100 nm pitch standard characterization for metrology applications

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ABSTRACT

In this paper we present and characterize a NIST-traceable, all-silicon, 100 nm pitch structure with the necessary quality attributes to calibrate CD-SEM tools used for metrology of sub-0.25 μm semiconductor process technology.
Keywords: pitch, 100 nm, CD-SEM, lithography, NIST-traceable, line edge roughness, LER

1. INTRODUCTION

Periodic pitch structures, or gratings, are the best type of samples to calibrate the magnification and to characterize the spatial distortions of an imaging system such as an optical microscope, electron microscope, or a scanning probe microscope. If the pitch structure is measured using a NIST-traceable method, then such pitch structure enables a NIST-traceable calibration of the imaging system.

Some of the critical quality attributes of a pitch standard are 1) the fundamental pitch distance, 2) the uniformity of the pitch, 3) the quality of the line edge roughness, 4) the imaging contrast that it produces, 5) the accuracy of the certified pitch value, and 6) the traceability of the certified pitch value to an internationally recognized standard.

In the past, difficulties in fabricating pitch structures with sufficiently good quality attributes, difficulties in calibrating the structures to a NIST reference material, and difficulties in delivering the standard in a format compatible with automated wafer handling technology, have prevented the calibration of CD metrology equipment for sub-0.25 μm lithography.

2. PHYSICAL PROPERTIES

Fig. 1 shows an electron microscope image of the 100 nm pitch standard.

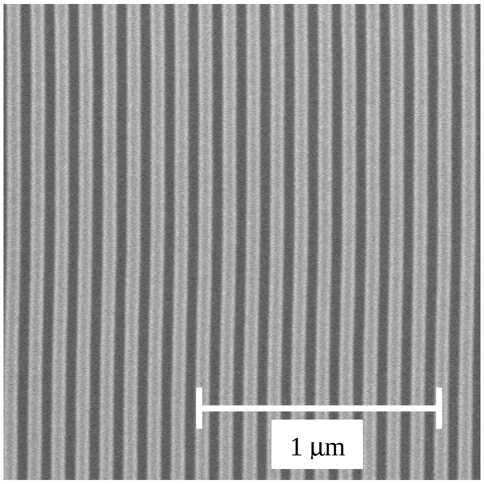

Fig. 1: SEM image of 100 nm pitch calibration sample

Fig. 2 shows a cross-sectional TEM image of the same structure. The standard is made of silicon. This particular sample was etched to a depth of 50 nm, with a sidewall angle of 85 degrees, and has a top CD of 45 nm, as measured from the cross-section TEM image. The selections of the material, etch depth, and etch profile, were dictated by the need for high contrast imaging in a CD-SEM. When imaged in an electron microscope this particular structure reveals a

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distinctively bright edge, which enables the use of software edge finding algorithms in a CD-SEM, and allows recipe set up for automatic calibration. Fig. 3 shows a typical intensity profile superimposed on the image, which reveals sharp, high contrast edges.

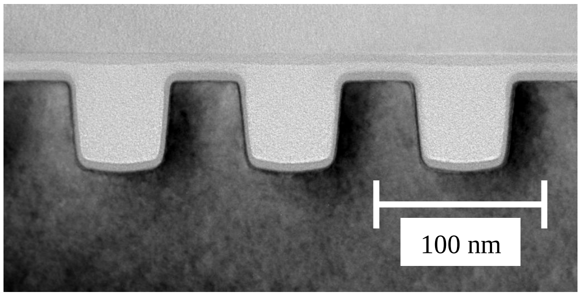

Fig. 2: High Resolution TEM image of a cross-section of the 100 nm pitch calibration sample

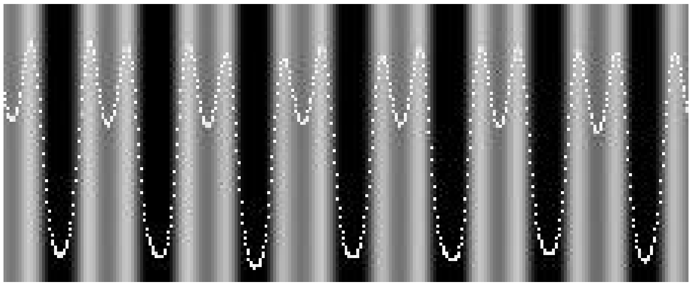

Fig. 3: SEM image of the 100 nm pitch calibration sample showing the intensity profile

A key quality attribute of the sample is the Line Edge Roughness (LER) of the lines. If the lines were rough, then an accurate pitch measurement would require averaging a large number of measurements over a large number of sample locations. If the lines are smooth and uniform, instead, the same accuracy can be achieved with fewer measurements, and therefore the calibration of a CD-SEM can be done much faster. The International Technology Roadmap for Semiconductors has defined requirements for LER control for the first time in the 2001 edition, calling for a LER control of 4.5 nm at the 130 nm node, 3.3 nm at the 100 nm node, and 2.1 nm at the 70 nm node[1]. The LER, as defined in the Roadmap, must be measured over both edges of a length of line equal to 4 times the technology node, and must be reported as the 3 Sigma total, with all frequency components included. With the 100 nm node in mind, we have measured the LER over a length of 400 nm. Because we are interested in pitch and not line width, we have measured the LER of a single line edge. We have divided the 400 nm section of line into 21 profiles, each spaced 20 nm apart. The SEM intensity profile is used to determine a unique edge position. The set of 21 edge positions is used to determine a best-fit line. The deviation of each profile from the best-fit line, Δx_i, is used to determine the edge roughness. The 3σ value of edge roughness is calculated as follows:

$$3\sigma = 3\sqrt{\frac{\sum_{i=1}^{n} \Delta x_i^2}{n-1}}\,, \tag{1}$$

where n is the number of measurements: n=21 in our case.

Fig. 4 shows how the gates are selected on the SEM image. LER measurements on several different areas of the sample support LER requirements at the 100 nm node. The specific sample shown in Fig. 4 had LER of 1.3 nm on the left edge and 2.1 nm on the right edge.

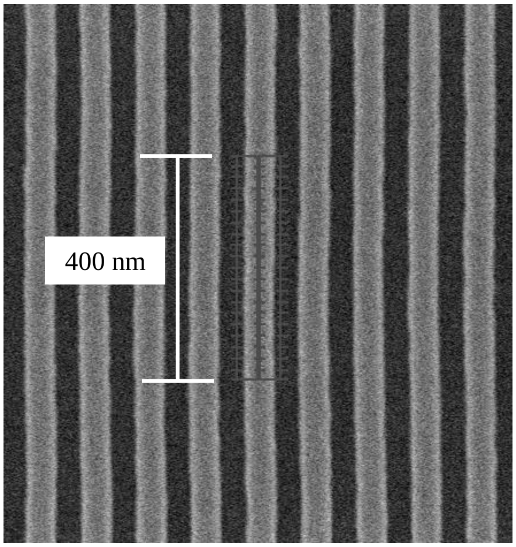

Fig. 4: Selection of the gates for the measurement of LER in support of the ITRS requirement for the 100 nm technology node. The 3σ LER value on this specific sample is 1.3 nm on the left edge and 2.1 nm on the right edge. The line edge roughness statistics are obtained from 21 individual measurements taken along the 400 nm long segment shown, at 20 nm intervals.

Another key quality attribute of a pitch sample is its uniformity across the calibrated area. To measure sample uniformity we took 100 pitch measurements with a CD-SEM across the calibrated area. The calibrated area is 800 μm x 800 μm. The 100 measurement locations were equally spaced across the calibrated area. Each of the 100 measurements was the average of 9 measurements in the same location. The standard deviation of the 100 measured values was 0.16%. This value of standard deviation is the combination of two contributions: 1) the non-uniformity of the pitch, and 2) the instrument repeatability. Therefore, the pitch non-uniformity on this particular sample was not greater than 0.16%. Figure 5 shows a histogram of the 100 measurements. At each location the pitch was obtained as the average pitch over 10 periods, as explained in section 3.

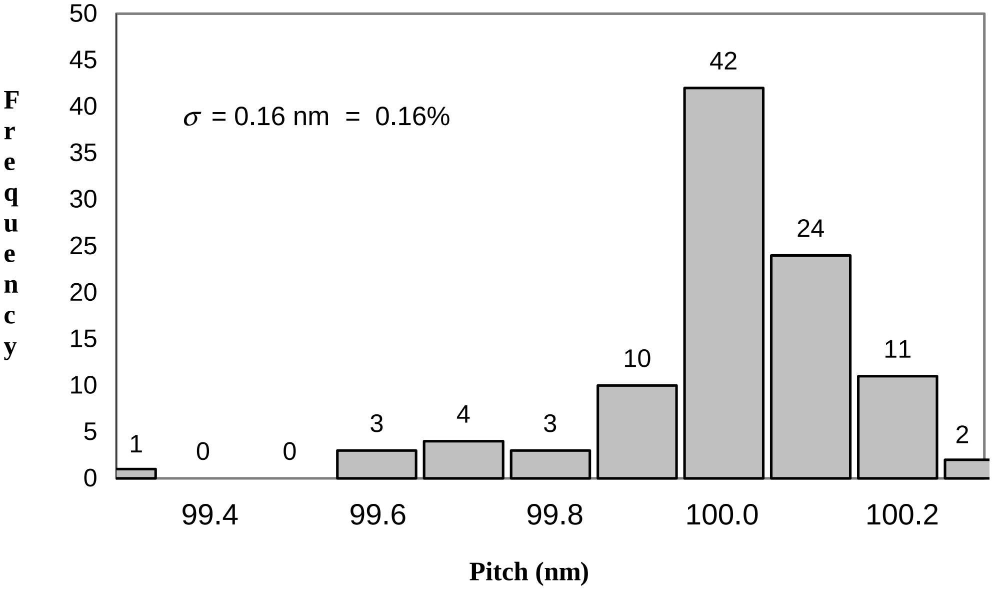

Fig. 5: Histogram of 100 measurements of the 100 nm pitch over an area of 800 μm x 800 μm showing a standard deviation of 0.16%.

3. CALIBRATION AND NIST-TRACEABILITY

The definition of traceability provided by NIST is the following[2]: “traceability is the property of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties”. The work presented in this paper was performed in adherence to the definition of traceability. The final total uncertainty was expressed according to the ISO Guide for the expression of uncertainty in measurements[3].

We achieve traceability through a calibrated pitch measurement of a 200 nm pitch standard performed by NIST using a Calibrated Atomic Force Microscope (C-AFM)[4, 5]. The C-AFM at NIST derives its traceability through an interferometrically calibrated stage. For the purpose of calibrating average pitch we measure five periods of the NIST-calibrated 200 nm pitch sample with a CD-SEM, and compare the measurement with 10 periods of our 100 nm pitch sample. This corresponds to a length of 1 micron. A proportional correction factor is applied to the measurement of the NIST-calibrated sample to reproduce in our laboratory the measurement reported by NIST. The same proportional correction factor is then applied to the measurement of 10 periods of our 100 nm pitch sample. In performing this direct comparison against the NIST master we use the same SEM beam parameters for the two measurements. This is critical, as explained in section 5.1. The measurement of the 1 micron segment is divided by 10 to obtain the NIST-traceable value of the fundamental pitch in our sample. This measurement is repeated 9 times in 9 predetermined locations that encompass the entire calibration area of size 800 µm x 800 µm, to account for spatial non-uniformities in the sample and for instrument repeatability, as shown in Fig. 6. In each of the 9 locations the measurement is repeated 10 times to reduce the error due to instrument static repeatability. The measured standard deviation of the average pitch in the 9 selected locations constitutes the component of uncertainty due to sample non-uniformity. The average standard deviation of the mean pitch value in each of the 9 selected locations is the component of uncertainty due to the static repeatability of the instrument. According to the Guide to the expression of uncertainty in measurement[3], sample uniformity and instrument repeatability are called type A uncertainties, and can be calculated statistically from direct measurements.

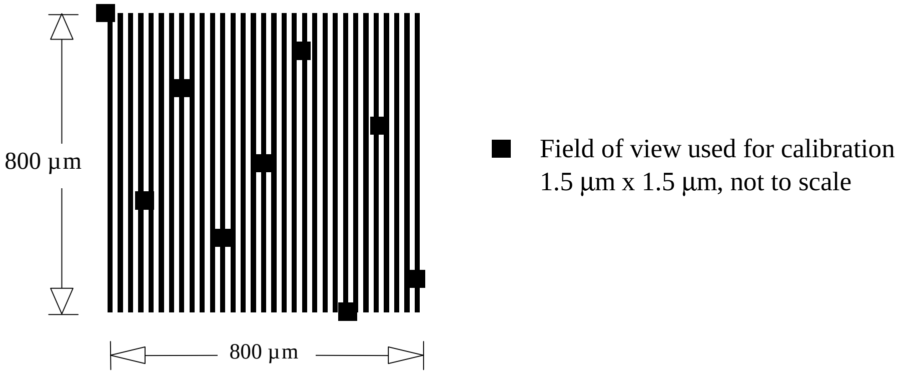

Fig. 6: Layout of the sampling strategy used for the measurement of sample uniformity and instrument repeatability. The calibrated area is 800 µm x 800 µm. Each black square represents an area of calibration.

In addition to type A uncertainties, we account for type B uncertainties, which are due to parameters that are not directly measured, and whose effects on the calibration are estimated. One such parameter is, for example, the effect on the magnification in our CD-SEM due to the difference in the working distance between the measurement performed on the NIST sample and the measurement performed on the 100 nm pitch sample. To account for this we have experimentally measured the effect of working distance variation on magnification for our instrument for a worst-case situation, and we added such effect as a component of measurement uncertainty. Another type B uncertainty is due to the thermal expansion of the silicon sample. This component of uncertainty is obtained by multiplying the thermal expansion coefficient of silicon times the uncertainty in the temperature of the sample during measurement. Because the temperature of the sample cannot be measured in our set up, we estimate a worst-case condition of 5 °C variation from the temperature reported in the measurement performed at NIST. We report the uncertainty in the temperature as a type B component of uncertainty.

To obtain the total expanded uncertainty, which is defined as the uncertainty corresponding to the 95% confidence interval[3], the total combined uncertainty is multiplied by the Student t-factor corresponding to the number of degrees of freedom of the measurement. The number of effective degrees of freedom for our sampling methodology, derived from the Welch-Satterthwaite formula[3], was 12, which corresponds to a student t-factor of 2.16 at the 95% confidence interval. Therefore we were able to certify the average pitch on this sample with a total expanded uncertainty of ±0.7%, or ±0.7 nm for the 100 nm nominal pitch value.

Table 1 lists the components of measurement uncertainty with their typical values.

Source of uncertainty	Type	1 Sigma uncertainty
Sample uniformity	A	0.18%
Instrument repeatability	A	0.05%
Local charging variations	B	0.05%
Working distance variations	B	0.0004%
Fine focus setting	B	0.02%
Sample skew	B	0.002%
Sample tilt	B	0.0002%
Temperature variations	B	0.0013%
NIST uncertainty of master	Combined	0.22%
VLSI Standards measurement of NIST master	Combined	0.13%
Total combined uncertainty		0.32%
Total expanded uncertainty (95% confidence)		0.69%

Table 1: Components of uncertainty in the certification of the 100 nm pitch standard, and their percentage values.

4. POCKET WAFER MOUNTING

Because it was not possible to fabricate the sample directly on a 200 mm or 300 mm wafer, a major challenge in making use of the sample was that of loading it into the CD-SEM. For this purpose we have developed a technology that we have called the "pocket wafer technology". It consists in etching a recess into a silicon wafer, and in precisely mounting the sample into the recess. The recess can be etched to precise lateral and vertical tolerances using alkali etchants commonly used in the MEMS industry, and compatible with IC fabrication. The sample is mounted in the recess using a specially formulated conductive material, which contains only hydrogen, carbon, and oxygen. This technology was first used on 4" and 6" aluminum wafers, where the pocket was machined into the aluminum, and the aluminum wafer had the same physical characteristics as SEMI standard silicon wafers. Unfortunately, it has been difficult to produce aluminum wafers of 200 mm and 300 mm diameter that meet bow and warp specifications of SEMI standard silicon wafers. The idea of etching a pocket directly into a silicon wafer with alkali etchants was originally proposed by NIST researchers. Fig. 7 illustrates schematically the silicon pocket wafer mounting technique.

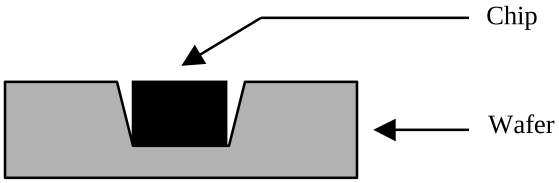

Fig. 7: Pocket wafer mounting

The chip to be mounted must be thinner than the carrier wafer in order for the chip to result at the same height as the carrier wafer after mounting. In our application it is important that the surface of the chip be coplanar with the surface of the carrier wafer to avoid calibration errors, as explained in section 5.1 below.

5. APPLICATIONS TO SUB-0.25 MICRON LITHOGRAPHY

Two applications for this sample in CD-SEM metrology are 1) the calibration of the magnification, and 2) the verification of scan linearity.

5.1 Calibration of magnification

The calibration of the magnification of a CD-SEM is key in achieving accuracy in all the lateral measurements performed by the CD-SEM. The ITRS[1] calls for a printed gate length of 65 nm with CD control of 4.5 nm at the 100 nm technology node. This corresponds to a measurement accuracy requirement of 7%. Errors in the calibration of magnification of the CD-SEM translate directly into errors in the accuracy of CD measurements because the uncertainty in the calibration of magnification is one component of uncertainty in the CD measurement. Therefore an accurate magnification calibration is necessary to qualify the accuracy of CD-SEM metrology. It is desirable to execute the calibration of magnification at the same magnification used in production. For example, if gate CD is measured at 200 kX, it is best to calibrate the CD-SEM at 200 kX.

In order to reduce the error in the calibration of the magnification it is preferable to do the calibration using as many consecutive pitch structures as possible. For example, when calibrating magnification up to 100 kX, it is desirable to use 10 pitch structures for a total length of 1 μm. This reduces the uncertainty in the measurement due to local line edge roughness or pitch non-uniformity. When calibrating a smaller field of view it becomes necessary to use fewer pitch structures, down to 5 at 200 kX, and possibly down to a single pitch structure at magnifications above 200 kX.

One critical factor to achieve accurate metrology with a CD-SEM is that the imaging parameters used during the calibration process remain the same when doing metrology on the sample of interest, or that appropriate corrections be performed to compensate for differences in the imaging parameters. For example, the magnification of a SEM may vary with imaging parameters such as focusing, landing voltage of the electron beam, astigmatism correction, sample charging, working distance, etc. It is therefore critical that these parameters remain the same when measuring the pitch standard sample and when imaging the specimen of interest. To avoid differences in the imaging parameters it is ideal to have the standard in the same format as the sample to be measured. Our use of the pocket mounting technology mimics a product wafer and therefore helps reduce differences in the imaging parameters when imaging the standard versus a product wafer.

5.2 Verification of scan linearity

An important quality attribute for a CD-SEM is the scan linearity across the field of view. A physical periodic structure with fine pitch, high uniformity, and small line edge roughness is ideal for measuring the linearity of the magnification across the field of view.

For this type of measurement one would measure the distance between adjacent pitch structures from the left of the screen to the right, and plot the measured distance against the nominal distance. Any systematic deviation from a straight line can be attributed to scan non-linearity.

5.3 Other applications

This standard may also be used for NIST-traceable calibration of scatterometers, scanning probe microscope, such as atomic force microscopes, and for qualification of line edge roughness measurement algorithms.

6. CONCLUSIONS

We have presented a 100 nm pitch structure built in silicon. We have obtained a NIST-traceable measurement of the pitch value by direct measurement comparison with another pitch structure that was measured and certified at NIST. The sample has ideal quality attributes for calibration of a CD-SEM for sub-0.25 μm lithography, including a fine, highly uniform pitch, with extremely low line edge roughness. We have qualified the sample for calibration of magnification and verification of scan linearity across the field of view of a CD-SEM.

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