Submicrometer Linewidth Metrology

In 1987, the semiconductor industry was undergoing a technological transition into the submicrometer range of device dimensions. Small dimensions that are very important to device performance or yield are called critical dimensions (CD). Optical metrology technology was adequate to measure the critical dimensions above 1 μm, but as these dimensions shrunk into the submicrometer regime, the industry felt that the development of a new technology would be necessary. Scanning electron microscopy began to be employed as the new "tool" to measure submicrometer structures. In an effort to assist the industry in this transition, two papers were published in the same issue of the NBS *Journal of Research* summarizing the knowledge on optical metrology at that time. These papers discussed the capabilities for extension into the submicrometer regime and reported on the promising scanning electron microscopy and its potential to take over from optical metrology. The two pioneering review papers, *Submicrometer Linewidth Metrology in the Optical Microscope* [1] by Diana Nyyssonen and Robert Larrabee, and *Submicrometer Microelectronics Dimensional Metrology: Scanning Electron Microscopy* [2] by Michael T. Postek and David C. Joy, helped to reorient the metrology direction of the semiconductor industry, with impacts being felt even today.

By the year 1987 optical microscopes had been used for looking at small things for several centuries and had been optimized for this purpose. However, they were not optimized for accurate dimensional metrology in the submicrometer regime. Scanning electron microscopes had also been used for looking at small things, but only for decades instead of centuries. They also were not optimized for submicrometer dimensional metrology. Accurate measurements of submicrometer dimensions in both kinds of microscopes were more difficult to make and interpret than was generally recognized at that time.

These two back-to-back papers [1,2] served to clarify a number of misconceptions by those in industry who were actually manufacturing the microscopes or using them to make critical submicrometer dimensional measurements. Both papers were aimed directly at submicrometer measurements for quality control purposes in the semiconductor and magnetic-storage tape-head industries. An unusually large number of requests for reprints were received from readers in the United States, and the oral feedback revealed that the papers were extensively faxed between colleagues in foreign countries. It is impossible to document the savings to industry due to the resulting improvements in quality control attributable to these papers because quality control information is often considered proprietary. Anecdotal feedback at subsequent technical meetings and during the authors' visits to industry clearly indicated that material in the papers was important and that the savings were substantial.

As the dimensions of interest continued to shrink in the years following publication, these papers helped set the stage: 1) for the improvements in the basic instrumentation used for optical and SEM metrology, 2) for the motivation to develop theoretical models for interpretation of such measurements, and 3) for the more intelligent use of the resulting measurement data. The information in these papers is still relevant to submicrometer metrology even though much progress has occurred since their publication. They should still provide useful background information on micrometer and submicrometer measurements for new metrologists and for new, or more demanding, applications in the new millennium (e.g., for linewidth and overlay measurements in the semiconductor industry and for critical dimensions in tape-head, microfabrication, micromachining industries).

The submicrometer optical metrology paper [1] assessed the capabilities and limitations of optical submicrometer dimensional metrology and how well it would be able to meet the measurement needs of future semiconductor processing technologies (e.g., linewidth measurements). The fact that the wavelength of the commonly used visible light in the optical measuring tools was comparable to the feature sizes of interest led to serious limitations. The paper discussed the need to model mathematically the effects of diffraction in the image and thereby develop a meaningful criterion for deciding which point on the image corresponds to the edge of the feature whose dimensions were being measured. Nyyssonen and Kirk developed such a model [4] and Nyyssonen used that model for the calibration of NIST's first photomask linewidth standards [5]. The modeling (and the measurement) is much more difficult for opaque specimens (e.g., silicon wafers) and becomes increasingly difficult as the feature heights become larger than about a quarter wavelength and as the aspect ratio (feature-height/width) approaches unity. These factors, plus the non-vertical edge shapes of the features, severely compromised the accuracy of dimensional measurements in the submicrometer regime.

The general problem of optical linewidth metrology was discussed with emphasis on: 1) definition of linewidth for non-ideal features, 2) precision and accuracy (now referred to as Type 1 and Type 2 errors), 3) effects of measurement errors on process control, 4) instrument design, 5) resolution of the measuring microscope, 6) optical-based linewidth standards, and 7) alternative linewidth measurement techniques. The factors affecting measurements of small feature dimensions were discussed and illustrated by calculated image waveforms for a typical patterned polysilicon line on a silicon dioxide layer upon a silicon substrate. In these calculations the waveform changed as the silicon dioxide layer thickness was varied and the edge geometry of the line deviated from vertical. In addition, the different kinds of microscopes used in optical metrology were discussed and illustrative image profiles under various illumination conditions were presented.

Perhaps the main message of this paper was that submicrometer optical metrology was more difficult than commonly envisioned at the time and that many factors came into play that were often overlooked, ignored, or inadequately treated in practical applications. With the ongoing impetus of the semiconductor industry toward ever-smaller submicrometer dimensions at that time, this attitude had to change if the anticipated future needs for decreased measurement uncertainty and increased accuracy were to be met. This paper helped set the stage for the change that did, in fact, occur.

The scanning electron microscope used in low accelerating voltage mode was initially felt to be the panacea for the problems encountered by optical submicrometer metrology. The paper by Postek and Joy [2] demonstrated that, although the SEM was capable of precise measurements, accuracy was another issue altogether. It also pointed out a number of pitfalls associated with the instrument, making use of a simple micrograph of a dime (Fig. 2). This micrograph drove home the point that just because an image came from an SEM did not mean that it was an accurate representation. As important as it was to understanding the instrumental problems, this paper also pointed out that the main limitation of the SEM for accurate submicrometer metrology is the electron beam/sample interaction, which affects the generation and collection of the measured signals. This was the first paper to stress the need for understanding the electron beam/sample interaction as a requirement for accurate metrology with the SEM.

Following the publication of this paper, a heightened awareness of the issues associated with SEM metrology prompted significant improvements in the instrumenta-

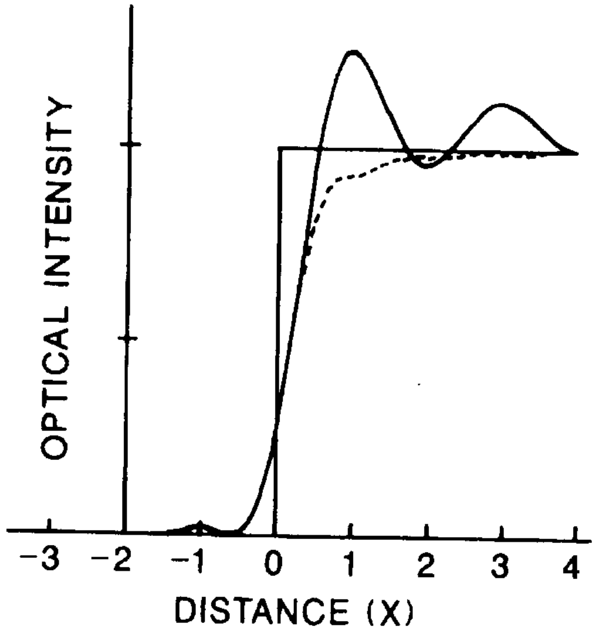

Fig. 1. Comparison of calculated image profiles of the edge of an opaque vertical-wall small-height (e.g., photomask) line. The ordinate is relative transmitted light intensity and the abscissa is the distance from the edge of the line in micrometers. The step-function rise to full transmission shown by the straight lines in the figure represents what one would ideally expect. The bright-field image (solid curve) and the confocal image (dashed curve) show that the edge is not located at the point of 50 % of full transmission.

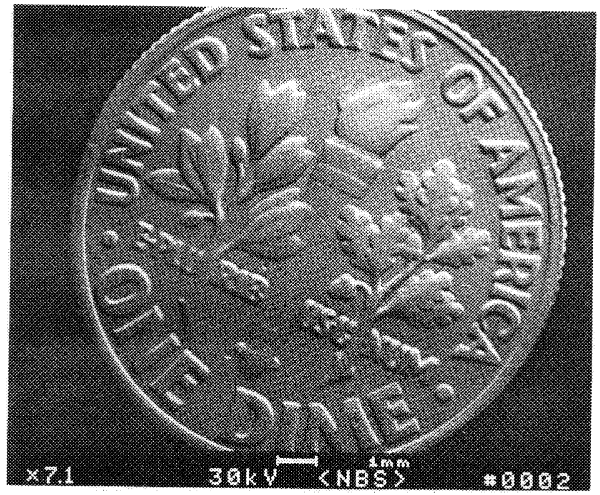

Fig. 2. Scanning electron micrograph of a dime. This image and the discussion in the original paper clearly demonstrated to the reader that one cannot assume that just because the micrograph was taken with an SEM and that the magnification and linescale are displayed that they are accurate. The proper magnification should be 4.6x. This simple demonstration showed that the read-out of the commercial SEM should not necessarily be trusted at face value and thus led many users to scrutinize their SEM measurements more carefully, setting the stage for many new improvements in SEM metrology.

tion as described in later publications [7,10]. Today, fully automated CD-SEM instruments are routinely be ing utilized in semiconductor production applications throughout the world.

Diana N. Nyyssonen joined NBS as a physicist in 1969 and quickly developed the first photomask linewidth standards. Her work at NBS showed how optical image simulation modeling could be used as a tool for applying optical microscopes in submicrometer metrology and, by so doing, exceed the classical resolution limits of imaging microscopes. She won the Department of Commerce Silver Metal for her work in this area. In 1985, she left NBS to form her own R&D company specializing in optical dimensional metrology. She later joined IBM Corporation and specialized in scanning probe microscopes.

Robert D. Larrabee joined NBS in 1976 as a physicist specializing in the electrical characterization of bulk silicon. In 1985 he became the Group Leader of the Microelectronics Dimensional Metrology Group, replacing Diana Nyyssonen. Under his leadership, the group continued the existing photomask linewidth projects and initiated new SEM metrology programs with Michael Postek and other members of his group [3]. He held the position of Group Leader until his retirement in 1994. In 1999 he participated in the award of the Department of Commerce Bronze metal Team Award for his post-retirement work in developing a new optical overlay metrology tool and a novel standard for use in its alignment.

David C. Joy is currently a Distinguished Scientist, Director of the EM Facility, and Professor at the University of Tennessee. He also holds a joint appointment with Oak Ridge National Laboratory, where he is a member of the Staff in the Materials and Ceramics Division. Since publication of the subject paper, he has contributed to the improvements in SEM and SEM modeling. He has recently published two books, *Monte Carlo Modeling for Microscopy and Microanalysis and Semiconductor Characterization by Scanning Electron Microscopy.* He has contributed to the evolution of the scanning electron microscope as a viable production tool through his research in low accelerating voltage electron microscopy, modeling, electron holography, and nano-tip development.

Michael T. Postek is currently the Leader of the Nano-scale Metrology Group at NIST. Since this paper appeared, he has worked closely with International SEMATECH and its member companies in the development of scanning electron microscopy as a tool for semiconductor production. He has been awarded a 1998 R&D 100 award for the development of SEM Monitor (a tool used to test the performance level of automated production SEMs) and two Department of Commerce Silver Medals for his work in metrology with the scanning electron microscope. He is currently completing development of an accurate low accelerating voltage SEM magnification standard (SRM 2090), a sharpness standard RM 8091, and a production-critical SEM width standard.

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