Sub-0.35-micron critical dimension metrology using atomic force microscopy

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ABSTRACT

The critical dimension atomic force microscope (CD-AFM) provides a number of unique capabilities for in-line metrology. In this paper, we evaluate the CD-AFM as a metrology tool and discuss its capabilities and limitations for semiconductor process development and production. We report that linewidth measurements made by the CD-AFM correlate well with those made by all other techniques generally used to measure submicron features, including scanning electron microscopy and electrical probing. Measurement repeatability is limited primarily by changes in probe tip shape with increased use. When the tip is accurately calibrated, this tool provides width, height, and slope data on etched and photoresist features with nanometer resolution. Increased throughput and improved automation may make the CD-AFM a key metrology tool for next-generation process development.

Keywords: atomic force microscope (AFM), critical dimension atomic force microscope (CD-AFM), critical dimension metrology, process control, process development

1. INTRODUCTION

As industry approaches quarter-micron technology and beyond, there is an increasing need to pursue innovative ways of improving linewidth measurement capabilities. Atomic force microscopy has recently emerged as a promising technique for aiding process development because of its unique capabilities for surface profiling and feature height and width determination. The conventional atomic force microscope (AFM), which scans with a conical or pyramidal probe tip, can effectively track surface roughness or other low-aspect-ratio, small-angle features.[2] The critical dimension AFM (CD-AFM), which scans with a boot-shaped tip and two-dimensional feedback, is capable of tracking a vertical or re-entrant profile and allows superior sidewall imaging and CD measurements.[3] This tool can provide width, height, and slope data on etched and photoresist features with nanometer resolution. Much of this information simply cannot be accessed with standard in-line metrology equipment, and knowledge of such information becomes vital as technology shrinks to the sub-0.35-μm range.

The low voltage scanning electron microscope (LVSEM) is currently the state-of-the-art metrology tool for in-line CD measurements. LVSEMs provide fast, automated linewidth measurements, but these measurements may depend upon many variables, such as the sidewall angles, the substrate material, external fields, or the CD extraction algorithm.[4] Moreover, LVSEM data contain no height information since the sample is imaged from the top-down direction. Tilt SEMs, which can tilt a wafer from 0 to 60 degrees, do provide visual height and sidewall information, but precise measurements cannot be made. In addition, the electron interaction with a photoresist pattern or insulating layer in a SEM can cause charging, which can change the CD measurements and may damage a sample. The cross section high

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voltage SEM (HVSEM) and the transmission electron microscope (TEM) provide more feature information (including sidewall, height, and width measurements) and improved resolution. However, these techniques are destructive to the sample and require long sample preparation times.

The CD-AFM has several distinct advantages over these tools for metrology applications. Most importantly, the CD-AFM can determine height and sidewall profile information, which are not easy to measure using an in-line SEM. In addition, the AFM requires no special sample preparation (in contrast to HVSEMs and TEMs) and does not require a vacuum to operate (as opposed to all SEMs and TEMs). When run in non-contact mode, an AFM has a negligible dependence upon substrate material, and scanning should not damage or affect the sample in any way.

This paper discusses the capabilities and limitations of the CD-AFM for semiconductor process development. We present data in Section 2 comparing CD-AFM linewidth measurements with measurements made by other standard metrology systems. Section 3 summarizes the factors we believe most limit the widespread use of the CD-AFM in the semiconductor industry, as well as those factors limiting measurement accuracy and repeatability. A systematic study of CD-AFM system stability is presented in Section 4. Finally, in Section 5 we examine a focus/exposure matrix test wafer using the CD-AFM as an example of a real process development application that exploits the unique capabilities of this tool. The CD mode of the Dektak SXM AFM, a non-contact system manufactured by IBM and distributed by Veeco Instruments, was employed in this study.

2. CD CORRELATION

The boot-shaped tip of the CD-AFM, pictured in Figure 2-1, is cylindrical with small lateral flares at the base. This tip shape is optimized to sense topography on vertical surfaces and can be used to profile vertical or even re-entrant sidewalls (where one-dimensional (1D) conical or pyramidal tips fail as a result of the finite cone angle that causes tip-sample convolution). Linewidth measurements at any height of a feature can be extracted directly from the three-dimensional feature profiles found with the CD-AFM. In addition to CD measurements, the CD-AFM gives information such as height and sidewall angles not readily accessible by any other in-line metrology tool. Here we present comparisons of linewidth measurements made by the CD-AFM with those made by all other metrology techniques generally used to measure submicron linewidths.

2.1 Comparison With LVSEM and Tilt SEM Data

This study compared CD measurements made using the Dektak SXM CD-AFM, two LVSEMs (the Opal7830 and the Opal7830i), and the JEOL 7700 Tilt SEM. The objectives of this study were to determine:

- the CD measurement bias between the different systems;
- how consistently the tools measure isolated, semidense, and dense features;
- how consistently the tools track across-wafer variations in CD;
- how the line profiles compare before and after etch.

We measured nominal 0.35-μm features of various spacings in five die on each a photoresist and an etched polysilicon wafer. The isolated line CD measurement bias of the systems was found by averaging over the CD data from the five die. The results are shown in Table 2-1.

In order to visualize how consistently the tools measure features of different spacings, the data have been offset in Figure 2-2 to align the isolated line CD measurements made by the various systems. These linewidth data, averaged over the five die, are plotted as a function of the feature spacing (isolated, semidense, dense, MOSX8=isolated, MOSX7=dense, where dense means equal line and space). Notice in Figure 2.2a that the measurements made by the different tools agree well (on average within the expected measurement uncertainty of 0.01 μm), with the exception of the Opal7830 data. The Opal7830 measured a CD for the dense features that is more than 0.03 μm smaller than that measured by the other tools. This system has difficulty detecting the secondary electron signal from the small trenches between semidense and dense sub-0.5-μm features because the detectors are positioned below the lens. The Opal7830i has newly-positioned through-the-lens (TTL) detectors that seem to give more accurate CD measurements on even closely-spaced small features. The Opal7830 measured an offset of about -0.01 μm with respect to the CD-AFM and Opal7830i data for dense polysilicon features (Fig. 2-2b). The smaller aspect ratio of the etched features as compared with the photoresist features improves the accuracy of dense feature measurements made by the Opal7830.

Figure 2-3 compares the across-wafer variations in CD as measured by the different tools. In these plots, the data have been offset to align the values measured at the center of the wafer. The systems fairly consistently track the across-wafer linewidth variations. Inconsistencies are due to uncertainties in the measurements (no averaging was done here). The JEOL Tilt SEM does the poorest job of detecting small variations in CD; this may be attributed to operator error, since CD measurements are made manually on this machine. Automated algorithms were used to measure the linewidth using the LVSEMs and the CD-AFM.

The CD-AFM line scans of semidense features before etch (photoresist lines) and after etch (polysilicon lines) are shown in Figure 2-4. The (after etch) - (before etch) CD offset is on average 0.030 μm. The sidewall angles, as measured by the CD-AFM, are approximately 87° for both polysilicon and photoresist lines.

2.2 Comparison With HVSEM Data

It is important that the CD measurements made by a metrology tool are accurate over a large range of feature sizes. To test this, we performed a CD linearity study on dense and isolated photoresist features using the Hitachi S-4000 HVSEM, the Opal7830i LVSEM, and the Dektak SXM CD-AFM. These tools were used to measure nominal linewidths ranging from 0.30 μm to 1.5 μm. The CD-AFM shows good correlation with the HVSEM (to within the uncertainty of each measurement), known to be one of the best systems for such measurements. The linewidths scale linearly down to 0.35 μm, with an R^2 value of 0.999 measured by the CD-AFM.

In addition to linewidth measurements, a CD-AFM image provides feature thickness and profile information. Since the CD-AFM closely tracks the entire sidewall of a feature, the linewidth at any height can be extracted. (The base CD measurement, found 5% up from the bottom of the feature, was used for comparison with the SEM measurements above.) Notice in Figure 2-5 that the CD-AFM tracks the standing waves in the sidewalls of the photoresist feature consistently with the HVSEM.

2.3 Comparison With Electrical Data

We also compared CD-AFM linewidth data with electrical CD measurements of dense and isolated nominal 0.35-μm etched polysilicon lines. Electrical measurements were made using the Prometrix EM1 electrical linewidth probing instrument. The advantages of electrical CD measurements include their low cost, excellent measurement repeatability, and high throughput, but the technique is limited to conducting substrates (as opposed to photoresist, oxide, etc.). Another drawback of this method is that an electrical CD measurement represents the average linewidth of a feature, and thus gives no indication of any CD variation along a line or of the sidewall angles. Figure 2-6 shows that the CD-AFM and electrical data consistently track linewidth variations across a field. The CD-AFM measures sidewall angles of approximately 94°. Re-entrant sidewalls would tend to make the base physical dimension *smaller* than the CD measured by electrical probing since the electrical measurement algorithm assumes perfect 90° walls. However, the CD-AFM measures a CD of 0.035 μm *larger* than that measured by the electrical technique for both dense and isolated lines. This measurement bias is consistent with that generally measured by LVSEMs[5] and may be attributed to surface contamination, which causes the physical line (as measured by an AFM or SEM) to be larger than the electrically active region of the line.[6]

3. CD-AFM LIMITATIONS

The accuracy, repeatability, and breadth of applications of the CD-AFM are limited by a number of factors. Some are fundamental limitations, while others may be improved with software and/or hardware improvements to current generation systems. What follows is a discussion of the areas in which we believe improvements should be made in order to allow more widespread use of this tool for semiconductor process development and/or production.

Throughput. The low throughput of the CD-AFM is the primary factor limiting the widespread use of this tool for CD metrology in a production environment. This tool is significantly slower than the LVSEM for measuring linewidths (current generation LVSEMs specify 25 to 40 wafers/hour at five sites per wafer, while current generation CD-AFMs get at best 4-5 wafers/hour throughput); the potential for better accuracy and more information will have to be weighed against this time factor. The throughput is currently most limited by the data acquisition rate and by overhead time. Due to the time it takes to acquire and store the x, y, and z tip position data, the actual CD-AFM image acquisition time is far greater than true time it takes for the tip to scan the required distance; this may be improved with optimized software and faster microprocessors. It is possible to enhance the physical scan speed of the AFM somewhat;[7] however, this may increase the risk of "tip crashes" (when the tip inadvertently hits the sample surface) that can damage or destroy the probe tips. Another proposal for increasing AFM throughput is to use multiple probes for scanning.[8] If the AFM were to scan simultaneously with 10,000 probes instead of a single probe, the speed could easily rival or surpass other imaging technologies. Some challenges of creating a multiple-probe AFM include the issues of tip stability, tip calibration, and individual feedback control of each tip.

Inspection. Significant overhead time is consumed prior to the actual AFM scanning in locating the feature of interest and positioning the tip appropriately. This overhead time would be greatly reduced and the measurement repeatability would be increased with improved inspection capabilities. A wafer map should be added to CD-AFM software to facilitate efficient positioning and to make this tool consistent with other in-line metrology systems such as the automated SEMs and the defect detection systems. Currently, a number of AFM scans must be performed in order to know the true location of the feature with respect to the probe tip. This is a time-consuming process that causes unnecessary tip wear. Improved optics may also allow more repeatable positioning.

Automation. The automated recipe capabilities of current generation CD-AFMs are inadequate in design and performance, hence virtually all measurements must be made manually. Improved automation would reduce the level of operator expertise required to run the machine. This will facilitate bringing the tool into production. Better inspection capabilities will improve recipe repeatability and reduce recipe setup times; better automation may in turn improve throughput.

Tip Calibration. The accuracy of information extracted from an AFM image is inextricably tied to an accurate knowledge of the tip shape and size. Therefore it is essential to monitor the tip shape accurately in order to extract meaningful CD information from a scanned image. The nonlinear geometrical tip-sample interaction, the so-called "tip convolution," has been well documented for the conical or pyramidal tips used for 1D scanning.[9,10] An image of the tip itself may be obtained by scanning the 1D tip over a vertical structure. The calibration techniques used to deconvolve the tip shape for 1D scanning cannot be used in CD scanning mode because of both the different tip shape and the different scanning mechanisms. No single calibration technique for boot-shaped tips has yet become widely accepted (*see Section 4.1*).

Tip Stability. If a probe tip truly does not contact the sample surface, the shape and size of a tip could remain constant indefinitely. But even running in non-contact mode, the tip does at times hit the surface, and the boot-shaped etched silicon tip profiles are observed to change quite dramatically with increased use. Thus it is vitally important to have a reliable and efficient tip calibration procedure in place to monitor the width and shape of a boot-shaped tip throughout the tip lifetime. Tip lifetimes are variable and the tip degradation mechanisms are not well understood. A better understanding of the causes of tip failure may allow the tip lifetimes to be maximized. The challenges of accurately measuring a boot-shaped tip width and of maintaining a stable tip size and shape are fundamental problems that must be addressed and solved before the CD-AFM can be fully accepted as a production tool *(see Section 4.2)*.

4. SYSTEM STABILITY

As mentioned previously, changes in tip size and shape with increased use most limit the system stability of the CD-AFM. A linewidth measurement is only as accurate as the known value of the tip width. Changes in tip shape also affect the system's ability to track features of various profiles. Therefore, it is essential to establish an efficient, *in situ* method of monitoring or calibrating the tip shape and size. Here we discuss a number of tip calibration schemes and report data on the extent of tip wear with increased use.

4.1 Tip Calibration Procedures

A tip calibration scheme must allow an accurate measurement of the tip width, since this value must be subtracted from all lateral measurements made by the CD-AFM. For next-generation technology, this tip width should be determined accurately to within 25 Å in order to satisfy the metrology requirements predicted by the Semiconductor Industry Association (SIA) roadmap for 0.25-μm technology.[11] In addition to tip width, the calibration should give some indication of the tip shape. The tip shape—including the length of the flared ends and the extent of tip rounding—determines how closely the tip can track features of various profiles. For example, a tip with no flares (a perfectly cylindrical tip) could accurately profile features with sidewalls up to 90°, but could not image re-entrant sidewalls. Recall also that the since the tip shape and size do change with increased use, the calibration scheme should be efficient enough to allow frequent monitoring of the tip.

Considering these requirements, an ideal calibration scheme would consist of a single calibration standard that can be scanned *in situ* under normal CD-AFM operation to reveal the tip shape and size. (Separate standards to determine size and shape might provide more information, but the unfortunate trade-off is the increased time it would take to calibrate the tip.) Neither NIST nor VLSI Standards currently have line standards appropriate for CD-AFM tip calibration. (LVSEM linewidth calibration standards are less than 500 Å in height, too thin for calibrating boot-shaped tips due to the finite rounding of the flared ends.)

The Dektak SXM has a silicon nanoedge grating on its stage that is used to calibrate the width of the boot-shaped tips. To calibrate the tip in this method, the tip is scanned over the grating; the true width of the nanoedge near its peak (an average width is known) is then subtracted from the measured width, yielding the tip width. We performed tip width measurements at various locations across this grating and found that the tip width as measured from a single nanoedge may vary by as much as 500 Å from that measured at a neighboring nanoedge on the grating (while measurements made at the same location yield better than 50 Å repeatability). The grating scheme is valuable for calibration efficiency (since the tip does not have to be carefully positioned in order to calibrate it, but can simple be placed down anywhere on the grating sample). However, the nonuniformity of the grating generates serious repeatability concerns since it is virtually impossible to return to precisely the same nanoedge for every calibration scan. Thus, to get an accurate tip width value, a number of scans must be taken and the results averaged; this is a time-consuming and impractical process. This current technique for calibrating boot-shaped tips does not provide repeatable tip width data and hence is inadequate for maintaining tight CD control.

For comparison, we studied an alternative calibration technique. We used a specially-fabricated etched silicon 0.35-μm isolated line with sloped sidewalls as a tip calibration standard, which yielded improved tip width measurement repeatability. The calibration sample was mounted on the CD-AFM stage and scanned with a boot-shaped tip. The "golden" CD values (as determined by HVSEM measurements of the same feature) were subtracted at the top, middle, and bottom of the line from the AFM-measured CD data, generating a tip width value at each height. Tip width data found using this sample agreed well with average values found using the nanoedge grating, but did not suffer from the sporadic bad data caused by the nonuniformities across the grating (and thus this calibration method is more efficient and more precise[12]). The tip width as found at three different heights of the line gives an indication of changes in tip shape; if the flared ends are sharp, the three tip width values are virtually identical (within 20 Å), while the three values may differ by as much as 300 Å if the flares are quite rounded or the tip has picked up a particle or some photoresist. Sharp flares are required to track features of various profiles accurately. This method does not give an indication of the length of the tip flares, which would be desirable if features of interest are likely to have severely re-entrant profiles.

4.2 Boot-Shaped Tip Width Stability With Increased Use

For the practical use of the AFM as a CD metrology tool, the tip width and shape must remain constant during the lifetime of the tip. Likewise, this lifetime must be sufficiently long to allow multiple scans to be performed without the need for re-calibrating or changing the tip. The stability of the etched silicon boot-shaped tips has until now been unknown. A number of variables could affect the tip stability, such as the material being scanned, the type of topography on the surface, the number of "tip crashes" (when a tip inadvertently hits the sample surface), and the size and shape of the fresh tip. In order to determine the frequency at which a tip must be re-calibrated, we must better understand the tip stability. For instance, if the tip is known to remain constant for z microns of scanning, then no calibration would have to take place during the first z microns of the life of the tip. It is seriously problematic, however, to measure the tip width before a scan run and again afterwards and find that the value has significantly changed. Thus a tip should generally only be used for scanning during the period in which its width remains stable to within a given specification. For 0.25-µm technology, the tip stability specification would approach 25 Å.

We monitored the tip width of 10 boot-shaped tips over the tip lifetimes using both calibration techniques discussed above (the nanoedge grating and the etched silicon calibration line). Representative tip width degradation curves of a "0.35-µm tip" (appropriate for scanning 0.35-µm dense features) and a "0.25-µm tips" (appropriate for scanning 0.25-µm dense features) are shown in Figure 4-1. There is evidence to suggest both wearing and chipping tip degradation mechanisms. The final catastrophic tip failure is almost always due to an abrupt increase in tip width, most likely due to the picking up of a particle or some photoresist from the sample surface. (This phenomenon may be minimized if the CD-AFM is operated in a clean room environment.) Data indicate that probe tips are more likely to be subject to catastrophic damage when scanning a photoresist wafer. The usable lifetime of all 0.25-µm tips is considerably less than the lifetime of the 0.35-µm tips. The flares at the ends of the 0.25-µm tips are less sharp than those of the larger tips. This poses a challenge to the two-dimensional feedback algorithm and may contribute to the faster degradation of the smaller tips. Wider tips demonstrating better stability can be used for scanning isolated features of any dimension.

Figure 4-2 shows CD-AFM images of the silicon calibration line taken with a fresh 0.35-µm tip and taken again with the same tip after it had been used for more than 20,000 µm of scanning (these are the raw AFM images; no attempt has been made to deconvolve the tip from either image). Notice that the true feature dimensions are distorted by apparent rounding of the tip flares. Because of the considerable variation in tip width with increased use, the boot-shaped tips must be calibrated regularly so that a current tip width is known to ensure accurate CD measurements. In all experiments described in this paper, we monitored the tip width quite frequently. CD-AFM data reported here were extracted from scans throughout which the tip size and shape remained constant.

5. FOCUS/EXPOSURE MATRIX STUDY

One application that takes advantage of the unique capabilities of the CD-AFM is the study of a focus/exposure matrix. In-line LVSEM linewidth measurements are made from the top-down direction, making it extremely difficult to determine the feature thickness. This poses a significant challenge to the process engineer responsible for selecting the optimal focus and exposure settings for microlithographic printing. For instance, several values of the focus and exposure may produce CDs within the linewidth specification, yet some of the features exposed in the extreme range of focus or exposure may have significant loss of photoresist thickness and/or sloped sidewalls. The CD-AFM's profiling capabilities can be exploited in the study of a focus/exposure matrix wafer. This study also demonstrates the CD-AFM's capabilities of profiling features of various profiles, since here the line profiles were intentionally varied across the matrix.

PROLITH/2 was used to simulate the 0.35-μm photoresist feature profiles across a focus/exposure matrix. We also measured using the Opal7830i LVSEM the photoresist feature linewidths across a focus/exposure matrix test wafer. This wafer was composed of a 0.3-μm-thick polysilicon layer with 650 Å SiON:H antireflective coating (ARC) deposited on top of it. The I-line photoresist SPR511 was exposed on an ASM/100 stepper. Figure 5.1 shows the simulated and measured dense feature CDs as a function of the focal position. The simulated and measured data are not in exact agreement, but they do identify similar trends. From these plots, it is quite difficult to pick out the optimal focus and exposure values. For example, at an exposure of 180 mJ/cm^2, the measured CD for both isolated and dense features is nearly constant over a focus range from -1.1 μm to +0.1 μm. CD-AFM data presented below will show that the line profiles actually change quite dramatically throughout this range.

Using the CD-AFM, we measured the isolated and dense 0.35-μm line profiles across the various focus and exposure values on the same test wafer. Figure 5-2a illustrates the CD-AFM's important ability to give good visualization of the changing line profiles and thickness loss due to variations in the focal position in the positive and negative direction of the stepper. These profiles found by the CD-AFM agree quite well with line profiles generated by PROLITH/2 simulations (Fig. 5-2b). The real photoresist features appear to have stronger standing waves in the sidewalls than the PROLITH/2 simulation predicts. This study suggests that another valuable application of the CD-AFM might in the calibration of process simulators. Figures 5-3 shows how the photoresist thickness, linewidth, and sidewall angles depend on focus (from both CD-AFM measurements and PROLITH/2 simulations). The CD-AFM measurements of isolated and dense photoresist features across this focus/exposure matrix wafer indicate an optimal exposure of 180 mJ/cm^2 and focal position of approximately -0.3 μm.

6. CONCLUSIONS

This report shows that linewidth measurements made by the CD-AFM correlate well with those made by all other systems generally used to measure submicron linewidths. Measurement repeatability is most hampered by variations in tip shape and size with increased use. This forces a user to calibrate the probe tip frequently since the tip width must be known to within 25 Å in order to satisfy the metrology requirements predicted by the SIA roadmap for 0.25-μm technology. An improved *in situ* tip calibration scheme was presented that yields a repeatable tip width value and monitors changes in tip shape.

The CD-AFM has the capability to perform a number of important metrology tasks. The study of a focus/exposure matrix was presented as an example of an application in which the unique capabilities of the tool are exploited. The results of this study show that the CD-AFM can provide accurate profile information on features of various dimensions—information that simply cannot be accessed with standard in-line metrology systems. However, the current generation tools are limited by low throughput, inadequate automation, and poor tip stability. Improvements in these areas should make the CD-AFM a key metrology tool for next-generation process development. If the throughput can be dramatically enhanced, the CD-AFM might also be valuable in a production environment for sub-0.35-μm technology.

7. ACKNOWLEDGMENTS

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8. REFERENCES

1. Now with the Department of Applied Physics, Stanford University, Stanford, CA 94305-4090.

2. G. Binnig, C.F. Quate, Ch. Gerber, "Atomic force microscope," Phys. Rev. Lett., v. 56, 930-933, 1986.

3. Y. Martin, H.K. Wickramasinghe, "Method for imaging sidewalls by atomic force microscopy," Appl. Phys. Lett., v. 64, n. 19, 2498-2500, 1994.

4. M.T. Postek, "Scanning electron microscope metrology," *Handbook of Critical Dimension Metrology and Process Control,* 46-90, SPIE, Bellingham, WA, 1993.

5. K. Phan, J. Nistler, B. Singh, "Metrology issues associated with submicron linewidths," Proc. SPIE, v. 1464, 424-437, 1991.

6. S.K. Jones, et. al., "Comparison of SEM, confocal light microscope, and electrical resistance measurements of microelectronic devices," J. Computer-Assisted Microscopy, v. 2, n. 4, 211-221, 1990.

7. R.C. Barrett, C.F. Quate, "High-speed, large-scale imaging with the atomic force microscope," J. Vac. Sci. Technol. B, v. 9, n. 2, pt. 1, 302-306, 1991.

8. S.C. Minne, P. Flueckiger, H.T. Soh, C.F. Quate, "Atomic force microscope lithography using amorphous silicon as a resist and advances in parallel operation," J. Vac. Sci. Technol. B, v. 13, n. 3, 1380-1385, 1995.

9. L. Montelius, J.O. Tegenfeldt, "Direct observation of the tip shape in scanning probe microscopy," Appl. Phys. Lett., v. 62, n. 21, 2628-2630, 1993.

10. F. Atamny, A. Baiker, "Direct imaging of the tip shape by AFM," Surf. Science, v. 323, L314-L318, 1995.

11. *The National Technology Roadmap for Semiconductors,* Table 18, 85, Semiconductor Industry Association, 1994.

12. R.D. Larrabee, M.T. Postek, "Parameters characterizing the measurement of a critical dimension," *Handbook of Critical Dimension Metrology and Process Control,* 2-24, SPIE, Bellingham, WA, 1993.

Measurement Bias, Isolated Line CD (um)			
	Dektak - Opal 7830i	Dektak - Opal 7830	Dektak - Jeol
Before Etch	-0.028	-0.025	-0.023
After Etch	-0.013	-0.016	+0.004

Table 2-1. Isolated line CD measurement bias between the Dektak SXM CD-AFM, the Opal7830 LVSEM, the Opal 7830i LVSEM, and the Jeol Tilt SEM.

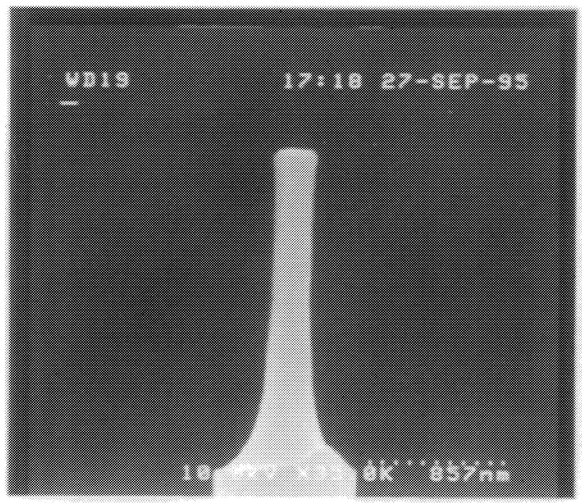

Figure 2-1. Boot-shaped tip is cylindrical with small lateral flares at the base. This tip shape is optimized to sense topography on vertical surfaces.

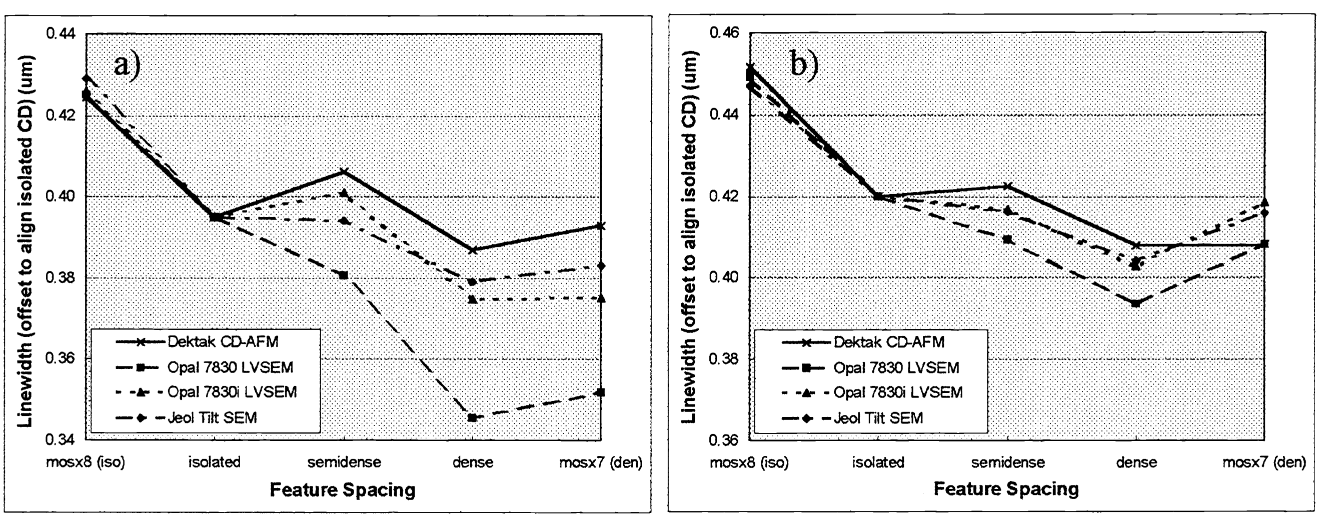

Figure 2-2. Linewidth dependence on feature spacing for (a) photoresist features and (b) etched polysilicon features (offset to align isolated CD) as measured by four different metrology systems.

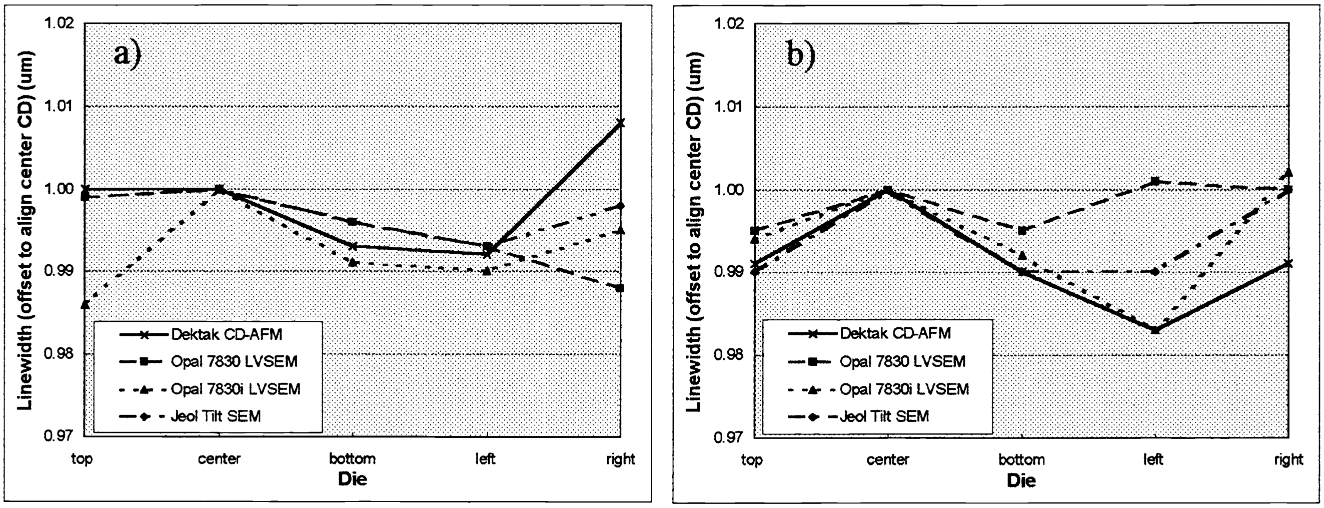

Figure 2-3. Across-wafer linewidth variations of dense (a) photoresist features and (b) etched polysilicon features (offset to align center die CD) as measured by four different metrology systems.

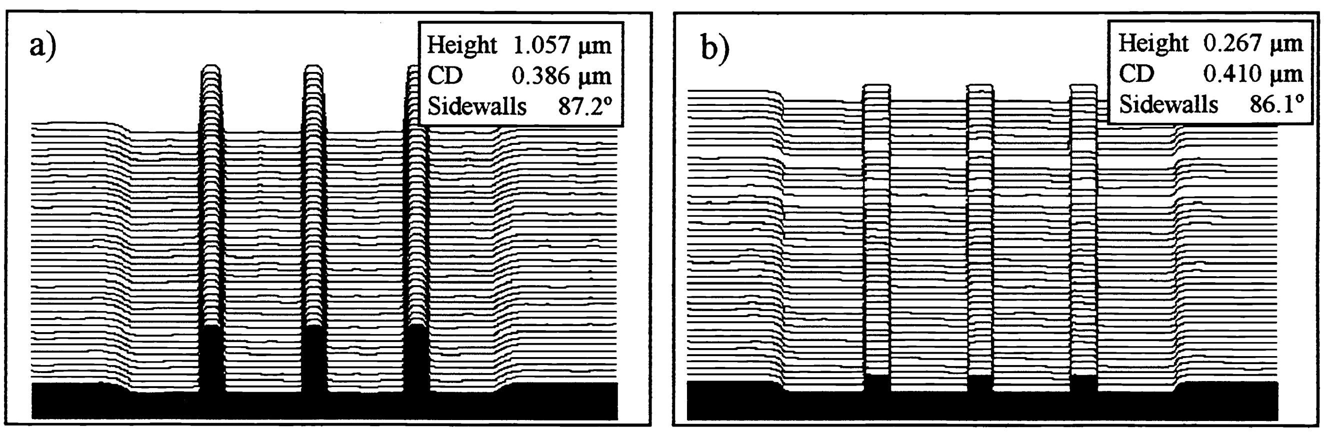

Figure 2-4. CD-AFM images of semidense 0.35-µm features (a) before etch (photoresist lines) and (b) after etch (polysilicon lines).

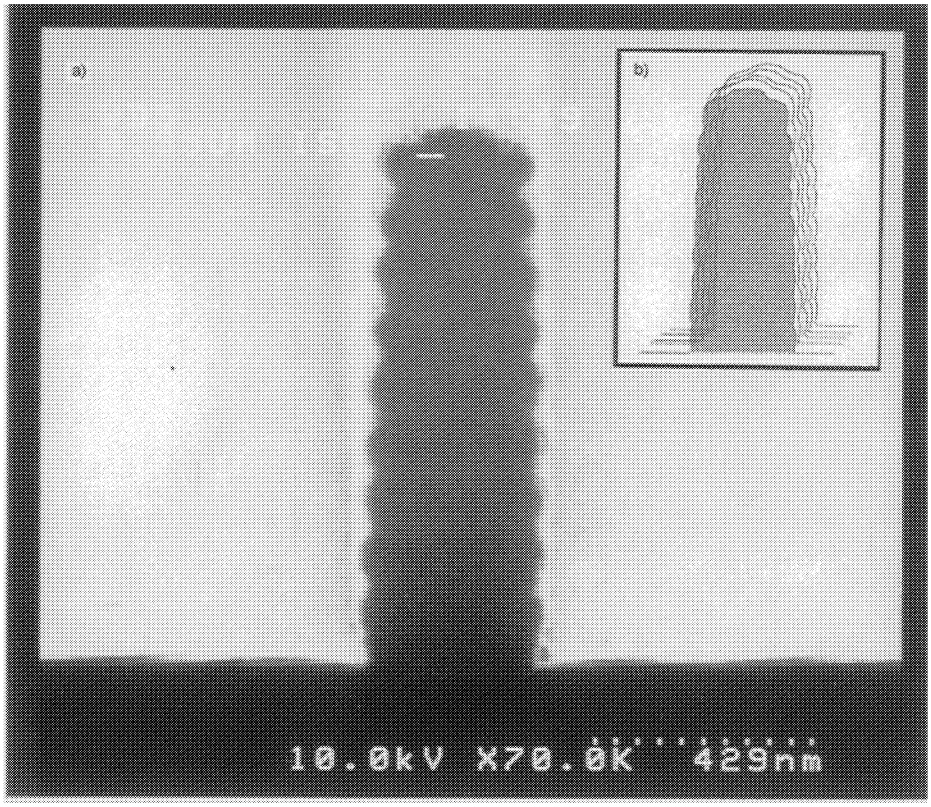

Figure 2-5. Images of isolated 0.35-µm photoresist line created by (a) HVSEM and (b) CD-AFM. Notice that the tools consistently track the standing waves in the sidewalls of the feature.

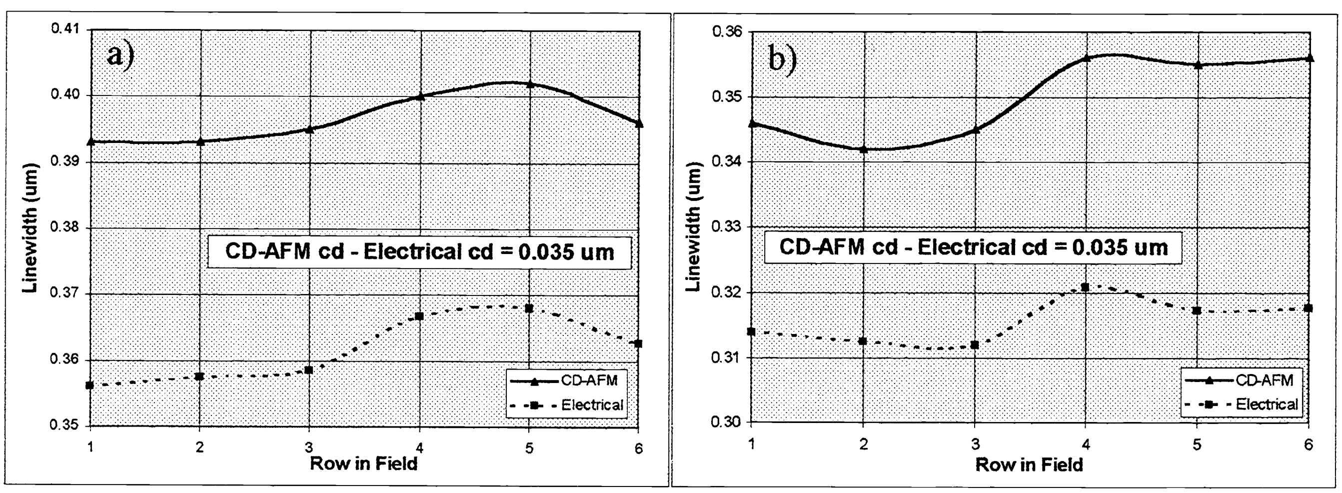

Figure 2-6. Comparison of linewidths measured by the CD-AFM and electrical probing of (a) isolated and (b) dense (equal line and space) 0.35-µm etched polysilicon features across a field.

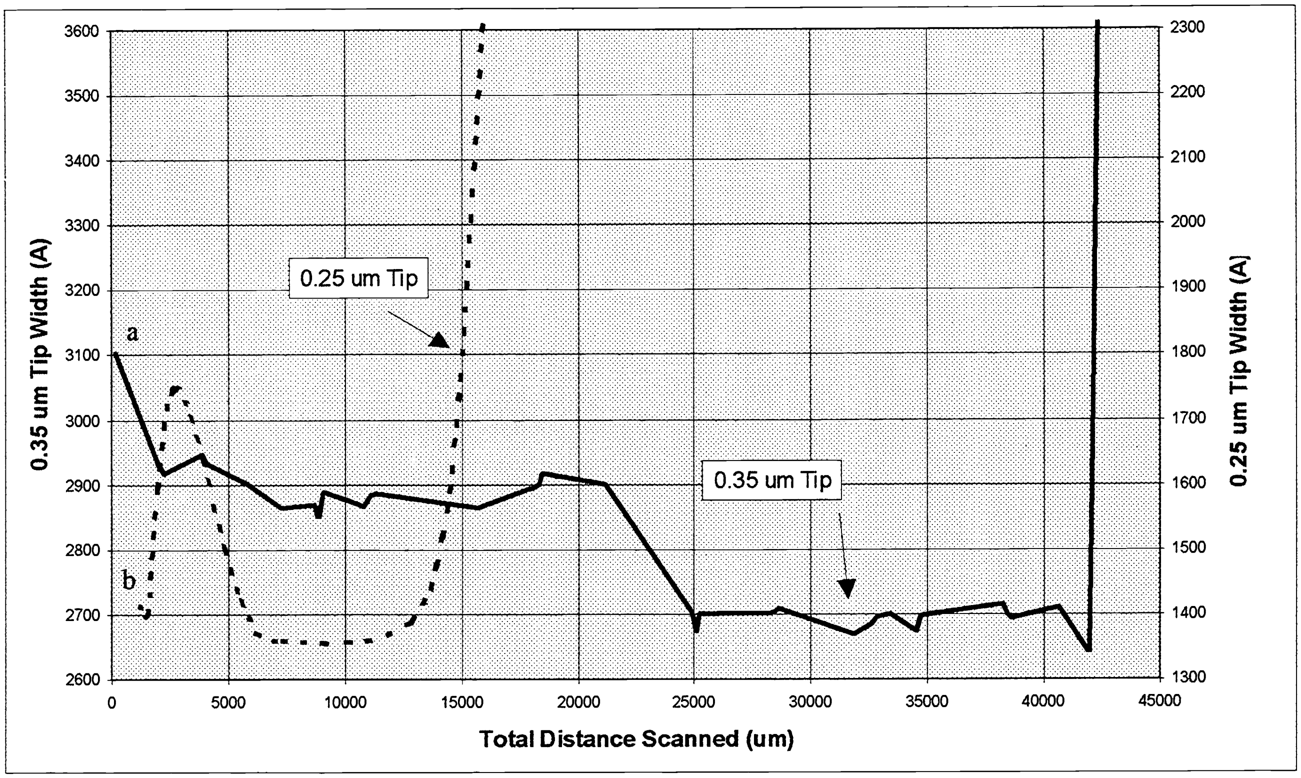

Figure 4-1. Boot-shaped tip width variation with increased use for 0.35-μm tip (curve a) and 0.25-μm tip (curve b). The data show evidence of three tip degradation mechanisms: wearing, chipping, and the picking up of a particle or some photoresist from the sample surface.

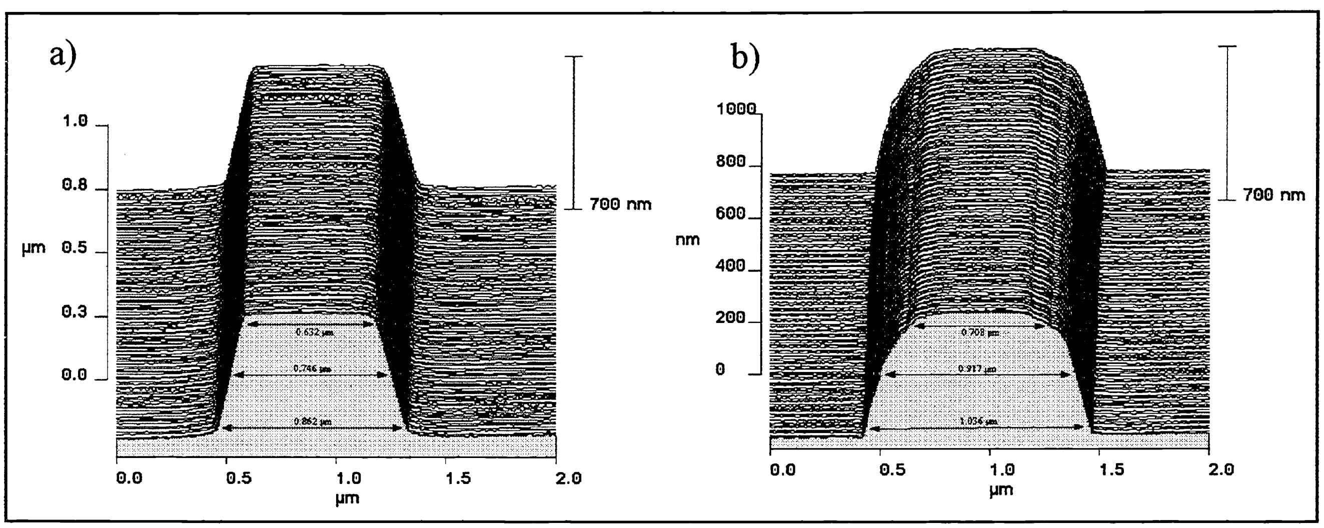

Figure 4-2. CD-AFM image of etched silicon calibration line scanned by 0.35-μm tip (a) when the tip was fresh and (b) after the same tip had been used for more than 20,000 μm of scanning.

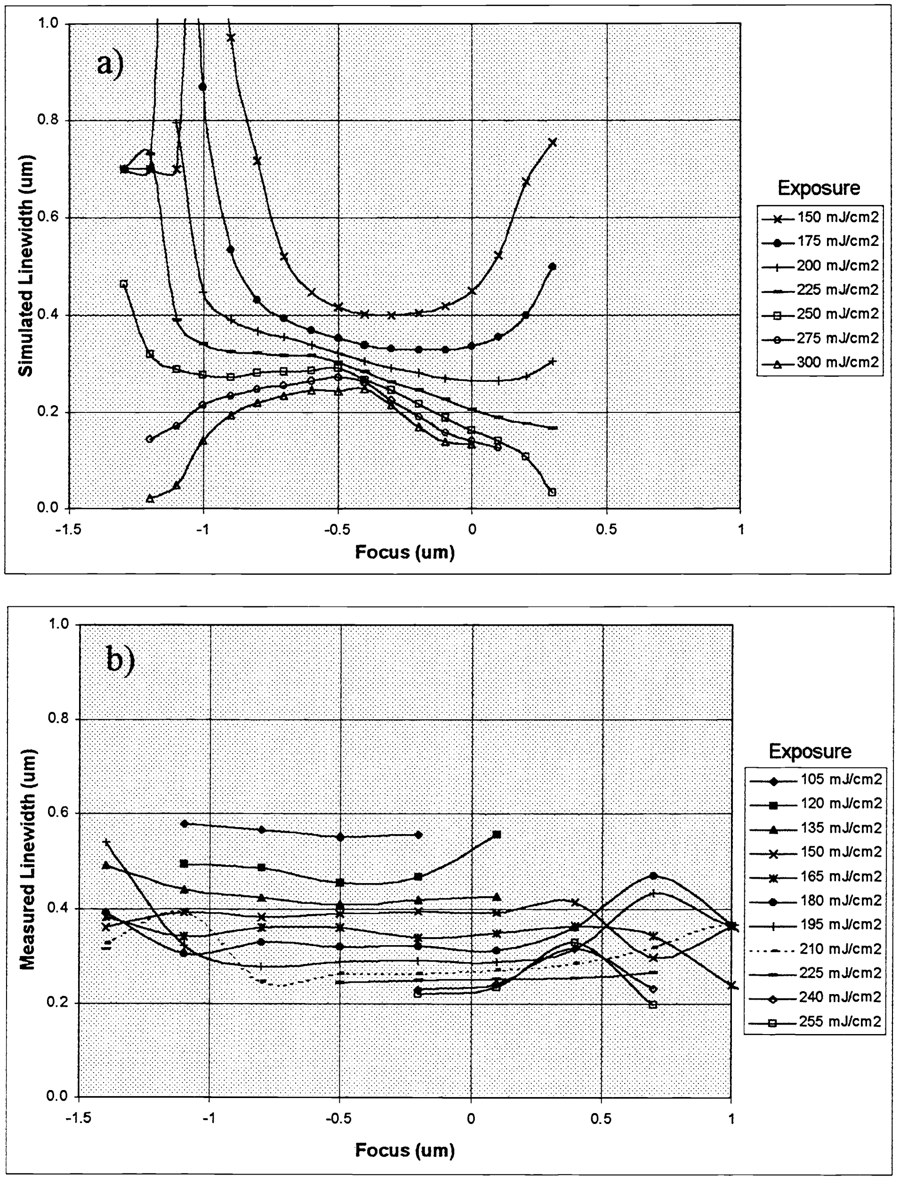

Figure 5-1. Linewidth as a function of focus and exposure for dense 0.35-μm photoresist features as determined by (a) PROLITH/2 simulations and (b) LVSEM measurements.

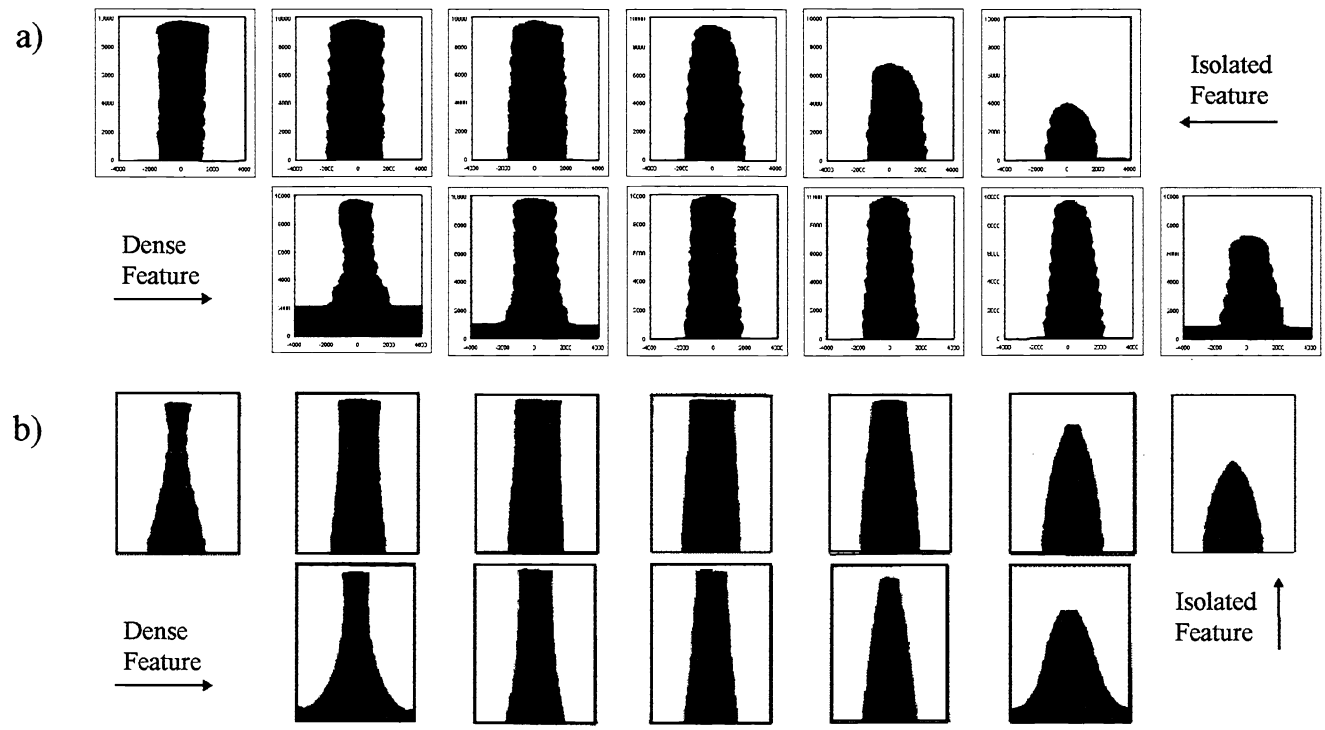

Figure 5-2. Isolated and dense 0.35-μm photoresist feature profiles as a function of focal position (focus increment = 0.3 μm) as found from (a) CD-AFM measurements and (b) PROLITH/2 simulations. The scale of each plot is 1.1 μm in height by 0.8 μm in width.

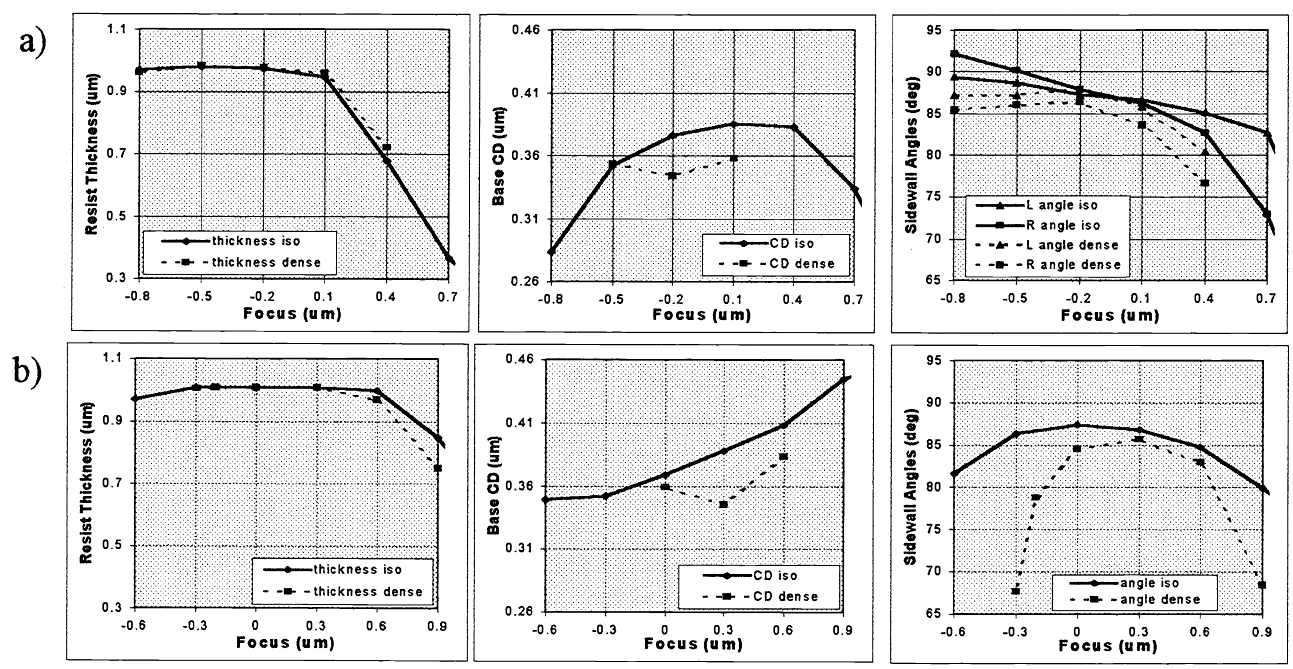

Figure 5-3. Photoresist thickness, base CD, and sidewall angle dependence on focus as found from (a) CD-AFM measurements and (b) PROLITH/2 simulations.