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Scanning Electron Microscope-based Metrological Electron Microscope System and New Prototype Scanning Electron Microscope Magnification Standard

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Abstract

A metrological electron microscope has been developed at the National Institute of Standards and Technology (NIST) traceable to national standards of length, and a new prototype magnification standard meeting the current needs of the scanning electron microscope (SEM) user community has been fabricated. This metrology instrument is designed to certify standards for the calibration of the magnification of the SEM and for the certification of artifacts for linewidth measurement done in the SEM. The artifacts will be useful for various applications in which the SEM is currently being used. The SEM-based metrology system is now operational at the Institute, and its design criteria and the progress on the characterization of the instrument are presented. The design and criteria for the new lithographically produced SEM low accelerating voltage magnification standard to be calibrated on this system are also discussed.

Certain commercial equipment is identified in this report in order to adequately describe the experimental procedure. Such identification does not imply recommendations or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best available for the purpose.

Key Words: Dimensional Standards, Scanning Electron Microscope, Magnification Standard, Dimensional Metrology, Metrology Stage, Standard Reference Materials

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Introduction

The National Institute of Standards and Technology has had a continuing effort for over a decade to develop feature-size measurement techniques and the associated dimensional standards for the optical microscope (OM). More recently, work began on a scanning electron microscope (SEM) feature-size measurement program specifically aimed at the development and certification of SEM magnification and linewidth standards and the associated techniques for their calibration and use. This program has three distinct tasks that have undergone simultaneous development (Postek et al., 1987a). These tasks are: (1) the development of an electron-beam metrology microscope to satisfy specific metrology requirements for certification of submicrometer dimensional standards, (2) the construction and certification of the actual micrometer and submicrometer magnification and feature-size standards and (3) the development of the computer models necessary to predict the accurate location of the edge of feature-size standards on image profiles obtained from the metrology SEM. In 1985, the initial phase of the development of an SEM-based metrological microscope was reported (Nyyssonen and Postek, 1985). Since then, progress has been made and the instrument is now functional and is undergoing evaluation. Furthermore, a prototype magnification standard has been fabricated. This presentation outlines some of the instrument design considerations, progress on instrument characterization and criteria for the development of the magnification standard.

The Instrument

The basis for the metrology microscope is a standard commercial scanning electron microscope (equipped with a lanthanum hexaboride electron gun) which has been modified to meet the specific needs of standards calibration. The initial criteria and the constraints imposed on an electron beam metrology instrument have been discussed previously (Nyyssonen and Postek, 1985). The basic principles of operation of

this instrument are similar to those of the optical certification instrument used to certify the NIST photomask Standard Reference Materials SRMs 473, 474, 475, 476 (Bullis and Nyyssonen, 1982) and the present electron-beam metrology instrument used to certify the NIST SEM Magnification standard SRM 484 (Hembree, 1986).

Instrument Operation

The metrology instrument can operate in either of two modes of operation. The first is the standard SEM mode which is used for inspection, location and alignment of the lines to be measured. The second mode is the measurement mode of operation. In this mode, the sample area to be measured is visually positioned using the raster scan, then the electron beam of the metrology instrument is "fixed" in position by going into spot mode. The electron beam acts as the reference point for the measurement. The philosophy behind this technique has been discussed previously (Nyyssonen and Postek, 1985). The object to be measured is then translated beneath the electron beam by an electromechanically scanned stage (Scire and Teague, 1978; Young, 1984). The linear displacement of the stage is precisely determined by use of a commercial optical interferometric measurement system. As the sample is scanned, the collected electron signal is stored simultaneously with the data from the interferometer system by a dedicated microcomputer system. Subsequent analysis of the resulting image profile relative to the displacement of the stage is used to determine the distance from one point to another across the scanned object.

Laser Interferometer Stage

A precise laser-interferometer stage custom fitted to the SEM chamber needed to be developed in order to accurately move the specimen a small amount (nanometers) under computer control when the instrument is in the measurement mode of operation (Figure 1). Thus, the equivalent of scanning the electron beam over the feature to be measured is achieved. The metrology stage used in this instrument is similar in principle but not in practice, to the stage used in the present NIST metrology instrument used to certify the SEM magnification standard SRM 484 (Hembree, 1986). In the stage described in this paper, the range of coarse stage motion is greater, therefore the larger samples generally associated with the semiconductor community (and others) can be accommodated (up to 100 mm). Furthermore, nanometer fine motion is available in both the X and Y directions. The stage has coarse motion of ± 25.4 mm using precision stepper motors, and the fine measurement motion is achieved by an additional piezoelectric stage having approximately 70 micrometers of travel (Scire and

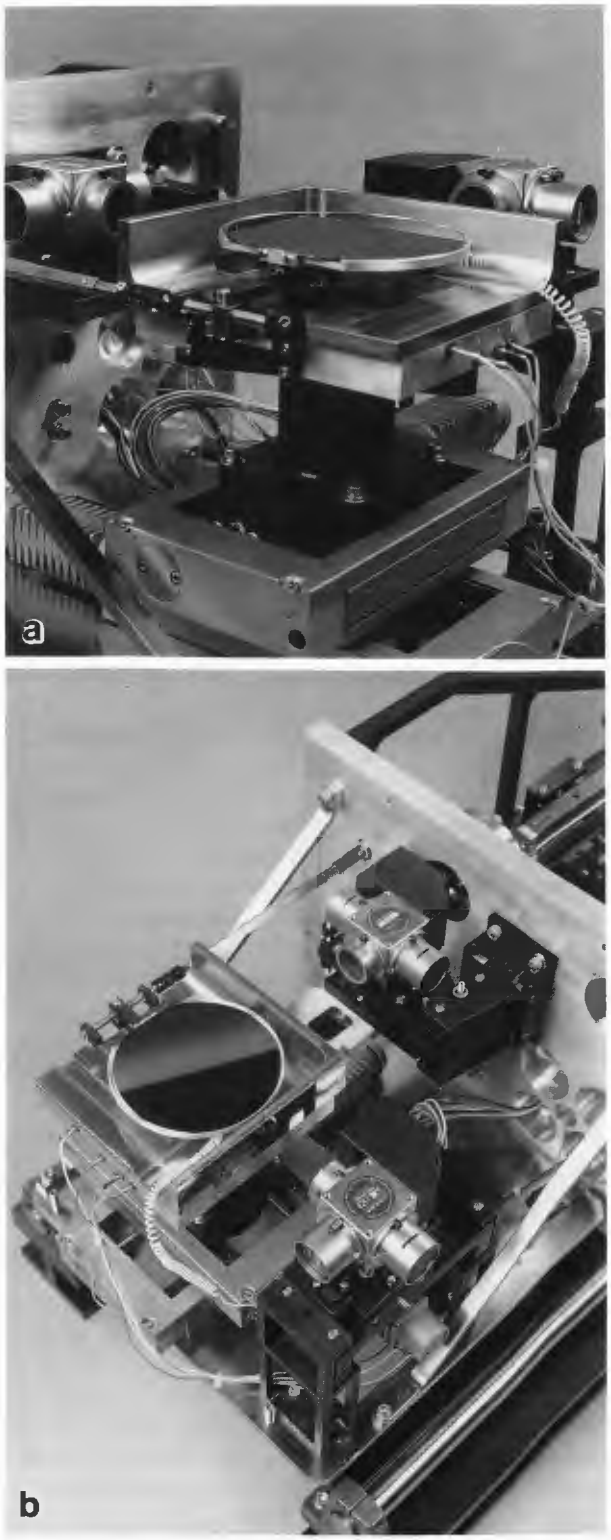

Figure 1. Photographs of the laser interferometer stage. (a) View of the laser interferometer stage unit with a 200mm (4 inch) wafer mounted in the sample position as a scale reference. (b) Interferometer stage unit showing the sample position and interferometry.

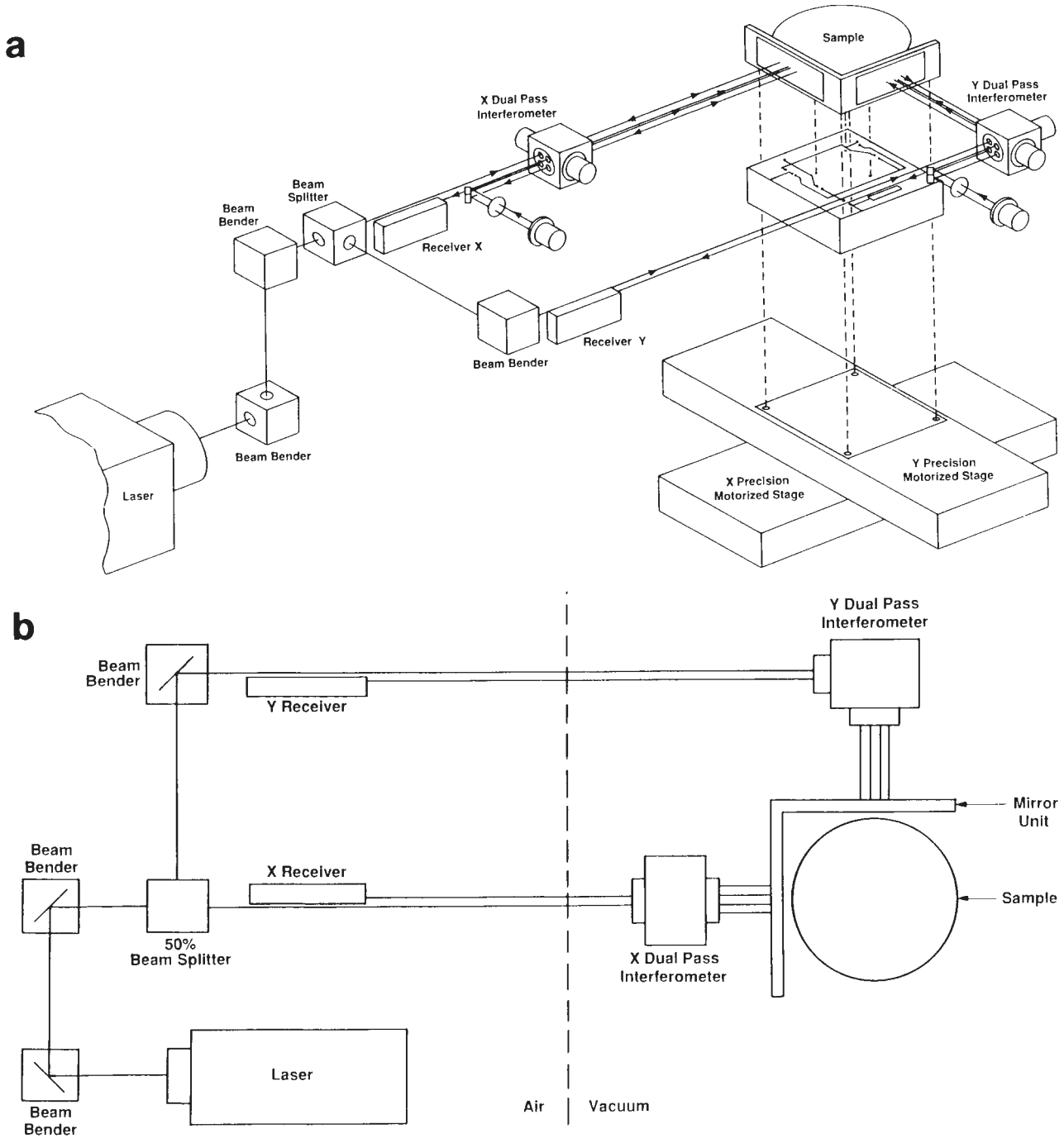

Figure 2. (a) Isometric view of the metrology stage interferometer system. The drawing has been expanded in all directions for clarity. (b) Overhead view of the stage interferometer system.

Teague, 1978; Young, 1984). The stage has been designed such that the sample resides at a fixed 12 mm working distance below the final lens polepiece of the instrument. The fixed working distance enables optimization of the interferometry to minimize any Abbé offset error in the interferometric measurement.

The stage motion is tracked by optical laser interferometry (Figure 2). The interferometers for both the X and Y measurements are dual-pass plane mirror (quad-beam) Michelson-type interferometers, (Baldwin and Siddall, 1984) with a least count of 3.9 nm in the present design but, with the potential of 2.5 nm with improved electronics. The interferometer is mounted directly in the vacuum chamber in order to minimize

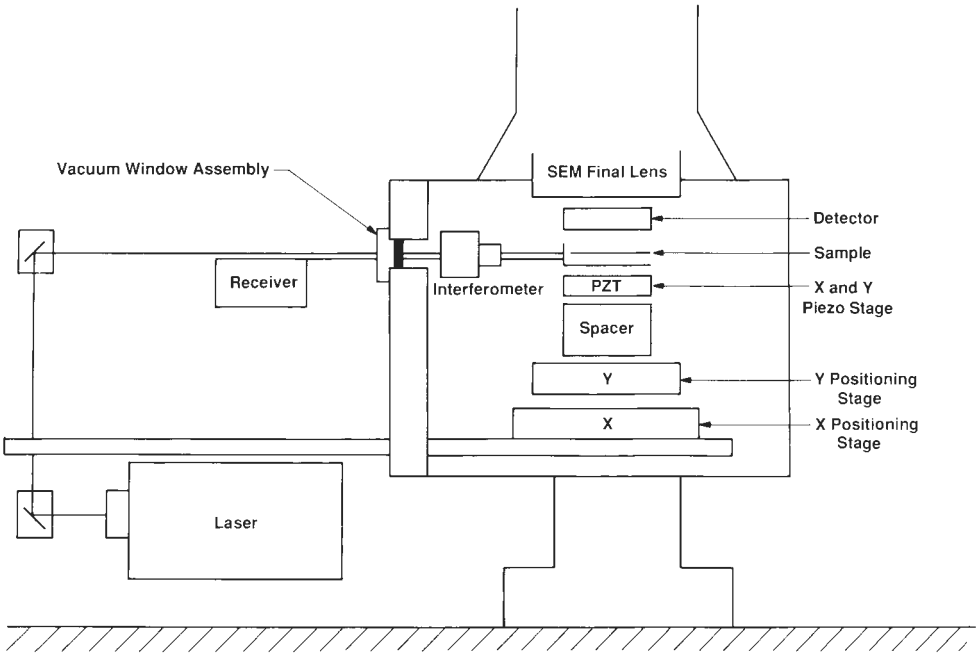

Figure 3. Diagrammatic side view of the laser interferometer stage unit. This figure shows the positions of the laser and directing optics residing externally to the vacuum and the interferometer optics, stage assembly and the sample within the vacuum chamber.

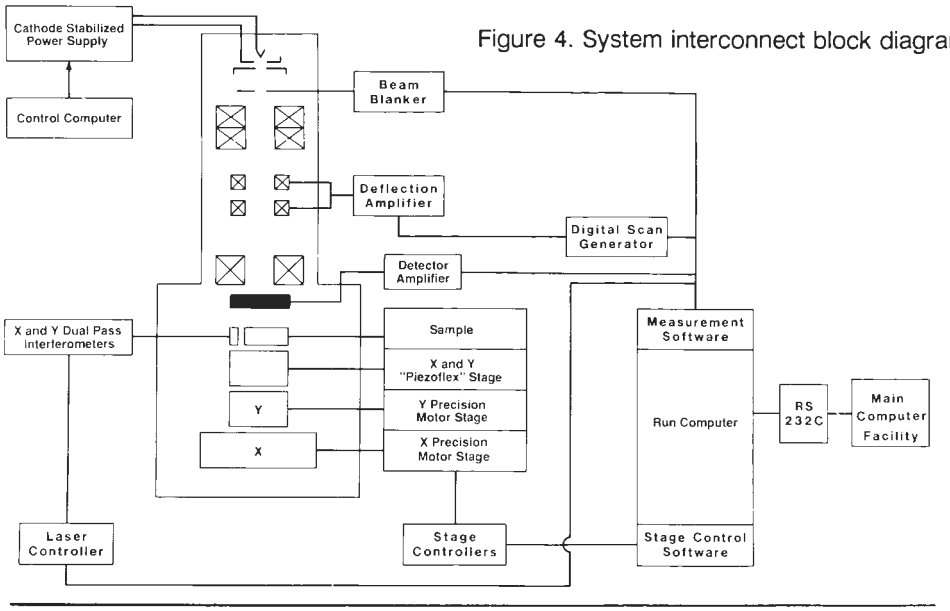

Figure 4. System interconnect block diagram.

both the dead-path and any environmental influences. The laser source is a Zeeman-stabilized He-Ne laser which emits reference and measurement beams of orthogonal linear polarization separated by a frequency of about 2 MHz. The mirrors reflecting the laser beam back are mounted in X and Y to the piezo stage in direct line with the sample. This minimizes any Abbé offset errors. Displacement of the mirrors appears as phase information on a radio-frequency carrier and is detected by standard heterodyne techniques. The entire laser-interferometer stage unit is composed of two joined sections: (1) the laser, the directing optics and the receivers which are all external to the vacuum; and (2) the interferometer optics, stage assembly and sample which are all in the vacuum space of the electron microscope (Figure 3). The entire stage is removable from the vacuum as a unit in order to facilitate all alignments before being installed within the microscope chamber. All the adjustments have locks so that once the stage has been placed into the

vacuum no changes in alignment should occur. With the laser interferometer stage retracted and a standard goniometer specimen stage installed in the sample chamber, the instrument can be used as a standard SEM.

Presently, the laser-interferometer metrology stage is designed around reflected-electron detection (secondary and backscattered electrons) and measurement. Modifications to the stage to enable both reflected and transmitted electron detection are anticipated in the future for the measurement of such samples as x-ray mask artifacts (Postek et al., 1989c).

Stage Control and Data Acquisition Software

The stage control for positioning and data acquisition is fully computer controlled by a microcomputer system (Figure 4). A "map" of the location of the edges to be measured is loaded into the computer and the measurements are made automatically. Data is taken from the laser system electronics and the electron detector electronics simultaneously and the data pairs are stored in the computer. A reduced set of the data for a pattern may be graphically displayed on the computer for review and the complete set may be printed out, stored to floppy disk, or transmitted to a larger computer for analysis and computation.

Instrument Mounting

The entire column and the laser stage have been placed on a vibration isolation table. The table is used not only for vibration isolation but also for a broad stable mounting platform for the laser interferometry. Precision levelers on three of the legs maintain the height of the table to ± 0.254 mm and keep it level, thus reducing any uneven forces which might be caused by tilting. In this way, to a first approximation, the entire SEM column, sample chamber, and interferometer metrology stage move as a unit in response to vibration sources.

Vacuum System

The pumping station supplied with the SEM has been replaced with a custom designed and fully interlocked cryopump system. This system consists of a standard commercial cryopump that has been vibration isolated through a series of isolation bellows. This system was designed at NIST and has demonstrated vibration levels equal to or lower than that of the turbomolecular pumping station initially supplied. Two other modifications to the system have also been implemented. The first of these was to have the compressor and cryopump motor modified to be capable of being remotely turned off from the SEM console. In this way, during the measurement sequence, the cryopump could be turned off, thus eliminating any residual pump-induced vibration. The second modification was to have the standard second stage array of the cryopump replaced with an array composed of lead rather than the standard material. The increased thermal mass of the leaded array enables the system to be "coasted" in the pump-off mode without appreciable loss of vacuum for approximately 30 minutes before the compressor and motor need to be turned on again to re-cool the pump. This is an adequate amount of time in the pump-off mode for the anticipated measurement sequence to be completed.

Microchannel-plate Electron Detection System

The laser-interferometer stage presents an imposing structure in the SEM chamber and the sample is designed to be located at a fixed 12 mm working distance from the polepiece of the final lens (Figures 4 and 5) therefore, no space remains for the standard Everhart/Thornley (ET) electron detector (Everhart and Thornley, 1960). The ET detector needed to be replaced by an electron-detection unit mounted above the stage within the available 12 mm of working distance. A solid-state backscattered electron detector could have been used for this purpose but has limitations (Postek et al., 1989a). Channel electron multipliers, channel-plates or microchannel-plates (MCP), have been used in scanning electron microscopes for several years (Hughes et al., 1967). More recently, microchannel-plate detection systems have been used for linewidth measurement applications (Russell, 1984, Russell and Mancouso, 1985 and Russell, et. al., 1984) and have been successfully used on a commercial metrology instrument. Since no commercial *system* (i.e., both detector and amplifier) was available for installation on the NIST instrument, a development program was instituted to design and build an appropriate system. A complete MCP system meeting the NIST specifications was developed and has been described elsewhere (Postek et al., 1989a). The MCP system developed for this instrument mounts directly on the SEM polepiece and is approximately 3.5 mm in thickness. The detecting unit is composed of three microchannel-plates and has a gain of approximately 10^8. The detector design enables either standard secondary electron detection or the collection of only backscattered electrons. Since the MCP detector becomes more efficient at lower accelerating voltages (i.e., below about 5 keV) due to the more efficient conversion of incoming electrons in the channels, low accelerating voltage calibrations are possible of either the secondary electron image or the backscattered electron image. The backscattered electron image may become more useful for linewidth metrology since it has been recently demonstrated that surface structure using low accelerating voltage backscattered electrons as the imaging mechanism can be visualized with high

resolution (Postek et al., 1989b). Further work at NIST is presently being done in this area.

Cathode Stabilized Power Supply

Accurate modeling of the electron beam/ sample interactions requires that the accelerating voltage applied to the electron be known with reasonable certainty. Some thermionic emission scanning electron microscopes, due to their self-biasing electron gun design, apply the chosen accelerating voltage directly to the Wehnelt grid with the filament supplied through a bias resistor. The voltage drop in the bias resistor is variable and not easily measured, but may be adjusted depending upon operating conditions. Therefore, the accelerating voltage (i.e., filament to ground potential) is not precisely known. The NIST metrology instrument has had this system replaced by a cathode stabilized high-voltage power supply added in order to control this voltage (Figure 5). The cathode-stabilized power supply has been fully incorporated into the SEM and is fully interlocked for safety. This system also provides another advantage in that it can be computer controlled. With this system and the computer control software developed at NIST, the filament can be automatically saturated (or cooled) and the emission current continually monitored for stability and automatically adjusted as needed by adjustment of the current applied to the filament.

Vibration Monitor

The level of vibration on the metrology stage will be continually monitored using a commercial vibration monitoring system. A miniature accelerometer will be placed directly in the vacuum, permanently attached to the specimen stage. Provision for isolated high-vacuum feedthroughs have been made to effectively transmit the signal to the analysis system. If the vibration specification is exceeded the measurement will be stopped.

The SEM Magnification Standard Prototype

The qualities necessary for a good SEM standard have been discussed previously by several authors (Ballard, 1972; Wells, 1974; Postek et al., 1987a). It has been determined through numerous visits and discussions with those in the semiconductor and SEM industry that a new magnification standard must be developed to supplement (not replace) the current SEM magnification standard, SRM 484, and it must meet all of the following general criteria:

1) The standard must be relevant to the needs of the majority of the users. A relevant standard must be able to be used on a wide variety of instruments and over a wide range of magnifications (less than 100x to over 300,000x). Therefore, a wide range

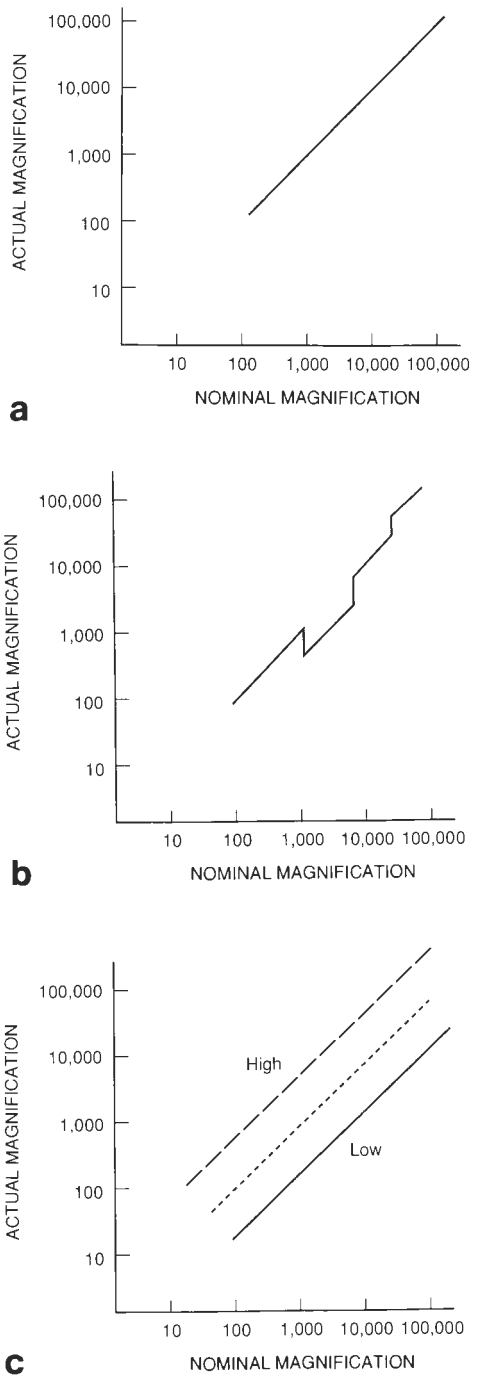

Figure 5. Decade magnification calibration of an SEM. (a) Ideal system where nominal magnification equals actual magnification. (b) Decade system of magnification calibration showing misadjustment between the decades (this has been exaggerated in the Y direction). (c) Proper decade calibration where the gain of the overall system can be adjusted higher or lower to achieve the proper magnification (central line).

of structures must be present so that several magnification ranges are represented. Most of these instruments use a decade-type magnification calibration system where a series of precision resistors are used. In many cases, the transition points between resistors must be adjusted using a calibration potentiometer to adjust the lower decade to the higher decade. In this way, a smooth transition is accomplished as the magnification is increased (Figure 5a). If a decade has drifted high or low relative to the adjacent decade, an unknown increase or decrease of the magnification will occur when that decade is entered (Figure 5b). This condition must be checked for and any variation corrected. Once this is done, the overall range offset is performed at a high magnification which sets the actual magnification calibration of the instrument (Figure 5c). Both operations must be done or at least checked to insure that the magnification of the instrument meets factory specifications in all decades. The frequency of this operation will depend upon the stability of the components of each individual instrument.

2) The standard must be useful at both high and low accelerating voltages. Low accelerating voltage operation was not common practice when the present SEM magnification standard SRM 484 was initially developed. At that time, if an instrument was operated at low accelerating voltages it was for reasons other than for metrology. Today the "non-destructive" inspection of semiconductor wafers in an SEM for inspection and metrology has placed a new emphasis on the need for calibration standards that can be used at both high and low (general range 0.5 to 2.5 keV) accelerating voltages. Today there is an emphasis on low accelerating voltage instrument calibrations. The philosophy behind the construction of SRM 484 unfortunately, makes it difficult to be used at accelerating voltages below about 3.0 keV. The main problem with the sample is a lack of sufficient contrast at low accelerating voltages (Postek, 1987b). The highly polished surface of SRM 484 can be etched to provide topographic contrast for low accelerating voltage operation but this results in other undesirable effects (Postek, 1987a). Therefore, any new standard needs to be functional at all accelerating voltages so that an instrument can be calibrated and the compensation circuitry checked when changes are made in the accelerating voltage.

3) The standard must be resilient so that it will stand up to use. For a calibration sample to be generally useful the materials chosen must be resilient to electron beam exposure. In use, the standard must not degrade or change shape. Materials such as etched silicon, patterned gold and others can degrade while being viewed in the scanning electron microscope (Figure 6). Thus for the new standard, materials such as heavy-metal silicides have been chosen be-

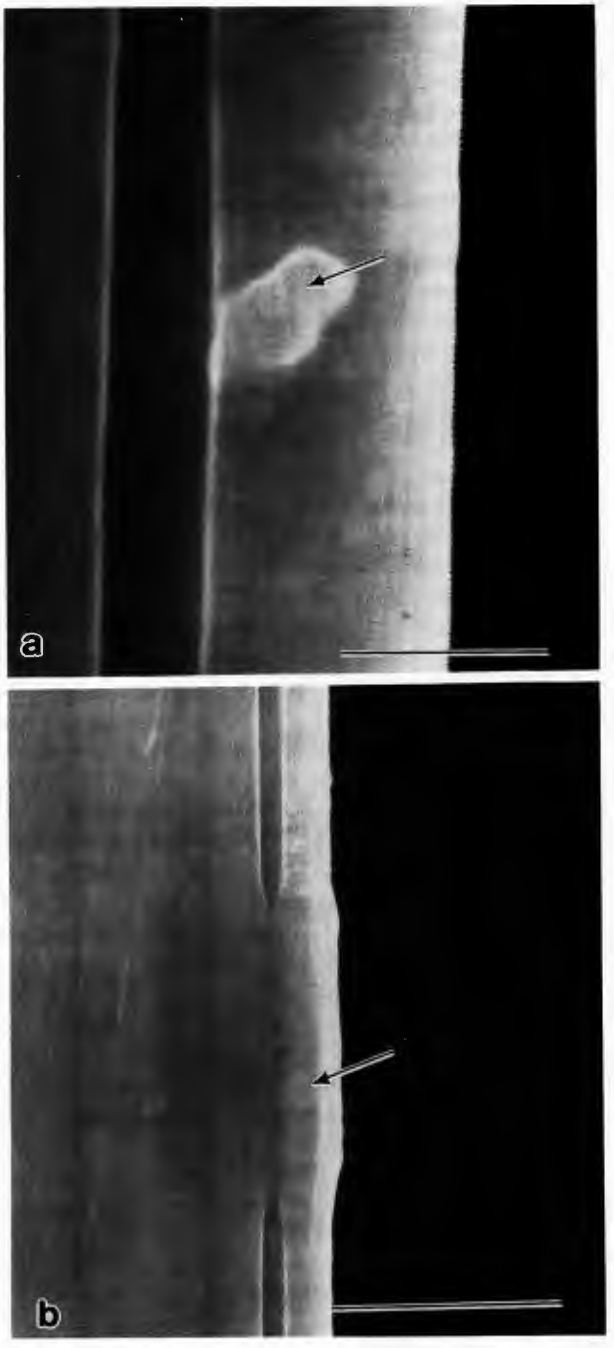

Figure 6. Example of sample damage induced by electron beam exposure. (a) Micrograph of the cross-section view of a silicon-etched silicon oxide sample overtopped with chrome. The etched oxide layer of this multilayer sample is approximately 100 nm in "width". [Accelerating voltage = 25 keV; line scale = 0.15 μm] (b) Micrograph of the sample viewed following approximately 2 minutes of electron beam irradiation at approximately 5 x 10^{-12} amps of beam current in the area affected. [Accelerating voltage = 25 keV; line scale = 0.75 μm]

cause they have been shown to be more resilient than the others tested. Sample contamination due to electron beam interaction with surface hydrocarbons may be unavoidable and cleaning procedures must be determined that will not degrade the sample or its certification.

4) The standard must have submicrometer structures. The present SEM magnification standard, SRM 484, does not have certified features below a nominal 1 micrometer. This means that for pitch calibrations the sample is only useful to approximately 30,000x magnification. This is not the uppermost decade of many current scanning electron microscopes. Therefore, it is necessary for NIST to provide a sample that has features which are in the submicrometer range. A sample having a pitch of a nominal 0.2 micrometers would provide the ability to calibrate an SEM into the 300,000x range.

5) The standard must be the thickness of a wafer. SRM 484, the present NIST SEM magnification standard, is composed of an approximately 15 mm high billet that must fit vertically in the SEM chamber. This is not a problem for many of the scanning electron microscopes, but with the introduction of the new dedicated SEM wafer inspection instrumentation, it has been found that this sample is too tall to fit into the instrument chamber. For a new standard to be universally useful, it will be necessary for it to be fabricated at the maximum thickness of a standard silicon wafer. Since this thickness varies with wafer diameter it may become necessary to have the artifact fabricated then diced and remounted in carriers mimicking the dimensions of the wafers being inspected. This will maintain the proper sample working distance for calibration. For instruments not having the tight space requirements of the dedicated wafer inspection instruments, the sample could be mounted directly onto a conventional specimen stub.

6) The standard must be constructed of materials that will not interfere with semiconductor processing. Many semiconductor processing engineers feel that some materials are inappropriate to bring into the semiconductor fabrication facility and to introduce into SEMs inspecting the in-process wafers. Materials such as gold (and other heavy or transition metals) could be excellent materials from the SEM standpoint but they can introduce undesireable deep-levels in silicon and therefore should not be brought into close proximity to in-process wafers. Therefore, the materials used in the fabrication of the standard that calibrates SEMs used to measure or inspect in-process wafers should be selected from materials currently used in the semiconductor processing to avoid any cross-contamination problem.

7) The standard must have structures in both the X and the Y directions. The transition adjustment between decades of the magnification system of an SEM (as discussed above) needs to be done (or at least checked) in both the X direction and the Y direction. Clearly, a sample such as SRM 484 when used in the calibration of an SEM could be physically rotated to provide both of the necessary scan calibrations, but many of the modern wafer inspection instruments do not have this feature or have only restricted rotation movement. Therefore, a range of calibrated structures from 3 mm to submicrometer dimensions is necessary in both the X and the Y direction.

8) The standard needs only to be based on pitch. The need for a SEM linewidth standard is well recognized by NIST and efforts are being directed to develop such a standard (Postek et al., 1987a). However, for a SEM magnification calibration standard, all that is necessary is a standard based on pitch meeting criteria mentioned above. The problems associated with the differences between pitch and width measurements in an SEM have been discussed previously (Jensen and Swyt, 1980). To develop a magnification calibration standard based upon structure width or space width (even to calibrate the final magnification range adjustment of the instrument) would require that the statement of edge-location uncertainty (due to the errors induced by the electron beam interaction) be made quite large - in the 10-15% range at high accelerating voltages, and even greater at low accelerating voltages. A better alternative would be for the development of electron beam/sample interaction modeling in order to determine the location of the structure edges (Postek et al., 1987a). Since the electron beam modeling is not necessary for a magnification standard based on pitch due to the error compensation associated with this technique, a magnification sample based on linewidth would unnecessarily complicate the magnification calibration procedure. Once this magnification sample has been produced it can serve as the prototype to be used in the continued development of the interaction modeling for the linewidth standard.

NIST Prototype Magnification Standard

NIST recently began a cooperative effort with the National Nanofabrication Facility at Cornell University to fabricate a prototype SEM magnification standard by electron beam lithography. A sample meeting the above criteria has been fabricated using electron beam lithographic techniques (Postek and Tiberio, 1988) and is undergoing further evaluation. The design of the standard is such that calibration features in both the X and Y directions are provided to calibrate the scans of the SEM without having to rotate the sample. Structures with a nominal pitch as large as 3 mm to as small as a nominal pitch of 0.2 micrometers (Figure 7)

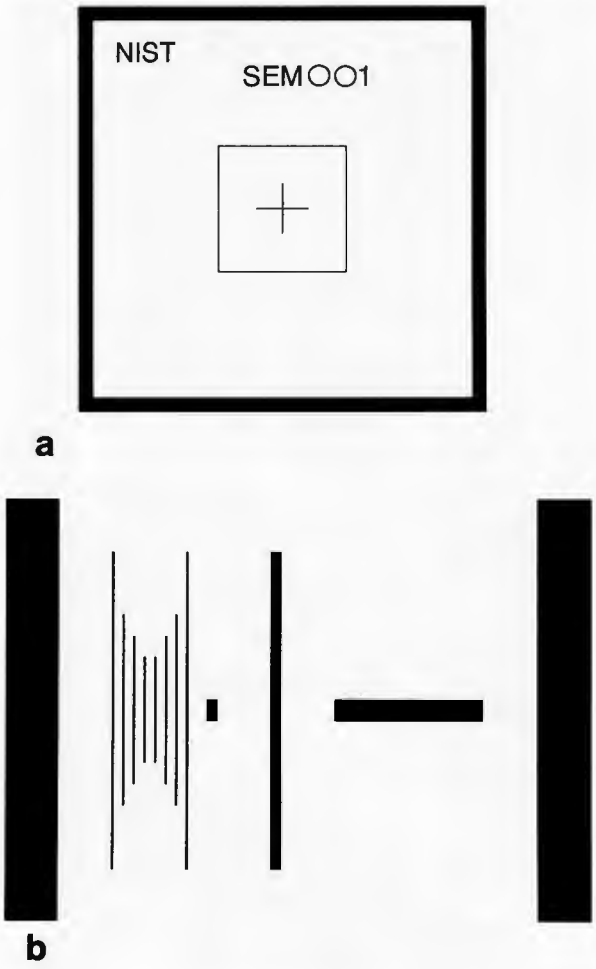

Figure 7. Diagrammatic representation of the proposed lithographically produced SEM magnification standard. (a) Low magnification view showing the overall 3 mm structure. (b) High magnification view showing the series of 0.2 μm pitch features.

permit calibration from the lowest magnification range to in excess of 300,000x. Prototype samples, designed both to test manufacturability and the ability to solve the present problems with SRM 484 were fabricated on semiconductor wafers. The structures of the prototype sample were fabricated from molybdenum-silicide on silicon and they demonstrate good contrast throughout the accelerating voltage range and resiliency to electron beam exposure. Figure 8 demonstrates the ability of the prototype sample to be viewed at both high and low accelerating voltages. The micrographs of Figure 9 show the calibration structures in increasing magnifications.

Conclusions

The completion of the development phase of the NIST metrology electron microscope and the production of the prototype SEM magnification standard culminates several years of effort at NIST to develop standards contemporary to the needs of the SEM community. Once a small production run of the prototype samples can be made, a round robin within the SEM community can be instituted. This round robin is planned during the upcoming year.

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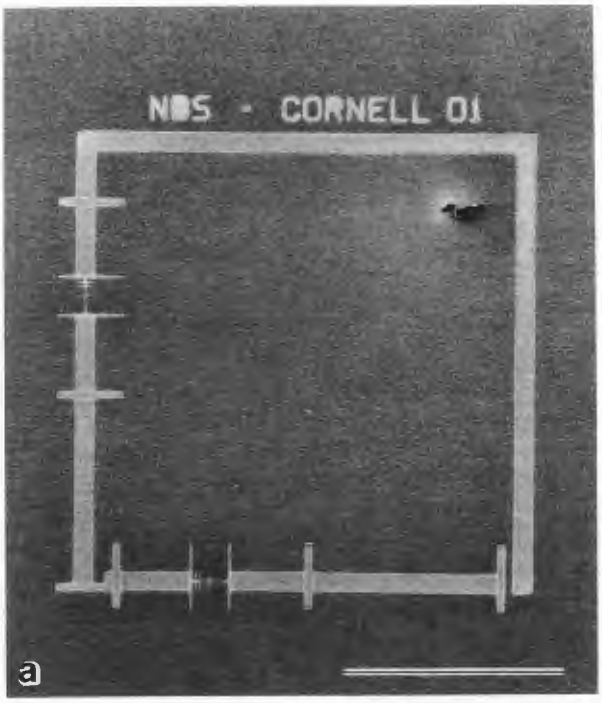

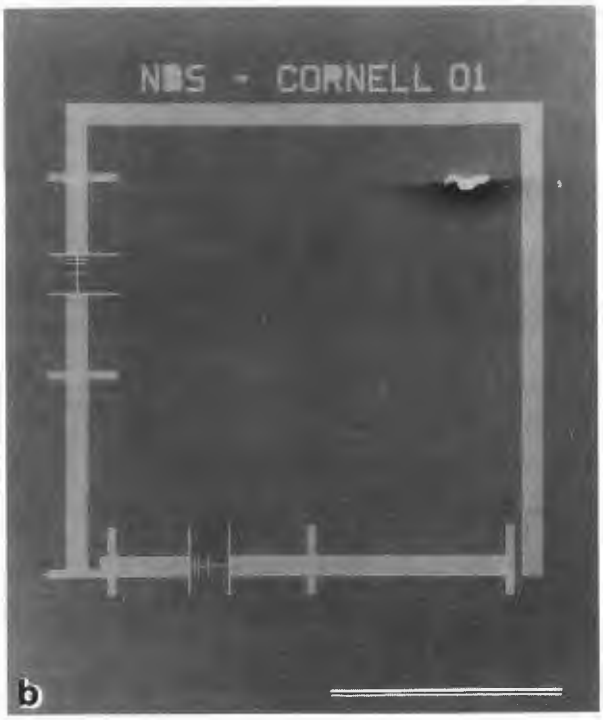

Figure 8. Micrographs of the SEM magnification prototype sample. (a) Low magnification low accelerating voltage. [Accelerating voltage = 1.0 keV; line scale = 500 μm] (b) Low magnification high accelerating voltage. [Accelerating voltage = 20 keV; line scale = 500 μm]

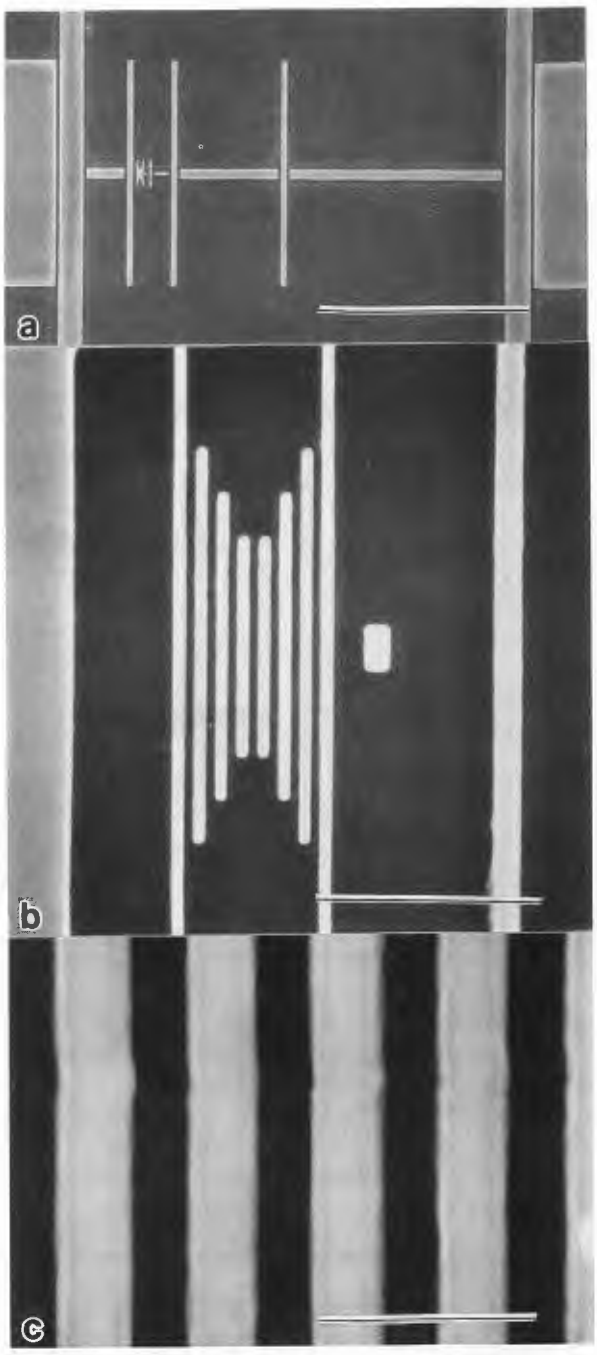

Figure 9. Micrographs of the SEM magnification prototype sample. (a) High accelerating voltage intermediate magnification showing the 100 μm pitch structure. [Accelerating voltage = 20 keV; line scale = 43 μm] (b) High accelerating voltage high magnification showing overall the .2 μm pitch structures. [Accelerating voltage = 20 keV; line scale = 1.76 μm] (c) High accelerating voltage very high magnification showing the potential for calibration of the instrument above 300x nominal magnification. [Accelerating voltage = 20 keV; line scale = 0.3 μm]

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Discussion with Reviewers

M. H. Bennett-Lilley. Have you conducted a survey of the semiconductor industry to determine "acceptable" or desired choices of substrate for the magnification and/or linewidth standard?

Author. Yes! Considerable research has been done parallel to the other phases of this program into the materials suitable for these standards. Substrate choice for a magnification standard (as described here) is really irrelevant as long as it meets the criteria described in this paper and it is made to look like a wafer (for the cassette-to-cassette metrology and inspection instruments) since pitch is the mode of measurement. As far as an actual linewidth standard is concerned, this is an area of great discussion. If the truth be known, the industry would prefer NIST to provide standards for each process step for each device. This would be impossible to do for too many reasons to go into at this time. However, computer modeling may be very helpful in circumventing this problem in the future. We envision it much like the situation that presently exists with quantitative x-ray microanalysis (Postek et al., 1987a). But this still remains a point of discussion.

P. E. Russell. You indicate that several materials tested for a standard degraded under electron beam exposure. Please elaborate.

Author. In the course of the development of the standard, several pre-prototype samples and materials were tested. Some of these materials were constructed with the calibration pattern and some were not. However, all had submicrometer features of some type. Irradiation of these samples with the field emission inspection instrument at NIST resulted in damage to several classes of the tested materials. Submicrometer patterned gold and silicon structures degraded under electron beam exposure quite rapidly. Further tests were undertaken to determine if beam-induced hydrocarbon con-

tamination contributed to or was being mis-interpreted as being actual sample damage. This type of contamination of the sample was shown to be a second class of problems that need to be handled and understood, but the cause of deformation of the structures under study was not due to contamination. Damage induced by the electron beam is demonstrated in Figure 6. This set of figures was chosen because of its dramatic reaction.

M. H. Bennett-Lilley. Do you feel that a linewidth as a standard would be more useful than one based on pitch? If so, can you approximate how long after a magnification standard is accomplished will the linewidth standard be completed.

Author. It would be advantageous if both the magnification calibration and the linewidth calibration problems could be solved by a single standard. However, at the present time the SEM users need a low accelerating voltage magnification standard more than they need (as a group) a linewidth standard. NIST serves all of commerce and the SEM user community spans that entire region. With the standard described here the magnification of an instrument can be calibrated and many instrument parameters and performance tests can be done to further test the instrument. These tests include short/long term magnification stability, measurement precision, lens hysteresis compensation and magnification compensation at different accelerating voltages to name just a few. Since this type of sample is based upon a pitch, electron beam modeling is unnecessary and thus it can be in the users hands more rapidly than one based upon linewidth.

The length of time that it will require for a linewidth standard to be issued will directly relate to the final manufacturability of the standard and the progress made in electron beam/sample interaction modeling in the upcoming future. Both of these factors are unable to be predicted at this time.

Reviewer IV. You indicate that using the microchannel-plate electron detector system designed for this instrument you are able to collect low accelerating voltage backscattered electrons. How low in accelerating voltage has this been tested?

Author. For several years, NIST has been developing an MCP system for the metrology microscope described in this paper. The main motivation and purpose of the system has been for metrology. Metrology of secondary electrons or even backscattered electrons is a viable possibility with this type of detection system due to the favorable collection geometry and efficiency. This is the subject of work currently in progress. There are applications to which the MCP detection system is also applicable other than metrology. These applications are described in Postek et al., 1989a and include low accelerating voltage backscattered electron collection. Too date, atomic number differentiation has been demonstrated (as shown in the attached figure) as low as 800 V accelerating potential taken with an AMRAY 1860 FE SEM and the NIST MCP detector system. [Line scale = 10 micrometers] The biggest problem we have had to overcome now that the detector is functioning properly is the sample selection. Surface damage due to polishing and surface contamination severely limits the success of this work to a greater extent than at high accelerating voltage. Finding samples that successfully demonstrate the utility of this detector has been a real challenge.

M. H. Bennett-Lilley. Could you elaborate on your choice of a fixed working distance of 12 mm?

Author. The fixed 12 mm working distance was expressly chosen in order to optimize the laser interferometry for the metrology stage. Since laser deadpath is not a serious problem in the vacuum in our design, the real problem is the Abbé offset errors associated with the interferometry. To minimize this type of error, the effective laser beam should lie in the extended sample plane. In our design, this is accomplished with the sample residing at 12 mm working distance since space had to be apportioned for the bulky interferometers. Shorter working distance would have favored electron optical performance but, compromises had to be made. As an early mentor of mine Dr. E. L. Thurston so aptly put it, we were forced to "optimize the compromises."

P. E. Russell. Why were stepper motors vs. linear or DC motors used?

Author. Expense and availability, at the time of procurement several years ago, were the basic reasons that stepper motors were used for this application. The type of motor used is not a concern to this particular measurement process since the motion

measured with the interferometry is the piezo stage motion and not the stepper motor motion. The stepper motors are only used for coarse positioning.

P. E. Russell. What are the vibration levels generated by the cryopumping system and how much are the vibrations attenuated by the isolation system?
Author. An undampened cryopump can generate vibration levels sufficient to prevent focusing of the SEM image even at low magnifications. A great deal of collaborative work between NIST, CTI Cryogenics and AMRAY resulted in a vibration isolation system that has attenuated the pump-induced vibration to such a low level that the instrument can prove ultimate resolution (5.0 nm) in the pump-on mode with no visible vibration present in the micrograph. This vibration isolation technique will be the subject of a separate publication.

P. E. Russell. What are the lithographic and deposition processes involved in the Mo-Silicide fabrication used for the standard?
Author. The processing steps used to make the prototype standard were discussed in Postek and Tiberio (1988). This is essentially a lift-off process typically employed at the Nanofabrication Facility at Cornell. The exact processing steps have little relevancy since this may be site specific.

P. E. Russell. What is the vibration specification which is referred to in the vibration monitor section and do you have any means to measure the motion of the specimen relative to the beam?
Author. The vibration specifications alluded to in that section have not been determined as of yet because more work is needed to determine what frequencies are actually contributing to sample motion relative to the electron beam and hence need to be monitored during the certification process. It has been our experience that once the major contributors to this vibration have been eliminated the last 5% or less of the ambient vibration is very difficult to measure. This vibration is so low that it is buried in the noise of the accelerometry systems available. This was studied when the initial survey work associated with the cryopump optimization was done. In all cases, it was found that the image (if viewed properly) was a far more sensitive vibration probe than the accelerometry. We are actively exploring other techniques for more sensitive vibration measurements using accelerometry. Alternatively, we are working on a technique for the measurement of the sample motion relative to the electron beam directly and will be reporting on this work at a later time.