Scanning Microscopy

Volume 2 | Number 4 Article 3

7-31-1988

An Experimental Scanning Capacitance Microscope

H. P. Kleinknecht
Paul Scherrer Institute c/o Laboratories RCA Ltd.

J. R. Sandercock
Zwillikerstrasse 8

H. Meier
Paul Scherrer Institute c/o Laboratories RCA Ltd.

Scanning Microscopy, Vol. 2, No. 4, 1988 (Pages 1839-1844)
Scanning Microscopy International, Chicago (AMF O'Hare), IL 60666 USA

0891-7035/88$3.00+.00

AN EXPERIMENTAL SCANNING CAPACITANCE MICROSCOPE

H.P. Kleinknecht*, J.R. Sandercock** and H. Meier*

* Paul Scherrer Institute c/o Laboratories RCA Ltd., Badenerstr. 569, CH-8048 Zurich, Switzerland
** Zwillikerstrasse 8, CH-8910 Affoltern a/A., Switzerland

(Received for publication May 02, 1988, and in revised form July 31, 1988)

Abstract

A fine needle stylus mounted to a three-dimensional piezo system is scanned across the sample in x- and y-direction, while a constant spacing between tip and sample, i.e., constant tip-to-sample capacitance, is maintained in z-direction. This is accomplished by vibrating the tip in z-direction at 1 kHz by typically 0.1 microns and by detecting the capacitance modulation from the shifting of the resonance of a tuned 1 GHz line. The horizontal resolution achieved so far is limited by the tip radius at about 200 nm and the vertical resolution is about 5 nm. The theoretical limits for finer tips are 7 nm and 1 nm for horizontal and vertical resolution, respectively.

KEY WORDS: scanning microscope, capacitance, capacitance detector, piezo system, fine point probes, resolution limit, shot noise, critical dimensions on ICs, in-process testing of ICs, sub-micron dimensions

* Address for correspondence:
H.P. Kleinknecht, Paul Scherrer Institute,
c/o Laboratories RCA Ltd., Badenerstrasse 569,
CH-8048 Zurich, Switzerland
Phone No. 01/ 492 63 50

Introduction

For the inspection and measurement of structures at a scale below the wavelength of light the scanning electron microscope is the normal choice, and for the atomic scale the tunneling microscope has become famous. However, there are important applications, where one needs non-destructive and fast inspection of samples which are not necessarily conductive. This is difficult to do with the SEM, and impossible with the tunneling microscope. Probably the most important application of this type is the in-process testing of critical dimensions of integrated circuits on silicon wafers at the manufacturing line. As these dimensions are moving down towards a few tenths of a micron, the tests become more important and at the same time unreliable if done with optical microscopes. The scanning capacitance microscope is expected to satisfy the above requirements. It has a lateral resolution equal to the diameter of the needle stylus, hence, is not limited by the wavelength of light. It does not require vacuum, works with somewhat reduced resolution also on dielectric samples and is potentially fast and robust. The comparison is summarized in Table 1.

	Optical	SEM	Tunnel	Cap
Resolution	200	3	0.3	10 nm
Vacuum ?	+	–	+	+
Dielectric ?	+	–	–	+

Table 1. Merit comparison of the various types of microscopes.

Matey and Blanc (1985) have evaluated this technique for the first time by using the RCA CED (Capacitance Electronic Disc) VideoDisc system (see list of references), where a stylus of insulating material and of relatively large area is mechanically sliding on the surface of the sample. The capacitance probe is formed by a metallic layer at the front face of the stylus. The layer is 0.15 micron thick and 2.5 microns wide, which

gives high resolution only in the scan direction, namely 0.1 microns. With this setup depressions in the top surface as low as 0.3 nm could be detected.

In the work reported here, we are also making use of parts of a VideoDisc system for some of the circuits, but for a stylus we are using a fine point supported by a 3-dimensional piezo system, which potentially gives full freedom for 2-dimensional scanning along an almost arbitrary sample surface without making mechanical contact to the surface. Because our capacitance probe is a fine point, we get the same resolution in both (x- and y-) directions.

Apparatus

The principle of our experimental capacitance microscope is shown schematically in Figure 1. The capacitance point probe is held at a close distance from the sample surface by an x-y-z assembly consisting of three piezo elements. During the x- and y-scanning the probe-to-sample capacitance is monitored by a high-frequency circuit, and a voltage proportional to the capacitance is fed back to the z-piezo to hold the point to sample spacing constant. This capacitance, typically 0.0001 pF, is a very small fraction of the total probe-to-ground capacitance of about 1 pF. In order to discriminate this small fraction, the z-piezo is excited by a 1 kHz oscillator, which via a high-voltage amplifier modulates the probe-to-sample spacing typically by ±50 nm. The modulation is detected by a capacitance detector. It consists of a 910 MHz tuned line which includes the capacitance of the point probe. The tuned line is driven by an oscillator with a frequency of 915 MHz, i.e., at the slope of its resonance curve, and the amplitude is peak detected and fed to a phase-sensitive amplifier (PSA). Any change of the probe capacitance gives a change of the resonance frequency and results in a change of the peak detector amplitude. The output of the PSA (tuned at 1 kHz) is proportional to the probe-to-sample capacitance. This signal is, via an integrator and the high-voltage amplifier, returned to the z-piezo. The scanning is done by applying suitable voltages to the x- and y-piezo elements. The "set level" at the integrator can be used to bias the z-piezo and select the desired probe-to-sample spacing. A recording of the z-voltage vs x- and y-voltages gives an image of the surface topography.

The point probe and the sample can be viewed perpendicular to the z-direction with an optical microscope (not shown in the figure) in order to monitor the spacing. There is also a vertical drive at the sample stage (not shown in the figure) with a linearized and calibrated piezo element, which allows the coarse adjustment of the spacing, before the feedback loop can take over. The calibrated piezo-driven sample stage can also be used to create an accurate z-scale on the recorder traces by lifting the sample by a known amount and recording the voltage change at the z-piezo which is necessary to compensate for it. The ratio of the lifting distance and the voltage change is the displacement sensitivity (microns/volt) of the z-piezo, called p in this paper.

The simple x-y-z piezo system, as sketched in Fig. 1, showed some interdependence between the three directions, which resulted in a skewed and curved motion of the probe, and also in a reduced displacement sensitivity. For this reason, a small, compact 3-dimensional stage was constructed with independent flexing leaf spring elements for the x- and for the y-motion, which are independently driven by the x- and y-piezo elements. Figure 2 is a schematic drawing of this design. For clarity we show the x- and the z-motion only.

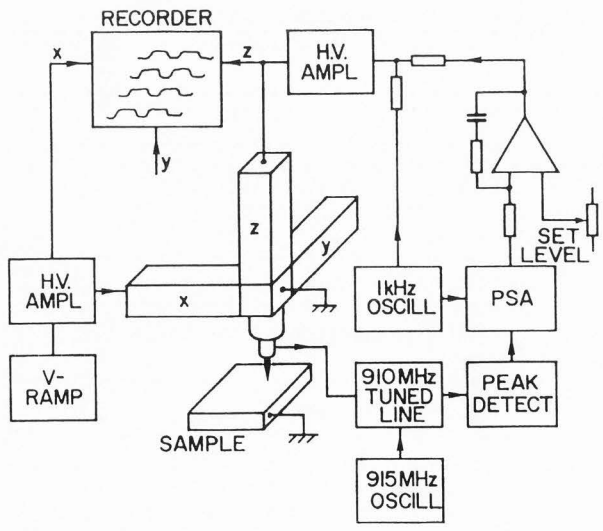

Figure 1. Experimental apparatus of the capacitance microscope.

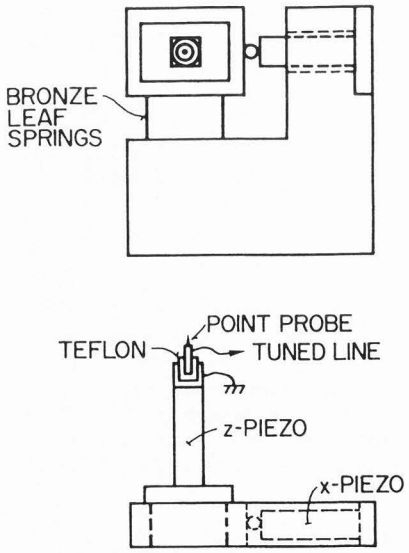

Figure 2. Design principle of the piezo stage for the capacitance point probe.

Preparation of the Fine Point Probes

Obviously, the lateral resolution of the capacitance microscope is only as fine as the probe size. For making fine points we are using a technique reported by Bryant et al. (1987). Our set-up is sketched in Figure 3. A piece of tungsten wire of 0.1 mm diameter is mounted by pressing one end into a brass pin. The etching is done electrolytically with an ac current in diluted KOH which is placed in a thin layer over a bath of CCl_4. The wire is hanging on a manipulator, pin down, through the KOH layer. During the etching, one can observe the process with a

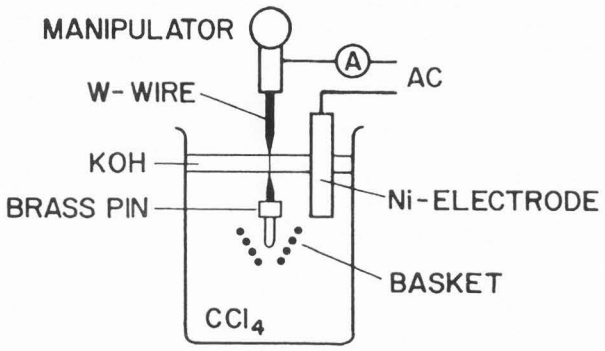

Figure 3. Set-up for the fabrication of the point probes.

microscope and change position and current as required for best results. As soon as the wire is etched through, the pin with the newly etched point falls down into the inert CCl_4 and is caught with a suitable basket. This prevents any further polishing after completion and preserves the fine point. So far, we have produced points with radii as small as 0.1 microns.

Experimental Scan Plots

Figure 4 gives some plots of capacitance scans of one of our first test samples, a square wave grating of a 5 micron period etched about 1 micron deep into a silicon wafer. The top scan was taken with a tungsten tip of 0.6 micron radius. We show two traces to give an indication of the repeatability. As can be seen by the apparent variation of the grating period along the x-axis, the scale in x-direction is somewhat non-uniform. This is due to the nonlinearity of the piezo motion. There is also a hysteresis, which makes it necessary to do all scans in one direction. Both of these problems will have to be solved in the future by linearizing the piezo motion with built-in displacement sensors and feedback loops for the x- and y-direction.

The middle part of Fig. 4 shows four scans taken with a steel needle having a tip radius, r, of about one micron and with four different tip-to-sample spacings, s, as set by various "set levels" at the integrator (see Fig. 1). The actual values of s were determined from the amplitude, V_c, of the 1 kHz signal at the output of the capacitance detector as will be described below. As expected, the resolution increases with decreasing spacing.

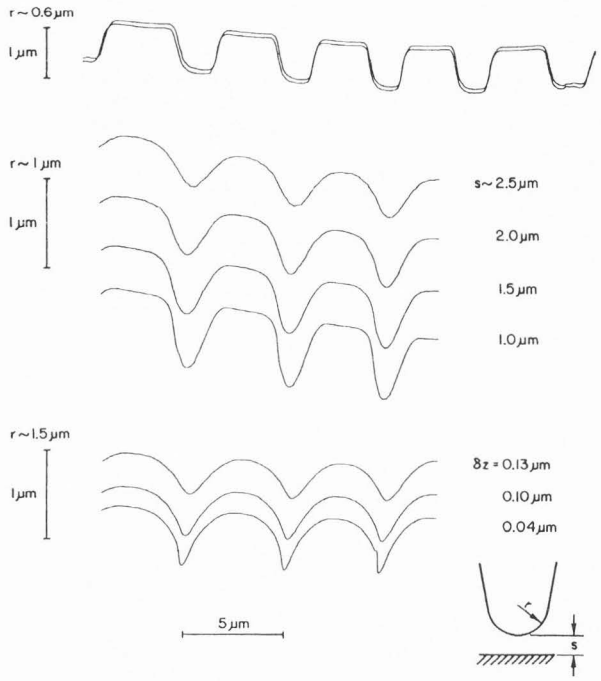

Figure 4. Scan plots of a 5 micron square wave grating etched into silicon.

The three lower traces were taken with a still coarser needle of about r = 1.5 microns. Here the parameters are the 1 kHz excursion, δz, (in microns) of the point probe. This quantity was calculated from the measured ac voltage, V_a, at the z-piezo and its displacement sensitivity, p. These experiments indicate, that for good resolution one must use small spacings, s, and low z-excursions, δz, in particular for profile features of a size close to the tip radius.

Figure 5 gives scans across a sine wave grating embossed in plastic and coated with 0.1 microns of gold. The grating period is again 5 microns. In the lower part of the figure a number of x-z scans are shown, which are displaced from one another by steps in y-direction (voltage steps applied to the y-piezo) in order to get a two-dimensional representation, which in this case indicates good uniformity in y-direction. At the moment these scans are recorded by a pen type x-y recorder. Obviously, in the future this will have to be done by computer graphics.

In Figure 6 we show scans of a 0.4 micron period sine wave grating in gold coated photoresist taken with a probe of r = 0.25 micron. The four scans are for different tip-to-sample spacings, s. As in Fig. 4 the resolution increases very critically with decreasing spacing, s, because r is close to the grating period. The 1 kHz z-oscillation of the probe is only 60 nm in this case. The actual shape of the profile is given by the SEM photograph of a perpendicularly cleaved cross-section of the same sample, which

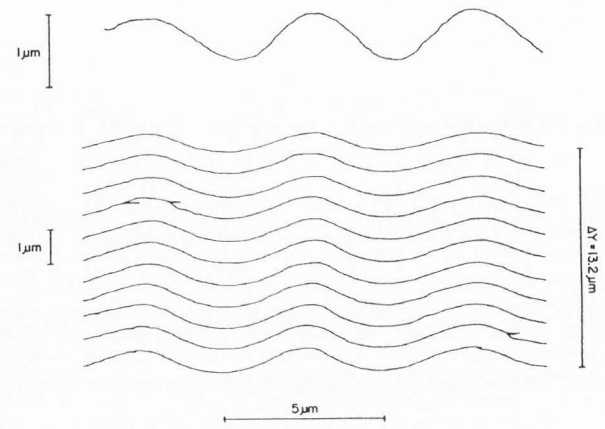

Figure 5. Scan plots of a 5 micron sine wave grating.

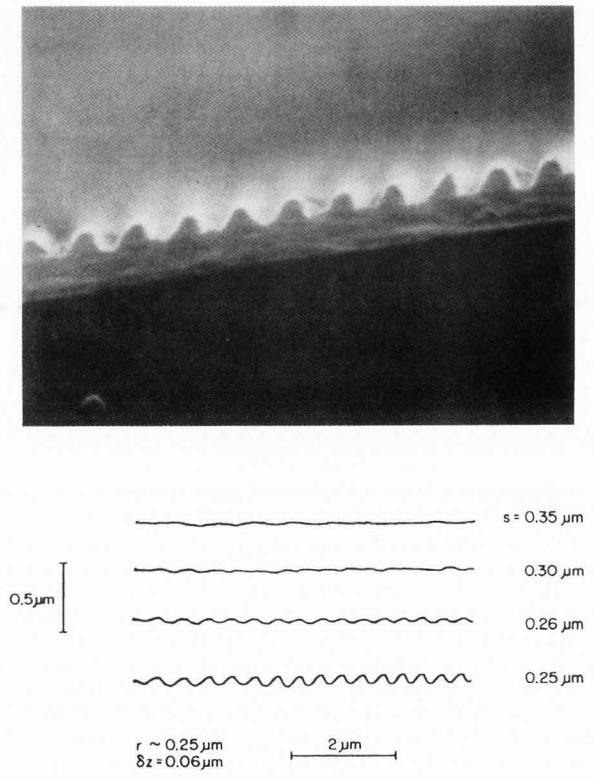

Figure 6. SEM photograph and scan plots of a 0.4 micron sine wave grating in gold coated photoresist.

is shown at the top of the figure. The two profiles look qualitatively alike. However, a detailed comparison considering qualitatively the x- and z-scales indicates that we have not achieved the full resolution. Obviously, one needs finer points for profiles of these dimensions.

In order to test the vertical resolution of our experimental system, shallow square wave gratings (etched into silicon) were scanned, and the results are shown in Figure 7. The periods of the top and the bottom sample are 5 and 10 microns, respectively. The measured depths can be assumed to be correct, because the tip was small compared to the grating periods in these cases. The depths are 10 nm and 35 nm, respectively. From the signal-to-noise appearance one can estimate a vertical resolution limit of about 5 nm.

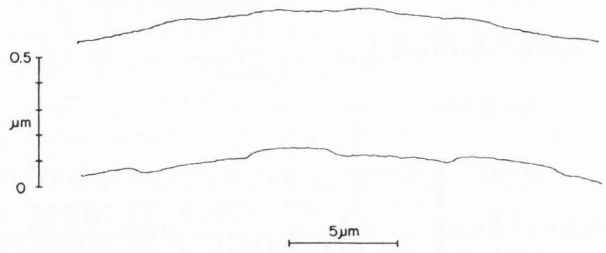

Figure 7. Scan plots of shallow square wave gratings of 5 and 10 microns period etched into silicon.

Theoretical Considerations

The horizontal resolution demonstrated in Figure 6 is obviously determined by the tip size, and the vertical resolution estimated from Fig. 7 is somewhat lower than expected. For this reason, it is rather important to estimate the basic resolution limits from theoretical considerations as a guide for future development efforts. The general problem, the calculation of the capacitance between a needle shaped probe and an arbitrarily shaped surface, is probably very involved and lengthy. A simplified problem, however, namely the approximation of the point probe by a conducting sphere and of a planar conductive or dielectric sample (see insert of Fig. 8), can be solved exactly and has turned out to be rather useful. Smythe (1950) treats this problem by using the method of images and gives the capacitance, C, in the form of an infinite series of terms containing hyperbolic sines only

$$C = 4\pi\varepsilon\, r \sinh(a) \sum_{n=1}^{n=\infty} B^{n-1}/\sinh(n\,a) \qquad (1)$$

where ε is the permittivity of free space ($= 8.85\ 10^{-6}$ pF/micron) with

$$\cosh(a) = s/r + 1 \qquad (2)$$

and

$$\begin{aligned} B &= 1 && \text{for conducting samples} \\ B &= (k-1)/(k+1) && \text{for dielectric samples} \end{aligned} \qquad (3)$$

where k is the relative dielectric constant. Since C is modulated by oscillating the probe in z-direction, one needs the derivative with respect to s. dC/ds is a function of (a) only, or through

(2), of s/r only. Hence, one can plot a universal curve of dC/ds vs s/r, which has been done in Figure 8. One can show that for a conductive sample and small s/r

$$dC/ds \sim 2\pi\varepsilon\ r/s \qquad (4)$$

which is indicated as a dashed line with slope one in Fig. 8. If one calls the sensitivity of the capacitance detector A_d (in volts/pF) and its ac output voltage V_c one has

$$V_c = A_d\ (dC/ds)\ p\ V_a \qquad (5)$$

These equations have been used to determine A_d for our system. By using a flat, metallic sample, a needle with a large tip radius, r, (measurable in the optical microscope) and a large, measurable

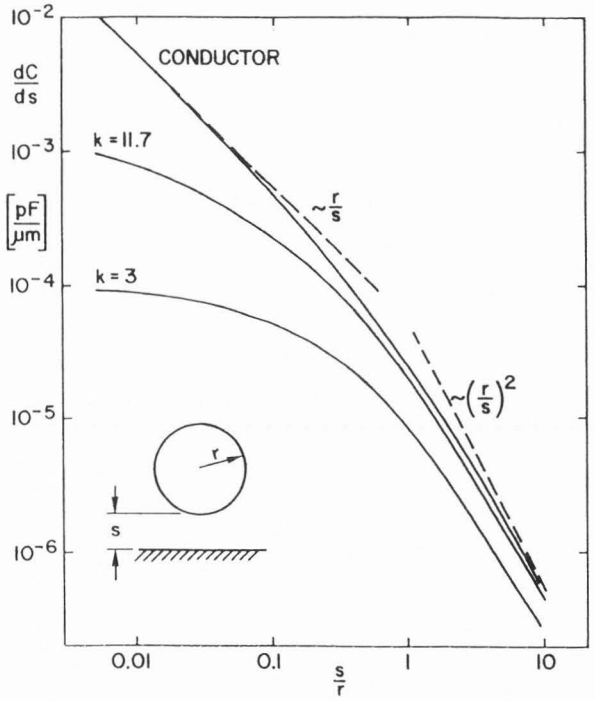

Figure 8. Theoretical curve of dC/ds vs s/r. C is the capacitance between a conducting sphere of radius r and a planar sample spaced at a distance s from the sphere.

spacing, s, we have calculated from the curve of Fig. 8 the derivative dC/ds and also measured V_c and V_a. Then equation (5) yielded the sensitivity A_d = 4800 V/pF for our set-up. With A_d known one can now use equation (5) to determine dC/ds for any probe setting by measuring V_a and V_c. Then the curve of Fig. 8 gives s/r, and with known r one gets the spacing s. In this way we have determined the s values given in Fig. 4 and Fig. 6.

Another characteristic quantity of the system is the smallest measurable tip-to-sample capacitance, C_{min}. It can be obtained, if for a known s/r setting (and known dC/ds) one reduces V_a to such a level, V_{amin}, that V_c is just visible above the noise. Then one has

$$C_{min} = (dC/ds)\ p\ V_{amin} \qquad (6)$$

which for our system gives 2 10^{-7} pF. If the capacitance detector itself does not contribute significantly to the noise, then the noise of V_c is due to the shot noise, i.e., fluctuations due to single electrons at the tip. Then C_{min} is the electron charge divided by the high frequency voltage at the tip. We estimate this voltage to be 0.1 to 1 volt, which gives C_{min} = 1.6 10^{-7} to 1.6 10^{-6} pF. Hence, V_c is indeed shot noise limited.

One can now make an estimate of the limit of resolution. Clearly, the resolution can be increased by making s/r small, because this makes the capacitance large and gives a high signal-to-noise ratio. Therefore we can use equation (4) instead of the curve in Fig. 8, considering a conductive sample for the moment only. Since the vertical oscillation amplitude of the point p V_a cannot be larger than s, we can write equation (6)

$$C_{min} < (dC/ds)\ s \qquad (7)$$

and with equation (4)

$$r > C_{min}/(2\pi\varepsilon) \qquad (8)$$

which gives r > 3.6 nm and an estimated horizontal resolution of 2 r = 7 nm.

The vertical resolution can be written in analogy to equation (6) as being equal to C_{min}/(dC/ds). However, we have to set somewhat arbitrarily a lower limit to s, which may be dictated by mechanical stability considerations. Assuming s = 1 nm, one can calculate s/r and dC/ds and get a vertical resolution of about 1 nm. These numbers of 7 nm and 1 nm for horizontal and vertical resolutions, respectively, have been calculated for conducting samples. Fig. 8 shows, that for dielectric samples the values dC/ds are lower, particularly for low s/r and more so for low dielectric constants. Correspondingly, the resolutions will be lower.

The horizontal and vertical resolution limits of 7 nm and 1 nm, respectively, have to be compared with the experimental results in connection with Figs. 6 and 7, giving resolutions of 200 nm and 5 nm, respectively. One can see, that an improvement of a factor of five for the vertical resolution is possible, probably by improvements of the feedback circuits and the mechanics. The horizontal resolution at the moment is limited exclusively by the tip radius with a good chance for improvement of more than an order of magnitude, if smaller tips are used. Therefore, there is also a good chance, that satisfactory resolutions can be obtained on dielectric samples.

Summary

We have reported on the construction of an experimental capacitance microscope. Preliminary results obtained with this set-up show horizontal and vertical resolutions of about 200 nm and 5 nm,

respectively. We have shown that the horizontal resolution is limited by the presently used point probe sizes. Theoretical estimates using the basic characteristics of our system allow the prediction of resolution limits of 7 nm and 1 nm for horizontal and vertical resolution, respectively, for tip radii of 3 to 4 nm.

Acknowledgement

The authors would like to thank B. Binggeli for consultation on the high frequency circuit.

References

Bryant PJ, Kim HS, Zheng YC, Yang R. (1987). Technique for Shaping Scanning Tunneling Microscope Tips, Rev. Sci. Instrum. 58, 1115.

Matey JR, Blanc J. (1985). Scanning Capacitance Microscopy, J. Appl. Phys. 57, 1437-1444.

RCA CED VideoDisc, see RCA Review 39, No. 1 (1978) and 43, NO. 1 (1982).

Smythe WR. (1950). Static and Dynamic Electricity, McGraw-Hill, New York, Toronto, London p. 121 and p. 203.

Discussion with Reviewers

U. Fischer: dC/ds, as shown in Fig. 8, has a rather weak dependence on distance. As a consequence, the shape of the tip is very important for capacitance microscopy, even of shallow relief structures, in order to obtain a high lateral resolution. On the other hand, the weak dependence yields a somewhat larger depth of field in comparison to other non-contact stylus microscopies. Therefore it could be a particular advantage of capacitance microscopy to allow for a somewhat larger working distance as compared to other such microscopies.
Authors: This is correct. For capacitance microscopy one needs indeed thinner, more pointed tips than for tunnel microscopy, which, on the other hand, enables us to measure deeper profiles. Also, with properly shaped tips, one can expect to be able to measure at larger distance with lower resolution, which could result in a Zoom function.

R.W. Wijnaendts-van-Resandt: What is the effect of variations of relative permittivity of layers under the structure to be scanned?
Authors: Variations of permittivity at or underneath the sample surface will produce some distortion of the measured profiles in z-direction. However, this does not influence the x-direction very much. Hence, linewidth measurements on integrated circuit samples are not distorted by this.

R.W. Wijnaendts-van-Resandt: Will it be possible to construct tips so that resist structures with very high aspect ratio (1 μm high, 0.25 μm wide) can be measured?
Authors: We are working at present towards improving our system in order to be able to do just that.

J.R. Matey: The authors correctly state that it is impossible to image non-conductive samples with a tunneling microscope and offer the capacitance microscope as an alternative. There is a variation on the tunneling microscope, the atomic force microscope, which can image non-conductive samples. How would the authors compare the capacitance microscope with the atomic force microscope?
Authors: The atomic force microscope is even more delicate and complicated than the regular tunneling microscope. The capacitance microscope uses much larger working distances and consequently is more robust. For applications of lower than atomic resolution, it will win out.