Application of transmission electron detection to SCALPEL mask metrology

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Linewidth measurements were performed on a $4X$ scattering with angular limitation in projection electron lithography (SCALPEL) e-beam lithography mask using the transmitted electron signal in a modified scanning electron microscope. Features as small as 0.24 μm were measured on the mask. The thin membrane mask structure that was used is found to provide sufficient transmitted signal contrast at energies ranging from 10 to 30 keV. The linewidth measurement accuracy is mostly limited by the variations in the material and not the measurement system. It is concluded that the linewidth measurement technique using transmitted electrons is suitable for the potential certification of SCALPEL mask standards.
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I. INTRODUCTION

The scattering with angular limitation in projection electron lithography (SCALPEL)[1] projection electron lithography system utilizes a thin membrane mask that is transparent to high energy electrons. Accurate measurements of SCALPEL mask feature sizes are an essential component of process monitoring during mask fabrication. There is also a need to have accurate mask feature sizes to unambiguously interpret measurements of the lithographic performance of the subsequent wafer processes (i.e., exposure tool performance). A SCALPEL lithography machine has demonstrated printing 0.08 μm features (isolated lines and contact holes) using a $4X$ mask.[2] SCALPEL masks have also been fabricated with features corresponding to printed feature sizes that are beyond the present silicon industry association (SIA) roadmap[3] for integrated circuit (IC) critical dimension (CD) scaling.[4] It is therefore appropriate to use the SCALPEL mask as a vehicle for investigating the mask metrology issues that will be relevant to future IC fabrication.

The scanning electron microscope (SEM) can be used to measure linewidths to very high precision.[5] However, an accurate measurement requires modeling of the interaction of the electron beam and instrument with the measurement object. The inputs to the model are obtained from corollary measurements either from a calibrated standard or another measurement technique such as atomic force microscopy (AFM) or cross section SEM.[6] In this article, we present preliminary measurements and analysis for determining the feasibility of an SEM measurement technique for the potential certification of SCALPEL mask SEM linewidth standards. The technique involves measurement of mask features using the transmitted electron signal in a modified SEM.

The calibration of an SEM with a standard requires that the standard be made of a structure that closely corresponds to the material structures that will be measured routinely. The standard must also be measured very accurately. That is, a detailed analysis of the components contributing to the measurement accuracy and its uncertainty must be done. In the SEM, a feature is measured by scanning a focused probe of electrons over the feature and measuring the signal generated by the interaction of the electron beam with the feature. The resulting signals that are products of scattering events within the sample include secondary electrons (SE), backscattered electrons (BSE), and, in our case, transmitted electrons (TE). Unfortunately, the measured SEM signal does not exactly trace the geometry of the feature and the signal must be modeled to determine the actual correspondence. The SE and BSE signals can give nonlinear signal profiles when compared to the feature profiles in the vicinity of the edges. In addition, SE emission is sensitive to charging effects that depend on sample conductivity, the material, the pattern, and the incident electron dose that is used during the measurement sequence, making it difficult to model. The transmission SEM (TSEM) signal is advantageous because it can be modeled using Monte Carlo (MC) simulation with fewer adjustable parameters than the SE signal.[6] Also, we will show that, for the SCALPEL mask structure, MC simulations of the TSEM signal give a more linear response to the feature edges than the SE signal.

To establish the correspondence between the signal and the measured feature, a point along the vertical wall of the feature is defined as the ''edge'' and the corresponding signal threshold (i.e., percent of the maximum signal contrast) is calculated using MC simulation. We have arbitrarily defined the edge as 50% of the vertical wall height. Since the MC simulation is a time intensive process,[6] it is not currently

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amenable to a multiparameter fitting routine. Therefore, the inputs must be determined from a knowledge of the instrument (i.e., accelerating voltage and detector specification) and a corollary measurement of the standard to determine its material structure and geometry.

The importance of these corollary measurements was reported in a previous study of x-ray masks where the TSEM signal was measured.[7] Although different from the SCALPEL mask, the x-ray mask results offer important insights into how to interpret the TSEM signal. The x-ray results showed that the measured linewidths are sensitive to the detailed geometry of the features. As an example, for 0.25 μm gold absorber lines, a 2° uncertainty in the verticality of the edges produces a 10% uncertainty in the signal threshold that is calculated from MC to correspond to the physical edge. Also, the calculated thresholds and uncertainties due to wall angle depend on the feature width.

Because the x-ray mask must absorb x rays to form an image of the circuit pattern, the patterned layer on the mask is thicker than that of the SCALPEL mask by an order of magnitude. Considering MC simulations for the SCALPEL mask structure that was used in this study and the improvements in mask processing that are projected, the SCALPEL mask may represent an almost ideal measurement object for the SEM. By careful design of the measurement conditions, it is possible to optimize the measurement using TSEM by minimizing the interaction of the electron beam with the mask while maximizing the contrast. This is achieved by the appropriate choice of electron beam energy and detector characteristics. A more detailed discussion of signal optimization for SCALPEL mask measurements is presented in a separate article.[4] The most significant advantage offered by the SCALPEL mask is that the aspect ratio of the features is small which leads to a smaller uncertainty in the edge location when compared to x-ray and projection ion beam masks.[4] We will show that our preliminary results are sufficient to indicate the relative importance of material structural parameters on the accuracy of the linewidth measurement.

II. EXPERIMENT

A. SCALPEL mask

The SCALPEL mask used in this study is shown schematically in Fig. 1. It is constructed from a thin membrane of low atomic number material (150 nm of SiN_x was used in the present measurements) upon which a thin film of high atomic number material is deposited to serve as the scatterer. The scatterer used in this work was a low stress bilayer of 50 nm tungsten and 10 nm chromium. Details of the mask fabrication are reported elsewhere.[8] The processing starts with a ⟨100⟩ silicon wafer on which the SiN_x and W/Cr are deposited. The backside of the wafer is patterned with a series of 1 mm squares on 1.2 mm centers. These are anistropically etched to open windows to the membrane material. The membranes are supported by struts that consist of the remaining silicon that separates the widows. Patterns are written and etched into the W on top of the membrane using e-beam lithography. The mask is then bonded to a support ring that facilitates handling.

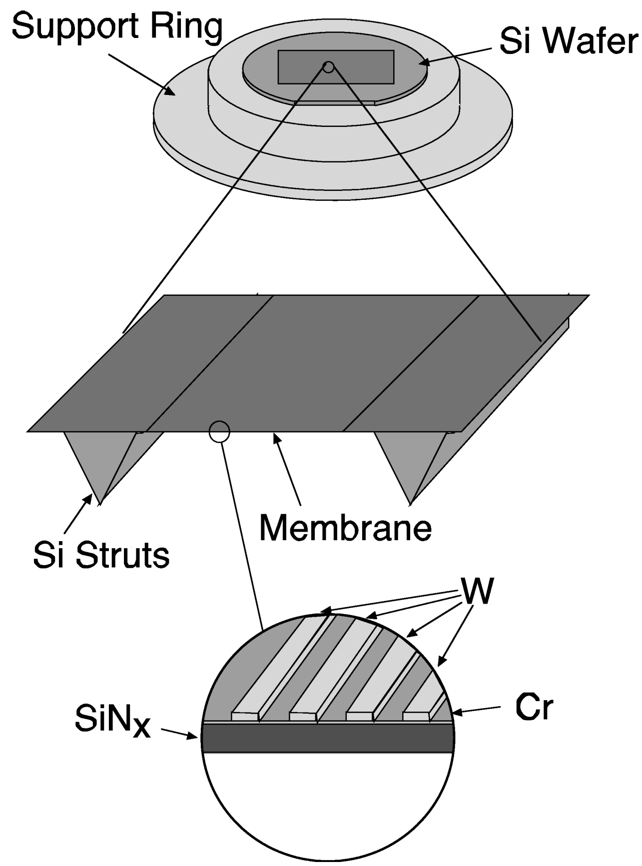

FIG. 1. Diagram of the SCALPEL mask used in the present study.

The pattern that was used for the linewidth measurements is a series of isolated spaces of widths 4.0, 2.0, 1.5, 1.0, 0.72, 0.6, 0.48, 0.4, and 0.24 μm that are separated by 4.0 μm. Since the SCALPEL mask is designed for 4*X* reduction, these spaces would print on the wafer with widths 1.0, 0.5, 0.38, 0.25, 0.18, 0.15, 0.12, 0.1, and 0.06 μm. A SEM micrograph of the nominal 0.24 μm feature typical of that used in this study is shown in Fig. 2. The surface of the membrane has a morphology (see Fig. 2) that is attributed to the grain structure of the chromium combined with surface roughening due to an oxygen plasma cleaning process. There is some roughness along the edges that was visible in high angle SEM images as evidenced by Fig. 3.

To model the interaction of the electron beam with this mask, it is important to characterize the topography in the vicinity of the feature edges. Sample preparation for cross section SEM is difficult with a thin membrane structure. However, AFM can be used to characterize the feature edges. Plotted in Fig. 4 is a representative AFM line scan across an edge on a similarly processed mask feature. The data were recorded in a scanning probe microscope with a balance beam force sensor using a cylindrical tip. Analysis of several AFM scans indicated that the wall angle of the edges is ∼20° from vertical. The thickness of the scatterer in-

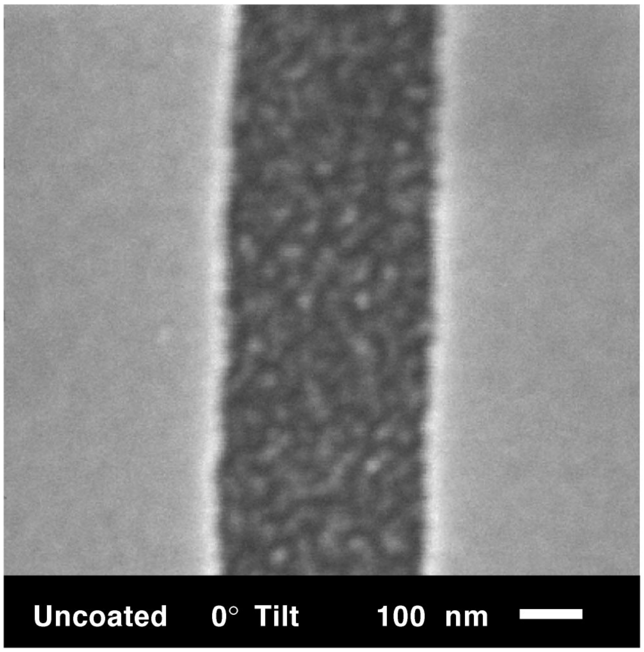

FIG. 2. SEM micrograph of 0.24 μm space on the mask.

creases towards the edge (see Fig. 4) which possibly results from an interaction of the resist with reactants from the plasma etch during pattern transfer.

B. TSEM measurement apparatus

The SEM that was used has been modified for these types of measurements on thin membrane masks and is described in an earlier article.[7] The mask is mounted on a holder along with the TSEM detector and preamplifier. A silicon PIN surface barrier detector was used. There is a thin ($\sim$0.5 μm) Cu foil placed over the detector to screen out highly scattered or low energy TE. The energy filter insures that the TE signal that is generated in the detector comes from electrons that have undergone very little energy loss in the mask. The SEM is operated under normal conditions when used in an imaging mode to find a feature of interest. In measurement mode, the electron beam scanning coils are turned off and the mask holder is moved with the translation stage under the fixed electron beam. Accurate position information about the location of the stage is provided by the use of laser interferometry. The stage position is recorded by the interferometer along with the TE signal from the detector. The interferometer provides a smallest pixel size of 2.5 nm for the measurement. The scans were done slowly over a range of approximately 15 μm in one direction. The slow scan speed enabled us to apply a low pass filter to the detector signal since bandwidth was not an issue. The stage was programmed to move even slower when the vicinity of the edges of the features is approached. The data were recorded in a computer system and then analyzed off line. There was usually more than one data point for each stage position. When this occurred, the average TSEM signal for that stage position was used. Each measurement was repeated at different segments along the length of the lines.

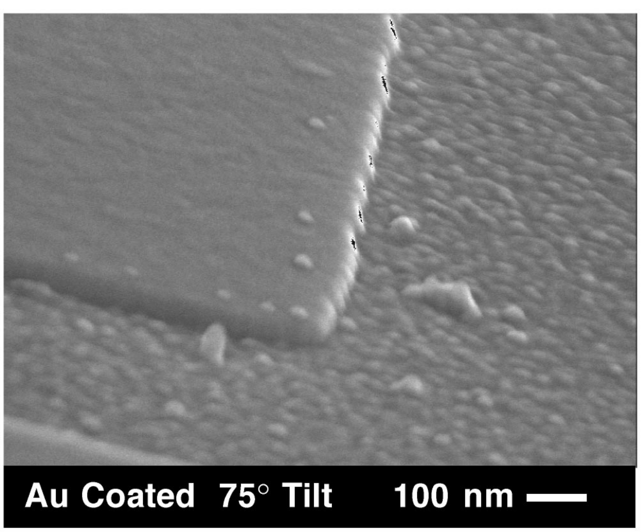

FIG. 3. SEM micrograph of the corner of a feature on the SCALPEL mask showing edge roughness.

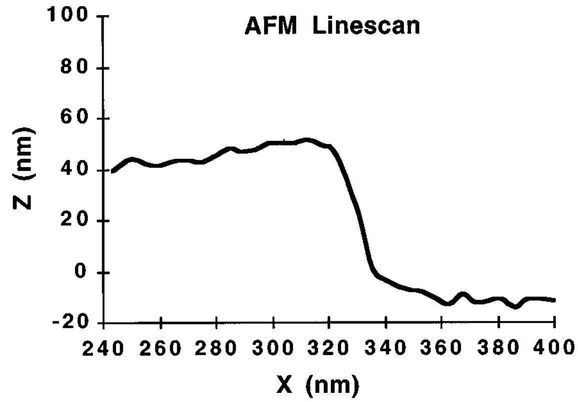

FIG. 4. AFM line scan showing the edge profile of a SCALPEL mask feature.

III. RESULTS AND DISCUSSION

Example TSEM line profiles that were recorded at 20 keV are plotted in Fig. 5. Measurements were also done at 10 and 30 keV. Each line scan consisted of more than 10 000 data points before averaging the data that were recorded with the same interferometer reading. There was an average of four measurements for each position with more in the vicinity of the edges. There were generally at least 20 data points defining the signal at the edge transition (after averaging). The noise apparent in the signal can be attributed to the surface and edge roughness of the prototype mask (see Figs. 2, 3, and 4). To suppress the surface roughness affects, an average was taken of 12 line scans. The result is plotted in Fig. 6 for the 0.24 and 0.4 μm features and compared with MC simulations. The transmitted electron flux was simulated for the mask structure assuming that the edges have a slope that is 20° from vertical. This wall angle was derived from the

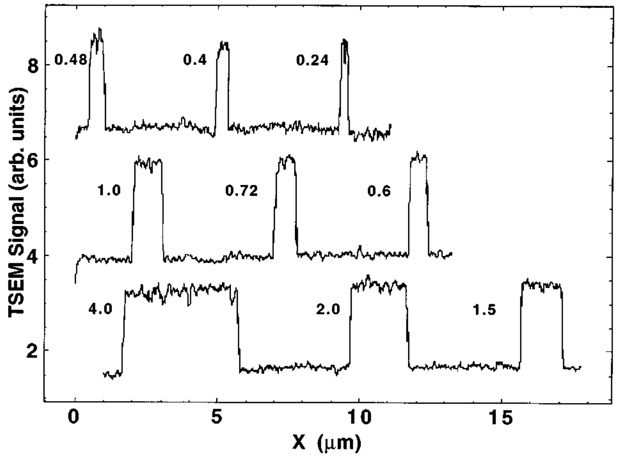

FIG. 5. Plot of TSEM signal vs interferometer reading (X) from the SCALPEL mask for spaces with nominal linewidths as indicated.

AFM measurements. The simulated line profiles deviate significantly from the experiment (see Fig. 6). The nominal 0.24 μm line has a printed width of 0.27 μm. For this study, the absolute error in the linewidth is of lesser importance than the deviation of the signal profile from the simulated profiles. The discrepancies are largely due to feature characteristics that were not included in the MC simulation input parameters and these are of major importance in the analysis of the measurements and the achievable measurement accuracy. Edge roughness, edge slope variations, footed edges, and edge rounding are evident in the mask features (see Figs. 2, 3, and 4). These can significantly effect the transmitted signal profile but were not included in the MC simulation.

A previous study showed that, of the edge anomalies that are possible in these kinds of structures, uncertainties in the wall angle and edge roughness pose the largest impact on the accuracy of the linewidth determination.[7] The wall verticality errors can be a result of the sample edge and/or deviations in the mask tilt (possibly from the translation stage or mask mounting hardware). It has been shown that even under the

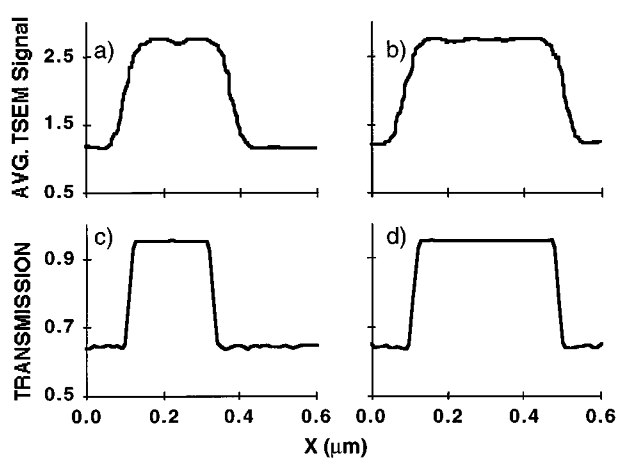

FIG. 6. Comparison of average TSEM signal profiles from nominal (a) 0.25 and (b) 0.40 μm spaces with MC simulated signal profiles, (c) and (d).

TABLE I. SCALPEL mask linewidths (μm).

Nominal	Measured	3σ
4.00	4.039	0.029
2.00	2.019	0.033
1.50	1.436	0.035
1.00	1.026	0.021
0.72	0.764	0.028
0.60	0.649	0.022
0.48	0.530	0.025
0.40	0.416	0.022
0.24	0.279	0.013

best circumstances that an uncertainty in the wall verticality of 2° is not unreasonable.[7] The uncertainty is mainly derived from the accuracy of measuring the wall angle with either cross section SEM or AFM and sample variability. The effect is much less for a SCALPEL mask than for the x-ray mask since the physical edge is more narrowly defined at any wall angle in the SCALPEL mask because the smaller metal thickness results in a smaller edge height. MC simulation of the SCALPEL mask threshold uncertainty due to wall angle is ~0.1% threshold uncertainty per degree of wall angle uncertainty. The measured uncertainty in the linewidth for the features used in these experiments was 1.2 nm per 1% uncertainty in the threshold. Combining these two results leads to ~1.2 Å linewidth uncertainty per degree of wall angle uncertainty.

The effects of wall edge roughness can be interpreted in two ways. One is that the location of the edge actually varies along the length of the edge. The other possibility is that there is a variation of the edge rounding at the top of the edge. This has been interpreted as an effective variation in the wall verticality.[7] There were variations in the edge rounding for the masks used in this study that was detected in the AFM scans and an analysis of transmission electron microscope images of similarly prepared SCALPEL masks indicate edge roughness of ~15 nm.[4] The large edge width of the TSEM average line profiles compared to the MC simulations can be attributed to edge roughness and edge rounding. The AFM edge profile also indicates the presence of a foot at the base of the edge. The rounding at the top of the TSEM line profile is probably caused by the foot in the edge profile. It would be useful to include this affect in the MC simulation. However, this was not implemented at the time of this study.

The threshold calculated from the MC simulations that corresponds to the 50% edge height is 49% of the maximum TSEM signal contrast. The linewidths of the measured SCALPEL mask features using the 49% threshold criterion are listed in Table I. A ±5% change in the threshold resulted in a ±6 nm change in the calculated linewidths. Unlike the x-ray case, there was no variation in the MC derived threshold as a function of linewidth for the SCALPEL mask features that were measured. The linearity of the calculated thresholds for these SCALPEL mask features is attributed to the small aspect ratios in the metal pattern layer, even for the smallest feature sizes. The 3σ values listed in Table I repre-

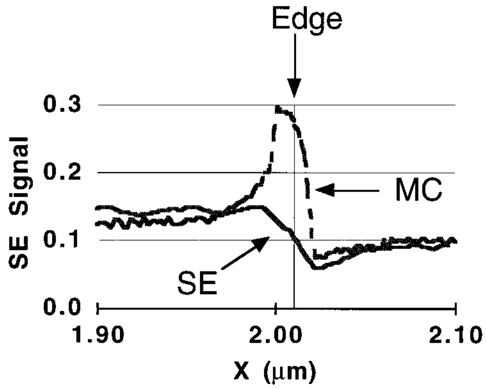

FIG. 7. Comparison of SE signal profile recorded at 5 keV with MC simulated signal profile. The vertical straight line locates the MC simulation feature edge at 2.05 μm. The corresponding SE signal feature edge is not known. The SE signal alignment and scaling relative to the MC simulation data is only for comparison.

sent the statistical variation of at least 11 measurements along the length of the lines. The average 3σ variation is 26 nm. We attribute this variation to edge roughness and linewidth control of the mask process. All of the machine dependent sources of measurement accuracy have been estimated to be less than 10 nm.[7] Therefore, the measurement object (the mask) is the limit to the accuracy of the linewidth measurements for SCALPEL masks at this time.

Since these measurements were taken, the SCALPEL mask structure has evolved. The SiN_x membrane thickness has been reduced to 100 nm and the W/Cr scatterer has been reduced to a combined thickness of 30 nm. This further reduces the aspect ratios of the features and will lead to an improved linewidth measurement accuracy. The largest improvement in accuracy would be gained by a reduction in the edge roughness. Since the edge roughness is limited by the grain size of the material that is deposited to define the features, improvements in the W deposition process are required. Also, the etch process for the mask is evolving so that improvements in the feature edge profiles are expected. This will further improve the linewidth measurement accuracy. We will not focus on machine dependent sources of measurement uncertainty at this time because the measurement object dominates the uncertainty. However, as the mask improves, the SEM related uncertainties will become more important. The relevant SEM issues are discussed elsewhere.[6]

Another important consideration is how to use TSEM measurements to calibrate SEM measurements of a mask. SCALPEL mask measurements are currently being done in the SEM using 5 keV electrons and only the SE signal.[4] MC simulations of the SE emission were done for the nominal 0.24 μm feature. The resulting SE simulated profile near the edge is plotted in Fig. 7 along with an experimentally obtained SE line profile. The discrepancy between these signal profiles is either due to surface contaminants or a residual film remaining from the plasma etch procedure as described earlier (see Fig. 4). It is difficult to unambiguously relate the experimentally determined signal to the MC simulation. It would be desirable if the calibration was done using the same edge definition as the certification procedure. However, this may not be practicable using the SE signal. Sample effects described earlier (i.e., charging) can significantly effect the SE emission. This may result in an uncertainty that is difficult to quantify when using SE signals for linewidth measurements. This uncertainty may be minimized by setting a limit to the allowed variation in the shape of the line profiles used for linewidth measurements from that which was used to calibrate the instrument. If there is little expected variation in structure from mask to mask, this would be a practical approach. Another solution would be to use a signal that is less sensitive to charging and surface contamination. The BSE has been shown to be better than the SE signal for accurate measurements of bulk materials.[6] The solution that would maximize the correspondence between the certification measurement and subsequent linewidth measurements would be to use the TSEM signal. Although we have shown that the TSEM signal is ideally suited for this measurement, it would be advantageous from the standpoint of cost if the present SEM tools could be used for the linewidth measurements with minimal modifications.

IV. CONCLUSION

The TSEM measurement is suitable for the certification of a SCALPEL mask standard. At this time, the accuracy of the linewidth measurement is limited by the mask and not the SEM. Since the SCALPEL mask process is still under development, it must be assumed that the SCALPEL masks that are fabricated for actual circuit manufacturing will have nearly vertical feature edges with acceptable edge roughness. These improvements will reduce the measurement uncertainty. Careful consideration needs to be given to the method and accuracy limits of linewidth calibrations using TSEM along with SE emission. Alternative linewidth measurement solutions may be needed to achieve the required accuracy for masks that are used for the sub-0.1 μm generation of ICs.

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