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TECHNIQUES FOR LOW VOLTAGE SCANNING ELECTRON MICROSCOPY LINEWIDTH MEASUREMENTS

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Abstract

Present scanning electron microscopy (SEM) linewidth measurement systems, although "state of the art", require better defined techniques in deriving operating parameters for precision measurements. Experiments were performed to check techniques used on cleaved and uncleaved specimens, void of conductive coatings to obtain optimum SEM operating parameters, and the variations in results due to changes in system operating conditions. In addition, a method was devised to select and use different calibration standards and evaluate SEM linewidth measurement systems.

Key Words: Dimensional metrology, linewidth measurement, scanning electron microscopy.

Introduction

In order to monitor processes used to fabricate present day integrated circuits, certain measurements must be made with a high degree of precision. Minimum feature sizes, known as critical dimensions (CD), must be maintained to insure proper device operation. Prior to dicing, the wafer must remain intact during inspection and/or measurement because the wafer must be returned to the fabrication process. Further, no additional coating on the surface of the wafer to aid inspection and/or measurement is allowed, since this would destroy the device. Different techniques were empirically checked in performing these measurements using a scanning electron microscope (SEM) [10, 26, 51] with an attached or integrated measurement system [17, 33, 39, 40, 49, 51]. The main reason for using an SEM for measurement and/or inspection of structures on devices at high magnifications is due to its high spatial resolution. Although alternative techniques may be used, after experimentation over several years, the techniques described in this paper were found to be adequate for precision measurements. The intent of this paper is to present the techniques and the results from using these techniques and not a new theoretical approach or a newly invented or patented instrument.

The SEM basically operates in the following manner. A focused beam of electrons is scanned across the surface of the specimen. The interaction of the electron beam (e-beam) with the specimen produces a variety of detectable electrons [20]. Among these electrons produced by the interaction are those of low energy, known as secondary electrons. A detector composed of an electron collector, scintillator, light pipe, and photomultiplier tube can be used to detect these secondary electrons [11, 59]. The signal from the detector is then used for such purposes as providing a magnified image of the specimen for analysis or by the measurement system associated with the SEM to make CD measurements. A plot of the electron [SE, backscattered electrons (BSE), etc.] intensity versus electron beam position along a horizontal line on the specimen is referred to as the line intensity profile.

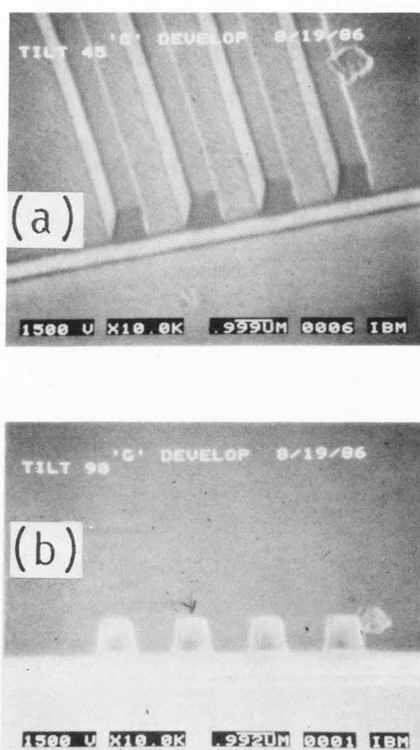

Figure 1. Micrograph of a cleaved specimen, tilted at 45 (**Fig. 1a**) and 90 (**Fig. 1b**) degrees. The specimen contained photoresist structures used for calibration purposes at a given step in the processing of semiconductor devices.

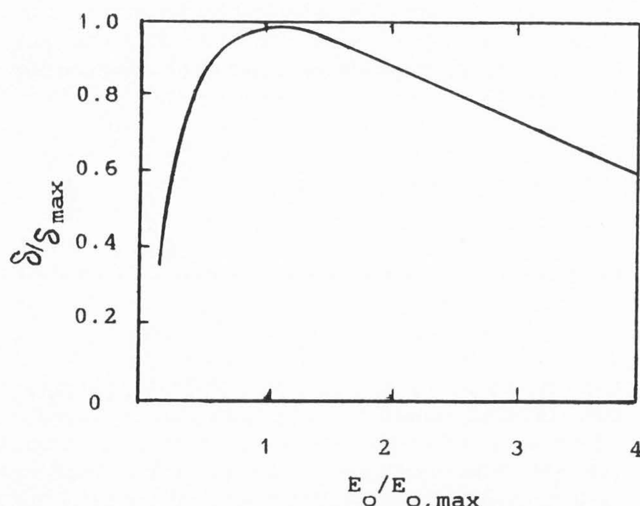

Figure 2. Ratio of secondary electron yield, (number of electrons emitted from the specimen surface versus the number of electrons impinging on the surface) sigma, plotted on Y-axis versus primary beam energy (keV), X-axis.

In order to obtain high precision measurements using a low voltage (0.5-5.0 keV) SEM, certain techniques can be used to enhance the performance of the measurement system. In an attempt to elaborate on the different techniques we employed during the measurement of structures, this paper is divided into the following major topics:

1) Optimization of SEM Operating parameters.
2) Selection and use of calibration standards.
3) Evaluation of the SEM measurement system.
4) Measurement Procedures.

The last item listed above will be covered by listing the necessary steps in obtaining precision measurements. These steps are listed according to their degree of importance as determined by the author over a period of several years in performing the work which serves as the basis for this paper. Items 1, 2, and 3 require a more in-depth discussion and thus will be covered in a more elaborate fashion.

Optimization of SEM Operating Parameters

Semiconductor measurements are typically made at comparatively low accelerating voltages (0.7-1.5 keV) on uncoated specimens to avoid or reduce charging [6, 12]. This causes the SEM operating parameters to play an even more critical role in obtaining precision measurements. In our experience, some of the operating parameters affecting precision measurements at low accelerating voltages are: accelerating voltage, working distance, angle of incidence of the e-beam on the specimen surface (tilt), focus, electron beam diameter, magnification, contrast and brightness setting, specimen alignment with respect to the direction of the scanning e-beam, and detector location. Some of the effects these parameters can have on measurement are described below. The use of a conductive coating aids in dissipating surface charge [12, 37, 38] and improving the signal derived from the detector, especially when the e-beam is scanning at the point of fracture (Figure 1b) with the specimen at 90 degrees tilt.

Accelerating voltage

Selection of the optimum accelerating voltage is critical for precise measurements. Ideally, for an optimum signal to noise ratio it is desirable to generate the maximum number of detectable secondary electrons. The emission of secondary electrons varies with material [18, 19], accelerating voltage, and surface topography [20-22]. There is a secondary electron yield versus primary electron energy curve [14], Figure 2, whose shape is essentially the same for most materials [35]. The value of the secondary electron yield varies with the work function of the material. Below the optimum accelerating voltage for a stable line intensity profile the structure being imaged on the SEM cathode ray tube (CRT) may be charged positive, and above the optimum accelerating voltage the structure may be negatively charged [39, 40]. One way in which the optimum accelerating voltage can be determined is by varying the accelerating voltage and observing the image. At low

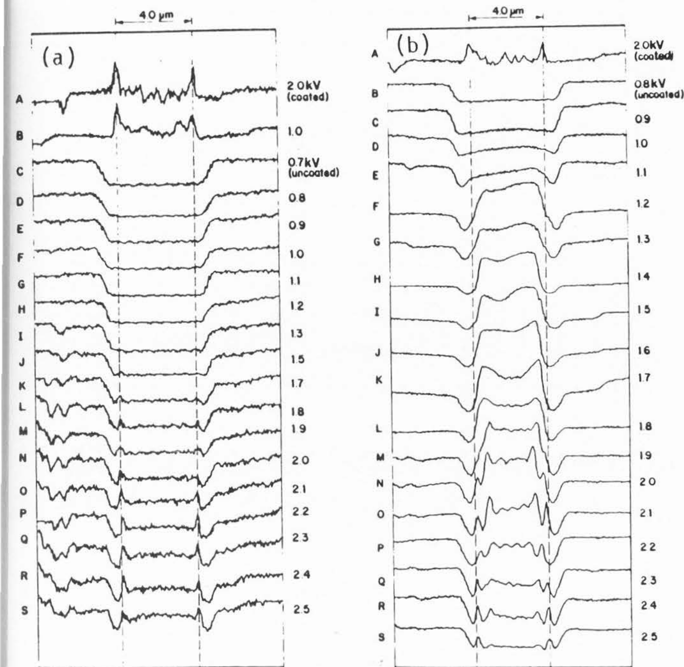

Figure 3a. Composite video profile of coated and uncoated photoresist on a chrome mask taken at 45 degrees tilt using accelerating voltages from 0.7-2.5 keV (uncoated mask) and 1.0 and 2.0 keV (coated mask). Line scale is equal to 4.0 μm.

Figure 3b. Composite video profile of coated and uncoated photoresist on a chrome mask taken at zero degrees tilt using accelerating voltages from 0.8-2.5 keV (uncoated mask) and 2.0 keV (coated mask). Line scale is equal to 4.0 μm. (Figures 3a and 3b are courtesy of Dr. Michael T. Postek, reference 41).

accelerating voltages, the structure under observation may appear dark due to the value of accelerating voltage or contamination. As the accelerating voltage is changed, the image of the structure will change until the structure appears very bright. Somewhere in between these two conditions the correct accelerating voltage will be found such that the line intensity profile will be stable and symmetrical. Our experience has shown that to find the optimum accelerating voltage in some cases can take several hours or the better part of a day [39, 40]. The change in line intensity profile versus accelerating voltage for photoresist on a chrome mask is shown in Figures 3a and 3b [41]. If the accelerating voltage is too low, indicated by deterioration of the intensity profile, then the system will not be able to make measurements with a 3 sigma precision in the range of 0.010 μm or better due to signal-to-noise limitation. As a result, there may be a tendency to make the accelerating voltage too high. This can result in specimen charging and distortion of the individual line intensity profiles, which affects the corresponding processed (smoothed and averaged) profile (Figure 4). This can be minimized by using TV rate linescans and averaging several linescans.

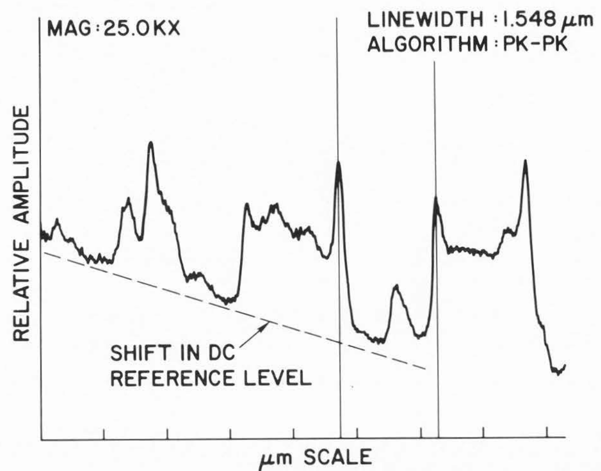

Figure 4. Line intensity profile from a given structure with the accelerating voltage of the SEM set at too high a value thereby causing charging of the specimen and shifting in the dc reference value.

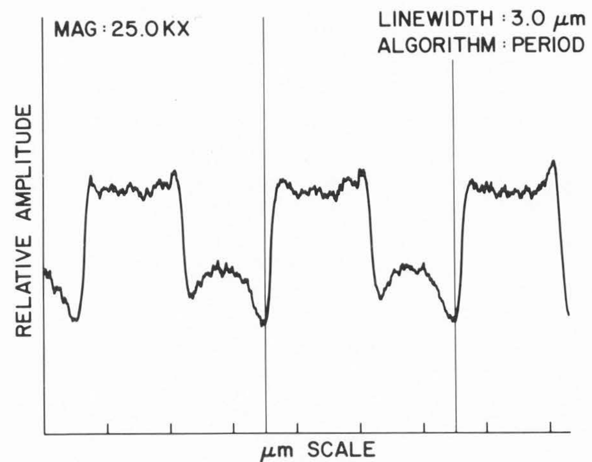

Figure 5. Line intensity profile from the same structure as the one shown in Figure 1a with the accelerating voltage of the SEM set to the proper value and the e-beam scanning orthogonal to the structure.

The time dependency of the charging as well as line or frame scan rate affects the reproducibility of the line intensity profile and consequently the measurement precision. Figure 4 also indicates the shift in the dc reference level due to charging. An acceptable version of the line intensity profile from the same specimen with the proper accelerating voltage is shown in Figure 5. As an example, to optimize the precision of the measurements from the structure shown in Figure 6b, the electron intensity profile ideally should be like the one shown in Figure 6a.

Experimentation has shown that the optimum accelerating voltage is specimen dependent since secondary electron emission is material dependent [2, 8, 18, 19]. Further, a change in accelerating voltage of as little as 50 volts can determine if it is even possible to generate

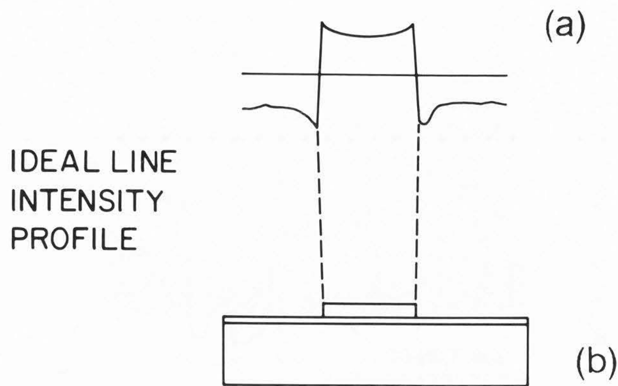

Figure 6. Ideal line intensity profile (**Figure 6a**) from the structure shown in **Figure 6b**.

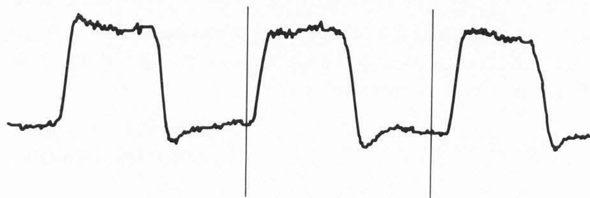

Figure 7. Line intensity profile with good symmetry and proper dc reference value obtained from a photoresist structure similar to the one shown in Figure 1a, using a Vickers DL3006 SEM.

a secondary electron intensity for precise measurements. Our experience has shown that one should adjust the accelerating voltage on the SEM until a symmetric, balanced line intensity profile similar to the one shown in Figure 7 is obtained. The profile in Figure 7 was obtained from the cleaved cross section shown in Figure 1b. A micrograph of the structures tilted at 45 degrees and slightly rotated is shown in Figure 1a. The raised structures in Figure 1a are developed photoresist on a layer of oxide which has an underlying layer of polysilicon. Distortion of the line intensity profile causes a loss in measurement precision or the inability of the system to perform measurements, can be an indication that the accelerating voltage is too high. Also, certain areas of the image may show time dependent bright or dark regions (Figure 8) that indicate charging [24, 49].

In some instances, increasing the accelerating voltage may reduce the surface charging due to conductivity of underlying layers. This, in turn, produces an acceptable, reproducible video signal. However, this may cause device damage due to e-beam irradiation [13, 25, 57].

High accelerating voltages, in addition to causing charging problems may also affect specimen contamination rates [1]. Induced contamination may be observed by first increasing the magnification setting to 2,000-5,000X, which increases specimen electron density per unit volume and then decreasing the magnification to 100-200X. A small, dark, rectangular area may appear

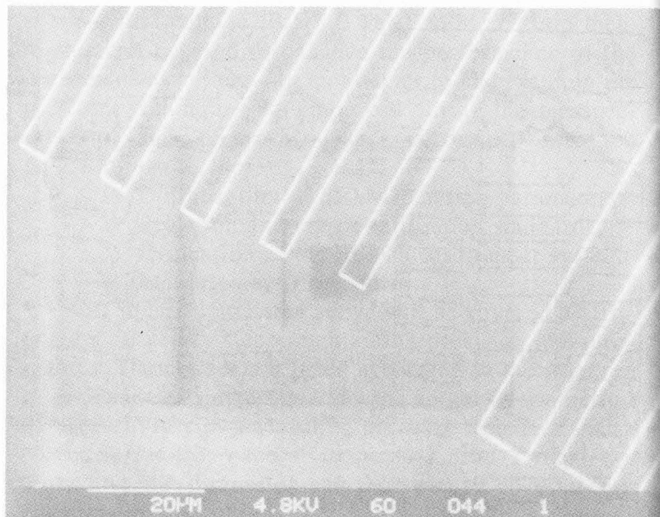

Figure 8. Contamination produced when the e-beam scans a given area initially at high magnification (dark area) for a long period of time with excessive beam current and accelerating voltage, and then the magnification is decreased.

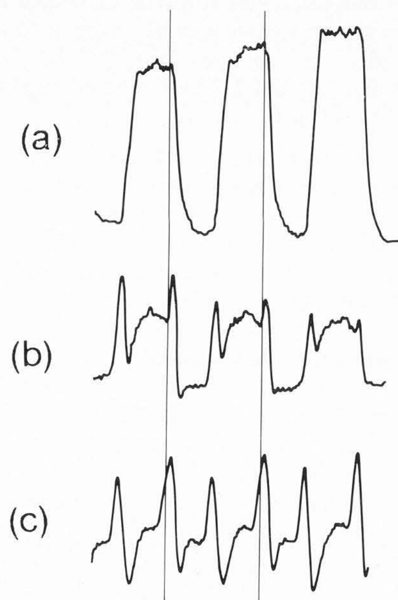

Figure 9. Line intensity profile obtained from the cleaved edge of a specimen similar to the one depicted in Figure 1b with the cleaved edge of the specimen orthogonal to the e-beam **(Fig. 9a)**; cleaved edge tilted 45 degrees with respect to the e-beam **(Fig. 9b)**; and with the e-beam at 45 degrees tilt, scanning the top surface of the specimen in an area away from the cleaved edge, and the structure aligned such that the structure is orthogonal to the direction of the e-beam scan **(Fig. 9c)**.

and remain on the image (Figure 8), indicating specimen contamination or positive charging. When the accelerating voltage is too high, electrons may dislodge surface

material, thus causing damage. The beam may also deposit carbonized vacuum fluids on the specimen surface [1]. In the case of positive charging, the darkened area may disappear with time or when the specimen is removed from beam exposure which in some cases may mean removal from the specimen chamber and reinsertion at a later date.

Once the best accelerating voltage for precise measurements of specific devices for different levels in the process is obtained, it is recommended that the value be recorded and used on similar devices.

Working Distance

The distance from the bottom pole piece of the SEM objective lens to the specimen surface can be defined as the working distance (WD) [12, 59]. The WD should be kept to a minimum in order to optimize resolution. An SEM operated at a low accelerating voltage (typically 0.5-2.0 keV) will usually have a working distance of 5 to 6 mm. A shorter working distance is even better, and in the case of an immersion lens, the working distance will be negative. In order to maintain a constant magnification during measurement of product, the "in-house" product or "golden" calibration standard (a specimen representative of a given step in the process), and the specimen to be measured should be at the same working distance. After completing the magnification calibration procedure for the SEM and a check of the linewidth measurement feature using the in-house standard, the specimen is moved into place and the focus adjusted using only the z motion of the specimen stage. The contrast control is then used to optimize the line intensity profile. In addition, if there is an indicator for the z-height (distance from the surface of the specimen to the final lens), this reading should correlate with the working distance indicator.

Measuring the final (objective) lens voltage using a digital volt meter (DVM), may be more precise than a working distance meter (WDM). Once the minimum WD is obtained for the measurement application using an accurate vertical stage positioning unit, the reading should be recorded for future reference. Experience has shown this method to be sufficient for precision measurements.

Tilt

Ideally, the specimen surface should be orthogonal to the path of the electron beam (zero degrees tilt) to minimize measurement discrepancies. The main reason that a specimen is tilted is: to increase emission of electrons, to reduce charging effects, and to improve detector collection efficiency thereby improving the signal for measurement purposes. It has been shown that the tilt angle for peak secondary electron emission is material dependent [8, 28]. When specimen tilt is used, the optimum tilt is a function of accelerating voltage, and working distance and can be compensated for by using scan rotation.

By using careful measurement practices, it is routinely possible to obtain adequate measurement precision on tilted specimens. If this is not the case for the SEM measurement system being used, a recheck of the calibration of the system with a known standard should be performed.

The effect of tilt on optimum line intensity profiles is especially noticeable when measuring insulating materials. One has to keep in mind that the key is to obtain the most symmetrical and noise-free line intensity profile practical.

During the fabrication of semiconductor devices, when cleavage is not possible, measurements are taken on uncoated, uncleaved wafers with the specimen surface tilted with respect to the e-beam. Due to the physical geometry and materials of the structures, the measurements may require verification. A general procedure used to validate a series of measurements taken at a particular tilt angle is to sacrifice a representative wafer from the batch of wafers. The specimen is cleaved and a conductive coating is deposited on the cleaved edge. Then measurements are performed on the cleaved surface at a tilt of 90 degrees. Figure 9 indicates the change in line intensity profile when the e-beam is not perpendicular to the device features. The line intensity profile obtained from the surface of a cleaved structure at 90 degrees tilt will be much more symmetrical and rectangular (Figure 9a) than the signal obtained at a tilt less than 90 degrees. Using the same gold coated specimen, measurements of the same structures are taken at points away from the cleaved edge with the specimen tilted at 45 degrees for correlation purposes. The measurement line intensity profiles are then evaluated using standard measurement algorithms in order to determine which algorithm gives the closest correlation to cross-section measurements. The evaluation of measurement algorithms is beyond the scope of this paper, however, as an example, the determination of proper threshold setting in applying a threshold algorithm would be evaluated by testing different threshold values. Another measurement algorithm that can be employed is linear regression [52]. Our experience with the regression method indicated good precision with noise-free and well defined line intensity profiles. The resulting measurements using the thresholding algorithm are shown in Table 1. Table 1 indicates the variations in measurements obtained by changing the threshold setting [41] (percent of the maximum amplitude of the line intensity profile where a measurement will be calculated). The maximum amplitude of the line intensity profile is usually referred to as 100% and the minimum amplitude 0%.

By comparing the results from the analysis in Table 1, the optimum threshold algorithm parameters can be assessed by determining the optimum correlation to results obtained from cross-sectioned specimens.

Focus

Generally, to obtain precise measurements it is essential to bring the sample into focus by mechanically adjusting the z-axis position of the stage with the z-axis control. This technique is used rather than changing the SEM working distance. By doing this, one to prevents

the loss of correlation between the focus of the electron beam and the WD as indicated by the SEM WDM. The specimen stage movement in the z (height) direction is monitored as the stage is moved and is changed to obtain best focus of the image as displayed on the viewing CRT. During the initial setup on the linewidth measurement system calibration standard, it is best to use the z-axis control to minimize the difference between the vertical stage position as indicated by an accurate stage position indicator and the working distance indicated on the WDM. This is done in order to reduce measurement errors due to hysteresis in the lenses caused by changes in the final lens current when the coarse focus control is used.

Subsequent to mechanical focus adjustment, the fine focus control is used to optimize the line intensity profile for best precision. The Vickers DL3006 SEM, used in our studies to check the effect of adjustment of the fine focus control on the measurements, indicated a 2.25% variation in the measurements over the full range of the fine focus control. A 50% threshold [45] was employed on the Vickers linewidth measurement system. Normally during measurements the fine focus control is not varied over the full range, and the fine focus control contributes no more than ± 0.5% measurement variation. This may be unacceptable, however, when measuring sub-half micrometer structures.

The important thing to remember with respect to focus is that there may be hysteresis in the lens used for focusing the e-beam. There may also be residual magnetism due to changes in accelerating voltage. To reduce hysteresis, the final lens may be degaussed by reversing the lens current to remove residual magnetism from the core of the final lens. This is done so that the current measured to determine magnification is not affected by a large value of residual magnetism. For this reason, the coarse focus setting is initially established during calibration of the measurement system and is not altered during measurements. Instead, the specimen stage is moved vertically by mechanical means to bring the image into a coarse state of focus. Furthermore, the inherent residual magnetism may also be reduced by increasing the accelerating voltage to a value above the one being used for measurements. Then it is decreased back to the appropriate voltage for measurements.

Beam Diameter

Due to the complexity of semiconductor device structures, e-beam/specimen interactions are very complicated [20, 39, 40]. At the present time, methods of modeling these interactions are being developed [21, 22] to provide a model signal profile from a given structure and material. This should quantitatively aid in assessing the effects of beam diameter and energy on the profile. In addition, modeling should provide a means of analyzing different profiles such that criteria can be established to detect the edge of a line for a given geometry and material. This should further aid in providing a more precise and accurate means of measuring micrometer and sub-micrometer structures.

Table 1. Typical measurements using the thresholding algorithm

A[1]	B[2]	(A-B)	(A-F[3])	(B-F)
1.032	0.980	0.052	0.064	0.012
1.026	0.970	0.056	0.058	0.002
1.040	0.971	0.069	0.072	0.003
1.006	0.978	0.028	0.038	0.010
1.018	0.975	0.043	0.050	0.007

Averages (A-B) = 0.0496 μm;
(B-F) = 0.0068 μm.

[1]Column A = readings taken at 50% threshold setting at locations away from the fracture and the specimen tilted at 45 degrees.

[2]Column B = readings taken at 70% threshold setting at locations away from the fracture and the specimen tilted at 45 degrees.

[3]F = 0.968 μm; reading taken at 50% threshold setting, on cleaved edge with specimen tilted at 90 degrees, and e-beam scanning bottom of structure shown in Figure 1b.

Note: Each reading in column A or B is the width of the line taken over a length of 5 μm.

The smaller the beam diameter, the higher the potential resolution of the SEM [12, 46], since the area of impact of the beam is smaller. In addition, resolution is affected by the size of the area of emission of the secondary electrons. In the absence of noise limitations, the smaller this area, the better the resolution of the SEM. However, decreasing the spot size too much may result in insufficient emission of secondary electrons for signal processing and the generation of good quality micrographs [21, 23]. It also affects the obtainment of line intensity profiles from a given area scanned by the e-beam.

Normally, the SEM is adjusted for best resolution. However, the signal to noise ratio of the signal used for measurement must be maintained at the proper level for precision measurements. It is important to remember to reduce the beam diameter by adjusting the condenser lens setting as far as possible to maintain resolution [12, 59], while at the same time providing sufficient signal levels for measurement.

At low accelerating voltages, the electron energy spread in the beam of an SEM with a field emission electron source can be much smaller than an SEM with a lanthanum hexaboride or tungsten electron source [39]. Thus, the resolving power (resolution) of the SEM using a field emission source can be better than an SEM with a tungsten or lanthanum hexaboride source. However,

the field emission SEM concentrates more current in a smaller area (diameter). This may cause specimen surface damage more easily than a tungsten or lanthanum hexaboride electron source unless it is controlled. We have observed different types of photoresist shifting [9] under continual bombardment by the electron beam from a field emission source during a 10-12 minute period. At this time the SEM had an accelerating voltage of 5 kV, probe diameter of 1500 nm, and probe current of 200 picoamps. It should be possible to overcome this by limiting the probe current. But again there should be sufficient probe current such that the signal to noise ratio is adequate for measurements or micrographs.

Present day SEM linewidth measurement systems usually incorporate a Faraday cup (cage) [32, 58] and a pico-ammeter to measure the e-beam probe current at the specimen surface. Measurement of the probe current is obtained by connecting a high resolution pico-ammeter to the Faraday cup. By checking the probe current at different values of certain SEM operating parameters, such as accelerating voltage, magnification and beam diameter, it will be possible to maintain the same surface charge density each time a set of measurements is to be taken on a given specimen. This is especially important for uncoated specimens where specimen surface charging is a problem. In this type of application of SEM linewidth measurement systems, it is imperative that image and line intensity profile distortion should be held to the absolute minimum.

A record should be kept of probe current at the specimen surface versus precision for various types of specimens that are repetitively measured. This is especially important in a semiconductor processing environment, where certain processes must be monitored as precisely as possible. This information can then be analyzed to determine optimum beam currents.

Specimen surface damage due to excess probe current or beam accelerating voltage can be reduced by beam blanking (turning off the e-beam) during stage movement and data acquisition and evaluation. Video signal processing and the use of an image processor will allow measurements to be taken from a buffered (stored) image instead of a dynamic image [31]. Using a stored image for measurements with the e-beam turned off reduces specimen damage. However, the measurements from a buffered image should be correlated with measurements in dynamic mode of operation. One does this using a coated calibration standard during the qualification of the SEM linewidth measurement system to determine if any differences exist. A system using stored image measurements may still have e-beam drift and specimen charging, but a much shorter time period is generally required to obtain the image for measurements. Scanning the area under measurement for a shorter period of time will reduce specimen damage, charging, and provide a more stable line intensity profile. Thus, with a more stable line intensity profile, the ease of operation of the system will be improved along with the reproducibility of measurements.

Magnification

Present SEM systems with the capability of a measurement feature are normally used to perform measurements on structures in the 0.25-1.0 μm range. In order to obtain measurements on structures in this range the SEM linewidth measurement system precision may require a resolution of 10 nm or better. The system may operate with a magnification setting of 20,000-50,000X or higher. An SEM is ordinarily not the tool of choice to make measurements at magnifications lower than 10,000X. In the case of digital beam and digital video signal storage (buffered images) if the number of pixels across the field of view is fixed, then the number used to characterize measurement is reduced as the magnification is reduced and the measurement precision can be correspondingly reduced. The precision required for the measurements is limited by the resolution of the SEM and the number of points into which the line intensity profile can be divided, such as 512, 1024, 2048, etc. The argument against working at low SEM magnifications arises from the relationship between the intrinsic resolution of the SEM and the spacing between individually sampled points (pixels) in an SEM image. Each point on a specimen scanned by the e-beam is displayed on a CRT as a picture element (pixel). The spacing between pixels limits the measuring accuracy of the SEM at low magnification settings. The line intensity profile of an individual scan across a particular structure represents the signal intensity level due to the emission of electrons from each point on the specimen scanned by the e-beam. It is important that the measuring accuracy be not too different from the intrinsic resolution for reasons described below.

If the structures to be measured are very uniform, the higher resolution of the SEM does not present a problem. However, if the structure is very irregular and the electron beam position in the x-y plane during the e-beam scan(s) for measurement is not accurately maintained, the variance in the measurements can reach unacceptable levels. In comparison to an optical linewidth measurement system, the variations routinely observable at 5,000-10,000X on an SEM are invisible to an optical system [30]. This is due to the spatial resolution of the light optical system which is poorer than that of an SEM. For instance, while the optical system detects the structure as one smooth line, the SEM will be able to resolve the irregularities not detected by the optical system. Consequently the SEM will measure them [30] which results in poorer precision. In addition, the area over which the measurements are made using an optical system, due to magnification, may be anywhere from 5 to 10 times the area scanned by an SEM. Thus as a means of improving measurement precision an SEM linewidth measurement system usually employs multiple scans per line scan. Figure 10 is an indication of how the non-uniformities of a structure become very evident as the magnification of the SEM is increased.

The Vickers DL3006 SEM with incorporated CD100A measurement system, used to perform the

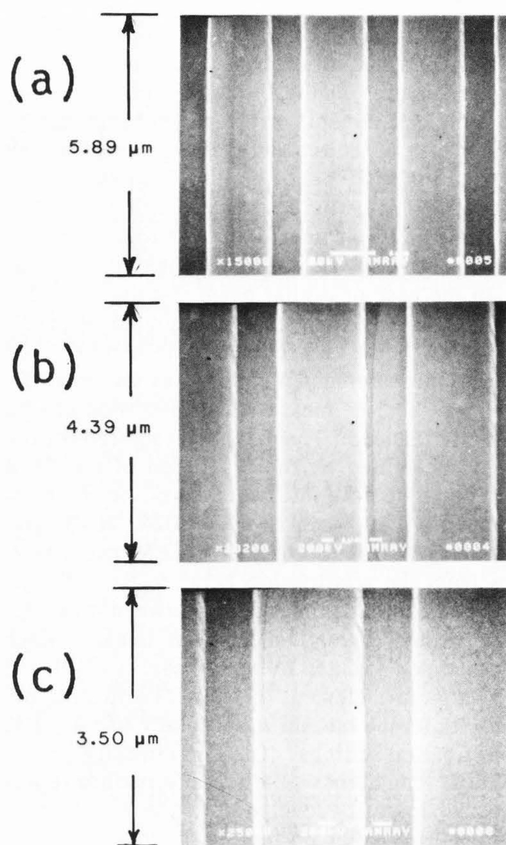

Figure 10. Change in appearance of the roughness of a structure under measurement with a change in magnification setting of the SEM.

measurements described herein, did not have the capability to make measurements at a magnification below 10,000X. In performing measurements below 10,000X, a micrometer marker (a bar on the SEM CRT) is used and the error encountered using this method is unacceptable. Therefore, comparisons between optical measurements and our SEM measurement system at magnifications below 10,000X were not possible. In addition, the measurements acquired using our SEM system were taken with a tilt of 45 degrees.

The length of the area scanned by the e-beam in the y-axis (y-axis scan length as measured using the micrometer marker as a gauge) during multiple line scans, along the line length during measurements, may be as small as 10 μm. For an SEM at a magnification of 25,000X, the y-axis scan length may be 3.5 μm (Figure 10c) depending on the aspect ratio of the SEM CRT. While at a magnification of only 1,000X, the y-axis scan length may be as large as 100 μm. This is true in the case where measurements are averaged over this distance. The longer the length of the structure measured, the more the variations along the length that can be averaged out, which in turn reduces the variations in the measurements. An SEM can produce sharp images at magnifications of 25,000X or greater whereas optical microscopes can only achieve good quality images at magnifications below 3,000X. Optical linewidth measurement systems, depending upon the slit size being used by the system, usually average the measurements along the structure being measured. Thus even an SEM, operated at low accelerating voltages, can be used to make measurements at magnifications not possible with optical systems. This is due to the differences in resolution and the interference and diffraction [16, 34] problems with optical systems.

Ideally a plot of measurement versus magnification of an SEM measurement system should possess no variations at magnifications sufficient for precision measurements. The response curve of a typical SEM linewidth measurement system as checked during the measurement of a photoresist pattern is shown in Figure 11. The variations indicated by this curve are due to the errors in the SEM magnification or possibly due to nonlinearities in the e-beam deflection circuitry. In addition, the e-beam may be deflected due to local fields on the surface of the specimen [27, 60]. The method used to check the accuracy of the e-beam deflection circuitry, will not be addressed here. In order to produce a linear response, it is necessary to calibrate the magnification with a known standard such as the National Institute of Standards and Technology (NIST) magnification Standard Reference Material (SRM) 484. If an accurate measurement calibration standard is available, then it should be measured at magnifications from 10,000X to 50,000X or the magnification range normally used in performing measurements. Consequently, one should calibrate the magnification of the SEM measurement system using SRM 484 first. Next make measurements over the range of magnifications that will be used, plot the results, and record them for future reference.

Contrast

In a standard metrology SEM using an Everhart-Thornley (ET) detector, the contrast setting of the SEM normally adjusts the dynode voltage of the photomultiplier tube (PMT), thereby controlling the gain of the PMT. The PMT amplifies the signal from the photocathode [60]. The video signal (Figure 12a), for a given e-beam scan on a specimen may be processed to provide an amplified, smoothed version Figure 12b of the original video signal before being used for measurements. Improper processing (i.e., extreme signal averaging, smoothing, etc.) shown in Figure 12c, of the original line intensity profile, may result in higher video signal saturation or black suppression. It may also create distortion, as shown in Figure 12c. In addition, misadjustment of the contrast control of the SEM, can alter the black to white levels of the original video signal, resulting in large discrepancies in measurements.

To help prevent these errors, the optimum line intensity profile of a given specimen should be retained as a reference profile for comparison purposes. This is usually done by storing the line intensity versus x-y e-beam position, pixel by pixel, in a memory such as a

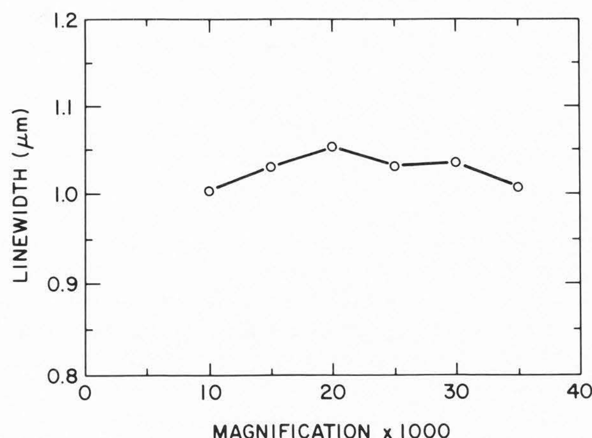

Figure 11. Variations in measurement with changes in magnification.

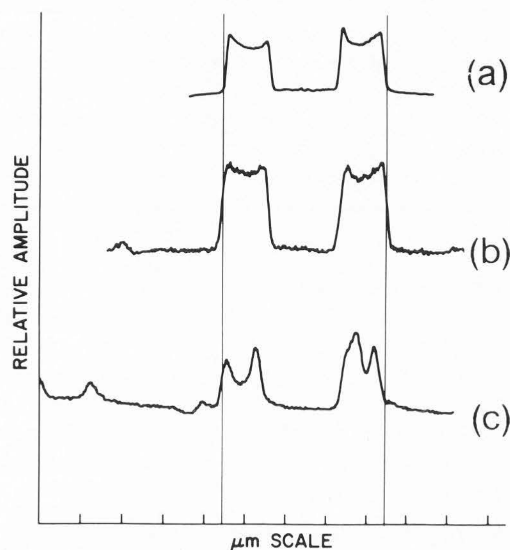

Figure 12a. Typical line intensity profile obtained from two raised structures with a trench between the structures such as those shown in Figure 1a, with the specimen tilted at 45 degrees and the e-beam scanning orthogonal to the structure.

Figure 12b. Processed (amplified, smoothed and averaged) version of the line intensity profile in Figure 12a.

Figure 12c. Severe distortion of the line intensity profile in Figure 12b due to overprocessing the line intensity profile.

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magnetic disk. An entire image can be stored on a frame basis (buffered) and measurements generated from the buffered image. This method allows experimentation with the contrast of the image so as to aid in providing symmetrical line intensity profiles. This data is then retrieved and plotted or displayed on a CRT for comparison with line intensity profiles from similar specimens. Then when a similar specimen is to be measured, the contrast is adjusted until the line intensity profile best matches the stored reference signal.

In general, there is a method for determining the signal-to-noise ratio (SNR) and is referred to as the "Rose criterion" [59]. Empirically, the author found that the contrast level should not be increased if the noise detected on the unsmoothed version of the line intensity profile is more than 5%-10% of the total signal variation. Otherwise, the precision of the measurements becomes unacceptable. Image contrast may be improved by adjusting the accelerating voltage [6] which may cause charging of the specimen, or by increasing the spot size. Meanwhile, the contrast level should be adjusted until the acquired signal is sufficient for precision measurements.

Specimen Alignment

Proper alignment of the specimen is critical for precise measurements [39, 40]. At the present time, manufacturers of SEM linewidth measurement systems recommend physical alignment of the specimen or calibration standard as one views the CRT, such that the e-beam is scanning perpendicular to the long axis of the structure. This will aid in producing a symmetrical line intensity profile. Symmetrical profiles also depend upon symmetrical, uniform, electron detector collection from the field of view. Another factor which has to be taken into consideration is how the structure being measured is aligned with respect to the electron detector. By rotating the specimen, and observing the line intensity profile as the specimen is rotated, detector location effects on the symmetry of the profile may be decreased. Scan rotation can be used to compensate for slight physical misalignment of the specimen. However, a check should be made between measurements made using scan rotation and those made not using scan rotation such that there is very good correlation. In any case, the measurement system should compensate for any residual asymmetry.

Most vendors of modern day SEM linewidth measurements systems do not recommend using raster rotation since this may introduce additional measurement errors. Some measurement systems attached to an SEM will not perform properly unless the pattern or structure to be measured is aligned parallel to the y-axis within 2 or 3 degrees. A check of this can be made using the following procedure with a coated "in-house" calibration standard (one that is representative of a certain process step and whose measurements have been previously verified). Initially one should obtain a line intensity profile from the known in-house coated calibration standard and make measurements with the specimen correctly aligned. Next, incrementally rotate the standard until the measurements are not acceptable and note the amount of rotation. Once the maximum allowable rotation is obtained, the same procedure should be repeated with an uncoated specimen. All measurements must be made within the alignment angular tolerances determined by this procedure. An attempt should be made to perform the precision measurements in the same amount of time it takes

to perform measurements on uncoated specimens that have a tendency to exhibit surface charging. One should keep in mind, however, that sample rotation introduces what is known as "a cosine error", due to the fact that the e-beam is not scanning orthogonal to the structure being measured. This is because the number of pixels representing the width of the structure are not the same as if the structure was perpendicular to the e-beam scan.

Detector Location

In general, there are two types of secondary electron detectors, those located in the specimen chamber and those placed inside or within the objective lens [50, 54]. The results reported in this paper (e.g., Table 1) were obtained using the standard ET detector placed in the specimen chamber [11]. In our experience, significantly better measurements were obtained using the standard detector configuration and a tilted specimen than those obtained under similar condition using an in-lens detector [50, 54] and an untilted specimen. The difference is probably related to greater SE production and collection at significant tilt angles and can become critical when measuring difficult samples, such as submicrometer photoresist structures. Ideally, detectors in SEM linewidth measurement systems are located so as to optimize the collection of electrons and aid in obtaining the most symmetrical line intensity profile. NIST has employed a microchannel-plate detector system which reportedly has performed very well [45]. Some systems have multiple detectors to aid in producing a symmetrical profile. In the case of two detectors, they are usually positioned diametrically opposing each other.

Selection and Use of Calibration Standards

Concepts

Pitch (periodicity of similar structures) and linewidth (distance between structures or distance across a given feature) are measured as a means of monitoring semiconductor processes. Precise measurements are usually defined as those which are very repeatable. Accurate measurements are those which represent the true dimension of a given feature. SEM linewidth measurement systems generally make very precise but not necessarily accurate measurements. In order to obtain accurate pitch measurements, the magnification of an SEM must be calibrated with the aid of an accurate magnification standard. The accuracy of pitch measurements can be checked using the NIST SRM 484 standard. A diffraction grating from the National Research Council of Canada (NRC), which has a nominal pitch of 0.833 μm, was used by the Vickers Corp. in the CD100A linewidth measurement feature. The CD100A was an integrated feature of the DL3006 SEM and the diffraction grating was used as a means of calibrating the linewidth measurement system to a given pitch.

Pitch measurements ordinarily do not require a thorough knowledge of the e-beam/materials interactions or the mechanisms involved in the generation of the line intensity profile. Any error caused by inaccurate determination of the edge of features is canceled if the measurements are precise and the structures and their associated profiles are translationally symmetrical. This is usually true if structures in an SEM image are compared with similar structures in the same image.

Accurate linewidth measurements, however, require a thorough knowledge of the nature and point of origin of the SEM signal used to generate the line intensity profile [20, 21]. The reason being that the e-beam electrons which penetrate the area being scanned by the e-beam travel some distance before exiting the surface. Thus, detected electrons usually do not emerge at the point where they initially penetrated the surface. This creates a problem if an accurate measurement of the location of the edge of a feature is required due the to so called "beam penetration effect" [60]. Further there are "edge penetration effects" [50]. Some primary high energy electrons may enter the top surface of a structure but escape after penetration through the side of the structure. Thus, accuracy of linewidth measurements is limited to the evaluation of the origin of the signal. Accuracy is also limited by the relationship between the actual surface of the feature being measured and the detected signal. This will require electron modeling for the electron beam/sample interactions, signal generation and instrument. Consequently, linewidth measurements can be checked precisely, but measurement accuracy is limited because of this residual uncertainty.

Presently, internationally accepted uncoated SEM linewidth measurement calibration standards for different materials in the micrometer and submicrometer range do not exist for use in low voltage SEM linewidth measurement systems. Until such time that an internationally accepted SEM linewidth standard for measurements is produced, either a certified diffraction grating, or a linewidth standard representative of a given process step (an "in-house" standard), will have to be used to calibrate the measurement system. Calibration of the system could be achieved by measurement of the periodicity of 3 to 10 lines of the in-house linewidth standard, with a check of the system measurement precision being performed on the periodicity of a primary standard. Then, nominal linewidth measurements can be made on the same standard. Though these linewidth measurements will not be precise to better than 10-30 nm, this information is necessary in order to check short and long term measurement precision. It can also provide a means of checking different measurement systems against each other.

The key issue is to use a calibration standard which will produce precision measurements. Truly accurate measurements will only be obtained from low voltage SEM measurement systems when universally accepted standards containing dimensions and materials representative of those used by manufacturers of semiconductor devices are available. In addition, SEM linewidth measurement systems capable of performing accurate measurements are a necessary requirement. Until

then, it will be possible to make precise, but not necessarily accurate, measurements using an SEM linewidth measurement system.

Procedures

Usually an SEM linewidth measurement system is calibrated in the following sequence. First, the SEM magnification accuracy and precision is verified using a primary standard, such as NIST SRM 484. Also a certified international standard containing periodic features in the micrometer range, such as a National Research Council of Canada (NRC) certified grating. These same standards can then be measured by the SEM linewidth measurement system for comparison purposes.

Next, a secondary standard containing single and periodic feature widths within the range of devices being fabricated, may be certified by an internationally recognized standards laboratory. These secondary standards usually contain a single layer of resist, a metal such as aluminum, chrome, or copper, on a bare silicon wafer, or a combination of these materials on a bare silicon wafer. Then the same secondary standard can be measured by the SEM linewidth measurement system after calibration of the SEM magnification and measurement of the primary standard. Finally, the pitch and linewidth of a device with features representative of a certain step in the process is measured. This is considered as a calibration standard for a given step in the fabrication process. The specimen to be used for this type of standard is usually statistically selected using measurements of a sampling of devices and the "average" device is classified as the "in-house-standard".

SEM magnification calibration measurements

The SRM 484 magnification standard is issued with a document of certification along with the measurements obtained by NIST. In addition, NIST lists some of the factors that affect SEM magnification to aid in the detection and correction of the source of magnification error(s).

The length of the micrometer marker (cursor) displayed on the SEM viewing CRT changes as the magnification is changed, and when used as a means of measuring structures, gives a rough indication of the length of the objects being viewed on the CRT. However, the SEM micrometer bar must be properly calibrated on the SEM CRT.

In order to insure that the marker may be used for approximate measurements, preliminary calibration of the SEM magnification is suggested using the NIST SRM 484 standard. Preliminary magnification calibration is performed by checking the spacings on SRM 484 at varying magnifications as indicated on the SEM viewing CRT. Normally this procedure is performed over the range at which the measurements will be taken (10,000-50,000X). A comparison is made between the length of the cursor and the magnification readout on the viewing CRT versus the distance between the line spacings on SRM 484. The SEM is then adjusted for the best possible match.

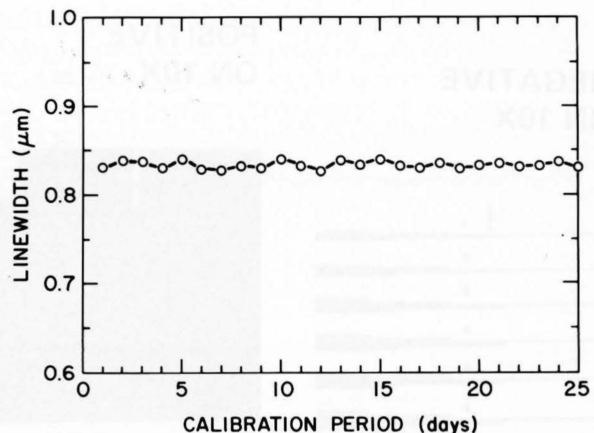

Figure 15. Twenty-five measurements of a photoresist structure on a processed wafer taken over a five week period during calibration of a SEM linewidth measurement system.

the structure, or off the structure when the electron beam is at an angle of incidence of 90° to the surface of the cleaved edge. This approach is usually acceptable for structures that are not totally square or rectangular in shape. The resultant line intensity profile can be processed to provide acceptable measurements using any one of several measurement algorithms.

If the structure shown in Figure 1a is tilted to 45 degrees and the cleaved edge is scanned by the e-beam at the bottom of the structure, the line intensity profile will appear as shown in Figure 9b.

However, if the specimen is tilted at 45 degrees, but the e-beam scans the top surface of the structure shown in Figure 1a a distance away from the cleaved edge, the line intensity profile appears as shown in Figure 9c. The line intensity profiles in Figures 9a, 9b, and 9c were the best that could be obtained with the SEM used in this investigation.

Once a calibration standard is obtained from a fractured specimen and the width of the lines measured with the e-beam orthogonal to the cleaved surface, then an unfractured specimen, tilted at 45 degrees with respect to the e-beam, should be measured for comparison. This is accomplished by adjusting the measurement feature with the specimen tilted at 45 degrees so as to obtain the same readings as those taken with the calibration specimen tilted at 90 degrees. A procedure such as this, allows the use of a complete wafer. If a threshold algorithm is used in the SEM measurement feature to obtain measurements of structures then only the threshold setting has to be changed to obtain equivalent measurements at 45 and 90 degrees tilt (Table 1).

Advantages and disadvantages of different calibration standards

The NIST SRM 484 calibration standard is universally accepted and is supplied with a certificate that indicates the measurements obtained by NIST for a given calibration standard which has been assigned a serial

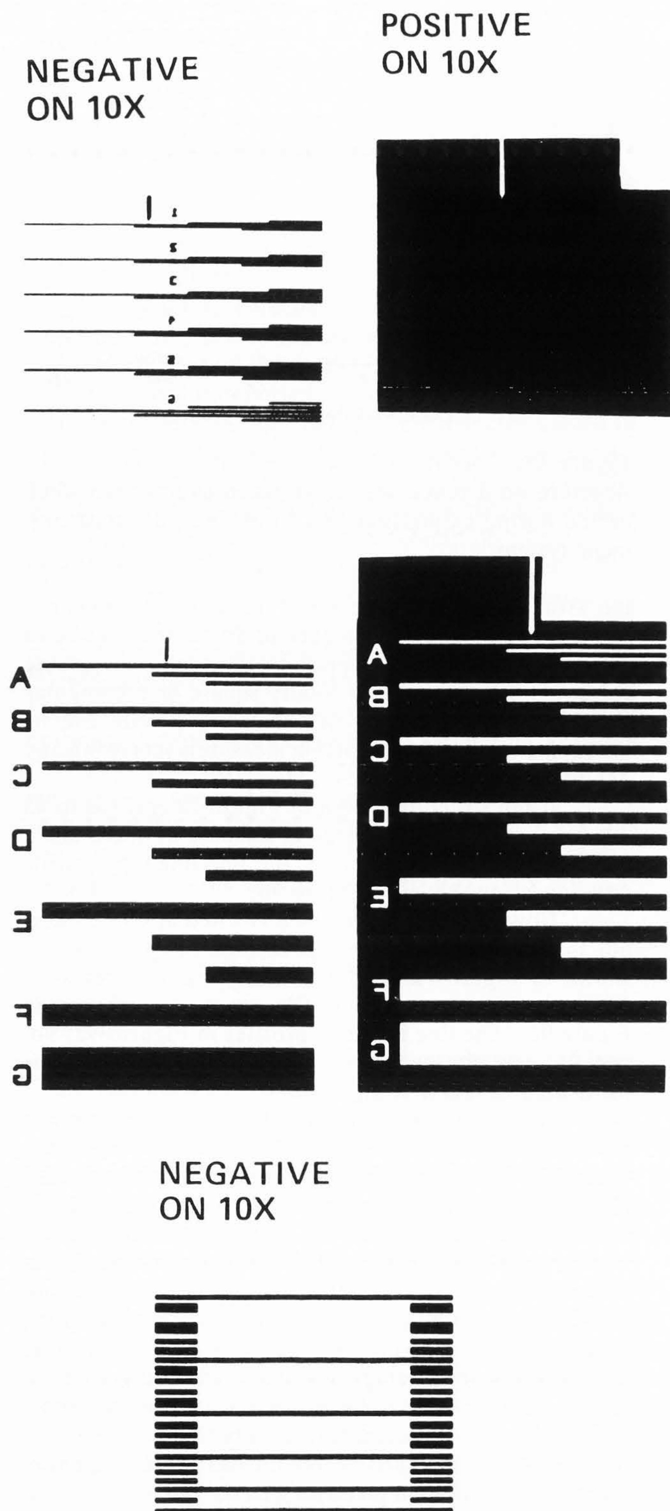

Figure 14. Basic patterns of the chrome-on-glass artifact consists of colinear single and multiple lines and spaces ranging from about 0.5 to 2.0 μm. (Reproduction of Figure 1 from Reference (48) courtesy of Dr. Hans R. Rottmann, IBM Corporation, East Fishkill, NY).

dioxide. Patterns having a periodicity of 0.5 μm have been generated by e-beam exposure of the resist and these specimens can be used for SEM linewidth measurement calibration standards. They may, however, over a period of time, present a problem as far as stability is concerned. Another kind of standard containing patterns on silicon with different pitches down to 0.5 μm have been produced by IBM Burlington [36]. The e-beam of an SEM is used to expose a layer of resist. In this case, the e-beam is held stationary while the specimen is moved during exposure. An accurately calibrated voltage is applied to a piezoelectric crystal thereby causing a stage affixed to the crystal to move a very precise distance [7]. In addition, a laser interferometer [39] monitors the movement of the piezoelectric stage. After exposure and development of the resist, the specimen undergoes a reactive ion etching process [5, 15, 53, 62-64]. The resist is then removed and the etched pattern can be coated with a thin layer of gold for high voltage operation. The specimen can also be used in calibrating an SEM linewidth measurement system in low voltage (0.5-2.0 keV) mode of operation. At the present time, neither one of these specimens is available to the general public.

Ideally, the structures on the specimen should be measured before and after deposition of the gold coating. When measurements of this nature are taken, we have found that the difference, as expected, is the thickness of the gold coating. One should remember that this procedure is used for calibration purposes only.

NIST has other calibration standards in production such as the "Low accelerating voltage SEM magnification standard" [42], the uncoated photoresist and silicon on silicide standards [43], and the new prototype SEM magnification standard [44].

Semiconductor calibration standards

In the semiconductor industry, measurements have to be made on specimens that cannot be coated with a conductive material. There are several ways in which SEM linewidth measurement systems being used in the manufacture of semiconductor devices can be calibrated. Some SEM systems may have an integrated circuit chip installed inside the specimen chamber. The chip contains known patterns with geometries of varying sizes. The patterns are usually line/space structures as shown in Figure 14 [47, 48]. The measurement system is then calibrated on the pitch (periodicity) of the smallest pattern.

Some manufacturers of semiconductor devices measure the pitch of a pattern on a chip selected from actual chips produced for shipment to the general public. The chip to be used as their "in-house" measurement standard is statistically selected after measuring the pitch of a given pattern on similar chips at a certain process step. The selected chip is recognized as being representative of that particular step in the process and therefore, is referred to as an "in-house standard".

In order for the in-house standard to be valid, it should be representative of a given process, and the ma-

terial content of the top layers of the specimen be well known. This is because SEM operating parameters have to be varied for different materials and structures. Consequently, there should be an in-house standard for each type of structure which has a different material for the top layer.

Figure 15 is an example of the calibration of an SEM linewidth measurement system over a one-month period using a structure on a semiconductor chip. Note the decrease in the variance in the measurements after the first week of calibration. This could be attributed to the "specimen learning curve". Each point on the graph represents a calibration reading for a given day. The specimen used for calibration was a line/space pattern consisting of photoresist on a layer of silicon dioxide on silicon. The measurements were taken from a specific line and over the same length of the line each time. A given measurement represents the average of measurements from eight locations along the length of the chosen line. Each location was scanned 32 times. This procedure was repeated three times to produce one point on the graph (one calibration reading for the day).

Semiconductor process systems producing device patterns, for instance, for use as calibration standards, are reported to introduce variations in the order of 10-50 nm depending on the location of the measurement [48]. Measurements on line plus space structures (pitch) consequently can display uncertainties of up to $\pm$ 25 nm. We have made pitch measurements on such structures and have found 3 sigma pitch variations in the range of 6-35 nm, which can be explained in terms of process and equipment noise. Subsequent measurements of associated linewidths of these patterns using a stored image on a screen has produced linewidth variations up to 0.060 μm on 1 μm structures over a length of 30 μm.

During fabrication of integrated circuits a calibration standard for a particular process step is used so that the operating parameters of the SEM can be properly set for the materials of the structures being measured at that point in the process. Then when critical dimensions of a product chip are measured at this particular process step, the results should be representative of dimensions generated by the process.

Further, if the top layer of the calibration standard is composed of resist, it is recommended that the standard be stored in a class 100 area [64], in an air tight container, at the temperature recommended by the manufacturer. Some resist specimens degrade with time and must be replaced if structural changes in the resist cause measurement variations.

In producing a calibration standard, a more symmetrical line intensity profile approaching a square wave is obtained if the physical profile of the structure being measured is square or rectangular. A line intensity profile approaching a square wave (Figure 9a) is obtained from the specimen shown in Figure 1b when the e-beam is scanned orthogonal to the cleaved edge and near the bottom of the structure shown in Figure 1b.

This is due to the fact that the e-beam is either on

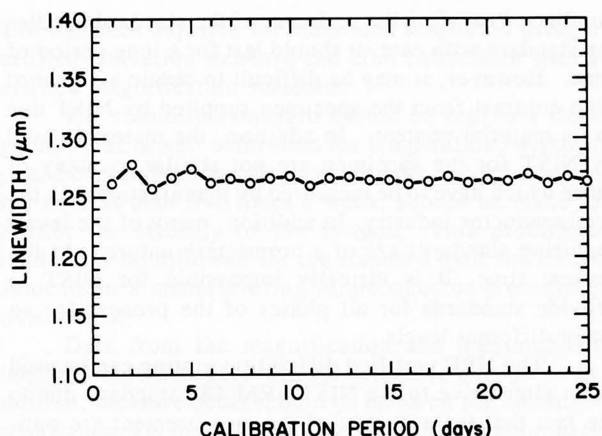

Figure 15. Twenty-five measurements of a photoresist structure on a processed wafer taken over a five week period during calibration of a SEM linewidth measurement system.

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the structure, or off the structure when the electron beam is at an angle of incidence of 90° to the surface of the cleaved edge. This approach is usually acceptable for structures that are not totally square or rectangular in shape. The resultant line intensity profile can be processed to provide acceptable measurements using any one of several measurement algorithms.

If the structure shown in Figure 1a is tilted to 45 degrees and the cleaved edge is scanned by the e-beam at the bottom of the structure, the line intensity profile will appear as shown in Figure 9b.

However, if the specimen is tilted at 45 degrees, but the e-beam scans the top surface of the structure shown in Figure 1a a distance away from the cleaved edge, the line intensity profile appears as shown in Figure 9c. The line intensity profiles in Figures 9a, 9b, and 9c were the best that could be obtained with the SEM used in this investigation.

Once a calibration standard is obtained from a fractured specimen with the e-beam orthogonal to the cleaved surface, then an unfractured specimen, tilted at 45 degrees with respect to the e-beam, should be measured for comparison. This is accomplished by adjusting the measurement feature with the specimen tilted at 45 degrees so as to obtain the same readings as those taken with the calibration specimen tilted at 90 degrees. A procedure such as this, allows the use of a complete wafer. If a threshold algorithm is used in the SEM measurement feature to obtain measurements of structures then only the threshold setting has to be changed to obtain equivalent measurements at 45 and 90 degrees tilt (Table 1).

Advantages and disadvantages of different calibration standards

The NIST SRM 484 calibration standard is universally accepted and is supplied with a certificate that indicates the measurements obtained by NIST for a given calibration standard which has been assigned a serial

number. Providing the recipient of the standard handles the standard with care, it should last for a long period of time. However, it may be difficult to obtain a signal of high contrast from the specimen supplied by NIST due to its material content. In addition, the materials used by NIST for the specimen are not similar to many of those which have to be measured by manufacturers in the semiconductor industry. In addition, many of the levels requiring standards are of a proprietary nature. At the present time, it is virtually impossible for NIST to provide standards for all phases of the process for so many different levels.

The NRC certified diffraction grating can be used as an alternative to the NIST SRM 484 standard due to the fact that the accuracy of the measurement are optically certified to a three sigma value of 0.010 μm by an internationally accepted organization. In addition, this type of standard will not deteriorate as rapidly as a photoresist standard. Subsequently, it will provide a better indication of drift in the precision of an SEM linewidth measurement system. The advantage of a diffraction grating over the NIST SRM 484 standard is that it contains multiple line-space structures which have a pitch that can be used as a means of calibrating an SEM linewidth measurement system. Calibrating an SEM linewidth measurement system using the pitch of the diffraction grating structures more closely approximates calibration using the pitch of the kinds of structures that are measured on integrated circuits (ICs). However, if this particular standard is used, it will only insure calibration of the measurement system at a specific distance, (namely, 0.833 μm and multiples thereof, which should suffice for many applications), but the system will not be calibrated over a range of distances.

A standard fabricated by a manufacturer of devices, containing line/space patterns in both the submicrometer and micrometer or greater range, such as the one produced by IBM Burlington, produces a very uniform pattern and may last for an extended period of time. However, when it is coated with a layer of gold that is too thick, the SEM image of the pattern on the specimen may be poor because of the lack of sufficient signal coming from the silicon. Therefore, the signal available for processing by the measurement feature may not be sufficient for precision measurements using a low voltage SEM. The reason being that there is not a sufficient difference in the number of electrons produced from the gold and silicon to clearly delineate the pattern etched in the silicon.

A major disadvantage of the three standards above is that the specimen used for the standard is not composed of materials similar to many of the materials used in the manufacture of semiconductors such as photoresist, silicon nitride, or polysilicon. It would probably be impossible for NIST to fabricate enough of these types of standards for the entire semiconductor industry. Thus commercial manufacturers of semiconductors must fabricate their own standards, representative of semiconductor devices at certain steps in the process. Although these standards have the advantage of being true representations of a device at a certain point in the process, they present problems when an attempt is made to perform measurements of structures on a given standard. Ideally, the top surface of these specimens should not possess a conductive coating to reduce charging. This causes a problem in obtaining optimum SEM operating parameters for symmetrical line intensity profiles. These particular standards may not be durable and due to their proprietary nature, it may not be possible to have measurements of structures on a given specimen certified by an internationally recognized institution.

Frequency of calibration

Initially, calibration of the SEM linewidth measurement system may be performed daily over a period of several weeks to determine system drift. Once this is done, a monthly check consisting of the measurement of specified lines each hour for one eight hour shift should be sufficient. The secondary standard is used to calibrate the linewidth measurement feature weekly or daily depending upon the required measurement precision. The in-house-standard is used to check measurement drift and system performance at the beginning of each shift or before making a large number of measurements.

The frequency of calibrating an SEM linewidth measurement system depends upon the required precision of the measurements. At times, a calibration standard may be required for a given step in the process. If this is the case, it is advisable to calibrate the measurement feature each time before the measurement of a calibration standard for a given process step. Otherwise, it may be sufficient to calibrate the measurement feature once each eight hours or once each 24 hours. Calibrating the system once a week or once a month is not recommended at the present time because this represents too long a period of time between calibrations for present day SEM linewidth measurement systems.

Evaluation of an SEM Linewidth Measurement System

The evaluation of an SEM linewidth measurement system should include the following items: duration of the evaluation period, types of specimens used for the evaluation, and specific checks to be made on the system.

Duration

Normally, a thorough check of the system should be made over a one month period with the system being operated for at least an eight hour period each day during the evaluation. The most thorough method would be to operate the system on a 24 hours per day basis for one week. However, in the case where the system has to be checked at the site of manufacture, checking the system during a one week period of eight hours each day will usually give a good indication as to the true capabilities and reliability of the measurement system.

Specimens

There are four types of specimens which should be considered as a means to test the system. The specimens chosen should contain at least one of each of the following types:

1) A resolution standard for checking the resolution of the SEM.

2) A measurement standard that has been certified such as the NRC diffraction grating or the NIST certified SRM 484 standard.

3) A specimen simulating commercial integrated circuit devices with the top layer containing resist features and an underlying layer of silicon dioxide. The structures on the specimen should include periodicities in the submicrometer range. In addition, a check should be made to see that the specimen has not deteriorated in any fashion so as to provide symmetrical structures for measurement.

4) Actual commercially fabricated devices possessing simple patterns of various materials with the top layer being some type of resist, silicon dioxide, silicon nitride, or metal. There should be one specimen for each of the types presently being measured. In addition, one should keep in mind that the specimens for system evaluation should be of a stable nature and a specimen containing resist may present a stability problem.

System checks

One of the objectives of making a thorough check of an SEM with an attached measurement system is not only to obtain a complete understanding of the operation of the total system, but to assess the "real" capabilities of the system. If a thorough evaluation of the system is performed, it will be possible to define the limitations of the system for a given application.

One should start with well-known specimens or certified specimens to allow verification of the measurements and to determine the precision of the measurements. One important item to improve the precision of the system and to insure the integrity of the test procedure for precision is to have identification marks on structures being measured. This will aid in performing measurements in the same location each time. The basis for this being that the resolution of the SEM allows detection of the variations in structures themselves and the attached or integrated linewidth measurement feature will measure these variations. Therefore, if the structure does not appear smooth at the magnification at which the SEM linewidth measurement system is making the measurements, there will be a much larger distribution in the measurements. In addition, if the SEM does not position the e-beam in the exact same x-y location for a repeat set of measurements on the same structure, then it is possible that a different set of measurements may be obtained for a given structure [29].

If it is possible, the structure should be measured over a 50 μm length to minimize the variations in measurements due to irregularities in the structure.

Precision measurements should be made after the SEM has been adjusted for maximum resolution using a certified resolution standard and after calibration with a certified magnification standard.

The resolution standard should be kept in a storage unit that is well controlled for temperature, humidity, and contamination. Regular periodic checks, preferably no less than five times a week, should be made to monitor the stability of the system. This procedure should also be followed for the standard used for measurements in a manufacturing semiconductor processing environment.

Data from the magnification and measurement standards should be recorded for reference purposes. In addition, measurements should be made on the measurement standard at magnification settings which encompass the magnification setting at which the system will perform measurements on various specimens.

Measurements made *in situ* (using a line intensity profile obtained immediately following the scan(s) of the e-beam at the measurement location) as opposed to measurements made from a stored image, will vary with specimen stage drift and e-beam drift. Specimen stage drift can be checked using the line intensity profile of submicrometer structures. A profile from a submicrometer structure can be displayed on the SEM viewing CRT over a short period (5-10 minutes). Then, while the profile is displayed, any shift in the profile can be observed to determine the amount of shift over the viewing period. Normally, the length of the period used to check e-beam drift should be at least as long as the amount of time it takes to perform any measurement of a given specimen. If the shift of the profile is not equal to, or less than the specified precision of the SEM measurement system, a check of the cause of the shift should be determined and corrected using a well characterized standard.

If the electron source of the SEM is tungsten or lanthanum hexaboride, the drift of the e-beam can be detected by imaging the electron source of the SEM after the SEM has reached the point of stabilization. In most cases, the SEM will take from 30 minutes to an hour after being powered up to insure, beyond any reasonable doubt, that the system will not drift. If the e-beam is drifting, the spot in the viewing screen representing the electron source will change position on the CRT. Any measurements, taken during e-beam or line intensity profile drift, will be invalid.

The specimen should be carefully aligned each time it is to be measured. Further, measurements should be made with the same operator and a comparison made between repetitive measurements at the same location on the specimen without moving the specimen. Then, measurements should be made when the specimen stage is moved to another measurement location and returned to the original measurement location while the specimen remains in the SEM specimen chamber. Finally, the specimen should be unloaded from the specimen chamber after a series of measurements have been taken, reloaded and remeasured. In doing so, this will give a true

indication of the precision of the system during normal operation.

Measurement procedures

Once the optimum SEM operating parameters have been determined and the SEM measurement feature calibrated to a known standard, there are several steps in the measurement procedure that should be adhered to in order to acquire the most reproducible measurements.

Our experience has shown that the following procedural steps are important when making measurements using a low voltage SEM with an incorporated or attached measurement system.

1) Thoroughly understand the SEM and its measurement system and know their limitations.

2) If it is necessary to perform measurements on sensitive structures, obtain SEM and measurement system operating parameters by examining an area adjacent to the measurement location which is not critically sensitive to e-beam damage [9, 13].

3) Experiment with simple structures of different materials and slopes to determine optimum SEM and measurement system operating parameters.

4) Optimize the SEM operating parameters for each specimen prior to making measurements.

5) Calibrate the SEM magnification on a National Institute of Standards and Technology (NIST) standard, such as the Standard Reference Material SRM 484 specimen. Also calibrate the attached or integrated measurement system using cleaved specimens with structures having a known periodicity. The angle of incidence of the SEM e-beam on the cleaved specimen surface should be 90 degrees.

6) Measure a known specimen representative of a given process step usually referred to as an "in-house" or product "golden" standard prior to making measurements on a similar specimen.

7) Make sure the specimen is properly aligned prior to making measurements and try to obtain a symmetrical line intensity profile with minimum variations in dc (base) reference level (Figures 4-5).

8) If it is possible, try to measure the width of a given structure over the same length that is commensurate with measurements using a high precision optical measurement system for comparison [55].

9) Perform pitch measurements and achieve minimum deviation of these measurements before measuring individual structures.

10) Check the line intensity profile for time dependent shifting, distortion, and charging when performing measurements.

11) Try to match the same profile from previous measurements on similar specimens.

12) Find the minimum number of scans for each measurement location on a line, number of locations where each structure will be measured, and number of times each location must be measured for acceptable statistical results.

13) Correlate measurements of unfractured structures at 45 degrees tilt with those taken at the cleaved edges of the same structures with the specimen at 90 degrees tilt, such as those shown in Table 1 and Figure 16.

14) Periodically perform precision checks on the measurement system and record the results to check system performance and drift (Figure 17).

15) Perform measurements on a stored image of the structure whenever possible if the limitations of the image processor in conjunction with the measurement system attached to the SEM are well known.

16) When performing measurements on semiconductor devices to monitor fabrication processes, choose the measurement sites statistically, to aid in detecting the source of measurement variations.

By adhering to the principles and procedures described above, it should be possible to obtain maximum precision when performing measurements with a given SEM measurement system.

Conclusions

Several operational parameters affect the performance of an SEM and subsequently the results of an attached or integrated linewidth measurement system. In order to optimize the parameters for precision measurements, various techniques have to be used.

Careful attention must be paid to the details involved in determining the best techniques. There are several procedural steps which can be used to obtain the best performance of the measurement system.

Measurements of unfractured structures should be correlated with measurements of the same structure after the structure has been fractured and measurements made at the cleaved edge with the e-beam orthogonal to the fractured edge of the specimen.

Until such time that certified accurate measurement standards representative of different materials and structures used in the semiconductor industry are available, certain techniques should be used to obtain maximum measurement precision. The techniques should aid in reducing operator dependency and decrease variations in measurements between different systems at all times.

Certified standards which have been accurately measured and linewidth measurement systems capable of performing accurate measurements are needed before the issue of accuracy can be adequately addressed.

In order to evaluate and compare measurement systems, one must allow enough time to perform all necessary checks using specially selected specimens to thoroughly test the performance of each system.

Additional theoretical work including modeling [21] is required to understand such items as correlation between the line intensity profile and the physical profile of different structures and materials.

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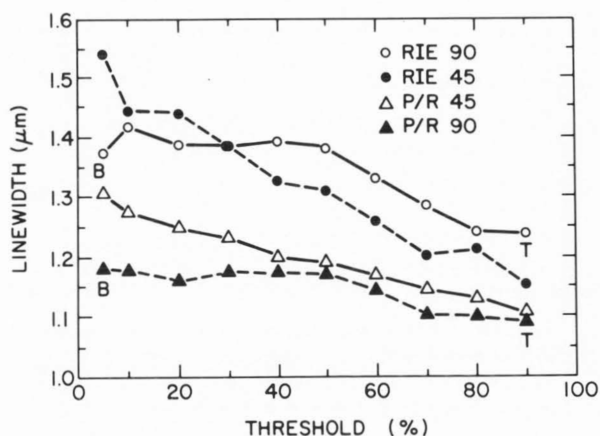

Figure 16. Measurements of a photoresist, (P/R) structure, similar to the one shown in Figure 1a, before and after reactive ion etching (RIE) taken at different threshold settings.

P/R 45 = Before RIE, 45 degrees tilt, e-beam impinging on top surface.

RIE 45 = After RIE, 45 degrees tilt, e-beam impinging on top surface.

P/R 90 = Before RIE, 90 degrees tilt, e-beam impinging on cleaved edge.

RIE 90 = After RIE, 90 degrees tilt, e-beam impinging on cleaved edge.

NOTE: T = top of structure B = bottom of structure

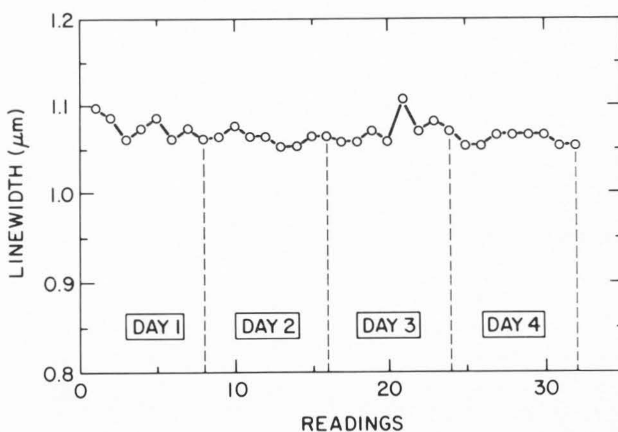

Figure 17. Measurements from a four day precision check of an AMRAY Model 1500 SEM linewidth measurement system.

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Discussion with Reviewers

J. B. Bindell: It is not clear why one should be measuring "stored images". How can one be sure that the conditions are reproduced in the SEM to exactly match those used on the stored image when it was first collected?

Author: One should be measuring stored images, since once an image of the structure is obtained and stored, the e-beam can be turned off and the stored image can be accessed for measurements. Then the SEM linewidth measurement feature can process a more stable line intensity profile, damage to the specimen is reduced, and charging of the specimen is decreased. Perhaps the term "buffered" should be used instead of "stored", since a buffered image is collected pixel by pixel under a given set of SEM operating conditions and stored or buffered as it were under the same set of SEM operating conditions.

J.B. Bindell: How does one perform a practical determination of the emission coefficient versus primary electron energy in order to optimize the choice of kV setting?

Author: In practice, one never really tries to determine the shape of the emission coefficient versus the primary electron energy, although this is a significant factor in obtaining stable line intensity profiles from the specimen. Normally, one finds that not only the accelerating voltage, but the current incident on the specimen, the tilt of the specimen, the e-beam scan rate and properties of the material are all important in controlling charging. Our experience has shown that the process engineer, or person responsible for the critical dimension measurements, must spend some time in determining the proper SEM operating conditions for the different process levels and the different types of materials involved in the process during the fabrication of semiconductors.

J.B. Bindell: There is a definite asymmetry in the signal displayed in Figure 5. One possibility for this is that as the beam jumps from one material to the next, there is a "charging time constant" that is in effect. Does this suggest that there is an optimum scanning rate or pattern that should be selected for precision measurements? If so, how does one determine it? If this asymmetry is caused by feature shadowing, would a different detector strategy be more effective than the one in use?

Author: There is a "charging time constant" which can be observed by scanning at different scan rates in what is known as "slow scan rate". When different slow scan rates are used the effect becomes readily apparent on the SEM CRT. One can see the bright to dark regions change, and if it is possible to set the e-beam scanning in a single line scanning mode, the line intensity profile observed will change in shape as the specimen becomes charged. Since the least charging effect possible is desired, faster scan rates like a TV scan rate (15,750 cps/line) are used. Experimentation has to be performed using TV scan rates to determine what accelerating voltage, tilt, beam diameter, and specimen current produce the best signal to noise ratio. The asymmetry can be reduced by rotating the specimen or by installing a second detector diametrically opposed to the first detector and balancing the output of the two detectors as an aid to reduce the effect of feature shadowing.

J.B. Bindell: When the SEM stage is tilted, there are geometrical distortions which are introduced (trapezoidal scan pattern) which could affect the results. How does one compensate to these potential errors? If the SEM makes "tilt corrections", how can the procedure be checked.

Author: Geometrical distortions which introduce a trap-

ezoidal scan pattern do not introduce potential errors which would be of a major concern. First one defines the top of the scan area (top of the image on the SEM CRT) as X1, the bottom of the scan area as X2. Then, assuming a field size (area scanned by the e-beam) as 10 μm and a magnification of 10,000X it can be geometrically shown that the ratio of X2/X1 at a tilt of 45 degrees is 1.0012. At a magnification of 20,000X, field size of 5 μm and a tilt of 45 degrees the ratio of X2/X1 is 1.0006. Most critical dimensions are measured at even higher magnifications and therefore, the distortion is even less.

J.B. Bindell: In Figure 12, the types of distortions introduced by improper processing are shown. Rather than doing this, can the author suggest what processing is correct in this application.
Author: One approach would be to display the line intensity profile and adjust the brightness and contrast of the SEM while observing the profile. This is done in order to determine the point at which the video signal is not being saturated causing a loss of information. Differential processing of the signal might produce less distortion or one could use decreased frame averaging.

J.B. Bindell: Most diffraction gratings are specified for an average pitch rather than for the accuracy of any particular portion of the ruled surface. Is the NRC standard a ruled grating? If so how many lines are averaged in the measurement? What magnification is used?
Author: The author has not contacted Bausch & Lomb, the company that fabricated the diffraction grating used in the Vickers Company (Now BIO-RAD) DL3006 SEM used to perform some of the experiments covered in this paper. The measurements were averaged over three lines using an algorithm installed by Vickers which could not be modified. The calibration was performed at a magnification of 50,000X. As a check, the calibration procedure was performed in several areas on the grating as a means of averaging the results. This method avoided the biasing of the numbers obtained if the calibration was made in only one area.

J.B. Bindell: SEMs often introduce magnification range changes when the deflection amplifier is adjusted. How can you be sure that the magnification tracks properly as its magnitude is changed? What is the cause of the 0.050 μm variation observed in Figure 11?
Author: Some variation is due to the precision variation in the measurement system but some is systematic magnification variation. These variations are compensated for by magnification calibration to see that the "magnification tracks properly". Further, improvement in signal detection can be used as a means of improving the SEM linewidth measurement system precision.

J.B. Bindell: The recommended frequency of calibration for SEMs is somewhat arbitrary. Can the author suggest a guideline for an adequate quality assurance (QA) program including precision requirements of the various VLSI technologies as well as the day to day instrument variations that may be expected?
Author: Normally, on a production line, each system is calibrated each day using an "in-house" standard whose surface has been coated with a conductive coating to improve the signal to noise ratio. The precision of these measurements is tracked and once the precision exceeds an acceptable value (10-30 nm) then the measurement system is calibrated before each set of measurements on a wafer but the magnification calibration is checked on a daily basis.

J.B. Bindell: How does one check for the presence of vibration which might interfere with the measurement, especially on the more automated instruments?
Author: Most, if not all, of the SEM linewidth measurement systems have a manual mode of operation which allows a slow scan mode of operation. During the slow scan mode of operation, the magnification of the SEM is increased and a visual check is made on the image of the SEM CRT. If there is vibration present, the left and right sides of the image will appear jagged so as to present a vertical sawtooth when one views the left and right edges of the image. This effect has been observed on some SEM linewidth measurement systems that are situated on a production line at magnifications as low as 25,000X.

S.H. Moll: The effect of beam voltage and specimen tilt in controlling charging is covered well in the paper. However, the path(s) scanned by the beam usually cross a number of different materials, usually of varying thickness, such as resist, oxide, etc., in the same field of view, i.e., when performing a measurement. In this case, it is found that there may not be an optimum, specific, beam voltage and in addition, both the incident current and beam scanning rate will also affect charging and the attainment of stable video signal profiles. Can the author comment on selecting optimum current levels and scan rates?
Author: Normally, the faster the scan rate the lesser the charge induced in the specimen. Ideally, one would like to be able to incrementally vary the scan rate while viewing the line intensity profile to obtain the best signal to noise ratio and the most symmetrical profile. However, since most SEM linewidth measurement systems usually only have three, maybe four slow scan rates, say 30, 60, 120, or maybe 200 seconds a frame, and a TV scan rate, one is limited in the choices of scan rates. Therefore, the TV scan rate is usually the one chosen and the accelerating voltage and tilt are varied while a check is made of the probe current to obtain the best signal to noise ratio and contrast level. One can check the appearance of a given structure at say 30,000X and see if the structure appears dark or very light as the accelerating voltage and tilt is varied. Usually, between the points at which a structure appears to go from dark to light one will find the optimum tilt and accelerating volt-

age for the most symmetrical line intensity profile. At this point the probe current is measured and recorded for future use.

S.H. Moll: The author suggests that the precision of the CD measurement capability of the SEM should be tested by performing repeated measurements, over significant periods of time, in the "same location". It has been correctly reported that contamination (hydrocarbon polymerization) will build up in the area scanned. This layer will produce changes in width measurements over time, lines will "grow" and trenches will "shrink". Pitch measurements may or may not change depending upon the edge detection algorithm employed. How is this slowly changing, systematic, effect treated when evaluating system reproducibility when the same area has been scanned many times a day over periods as long as a month?
Author: The problem of lines that "grow" and trenches that "shrink" due to scanning the same areas many times is reduced by cleaving several specimens and using half of the specimen for the calibration of optical systems. The optical system measurements are correlated with the SEM measurements. Both the SEM and the optical systems are monitored for their precision. A correlation factor is generated to check how the measurements are varying around a nominal value. In addition, more than one SEM linewidth measurement system is employed so that there is a check of one system against another. Further the half of a given specimen which has been used to calibrate an optical system may be removed and remeasured on the SEM suspected of precision drifting.

S.H. Moll: The author comments (Figure 8) that the "raster pattern" left by the electron beam is hydrocarbon polymerization, and indeed this is one possibility. However, is it not true that these residual patterns are also often stored charge which produce changes in the SE emission?
Author: It is true that the residual patterns are also often stored charge which produces changes in the SE emission. A check can be made as to whether hydrocarbon polymerization has taken place by removal of the specimen and reinserting the specimen at a later date. If, the darkened area that appeared initially when the area was scanned does not appear the second time the same area is scanned then it becomes apparent that the darkened area was due to a charging effect. If, the darkened area is still evident then this is usually due to hydrocarbon polymerization.

S.H. Moll: If a true polymerized hydrocarbon layer is pinned to the surface, how does this affect subsequent processing steps as etching, sputtering etc.?
Author: Normally, most CD measurements are made after resist development and post-reactive ion etching (Post-RIE) and in an area adjacent to the device area to prevent damage to the devices. However, there is usually a pre-deposition, PostRIE cleaning process to remove foreign material and the wafers are inspected to see that they are contaminant free. This procedure is especially true of wafers that have been subjected to measurement in the SEM. Further, the SEM linewidth measurement systems used in production have a beam blanking control that turns the beam off when the stage is moved from one measurement area to another. If polymerized hydrocarbon remains on the surface of the device there will be an adhesion problem which will show up later in the process.

M.T. Postek: What effects in measurement precision have you observed relative to variations in wall angle between the "standard" product type sample and the actual in-line product?
Author: The author has observed very little, if any, difference in measurements when the wall angle is in the 85 to 90 degree range. Below 85 to 80 degrees the variation in measurement is within the range of the precision of the normal SEM linewidth measurement system. However, the author has not experimented with the effect on precision when the wall angle is less than 80 degrees.

M.T. Postek: Many of the semiconductors wafer production lines are using quite large wafers such as 6 or 8 inches (and larger in the future). What have you observed relative to the wafer flatness and its effect on precision of the SEM measurements?
Author: The author has not observed any adverse effect on measurement precision due to wafer flatness. This is probably due to the fact that the wafer specifications for flatness is well within the limits of the SEM depth of focus and measurements are not performed unless the SEM is well focused.

M.T. Postek: With all of the caveats you have described considered, is fully automated SEM wafer inspection possible?
Author: The author has been very involved in SEM metrology and at the present time, structures at certain steps in the process are being measured fully automatically on certain SEM linewidth measurement systems. Also, fully automatic inspections using an optical system to locate defects and record the x-y coordinates is being performed on semiconductor device fabrication lines. Then the SEM uses these x-y coordinates to perform X-ray analysis measurements, and generating micrographs at high magnification in an automatic mode of operation. If the semiconductor industry is willing to accept the time required for video processing of the SEM images at high magnification in order to detect defects that are in the micrometer and sub-micrometer range, then fully automated SEM wafer inspection systems are a definite possibility.

M.T. Postek: The collection field used by the Everhart/Thornley-type secondary electron detector can be affected by many factors, such as, proximity of the pole-

piece, stage components etc., all which can affect the video waveform. You are advocating doing everything you can to obtain a symmetric video waveform (I agree that a symmetric waveform is important) but, have you investigated if the waveform changes in symmetry as the stage drives across the wafer due to variations in collection field efficiency?

Author: The author has not investigated if the waveform changes in symmetry due to variations in collection field efficiency. Normally, the only variation has been due to a structure being misaligned with respect to other structures. Additionally the structure may be out of focus due to the flatness of the wafer being out of specification. Each wafer is thoroughly pre-aligned in the SEM at a magnification of 3,000-5,000X before measurements are performed and consequently only misaligned structures present a line intensity profile symmetry problem.