Defect printability measurement on the KLA-351: Correlation to defect sizing using the AVI Metrology System

Peter Fiekowsky, Automated Visual Inspection, Los Altos, CA

Daniel Selassie, Intel Corp. Santa Clara, CA

Presented at the SPIE 19th Annual BACUS Symposium on Photomask Technology and Management Conference 3873: September 1999.

ABSTRACT

The search for the "holy grail" of a fast, reliable, inexpensive predictor of defect printability has reached a new level. Taking images from several inspection tools (KLA-351, KLA-353, and KLA Starlight) during defect review, the AVI Photomask Metrology System provides measurement repeatability better than 5 nm, and significantly better correlation to printability than Scanning Electron Microscope (SEM) measurements.

SEM measurements of printed defects are compared to various measurements of the defects on the mask. Analysis shows, as expected, that optical area measurements provide the best correlation to printability. Further, images from existing inspection tools are shown to be sufficient to produce these measurements using AVI's new "Flux-area" technique.

Keywords: printability, critical defect, mask inspection, metrology, measurement, photomask

1. INTRODUCTION

The measurement of defects and linewidths on photomasks is critical to the success of photolithography processes and the development of new processes. As geometries shrink, new metrology techniques are required. Conventional optical measurement techniques consist of measuring the distance from one side of a feature (defect, line, or contact) to the other. These methods start failing when the size of the feature gets smaller than the wavelength of light used to examine it (0.5µm for optical, 0.38µm for *I*-line, and 0.24µm for deep ultra violet (DUV)). The "edge" cannot be reliably identified in a complex blurry image.

The new flux-area technique allows the measurement of features smaller than 1/5 λ(0.1µm with visible light) , and provides accuracy and repeatability in the range of λ/100 (5 nm with visible light). In addition, it measures area rather than linear dimension, which correlates better to defect and line printability.

Most production metrology systems still use visible light (0.5 µm) or I-line (0.34µm), but new semiconductor processes are requiring the measurement of defects down to 0.25 or 0.3 microns.

Mask shops are beginning to use scanning electron microscopes (SEMs) for measurements below 0.5µm, where optical microscopes provide inadequate spatial resolution. SEMs promise high accuracy, and excellent repeatability but they are expensive, relatively slow and sometimes damage the object being measured. Because of charging and other effects, the edge-to-edge dimensions measured by SEM may not correlate with what actually prints on the wafer.

This paper presents data for the accuracy and repeatability of defect size measurements taken with the AVI system, and presents data on the correlation of those measurements to the printed wafer.

In this paper we compare four different defect measures: the defect size measured on an AVI system, measured on an SEM, measured by Dupont when the mask is produced, and the design size of the Verimask defects. We compare these measures to each other and the size of the defects after being printed on the wafer, measured by a SEM.

The ultimate size standard for most processes is the defect size as printed onto the wafer. This is a valid test when the defect is on an edge which is sufficiently distant from other edges. Isolated defects are not a useful test because their printed size depends largely on the processing. Similarly, edge defects close to other geometry are affected by diffracted light from nearby edges, and that affect depends largely on the process. Edge defects distant from other geometry is a good measure because the whole edge is affected by the process in the same way. Thus the position of the edge may change as the process changes, but the size of the defect relative to the edge (e.g. the change in critical dimension (CD)) will be affected only by the size of the defect on the mask.

Figure 1 shows a typical Verimask defect, as seen in an SEM, visually in a KLA353UV, and as printed on a wafer, imaged in an SEM. The somewhat asymmetrical shape of the original defect can be seen in 1A, leaving some uncertainty as to how to measure the edge positions. Figure 1C shows how much the defect is blurred when it is printed compared to the UV image in 1B. This shows that it is the area of the defect that affects the printed CD: its (edge to edge) geometry will correlate less well to the wafer CD change.

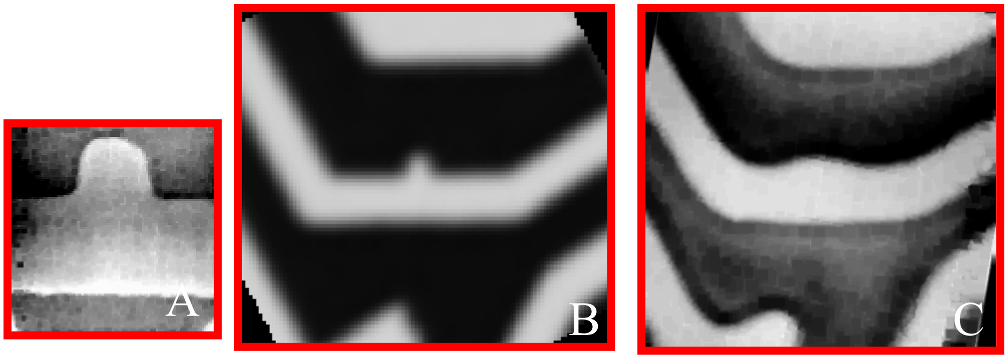


Figure 1. Defect B6 (0.56 μm) on a Dupont Verimask 890 plate. A) Mask, imaged on an SEM, black/white reversed. B) Mask imaged w/ KLA353UV. C) Wafer imaged on a SEM, black/white reversed, left/right reversed, and reduced to match the scale from the mask image.

SEM measurements of Verimasks correlate reasonably well because the edge defects are nearly square, except for the smallest defects, which are flattened. In those cases the SEM under-measures the effective size of the defect. Other edge-to-edge techniques, such as the Vickers microscope, also under-measure small defects.

1.1. The Flux-Area technique

The AVI Photomask Metrology System employs the flux-area technique to provide SEM repeatability and accuracy while on visible light or UV microscopes. It offers several advantages to mask shops and mask users:

1) The area of a small defect is a better predictor of its printability than is the size of one or two dimensions.
2) Flux-area measurements eliminate the judgement issues of "where is the edge?". This reduces the time required to disposition a defect or mask.
3) Measuring defects while the mask is on the reticle inspection tool eliminates the time, cost, and risks involved in transferring a plate to a separate metrology system.
4) Using existing imaging tools (typically a reticle inspection system) saves significant production time, cost and cleanroom area.

1.2. How it works

In brief, the flux-area technique involves digitizing the microscope image, digitally removing the background around the feature to be measured, and then summing the total flux of light absorbed or transmitted by the feature. That total flux change is proportional to the area of the feature. Small defects are then described by the circular diameter corresponding to that area. Linewidths are computed by dividing the area by the length of the region measured.

The specific steps in flux-area measurement are as follows: First an image is acquired as in figure 2A, typically by digitizing a video image from an existing microscope, reticle inspection system, or metrology system.

Next, a reference image is acquired using image processing techniques. The reference image is subtracted, removing the background from the image. What remains is an image of only the defect or line to be measured (figure 1a). The total change in light flux due to that feature is then summed over a region big enough to include 99% of the light diffracted by the features' edges (box in figure 2). The total flux change is the sum of the intensity of each pixel (positive or negative) in the summing box (in digitizer levels). The magnitude of that flux change is then divided by the difference in digitizer levels between clear and opaque, giving the feature's area in square pixels.

That area is converted to μm^2 by multiplying by the magnification of the microscope. If the magnification isn't known, it is computed by measuring a known feature, such as a 1μm defect or line.

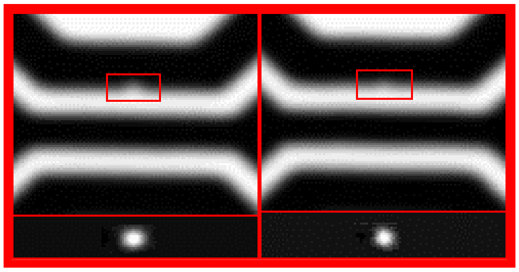


Figure 2: Images of 0.2 and 0.1 micron defects before and after background subtraction. Background subtracted images (B and D) are contrast-enhanced. The small box indicates the integration area.

The area is converted to an equivalent diameter D (for small defects), $D = 2\sqrt{A/\pi}$.

or linewidth W (for lines): $W = A/H$.

In these equations A is the area as measured, and H is the length of the integration box along a line. This process takes less than a second after the user identifies the feature to be measured.

2. THEORETICAL RESOLUTION AND ACCURACY

2.1. Calculation of resolution

The minimum resolution provided by the flux-area technique is similar to other gray-level techniques, that is, the pixel resolution, in microns divided by the number of useful gray levels. The flux area technique measures the area, while providing the result as an equivalent diameter, so the final resolution is

$R = 1/(S * G * \sqrt{nPix})$. Where R is the resolution in microns, S is the pixel scale in pixels/micron, G is the number of useful gray levels, and $nPix$ is the effective area of the feature in pixels.

For a typical defect (.3 microns diameter, 20 pixels/micron scale, 200 gray levels) this gives a theoretical resolution of 0.04 nm, which is 25 times smaller than the noise in a typical measurement, about 1nm. Thus moderate changes (by factors of 2 to 8) in the scale factor or number of digitizer levels have no significant effect on measurement repeatability or accuracy.

There are several factors that affect the theoretical accuracy of flux-area measurement: 1) Initial calibration (typically performed on a 1-2 micron feature which can be measured to better than 1% accuracy with conventional means). 2) Non-linearity of measurements as feature size decreases, 3) Accurate translation of measurements from the test wavelength (optical or I-line) to the stepper wavelength (DUV, 0.24 microns). 4) Consistent measurement of the actual intensity range in each image.

Initial calibration contributes the majority of the accuracy uncertainty, typically 1%. Non-linearity is expected to be zero, because we are measuring the quality we want to know (effective light-absorbing area). Further, comparisons of flux-area measurement to SEM measurements of small (0.1-0.2 micron) defects confirms this linearity. Translation of measurements between wavelengths is not an issue with chrome features because even though the transmission of the chrome changes somewhat at different wavelengths, the intensity calibration is based on the actual chrome transmission. This means that at any transmission ratio a chrome defect of a given size will be measured correctly. This is not true of all soft defects, but experience has shown that most soft defects absorb similarly at the stepper wavelength and the reticle inspection wavelength.

The last factor, measurement of the intensity range, can add significant error. Typically the intensity range can be measured to an accuracy of 0.5 percent. This gives an overall theoretical accuracy of 1 to 2 percent for the technique.

2.2. Testing

A Verimask 890 was measured with an Hitachi 6180 SEM and using flux-area measurement as implemented on an AVI Photomask Metrology System taking images from a KLA-353UV reticle inspection system. The mask was then printed onto a wafer using a DUV stepper and 0.25 micron process. On completion of processing the wafer was also measured on the Hitachi SEM. Only edge defects were measured in the A0-A9, B0-B9, C0-C9, and D0-D9 series.

The SEM mask measurements were made by measuring the CD at the defect and then subtracting the CD from a reference image. The SEM measurements of the wafer were made by taking the SEM image, digitizing it and processing it to eliminate artifacts, and then finding the centroid of the edges at the defect, above and below it, and right and left of it. These measurements yielded two values, a "horizontal reference" size and a "vertical reference" size. When there was a wide disparity between these sizes the bad reference point was replaced by the interpolation of data from the previous and next images.

3. RESULTS

3.1. Repeatability

Measurements of the B2 defect (nominally 0.12 micron diameter) on a 690 Verimask imaged on a KLA353UV over 5 minutes showed an "instantaneous" repeatability (1σ) of 1.2nm. Variability of 0.5% of the feature size is typically expected due to illumination variations, thus larger defects are expected to exhibit larger σ's. The effective illumination can vary for many reasons, such as thermal changes in the illuminator or the detector.

For features such as this, smaller than λ/2, individual measurements exhibit larger variability due to noise in the very small flux of light collected. Averaging multiple measurements is usually sufficient to improve repeatability to the 0.5% level.

Long term repeatability is affected by magnification, illumination, and the cleanliness of the optics. Current inspection tools, such as the KLA351 control these parameters well, so that long term variability is less than twice that of the short term, typically <1%.

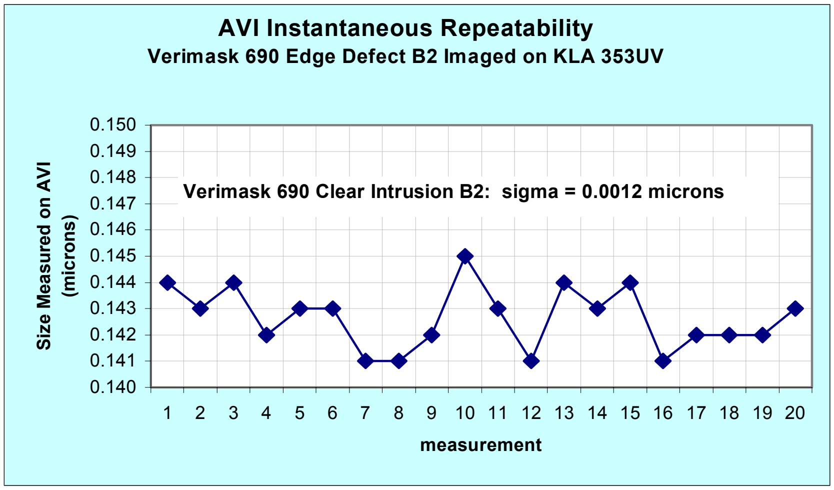


Figure 3. Repeatability data for a small defect.

3.2. Accuracy

Defining the accuracy of a metrology system is much more difficult than defining repeatability because it requires an external reference, or "gold standard" to which the test measurements are compared. Traditionally mask shops have used the Dupont Verimasks and the defect sizes provided with them as the gold standard, much as NIST linewidth standards are often used to calibrate linewidth metrology systems. The "nominal defect sizes" reported by Dupont are measured by a technician using a Vickers optical shearing microscope with an accuracy of about 0.1μm (figure 4).

Figure 4 compares the flux-area measurement from an AVI system, measurements of the Verimask on a SEM, measurements of the processed wafer on the SEM, and the size provided by Dupont of each of the defects.

The data comparing AVI and SEM measurements show that although both correlate well to the design size of the Verimask defects, the AVI measurements are noticeably closer.

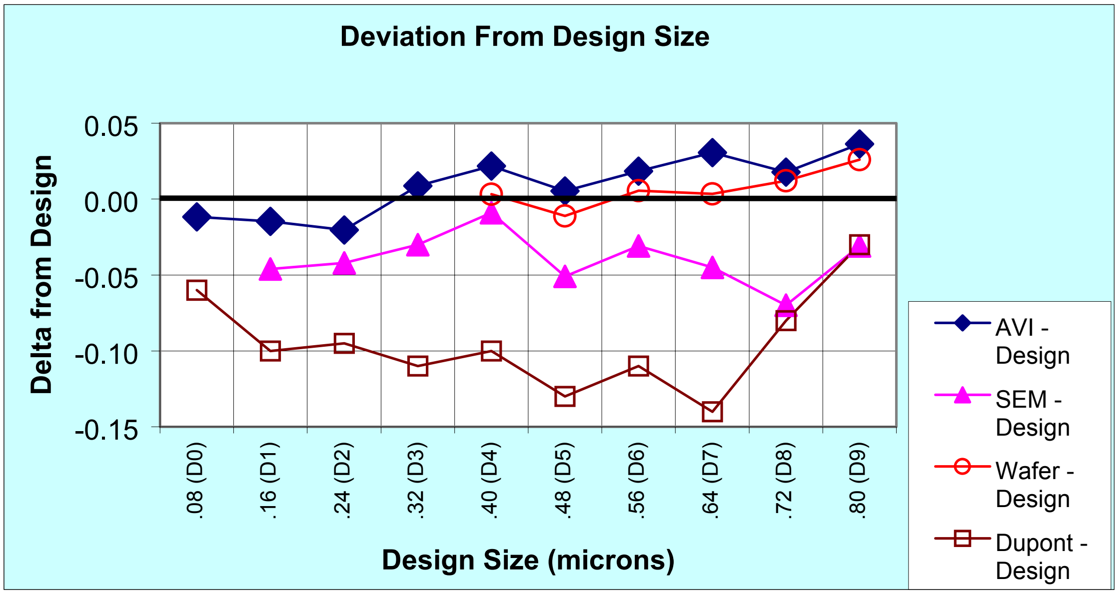
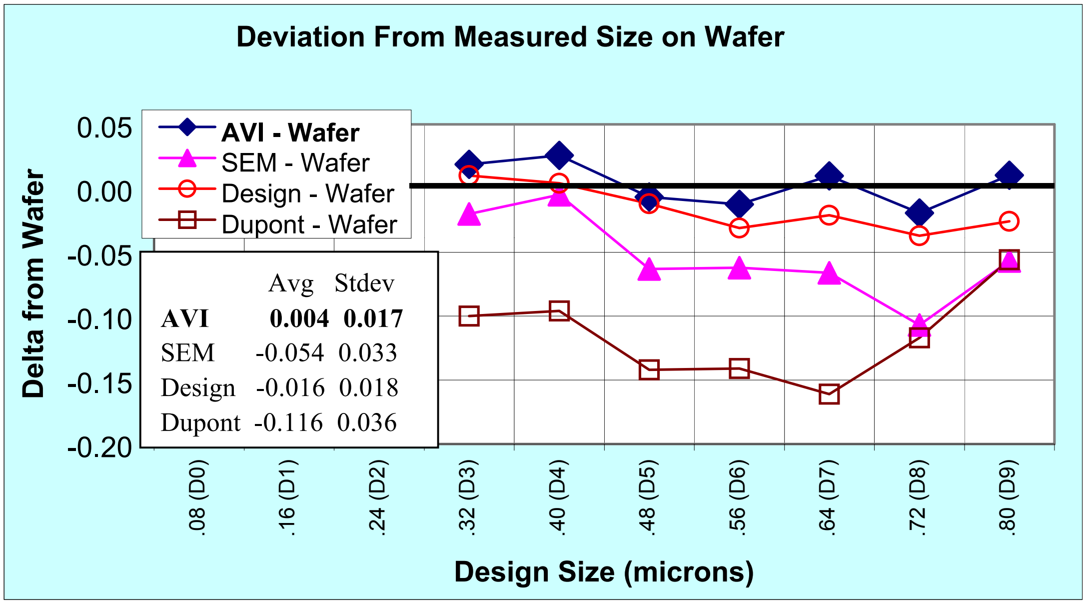


Figure 4. Comparison of four defect size measures to Verimask design size. Verimask 890, chrome extensions D0-D9 (0.08 to 0.8 microns).



	Avg	Stdev
AVI	**0.004**	**0.017**
SEM	-0.054	0.033
Design	-0.016	0.018
Dupont	-0.116	0.036

Figure 5. Comparison of four defect size measures to measured size on wafer.

The data in figure 5 shows that the AVI measurements have a considerably better correlation to the defects' actual printed size on the wafer. While some variation due to process offsets is expected, the AVI's standard deviation of 0.017 microns is much less than that from the SEM or Dupont measurements.

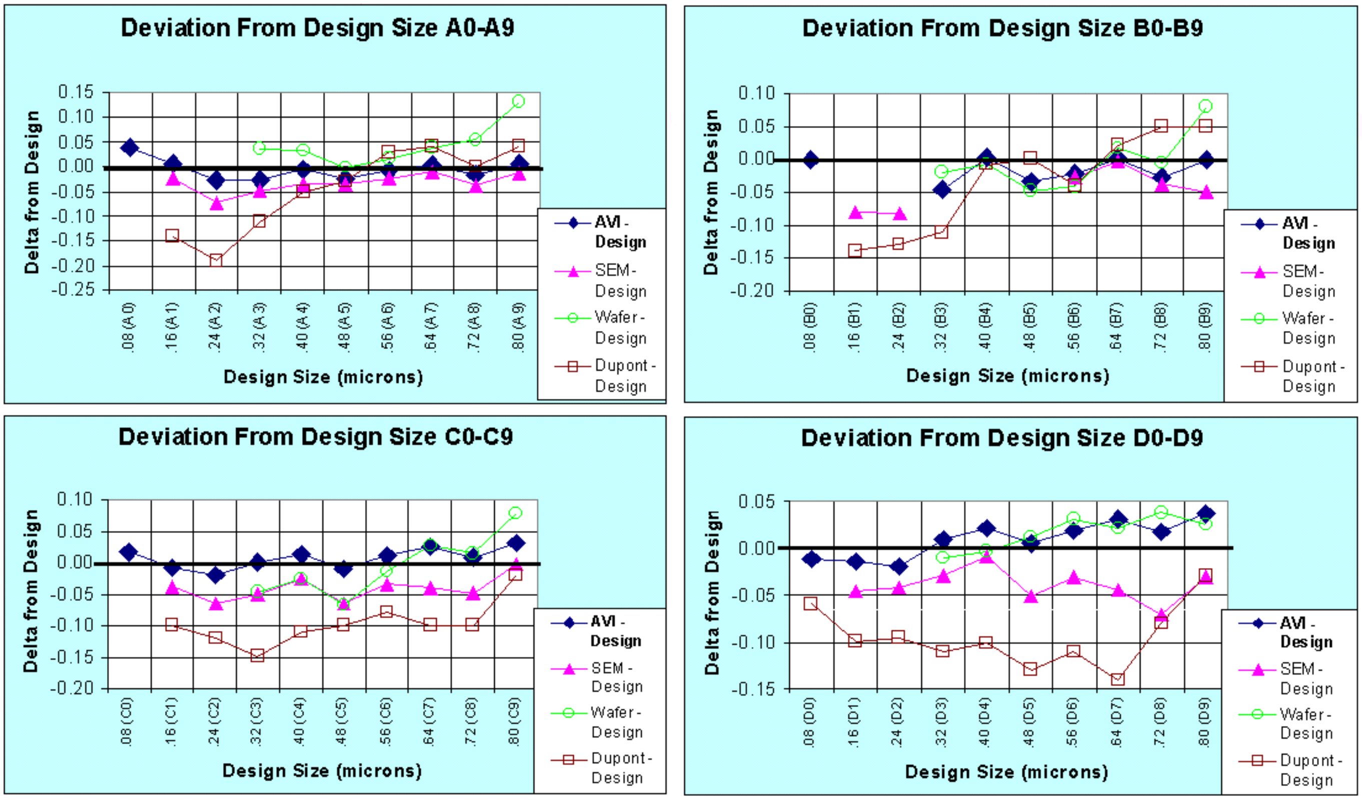


Figure 6. Accuracy from 0.08 Micron to 0.8 Micron

The graphs in figure 6 display measurements of all the edge defects on the Verimask 890. The measurements are plotted as deviations from the design size of the defects because wafer measurements aren't available below 0.3 microns.

These graphs illustrate several points: 1) The AVI measurements match the design closely at all sizes, 0.08 to 0.8 microns. 2) The SEM measurements have twice AVI's deviation from design size and from size on printed wafer. 3) Dupont measurements have relatively large deviations from both design and wafer sizes (Δ=0.1 to 0.2 micron)

4. CONCLUSION

Of the four measures tested, AVI, SEM, Design size, and Dupont Size, the AVI flux-area measurements give the best correlation to defect size as printed on a wafer. While the AVI and SEM both correlate well with Verimask defect design sizes, the AVI measurements correlate to the design size significantly better than the SEM does. Systems using flux-area measurement are typically attached to reticle inspection systems, analyzing images of defects during review, and providing instant measurements without transferring plates.

The flux-area measurement technique allows defects and linewidths from 0.1 to 0.8 μm to be accurately and repeatably measured with conventional optical microscopes. The accuracy and repeatability exceeds that attainable from SEMs because the measurement intrinsically measures area, and because it measures the quality that affects printing: the amount of light passed, rather than the relative positions of edges.

Correspondence for Peter Fiekowsky: Email: autvisinsp@aol.com; WWW:www.aviphotomask.com; Phone 650-941-6871; Fax 650-941-4821; Automated Visual Inspection, 952 S. Springer Road, Los Altos, CA 94024