This effect is called **convolution**.

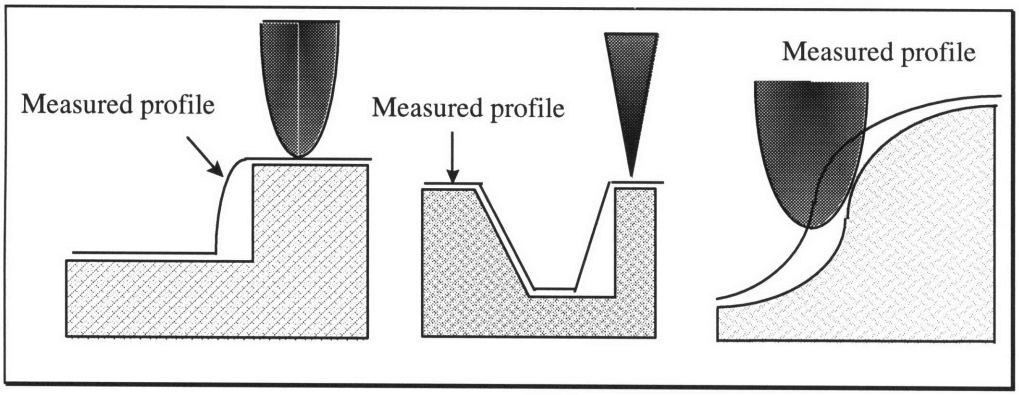

Figure 17 : Image convolution.

Convolution arises when the slope of the probed surface is so high that the AFM or the STM probe touches the sample surface at a point other than the nominal tip position of the probe. The result is that the apparent edge of the of the surface feature is shifted and the corners of step-like features appear rounded [28].

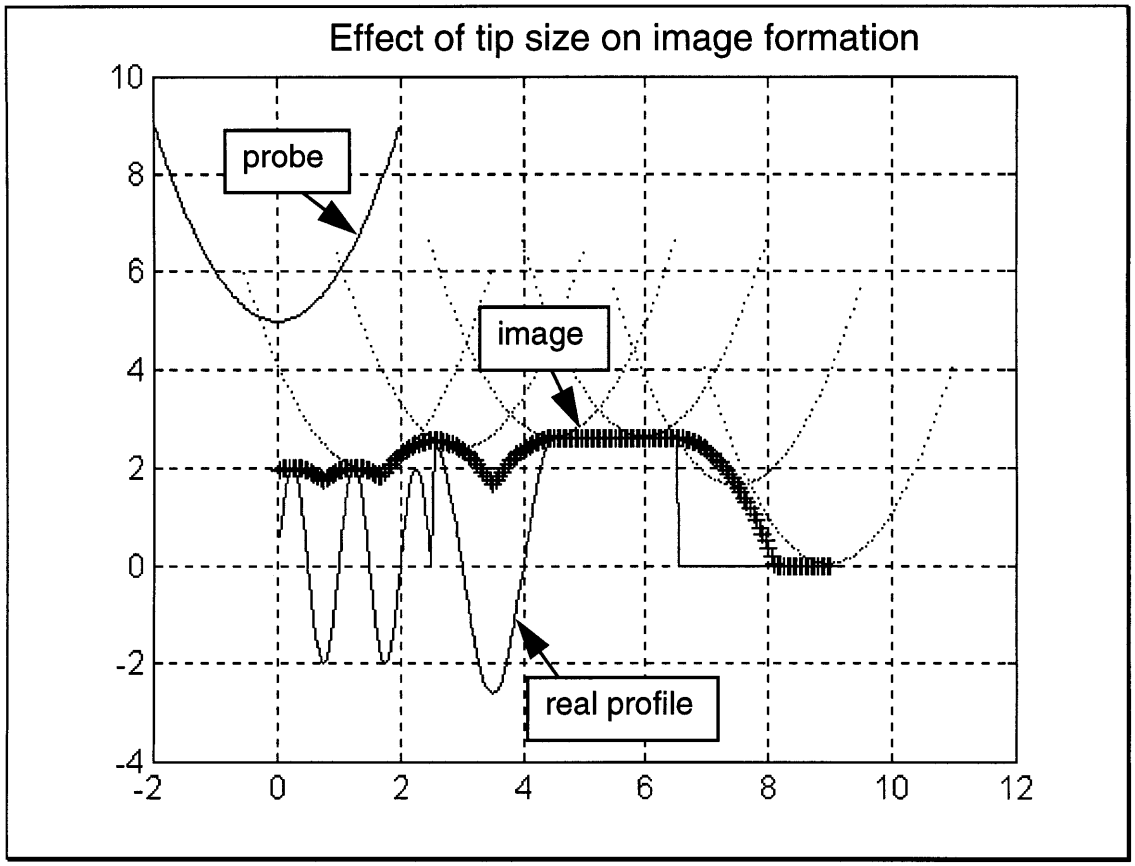

Figure 18 : Image rounding and shifting due to convolution.

It is clear that the larger the tip, the further away from the actual profile is the image generated. If the true point of contact can be calculated from the image surface and the probe shape, than the real profile can be reconstructed from the distorted image. Characterization of the probe tip to acquire its shape is possible. The most common probe characterization method is the inspection in a Scanning Electron Microscope (SEM). However, this implies that the probe has to be frequently removed from the profilometer which is impractical. It is possible, however, to use the AFM itself to characterize the probe [16]. The image generated by scanning a step wall reflects the shape of the probe (fig 19). The deconvolution filter is then used. It removes the shape of the probe from the image generated by the scanning, rendering the "true" profile [16, 17]. A characterization system may be as simple as a grating surface with known stable profile. This type of characterization, however, contributes to probe wear and deformation.

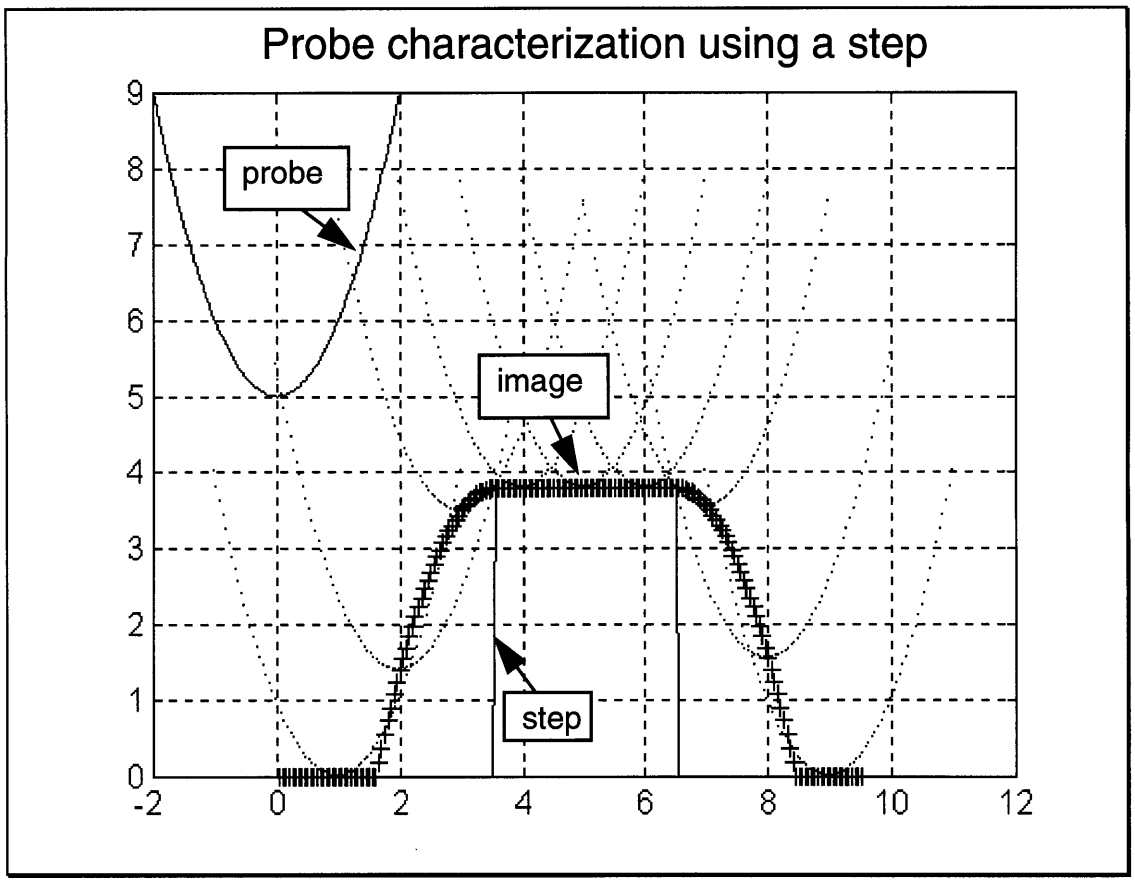

Figure 19 : Probe characterization.

To reconstruct the image, two quantities are necessary. **(1)** The horizontal distance between the true contact point and the apparent contact point, i.e., the tip of the probe (Δx). **(2)** The vertical distance between the true contact point and the ultimate probe tip must also be known (Δs). At the point of contact, the probe and the real profile have the same slope since they are tangent with respect to each other. In addition, the slope of the apparent image, traced by the probe tip, also has the same slope as both the probe and the surface at the true contact point. To demonstrate that, we use the same notation of as Keller [17].

- $s(x)$ is the true sample profile.
- $i(x')$ is the apparent image traced by the probe tip end, which is the image provided by the AFM..
- x is the location of the contact point.
- x' is the location of the probe tip.

- Δx is the lateral distance between the probe tip (x') and the contact point (x).
- Δs is the vertical distance between x and x'.
- $t(\Delta x)$ is the shape of the probe.

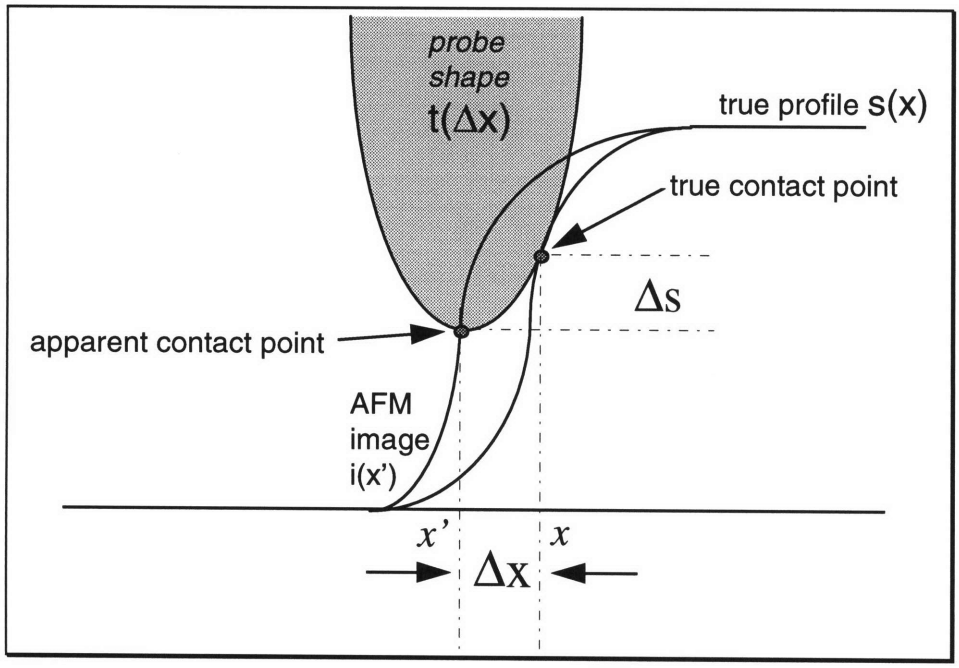

Figure 20 : Geometrical aspects of probe and surface contact.

Since $s(x)$ and $t(\Delta x)$ have the same slope at the contact point, one can write:

$$\frac{dt}{d(\Delta x)}(\Delta x)=\frac{ds}{dx}(x) \qquad (1)$$

As the probe moves, x' moves together and Δx will also change. Therefore:

$$\Delta x=\Delta x(x') \qquad (2)$$

And since Δx is the lateral distance between the apparent and true contact points, and Δs is the vertical distance, it results that:

$$x=x'+\Delta x(x') \qquad (3a)$$

$$s(x)=i(x')+\Delta s(x') \qquad (3b)$$

Also note that Δs(x') is equal to the value of the probe shape function t(Δx) evaluated at the contact point.

$$\Delta s(x')=t[\Delta x(x')] \qquad (4)$$

Taking the derivative of equation (2), we find that:

$$\frac{dx}{dx'} = 1 + \frac{d(\Delta x)}{dx'}(x') \tag{5}$$

From equations (1), (3b) and (4), one can write:

$$\begin{aligned} \frac{di}{dx'}(x') &= \frac{ds}{dx}(x)\frac{dx}{dx'} - \frac{dt}{d(\Delta x)}(\Delta x)\frac{d(\Delta x)}{dx}(x') \\ &= \frac{ds}{dx}(x)\left[\frac{dx}{dx'} - \frac{d(\Delta x)}{dx'}(x')\right] = \frac{ds}{dx}(x) \end{aligned} \tag{6}$$

In equation (6), it is implied that the slope of the AFM image at x' is the same as that of the real surface at x.

With the results (1) and (6), we can state that:

$$\frac{dt}{d(\Delta x)} = \frac{di}{dx'}(x') \tag{7}$$

With the result in number (7), the image reconstruction is possible. For each point in the AFM image, the image slope is evaluated. Then comparing this slope to the slopes of the probe shape (it is assumed that the probe shape is available), we can find the point x where (7) is true (i.e. the two slopes are equal). With x, we can evaluate the value of the quantities Δx (from x - x') and Δs (from $t(\Delta x)$).

In figure 21, we show a simulation result of the deconvolution procedure. An "edge-like" profile is scanned using a finite size tip. Note that the AFM image departs from the real profile. The deconvolution based on the probe shape knowledge corrects the image.

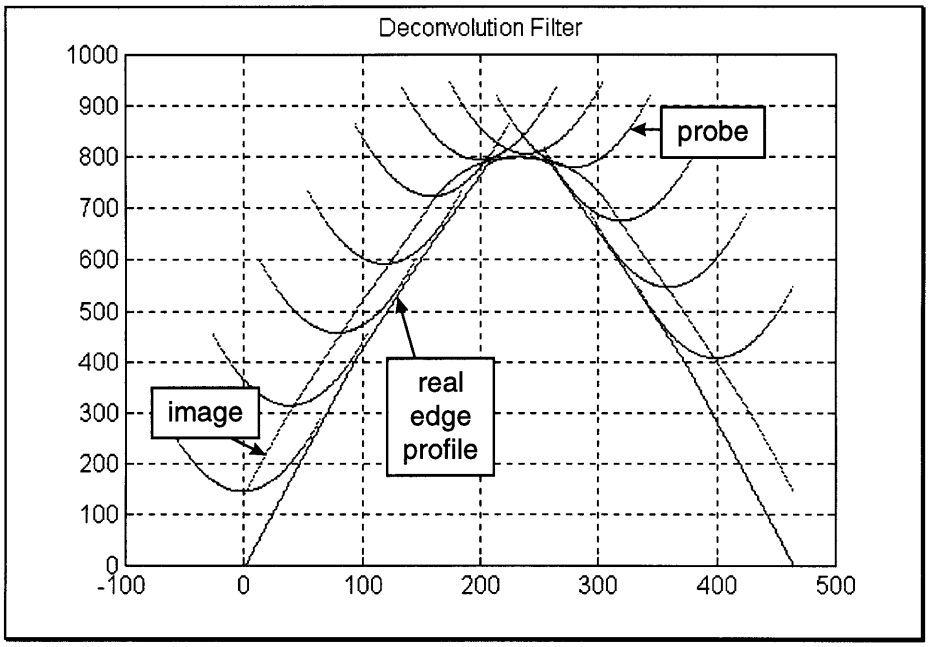

Figure 21 : Image deconvolution of a high aspect ratio feature.

In the same picture, note that very close to the tip of the edge, the point of the probe that is touching the surface is approximately the probe tip. For this reason, the convolution distortions at the very tip of the edge are minimum. That is the reason the **vertical** scanning minimizes convolution problems.

8 Profilometer Function Analysis

To correctly perform the profilometry of the tip of the closed edge, the equipment must be able to carry out some sequential functions. These functions include **aligning** the probe with the center of the hole and **inserting** the probe into the closed edge hole. After the probe is inserted in the hole, the probe must be **oriented** with respect to the edge so that the former becomes normal to the latter. Then, an **approach** action is taken. It brings the probe in contact with the edge surface. After that, the **scanning** can take place. After one region of the perimeter is scanned, the probe is **retracted** to the center of the hole. The sample is then **re-oriented** and the probe **re-approaches** the surface edge, for a new scanning, with the proper normal orientation. After the eight regions of that hole are profiled, the probe is retracted to center of the hole; it then moves away from that hole. Finally, it is realigned with another hole for a new set of scannings.

8.1 Alignment and Insertion Action

In the same sample there may be several holes. In order to correctly and robustly insert the probe in the holes, the location of each hole must be assessed. The alignment system must be able to

(1) distinguish the sample from background objects,

(2) distinguish holes inside the same sample,

(3) distinguish one hole from another,

(4) find the area centroid locations of the holes,

(5) translate the centroid location into motion coordinates for the probe stage,

(6) apply a relative motion between sample and probe stage so that both are aligned,

(7) apply a relative motion between sample and probe stage so that the probe is inserted in the hole.

8.2 Orientation Action

Once inside the hole, it must be ensured that probe and edge are normal with respect to each other. For that to happen, the orientation system must perform the following actions:

(1) identify the perimeter of the hole,

(2) calculate the normal directions to the perimeter,

(3) rotate probe stage and sample with respect to each other so that they become normal.

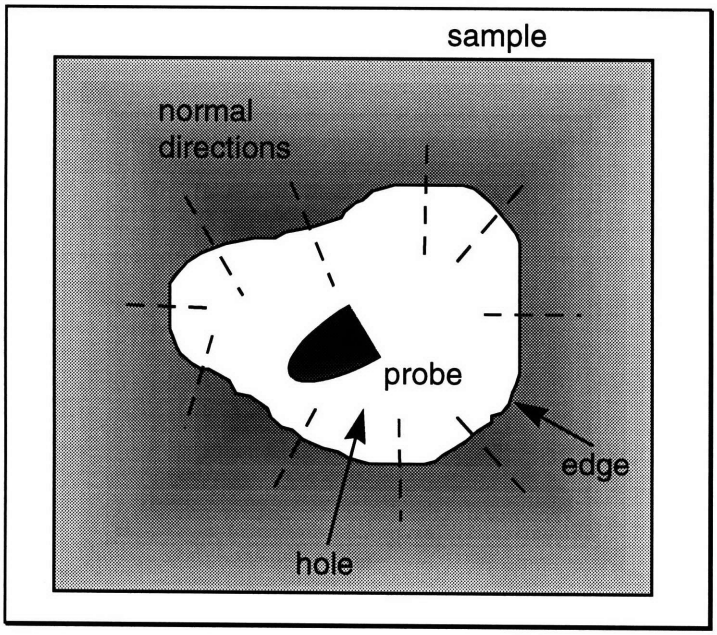

Figure 22 : Orientation Action.

8.3 Approach and Scanning Action

With the probe aligned in the direction normal to the edge, the approach system brings the probe in contact with the surface. The scanning action then begins.

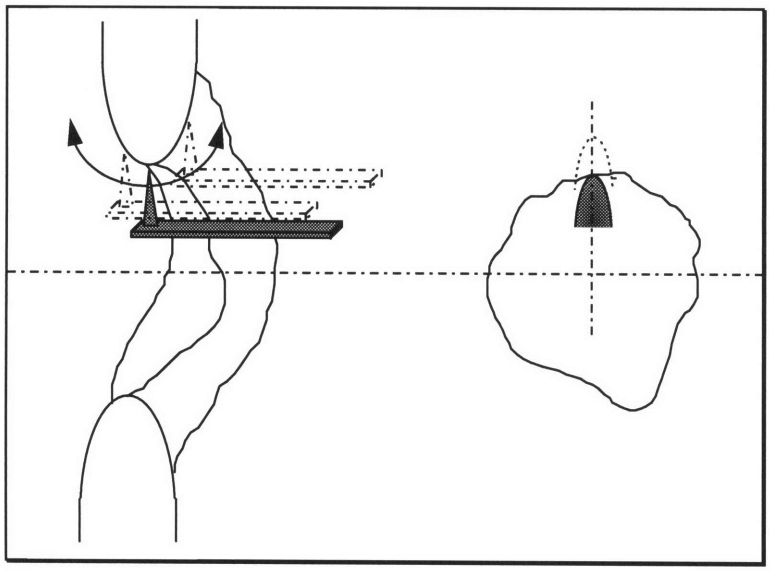

Figure 23 : Approach and Scanning.

In almost all AFMs, a piezoelectric scanner is used for fine motion of the probe over the sample (or vice-versa). Normally, the AFM electronics drive the piezo-scanner in a raster pattern that is shown on figure 24.

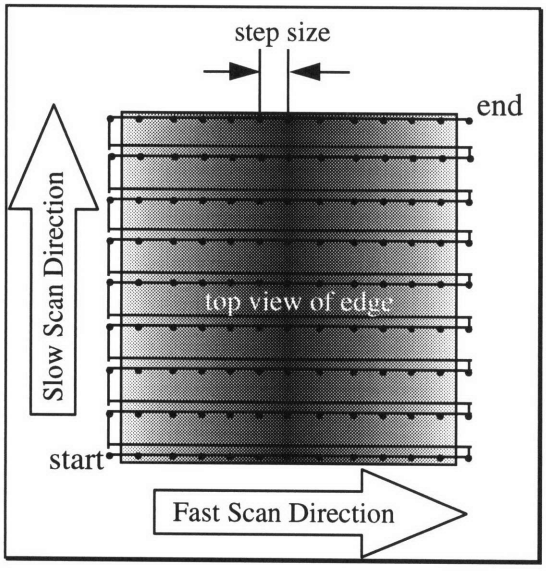

Figure 24 : Scanning of the edge.

AFM data is normally collected in just one direction, represented by the lines with dots, the data points. This direction is called the fast scan direction. Data is not retrieved in the way back to avoid histerisis problems. The perpendicular direction is called the slow scan direction. While the AFM probe, driven by the piezo-scanner, is moving along a scan line, data (in the form of sample heights) is digitally retrieved. The spacing between two data points is called step size. The step size is equal to the scan line size (usually from tens of angstroms up to a hundred microns or so) divided by the number of data points (typically from 64 up to 512 points).

8.4 Retract and Repeat Action

After one region is scanned, the probe is retracted to the center of the hole. The probe stage is reoriented with respect to the normal direction to the next region to be scanned. The probe approaches the new region of the edge and another scanning takes place.

Once one edge is characterized, the probe is retracted from the hole. The alignment unit will position the probe for insertion into another hole and the other procedures are repeated in order to characterize this new edge.

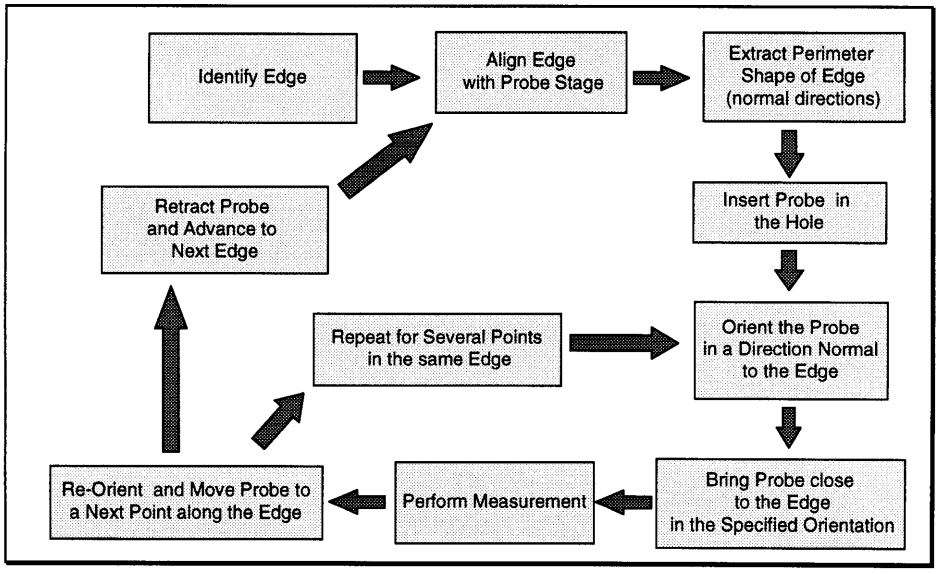

Figure 25 : Profilometer Functions.

8.5 Motion Requirements and Design Procedures

In order to perform the actions specified above, the correct set of actuators must be chosen. A first order analysis is carried out to evaluate which groups of actions must be performed by a single groups of actuators. For instance, insertion and alignment might be done with similar actuators since required range and motion resolution are similar. Approach and orientation actions are medium range motions (millimeters) and it might be difficult to perform these actions with the same type of actuators used for insertion or alignment. Finally, scanning action, due to its high precision and nano-scale range, certainly requires a special set of actuators.

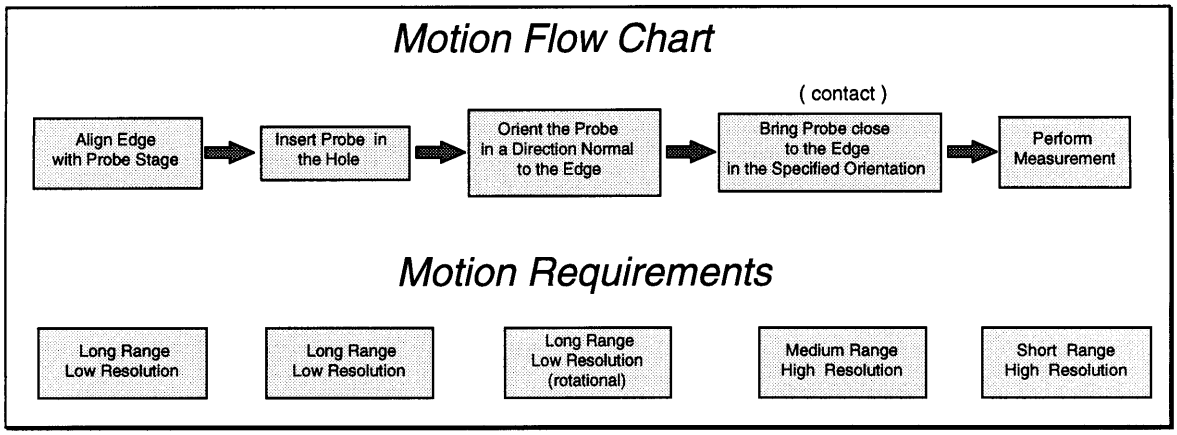

Figure 26 : Motion requirements.

Once the functionality with which the instrument must be embedded with is understood, the design continues towards sub-systems specification. Each function is analyzed and a suitable set of actuators and sensors is selected.

9 Critical Experiments

In order to assess the feasibility of the proposed design considerations and the attainability of the required resolution, experiments were carried out. The study addressed a wide variety of issues concerned with data acquisition and tip shape deconvolution. The experiments included:

(1) Proof of concept for edge locating methods, i.e. defining the approaches which will facilitate robust location of the sample edge by the probe

(2) Demonstration of the feasibility of the proposed probe characterization technique

(3) Definition of the scan range, i.e. verify if 0.5, 1 or even 2 micrometers from the edge tip can be profiled accurately and repeatably

(4) Generation and test of deconvolution algorithms, including comparison with samples measured with scanning electron microscopy (SEM)

(5) Examination of resolution issues, including definition of the resolution required to measure the edge tip radius

(6) Analysis of tip wear and toughness

(7) Analysis of the effects of AFM feedback loop gains and scan speed on image generation

The results can be summarized as follows:

9.1 Tip locating method

The AFM cantilever must land on the sample edge as part of the **approach** action. In order to achieve that, the following procedure is followed:

(1) The sample is fed into a commercially available AFM unit (by Park Instruments)

(2) With an optical system composed by a CCD digital camera and magnification lenses, the sample edge is found

(3) The sample edge position relative to the probe position is assessed. The probe, before the approach, is located over the sample

(4) Sample edge and probe are aligned so that they superpose each other in the vertical direction

(5) An automatic approach is commanded and the probe lands on the sample, at some point along the cantilever

(6) The probe is retracted until the ultimate sample edge is found and then the scanning begins

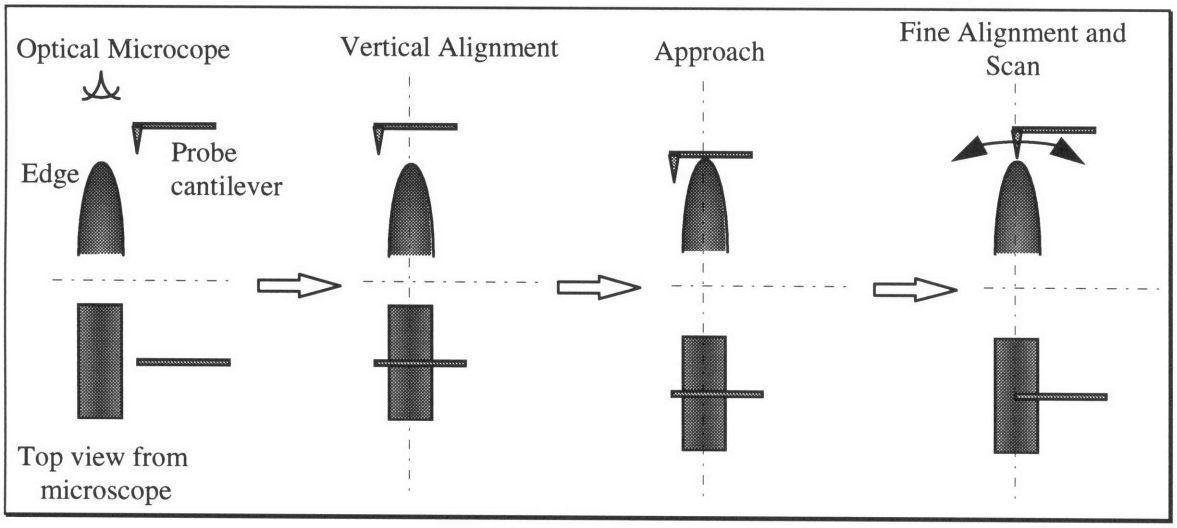

Figure 27 : Approach and Scan procedure.

The tip location method for approach and scanning was repeated several times (over a thousand) times and proved to be very reliable and reproducible. The functions of locating the edge tip relative to the probe and aligning the probe with can be done automatically with image processing techniques and high precision visual servoing.

When the probe lands on the sample along its cantilever, the laser bouncing signal detects the contact. For this reason, as long as the cantilever or the probe tip touches the sample, the other actions can be done robustly.

Since the cantilever is around 100 micrometers in length, optical methods can be used for the alignment and approach, without the need of extremely high resolutions.

For the fine alignment, an automatic system must be able to recognize the edge tip. This can be done by following the slope of the sample until the maximum height point is found.

9.2 Probe Characterization Method

A fine grid of steps was used in order to characterize the probe. Two hundred and fifty six (256) cross sections of the step image were used to obtain an accurate average image of the probe tip. The procedure was repeated several times. The average probe tip profiles were compared and showed reasonable similarity. The experimental tip shape was then used to deconvolve the image profile.

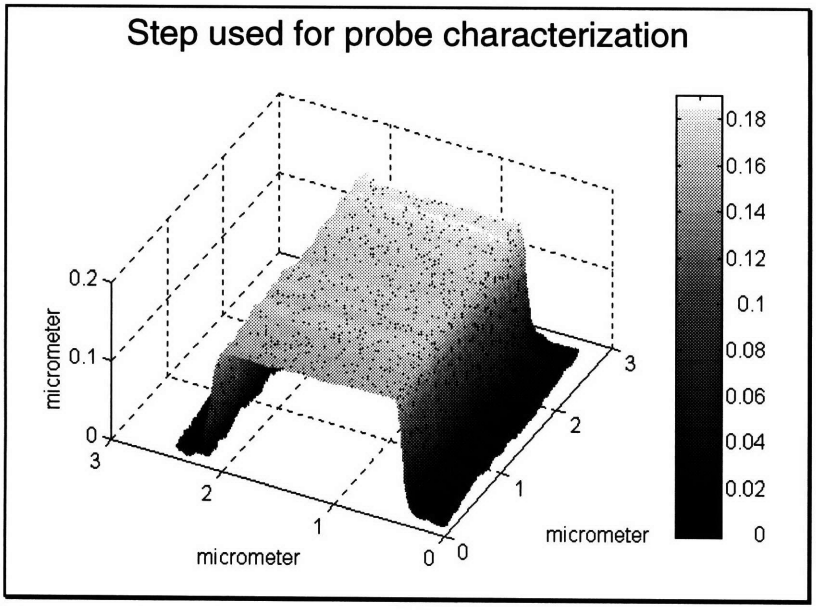

Figure 28 : Step used for probe characterization.

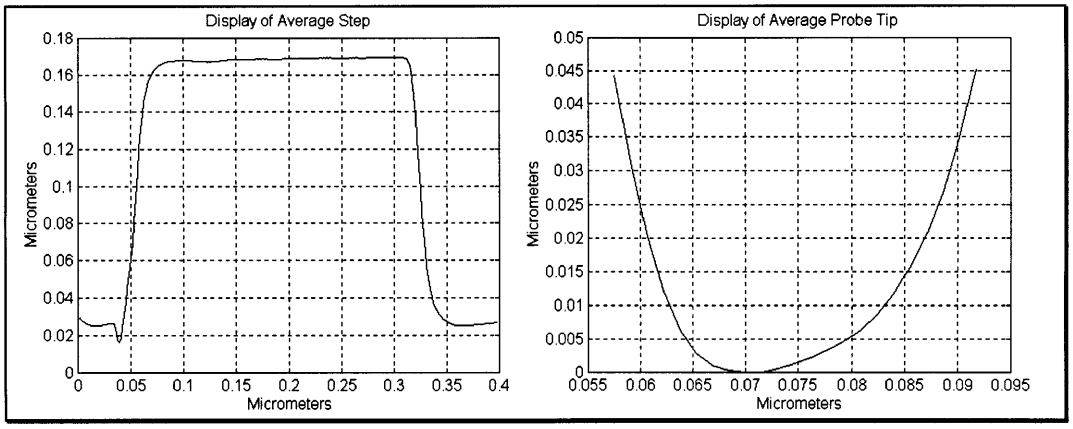

Figure 29 : Probe characterization

9.3 Deconvolution trials

A deconvolution algorithm was written and applied to reconstruct the image of the sample. A so called visual proof was also implemented as in figure 21 but this time with the experimental data. The results show that by scanning in the normal fashion, the distortions due to convolution are minimized in the region of interest. It was shown that for the purpose of measuring the tip curvature of the edge sample, the convolution effects can be safely disregarded.

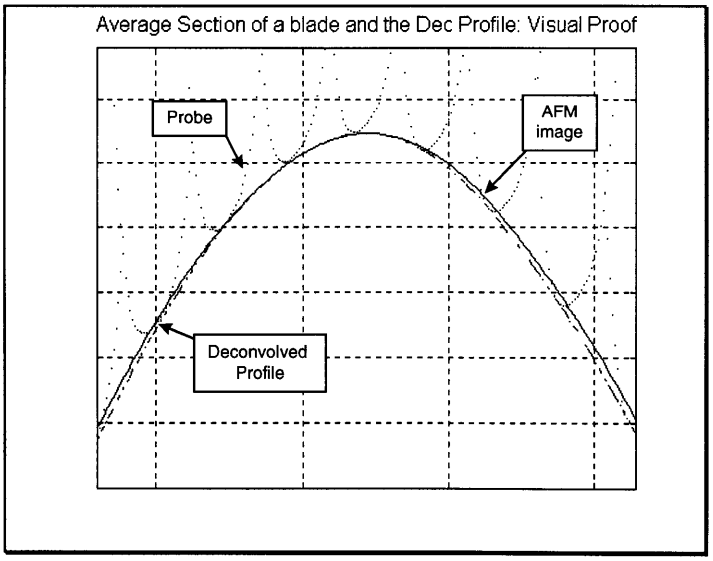

Figure 30 : Example of deconvolution filtering on experimental data.

9.4 Feedback control loop considerations

The cantilever probe assembly presents inherent compliance and damping as well as effective mass. The AFM operates in contact and constant force mode and the probe actively tracks the sample surface. Due to the mechanical behavior of the assembly, higher proportional gains will improve the tracking performance. However, high gains make the assembly more prone to vibrations at the resonant frequency. The reason is that the system's loop transmission will not be sufficiently attenuated at the resonant frequency. The result is that, for highly irregular spots in the sample such as deeps or damaged points, a feathering effect arises; the image surface appears rippled. Very low gains will induce poor surface tracking that actually has the effect of gradually smoothing down the image until no surface detail is captured. The system rejects high frequency surface profile changes.

9.5 Edge curvature analysis

In order to validate the metrology data retrieved with the AFM, an edge curvature analysis was carried out. The curvature of the tip is obtained by fitting a circle to the edge of the sample, cross section by cross section. For each scanning, the average radius is obtained from 256 cross sections. The results were close to data coming from an SEM analysis of the samples. With the AFM approach, average curvatures that were around 50nm apart could be distinguished robustly. Moreover, the AFM technique had the clear benefit of rendering true metrological data contrary to SEM imaging where no metrological frame is available and analysis is based on image comparison to other standards.

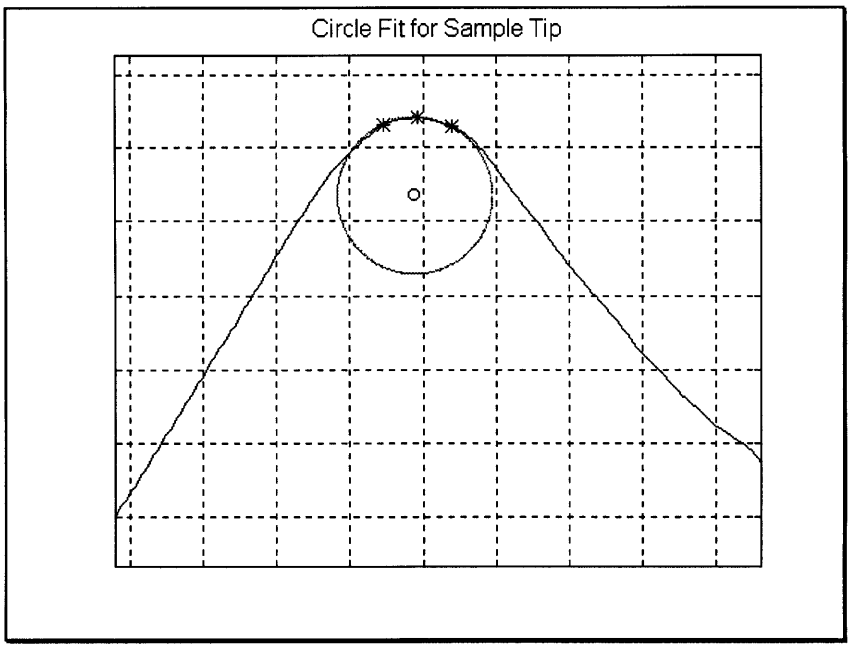

Figure 31 : Sample tip curvature.

9.6 Other experimental issues

One of the main issues related to AFM imaging is the shape stability of the probe. In contact mode, the probe tip continually rubs against the sample. Although contact forces are low (order of nano-Newtons), probe wear can occur. From the experiments, it was realized that probe wear is not significant even over an extended number of scannings. This verification was done by scanning and re-scanning certain special topographic features (like little defects on the edge) repeatedly. The image does not change implying that the probe geometry remains the same. Also, in the probe characterization phase, a micro-step was scanned several times. The image slopes at the sides of the step reflect the probe shape. For almost a thousand cross sections, the probe shape remained the same. The conclusion is that the same probe can be used safely for several scannings without incurring in significant probe geometry changes. Even if geometry changes are induced, the normal scanning procedure will ensure minimal distortions at the region of interest.

Another important issue is the imaging speed. The scanning speed (lines per second) influences the quality of the image. Fast scannings might cause loss of image details. Slow speeds might cause the scanning procedure to be unnecessarily time consuming. In order to operate in high speeds, higher control gains must be used which might excite resonant behavior. A trade off between speed and image detailing must be met.

Finally, in most AFMs, the cantilever is positioned inclined with respect to the sample. This is done so as to ensure that the probe is the first part to touch the sample (not any part of the cantilever or the probe holder). However, for high aspect ratio samples, an inclined cantilever poses a problem: the probe tip will touch one side of the sample but due to the inclination, it will not the opposite face. For this reason, the AFM holder had to be tilted so that probe and sample are normal.

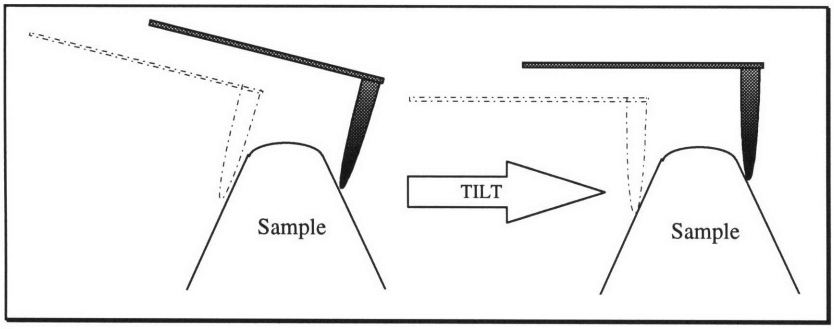

Figure 32 : Cantilever tilt for normal positioning.

10 Conclusions

Given the tight measurement resolutions required to correctly assess the geometry of the special samples, the AFM technique was considered the most suitable. The technique can be used for conductive or non-conductive samples thus enabling the user to profile samples made of a wide range of materials. In order to be sure about the method selection suitability, an extensive survey on profilometry methods was carried out.

The geometry of the sample poses extra difficulties on the design: (1) the proper alignment and (2) insertion of the probe in the edge hole. To perform these operations special alignment and insertion systems will have to be developed, all with micrometric accuracy. This can be achieved through the use of modern motion control techniques and, potentially, visual servoing. A departure from the usual AFM sensing method (laser bouncing) will have to be sought for since the geometry of the sample would block the beam. Piezo-resistive cantilevers is a potential technology.

Error budgeting during the design phase is of paramount importance since all insertion, and alignment actions require micrometric resolution and the approach action, nanometric. All combined actions will have to render up to a maximum motion error without compromising accuracy of measurements.

The preliminary experiments revealed that the desired accuracy and repeatability can be achieved through AFM imaging. It also showed that most actions such as alignment and approach could be automated. Data retrieved with the AFM is ready for digital filtering and profile analysis, with a real metrology frame.

This research project consisted of a clear exercise of design analysis. First, the problem was stated and basic specifications outlined. Then, the problem was dismembered into many groups: selection of profilometry method, understanding of geometric aspects, understanding of imaging limitations and definition of machine functions. From this point on, a synthesis problem takes place. Each function must be accomplished by a certain set of actuators, sensors and suitable logic. Each subpart interacts with the other and an understanding of this interaction and its contribution to measurement accuracy must be understood.

Appendix A: Comparative Table of Profilometry Methods

Name	Actual Physical Quantity Measured	Min. Vertical Resolution	Min. Lateral Resolution *	Typical Vertical Measuring Range**	Typical Lateral Measuring Range**	Transducer Technology	Data Acquisition Speed	Types of Surfaces that can be measured	Advantages	Disadvanta-ges
mechanical stylus [4, 6, 15]	surface contact force (10^{-3} to 10^{-6} N)	< 1nm (state of the art)	0.1 μm (limited by mech. rigidity of stylus tip	up to approx. 5 mm	"infinite" (sample/tip moves on linear bearings)	LVDT and laser interfero-metry commonly used	slow - linear data acquisition; typical speed 1mm/s	no restriction (but see Disadvan-tages)	+well established technology + excellent for micron (and larger) sized features + relatively low cost to implement + form following	- stylus will damage soft surfaces (i.e. thin films)
fringe-field capacitance [34]	capacitance between perpendicula r plane probe and surface	min. 0.1 μm	approx. 0.8 μm (limited by probe size)	30 μm max.[34]	"infinite" (sample/tip moves on linear bearings)	probe itself is sensor	relatively fast - linear data acquisition; speeds up to 25 mm/s	electrically conductive or partially conductive surfaces	+ since sensor is enclosed in large skid housing, sensor is robust, and sample damage is minimized	- low vertical and lateral resolution - sample types restricted

Name	Actual Physical Quantity Measured	Min. Vertical Resolution	Min. Lateral Resolution *	Typical Vertical Measuring Range**	Typical Lateral Measuring Range**	Transducer Technology	Data Acquisition Speed	Types of Surfaces that can be measured	Advantages	Disadvanta-ges
contact atomic force microscope (AFM) [27]	surface contact force (10^{-8} to 10^{-11} N)	<= 1 angstrom	approx. 1nm (note that this is greater than STM's)	piezotube... typ. 2 μm (up to 7μm possible)	piezotube... typ. 10 μm square (80 μm square possible)	optical lever method most common; other schemes include laser-diode feedback	slow - linear data acquisition; scanner speed usually < 10 kHz	no restriction (but see disadvan-tages)	+ well established technology + high lateral resolution + relatively low cost to implement	- stylus will damage extremely soft surfaces
phase-measuring interfero-metry & related techniques *** [4]	surface reflectivity	0.5 angstroms	approx. 0.5 μm (limited by far-field wavelength of light/ objective dependent)	up to 100 μm (objective dependent)	70 μm to 7 mm square	photodiode array detectors	extremely fast- parallel data acquisition (e.g. < 5 seconds for 60,000 data points)	surface reflectivity > 4%	+ non-contact + extremely fast data acquisition	- measurement dependent on surface reflectivity (need to recalibrate for different materials) - massive computing resource required (****)

Name	Actual Physical Quantity Measured	Min. Vertical Resolution	Min. Lateral Resolution *	Typical Vertical Measuring Range**	Typical Lateral Measuring Range**	Transducer Technology	Data Acquisition Speed	Types of Surfaces that can be measured	Advantages	Disadvanta-ges
optical critical angle of total reflection & related techniques [35]	surface reflectivity	< 1 nm	approx. 0.5 µm (limited by far-field wavelength of light/ objective dependent)	3 µm [35]	"infinite" (dependent on sample stage)	photodiode array detectors	relatively fast - linear data acquisition (10 mm/s for 1 µm resolution)	surface reflectivity > 4%	+ non-contact + relatively low cost to implement	- measurement dependent on surface reflectivity (see above)
scanning tunneling microscope (STM) [4]	tunneling current between tip and sample	<= 1 angstrom	<= 1 angstrom	piezotube... typ. 2µm (up to 7µm possible)	piezotube... typ. 10 µm square (80 µm square possible)	probe itself is sensor	slow - linear data acquisition; scanner speed usually < 10 kHz	electrically conductive surfaces	+ well established technology + non-contact + extremely high lateral resolution	- sample types restricted
scanning near-field optical microscope (SNOM) [3, 29]	near-field light intensity	few hundred angstroms (limited by ability to form reproducible subwave aperture)	approx. 12nm [3, 29]	piezotube... typ. 2µm (up to 7µm possible)	piezotube... typ. 10µm square (80 µm square possible)	transmitted or reflected light is viewed directly and also used in piezoactua-tor feed-back	slow - linear data acquisition; scanner speed usually < 10 kHz	translucent or reflective surface (micro-scope dependent)	+ non-contact + can be used to image (semi) transparent samples	- measure-ments dependent on surface reflectivity - technology not well developed

Name	Actual Physical Quantity Measured	Min. Vertical Resolution	Min. Lateral Resolution *	Typical Vertical Measuring Range**	Typical Lateral Measuring Range**	Transducer Technology	Data Acquisition Speed	Types of Surfaces that can be measured	Advantages	Disadvanta-ges
non-contact atomic force microscope [14]	cantilever probe deflection due to Van de Waals force gradient	<= 10 angstrom [14]	approx. 1 nm [14]	piezotube... typ. 2µm (up to 7µm possible)	piezotube... typ. 10 µm square (80µm square possible)	same as contact AFM	slow- linear data acquisition; scanner speed usually < 10 kHz	no restriction	+ non-contact	- slower and less robust than STM/AFM (tip must be kept with a few nm of surface to sense weak Van de Waals force)
scanning magnetic force microscope [31]	cantilever magnetic probe deflection due to magnetic force gradient	similar to non-contact AFM	10nm (state of the art)	piezotube... typ. 2µm (up to 7µm possible)	piezotube... typ. 10µm square (80µm square possible)	same as contact AFM	slow - linear data acquisition; scanner speed usually < 10 kHz	magnetic sample	+ non-contact (typ. gap spacing is 20-200nm)	- coupling of topographic & magnetic force gradient (need to separate)

Name	Actual Physical Quantity Measured	Min. Vertical Resolution	Min. Lateral Resolution *	Typical Vertical Measuring Range**	Typical Lateral Measuring Range**	Transducer Technology	Data Acquisition Speed	Types of Surfaces that can be measured	Advantages	Disadvanta-ges
scanning capacitance microscope [2]	capacitance between microtip and sample	dependent upon tip size (e.g. sub 100nm tip in [2])	25nm (limited by tip size)	piezotube... typ. 2μm (up to 7μm possible)	piezotube... typ. 10μm square (80μm square possible)	probe itself is sensor	slow - linear data acquisition; scanner speed usually < 10 kHz	electrically conductive sample	+ non-contact (typ. Gap spacing is 20-200nm)	- coupling of topographic & electro-static force gradient (need to separate) - varying dielectric constant (i.e. varying thickness of thin film, etc.)
scanning thermal microscope [2]	temperature of heated tip as a function of gap spacing	< 3nm to atomic resolution (state of the art)	35nm (state of the art)	piezotube... typ. 2μm (up to 7μm possible)	piezotube... typ. 10μm square (80μm square possible)	probe itself is sensor	slow - linear data acquisition; scanner speed usually < 10 kHz	no restriction (can even be used on liquids)	+ non-contact + can be used with gap spacing > 10nm (even 0.1μm)	- coupling of topographic information & thermal gradient

Name	Actual Physical Quantity Measured	Min. Vertical Resolution	Min. Lateral Resolution *	Typical Vertical Measuring Range**	Typical Lateral Measuring Range**	Transducer Technology	Data Acquisition Speed	Types of Surfaces that can be measured	Advantages	Disadvantages
scanning electron microscope (SEM) [4] (*****)	scanned electron beam causes secondary emissions in sample	poor vertical resolution (need accompanying profile to correlate height information)	coarse lateral resolution	magnification dependent	magnification & scan area inversely proportional (i.e. x 10,000 => 0.01 mm^2 scan area		relatively fast - data can be collected at "video rates" (though obvious not at highest resolution)	electrically conductive sample, (sample is often coated with a thin layer of metal)	+ "high quality" non-quantitative visual information	- non-quantitative data (need reference) - bombarding electrons can easily damage soft samples (e.g. biological samples)

Notes:

* This is assuming a "flat" surface; real lateral resolution will be determined by a combination of probe tip size and surface roughness.

** Vertical and lateral measuring ranges are highly dependent on the design of the device.

*** Note that there are a host of optical techniques not mentioned (i.e. confocal optical microscopy, etc.) but they are all limited in lateral resolution by the far-field aperture size.

**** Recently developed white light interferometry based profilometers have a reduced computational load. Furthermore, they have much less dependency on sample material characteristics and environmental conditions in the lab. [37]

***** To improve accuracy, a metrology frame, for instance a high precision stage can be used to provide the system with a reference. By doing that, resolutions can be greatly improved (5nm).However, the SEM *WITHOUT* a reference frame only provides a contrast based image (relative) that exposes three dimensional features without providing any numerical (absolute) data. Non-conductive samples can be used with new high performance SEM techniques that were not investigated in this research.

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