Submicron linewidth measurement using an interferometric optical profiler

Katherine Creath

WYKO Corporation, 2650 E. Elvira Rd., Tucson, AZ 85706
and
Optical Sciences Center, University of Arizona, Tucson, AZ 85721

ABSTRACT

Optical instruments for submicron linewidth measurement are limited by the resolution associated with the wavelength of light. By measuring phase, rather than intensity, the lateral resolution of the system can be improved. This paper describes a system based upon an interferometric optical profiler using a Linnik interferometer and narrowband illumination. The system measures surface height directly using phase-measurement interferometry techniques. Three-dimensional maps of surface structure over 1024 x 1024 pixels are produced. The system includes an 80486-based AT-compatible computer and a Videk Megaplus camera. The Videk Megaplus camera has 1320 x 1030 active square pixels spaced at 6.8 μm intervals. It outputs an 8-bit digital signal which is interfaced to a framegrabber and intensity is displayed live on a high resolution monitor. The incoherent optical resolution of the system is 0.34 μm, and the detector samples the surface every 0.034 μm. It has been found that features as small as 0.5 μm can easily be measured. Two calibration standards traceable to NIST with feature sizes on the order of 1 μm have been used to calibrate the lateral dimensions of the system. Results of measurements of photoresist lines on silicon with 0.5 μm lines are presented.

1. INTRODUCTION

The most common method for determining submicron linewidths is the measurement of intensity using an optical microscope. The reflected intensity profile across a line will depend upon the relative reflectivities and induced phase shifts of the materials composing the line and the substrate. Because of diffraction effects, the edges of the line will not be sharp. There are many ways to determine the edges of the line. The most common method measures the width at the one-half intensity value between the top of the line and the substrate. Standards traceable to NIST are available for line widths down to 1 μm. To calibrate linewidth measurements, a number of standards are available for each linewidth which have different relative phase shifts between the line and substrate. This is so that different materials and different line heights can all be calibrated. Intensity measurement techniques work well down to 0.7 μm lines with measurements on 0.5 μm lines possible. It is possible to see a 0.1 μm wide line with an optical microscope viewing intensity; however, it is not possible to determine the width of this line accurately because of diffraction effects.

It is much easier to measure the spacing between a number of identical features than it is to measure the size of an individual feature. With a periodic structure, measuring the period is simple when a number of periods are present. When a single feature is measured, the measurement technique needs to be 3 to 10 times more precise than the tolerance on that dimension. This means that a 0.5 μm linewidth with a tolerance of 0.05 μm needs to be measured using a technique with an uncertainty of 5 to 15 nm. Optical microscopes can be modified to provide dark-field or florescence measurements which enable optical microscopes to measure linewidths as small as 0.4 μm. These different illumination schemes enhance the edges of the line and make it easier to determine the edges; however, diffraction effects are still noticeable and the optical resolution is not improved.

Another technique used for critical dimension (CD) measurement is a stylus profiler. A stylus contacts the test surface, and may harm soft surfaces. Stylus profilers have claimed to have lateral
resolutions as small as 0.2 \mu m;\(^5\) however, these measurements require a very stable environment, have slow scan rates, and are not convenient to use for three-dimensional surface mapping.

Technology utilizing scanning-electron microscopes (SEM) to measure linewidths is the current state-of-the-art in research labs. SEM systems are very expensive, and require coating the sample with a conducting layer and possibly cutting up the sample. After a sample is placed in the instrument, a vacuum must be obtained to make the measurement. Accurate linewidth measurement using an SEM is difficult because of interactions between the electron-beam and the test sample material.\(^2\) These instruments also require a highly skilled operator to set the measurement parameters correctly.

Some new technology which seems promising for linewidth measurement is scanning-probe microscopy (SPM).\(^6-7\) SPM refers to a number of similar techniques which move a probe close to the surface and measure some property of the surface at a single point as they scan the surface to map features. The most well-known of these probes is the scanning-tunneling microscope (STM). The STM requires a conducting surface so that most semiconductor surfaces need to be coated with a conducting layer. Atomic force microscopy (AFM) does not require a conducting surface. It measures atomic forces between the scanning tip and the surface. These forces change from material to material, so that the material constants need to be well-known to get accurate height information. The main problem with AFMs is that they can not handle large samples such as a wafer. They also are not very fast. Experts in AFM claim it takes about one-half of an hour for a skilled operator to get a good measurement. AFM has good potential once it can handle large samples, be used by an unskilled operator, and provide a high throughput. Another scanning probe technique which has possibilities is near-field scanning optical microscopy (NSOM).\(^8\) This technique scans a very small aperture over a surface and detects the intensity at each point. The small apertures are hard to produce and their size limits the resolution of the instrument. For all SPM techniques, the size of the probe determines the linewidths which can be measured. If the height of the line is greater than a fraction of a micrometer, the measured width will not be accurate because the probe can not follow steep steps accurately smearing the image of the line.

There are also a number of other optical techniques being investigated for linewidth measurement. One technique is confocal microscopy.\(^9\) The difference between a standard optical microscope and a confocal microscope is that the confocal microscope images a small aperture onto the surface and then detects the light from the image of the aperture on the surface using another small aperture. This enables the microscope to have a very small depth of field and see one of many layers of a multi-layer structure. Because of the small apertures used in the imaging system, the optical resolution is improved by about 10-20\% over a standard optical microscope.\(^9\) Since white light sources are used, different colors in an image relate to different heights. When the object is scanned along the optical axis of the system, three-dimensional maps of surface structure can be generated.\(^10\) This is done by only including points which are in focus for a given focal position. The three-dimensional surface maps are an improvement over standard optical microscopy; however, the improvement in lateral resolution is not significant.

An instrument which modifies the transfer function of the optical system to improve optical resolution has been proposed by Xu et al.\(^11\) For this system, a phase mask is scanned in close proximity to the object. This technique requires that the height of a line be small compared to its width, and the mechanical constraints of trying to scan a mask a few tens of nanometers above the test surface make it very hard to implement for submicron features.

Microscope systems utilizing UV sources have been built for submicron linewidth measurement.\(^12\) Using a HeCd laser at 325 nm, it is possible to get a factor of two in optical resolution over standard visible light microscopes. However, designing such a system is expensive and finding suitable detectors is difficult.
A technique similar to confocal microscopy is called a coherence probe. This microscope uses a high magnification Linnik interferometer with a white light source and measures fringe visibility at every point in the image as the focus is scanned over the range of the feature heights. Points with the highest mutual coherence function (or fringe visibility) are in focus and recorded, while other points are ignored. A three-dimensional map of the surface is built up by combining the data from a number of focus positions. The lateral resolution is increased over a standard optical microscope because the point-spread function (PSF) of this instrument is relatively independent of surface reflectivity changes. This can lead to a factor of three improvement in line edge location. The company manufacturing this instrument claims accurate measurements of 0.7 μm lines with a precision of ±0.02 μm.

Very little work has been done on the measurement of phase with optical microscopes. Tychinsky from the U.S.S.R. has shown that by measuring phase rather than intensity, it should be possible to measure dimensions which are 0.1 to 0.01 the size of the Airy disk. He shows that the two-point resolution of the phase for a given PSF is smaller than the two-point resolution of the intensity with the same PSF. The author contends that phase values can be resolved at arbitrarily closely spaced points as long as the field (in the form of its intensity) is measurable and that this is only limited by signal-to-noise considerations. He states that wherever the intensity is zero, the field is actually changing sign, which is equivalent to a π phase shift. The effect of the PSF is to reduce the phase change modulation rather than affect the position of phase features. His proof that superresolution can be performed by measuring phase is hard to follow, and systematic research backing up these claims has not been performed. At a recent conference, Tychinsky showed results of measuring a 0.2 μm wide etched channel using his Airyscan system. The measurement results show that this system has a lateral resolution of 0.1 μm. Even though his claims are unproven, this is the most promising work to date showing that optical phase measurement can measure 0.1 μm features.

The advantage of measuring phase is that both height and width of a feature can be obtained rather than just the width. If the material composing the line has different optical constants from that of the substrate, the height of the line can be determined by knowing the optical constants and measuring the feature at two separate wavelengths. In comparison to other techniques, the phase-measuring optical profiler is very easy to use, nondestructive, and fast (answer in a few seconds) at a reasonable cost.

2. DESCRIPTION OF INTERFEROMETRIC OPTICAL PROFILER

The interferometric optical profiler used for this work consists of an interferometric optical microscope with magnifications ranging from 1.5x to 200x. The source is a tungsten-halogen lamp with a 40 nm wide narrowband filter centered at 650 nm. The optical system is shown schematically in Fig. 1. The interference fringes are detected by a Videk Megaplus camera which has 1320 x 1030 active square elements spaced 6.8 μm apart. An 8-bit digital signal from the camera is sent to a Univision framegrabber in an 80486-based AT-compatible computer. Rather than measuring intensity, surface height is directly measured using phase-measurement techniques. This enables a three-dimensional map of the test surface to be generated. A schematic of the entire system is shown in Fig. 2. Each objective for this system contains an interferometer which compares the test surface to a reference surface. Low magnification objectives (1.5x, 2.5x, & 5x) utilize a Michelson interferometer, medium magnification objectives (10x, 20x & 40x) consist of a Mirau interferometer, and high magnification objectives (100x & 200x) contain a Linnik interferometer. These three interferometer types are shown in Fig. 3.

In addition to the tungsten-halogen source, a xenon source was used to provide more light at shorter wavelengths. Narrowband filters (approx. 40 nm wide) with center wavelengths of 400, 450, 500, 550, 600, and 650 nm were used to determine the shortest wavelength the system could use and still have sufficient light for the detector. Unfortunately, the Videk Megaplus camera has a UV cutoff which limits its use to a wavelength of 500 nm or greater. In the future, Videk may improve the short wavelength response of its sensor, but until then, this camera is limited to wavelengths longer than 500 nm. Ideally, a sensor with a
short wavelength response (~400 nm) with small pixels is the most desirable camera to use for submicron feature measurement. Either a xenon or a mercury source is suitable for use in the vicinity of 400 nm wavelengths.

The optical resolution of this system is given by the Sparrow criterion which determines the minimum distance between two points in order to resolve them. The optical resolution for an incoherent imaging system can be written in terms of the illumination wavelength \( \lambda \) and the numerical aperture NA of the system by

\[
\text{Optical Resolution} = \frac{\lambda}{2 \ NA}.
\]  

In addition to the optical resolution, the size of measurable features also depends upon the sampling of the image by the detection system. Because detectors do not contain ideal point detectors, the image after the optical system will be further smoothed by the detector elements. Thus, both the optical system and the detection system will smear the object. There will be a point-spread function (PSF) for each system which is the image of a point object. The final image will be the convolution of the object with the optical PSF convolved with the detection PSF. We can also think of the image in terms of spatial frequency content. The frequency spectrum of the image will be the frequency spectrum of the object multiplied by the
The effective size of a pixel is not necessarily equal to its spacing, and is usually larger than its physical size. This is most likely due to charge leakage to neighboring elements. Thus, the MTF of the system will be further reduced by the detection system and oversampling is necessary. Typically, 3 pixels per resolution element ensures that the system is resolving features on the order of the optical resolution. We measured the effective size of the detector elements for the Videk Megaplus in both the x and y directions by measuring a tilted mirror. The tilted mirror provided high frequency interference fringes. By increasing the fringe frequency until aliasing is seen, the maximum measurable fringe frequency was determined. For the Videk Megaplus...
camera, 2.64 pixels per fringe were required in the x direction, and 2.85 pixels per fringe were required in the y direction. This indicates that although the pixels are spaced at 6.8 μm intervals in both x and y, they are effectively 8.98 μm wide in the x direction and 9.69 μm wide in the y direction.

To accurately determine linewidths, it is essential to calibrate the instrument. Two different types of calibration standards have been found. VLSI (of Mountain View, CA) produces a linewidth standard with lines down to 1 μm wide which is traceable to NIST. Unfortunately, there are no traceable linewidth standards of smaller lines. NIST also produces standards with monolayers of microspheres for the calibration of microscope systems. These spheres come in two sizes: one on the order of 3 μm diameters, and the other on the order of 1 μm diameters. This is a good way to calibrate the magnification of an optical microscope system. Measurements of both of these standards are shown in the section on results.

The smallest features we could obtain were on the order of 0.5 μm wide. These lines were definitely measurable; however, determining focus was difficult because of the quality of the eyepieces. The detector was able to see things that the eye could not resolve by looking through the eyepieces. Best focus was obtained by making a number of measurements at different focal positions. Results of measuring sample lines are shown in the next section of this report.

3. RESULTS

To experimentally determine the effect of detector size and optical resolution on measurements, the instrument described in the last section was used to measure a 300 line/mm sinusoidal phase grating with a 3.3 μm period. This grating had been previously measured on a stylus profiler yielding a peak-to-valley (P-V) amplitude of 42.4 nm. Results of measuring this grating with objectives having magnifications of 10x, 20x, 40x, and 200x are shown in Fig. 5. All measurements were made with an illumination wavelength of 650 nm. It is obvious that the measured amplitude of the grating is a function of the objective numerical aperture. This illustrates what we already know about the frequency transfer function of the system. Some frequencies are attenuated more than others. Since these measurements are limited by the optical system and not the detection system, it is obvious that we need a high numerical aperture in order to accurately measure the amplitude of the grating. The period of the grating can be determined from any of the measurements. Therefore, if a feature is barely resolvable, we have a chance of accurately determining its width, but the height may not be accurate if the optical system attenuates important spatial frequency information.

![Figure 5](image-url)

Figure 5. Comparison of measurements with four different magnification for a 300 line/mm (3.3 μm period) sinusoidal phase grating with 6.8 μm detector spacing. Heights are in nm, and x distances are in μm.

Because the detector array does not contain point detector elements, the detection system also has an effect on the measured features. Figure 6 shows the same sinusoidal grating measured at 40x and 200x with two different detector arrays. One array is the Videk Megaplus camera with the 6.8 μm detector element spacing. The other is a Reticon 256 x 256 diode array with a 40 μm detector element spacing. For 200x, the difference between the measurements is not very noticeable. The larger detector elements are...
sampling at the Nyquist frequency of two samples per optical resolution element, whereas the smaller
detector elements are oversampling by a factor of 5. Major differences in results can be seen at 40x. At
this magnification, the larger detector elements are undersampling the image, and the smaller detector
elements are oversampling the image. These data show the importance of sampling the image
sufficiently to resolve the highest frequency passed by the optical system. If the detector is not sampling
the image sufficiently, the height data will not be accurate.

Two calibration standards were measured to check the accuracy of the instrument. Figure 7 shows a
measurement of a monolayer of microspheres in a hexagonal array. The diameter of these spheres were
calibrated by NIST to be 0.895 μm. This standard can be used to calibrate the magnification of the
system. The distance from sphere-to-sphere measured by this system is 0.92 μm yielding a magnification
of 194.6x.

The other standard is an NIST traceable linewidth standard manufactured by VLSI. The line
shown in Fig. 8 is 1.0 μm wide. Width of this line as measured at the full-width half maximum (FWHM)
value is 1.03 μm. Assuming the line is a sharp discontinuity, the spread of the line is about 1/2 μm. From
measurements of this standard, the phase-measuring interferometric microscope is able to measure
within the accuracy of the standard.

To determine the limits of the current instrument below 1 μm, some samples of smaller features were
obtained. Figure 9 shows the measurement of 0.8 μm lines and spaces. The spaces are slightly larger
than the lines, but since this sample has not been characterized by any other technique, it is not known if
this is the surface structure or an artifact of the measurement.
Measurements of 0.5 \( \mu \text{m} \) features are shown in Fig. 10.\textsuperscript{28} This wafer had the same pattern repeated with a number of different exposure times. Each of the three measurements is a different exposure time, where the top is the shortest and the bottom is the longest. Since negative photoresist was used, a longer exposure will produce a fatter line. The lines were hard to focus on visually by looking through the microscope eyepieces because of the reduction of the optical resolution by the eyepieces. For this system, the detector array is able to resolve more than the eye. To obtain this data, a number of measurements with different focus positions were taken and the best ones are shown. The top profile in Fig. 10 shows some ringing either caused by the optical thickness of the line or by diffraction effects (or a combination of the two). The width of the line measured between the two peaks is 0.46 \( \mu \text{m} \). It is not known if this is the edge of the line, but it is the most likely position. There are numerous ways to define the width of a line and they do not all produce the same linewidth.\textsuperscript{1-3,29-31} The middle profile shows a width of 0.56 \( \mu \text{m} \) at the FWHM value, and the bottom profile is 0.66 \( \mu \text{m} \) wide. These measurements are in agreement with the design specifications and with independent measurements made on similar wafers.\textsuperscript{28} The heights of the lines vary a lot. If the slope of the line edges is great, and the line is thicker than \( \lambda/4 \), we need to measure the feature at two different wavelengths to determine the correct height.\textsuperscript{32} This is because the phase-measurement algorithm assumes that the height does not change by more than \( \lambda/4 \) between adjacent pixels.\textsuperscript{21}

4. CONCLUSIONS

From the measurements shown, it can be seen that linewidths smaller than 0.5 \( \mu \text{m} \) can be measured. This limit could be reduced to about 0.3 \( \mu \text{m} \) using a source with wavelength of 400 to 450 nm. A short wavelength would require finding a detector array with small detector elements which will respond to these wavelengths. Such a camera should not be hard to find. Some technique needs to be developed to determine the most likely size of the line. This is where the application of object reconstruction and estimation techniques would help in accurate linewidth determination. Without the addition of
estimation techniques, standard algorithms such as FWHM could be used with this instrument down to linewidths of 0.3 μm. With the addition of estimation techniques, it is anticipated that linewidths as small as 0.1 μm can be determined to within the location of one-pixel on the surface or 0.034 μm. Precision on the order of 0.003 μm should be obtainable with interpolation and averaging data sets. Accurate heights of lines less than 0.5 μm wide may not be obtainable. For wider lines, height data should be easily obtainable unless the edge of the line has a slope larger than 1/4 wavelength per pixel. This is due to the sampling of the image. Higher lines could be measured using two or more measurement wavelengths.

5. ACKNOWLEDGEMENT

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6. REFERENCES


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