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Scatterometry for Lithography Process Control and Characterization in IC Manufacturing

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ABSTRACT

As modern circuit architecture features steadily decrease in size, more accurate tools are needed to meaningfully measure critical dimensions (CD). As a general rule, a metrology tool should be able to measure 1/10 of the product tolerance. An emerging technology for high speed, high accuracy CD measurement is scatterometry. This paper describes scatterometry-based measurements of metal features of 350 nm with a space of 450 nm (pitch of 800nm) on top of a complicated layer stack and compares them with the results of an atomic force microscope (AFM). We also looked into lithography cell monitoring and trending by measuring CDs on 3 daily litho cell monitors over a period of 40 days. Our long term results show excellent agreement with those of a scanning electron microscope (CD-SEM).

INTRODUCTION

The critical dimension scanning electron microscope (CD-SEM) is the current standard for inline metrology tools. The technique however, suffers from a number of disadvantages. Due to loading wafers into a vacuum chamber, the throughput is quite limited. Surface/site charging by the electron beam can lead to inaccuracies in measurements. Finally, accuracy of results depends on interpretation algorithms used to realize the image acquired by the CD-SEM. Scatterometry, on the other hand is an optical metrology based on the principle of diffraction. By measuring and analyzing the light scattered, or diffracted, from a patterned periodic sample, the dimensions of the sample itself can be measured. Applications of the technique have included the characterization of photomasks[1], the monitoring of focus[2], dose[3] and the post exposure bake process[4], and even the characterization of three-dimensional features such as contact hole and DRAM arrays[5]. The method is implemented in two parts known as the 'forward' and 'inverse' problems. The forward problem is the measurement of the scatter signature and the inverse problem is fitting of the data from first principles to extract meaningful results. Although many types of scatterometers have been investigated over the years[6], in this work we use the 2-Θ or *angle-resolved* implementation of the technique, were the intensity of the 0-th diffraction order is recorded as a function of the angle of incidence. Several different approaches have also been explored for the solution of the inverse problem[7]. The most common method has been to generate a library, or 'look-up' table, of scatter signatures using a rigorous diffraction model (Rigorous Coupled-Wave Theory). The signatures are generated in advance, and the measured scatter signature is compared against the library to find the closest match.

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EXPERIMENT

The samples investigated in this study were a series of 25 wafers processed by SEMATECH. Only 6 of these wafers however, were also measured with an AFM and here we will concentrate on that common set. The layer stack began with a silicon substrate, upon which was deposited 3000 Å of oxide. Next, a Ti layer (250 Å thick) was added, followed by an AlCu layer (nominal 6000 Å thick), and finally a TiN layer (350 Å thick). BARC and resist layers were added last for lithography. The targeted printed feature sizes (in photoresist) were 350 nm for the lines and 450 nm for the spaces (which results in a grating with a pitch of 800 nm). All wafers were printed at nominal dose and focus. The scatterometry measurements were carried out on a CDS-2 system from Accent Optical Technologies which uses a 632.8 nm laser as its light source while the AFM was a DEKTAK-SXM in operation at SEMATECH.

In order to show reproducibility performance of this technique, we carried out separate measurements on a daily set of 3 wafers over a period of 40 days. The grating structure consisted of 5500 Å of UV86 photoresist on a 560 Å uniform DUV30 ARC layer on a silicon substrate. For each wafer we measured CDs on 13 sites across including 5 sites within a middle die. Those sites were also measured using a CD-SEM.

Library Details

An important consideration in the generation of any scatterometry library is the number of modes, or orders, retained in the calculation. The higher the number of modes, the more accurate the theoretical results are. A large number of modes however, results in longer library computation times. The determination of the optimal number of modes is done automatically by the system software using the system's signal-to-noise as a convergence criterion. For the first part of this study, we created two libraries, one for the pre-etch (resist) study and one for the post-etch measurements. The former used four fitted parameters: resist thickness, resist sidewall angle, resist CD, and BARC thickness. The AlCu layer was thick enough to act as a substrate in this case. The later used as parameters the AlCu layer thickness, the linewidth of the metal features, the thickness of the etched part, and the thickness of the unetched part of the oxide layer. Library details can be seen in Table I and II. For the trending part of the study, we created a library that varied CDs and sidewalls.

Table I. Library parameters for the resist stack measurements.

Parameter name	Lowest iteration	Highest iteration	Resolution (step size)	Number of iterations	Lib. Size (# of signatures)
Linewidth	300 nm	360 nm	2 nm	31	31 x 11 x 37 x 11 = **138,787**
Sidewall	86°	91°	0.5°	11	
Resist Thk	9800 Å	10700 Å	25 Å	37	
BARC Thk	600 Å	850 Å	25 Å	11	

Table II: Library parameters for the etched stack measurements.

Parameter name	Lowest iteration	Highest iteration	Resolution (step size)	Number of iterations	Lib. Size (# of signatures)
Linewidth	210 nm	270 nm	2 nm	31	31 x 41 x 37 x 13 = **611,351**
AlCu Thk	6000 Å	7000 Å	25 Å	41	
Etch Ox Thk	100 Å	1000 Å	25 Å	37	
Unif Ox Thk	2100 Å	2400 Å	25 Å	13	

RESULTS

Metal features

Figure 1 shows the scatterometer resist (pre-etch) linewidth results in comparison to AFM data for three wafers (identified as 5, 13 and 21). In the figure results from these three wafers are grouped together in succession on the x-axis, but lines have been drawn to indicate the different wafer data. The AFM measurements are showing considerable linewidth variation for wafers 5 and 21, and to a lesser extent on wafer 13. These variations are probably an artifact due to the difficulty in performing AFM measurements on a 'sticky' material such as photoresist. A similar resist stack (APEX on BARC, also processed at SEMATECH) was measured in previous research[8] and did not show this degree of variation. Furthermore, the sister-etched wafer (wafer 1) from this group did not exhibit this degree of variation (see figure 3, wafer 1). Overall the scatterometry results show consistent linewidth measurements across each wafer, which was to be expected for this process.

The resist sidewall angle results are shown in figure 2. In this case there is good agreement between the AFM (which are the average of the left and right wall angles) and CDS-2 results. Recall that the scatterometry model used 0.5 degree increments for the sidewall angle parameter (although this is not the ultimate resolution of the tool for performing sidewall measurements), and as a result the scatterometry data only vary between 89.0 and 89.5 degrees. The scatterometer results also seem to track the correct trends as observed by the AFM; measurement number 6, 7 and 8 (from wafer 5) show a "low-high-low" trend that was observed on both tools.

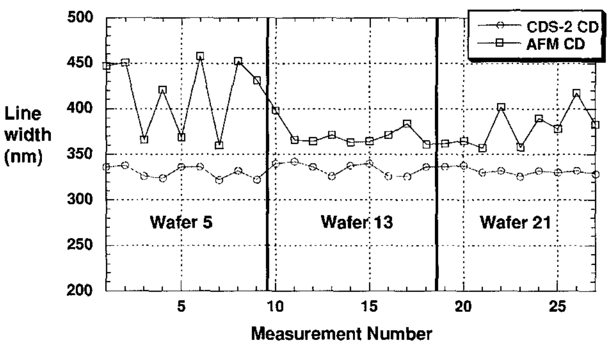

Figure 1. Scatterometer and AFM measurements of the resist (pre-etch) linewidth.

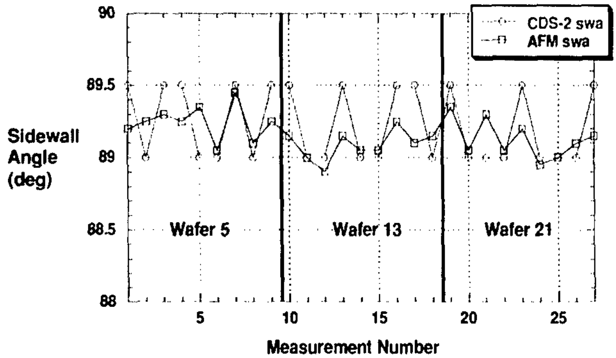

Figure 2. Scatterometer measurements of the resist (pre-etch) sidewall angle.

Figure 3 shows the etched linewidth measurements performed by both scatterometry and the AFM. The results for the first wafer in the set (wafer 1) show a good correlation with an average CD of 375 nm for the AFM and 260 nm for the scatterometer. The correlation is lower for the middle wafer (#9) and third wafer (#17). Some of the measurement sites for the third wafer were damaged as was determined by both a visible inspection and by the etched layer thickness measurements. Overall there is clearly an offset (~150 nm) between the two measurement types, which is best illustrated in the data from wafer 1. This offset is due to the AFM tip not being deconvolved out of this measurement (the tip width was set to 0 Å). It is worth noting that, as one would expect, the scatterometry CD trends observed on all the individual wafers are similar to the trends observed in the resist measurements (refer back to figure 1). This is exactly what one would expect from a typical litho-to-etch process; the resist CDs are transferred into the etch. We also carried out measurements of the etched layer thickness with both the scatterometry system and the AFM and they were found to be in excellent agreement. Note that the scatterometry thickness results are the sum of the four individual layer thickness: the etched oxide region, the Ti thickness, the AlCu thickness, and the TiN thickness. The scatterometer actually determines the different thickness of these materials, whereas the AFM does not – it measures the total thickness.

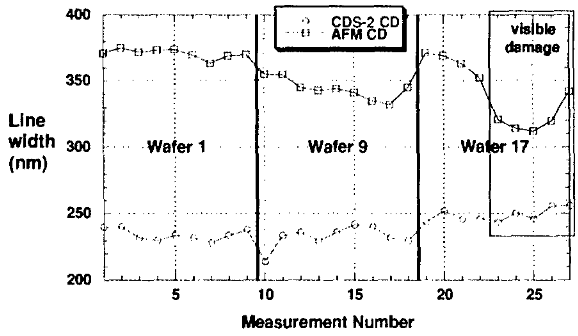

Figure 3. Scatterometer and AFM measurements of the etched metal linewidth.

Litho Cell Monitoring

Lithography cell monitors are used to monitor stepper health. The large arrays of line/space pairs make cell monitors an ideal application for scatterometry. Measurements were made on cell monitors over a 40 day period on both CD-SEM and scatterometer. Figure 4 presents CD and sidewall angle trending data for the scatterometer. Figure 5 presents CD trending data for the top-down CD-SEM.

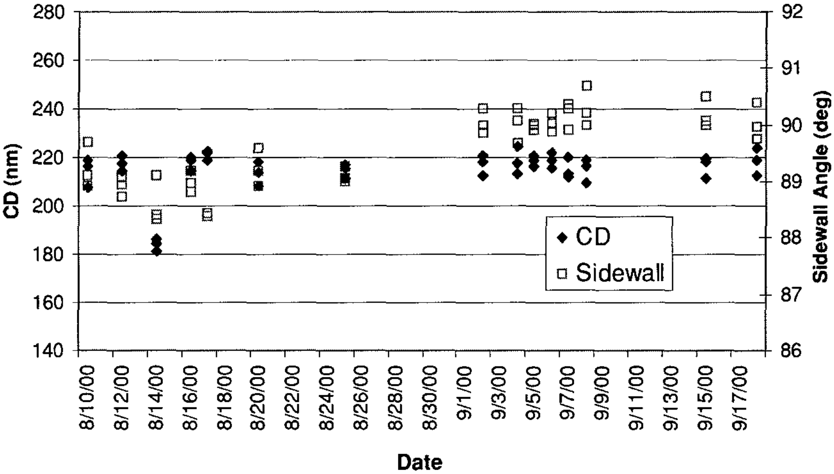

Figure 4: Lithographic cell monitor CD and sidewall angle trending data for scatterometer.

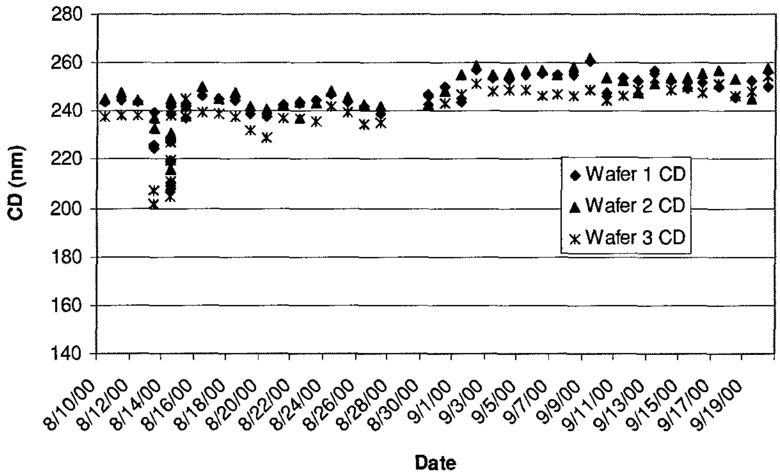

Figure 5: Lithographic cell monitor CD trending data for CD-SEM.

In comparing the results from the two metrology tools, there are three noticeable observations. The first is that there is an approximately 30 nm offset between scatterometer CD and CD-SEM CD, with the CD-SEM measuring higher. Both tools detect a temporary downward shift in the measured CD on the day of 8/14/00 (with the scatterometer also showing generally poor fits to the data for this day). The second is the response to a process shift occurring between the months of August and September. The top-down CD-SEM measured an approximate 10 nm increase in CD during the process shift, while the scatterometer measured no CD increase. However, the scatterometer does show an increase in the sidewall angle during the process shift, from an 89 degree to a 90 degree vertical sidewall. Limited cross-section CD-SEM data was taken between this process shift, which saw the sidewall angle increase from 88 degrees to 90 degrees. The trend in increasing SEM/scatterometer CD offset with more vertical sidewalls has also been observed in prior work[4,5], and the measured offset is consistent with what has been seen in those publications.

CONCLUSIONS

A novel, optical non-contact technique based on scatterometry was employed to measure CDs and sidewall angles on a 4 layer composite grating and the results were compared to AFM measurements. The wafers comprised both resist and etched metal samples with nominal 350 nm (resist) and 250 nm (etch) linewidth. Comparisons to AFM measurements on the same samples showed good correlation and consistency. In addition, we examined long term trending capabilities of the technique on a 40 day period and compared with the performance of a top-down CD-SEM. We found that a process shift in sidewall angles, caused the CD-SEM to report an artificially increase in CDs by 10 nm while the scatterometry measurements were able to distinguish between the CD and sidewall angle changes. Finally, the precision of these measurements were determined, and indicate that scatterometry is an attractive alternative for high volume, high precision inspections.

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