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U.S. DEPARTMENT OF COMMERCE/National Institute of Standards and Technology

*Standard Reference Materials:*

## **Bright-Chromium Linewidth Standard, SRM 476, for Calibration of Optical Microscope Linewidth Measuring Systems**

**Carol F. Vezzetti, Ruth N. Varner, and James E. Potzick**

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U.S. DEPARTMENT OF COMMERCE, Robert A. Mosbacher, Secretary  
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## Preface

Standard Reference Materials (SRM's) as defined by the National Institute of Standards and Technology (NIST) are well-characterized materials, produced in quantity and certified for one or more physical or chemical properties. They are used to assure the accuracy and compatibility of measurements throughout the Nation. SRM's are widely used as primary standards in many diverse fields in science, industry, and technology, both within the United States and throughout the world. They are also used extensively in the fields of environmental and clinical analysis. In many applications, traceability of quality control and measurement processes to the national measurement system is carried out through the mechanism and use of SRM's. For many of the Nation's scientists and technologists, it is therefore of more than passing interest to know the details of the measurements made at NIST in arriving at the certified values of the SRM's produced. The NIST Special Publication 260 Series is a series of papers reserved for this purpose.

The 260 Series is dedicated to the dissemination of information on different phases of the preparation, measurement, certification, and use of NIST SRM's. In general, much more detail will be found in these papers than is generally allowed, or desirable, in scientific journal articles. This enables the user to assess the validity and accuracy of the measurement processes employed, to judge the statistical analysis, and to learn details of techniques and methods utilized for work entailing greatest care and accuracy. These papers also should provide sufficient additional information so SRM's can be utilized in new applications in diverse fields not foreseen at the time the SRM was originally issued.

Inquiries concerning the technical content of this paper should be directed to the author(s). Other questions concerned with the availability, delivery, price, and so forth, will receive prompt attention from:

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## Contents

1. Introduction . . . . .	1
2. Physical Characteristics of SRM 476 . . . . .	1
3. Calibration of SRM 476 . . . . .	2
3.1 The Measurement System . . . . .	2
3.2 SRM Calibration Procedure . . . . .	3
3.3 Feature Measurement Sequence . . . . .	3
3.4 Edge Location Determination . . . . .	4
3.5 Precision and Accuracy . . . . .	5
4. Using SRM 476 . . . . .	7
4.1 Special Precautions . . . . .	7
4.2 Microscope Calibration Procedures . . . . .	8
5. Acknowledgments . . . . .	11
6. References . . . . .	11
Figures . . . . .	13
Appendix: Process Control for SRM 476 Calibration . . . . .	22
A. Introduction . . . . .	22
B. Initialization of Process Parameters . . . . .	22
C. Procedures for Process Control . . . . .	24
D. Updating Process Parameters . . . . .	25
E. Uncertainty Statement for SRM 476 . . . . .	28
Acknowledgments . . . . .	30
References . . . . .	30
Tables . . . . .	31
Figures . . . . .	32



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\*Send order with remittance to Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20102. Remittance from foreign countries should include an additional one fourth of the purchase price for postage.

\*\*May be ordered from: National Technical Information Service (NTIS), Springfield, VA 22161

BRIGHT-CHROMIUM LINEWIDTH STANDARD, SRM 476,  
FOR CALIBRATION OF OPTICAL MICROSCOPE  
LINEWIDTH MEASURING SYSTEMS

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ABSTRACT

Standard Reference Material, SRM 476, was developed for use in calibrating optical microscopes used to measure linewidths in the range of 0.9 to 10.8  $\mu\text{m}$  on bright chromium photomasks, such as those used in the production of integrated circuits. The SRM, the measurement system, and the procedures used to calibrate the SRM are described. The algorithm for determining the line edge location uses a threshold criterion derived from analysis of microscope image profiles. The profiles are predicted by computer modeling based on the theory of partial coherence. The performance of the system is monitored by measuring line features on a control photomask before and after calibrating each SRM.

Precautions concerning care and handling and instruction for the use of SRM 476 to calibrate optical microscopes for photomask linewidth measurement are given.

KEY WORDS: accuracy; bright chromium; calibration; control charts; critical dimensions; integrated circuits; linewidth; measurement; optical microscope; photomask; precision; process control; semiconductor industry; standard reference material; threshold; uncertainty.



## 1. Introduction

The ability to measure and control critical dimensions during the production of integrated circuits is essential to the semiconductor industry. Many measuring systems claiming high precision are now commercially available for measuring some of these critical dimensions. As part of a continuing effort to provide means for calibrating these systems, the National Institute of Standards and Technology (NIST)\* has developed Optical Microscope Linewidth Measurement Standard Reference Materials.

Standard Reference Material (SRM) 476 is designed for calibrating optical microscope systems to measure linewidths on bright-chromium photomasks. It was produced using conventional technology by a commercial photomask manufacturing facility. In addition to isolated opaque and clear lines for linewidth calibration, the SRM contains line patterns for checking length scale, adjusting video-type micrometers, and detecting mechanical or optical nonlinearities. The design of the calibrated pattern is described in section 2.

A photometric microscope with lenses selected for least aberration was modified at NIST for calibrating the SRM line features. Except for the initial positioning, aligning, and focusing of the photomask, the entire calibration process is automated. Linewidths are determined from the image profile (image intensity versus position across a feature). The quality of the feature edge geometry of a sample from each production batch of SRM photomasks is examined using a scanning electron microscope. The limit of accuracy of the calibration measurements given in the certificate data is based on this sampled edge geometry and the agreement between theoretically modeled and experimentally generated image profiles. Section 3 contains brief descriptions of the NIST linewidth calibration system and the automated calibration process as well as discussions of the line edge location algorithm, precision, and accuracy.

Section 4 gives information and precautions on using this SRM to calibrate an optical linewidth measuring system. Because of the variety of linewidth measurement systems in use today, no attempt has been made to give specific instructions for each type of microscope.

The process control procedures used in the calibration of this SRM are discussed in some detail in the Appendix.

## 2. Physical Characteristics of SRM 476

SRM 476 is made from a bright chromium photoplate by conventional photolithographic techniques. The substrate is a borosilicate glass plate nominally 63.5 x 63.5 x 1.5 mm (2.5 x 2.5 x 0.060 in). The nominal thickness of the chromium layer is 100 nm.

Figure 1 shows the overall pattern on the chromium-coated side of the standard. The cross-shaped relatively clear area contains a series of horizontal and vertical lines that are used to help locate the basic measurement pattern which is repeated at eight locations around the center of the standard as shown in figure 2 (a magnified view of central area of fig. 1).

\*formerly the National Bureau of Standards (NBS)



An underlined pattern identification number (1 through 8) is located to the left of each basic pattern. The accompanying certificate identifies which of these eight patterns was certified by NIST.

Figure 3 shows the details of the features in each of the eight identical patterns on the SRM. Letters A, B, E, F and G designate the row locations, and numbers 0 through 9 designate column locations. Thus, each feature can be identified by its row and column coordinates; for example, A-5 refers to the opaque line in row A and column 5. Row A consists of opaque lines on a clear background, and row B consists of clear lines on an opaque background. These opaque and clear lines are used for calibrating optical microscopes used to measure linewidths of isolated lines of either or both polarities. Row E consists of patterns with opaque line pairs (the two interior lines of shorter length)\* for calibrating the length scale of optical microscopes by measuring the distance between line centers (pitch). Row F consists of patterns with two adjacent lines and the intervening space (two interior lines of longer length and the intervening space)\* with approximately equal line and space widths. These patterns are used in setting the line-to-space ratio (contrast, threshold level, or linearity) on video image-scanning instruments. The widths of the left interior line and central space are certified. Row G consists of two patterns, with a series of 10 approximately equally spaced opaque lines in each pattern, to be used as a linear scale in checking for errors in the linewidth measurement system (e.g., the magnification as a function of position over the field of view). The center-to-center distances from the first line to each of the other nine lines of these patterns are certified. All rows on this SRM contain a broken horizontal fiducial line which is used to define the measurement position of each pattern.

### 3. Calibration of SRM 476

#### 3.1 The Measurement System

All measurements of the SRM feature dimensions were performed at NIST in a laboratory with temperature controlled at 21 °C ( $\pm 2^\circ$ ) using the optical linewidth measurement system diagrammed in figure 4 [1].

The carefully aligned optical transmission microscope is mounted on a vibration isolation table. The photomask is placed on a scanning piezoelectric flexure-pivot stage with finely controlled motion in the X (scanning) and Z (focus) directions; this stage is mounted on another stage with coarse motion leadscrews in the X and Y directions to allow positioning of the desired feature in the field of view.

The photomask is illuminated from below using Köhler illumination (i.e., each point on the lamp filament evenly illuminates the entire specimen) from an incandescent source filtered at 530 nm wavelength with a coherence parameter of 2/3 (.60 numerical aperture condenser lens and .90 numerical aperture objective lens). A 20 by 400  $\mu\text{m}$  slit is fixed on axis in

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\*The two outer lines of each pattern in rows E and F serve as "guard lines" during the photolithographic etching process to equalize proximity effects along the line edges and are not calibrated.

the image plane in front of a photomultiplier tube. Image magnification at the slit is 157 times, giving an effective measurement area on the photomask of 0.127 by 2.55  $\mu\text{m}$ , which is centered top-to-bottom on the feature (at the fiducial line). The photomultiplier output is amplified and digitized by a 12-bit analog-to-digital converter (ADC). Stage motion in the scanning direction is measured by a laser interferometer with resolution of 125 points/micrometer. All these devices are connected via appropriate control hardware and IEEE-488 bus to a dedicated desktop digital computer.

### 3.2 SRM Calibration Procedure

An outline of the overall calibration procedure is charted in figure 5. Before each complete SRM calibration, selected features on a control photomask are measured and compared with control history to ensure that the system has not changed or drifted. These selected features include spacing patterns E-4, E-5, and G-1 which have been independently calibrated by the Dimensional Metrology Group at NIST. Then each feature on the SRM being calibrated is measured in sequence and the sequence repeated nine times. After each SRM calibration is completed, the control photomask is measured again.

All measurements, including the control measurements, are entered into the linewidth database. Then the database is searched to ensure that the control was measured before and after the calibration and that these two control measurements were statistically invariate. The database entries for the calibration are combined and examined statistically: the standard deviation for each feature is calculated, number of measurements checked, etc. Criteria must be met for each of these statistical factors. If necessary, more measurements can be made and added to the database.

Once all the above conditions are met, the certificate is printed and the SRM linewidth standard is released for sale. All of the calibration database files for this serial number are then stored on one flexible disk along with summary data. The disk is kept for archival storage along with the printed calibration results for each measurement, a printed summary of the statistical data, and dark-field illumination micrographs of the calibrated pattern.

### 3.3 Feature Measurement Sequence

A chart of the main steps of the feature measurement sequence is given in figure 6. The feature to be measured is first centered in the field of view, then focused and scanned as the optical profile position and intensity data are taken and stored as two one-dimensional arrays. The data are then low-pass filtered to reduce extraneous noise and processed to find the edge locations. Linewidth is then calculated.

Image profiles such as those in figure 7 are presented on the computer screen during data acquisition and processing to allow monitoring system operation. After passing several data quality checks, the results are entered into a database for the SRM being calibrated. A more detailed description of the measurement sequence and system can be found in reference [1].

### 3.4 Edge Location Determination

Analysis of optical microscope imaging gives the following equation for image intensity at the edge of a line [2]:

$$T_c = R_t (I_o + I_m + 2\sqrt{I_o I_m} \cos \phi), \quad (1)$$

where  $T_c$  is the intensity of the light at the threshold point (edge) on the image profile (see fig. 8);  $I_o$  is the intensity of the light passing through the chromium layer;  $I_m$  is the intensity of the light passing through the clear areas (beyond the diffraction peaks); and  $\phi$  is the phase difference between  $I_o$  and  $I_m$ .  $R_t$  is a theoretically derived ratio, of approximately 0.25, which varies slightly depending on the coherence factor, viewing slit width, focus, proximity of the next edge, and other imaging conditions. For the conditions of measurement of this SRM in the NIST calibration system,  $R_T = 0.27$  (see below).

Real microscope images often include some flare light (light scattered off the microscope components illuminating the otherwise opaque features on the photomask from above or reaching the image plane by indirect paths). In nonlaser illumination systems, this light is temporally incoherent with respect to the light comprising the diffraction pattern (image profile) and simply adds incoherently (intensity-wise) to each intensity of the image profile.

To a first approximation the intensity of the flare light is not a function of position across a feature. Therefore, the effect of the flare light can be incorporated into eq (1) by simply subtracting its value from each intensity component on the image profile:

$$I_o = I'_o - I_f; \quad I_m = I'_m - I_f; \quad T_c = T'_c - I_f, \quad (2)$$

where the prime designates an observed intensity (including the effects of diffraction, transmission, and flare) and where  $I_f$  is the magnitude of the flare light component in the image profile for each feature. Substituting into eq (1) and solving for  $T'_c$  gives:

$$T_c = R_t [(I'_o - I_f) + (I'_m - I_f) + 2\sqrt{(I'_o - I_f)(I'_m - I_f)} \cos \phi] + I_f. \quad (3)$$

Both  $\phi$  and  $I_f$  must be known to evaluate the threshold condition.  $I_f$  is feature and background dependent and must be evaluated for each feature, but this is difficult unless either  $I_o$  or  $I_m$  is independently known. However if the coated layer is known to be homogeneous, the phase difference,  $\phi$ , and the transmissivity can be taken as constant over the mask. The transmissivity of the SRM was determined by using the linewidth measuring system to measure the intensity of light passing through the chromium near the center of the



large chromium-covered upper-left quadrant of the mask and was found to be less than 0.1% of the incident intensity, and  $I_o$  can be considered zero. Then, from eq (2),  $I_f = I_o'$  and eq (3) becomes:

$$T_c' = R_t (I_m' - I_o') + I_o', \quad (4)$$

and it is not necessary to determine a value for  $\phi$ . This is a significant simplification as there is no known simple method for determining  $\phi$ .

A further simplification may be accomplished by shifting the intensity zero level so that  $I_o' = 0$  (subtracting out the flare light); then the equation becomes:

$$T_c = R_t (I_m'). \quad (5)$$

A recent study of image profiles generated by a computer model, based on the theory of partial coherence, indicates that, with the NIST microscope and the SRM measurement conditions, the ratio  $R_t$  varies from 0.25 to 0.28 for ideal (vertical-walled, thin) lines and spaces 0.75 to 10.0  $\mu\text{m}$  wide (see fig. 9A). By setting  $R_t$  equal to 0.27 for determining edge location throughout the measurement of this SRM, the resulting contribution to linewidth error (difference from true linewidth) is less than  $\pm 0.01 \mu\text{m}$  (see fig. 9B).

### 3.5 Precision and Accuracy

The SRM certificate reports the measured linewidths and pitches (spacings). The reported values are the average of nine repeated measurements. The certified linewidths and pitches have separate uncertainty values because of subtle differences in the way errors affect the measurement of widths and pitches. The uncertainty statement given is based on two contributing factors: precision and accuracy.

Process precision is defined as the variability observed in repeated measurements of a single physical quantity under essentially the same conditions [3] and is intended to describe the reproducibility of the measuring device, the optical microscope, as well as all of the environmental conditions which may affect the measurement [4]. A numerical value for process precision cannot be determined until the measuring system is operating in a state of statistical control and the source of variability is shown to be random in nature and stochastically stationary. When these criteria have been met the process standard deviation quantifies this random error. The value for the process precision on the certificate of calibration includes the variability of the control measurements and the variability of the nine repeated SRM measurements. The details for computing this value are given in the Appendix.

Accuracy is the closeness of agreement between an observed value and an accepted reference value [5]. Pitch measurements of several features in a control SRM have been independently calibrated by the Dimensional Metrology Group on the NIST Line Scale Interferometer.

Comparison of these measurements with measurements of the same features made on the NIST linewidth measurement system shows a small scale factor difference. The source of this difference is not fully understood, but may be attributable, in part, to a small Abbé offset error on the linewidth measurement system. Hence, a correction factor is applied to all the SRM calibration measurements, using the NIST Line Scale Interferometer results as the standard, and the variance introduced by this procedure is included in the uncertainty given for all measurements (widths and pitches).

In the field of optical submicrometer linewidth metrology, the ideal reference standard with features which have vertical walls and smooth edges does not exist. Instead, real features have erratically varying, nonvertical edge geometries and raggedness along their length [6] (see fig. 10). To account for these systematic errors in the uncertainty statement, the feature edge geometry is examined using a scanning electron microscope (SEM). As this examination precludes use of the photomask as an SRM, only one sample from each photomask production batch is examined. The effective length of the viewing slit in the NIST instrument is  $2.6\text{ }\mu\text{m}$ , and the linewidth reported is the average over this length, positioned at the center of the line. Therefore both the nonvertical edge geometry and the raggedness along the length of the line are estimated as averages along the edge of the line.

Differences between the edge locations (and therefore linewidths) at the top surface and at the substrate were estimated at uniformly spaced intervals along a  $1\text{ }\mu\text{m}$  section of the sample as imaged in an oblique view SEM micrograph. The average of these differences is the estimated uncertainty due to the nonideal edge shape. The uncertainty thus estimated for SRM 476 is  $\pm 0.015\text{ }\mu\text{m}$  for each edge. The SEM micrographs also show that raggedness along the length of a line typically is less than  $30\text{ nm}$  and has a spatial period of  $0.1\text{ }\mu\text{m}$  or less. If the user's measurements of the SRM are averaged over a length comparable to that at NIST, then uncertainties due to edge raggedness become insignificant.

For width measurements, edge location errors for the right and left edges tend to add, making the linewidth uncertainty twice the edge location uncertainty [7]. The resulting level of inaccuracy,  $\pm 0.03\text{ }\mu\text{m}$ , is larger than the standard deviation of the calibration measurement, thus showing that the major contribution to the uncertainty of calibration is the nonideal edge geometry of the patterned features on the SRM.

For a typical series of SRM 476 photomasks the maximum systematic linewidth uncertainty, for rows A, B, and F, is estimated to be  $\pm 0.05\text{ }\mu\text{m}$ . This value includes the  $\pm 0.03\text{ }\mu\text{m}$  uncertainty resulting from the nonideal edge geometry estimated from the SEM photomicrographs, the  $\pm 0.01\text{ }\mu\text{m}$  maximum error introduced by use of the fixed value of 27% of the intensity,  $I_m'$ , as the edge location threshold (see sect. 3.4); and an estimated maximum  $0.01\text{ }\mu\text{m}$  of less quantitatively defined systematic errors.

Because pitch measurements involve measuring the distance from one location (left edge, right edge, or center) on one feature to the same location on another feature, edge detection errors tend to cancel and are not included in the maximum uncertainty reported for row E and G measurements.

The measurement precision is determined for each SRM photomask as described in the appendix and the pooled 95% confidence levels are reported for the width (rows A, B, and F) and pitch (rows E and G) measurements on the certificate data sheet.

The maximum uncertainty of the width and pitch values reported is a combination of the appropriate systematic uncertainties and measurement precision.

The user is advised to examine the edge properties of the photomasks to be measured. If the quality of the edges of the features on the user's photomasks is significantly inferior to that of this SRM, an additional level of uncertainty should be added to the uncertainty of measurements made on the user's photomasks.

#### 4. Using SRM 476

The following section provides information on the care and handling of the SRM photomask and gives basic instructions and precautions on its use for calibrating optical microscope systems for measuring linewidths of features on bright-chromium photomasks or similar artifacts.

##### 4.1 Special Precautions

Contamination or damage can change the measured linewidths, invalidating the NIST calibration. Particular care should be taken during use to avoid bringing the microscope objective, or any other object, into contact with the top (chromium-coated) surface of the SRM. It is recommended that users calibrate secondary standards of their own design and use these in routine calibrations while keeping the NIST standard in safe storage. If this is done, the secondary standards should be checked periodically against the NIST standard. Also, it may be advisable for the user to calibrate one or more of the uncalibrated patterns on the SRM for use in the event that the NIST calibrated pattern is destroyed.

This SRM is designed specifically for use with optical microscopes and, as no criterion has been established for edge location in an SEM image, this SRM can not be used to calibrate an SEM for linewidth measurements. Its use in an SEM is further discouraged because the profile of the feature could change as a result of coating the SRM with an evaporated film to reduce electrical charging, of deposition of contamination during operation of the SEM, and of detachment of the chromium during cleaning to remove evaporated films or contaminants.\*

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\*By using great care and low KV techniques, it is possible to view this SRM in an SEM without an evaporated film and thereby check the magnification of the SEM by measuring the spacing (pitch) of the features in rows E and G. However, other NIST SRMs, designed specifically for calibrating the magnification of SEMs, are recommended for this purpose. Also, after this SRM has been used in an SEM, its use for optical linewidth system calibration may no longer be valid.



Precautions should be taken to prevent the accumulation of airborne and other contaminants on the SRM. If cleaning becomes necessary, use only noncorrosive wetting solutions (surfactants) at room temperature.

For cleaning we recommend the following procedure:

Soak the SRM for 15 minutes to several hours in a mild solution of commercial mask cleaner and de-ionized water.

While the mask is still immersed, brush the coated side gently with a soft lens brush - stroke parallel to the calibrated line length and in one direction.

Rinse the mask thoroughly with de-ionized water.

Blow away water droplets with a stream of clean, dry air or nitrogen at room temperature.

If the contamination persists, apply a few drops of undiluted mask cleaner directly on the SRM before repeating the above cleaning process.

Removing fingerprints or other greasy contamination may require rinsing the SRM with alcohol or acetone.

#### 4.2 Microscope Calibration Procedures

The following procedure is recommended for using this SRM to calibrate optical microscope systems for measuring linewidths on bright-chromium photomasks. It is assumed the user is familiar with the operation of the microscope system being calibrated, and no attempt is made to give instruction on the use of microscope systems; however, instructions on setting up an optical microscope with Köhler illumination for dimensional measurements can be found in reference [8].



## Procedures

1. Set up the measurement system for dimensional measurements using the same procedures that will be used for measuring photomasks.
2. Locate within the microscope field-of-view the specific pattern group on the SRM that has been calibrated by NIST.
3. Check the resolving power of the microscope objective using feature G-0. If the objective cannot clearly resolve the 10 lines, use another objective.
4. Align the SRM so that lines are measured in a direction perpendicular to their length.
5. Adjust the measurement system length scale using feature E-5 (see fig. 3) to give the same reading for the spacing of the two inner lines as the NIST value.
6. Check for mechanical nonlinearity and/or optical distortion by measuring the spacings of the 10 lines in feature G-0 (or G-1) and comparing the results with the NIST values.

For all further measurements, use only the portion of the field of view corresponding to the location where the differences from NIST values are relatively constant or that portion of the video-display which exhibits minimum distortion.

## Explanatory Notes

Consult reference [8] for recommended procedures including adjustments for Köhler illumination.

Each pattern group has a pattern number located to the left of Row E. The SRM Certificate identifies the calibrated pattern group (see fig. 2).

The features within each pattern group are located by reference to an alphanumeric grid with the letters A, B, E, F, and G identifying the row and the numbers 0 through 9 identifying the column (see fig. 3).

The long vertical line, running from row A to row G at the far right (see fig. 3), may be used as an alignment aid.

Do not use any other standards or procedures for this adjustment of the length scale unless specifically instructed otherwise by the manufacturer of the instrument.

To differentiate between optical and mechanical errors, multiple tests must be made. For example, repeat the test with interchanged optics while using the same screw thread to determine if a given error pattern is due to mechanical errors rather than optical distortion. If the errors are small, restricting the field of view may eliminate the necessity of identifying the error source.

7. Adjust the line-to-space ratio on video-type image-scanning micrometer attachments by measuring the calibrated line and space of a feature in row F.

The widths of the left inner (long) line and the adjacent space between the two inner lines are certified.

Adjust the system contrast, brightness, and/or threshold until both measured widths agree as closely as possible with the NIST values.

Accurate linewidth measurements require a fixed relationship between a threshold in the image intensity profile, which corresponds to the physical line-edge location, and the video output or other signal from which the measurement is obtained.

Subtract out the flare light by setting  $I'_o$  to zero (see fig. 8 and eq (4) and (5) and determine the ratio  $T'_c/I'_m$ . Use this ratio to set the threshold for each subsequent measurement in this calibration session.

A flare light correction should be made when measuring linewidths on all photomasks (not only this standard).

NOTE: If any changes other than refocusing, repositioning and adjusting for flare are inadvertently made during the following steps discard the data and start again with Step 5.

8. Measure and record the widths of the calibrated features in rows A and B.

Use the same focusing criteria throughout.

For optical systems with Köhler illumination, a fine bright band (or other diffraction effects) may appear along the edge of the line image at best focus.

Do not refocus between setting on the left and right edges of the same line.

Make all measurement in the same direction of travel.

Some mechanical systems exhibit backlash when their direction of travel is changed.

9. Measure and record the line spacings (pitch) of NIST calibrated line pairs in row E.

10. Derive the calibration curves as described in reference [9].

These calibration curves apply only to this system/operator combination.

The system is now ready for measurement of other bright chromium photomasks or artifacts with similar optical properties to SRM 476 (high reflectivity and very low transmissivity) using the same threshold value and flare light correction procedure. If the user attempts to measure artifacts with chromium layers having transmission greater than 0.2%, it may be necessary to measure the phase angle,  $\phi$ , and use eq (3) to determine a different edge location threshold. These procedures are beyond the scope of this report.

Repeat the complete calibration procedure on a routine periodic basis and whenever a substantial change is made in the measurement system. The time between periodic calibrations may have to be determined empirically.

## 5. ACKNOWLEDGMENTS

Parts of this document (especially the procedures in sect. 4) are based on the earlier SRM 474 and SRM 475 Handbook prepared by Diana Nyysönen and John Jerke.

The photomicrographs used to examine the edge geometry were provided by the Scanning Electron Microscope Section, Sam Jones, William Keery, and Michael Postek, of the Microelectronics Dimensional Metrology Group.

Many thanks to Robert Larrabee for his guidance and advice and to Beverly Wright and her word processor for typing the numerous revisions of this document.

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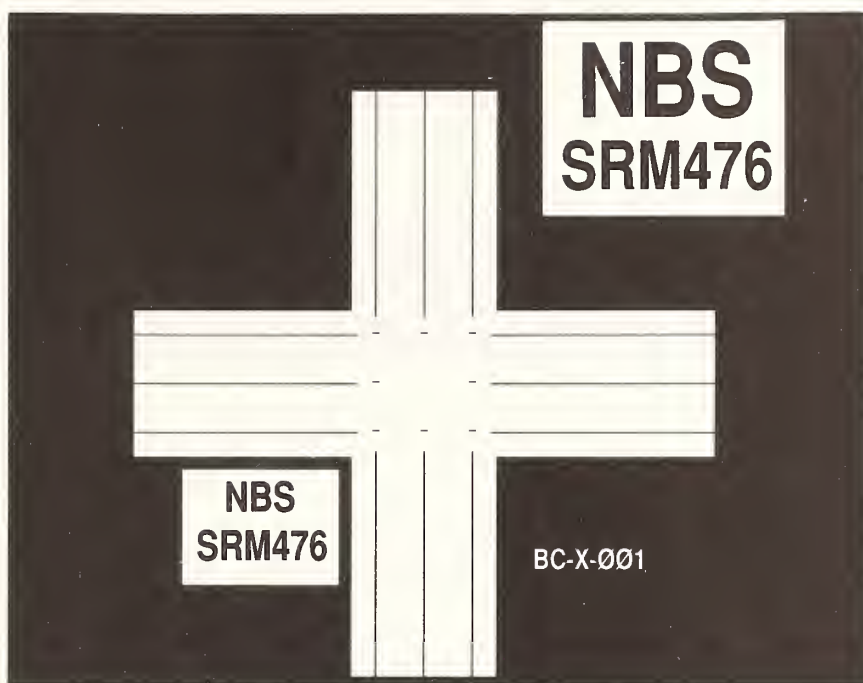


Figure 1. A view of the overall pattern on SRM 476. The basic measurement pattern is repeated eight times about the center. The horizontal and vertical lines help locate the patterns.

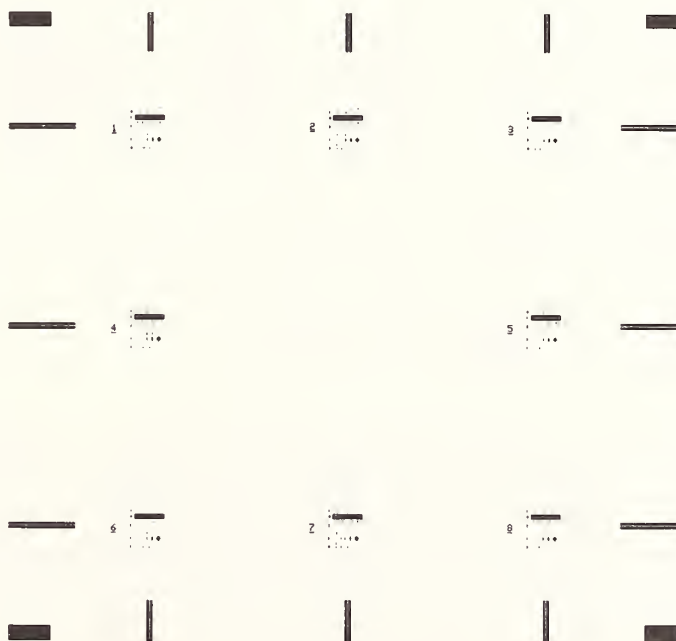


Figure 2. A view of the center of the SRM. The pattern number given with the serial number on the calibration sheet identifies which pattern has been measured by NIST. Pattern identification numbers can be seen to the left of each basic measurement pattern.



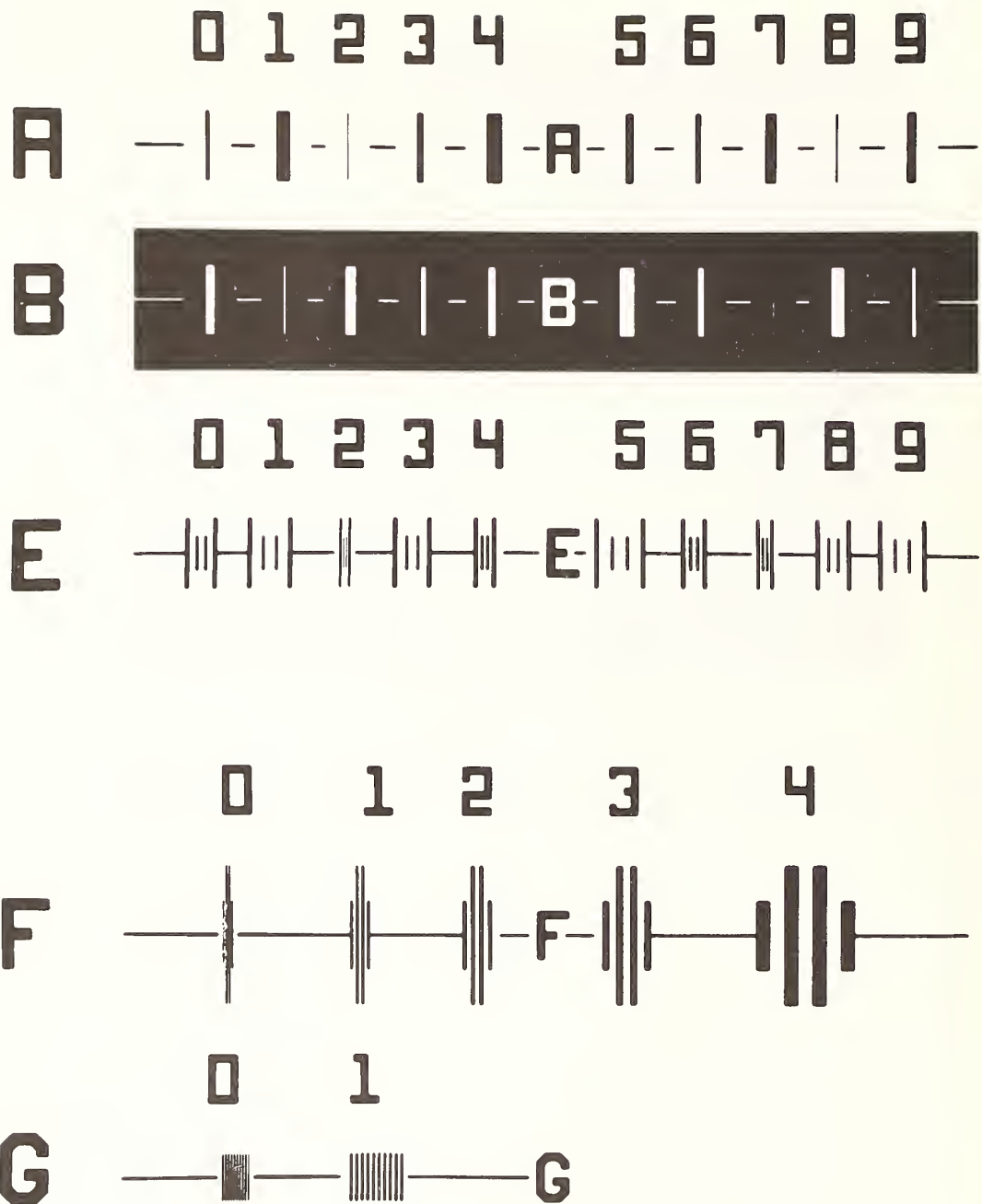


Figure 3. A view of one basic measurement pattern on the SRM. The individual lines and line patterns are located by reference to an alphanumeric grid with the letters identifying the row and the numbers identifying the columns. The long vertical line on the right is used to align the pattern on the measurement system. The broken horizontal lines mark the central calibrated area of the features.

Calibration values are given for: widths of opaque lines in row A and clear lines in row B; center-to-center spacing of the two inner (short) lines of each line pattern in row E; widths of the left inner (long) line and the space to its right of each line pattern in row F; and center-to-center spacings of lines relative to the first line on the left of each line pattern in row G.

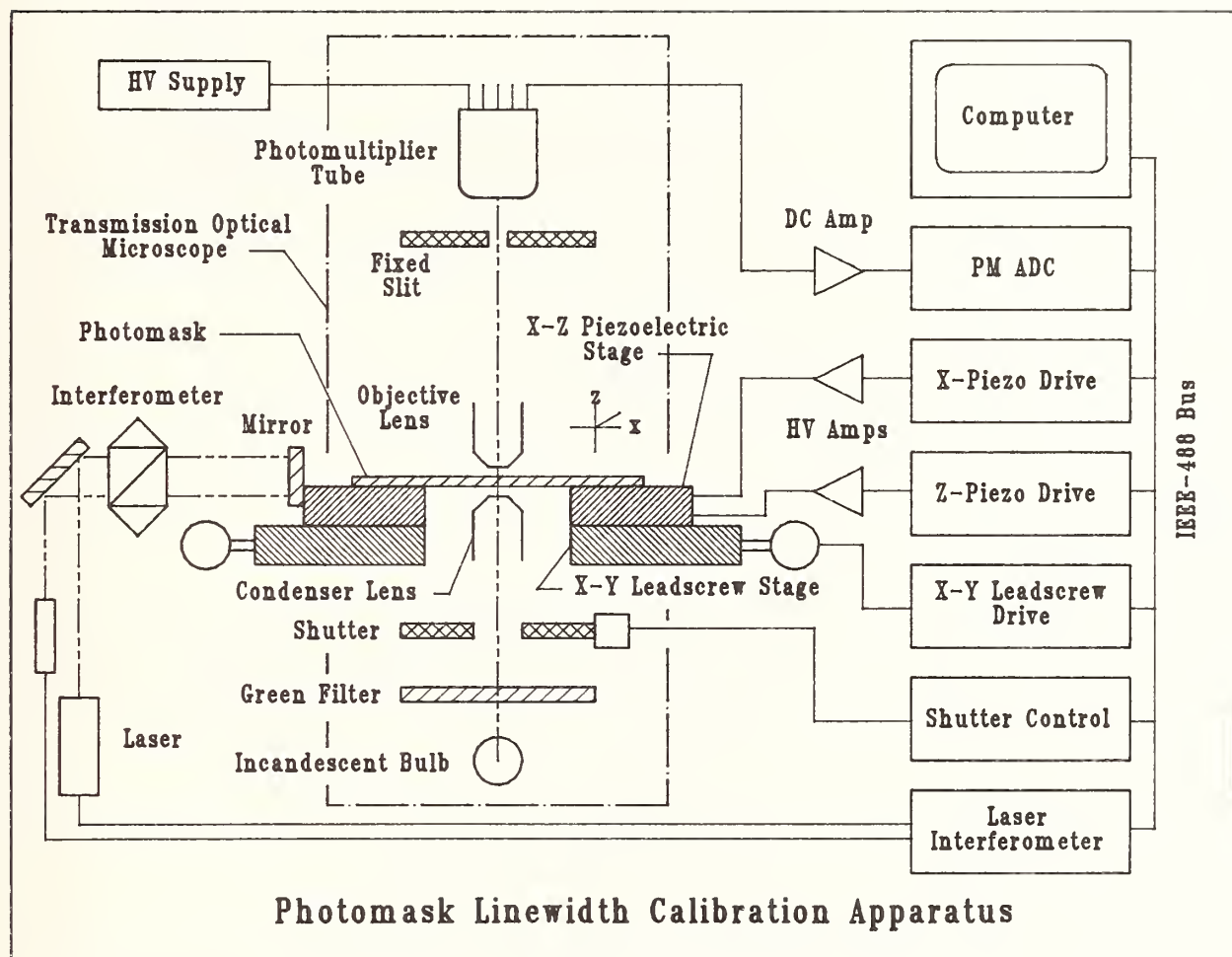


Figure 4. Schematic of the NIST automated optical linewidth calibration system. The photomask is placed on the scanning piezoelectric stage and is illuminated from below using partially coherent light from a filtered incandescent source. The measuring slit remains fixed while the image of the feature being measured is scanned past the slit by moving the photomask. The motion is measured with a laser interferometer and the image intensity at the slit is monitored with a photomultiplier. The digitized and amplified output of the photomultiplier and the interferometer output are connected via the IEEE-488 bus to the computer.



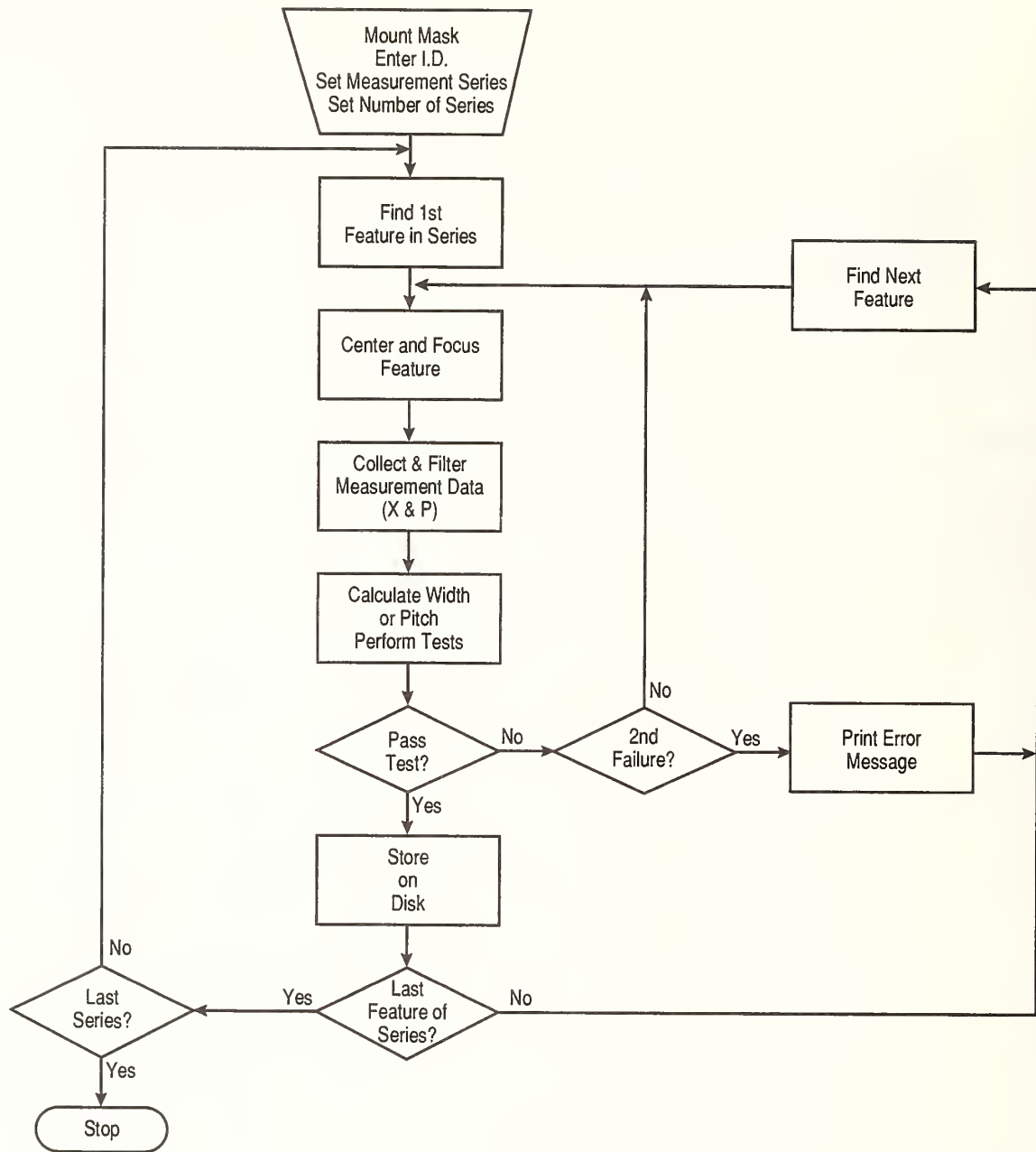


Figure 5. Flow chart outline of the overall calibration procedure for the calibration of SRM photomasks using the NIST optical linewidth measurement system. First, measurements are made on a control photomask and tested statistically to determine if the system is operating properly. Then, the SRM photomask is calibrated and the system operation is checked again by measuring the control photomask. If all tests indicate the system is within statistical control, a calibration certificate can be printed for the SRM photomask.

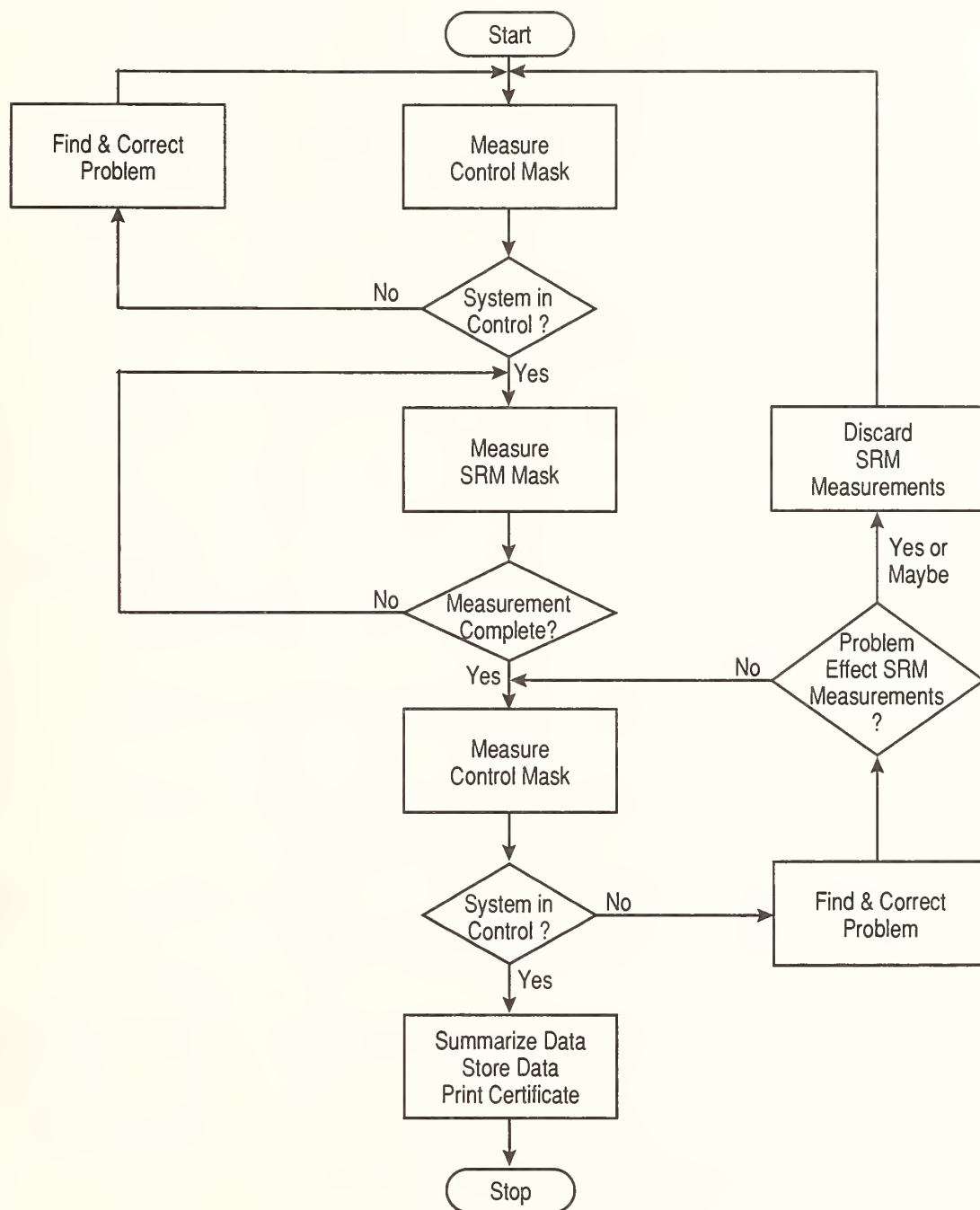
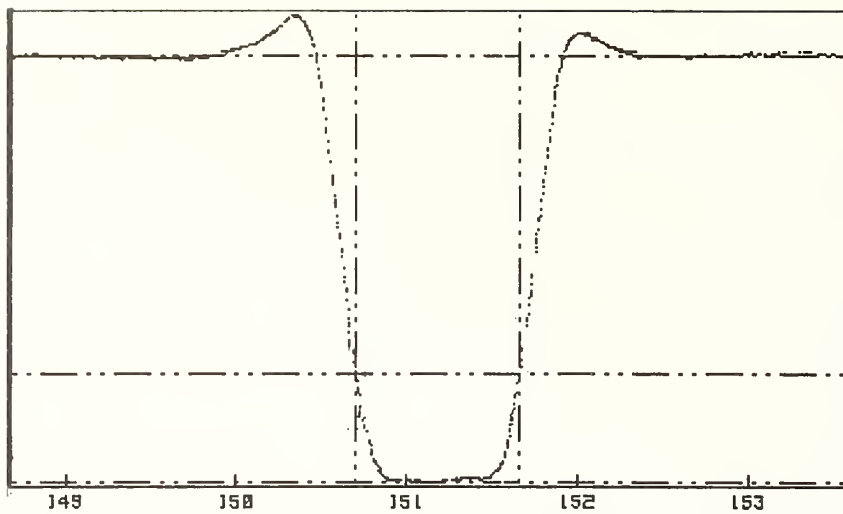
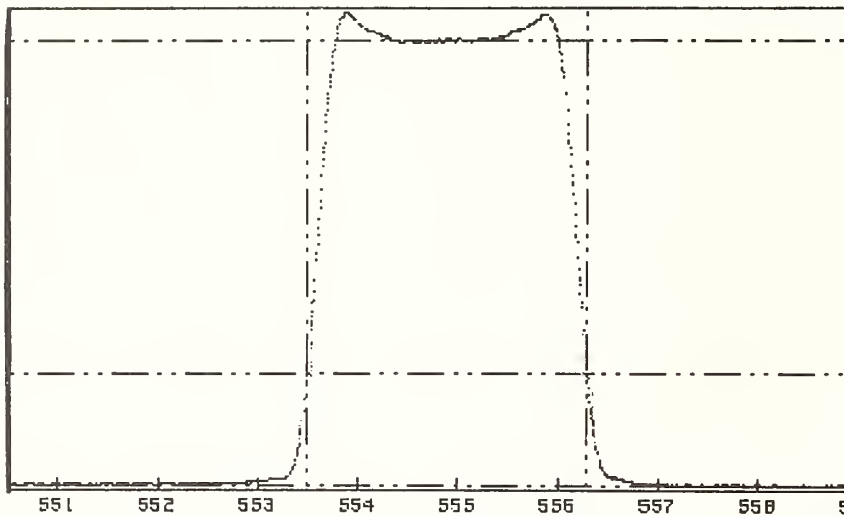


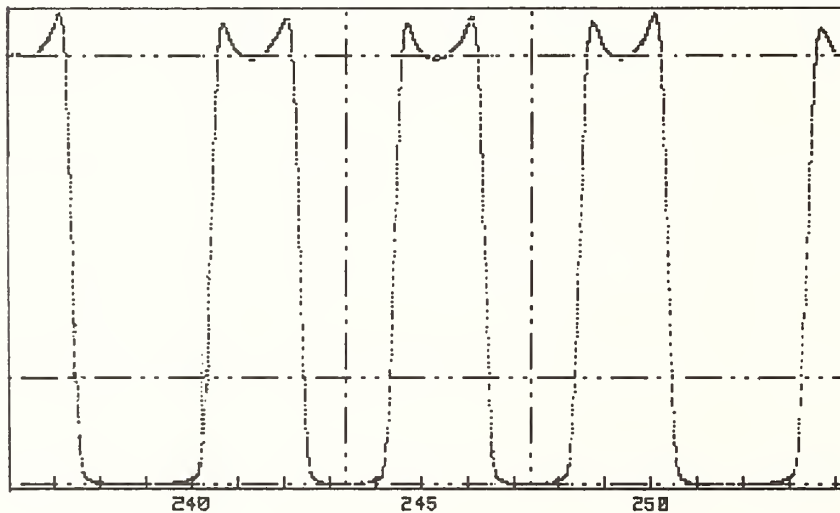
Figure 6. Flow chart of the main steps of the measurement sequence performed by the NIST optical linewidth measurement system. Each feature on the SRM photomask is located, focused, and measured in sequence. The sequence is repeated until each feature has been measured nine times. The optical profile position (X) and intensity (P) data are taken and stored as two one-dimensional arrays.



A. Profile of an opaque line in row A.



B. Profile of a clear line (space) in row B.



C. Profile of a line pair in row E. The profile includes the two outer guard lines as well as the line spacing pair.

Figure 7. Samples of optical profiles (measured light intensity versus position) displayed on the computer screen during the calibration process.

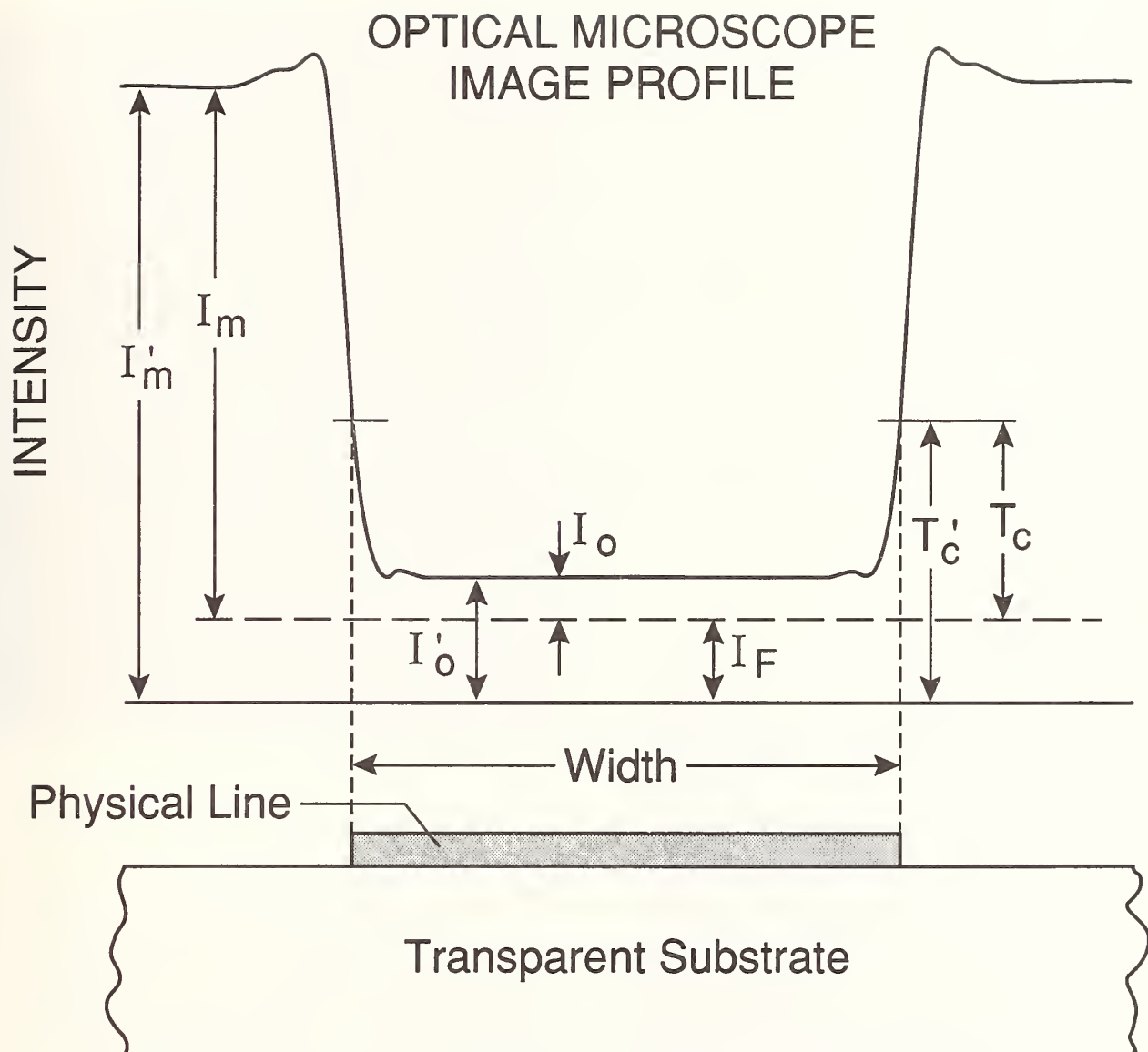


Figure 8. Schematic of the cross section of a vertical-edged chromium line and the corresponding optical profile of its microscope image.  $I_m$  is the intensity of the light passing through the clear area;  $I_o$  is the intensity of the light passing through the chromium;  $T_c$  is the intensity at the physical edge (threshold);  $I_f$  is the intensity of the flare light. The prime designates an observed intensity. The vertical axis is optical intensity and the horizontal axis is distance.

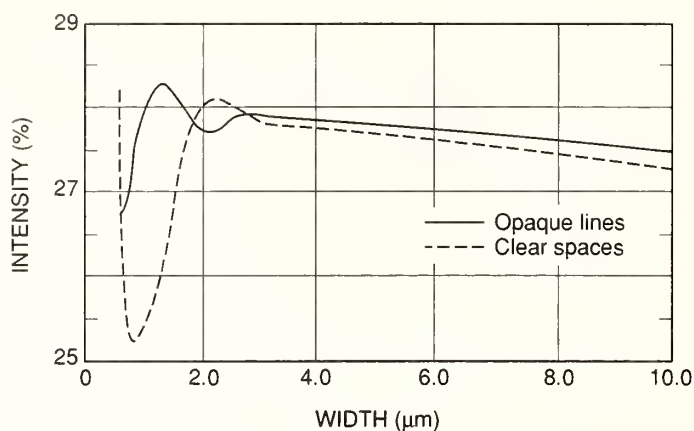


Figure 9. A - Optical intensity [% of  $(I_m - I_o)$ ] at edge location versus linewidth, from a computer model of the NIST calibration system.

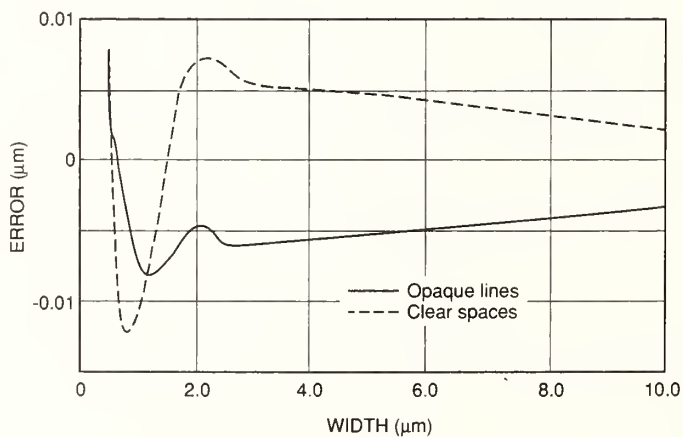


Figure 9. B - Theoretical linewidth error versus linewidth, assuming 27% of  $(I_m - I_o)$  is used as the threshold to determine edge location of lines and spaces using the NIST calibration system.

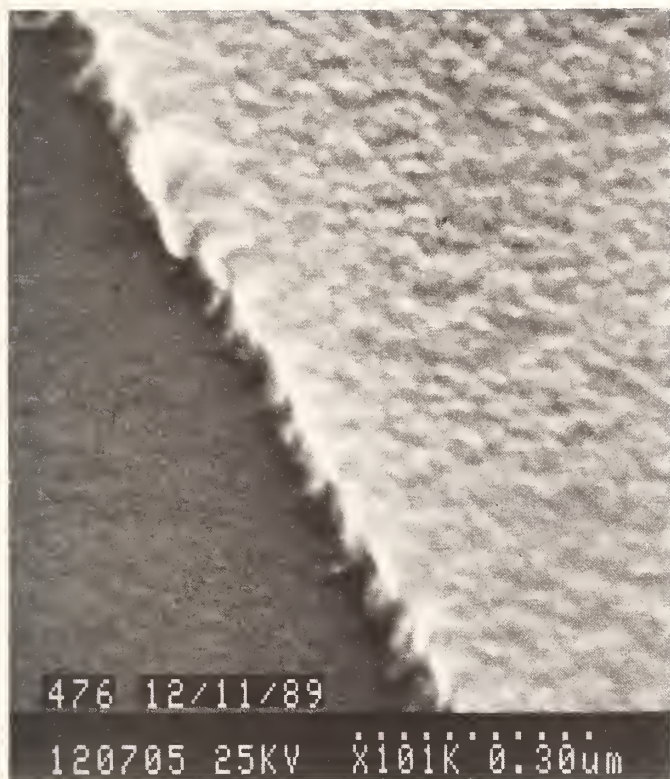


Figure 10. SEM photomicrographs showing the nonideal nature of line edges on a bright chromium photomask. The scale is indicated by the row of eleven dots in the lower right of each photomicrograph. In the upper photomicrograph, the dots are  $0.03\ \mu\text{m}$  apart and in the lower photomicrograph, they are  $0.06\ \mu\text{m}$  apart. Beam energy was 25 keV in both cases and the specimens were uncoated.





## Appendix

### Process Control for SRM 476 Calibrations

#### A. Introduction

The procedures used to assure statistical control of the linewidth SRM measurement system are defined. A control photomask with the same characteristics as the SRM photomask is used for measurement process control. Six of the features on the control photomask are measured each time an SRM photomask is calibrated. The six features are: the nominal 2.7 and 9.5  $\mu\text{m}$  lines from row A; the nominal 9.5 and 2.7  $\mu\text{m}$  lines from row B; and the nominal 4.0 and 10.8  $\mu\text{m}$  pitch patterns from row E. These correspond to features A-0, A-1, B-8, B-9, E-4, and E-5 as shown on the diagram of a pattern in figure A.1.

The purpose of the control photomask measurements is to provide a database that can be used to determine whether or not the measurement system is in a state of statistical control. There are several factors which may cause the optical measurement system to be out-of-control. There may be a change in the measurement system or a change in environmental conditions. This document describes the initialization of the database of control measurements, use of the database to determine if the measurement system is in control, and the maintenance of the database over a long period of time.

#### B. Initialization of Process Parameters

When the measurement system is determined to be ready for performing SRM calibrations, a database is initialized. This database consists of at least 15 sets of repeated measurements of the six selected features on the control photomask taken over a period of several weeks [1A]. This period is representative of normal operating mode of the optical measurement system. The six features measured are identified as A-0, A-1, B-8, B-9, E-4, and E-5. These features cover the extremes of the feature sizes and the range of the feature locations on the photomask. The database includes not only the measured width or space but also other pertinent information such as the date and time of the measurement and feature identification and any other potentially useful information (temperature, scan rate, etc.).

A plot, measured width or pitch versus time, of the repeated measurements for each feature is made to detect any possible anomalies in the measurement system and to verify that the system produces stable measurements whose variability is random in nature. The control database is accepted as being representative of the normal operating environment of the measurement system if no more than 5% of the measurements are suspected outliers (unexplained anomalies). If this is not the case, an effort is made to determine the cause and pertinent adjustments are made to the measurement system. The control database is then reinitialized.

The initial control database is used to estimate the mean vector (accepted mean values for each control feature) and the matrix of covariances between them. These are required elements for the multivariate Hotelling's  $T^2$  test statistic [2A]. The details for computing the estimate of the mean vector and the matrix of covariances are given below. The use of this test statistic and updating procedure for this statistic are given in following sections of this document.



From the database of control measurements for features A-0, A-1, B-8, B-9, E-4, and E-5, a matrix [X] is constructed, as shown below, of the N initial repeated measurements on the control photomask. Each of the features has the same number of repeated measurements,

$$X_{ij} = \begin{bmatrix} X_{A0,1} & X_{A0,2} & \dots & X_{A0,N} \\ X_{A1,1} & X_{A1,2} & \dots & X_{A1,N} \\ X_{B8,1} & X_{B8,2} & \dots & X_{B8,N} \\ X_{B9,1} & X_{B9,2} & \dots & X_{B9,N} \\ X_{E4,1} & X_{E4,2} & \dots & X_{E4,N} \\ X_{E5,1} & X_{E5,2} & \dots & X_{E5,N} \end{bmatrix} \quad \text{where } i = 1,2,\dots,6 \text{ and } j = 1,2,\dots,N . \quad (B.1)$$

The average is computed for each of the features based on the N repeated measurements,

$$\begin{aligned} \bar{X}_{A0} &= \sum_{j=1}^N \frac{X_{A0j}}{N} & \bar{X}_{A1} &= \sum_{j=1}^N \frac{X_{A1j}}{N} \\ \bar{X}_{B8} &= \sum_{j=1}^N \frac{X_{B8j}}{N} & \bar{X}_{B9} &= \sum_{j=1}^N \frac{X_{B9j}}{N} \\ \bar{X}_{E4} &= \sum_{j=1}^N \frac{X_{E4j}}{N} & \bar{X}_{E5} &= \sum_{j=1}^N \frac{X_{E5j}}{N} . \end{aligned} \quad (B.2)$$

These values are the elements of the vector of means as denoted below:

$$M = \begin{bmatrix} \bar{X}_{A0} \\ \bar{X}_{A1} \\ \bar{X}_{B8} \\ \bar{X}_{B9} \\ \bar{X}_{E4} \\ \bar{X}_{E5} \end{bmatrix} , \quad (B.3)$$

A matrix is computed of the differences of the measured values minus the mean values,

$$Z_{ij} = X_{ij} - M_i \quad \begin{array}{l} \text{where } i = 1, 2, \dots, 6 \\ \text{and } j = 1, 2, \dots, N, \end{array} \quad (\text{B.4})$$

and the variance-covariance matrix,  $S$ , of size  $6 \times 6$ , of the control database is computed with elements:

$$S_{ij} = \frac{1}{N-1} \sum_{k=1}^N (Z_{ik}) (Z_{jk}) \quad \begin{array}{l} \text{where } i = 1, 2, \dots, 6 \\ \text{and } j = 1, 2, \dots, 6. \end{array} \quad (\text{B.5})$$

The inverse of the variance-covariance matrix is computed and is used in conjunction with future control measurements to determine if the measurement system remains in a state of statistical control.

### C. Procedures for Process Control

At the beginning of an SRM measurement session the features A-0, A-1, B-8, B-9, E-4 and E-5 on the control mask are measured and the multivariate Hotelling's test statistic  $T^2$  is computed as follows:

$$T^2 = \left( \frac{N}{N+1} [Y - M]' S^{-1} [Y - M] \right), \quad (\text{C.1})$$

where  $Y$  is a vector of newly determined widths and pitches for the above mentioned features.

The system is in control at a 95% confidence level if

$$\frac{(N-6)}{(N-1)6} T^2 \leq F_{.05}(6, N-6), \quad (\text{C.2})$$

where  $F_{.05}(6, N-6)$  values are found in table I. The value  $(N-6)$  corresponds to  $\nu$  in table I.

At the end of the SRM measurement session, the control is remeasured and the test is repeated. If the system is still in control the SRM data are summarized and a certificate of calibration produced. The value of  $((N-6)/6(N-1))T^2$  is saved in the control database.

If the test indicates the system is not in control, the data is tagged when it is saved in the control database. The system is then checked to determine the cause of the test failure. A control chart may be used to determine which feature is causing the problem or to see trends in the control data. A control chart for each feature is constructed from the control database as follows:

The mean,  $\bar{X}$ , and the standard deviation,  $\hat{\sigma}$ , for each feature are computed using the  $N$  repeated measurements from the control database:

$$\bar{X} = \frac{\sum_{i=1}^N X_i}{N} \quad \text{and} \quad \hat{\sigma} = \sqrt{\frac{\sum_{i=1}^N (X_i - \bar{X})^2}{(N - 1)}} \quad (C.3)$$

Control limits are computed using the following equations:

$$\begin{aligned} & \bar{X} \pm \hat{\sigma} t_{.975}(N-1) \text{ for the } 2\sigma \text{ limit} \\ \text{and} & \\ & \bar{X} \pm \hat{\sigma} t_{.995}(N-1) \text{ for the } 3\sigma \text{ limit.} \end{aligned} \quad (C.4)$$

The value of  $t$  is found in table II. The value,  $(N - 1)$ , denotes degrees of freedom,  $df$ , in table II.

Figure A.2 is an example of a control chart of the initial 19 measurements of feature A-0. Future measurements are added to the chart. The control limits remain the same until the process parameters are updated.

If it is determined that the cause of the failure did not affect the SRM measurements (for example, the control photomask was misaligned), the appropriate adjustments are made and the control photomask is remeasured. If the test then shows the process is in control, the system is ready for SRM measurements.

If it is determined that the cause of the failure may also have affected the SRM measurements (for example, the air-conditioning unit malfunctioned during calibration), the SRM must be re-measured after the problem has been corrected and the test indicates the system is once again in control. Major changes to the measurement system dictate reinitialization of the database.

#### D. Updating Process Parameters

If the measurement system remains unchanged, after collecting a minimum of 30 new (good) sets of control photomask measurements, the process parameters,  $M$ ,  $S$ , and  $\hat{\sigma}$  are updated. Equation (B.3) is used to compute  $M_2$ , a vector of estimated means for the recently collected control measurements; eqs (B.4) and (B.5) are used to compute  $S_2$ , the corresponding variance-covariance matrix; and eq (C.3) is used to compute  $\hat{\sigma}_2$ , a vector of standard deviations for the repeated measurements for each feature. In the updating process, values that have been flagged as out of control are omitted.

Before updating the control database, a comparison is made between the two databases, the old versus the new, to determine whether or not there is a significant difference in terms of the mean vectors and the variance-covariance matrices. The equivalency of variance-covariance matrices is tested as follows:

$$\text{let } \ell = N_1 + N_2, \quad (\text{D.1})$$

where  $N_1$  = number of repeated observations in the control database  
and  $N_2$  = number of repeated observations in the new set of control observations.

The new control database will contain both new and old measurements.

$$\text{Let } S = \frac{(N_1 S_1) + (N_2 S_2)}{\ell}, \quad (\text{D.2})$$

where  $S_1$  is the variance-covariance matrix of the current control database  
and  $S_2$  is the variance-covariance matrix of additional new control measurements.

Compute the statistic [3A]:

$$D = 0.5N_1 \text{ trace } [(S_1 - S)S^{-1}]^2 + 0.5N_2 \text{ trace } [(S_2 - S)S^{-1}]^2; \quad (\text{D.3})$$

and test whether:

$$D \leq \chi_{df}^2(0.05).$$

D is distributed as a chi-square random variable with df (degrees of freedom) =  $0.5p(p+1)$  where  $p = 6$ , the number of features measured. The value of  $\chi_{21}^2(0.05)$  is 32.67. If  $D \leq 32.67$ , then the differences between the old and new covariance matrices can be attributed to measurement error at the 95% confidence level. However, if the test fails, ( $D > 32.67$ ), this suggests that the process has changed in some manner and the cause needs to be identified and evaluated. If the change is significant, appropriate action must be taken and the control process re-initialized.

If the covariance matrices are statistically the same, the means are compared. To do this, first a pooled covariance matrix is computed:

$$S_p = \frac{[(N_1-1)S_1 + (N_2-1)S_2]}{\ell-2}, \quad (D.4)$$

where  $S_1$  and  $S_2$  are defined in (D.2).

Then the statistic is computed:

$$T^2 = \frac{(\ell-p-1)(N_1N_2)}{(\ell-2)p(\ell)} (M_1 - M_2)' S_p^{-1} (M_1 - M_2); \quad (D.5)$$

and tested whether:

$$T^2 \leq F_{.05}(p, \ell-p-1)$$

where  $N_1$ ,  $N_2$  and  $\ell$  are defined in (D.1),

$M_1$  is the mean vector for the current database,

$M_2$  is the mean vector for the newly collected control data,

and  $p = 6$ , the number of measured features.

$T^2$  is a random variable with an F-distribution with  $p$  degrees of freedom in the numerator and with  $\ell-p-1$  degrees of freedom in the denominator. The  $F_{.05}(p, \ell-p-1)$  value is given in table I. If  $T^2 > F_{.05}(p, \ell-p-1)$ , this suggests that there has been a change in the measurement process. The change needs to be identified and appropriate action needs to be taken to reestablish the measurement system and begin the process control anew. However, if  $T^2 \leq F_{.05}(p, \ell-p-1)$  then the differences between the old and new mean vectors can be attributed to measurement error at the 95% confidence level. Since the test for equality of means was only performed if the hypothesis of equal covariance matrices was not rejected, it can be said that there has been no statistically discernable change in the measurement process at the 90% confidence level and the control may be updated to include the new measurements. The covariance matrix is updated as shown in eq (D.4) and the current covariance matrix is:

$$S = S_p. \quad (D.6)$$



The mean vector is updated as shown below:

$$M = \frac{N_1 M_1 + N_2 M_2}{N_1 + N_2} . \quad (D.7)$$

The standard deviation for each feature is updated as follows:

$$\hat{\sigma} = \sqrt{\frac{(N_1 - 1)\hat{\sigma}_1^2 N_1 + (N_2 - 1)\hat{\sigma}_2^2 N_2}{N_1 + N_2 - 2}} . \quad (D.8)$$

#### E. Uncertainty Statement for SRM 476

The uncertainties for the certified linewidth and pitch values given in the certificate include small contributions from the measurement precision (random error) and a contribution due to systematic error. The systematic error for pitch values consists of the variance introduced by correcting the measurements to agree with the NIST Line Scale Interferometer measurements (see sect. 3.5). The systematic error for the linewidth values has a significant contribution ( $\pm 0.05 \mu\text{m}$ ) resulting from the finite material edge geometry of the features (see sect. 3.5) plus a small contribution from the correction factor mentioned above.

Before determining the total uncertainty for the reported certificate values, it is assumed that all the measurements on the SRM and in the control database have been corrected to compensate for the difference of measurements between the NIST Line Scale Interferometer System and the optical linewidth measurement system. The correction factor is derived by using the model given below and ordinary least squares to estimate  $\alpha$  and its variance:

$$X = \alpha Y + \epsilon \quad (E.1)$$

where  $X$  represents a measurement from the linewidth measurement system,  
 $Y$  represents a measurement from the line scale measurement system,  
and  $\epsilon$  is the random error of measurement.

Then the uncertainties,  $U_L$  and  $U_p$ , for linewidth and pitch measurements are determined by the equations below:

The variance of each SRM measurement,  $\hat{s}_j^2$ , is

$$\hat{s}_j^2 = \bar{x}_j^2 \frac{\text{var}(\hat{\alpha})}{\hat{\alpha}^2} + \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x}_j)^2 \quad (\text{E.2})$$

where  $\bar{x}_j$  is the average of the  $j$ th feature,  
 $\text{var}(\hat{\alpha})$  is the estimated error of the slope,  
 $\hat{\alpha}$  is the least squares determination of the slope,  
and  $n$  is the number of repeated measurements.

The variance of the control measurements,  $\hat{\sigma}_k^2$ , is

$$\hat{\sigma}_k^2 = \bar{c}_k^2 \frac{\text{var}(\hat{\alpha})}{\hat{\alpha}^2} + CV_k \quad (\text{E.3})$$

where  $\bar{c}_k$  is the average of the  $k$ th control feature  
and  $CV_k$  is the diagonal of the variance-covariance matrix for the control data.

Then the pooled variance from the  $N$  repeated measurements in the control database and the  $n$  repeated measurements of the SRM,  $\hat{s}_p^2$ , is

$$\hat{s}_p^2 = \frac{(N-1) \sum_{k=1}^p \hat{\sigma}_k^2 + (n-1) \sum_{j=1}^q \hat{s}_j^2}{(N-1)p + (n-1)q}. \quad (\text{E.4})$$

The uncertainty for pitch measurements is:

$$U_p = \pm(1.96 s_p/\sqrt{n}) \mu\text{m}. \quad (\text{E.5})$$

The total uncertainty for linewidth measurements is:

$$U_L = \pm(1.96 s_p/\sqrt{n} + 0.05) \mu\text{m} \quad (\text{E.6})$$

where  $s_p$  is determined by using eqs (E.2), (E.3), and (E.4) for pitch and linewidth measurements on the SRM and in the control database.

#### ACKNOWLEDGMENTS

The authors thank Susannah Schiller for suggesting the statistical tools to assure process control of the linewidth SRM measurement system and for her review of this documentation.

#### REFERENCES

- [1A] Croarkin, Carroll. Measurement Assurance Programs Part II: Development and Implementation. Natl. Bur. Stand. Spec. Publ. 676-II; 1985. pp. 35.
- [2A] Anderson, T.W. An Introduction to Multivariate Statistical Analysis, Second ed. John Wiley and Sons, 1984. Chapter 5, pp. 156-190.
- [3A] *ibid.*, p. 423.

Table I Critical Values of  $F_{\alpha, \nu_1, \nu_2}$  of the F - Distribution

$\nu_1$	$F_{\alpha, \nu_1, \nu_2}$
10	3.217
12	2.996
14	2.848
16	2.741
18	2.661
20	2.599
22	2.549
24	2.508
26	2.474
28	2.445
30	2.421
32	2.399
34	2.380
36	2.364
38	2.349
40	2.336
42	2.324
44	2.313
46	2.304
48	2.295
50	2.286
52	2.279
54	2.272
56	2.266
58	2.260
60	2.254
62	2.249
64	2.244
66	2.239
68	2.235
70	2.231
72	2.227
74	2.224
76	2.220
78	2.217
80	2.214
82	2.211
84	2.209
86	2.206
88	2.203
90	2.201
92	2.199
94	2.197
96	2.195
98	2.193
100	2.191
102	2.189
104	2.187
106	2.185
108	2.184
110	2.182
112	2.181
114	2.179
116	2.178
118	2.176
120	2.175
$\infty$	2.099

Table II Critical Values of  $t_{\alpha, \nu}$  and  $t_{0.95, \nu}$  of the Student's t Distribution

$\nu$	$t_{\alpha, \nu}$	$t_{0.95, \nu}$
10	2.228	3.169
12	2.179	3.055
14	2.145	2.977
16	2.120	2.921
18	2.101	2.878
20	2.086	2.845
22	2.074	2.819
24	2.064	2.797
26	2.056	2.779
28	2.048	2.763
30	2.042	2.750
32	2.037	2.738
34	2.032	2.728
36	2.028	2.719
38	2.024	2.712
40	2.021	2.704
42	2.018	2.698
44	2.015	2.692
46	2.013	2.687
48	2.011	2.682
50	2.009	2.678
52	2.007	2.674
54	2.005	2.670
56	2.003	2.667
58	2.002	2.663
60	2.000	2.660
62	1.999	2.657
64	1.998	2.655
66	1.997	2.652
68	1.995	2.650
70	1.994	2.648
72	1.993	2.646
74	1.993	2.644
76	1.992	2.642
78	1.991	2.640
80	1.990	2.639
82	1.989	2.637
84	1.989	2.636
86	1.988	2.634
88	1.987	2.633
90	1.987	2.632
92	1.986	2.630
94	1.986	2.629
96	1.985	2.628
98	1.984	2.627
100	1.984	2.626
102	1.983	2.625
104	1.983	2.624
106	1.983	2.623
108	1.982	2.622
110	1.982	2.621
112	1.981	2.620
114	1.981	2.619
116	1.981	2.618
118	1.980	2.617
120	1.980	2.616
$\infty$	1.960	2.576



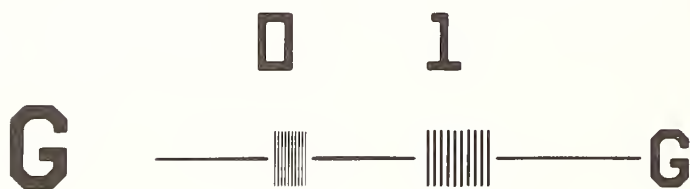
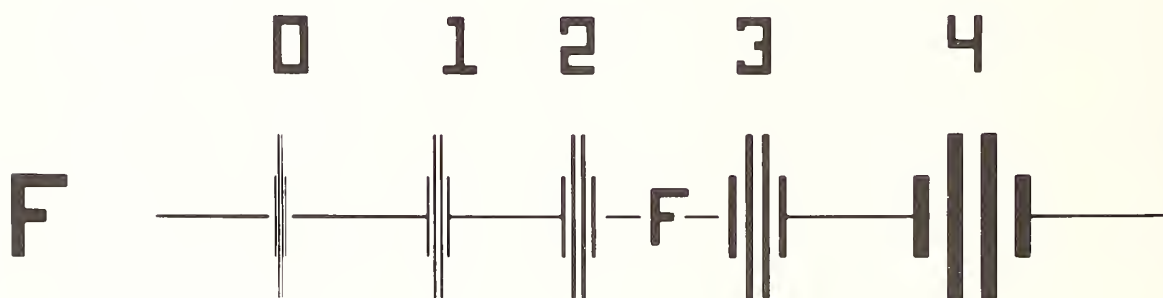
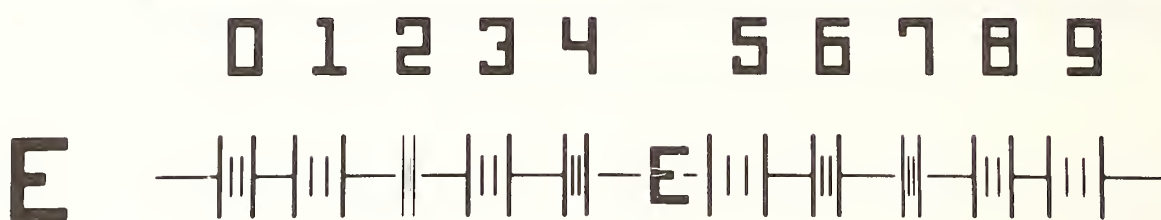
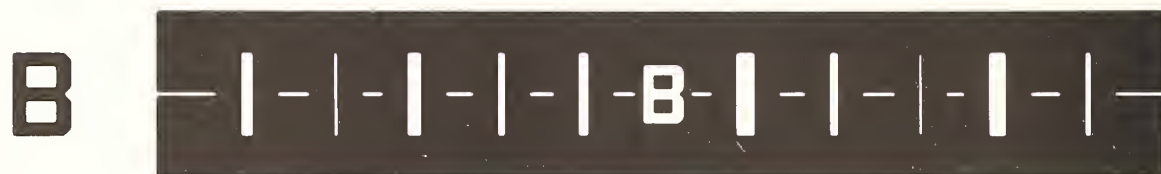
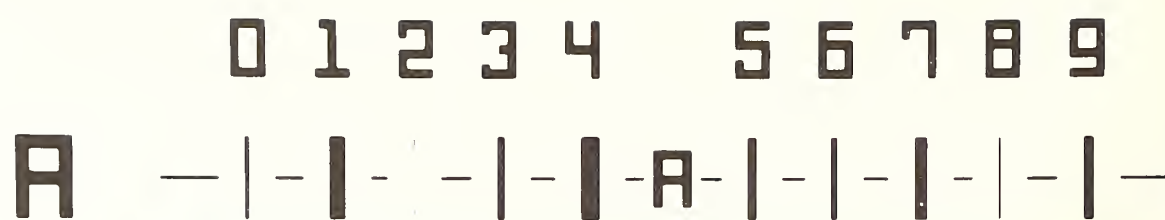


Figure A.1. A view of the basic pattern on the SRM 476 control photomask. Features 0 and 1 in row A, 8 and 9 in row B, and 4 and 5 in row E are measured before and after each SRM is calibrated. Features 4 and 5 in row E and feature 1 in row G have been independently calibrated on the NIST Linescale Interferometer by the NIST Dimensional Metrology Group.

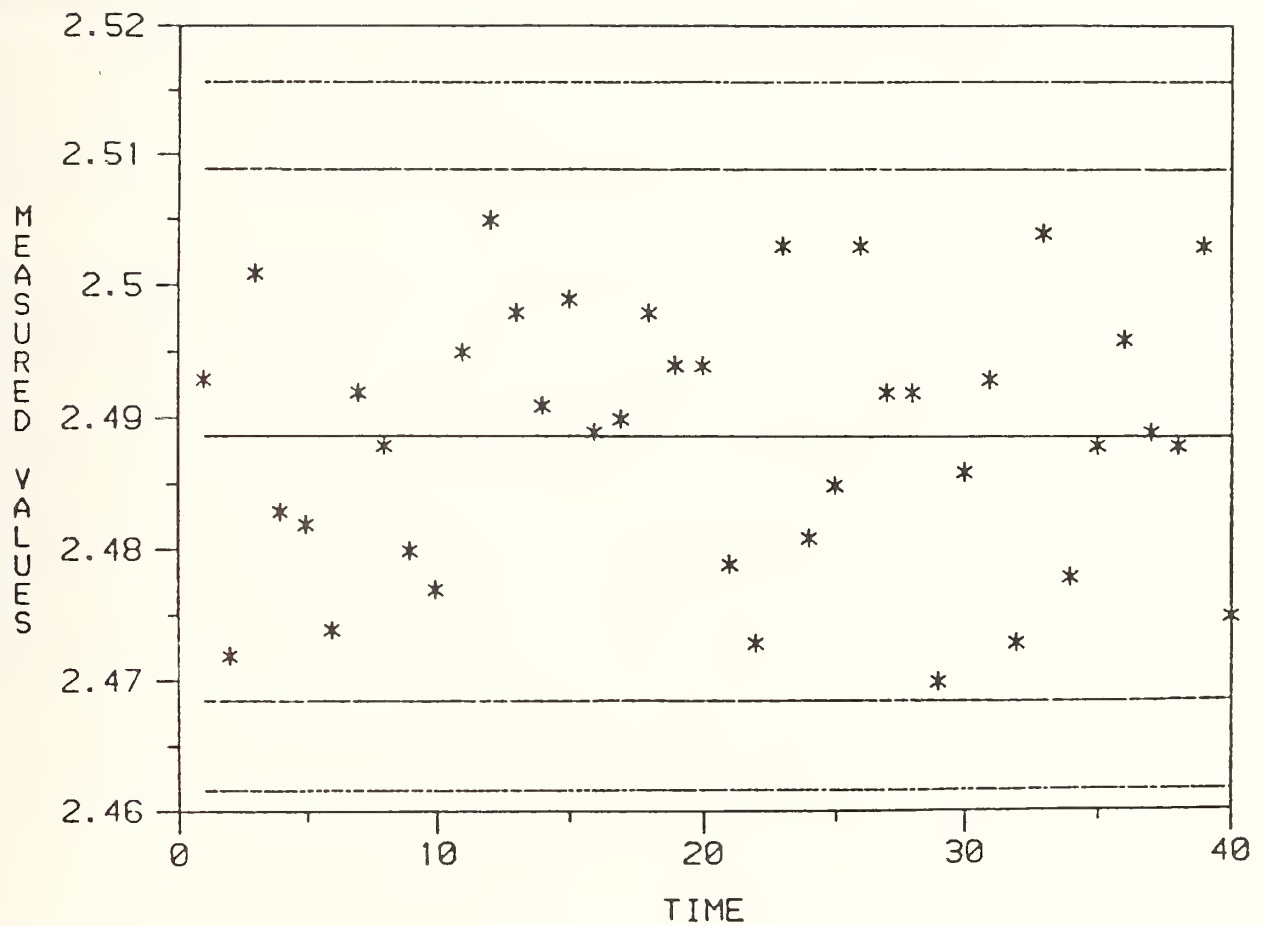


Figure A.2. Control chart of feature A-0. Solid line is the mean; dotted line is the 99% level; and the dashed is the 95% level.

The chart includes the first 19 measurements of the feature. Future measurements are added to the chart.



# BIBLIOGRAPHIC DATA SHEET

4. TITLE AND SUBTITLE

Bright-Chromium Linewidth Standard, SRM 476, for Calibration of Optical Microscope Linewidth Measuring Systems

5. AUTHOR(S)

Carol F. Vezzetti, Ruth N. Varner, and James E. Potzick

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☐ DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

Standard Reference Material, SRM 476, was developed for use in calibrating optical microscopes used to measure linewidths in the range of 0.9 to 10.8 micrometers on bright chromium photomasks, such as those used in the production of integrated circuits. The SRM, the measurement system, and the procedures used to calibrate the SRM are described. The algorithm for determining the line edge location uses a threshold criterion derived from analysis of microscope image profiles. The profiles are predicted by computer modeling based on the theory of partial coherence. The performance of the system is monitored by measuring line features on a control photomask before and after calibrating each SRM.

Precautions concerning care and handling and instruction for the use of SRM 476 to calibrate optical microscopes for photomask linewidth measurement are given.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

accuracy; bright chromium; calibration; control charts; critical dimensions; integrated circuits; linewidth measurement; optical microscope; photomask; precision; process control; semiconductor industry; standard reference material; threshold; uncertainty.

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