The Challenge of Nanometrology

Michael T. Postek
Nanometer-Scale Metrology
National Institute of Standards and Technology*

ABSTRACT

The promise and challenge of nanotechnology is immense. The National Nanotechnology Initiative provides an opportunity to develop a new technological base for U.S. Industry. *Nano*metrology is the basis of the new measurement methods that must be developed to support the nanotechnology. Nanometrology has played a key role in support for the semiconductor and other U.S. industries already developing products with nanometer-sized dimensions. Nanometrology techniques, standards and infrastructure development are needed to control fabrication and production, ensure product quality, and enable different parts to work effectively together. Size and tolerance are important considerations and require standardization. Metrology is critical to developing a complete understanding of any new phenomenon or process. Only those things that can be measured can be fully understood. Ultimately, this understanding is critical to obtaining the immense economic benefits predicted by the National Nanotechnology Initiative for U. S. industry.

Keywords: National Nanotechnology Initiative, Metrology, Molecular Measuring Machine, Standards, Modeling, Nanometer, Scanning Electron Microscopy, Scanned Probe Microscopy, Proximal Probe, Lithography, Critical Dimension, Interferometry, Traceability

1.0 INTRODUCTION

The promise and challenge of nanotechnology is immense. According to the National Nanotechnology Initiative (NNI),[1] the "essence of nanotechnology is the ability to work at the molecular level, atom-by-atom, to create large structures with fundamentally new molecular organization….nanotechnology is concerned with materials and systems whose structures and components exhibit novel and significantly improved physical, chemical, and biological properties, phenomena, and processes due to their nanoscale size." This can be interpreted a number of different ways depending upon the perspective chosen. Nanotechnology may make possible huge leaps in computing power, vastly stronger yet much lighter materials, improved materials properties, and advances in medical technologies, as well as devices and processes with lower environmental costs due to much lower energy consumption and thus, lower environmental costs. It is thought that the potential technological advances in the nanometer-regime may actually rival the development of the transistor, and many significant breakthroughs may become possible with the parallel development of the necessary infrastructure. The development of metrology for nanotechnology is a challenge, an infrastructural necessity, and an important investment in the future strength of America's economy, industrial base, and scientific leadership. Metrology is the science of measurement, and as used here, ***nanometrology*** involves the development of the techniques, tools and theory to measure those

---

[*] Contribution of the National Institute of Standards and Technology, not subject to copyright

Nanostructure Science, Metrology, and Technology, Martin C. Peckerar, Michael T. Postek, Jr., Editors, Proceedings of SPIE Vol. 4608 (2002) © 2002 SPIE · 0277-786X/02/$15.00

devices to tolerances necessary for them to function properly at the atomic level. Just as the promise of nanofabrication involves atom-by-atom manipulation, ultimately, it may be necessary to measure a manufactured device atom-by-atom.

Nanometrology techniques, standards and infrastructure development are needed to control fabrication and production, ensure product quality, and enable different parts to work effectively together. Size and tolerance are important considerations and require standardization. A truism in the semiconductor industry is that “if you can’t measure it, you can’t make it.” Therefore, metrology is critical to developing a complete understanding of any new phenomenon or process. Only those things that can be measured can be fully understood. Ultimately, understanding the manufacturing process is critical to obtaining the immense economic benefits predicted by the NNI for the U.S. economy.

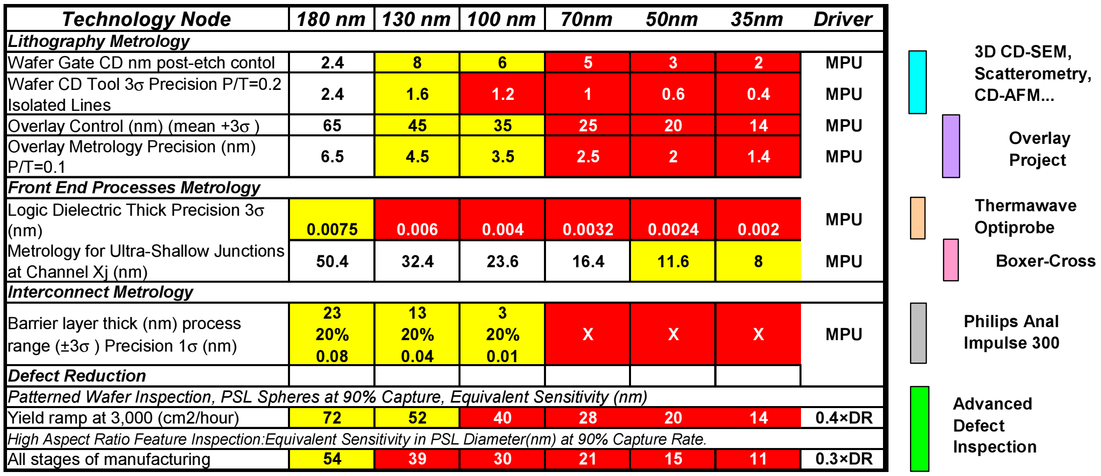
This paper represents a limited overview of nanometrology that was presented at the Nanostructure Science, Metrology and Technology Workshop from the viewpoint of a metrologist. A strong case is presented for the need for the development of nanometrology parallel with any form of nanotechnology. The value of nanometrology is demonstrated by showing the value-added provided to current semiconductor manufacturing where critical structures having nanometer-sized dimensions are already being measured.

2.0 NANOMETROLOGY

The small size and complexity of nanometer-scale structures makes the development of new measurement technologies more challenging than ever. There is a significant need for new metrology and improved measurement instrumentation. Once developed, the instrumentation will require qualification and calibration. New measurement techniques need to be developed at the nanometer-scale and may require new innovations in metrological technology. Accurate measurement techniques and standards need to be developed and physical models for the nanometer-scale structures need to be developed so that theory and experiment relative to the measurement process can be compared. *The understanding of the metrological issues and needs and finding correct solutions is the strength of the scientists at the National Institute of Standards and Technology (NIST).* The achievement of accurate measurements requires a full assessment and understanding of the measurement process. All too often industrial users doing metrology only concern themselves with the goal of obtaining precise (i.e., repeatable) measurements and not accurate measurements. Many in the semiconductor industry have found that, as the device structures shrank, the value of accurate measurements became greater. Hence, because of the minute dimensions involved, success with nanometrology will require an even greater emphasis on the accuracy of the measurement. Metrology will remain a principal enabler for the development and manufacture of many nanotechnology-developed products.

2.1 Semiconductor Industry as a Nanometrology and Nanotechnology Driver. The semiconductor industry, although not meeting the “strict” definition, which was outlined for nanotechnology, is and has been a driver for measurements at the nanometer level for some time. Metrology has been a key enabler for the semiconductor industry and will remain so for future generations of semiconductor devices as long as Moore's Law[2,3] is in effect and as semiconductor structures continue their exponential decrease in size. Nanometrology will become just as key an enabler when the industry moves to molecular electronics. But, the industry is already there in many instances and hence is already developing the basis for nanometrology. Small factors of an atomic dimension are being approached in logic circuits and microprocessors. In the near future, gate lengths of transistors will approach 25 nm or less. Such a gate would be fewer than 5 unit cells or fewer than 20 atomic layers wide. This is truly nanotechnology requiring accurate nanometrology. The ***accuracy*** of the needed metrology is already becoming starkly apparent to many companies.

The strongest push and clearest direction for nanometrology is currently provided by the ever-demanding needs of the semiconductor industry. ***Solving the advanced metrology needs of the semiconductor industry allows rapid application to other industrial sectors as the needs arise***. The International Technology Roadmap for Semiconductors (ITRS)[4] currently directs the semiconductor industry. The ITRS is sponsored by the Semiconductor Industry Association (SIA) in cooperation with the European Electronic Component Association, Electronic Industries Association of Japan, Korea Semiconductor Industry Association and the Taiwan Semiconductor Industry Association. The ITRS is organized by International SEMATECH (ISMT). Figure 1 outlines some of the metrology needs described by the ITRS and demonstrates the applicability of nanometrology to these needs. The Nanometer-scale Metrology Program at NIST is attacking some of those issues that fall within their expertise.[5]



Technology Node	*180 nm*	*130 nm*	*100 nm*	*70nm*	*50nm*	*35nm*	*Driver*
Lithography Metrology							
Wafer Gate CD nm post-etch contol	2.4	8	6	5	3	2	MPU
Wafer CD Tool 3σ Precision P/T=0.2 Isolated Lines	2.4	1.6	1.2	1	0.6	0.4	MPU
Overlay Control (nm) (mean +3σ)	65	45	35	25	20	14	MPU
Overlay Metrology Precision (nm) P/T=0.1	6.5	4.5	3.5	2.5	2	1.4	MPU
Front End Processes Metrology							
Logic Dielectric Thick Precision 3σ (nm)	0.0075	0.006	0.004	0.0032	0.0024	0.002	MPU
Metrology for Ultra-Shallow Junctions at Channel Xj (nm)	50.4	32.4	23.6	16.4	11.6	8	MPU
Interconnect Metrology							
Barrier layer thick (nm) process range (±3σ) Precision 1σ (nm)	23 20% 0.08	13 20% 0.04	3 20% 0.01	X	X	X	MPU
Defect Reduction							
Patterned Wafer Inspection, PSL Spheres at 90% Capture, Equivalent Sensitivity (nm)							
Yield ramp at 3,000 (cm2/hour)	72	52	40	28	20	14	0.4×DR
High Aspect Ratio Feature Inspection:Equivalent Sensitivity in PSL Diameter(nm) at 90% Capture Rate.							
All stages of manufacturing	54	39	30	21	15	11	0.3×DR

Figure 1. A portion of the published ITRS lithography roadmap needs for several device generations. Several of the technology nodes at and below 100 nm currently have no apparent solutions and work is currently being done in nanometrology to find answers to those needs. (Courtesy of ISMT)

2.2 Value of Nanometrology. The semiconductor industry is a $200B dollar industry that has been predicted to grow to $312B by 2003. (The current economic environment may scale that back somewhat.) A huge manufacturer base supports it. With this magnitude, small improvements in yield result in large savings and increased profits to the industry. Historically this has been the case and this industry can be a case study for the future nanotechnology industry. A study of the impacts and outcomes of the use of accurate standards on the semiconductor industry was done when the worldwide photomask sales were about $375 million per year. The use of the accurate NIST linewidth standard was attributed with $30 million in savings to the industry per year.[6] Since that initial study, the 2001 photomask market has grown to an estimated $2 billion.[7] Over the years NIST has introduced a series of more accurate photomask linewidth standards, and a new one is currently being prepared for release.

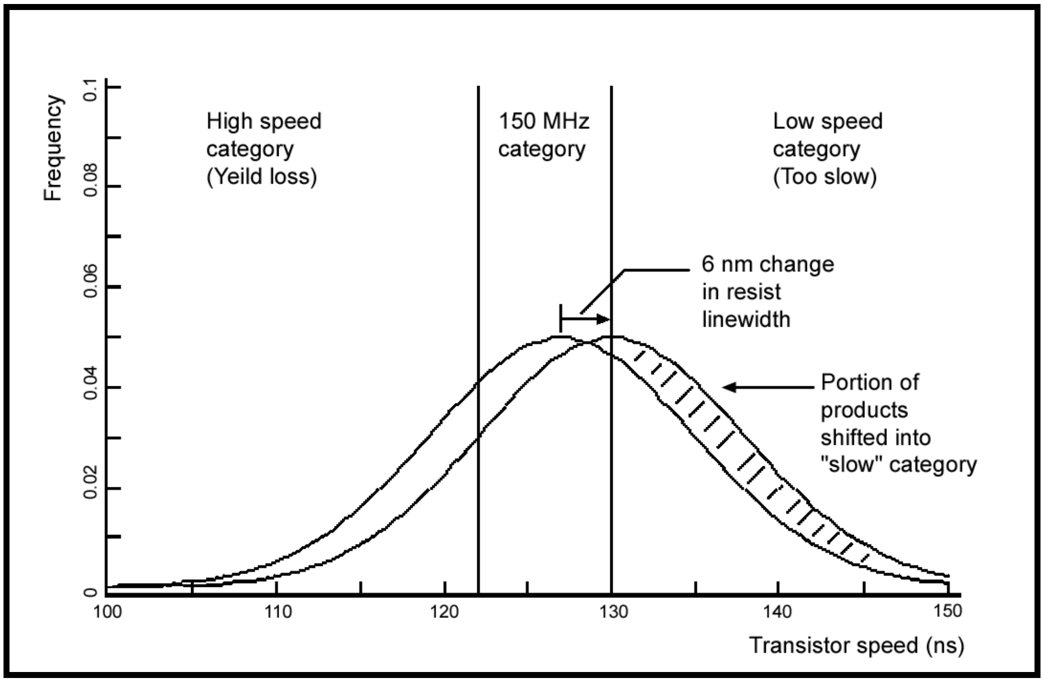


Figure 2. Figure 2. Graphic example of the effect of nanometer control of the manufacturing process and the shift in microprocessor speed, which relates to the overall value of the product. (Courtesy of Bill Banke, IBM).

Another and more interesting example of the value added by nanometrology again comes from the semiconductor industry. As stated above, the goal of Moore's Law is to reduce gate length in order to reduce capacitance, increase microprocessor speed and make more chips on a given wafer. All of these goals have been well documented for the various generations of microprocessors. Figure 2 is a graphical example of speed sorting of devices. This graph shows the effect of maintaining process control through metrology. If the targeted size of the gate is too small, yield loss results, and if it is too large the transistor operates too slowly and a loss in value of the product results. For each 2 nm of shift in manufacturing control, the result is about 1 ns of speed gain or loss.[8] It is clear that the faster the microprocessor operates, the higher the price. Ausschnitt and Lagus (1998) estimated that for 180 nm gates, a 10 nm improvement in the control of the critical dimension leads to an increase of $100 in market value per microprocessor.[9] That being the case, the value of the critical dimension control for that generation of microprocessor "exceeds $10 per nanometer."[9] In 1999, the worldwide PC sales exceeded 113 million units.[10] That means that all things being equal and if these savings could be applied across all of the units, **the value of a nanometer of critical dimension control is about $1 billion**.[11] Even if this amount was only one-tenth of that figure, it still is a lot of money that can be claimed as profit to the industry that would be lost without the controls provided by the metrology. Therefore, attention to metrology does provide a significant economic benefit.

Often this benefit is buried and is not as obvious to the auditors as other assets, but it does ultimately contribute to the bottom line. Through the nanometrology programs at NIST all U.S. industry is being assisted through technology transfer to improve its profitability through the development of new and innovative measurement techniques for a vast array of applications.

3.0 A ROLE OF STANDARDS IN NANOMETROLOGY

Established in 1901, the National Bureau of Standards, now the National Institute of Standards and Technology (NIST)[12] has the mission "to develop and promote measurement, standards and technology to enhance productivity, facilitate trade, and improve the quality of life."[13] Typically, NIST expertise is applied to metrology problems for industry and other scientific interests. NIST carries out its mission through four interwoven programs (www.nist.gov):

- **The NIST Laboratories** provide technical leadership for vital components of the nation's technology infrastructure needed by the budding U.S. nanotechnology industry to continually improve its products and services.
- **The Baldrige National Quality Program** recognizes business performance excellence and quality achievement by U.S. manufacturers, service companies, educational organizations, and health care providers.
- **The Manufacturing Extension Partnership** is a nationwide network of local centers offering technical and business assistance to smaller manufacturers.
- **The Advanced Technology Program** accelerates the development of innovative technologies for broad national benefit through R&D partnerships with the private sector.

All four of these programs work together to achieve success in the development of metrology techniques, standards and infrastructure for all forms of metrology including nanotechnology. As the National Measurement Institute (NMI) for the United States, it is the role of NIST to develop the necessary metrology for nanotechnology. Where Metrology is concerned, there are three general concepts directly related to the success of nanometrology that must be considered. These three concepts are: accuracy, traceability and uncertainty.

3.1 Accuracy. No measurement is perfectly "accurate." Accuracy and reproducibility (precision) of measurements are distinct concepts.[14,15] Accuracy of a measurement is defined as:

> "Closeness of the agreement between the result of a measurement and a true value of the measurand" *(International Organization for Standardization, 1993).*[16]

Researchers and process engineers want accurate dimensional measurements, but accuracy is an elusive concept that everyone would like to deal with simply by calibrating their measurement system using a standard developed and certified at NIST. Unfortunately, it is not always easy either for NIST to calibrate nanometer-sized standards or for the engineer to correctly use standards in calibrating instruments. *Much of the work done at NIST is involved in the basic research associated with both of these issues and is the basis for the need for the investment in development of infrastructural nanometrology.* Furthermore, it is often difficult for NIST to have state-of-the-art standard artifacts fabricated acceptably. For many types of artifacts fabrication is better accomplished elsewhere. Industrial support is critical.

3.2 Traceability. The National Institute of Standards and Technology provides the U.S. industry with traceability to the International System of Units, universally abbreviated SI.[17,18] The SI is the modern metric system of measurement that is becoming the dominant measurement system used in international commerce. Traceability ensures the accuracy and precision of measurements used in the nanometer-scale characterization and is assured by NIST through scientific research and development, standards, calibration sources and infrastructural metrology. Traceability ensures that measurements are accurate representations of the specific quantity being measured. Further, to prevent future barriers to international trade standards must be harmonized. This is the job of the National Measurement Institutes (NMI) such as NIST and similar institutes in other countries and is accomplished with coordinated intercomparisons and round robin measurements. Traceability is a desired feature for any standard. The definition of traceability is:

> *"The property of a result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an* ***unbroken chain*** *of comparisons all having stated uncertainties" (International Organization for Standardization, 1993).*[14]

Traceability is a way of approaching the concept of "accurate" measurements in actual practice. A measurement could, in principle be very reproducible but, also very inaccurate. Measurement reproducibility is a necessary but not sufficient condition for accuracy. What is needed in addition to reproducibility is some tie to the "true value" as defined for accuracy. Traceability to a NIST standard through an unbroken chain of comparisons with each measurement accompanied by a statement of uncertainty is one way of achieving this. For example, at NIST, the most convenient way to achieve traceability for *length* measurements is through using laser interferometry. Laser interferometry provides a tie to the meter. The meter is internationally defined as "the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second." This definition has the effect of fixing the speed of light, c, to 299,792,458 m/s. Once the frequency, f, is measured, the wavelength is readily determined. The uncertainty of frequency determination is negligible for these purposes owing to the high accuracy with which time can be measured using atomic clocks. Because the wavelength is typically measured in air while the meter is defined for the vacuum, corrections (where applicable) must be applied which account for the actual index of refraction in air. These corrections, too, are known with small uncertainty compared to the remaining steps in the traceability paths.

3.1.3 Uncertainty. Uncertainty is an additional concept that measures how close to the "accurate" value an experimental result lies or said another way the "doubt about the validity of the result of a measurement."[19] The definition of uncertainty is:

> *"Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand" (International Organization for Standardization, 1993)."*[14]

Clearly, NIST cannot make or have made perfect standards and thus there is always some non-reproducibility error in the measurement. There is also some error in relating its calibration measurements back to the "true value" which must be considered. The combination of these errors is called uncertainty. In a critical dimension or linewidth correlation study[20] an uncertainty budget was developed according to NIST guidelines,[21] which listed the major components contributing to the measurement uncertainty for three metrology instruments commonly used in nanometer scale metrology in semiconductor production (i.e., scanning electron microscope metrology, atomic force microscope metrology and electrical metrology). This study provided some very revealing information regarding these measurement techniques. Thus, by carefully determining and listing the components making up the measurement uncertainty budget provides a tool for understanding the measurement process and the determination of opportunities for improving the measurement process and thus its accuracy.

In order to complete the traceability chain, it is appropriate and convenient for metrologists to calculate and state an uncertainty of their measurements with respect to an NMI. The NMI is required to demonstrate traceability to the SI system of units maintained by the Bureau International des Poids et Measures.[22] One thing that is important to remember about traceability is that it is often a legal or contractual requirement.

4.0 NIST LABORATORY PROJECTS IN NANOMETROLOGY

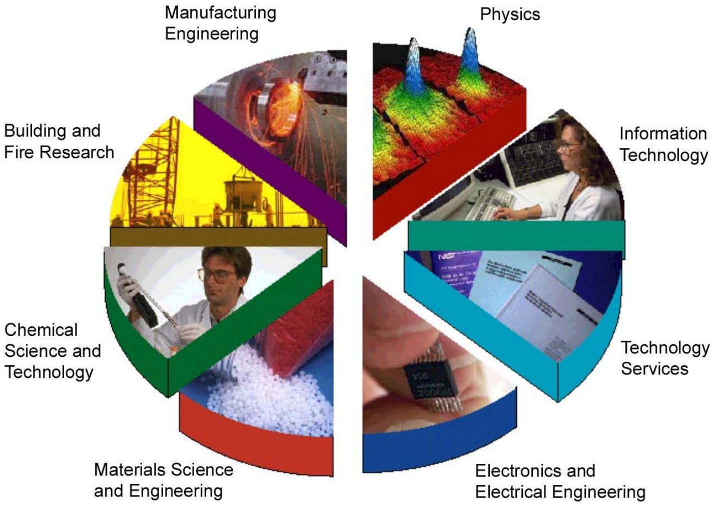


Figure 3. Laboratories at NIST

There are eight laboratories at NIST as shown in Figure 3. Within those laboratories are numerous research projects that support nanotechnology and nanometrology. Each of these projects presents an opportunity for nanometrology research collaboration between NIST, industry and universities. Space in this presentation does not permit a full review of all of these programs and projects. But, it is possible to define a snapshot of only a small portion of this work.

4.1 Molecular Manipulation and Nanometrology. Control of atom deposition is one type of molecular manipulation. A project within the Physics Laboratory attempts to control chromium atoms that are "steered" into position to form a grating. The laser-focused-atom-deposited chromium grating is a line grating that is made by depositing neutral chromium atoms on a suitable substrate such as a silicon wafer by the use of a standing wave of high-intensity laser radiation, tuned near an atomic absorption line. The atoms interact with the radiation field and are focused into lines at the node spacing of the light. This technique for making chromium gratings was developed by McClelland, *et al.* [23] at NIST and may be valuable for other forms of nanotechnology, as well.

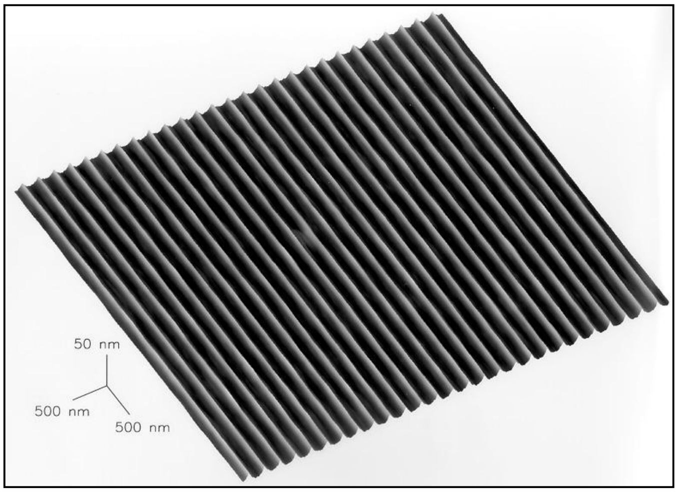


Figure 4. Molecular measuring machine image of a 6 µm by 5 µm area of a laser-focused atomic-deposition Cr grating specimen. (Image courtesy of John Kramar)

The chromium deposition takes place in a vacuum, so the node spacing is expected to be directly related to the laser frequency, which is accurately known. Collaboratively, with the Manufacturing Engineering Laboratory this grating has been measured using the Molecular Measuring Machine (M^3). [24,25] This research is currently in progress. Figure 4 shows an image of the grating. The calculated line spacing of the specimen is 212.78 nm with a preliminary expanded uncertainty of 0.02 nm, coverage factor, k, of 2. A full description including an uncertainty estimate for M^3 as related to this work is found in Kramar et al. (1999). [24]

4.2 Atom-Based Standards. An atom-based standard relies upon the concept that the structures have dimensions based on an intrinsic property of the material such as an integral number of atomic planes. This is a project within the Manufacturing Engineering Laboratory and the development of atom-based artifacts for step-height, linewidth, and pitch are currently in progress. The atom-based metrology effort is focusing on developing artifacts which can be atom counted and then measured in a number of different metrology tools such as the scanning electron and atomic force microscopes. The integrity of the line geometry, such as sidewall angle, is crucial to having useful artifacts for linewidth specimens. These edge geometry requirements are not as stringent for the magnification standards since feature symmetry is the most crucial element in these measurements. This work utilizes existing *in-situ* processing apparatus and techniques from an ultra-high vacuum scanning tunneling microscope and concentrates on the reproducible production of atomically ordered silicon (Si) surfaces and Si (111) step and terrace structures.

In addition to manufacturing the atom-based artifacts, the first direct measurement of the surface atom spacing has been done using a traceable interferometer.[26] This has been accomplished by fitting the instrument with a high accuracy sub-angstrom resolution interferometer and the first atomic resolution measurements with full interferometer length basis have been accomplished.[26] The successful completion of this aspect has enabled direct distance determination with simple atomic counting; in effect verifying the intrinsic ruler accuracy.[27]

4.3 Attogram Analysis of Nanometer Structures. The chemical constituents of fabricated nanostructures need to be identified accurately and this presents new analytical challenges.[28] Electron beam excited analytical methods for chemical microanalysis typically rely upon either energy dispersive (EDX) or wavelength dispersive (WDX) x-ray microanalysis systems.[29] Each of these methods has its own advantages and disadvantages for analysis of nanostructures. The major issue is that the electron beam, as it scans the nanostructure, enters into that structure a defined amount based upon the component material present and the accelerating voltage applied. The electron beam penetration in a photoresist sample on silicon is shown in Figure 5. In a more dense material such as barium titanate ($BaTiO_3$) the electron beam penetration would be less. When $BaTiO_3$ is irradiated by a 20 keV electron beam, the beam enters into that material to a depth of about 2.1 micrometers where it can generate X-rays from deep within the sample. Thus, subsurface information is obtained. The electron beam penetration depth can be restricted to about 50 nm in $BaTiO_3$ by dropping the accelerating voltage to 2.5 keV. At this low accelerating voltage, the volume excited by the electron beam that generates about 90% of the x-rays is about 12,000 nm^3, which represents about 72 attograms of material.[30] Standard energy dispersive X-ray microanalysis, as shown in Figure 6, cannot resolve many of the X-ray lines because of the low inherent X-ray count rate and

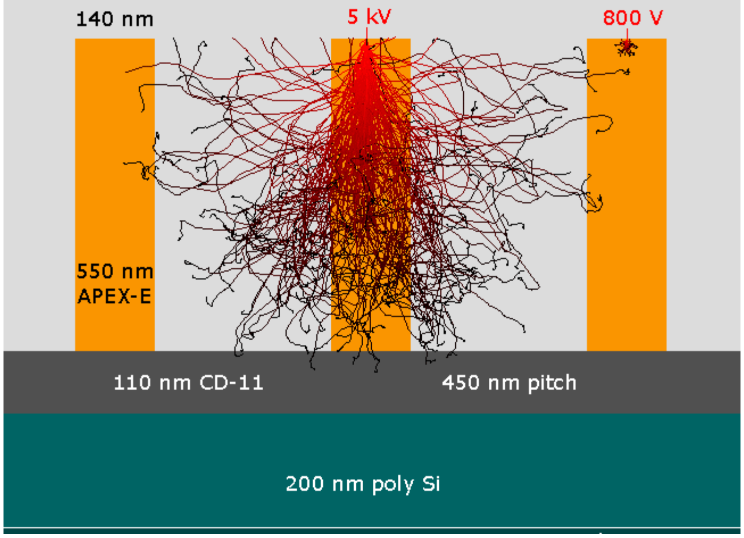


Figure 5. Graphic example of the modeled penetration of an electron beam in bulk photoresist on silicon at two accelerating voltages. Note the difference in electron scattering and the depth of penetration between the higher accelerating voltage (5 kV) and the lower accelerating voltage (800V). (Courtesy of Andras Vladar, NIST)

resolution at the low energy end of the X-ray spectrum where the elements of interest are located. A new methodology based on collaborative work between the NIST Electronics and Electrical Engineering Laboratory and the Chemical Science and Technology Laboratory developed a high resolution microcalorimeter energy dispersive x-ray detection system capable of analyzing the lighter elements with resolution rivaling the wavelength dispersive X-ray microanalysis system.[31,32] Figure 6 is an example of a comparison of spectra from the microcalorimeter and the standard energy dispersive X-ray microanalysis systems.

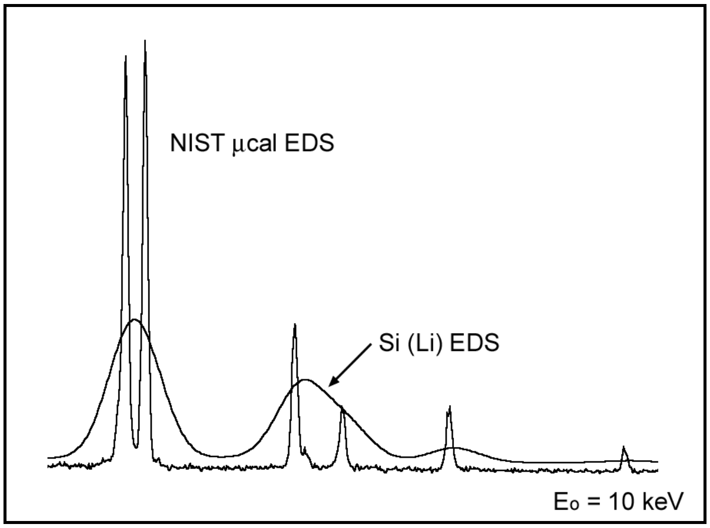


Figure 6. Comparison of spectra of barium titanate obtained from the standard energy dispersive X-ray microanalysis system and the NIST microcalorimeter both at 10 keV accelerating voltage showing the improved resolution provided by the microcalorimeter (Courtesy of Dale Newbury, NIST)

4.4 Accurate Nanometrology with Scanning Electron Microscopy. The most common high resolution-imaging tool in semiconductor metrology is the scanning electron microscope.[33] It is expected that this tool will be an integral component of future nanometrology. Currently, this instrument is imaging and measuring nanometer-sized structures daily. The scanning electron microscope is used in applications from on-line critical dimension metrology to off-line particle analysis, cross-section analysis and a host of other applications. As a metrology tool the scanning electron microscope is highly precise, but is not yet accurate for the measurement of the width of structures and particles.[32] The achievement of accuracy requires an intimate understanding of the measurement instrumentation, how signals are generated, collected and measured. Further, understanding all the measurement processes occurring within the instrument (manufacturers often consider the instrument electronics characteristics and algorithms to be proprietary), coupled to an accurate model that has been verified with experiment is critical. In addition the model should be as universal as possible since many different materials at the nanometer-scale are being investigated in that instrument. A great deal of research within the Manufacturing Engineering Laboratory in collaboration with the Electronics and Electrical Engineering Laboratory has been done to achieve accurate length metrology with the scanning electron microscope. An SEM image can be considered to be a "distorted" representation of the feature. It is a 2 dimensional intensity pattern derived from the interaction of an electron beam with a 3 dimensional object. Since it is not possible to intimately understand each particular instrument design and its effect on that image, the concept of model-based metrology is appealing as a path to accuracy.[34] The method works by comparing the measured image of a feature to a library of calculated images for similar features, each differing slightly in size or shape. The images in the library correspond to a range of possibilities and may be interpolated for better resolution. The experimental image obtained in the scanning electron microscope is then compared to the computed image and the closest match is deemed to be the shape of the feature that produced the measured image. Currently work is in progress to verify this concept. However initial results, as shown in Figure 7, are very encouraging.

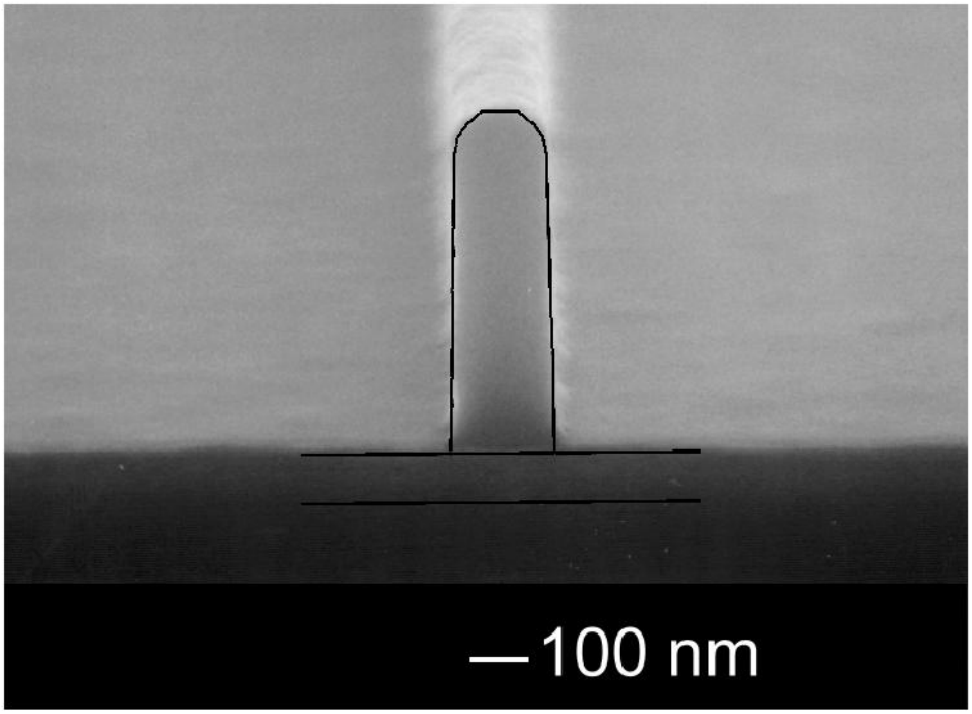


Figure 7. Scanning electron micrograph of a cross-sectioned photoresist line. Superimposed upon the line is a modeled expectation of the line as viewed in top down view. Note the good agreement between the modeled and experimental views of the line. (Courtesy of Andras Vladar, NIST)

4.5 Molecular Electronics. A new components technology is necessary in order to maintain the uninterrupted succession of smaller and faster microelectronics devices. Moore's Law is expected to eventually run-out and potentially a new nanotechnology utilizing molecules to perform the function electronic components may become possible. There have been some recent advances and positive results in this area. The NIST Chemical Science and Technology Laboratory and Electronics and Electrical Engineering Laboratory have begun competence programs to develop measurement tools and information infrastructure necessary to predict, measure, and control the flow of charge through molecules and assemblies of molecules.

5.0 CONCLUSION

Nanotechnology is the future of U.S. manufacturing. One key enabler to the success of nanotechnology will be nanometrology just as it has been a key enabler for the semiconductor industry. Metrology has clearly demonstrated its value to semiconductor production and if nanotechnology considers profits to be a goal then metrology must be a part of the equation. There are many diverse activities in nanotechnology and perhaps some focus is appropriate. One valuable lesson that the budding nanotechnology industry can glean from the example of the semiconductor industry is the development of an industry roadmap. The International Technology Roadmap for Semiconductors has provided targeted goals and provided a direction to the industry and equipment manufacturers. It may be valuable for the nanotechnology movement to develop a similar road mapping targeting a few critical products. Progress in obtaining these goals will provide impetus to the entire program.

6.0 ACKNOWLEDGEMENTS

The author would like to thank John Villarrubia, Andras Vladar and Robert Larrabee for critical review of this manuscript and the following for their invaluable assistance during the preparation of this presentation: Chad Snyder (NIST Program Office); John Kramar, John Villarrubia, Richard Silver, Andras Vladar, John Dagata, Ted Vorburger and Ron Dixson (Manufacturing Engineering Laboratory); Dale Newbury and Roger Van Zee, Chemical Science and Technology Laboratory); Robert Shull (Materials Science and Engineering Laboratory); Robert Celotta (Physics Laboratory); Piedong Yang (U.C. Berkeley). The author would also like to thank Steven Knight and Jack Martinez of the NIST Office of Microelectronics Programs and Marylyn Bennett and Hal Bogardus of International SEMATECH for their partial funding for this work.

7.0 REFERENCES

---

1. Subcommittee on Nanoscience, Engineering and Technology. 2000. National Technology Initiative. The Initiative and its Implementation Plan. (http://www.nano.gov).
2. Moore, G. E. 1995. Lithography and the future of Moore’s Law. Proceedings SPIE Microlithography 2439: 2-17.
3. Moore, G. E. 1965. Cramming more components onto integrated circuits. Electronics 4:114-117.
4. Semiconductor Industry Association. 1999. The International Technology Roadmap for Semiconductors. SIA, San Jose, CA.
5. Postek, M. T. 2001.Nanometer-Scale Metrology: Meeting the Nanotechnology Measurement Challenges. This volume.
6. Baum, M. 1987. Life on the edge: Measuring Linewidths. NBS Research Reports. Special Publication 733: 15-18.
7. Marylyn Bennett, International SEMATECH, Personal communication.
8. G. W. Banke, IBM presentation at this Workshop.
9. Ausschnitt, C. P and Lagus, M. E. 1998. Seeing the forest for the trees: a new approach to CD control. SPIE 3332: 212-220.
10. International Data Corp.
11. John Villarrubia, NIST. Personal Communication.

---

12. Omnibus Trade and Competiveness Act of 1988
13. http://www.nist.gov/public_affairs/general2.htm
14. Larrabee, R. D. and Postek, M. T. 1993. Parameters characterizing a critical dimension measurement. SPIE Critical Review CR52 pg. 2-25.
15. Larrabee, R. D. and Postek, M. T. 1993. Precision, accuracy, uncertainty and traceability and their application to submicrometer dimensional metrology. Solid-State Elec. 36(5):673-684.
16. International Organization for Standardization (ISO). 1993. International Vocabulary of Basic and General Terms in Metrology second edition.
17. Taylor, B. N. 2001. The International System of Units (SI). NIST Special Publication 330, 2001 Edition.
18. Traceability – NIST policy and supplementary materials. (www.nist.gov/traceability)
19. International Organization for Standardization (ISO). 1993. Guide to the Expression of Uncertainty.
20. Villarrubia J. S., Dixson R., Jones S., Lowney J. R., Postek M. T., Allen R. A., and Cresswell. 1999. Inter-comparison of SEM, AFM, and Electrical Linewidths. Proceedings of SPIE Vol. 3677, pp. 587-598 (1999).
21. Taylor, B. and Kuyatt, C. 1994. Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. NIST Technical Note 1297.
22. Bureau International des Poids et Measures (BIPM). 1983 17th Conférence Générale des Poids et Mesures, (1983), Resolution 1. http://www.bipm.fr
23. McClelland, J. J. Scholten, R. E., Palm, E. C, and Celotta, R. J. 1993.Laser Focused Atomic Deposition. *Science*, 262:877-880.
24. E. Clayton Teague, "The National Institute of Standards and Technology molecular measuring machine project: Metrology and precision engineering design," *J. Vac. Sci. Technol.* ***B*** **7**(6), pp. 1898-1902, 1989.
25. Kramar, J., Amatucci, E., Gilsinn, D., Jun, J., Penzes, W. Scire, F., Teague, E. C., Villarrubia, J. 1999. Toward nanometer accuracy measurements. Proceedings SPIE 3677: 1017-1028.
26. R. M. Silver, S. Gonda, C. Jensen, and L. Howard, "A New Tunable Diode Laser Method for sub-nanometer Resolution Interferometry" (in preparation).
27. Gonda, S., Zhou, H., Fu, J., and Silver, R. 2001. A new design and uncertainty budget for a metrology UHV-STM used in direct measurements of atom spacings. (this volume)
28. Newbury, D. E. 1990. Microanalysis to nanoanalysis: measuring composition at high spatial resolution. Nanotechnology 1: 103-130.
29. Postek, M. T., Howard, K.S., Johnson, A.J., and McMichael, K. 1980. Scanning Electron Microscopy - A Student Handbook. Ladd Research Industries, 305 pp.
30. Dale Newbury, personal communication.
31. Wollman, D. A., Irwin, K. D. , Hilton, G. C., Dulcie, L. L. , Newbury, D. E. and Martinis, J. M. 1997. High-resolution, energy dispersive microcalorimeter spectrometer for x-ray microanalysis. J. Microsc 188:196-223.
32. Newbury, D., Wollman, D., Irwin, K., Hilton, G. and Martinis, J. 1999. Lowering the limit of detection in high spatial resolution electron beam microanalysis with the microcalorimeter energy dispersive x-ray spectrometer. Ultramicroscopy 78:73-88.
33. Postek, M. T. and Vladar, A. E. 2001. Critical-dimension Metrology and the Scanning Electron Microscope. In: Handbook of Silicon Semiconductor Metrology (Diebold, ed.) 295-333.
34. Villarrubia, J.S., Vladar, A. E., Lowney, J. R. and Postek, M. T. 2001. Edge determination for polysilicon lines on gate oxide. Proceedings SPIE 4344:147-156.