Lithographic Process Evaluation by CD-SEM

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Abstract-- In lithography employed in IC fabrication, focus and exposure directly determine the printed resist image. Focus and exposure settings may be optimized with a focus exposure matrix (FEM) in which one parameter is varied by column and the other parameter is varied by row. A focus exposure matrix should be measured on a highly accurate and precise metrology tool, such as a CD-SEM. This experiment was performed using a Canon FPA 2000-i1 stepper, an SSI 150 coat/develop track, and a Hitachi S-6780 CD-SEM. ProData was used to graphically analyze the numerical data collected on the CD-SEM. Data collected in this experiment shows that, for the given equipment, varying exposure from 120 to 200 mJ/cm^2 in 10 mJ/cm^2 increments and focus from –0.5 to +1.5 microns in 0.25 micron increments gives a CD range beyond the +/-10% needed.

1. BACKGROUND

In the most basic sense, lithography is simply the transfer of a mask image into photoresist, a light-sensitive material. In practice, lithography is much more complex than that statement suggests. Success in Lithography, as in any other area of microelectronics, depends on successfully manipulating an extensive array of checks and balances. Broadening the tolerance on one parameter inversely tightens the tolerance on another. In a simplified view of day to day stepper operation, proper linewidth printing depends on focus and exposure dose. Critical dimensions may be plotted against focus and dose to represent the latitude for the given process. Most processes require a CD specification of less than +/- 10%. Ignoring focus variation yields the exposure latitude of the given process for the given CD specification. Exposure latitude simply represents the maximum exposure dose variation possible to meet the given CD specification. Ignoring exposure variation gives the depth of focus (DOF) for the given process and CD specification. DOF shows the most focus variation possible to print the CD within desired specifications. The depth of focus must account for variation in stepper focus and the wafer topography created by processing prior to the current level. As mentioned above, considering exposure variation, focus variation, and allowable CD variation yields the process latitude or process window. The depth of focus available for a given process window is the usable depth of focus (UDOF).

Even in a simplified view such as the one above, it is vital to realize that dense features and isolated features will print optimally at different focus and exposure settings. This is largely accounted for by mask level corrections. Features may be given a mask bias based on how an unbiased feature prints. In some cases an isolated feature may be surrounded by "dummy features" to closely simulate dense features. The exposure process may then be optimized for dense features. The "dummy features" are likely printed on the mask small enough that they are below the resolution capability of the exposure tool; therefore, these "dummy features" are not transferred into a resist image. Even though these features are below the resolution capability of the exposure tool, they do modify the aerial image of the isolated feature which is actually transferred to resist.

Assuming no mask biases or corrections are present, isolated and dense features will print differently. To print these different features as designed (and without a mask bias), different process settings are necessary. Since isolated and dense features often co-exist on the same level, process settings must be chosen to adequately print both feature types making process latitude more important. The portion of the process window in which both dense and isolated features print adequately is often referred to as the process window overlay.

A dose to clear, or E0, wafer is useful as a daily or bi-daily test to baseline the lamp performance of each exposure tool used. A clear reticle may be used to expose the E0 wafer. Exposure is altered by a user specified amount at each die in the step pattern. The dose to clear can be determined by visually examining the wafer or measuring resist thickness remaining in die that appear nearly cleared. An E0 check must be performed separately for each exposure tool used.

An E0 wafer is actually a focus exposure matrix (FEM) with the focus change set to zero. The FEM, often called a FOCEX or FOCEXPO, varies one parameter by column and the other parameter by row. CD measurement

of CDs in the matrix reveal the process latitude available. Each die on a FOCEX wafer is essentially one "run" of a designed experiment. Multiple "runs" can be performed by processing multiple FOCEX wafers together. Depending on exposure tool software, it may be possible to hold focus constant on multiple columns (or exposure constant on multiple rows) to perform multiple "runs" on a single wafer. It is important to note that a focus exposure matrix must be performed separately for each level and probably for each level/exposure tool combination.

Sub-micron features are difficult to measure precisely and accurately with optical metrology tools. At some small CD, any specific optical metrology tool becomes completely inaccurate. Sub-micron CDs are best measured with scanning electron microscopes (SEMs) to guarantee precise, accurate CD measurement. Many CD-SEMs are designed to automatically drive from die to die and acquire a pre-selected CD. The CD-SEM acquires the CD by comparing what it sees to an image previously chosen and saved by a human user. CD-SEMs can measure the top and bottom of a CD and approximate the sidewall angle and a horizontal dimension part-way up the vertical axis. Since modern CD-SEMs are automated, they allow relatively quick measurement of a high number of CDs per wafer. This is necessary to reduce negative impact on wafer cycle time.

2. EXPERIMENTAL

This experiment was performed using a Canon FPA 2000-i1 stepper, an SSI 150 coat/develop track, a manual spin coater, a Nanospec Film Thickness Measurement scope, and a Hitachi S-6780 CD-SEM. OiR 620 photoresist and CD-26 developer were used. Wafers were patterned with the Canon test reticle which contains clusters of measurement CD's at 0.05 micron increments. Each cluster consists of five adjacent features. The center and outside 0.5 micron vertical lines were measured to simulate dense and isolated lines, respectively. ProData® was used to analyze the numerical data collected on the CD-SEM.

A preliminary wafer was run with focus and exposure settings determined theoretically in ProLith®, a lithography modeling software package from Finle Technologies. A final wafer was run with FE settings determined from CD measurements taken from the preliminary wafer. Besides FE settings, processing was the same for both wafers except for the coat step (and related bakes in the coat program). The preliminary wafer was coated on the SSI track. The final wafer was coated on a manual spin coater and baked on a hot plate for the dehydration and soft bakes. This discrepancy was necessary since the spin module in the coat track was under repair. The develop track was functional for processing of both the preliminary and final wafers.

A. General Process

Dehydration Bake (200° C, 45 seconds)
HMDS Prime
OiR 620 positive resist coat
Soft Bake (90° C, 60 seconds)
Canon Exposure
Post Exposure Bake (PEB) (105° C, 60 seconds)
CD-26 Development (70 seconds)
Hard Bake (120° C, 45 seconds)
Nanospec resist thickness measurement
Hitachi CD-SEM CD Measurement

B. Preliminary Wafer

The preliminary wafer was coated on the SSI track at a spin speed of 4500 RPM for 60 seconds. This wafer was exposed with focus varied by column from –2 to +2 microns in 0.5 micron increments and with exposure varied by row from 60 to 300 mJ/cm^2 in 30 mJ/cm^2 increments.

C. Final Wafer

The final wafer was coated on a manual spin coater at a spin speed of 3000 RPM for 25 seconds. This wafer was exposed with focus varied by column from –0.5 to +1.5 microns in 0.25 micron increments and with exposure varied by row from 120 to 200 mJ/cm^2 in 10 mJ/cm^2 increments.

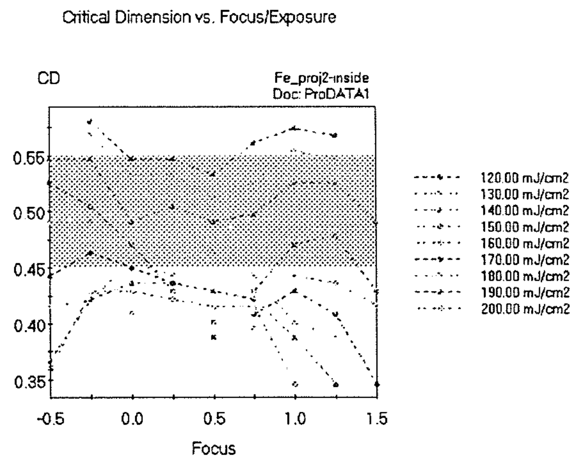

Figure 1: Inside Feature CD versus FE ProData plot

3. RESULTS

The preliminary wafer which was coated on the SSI track had an average resist thickness of 9812 Å and a range

Table 1: Site-by-Site CD Data for Inside 0.5 Micron Vertical Line (Exposure across top row, Focus down left column)

	120	130	140	150	160	170	180	190	200
1.50			0.491	0.429	0.416	0.346			
1.25	0.568	0.548	0.526	0.478	0.436	0.408	0.388	0.346	
1.00	0.574	0.554	0.526	0.471	0.443	0.429	0.401	0.387	0.346
0.75	0.561	0.526	0.498	0.429	0.395	0.408	0.443	0.422	0.415
0.50	0.533	0.512	0.491	0.401	0.387	0.388	0.464	0.429	0.415
0.25	0.547	0.533	0.505	0.429	0.436	0.436	0.443	0.436	0.422
0.00	0.547	0.533	0.491	0.471	0.409	0.450	0.456	0.436	0.429
-0.25	0.581	0.568	0.547	0.505	0.491	0.464	0.422	0.422	0.429
-0.50			0.547	0.526	0.491	0.443	0.415	0.367	0.360

of 32 Å for the five sites measured on the Nanospec film thickness measurement tool. The final wafer which was coated on the manual spin coater had an average resist thickness of 7744 Å and a range of 477 Å for five sites. This range was due to an area of thicker resist in the center of the wafer. Ignoring the center site (8101 Å), the four outer sites had an average thickness of 7655 Å and a range of 82 Å.

Site-by-site data for inside 0.5 micron vertical lines is given in Table 1. Figure 1 shows a CD versus focus/exposure plot for the inside feature as plotted by ProData. Numerical and graphical results for the outside 0.5 micron line are omitted since they matched those of the inside feature almost exactly. The average inside-to-outside difference was 0.00926 microns and the largest discrepancy was 0.041 microns.

SEM and operator measurement repeatability were tested by measuring a CD, leaving the site, and returning to measure the same CD. Six such measurements showed the SEM repeatability to be 0.043 microns or +/- 0.0215 microns. This number could have increased if more measurements had been taken.

4. ANALYSIS

The final wafer showed incorrect results at several center die due to poor across-wafer resist uniformity from manual spin coating. ProData rejected six data points (all center die locations) since they were statistically incorrect. These data points are plotted in Figure 1 but are not connected to they're respective exposure trend. The final wafer had a thicker resist coating in the wafer center generally meaning more exposure energy would be necessary. This effectively makes the exposure energy delivered look smaller, a case of underexposure. Underexposed lines in positive resist should print larger than desired. However, the center die features printed smaller than expected. There is likely a more complicated swing curve interaction here. (Swing curves are caused by reflection of exposing light off the substrate back into the resist.) The swing curve for 0.5 micron lines has never been investigated since, until now, an adequate linewidth measurement tool such as the Hitachi CD-SEM has not been available.

The linewidth difference between the inside and outside 0.5 micron vertical line is within the noise level of the Hitachi S-6780's measurement capability. SEM repeatability tests show a range in CD measurement of 0.043 microns or greater and the average and maximum inside to outside linewidth difference was 0.009 and 0.041 microns, respectively. The outside feature may actually print slightly differently than the inside feature, but the difference is negligible. Also, the outside feature does not adequately simulate an isolated feature.

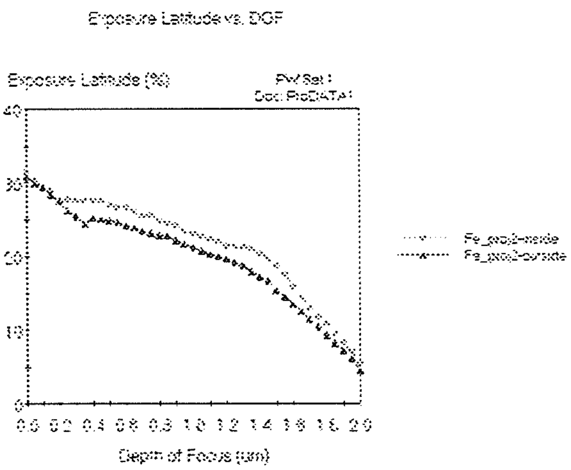

Figure 2: EL versus DOF for Inside and Outside Feature

The ProData plot given in Figure 2 plots exposure latitude against DOF with separate trends for the inside and outside 0.5 micron vertical lines. Since the difference between these data sets is within the noise level of the CD-SEM, Figure 2 shows process latitude variation based on SEM measurement variation.

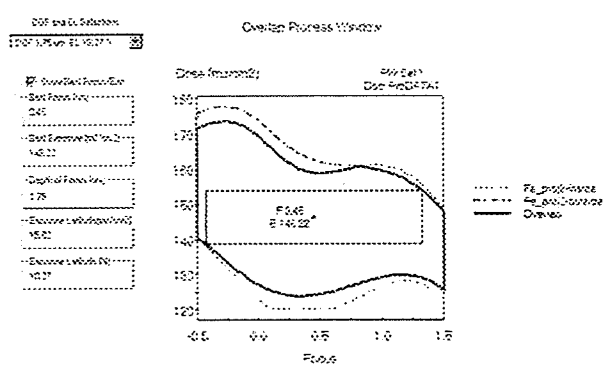

Figure 3: Process Window Overlay

The ProData plot in Figure 3 the process window for each feature measured and the process window overlay. Computer calculated DOF and EL combinations may be selected in ProData from the drop down list (top left corner of Figure 3). Figure 3 shows the process window plot for 1.75 micron DOF and 10.27% EL. Figure 4 shows EL versus DOF with a line drawn to the DOF / EL combination selected in the drop list. The trend in Figure 4 combines the two trends in Figure 2 by taking the worst case (lowest EL) at each DOF value.

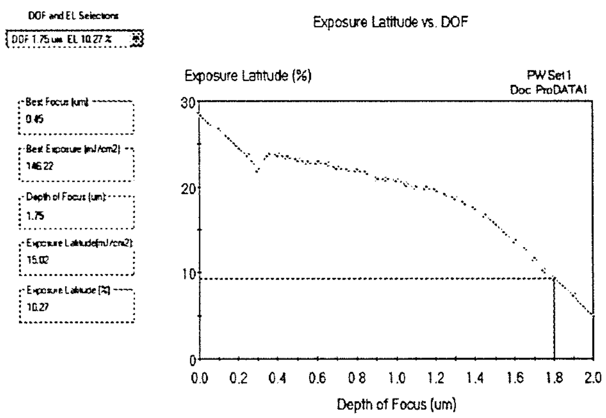

Figure 4: EL versus DOF for Feature Overlay

Table 2 gives representative sets of best focus, best exposure, DOF, and EL. All numbers were attained through ProData analysis. As DOF increases EL decreases and vice versa.

Table 2: Representative Data Sets from ProData

Best Focus	Best Exp	DOF	Exposure Latitude	
(um)	(mJ/cm2)	(um)	(mJ/cm2)	(%)
-0.07	149.94	0.00	42.53	28.37
-0.07	149.94	0.05	41.26	27.52
0.57	142.50	1.70	16.47	11.56
0.45	146.22	1.75	15.02	10.27
0.48	145.60	1.80	13.53	9.29
0.50	144.36	2.00	7.21	5.00

5. CONCLUSIONS

Focus and exposure settings directly determine the linewidth of the resist feature printed. A focus exposure matrix (FEM) may be used to optimize focus and exposure and to investigate depth of focus (DOF) and exposure latitude (EL). DOF and EL change inversely, so high DOF is bought at the cost of reduced EL and vice versa. The outside feature in a five feature set does not adequately simulate an isolated feature. The difference between the inside and outside 0.5 micron vertical lines was within the noise level of the Hitachi S-6780 CD-SEM. The data measured in this experiment was negatively impacted by poor resist uniformity due to a manual spin coater. Despite this, the FE settings used showed more than +/-10% CD variation and allows for adequately small changes in FE. The exposure was varied from 120 to 200 mJ/cm^2 in 10 mJ/cm^2 increments. Focus was varied from –0.5 to +1.5 microns in 0.25 micron increments. Since this experiment was performed on bare Silicon wafers (no devices or other processing), it is not useful to determine a "best process."

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ACKNOWLEDGMENTS

The author acknowledges Suebphong Yenrudee for initial work on this project including ProLith simulation.

The author also acknowledges Dr. Bruce Smith and Dale Ewbank for guidance on this project. The author extends special thanks to Joe Perez for technical assistance with the Hitachi CD-SEM, Canon stepper, and SSI track and to Bruce Tolleson for assistance with and maintenance of the CD-SEM. The author would also like to extend special thanks to Canon for making special effort to repair RIT's Canon FPA 2000-i1 in a timely manner despite the over-filled schedule of Canon repair technicians. Without this extra effort, completion of this project would not have been possible.

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