# A New Line Width Standard for Reflected Light Inspection

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## ABSTRACT

A new Line Width Standard has been developed. It is a physical specimen consisting of calibrated lines and spaces patterned in metal and dielectric layers on a silicon substrate. The standard is for calibration of reflected light measurement systems. The Line Width Standard is designed such that the optical profile of the standard can be very nearly matched to the optical profile of the specimen the user wants to measure. The calibration of the Line Width Standard is based on first principles of physics and is therefore a primary standard. A special measurement system based on an optical scanning microscope developed at the National Bureau of Standards was built to calibrate the line and space dimensions.

## 1. Introduction

As lithographers continually shrink the dimensions of microelectronic features, the science of measuring line widths is constantly being challenged. There are three major methods presently used in the semiconductor industry to measure critical dimensions of features on silicon wafers. These methods are: reflected light optical microscopy, scanning electron microscopy and electrical test structures.

Reflected light line width metrology holds several advantages over the other two methods. Optical line width measurement instruments provide a quicker turn around time than electrical testing. Compared to scanning electron microscopes, optical systems are non-destructive and offer faster throughput. However, the recent trend in the industry has been to rely more upon scanning electron microscopes and electrical test structures and less upon optical instruments for the most critical measurements. This is because reflected light microscopes have exhibited inaccurate measurements on features a few micrometers in width and smaller [1].

Are optical microscopes simply incapable of accurately measuring features this small? This is apparently not the case.

The National Bureau of Standards has done extensive theoretical modeling of optical line width measurements [2,5,6]. This includes both reflected light systems used to measure features on wafers and transmitted light systems used to measure features on photomasks. They have shown that both types of systems can theoretically perform accurate measurements of features which have dimensions as small as the wavelength of the inspection light. This means an ideal visible light system should be able to measure features as small as 0.5 micrometer in width.

Transmitted light line width measurement systems are routinely used to measure micrometer and submicrometer line widths on photomasks with acceptable accuracy. Why have reflected light systems been unable to perform up to their theoretical potential or at least as well as transmitted light systems? The most significant reason is that they are often not calibrated correctly.

To maintain accuracy of transmitted light photomask measurement systems, calibrated reference standards are available from several sources including the National Bureau of Standards [8]. However, until now, there have been no reference standards available to calibrate reflected light line width measurement systems. This paper describes a line width standard specifically designed for this purpose.

## 2. Primary Reference Standards

Since no reference standards presently exist to calibrate reflected light line width measurement instruments, any new accurate reference standard developed must be derived from basic physical principles. This is called a primary standard. To make a primary standard, the following steps must be accomplished:

1) A rigorous theoretical model of the measurement procedure must be developed which is based upon fundamental physical principles and takes into account all the parameters which influence the measurement.

2) The measurement instrument used to calibrate the standard must operate consistent with the theoretical model.

3) The standards to be calibrated must also be consistent with the theoretical model.

## 3. Line Width Measurement: The Optical Profile

Most line width measurement instruments presently used to measure features on silicon wafers operate in the following manner:

1) A reflected light optical microscope produces a magnified image of a microelectronic feature (line or space).

2) A photometric mechanism in the image plane of the microscope generates an optical profile of the feature. The optical profile data is electronically digitized and stored in a computer.

3) The optical profile is then analyzed by a software algorithm to yield a line or space width value.

An optical profile is the intensity cross-section of the image of the feature. When graphed, as shown in Figure 1, the vertical axis of the optical profile is the image intensity and the horizontal axis is distance.

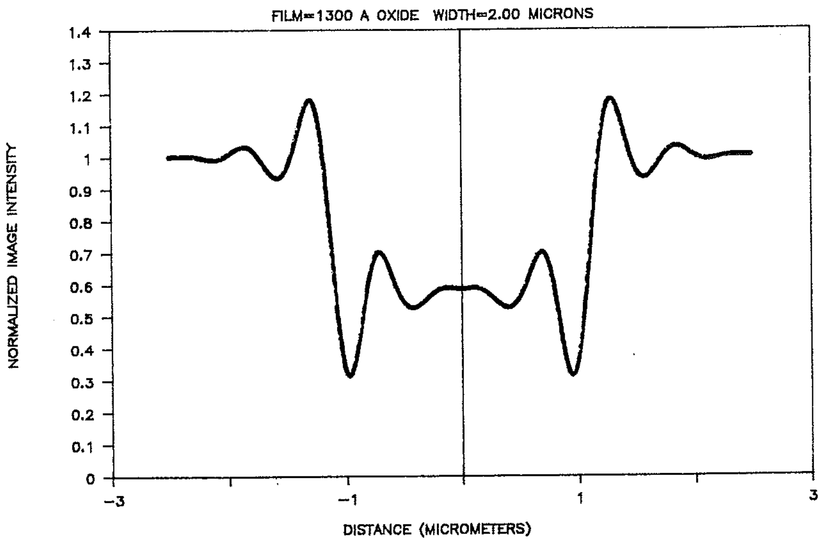

Figure 1. Typical optical profile.

## 4. The Problem: Correct Edge Detection

Once the optical profile is measured, the software algorithms must analyze the optical profile data and accurately deduce the width of the line or space. Specifically, the algorithm must find the two points on the optical profile which correspond to the physical edges of the feature. The most common algorithm is to draw a horizontal line, or threshold, through the optical profile. The points where the threshold crosses the profile are assumed to be the feature edges. Another common algorithm chooses the minima as the location of the feature edges.

Figure 2 demonstrates how two different algorithms, A) the 50% threshold and B) the minima, would measure the same optical profile. It is clear that these two algorithms would produce two different line width values [4]. The actual physical line is drawn on the graph for comparison. Which algorithm is correct (if either)? A critical step in calibrating a line width measurement instrument is finding the algorithm which correctly detects the edges of a line or space. If all features encountered in the semiconductor industry produced the same optical profile in a reflected light microscope, calibration would be greatly simplified. However, this is not the case. The range of images (and the resulting optical profiles) encountered is extremely varied.

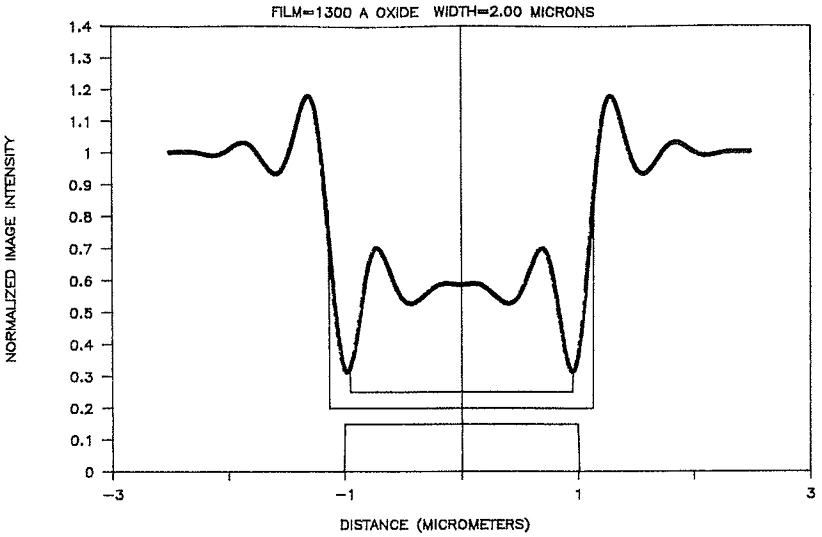

Figure 2. Two different measurement algorithms.

Figure 3 compares the (theoretical) optical profile of two typical microelectronic features: a silicon dioxide line on silicon (1800 angstrom thick oxide) and a silicon nitride line on silicon (500 angstrom thick nitride). The actual physical line is drawn on each graph for comparison. In the case of the oxide line, points on the optical profile very near the minima correspond to the true physical edges. However, for the nitride line, the points on the optical profile corresponding to the physical edges are not near the minima.

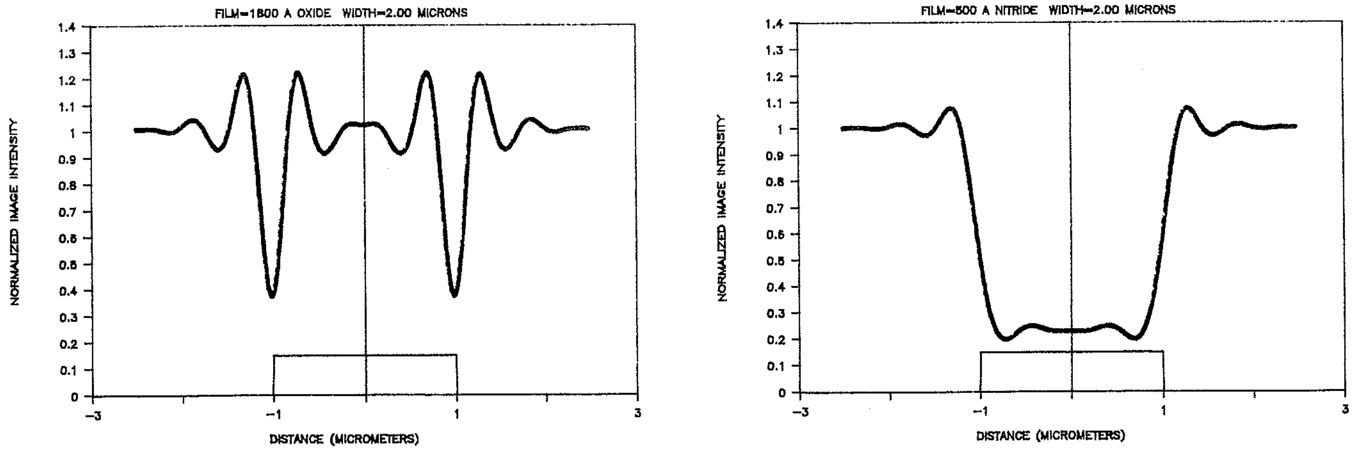

Figure 3. Two significantly different optical profiles.

If the nitride line width is measured using minima finding as the edge detection algorithm, an error of roughly 0.4 micrometers would result. It is clear that the same edge detection algorithm could not correctly measure the width of both lines. Separate algorithms would have to be developed for each of these two cases.

A calibration standard can be used to determine the correct edge detection algorithm for a specific optical profile of a feature to be measured. We call this image specific or profile specific calibration. This implies:

1) The optical profile of the calibration standard must closely match the optical profile of the feature to be measured.

2) If the instrument is to measure more than one type of feature, separate calibration will be required for each feature type (if they produce significantly different optical profiles).

It should be noted here that we are concerned with matching optical profiles, not the features themselves. One of the basic design principles of this standard is that two different features, built of completely different materials and of different thickness, can produce identical images.

## 5. Theoretical Model

The model used to determine the correct edge detection algorithm must be able to theoretically predict the optical profile of a line or space. The parameters which govern the optical profile in a reflected light microscope threatened to be so numerous as to make any theoretical model intractable. For this reason, the following assumptions were made to simplify the model.

1) Highly Coherent Microscope.
2) Monochromatic Illumination.
3) Vertical and Straight Line Edges.
4) Patterned Layer Thickness < One Quarter the Illumination Wavelength

To further simplify the theoretical model, it was desirable to be able to describe the feature being measured with as few parameters as possible. In work done earlier by Nyyssonen [2,3], it was shown that any line or space can be described by the two image parameters, relative reflectance and phase shift at the line edge.

Any surface has a reflectance value between 0 and 1 which is a measure of how well that surface reflects light. Reflectance is determined by the film materials, film thicknesses as well as the wavelength and angle of incidence of the illumination. A line or space feature has two surfaces; a top surface and a bottom surface. In this paper, the relative reflectance (R) of a line or space is defined as:

$$\text{Relative Reflectance} = \frac{\text{Reflectance of the Dimmer Surface}}{\text{Reflectance of the Brighter Surface}}$$

Take the example of a 1160 Å thick silicon dioxide line on bare silicon which is being illuminated by green light (546 nm). The oxide surface (of that specific thickness) has a reflectance of 0.17 and the bare silicon surface has a reflectance of 0.36. The relative reflectance of this line is then: 0.17 / 0.36 = 0.47. Therefore, relative reflectance is the inverse of the contrast of the image: high values of relative reflectance correspond to low contrast images, low values of relative reflectance correspond to high contrast images. Since relative reflectance is defined as a ratio with the reflectance of the brighter surface as the denominator, relative reflectance will always have a value between 0 and 1.

Light is a traveling electromagnetic wave and can be phase shifted. For this theory, there are two sources of phase shift: 1) phase shift upon reflection at each surface. 2) phase delay due to the extra optical path caused by the step height of the feature. The total phase shift (ø) is defined as:

$$\begin{array}{c} \text{Total} \\ \text{Phase Shift} \end{array} = \begin{array}{c} \text{Bottom Surface} \\ \text{Phase Shift} \end{array} - \begin{array}{c} \text{Top Surface} \\ \text{Phase Shift} \end{array} + \begin{array}{c} 2kd \\ \text{(delay)} \end{array}$$

where: k = the wavenumber of the light (2xpi/lambda)
d = step height

The phase shift of a line or space dictates the contrast of the interference fringes which form at a feature edge when viewed in an optical microscope. The influence of phase shift upon fringe contrast is cyclic. Phase shifts nearly equal to even multiples of pi (ø = 0, 2pi, etc.) produces faint interference fringes and phase shifts equal to odd multiples of pi (ø = 1pi, 3pi, etc.) produces strong interference fringes. Phase shift enters into the theoretical model as cosø.

The parameters R and cosø which determine the shape of the optical profile are bound values; 0 < R < 1 and -1 < cosø < +1. These parameters form a bound space where one variable is the x-axis (usually cosø) and the other variable is the y-axis (usually R). Any line or space feature can be represented by a point in R, cosø space.

A computer program written in Pascal was developed to calculate image profiles based on the mathematical model. The program requires the following input parameters:

| Instrument | Feature |
|---|---|
| Illumination Wavelength | Line Width |
| Objective N A | Relative Reflectance |
| Condenser N A | Phase Shift |
| Slit Width | |

The program also has the ability to model defocus and spherical aberrations. The output of the program is the optical profile which will be generated by an instrument and feature given the parameters specified. Using this program, the real physical edge can be equated with a precise point on the optical profile. The software described here is directly based upon software developed at the National Bureau of Standards [7].

## 6. Instrument

The instrument used to calibrate line width standards based on physical principles will be different from most other systems. The primary criteria is to build an instrument which can be mathematically modeled. This is necessary so that the optical profiles measured by the instrument can be compared to theoretical predictions. Such an instrument, therefore, will accurately locate feature edges.

An off-the-shelf measurement system was adapted for this purpose. All the optical elements required better alignment to the optical axis than typically provided by the manufacturer. In addition, the illumination was set up to meet the Kohler criteria.

In order for the system to be consistent with the mathematical model, the system required several modifications. The illumination is effectively monochromatic. A mercury arc lamp, filtered to isolate the 546.1 nanometer mercury line, is used as the light source. An interference filter with a bandwidth of 19 nanometers is used. The coherence parameter of the system, the ratio of condenser to objective N.A., is 0.2. This high degree of coherence is achieved by using a very small aperture diaphragm. Results show excellent agreement between the measured optical profiles and the theoretical model. See Figure 4.

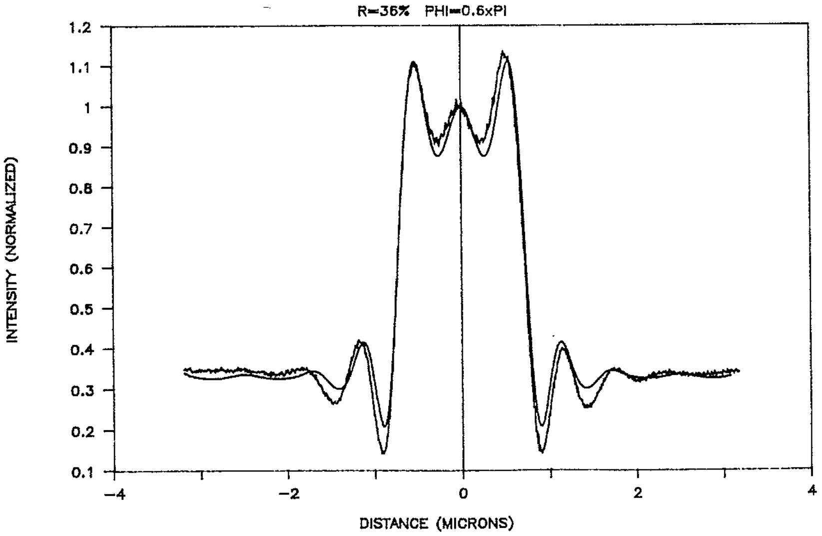

Figure 4. Comparison of theoretical and experimental profiles

## 7. Line Width Standard Set

The Line Width Standard is fabricated from a silicon wafer. The wafer is cut into 10 mm X 10 mm silicon die. A thin metal or dielectric layer on the top surface of the silicon die is patterned to form the calibrated lines and spaces. The pattern on each of the six samples is identical.

The pattern design of the measurement region is shown in Figure 5. Within this region are eight calibration sites. Six of these sites are for line width calibration and each contains a line and a space. Each line and space is labelled with a letter. The nominal line widths range from one to five micrometers.

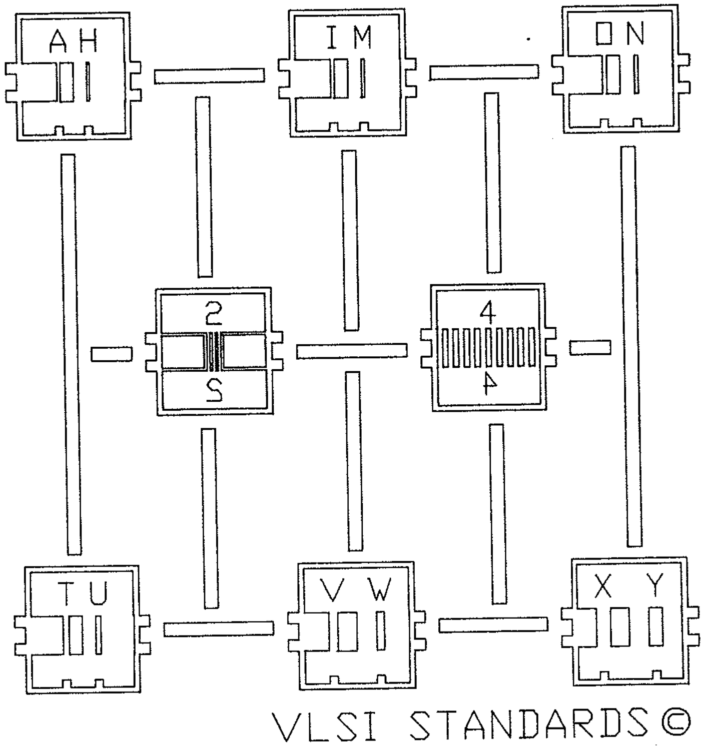

Figure 5. Line Width Standard Pattern.

The other two sites are for pitch measurement. Pitch is used for magnification calibration. These sites have a nominal pitch value of 2.0 and 4.0 micrometers.

The thickness and material of the patterned layer varies from sample to sample to give each a unique combination of relative reflectance and phase shift. In each case, however, the patterned layer is thin enough to avoid thick layer image effects [5,6]. A proprietary etch process is used to insure straight, vertical line edges. The six different samples have the following (nominal) relative reflectance and phase shift values:

| Relative Reflectance | Phase Shift (radians) |
|---|---|
| 0.16 | 0.50 x pi |
| 0.17 | 0.65 x pi |
| 0.25 | 0.91 x pi |
| 0.47 | 0.56 x pi |
| 0.47 | 0.76 x pi |
| 0.81 | 0.63 x pi |

Figure 6 shows how these points are distributed in R, cosø space.

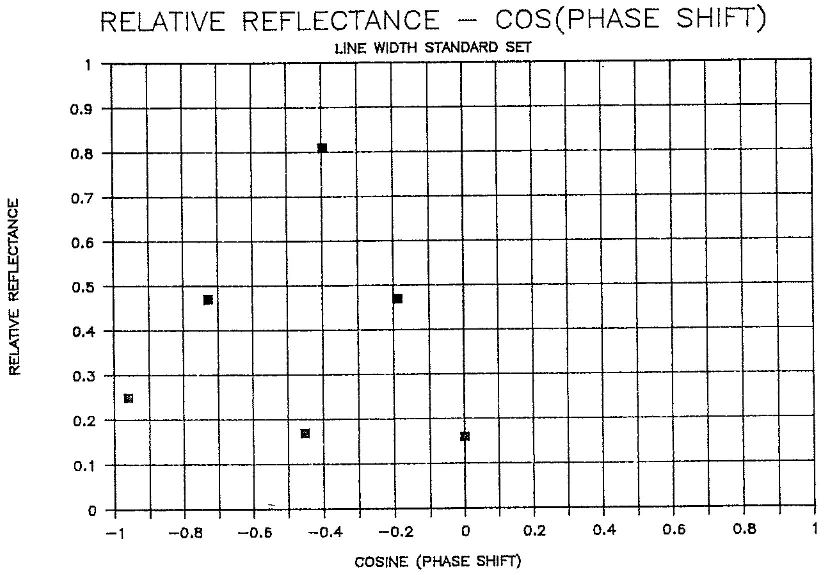

Figure 6. The points in R, cosø space occupied by the samples in the Line Width Standard set.

The selection of relative reflectance and phase shift values chosen for this set is based on the optimal design developed at the National Bureau of Standards [7].

Once the Standard is fabricated, it is calibrated on the special high coherence system previously described. Now this standard can be used to evaluate other instruments. As an example, the line width standard was measured on a typical line width instrument (which has not been theoretically modeled). A measurement was made of each line and space on each sample of the set of standards. The same edge detection algorithm (50% threshold) was used for each sample of the standard. A linear regression was calculated between each set of the measured data and the calibrated values. The results for two of the samples of the line width standard were:

| | R = 0.16 ø = 0.50 x pi | | R = 0.81 ø = 0.63 x pi | |
|---|---|---|---|---|
| | Lines | Spaces | Lines | Spaces |
| R sqd. | 0.9999 | 0.9999 | 0.9985 | 0.9995 |
| x-coef. | 0.9913 | 1.0130 | 0.9862 | 0.9833 |
| y-int. | -0.1741 | 0.2275 | 0.4297 | -0.2904 |

The correlation coefficient (R squared) of the fit is a measure of the linearity of the line width measurement and should be very close to 1.00. The x-coefficient measures how well the magnification calibration was performed and should also be very close to 1.00. For the examples shown here, linearity and magnification of the system was very good.

The y-intercept is a constant additive offset for all measurements. An incorrect edge detection algorithm will cause a constant line width error regardless of line width and therefore will affect the y-intercept of the regression fit. In the example shown, this error is as high as 0.4 micrometers.

## 8. Conclusions

Reflected light line width measurement can be <u>accurately</u> performed on features as small as one micrometer. However, in order to achieve this, the measurement instrument must be calibrated.

Calibration of reflected light line width measurement instruments is <u>not</u> only dependent on the instrument design, but also on the feature being measured. For accurate measurements, the instrument must be calibrated for the specific optical profile of the feature being measured.

This paper describes a calibration standard designed for profile specific calibration of reflected light line width measurement instruments. The calibration of the standard is derived from fundamental physical principles and is thus a primary calibration standard.

A theoretical model, developed by the National Bureau of Standards, calculates from first principles the optical profile produced by highly coherent reflected light line width system. An off-the-shelf line width measurement system has been adapted to perform measurements consistent with this theoretical model. Agreement between theory and experiment has been shown to be excellent for this system.

The calibration standard described here will extend the useful range and improve the accuracy of reflected light line width measurement systems down to one micrometer critical dimensions.

## 9. References

1. Nyyssonen, D. and Larrabee, Robert D., Submicrometer Linewidth Metrology in the Optical Microscope, J. Res. Natl. Bur. Stds. 92, 187-204, (May-June 1987).

2. Nyyssonen, D., Theory of Optical Edge Detection and Imaging of Thick Layers, J. Opt. Soc. Am. 72, 1425-1436 (1982).

3. Nyyssonen, D., Calibration of Optical Systems for Linewidth Measurement on Wafers, Opt. Eng. 21, 882-887 (September-October 1982).

4. Nyyssonen, D., A Practical Method for Edge Detection and Focusing for Linewidth Measurements on Wafers, Opt. Eng. 26, 81-85 (January 1987).

5. Nyyssonen, D., Computer Software for the Computation of the Scattered Field and the Optical Microscope Image of Line Objects Patterned in Thick Layers, NBSIR 87-3618 (December 1987).

6. Nyyssonen, D., and Kirk, C. P., Modeling the Optical Microscope Images of Thick Layers for the Purpose of Linewidth Measurement, Proc. SPIE Vol. 538, Optical Microlithography IV, 179-187 (1985)

7. Nyyssonen, D., Narrow-Angle Laser Scanning Microscope System for Linewidth Measurement on Wafers, to be published.

8. National Bureau of Standards, Optical Microscope Linewidth Measurement Standard, Standard Reference Material 475.