New Optical Metrology For Masks: Range and Accuracy Rivals SEM

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ABSTRACT

Metrology is essential to success in all manufacturing processes. In microlithography metrology techniques have begun to shift from optical to SEM. In this paper we compare the capabilities of the new Flux-Area optical technique and of SEM techniques.

SEM measurement has been increasing in mask shops because of the higher resolution it provides, despite disadvantages including damage to masks, charging effects, and inability to operate with pellicles. Optical measurements of photomasks are preferred because they are performed with light, in transmission. Thus the results of optical metrology are consistent with the output of steppers. The success of virtual stepper software, which uses optical images in simulating stepper output, has demonstrated that optical images contain sufficient information to predict the results of even subwavelength lithography.

Flux-Area measurement allows optical instruments to accurately measure features as small as λ/6, or 0.08 μ using visible light (Fiekowsky and Selassie, 1999). It also allows the measurement of "Optical Dimensions". This is the width of a line defined by the flux of light it transmits to the objective lens.

In this study Flux-Area measurements of linewidths and contact are made of several test masks and compared to SEM measurements and DUV AIMS microscope images. Results show that Flux-Area measurements are linear down to the smallest lines and holes tested, 0.23 μ and 0.4μ respectively. Thus the Flux-Area technique provides a practical alternative to SEM for metrology on current and future generation photomasks.

Keywords: Photomask Metrology, SEM, flux-area

Introduction

Shrinking chip feature geometries have forced similarly shrinking features on photomasks. As line and contact dimensions shrink mask makers and their customers find it more and more difficult to perform the measurements required to maintain tight control over their processes. The conventional edge-to-edge measurement technique using optical microscopes is limited to feature sizes generally larger than the measurement wavelength; so continued use of conventional techniques has depended on use of shorter wavelength illumination as features shrink. The use of SEMs is now increasing, but SEM tool cost is high and SEM measurements have a number of other disadvantages related to the use of electrons rather than photons: Charging of isolated features, damage to the chrome, deposition of a thin film, the requirement that any pellicle be removed, and masks require extra handling to be put into the SEM's vacuum chamber.

Convention suggests that SEM is the only access to useful measurements of subwavelength features. This may not be true. Just as Aerial imaging, as performed by the Zeiss AIMS tool, has become the standard for printability measures, quantitative flux measurements from the white, I-line, and DUV images can provide meaningful measurements of subwavelength features using the Flux-Area technique. This study has provided solid evidence that the Flux-Area technique can provide accurate linewidth and contact CD measurements of features much smaller than the wavelength of light being

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used. Furthermore, these optical measurements naturally match more closely the optical effects in a stepper/scanner than SEM measurements do.

Accuracy to What?

Metrology quality is generally measured by the accuracy and repeatability of measurements of the features in question. Measurement repeatability is well defined, but accuracy depends on a "gold standard" that the measurements should duplicate. Figure 1 shows that there are two types of measurement performed on masks, pattern fidelity, and printability measurements. Pattern fidelity testing measures the ability of the mask manufacturing process to generate physical patterns on the mask that match the design. Printability measurements measure the ability of the mask to generate the desired feature on the printed wafer.

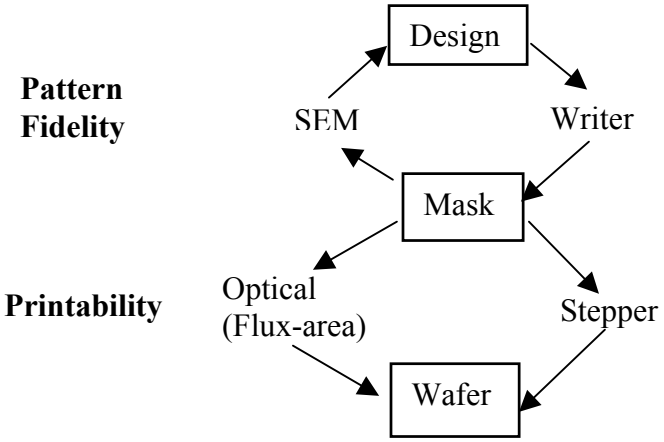


Figure 1. The microlithography process and its measurements

Pattern fidelity is primarily a process control issue concerning the mask maker. For pattern fidelity measurements, the correlation between the written mask and the design is sensibly measured with a SEM. Shape is important; light transmission is not an issue. Since the mask is frequently written with an electron beam, it is reasonable to measure it the same way. Only a tool with the edge resolution of a SEM can report whether complicated shapes are written correctly. Pattern fidelity measurements are frequently referenced to a NIST size standard, although that is not important because the accuracy really needed is between 0.1% and 1.0%. (given edge roughness of typically 5 nm, and features sizes between 300 and 1000 nm, any accuracy beyond 0.1% will be lost in the roughness of the edges being measured.

The mask users (the wafer fabs) are primarily interested in printability. They want to know that the features they designed will print correctly on the wafer. In the simple case of a linewidth the difference between a printability measurement and a fidelity measurement will generally be a constant offset. But in the case of a contact hole only the area and centroid location of the hole affects printability (Fiekowsky, 2001). Thus, information about the mask contact shape (e.g. corner radius), although useful to the mask maker for process control, is irrelevant to the mask user. The wafer fab instead needs to know the contact's optical area. And due to issues such as under-etching, the optical area may be significantly different from the area measured on a SEM.

Other complex features, such as line end OPC serifs also are most easily measured optically for the advantage of the wafer fab (Fiekowsky, 2001).. Two Flux-Area measurements, the serif area and the effective separation distance of a line end are sufficient to accurately predict wafer line-end separation. On the other hand, typical pattern fidelity measurements of OPC features are quite complicated, and may not predict printability. For example, if one side of a line-end serif is too large, and the other side correspondingly small, the printed line end will have the correct length, but will be shifted to one side by a few nanometers, an amount hidden in the noise of edge roughness.

As with pattern fidelity measurements, NIST traceability of printability measurements is not needed because accuracy of 1% is generally sufficient, for the same reason described for pattern fidelity measurement. In printability measurements the most important quality is repeatability. It is very important to a wafer fab that its mask vendors get the same size when measuring the same feature. Without this repeatability size specs become meaningless, and the fab becomes unable to maintain chip quality if the masks come from a different mask shop.

Metrology Methods

Conventional metrology techniques (optical and SEM) are linear, measuring the size of features edge-to-edge. Although sensible, this technique runs into several problems on modern photomasks. First of all, the definition of an edge is critical, and on features whose size approaches the wavelength of light being used to measure, the observed edge position of an edge depends highly on the position of nearby edges. This is why conventional metrology systems generally stop operating when the size to be measured gets to within 10% of the measuring wavelength. Even with SEM images, there is always a question of whether to use the middle of the edge, or the "bottom of the chrome", where light transmission is presumed to start.

Secondly, the linear size of a 2D feature, such as a contact, a line end, or a corner is not adequate to accurately describe the effect of that feature in the lithography process. Because the result on the wafer's photoresist depends on the total light flux at any position, the best measure of a lithographic feature's size is the amount of light flux that passes through it.

AVI's Flux-Area technique measures this light flux, generally bypassing the question of edge location that confounds conventional measurements.

Flux-Area Measurement

The Flux-Area technique allows the measurement of features much smaller than λ, and provides accuracy and repeatability in the range of λ/100 (5 nm with visible light). Rather than edge-to-edge dimension, it measures optical area, which correlates to printability on the wafer. The technique consists of subtracting the background; integrating the total light flux that is transmitted by the feature, converting that flux to square pixels, and then scaling pixels to microns.

For metrology, the most important aspect of the Flux-Area technique is that it is linear over the whole range of feature sizes used in microlithography. This allows use of a one-point calibration, typically by measuring a known line pitch. Because line pitch is process independent, the manufactured line pitch on a mask is always within 0.1% of the design. Typical Flux-Area calibration takes just a few minutes and is consistently repeatable to within 0.3%. Furthermore, this calibration does not change unless the optical geometry is changed, so recalibration is only required after major optical adjustments.

This allows mask makers and wafer fabs to be easily confident that their tools are calibrated to match within 0.3%.

Study Description

This study was performed with several existing binary COG metrology test masks at TSMC and Photronics. The masks were all written on e-beam writers to allow generation of the smallest features. At TSMC a metrology calibration plate with clear and dark lines, and contact holes down to 0.3 μ was measured with a SEM (Hitachi), a KMS-400 white light tool, and the AVI using same images from the KMS. At Photronics a metrology test plate was measured with an LWM 250uv system at G-line (.48μ) and I-line (.365 μ). Those images were also measured with the AVI, and the lines remeasured on a SEM (KLA8100). At Photronics a contact hole test plate with contact holes of 0.6, 0.8, 1.0, and 1.2 μ was measured on a SEM, with the AVI using images from a KLA353uv system, and with the AVI using DUV images from a Zeiss AIMS tool.

Flux-Area vs. SEM and KMS: Lines and Contacts

Figure 2 shows the difference between SEM and Flux-Area linewidths and contact sizing. One immediately sees that there is an apparently constant size offset between the SEM and optical measurements. This offset is not observed using conventional edge-to-edge optical CD measurements because those systems normally use a multipoint calibration to SEM measurements. Thus the offset is removed in the calibration. Figure 3 shows the same data with a constant 130 nm correction added to the AVI clear linewidths, and subtracted from the dark linewidths.

This offset appears to be due to light passing near the edge getting diffracted away from the microscope lens. The magnitude of the offset appears to fit the rule: Offset = (1-NA) * λ. Thus a larger lens will capture more of the diffracted light, leading to a smaller offset. In this case, using white light and an NA=.9 lens, the offset from each edge is approximately λ/10. The contact holes' offset is seen to be 180 nm. The difference is probably due to corner effects. Other data sets have been consistent with the contact hole offset being 30-50% larger than the edge offset, although further measurements are required to delineate a definite rule.

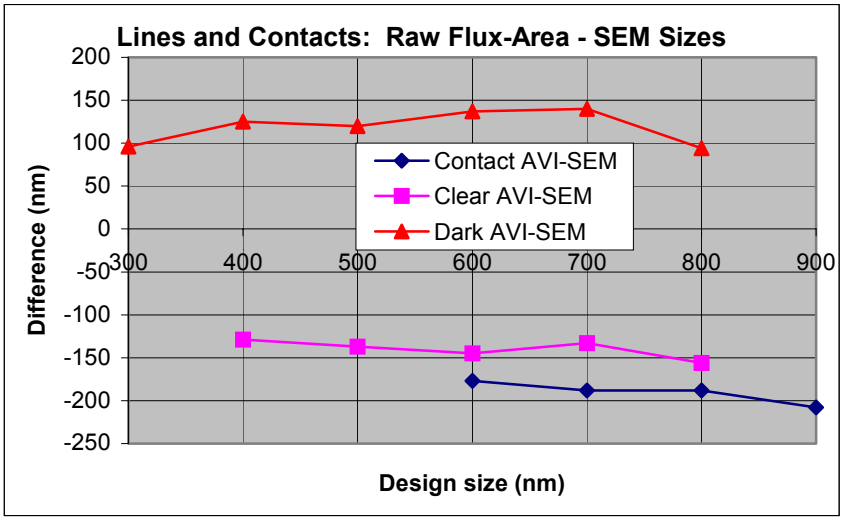


Figure 2. Raw Flux-Area measurements compared to SEM for clear & dark lines and contact holes. Note the constant size offsets, related to edge diffraction.

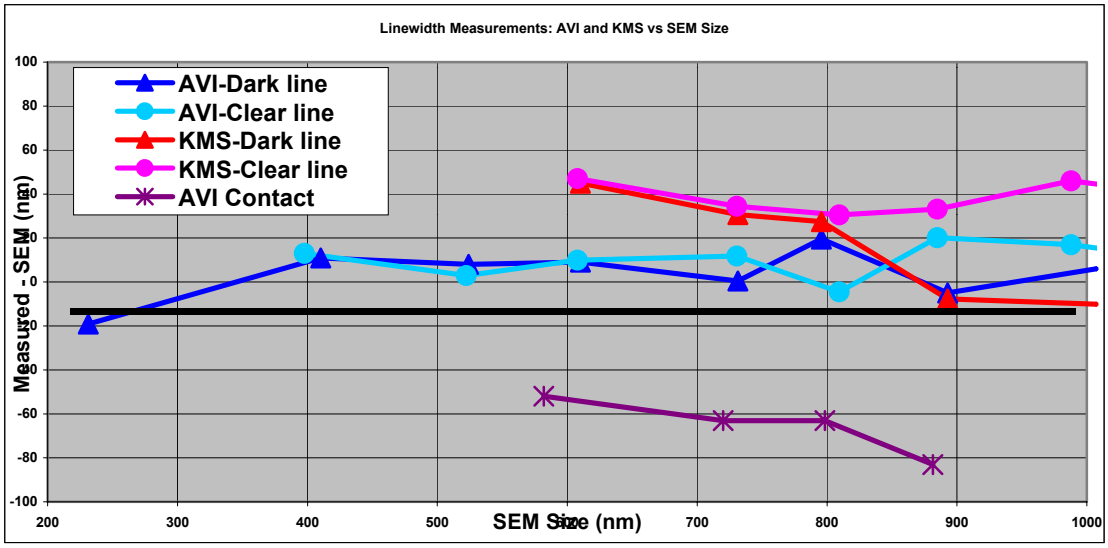


Figure 3. Same data as Figure 2, with offset Flux-Area measurements and KMS measurements plotted against SEM size. Note that contact sizes are still 60 nm smaller than SEM—probably related to corner rounding. Courtesy TSMC.

Figure 3 plots the linewidth data from figure 2 against SEM size, rather than design size, and compares the KMS edge-to-edge linewidth data from the same images. Note that the edge-to-edge measurements stop at 600 nm, approximately the inspection wavelength, while the AVI Flux-Area measurements continue to track the SEM sizing down to the smallest printed ine, a .23 μ dark line (λ/2.5).

Contacts: Optical Area Approaches Zero Before Physical Size

Figure 4 displays measurements of 60 different sized contacts, 0.6 μ to 1.2 μ by SEM, I-line Flux-Area, and DUV Flux-Area. The DUV images came from a Zeiss AIMS too, and only include one contact from each size group, plus 5 different OPC sizes in the 1μm group. The measurements all appear linear, as expected from the previous data.

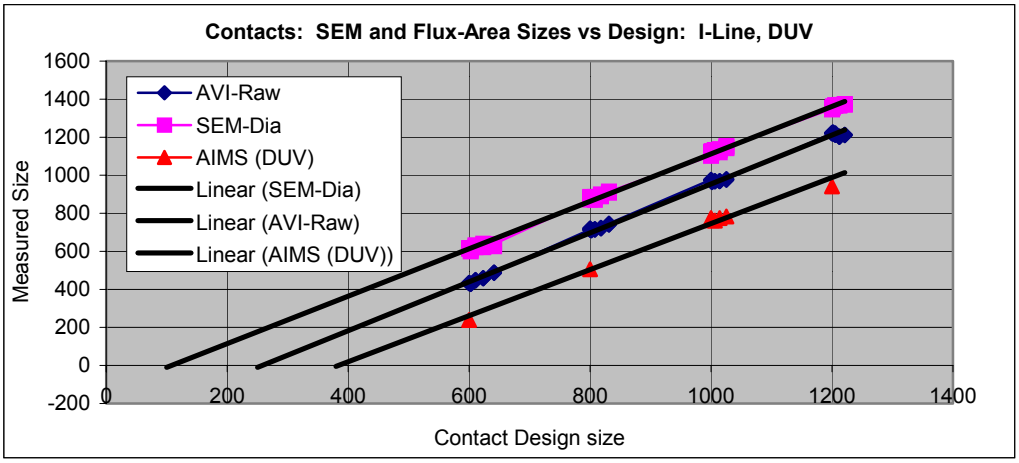


Figure 4. Contacts measured by SEM and raw Flux-Area measurements made with I-line and DUV images. Note that the DUV images have twice the size offset of the I-line images because they are taken at a lower NA.

The Flux-Area measurements from I-line and DUV images are raw, i.e. not offset. It is interesting to note that the DUV images have twice the offset from the SEM (and design) sizes that the I-line images do. This is due to the fact that the NA of the I-line imaging is approximately 0.8, while the NA of the DUV imaging is 0.6.

It is also interesting to note that it appears that approximately zero light is expected from the DUV optics with 0.4 μ contact holes. Presumably the curve becomes non-linear at those sizes. Note that the printed contact size of the 0.6 μ contacts was zero on a 0.25 μ wafer process.

Flux-Area vs. SEM Using LWM Optics

Images of dark lines from a LWM-250 exhibit a phenomenon we call "halos" (Figure 5). images differ from KMS and KLA images because they have bright "halos" around clear lines. The flux from these halos adds to the dark line width.

The nature of the halos is not yet understood. Clear lines and contacts do not exhibit halos, and are unaffected

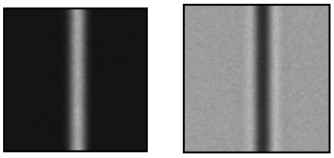
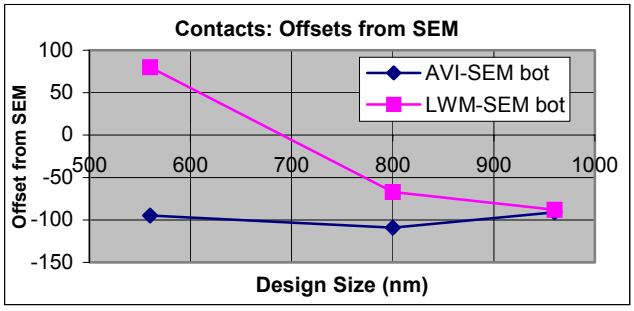


Figure 5. Typical line images from LWM250, showing halo on the dark line.



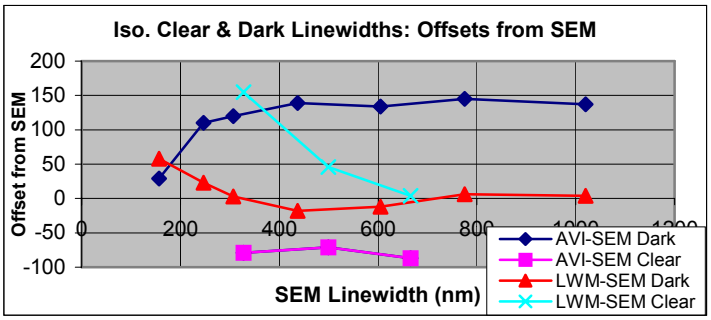


Figure 6. Contact sizes and clear & dark linewidths from I-line images from LWM-250. LWM linewidth measurements displayed for comparison.

Figure 6 shows contact and linewidth CD measurements taken from the LWM 250 images. The effect of the halo on the dark lines can be seen. The measurements of clear lines and contacts appear very linear down to the smallest sizes measured, as expected from the data from other non-halo images.

Conclusions

We started this study with a comparison of the metrology goals for pattern fidelity vs. printability. The purpose of pattern fidelity measurement is the optimization of mask manufacturing processes, so there is no fundamental reason to use optical techniques. However printability measurements are best performed optically in order to simulate best the function of the mask in the stepper/scanner.

Examination of a wide range of data indicates that the Flux-Area technique, as implemented on the AVI Photomask Metrology System provides linear size measurements of clear and dark lines and contact holes. This linearity has been demonstrated on lines as small as 0.23 μ. Line and contact size measurements from the flux area technique display a constant offset from SEM measurements, which appear to be due to edge diffraction. These offsets decrease with a decrease in λ, and they decrease with increased NA.

Thus it is necessary to determine and include that offset when comparing SEM measurements with Flux-Area measurements. Determining the offset is accomplished by measuring one or more lines that have been measured by the SEM whose sizing is trying to be duplicated. The offset also is calculable from the wavelength and NA.

We have compared Flux-Area measurements to standard optical edge-to-edge measurements and shown that Flux-Area measurements are able to accurately measure small features well below the limit of conventional techniques. However the multipoint calibration of conventional systems does serve to hide some of the physics—in particular the size offset between optical and SEM measurements and the halo effect. The disadvantage of using the multipoint calibration is that it is relatively hard to duplicate from machine to machine.

We have noted that optical metrology is especially suited to determining printability. At the same time, SEM measurements are well suited for pattern fidelity measurements. The measurement of linewidths by SEM or Flux-Area techniques are generally interchangeable. However 2D feature measurements such as contact sizing for printability determination are probably best performed optically, in order to properly take into account the interaction between corners and photons.

It appears that the Flux-Area technique is limited by two factors, noise and intensity calibration. Noise comes from video noise and vibration, as well as the physical background of the feature being measured. Noise and vibration are reduced by image averaging. The background noise primarily affects defect measurement, which is not discussed in this study.

The size offset relative to SEM measurements suggest that the Flux-Area technique is limited to clear features above a size determined by the wavelength and NA. However this limitation should never be a problem in practice because features that small won't possibly print on the wafer, because the stepper/scanner optics behave similarly to the inspection/metrology optics.

Future Work

There are a number of interesting areas of investigation suggested by this work. First, there is the understanding and correction of the halo in LWM dark line images. Second is the understanding of the 30-50% increase in the size offset for contact holes, as compared to line sizes. With that it will be interesting to investigate the flux vs. contact size curve for cases where the line extrapolates to zero flux.

Finally there needs to be extended investigation of Flux-Area techniques used with a range of non-binary masks, such as phase shift masks.

REFERENCES

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