The MEEF Shall Inherit the Earth

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ABSTRACT

Deep-UV lithography using 248 and 193-nm light will be the imaging technology of choice for the manufacturing of advanced memory and logic devices for the next decade. The extension of 248nm technology to 0.150µm and beyond has been accelerated with techniques, such as, Off Axis Illuminaton (OAI), Optical Proximity Correction (OPC) and Phase Shift Masks (PSM). Rapid development of such enhancements could provide a viable solution for the 0.13µm node. This continuous reduction of k_1 to near ½ wavelength has intensified and issues related to Mask Error Factor (MEEF) have become a concern. Mask Error Factor, a phenomenon first discussed by Maurer et al., is defined as the CD Error at wafer level divided by the CD error at the reticle level multiplied by the lens magnification.

The authors have been focusing on several key issues related to this high MEEF at various duty cycles. First, is the impact of MEEF across the entire exposure field for sub-0.15µm imaging with KrF imaging. Secondly, the authors will discuss the coorelation between MEEF through pitch vs critical dimension with respect to partial coherence for bright and dark field imaging. Finally, the process window must be ***"corrected"*** to account for across plate CD variation once the Mask Error Factor for a given critical dimension, pitch, reticle type, illumination condition and photoresist are determined. The authors will address the use of this new metric that can also assist in the specification of reticle CD's. Furthermore, we will address the various imaging solutions, briefly discussing how improvements in photoresist technology can assist and their impact on darkfield and lightfield imaging.

(1.) Introduction

Device manufacturers will use KrF deep ultraviolet imaging to produce 180nm and sub-180nm geometry's for DRAM and related logic technology. Progress on 193nm technology has been slow and device manufacturers are preparing to use KrF for manufacturing at this dimension and

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for early development work at 130nm. However, there are concerns about obtaining both the mask and wafer CD control necessary to achieve good yielding product.

Device manufacturers will need to develop processes using both OPC and PSM, although there are many issues associated with implementing either technology. Most device manufacturers have developed some form of OPC, from simple biasing to more complex OPC based on defined rules (1). Defect related issues for OPC and PSM will be critical. The intention of this paper is to investigate the impact of full field mask error factor using conventional resist and illumination techniques to support the fabrications of 180nm device development. The authors will also demonstrate the impact of illumination conditions on MEF, and that there could be a correlation between CD and MEF with respect to choice of photoresist, illumination conditions and imaging pitch. The key process latitude parameters for gate level lithography will be determined. The continued development by researchers will continue to push down geometry's with KrF perhaps to 100nm imaging for logic gate applications. This will of course depend on the development of ArF and PSM strong shifter technology. Significant improvements in optics, illuminators, reticles, photoresist technology continue to play a very important role for KrF, ArF and now F_2 (157nm λ). There have been several publications over the past year (2) on the tuning of the illuminator to significantly enhance aerial image intensity for specific geometry's and pattern pitch. Since there continues to be major improvements in many areas there is renewed focus on the improvement of reticle CD control for with chip, within die and within field control. The use of KrF for 0.13μm is a reality and the continued focus will remain on how much further optical lithography will proceed into the future.

(2.0) Experimental

Simulations were performed with Prolith® 6.0 from Finle Technologies for aerial imaging calculations and in resist with the UV6 photoresist model with various illumination conditions. LMS Optimus was used with Prolith® and 0.70NA with Prolith Imaging experiments were conducted on a ASML /700 step and scan system with 0.63NA and 0.85σ with UV110 photoresist at a film thickness of 5500Å over an inorganic bottom antireflective coating.

(3.0) Results and Discussion

Figure 1 below is a breakdown of the various components that can contribute to the CD budget which are used for demonstration purposes only!! However, for our discussion we will focus on effective reticle multiplier which is the MEF factor. We would also ask the reader to give special consideration to the "across chip linewidth variation" section to focus on the reticle multiplier effect and the impact on the total budget. The data demonstrated in this spreadsheet in based on simulation for binary reticles with scattering bars; however, from this we should understand what that impact can be on our overall CD budget, based on the multiplier or MEF this could consume a very large percentage of the CD budget.

Figure 1:

Across Chip Linewidth					
Within	*All data 3 sigma*				
L CD:	***0.25/0.70u***	***0.18/0.60u***	***0.15/0.54u***	***0.13/0.36u***	***0.10/0.30u***
Exposure Field	8.1	8.9	9.6	14	14
Reticle CD	14	10	10	8	8
Nonlinear Effect	1.1	1.7	3	4	6
Effective Reticle CD	15	17	30	32	48
Proximity	6	6	6	6	6
Reflective Notching	6	6	6	6	6
Total	19.	21.	32.	35.	50.
Spe	28.	23.	19.	16	12
Spec	**8.6**	**2.0**	-	-	-

$$\mathrm{MEEF} = \partial \mathrm{CD}\ \textit{resist} / \partial \mathrm{CD}\ \textit{mask} * \textit{reduction ratio}$$

(3.1) CD Through Pitch vs. Partial Coherence vs MEF

Figure 2

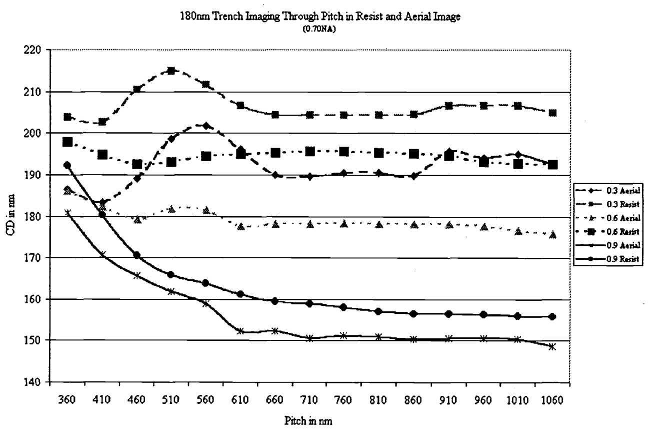
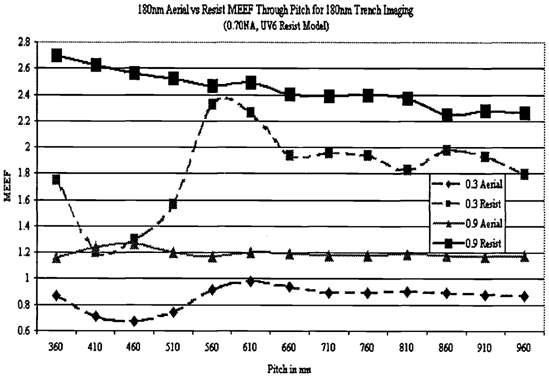
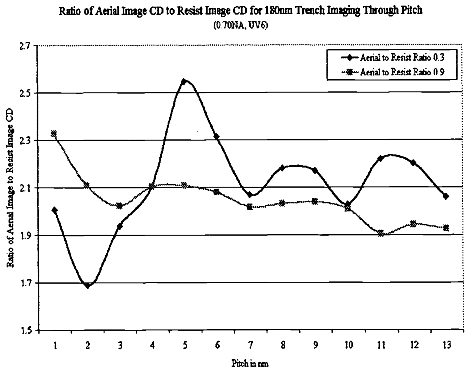


Figure 3



There have been a number of recent publications where authors have published the impact of CD through pitch for a given geometry at a given pitch [1,2,3,4,5, 6]. Figure 2 is simulated CD through pitch vs partial coherence for 180nm imaging in resist and aerial image for a numerical aperature of 0.70 with σ=0.3, 0.6 & 0.9. In figure 3 we have plotted MEEF through pitch for both the aerial image and resist CD for 180nm imaging through pitch. In this graph it is demonstrated that there is a difference between the MEEF for aerial image and resist. In figure 4 we have plotted the ratio of aerial image to resist for 180nm CD's through pitch. This ratio is about 2 through pitch and provides insight into the resists contribution to MEEF when printed in resist.

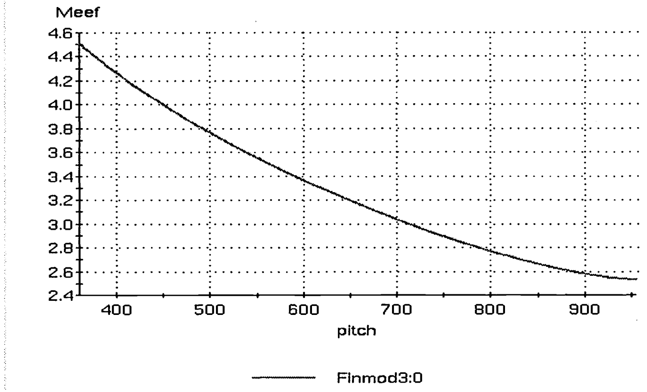
Figure 4



(3.13) Optimizing Resist to Reduce MEEF

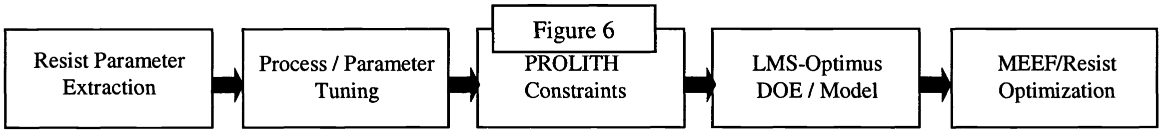
The authors have plotted simulated MEEF for 180nm nested lines using 0.7NA with 0.9σ in figure 8. The intention is not to focus on the absolute numbers but to demonstrate that MEEF is higher for nested imaging and decreases with pitch, however, in terms of the absolute numbers is very high for these geometrys. Our work is now to find an optimum set of chemical amplified photoresist parameters that can reduce MEEF through pitch using a series of designed modeling experiments and optimization. For our modeling and simulation work we used the Prolith3 simulation engine coupled to LMS Optimus. The authors performed "set-up" experiments before the final DOE was created – the actual flow is shown below in Figure 9.

Figure 5



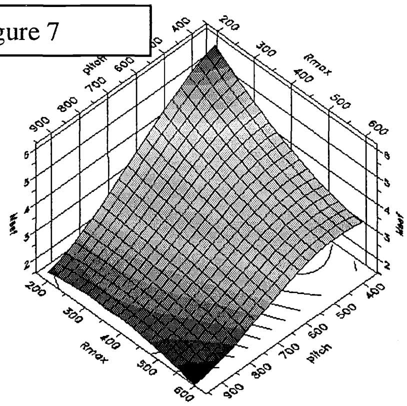
First, without using LMS Optimus, we used Prolith to find an overall NA and best sigma for the following process: 400nm thick chemically amplified resist on 30nm silicon nitride over 800nm oxide / silicon. The lithography was an 180nm space on a 360nm & 960nm pitch at a best focus of –0.2μm with an exposure dose ~20 mj/cm^2 from a calibrated resist model. A 60 second puddle develop with 130°C for 60 second softbake and 130°C post exposure bake. Nominal Prolith® parameters R*max* = 340nm/sec, R*min* = 0.4nm/sec, n=23, Mth=0.55 B=1.4. The real resist index N = 1.75 @248nm, the numerical aperture was 0.70 and full scalar model was employed.

Figure 6



NA and sigma optimization: After running several thousand Prolith simulations using the feature sizes and pitches mentioned above. It became obvious that the best setting for sigma was somewhere between 0.6 and 0.9 (dense features like a higher sigma). The authors decided to use σ=0.75, this quasi-optimized NA & σ setting yields a DOF of

Figure 7

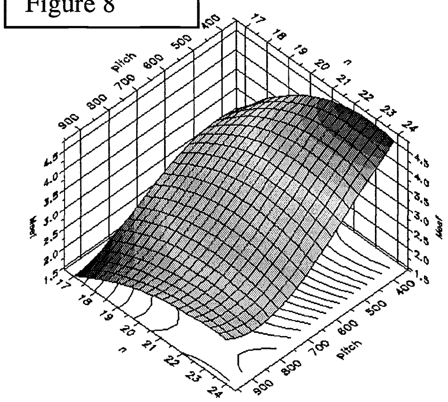


0.6µm for the isolated features and 0.5µm for the dense features. The exposure latitude was ~8% for both isolated and dense features.

Parameter sensitivity: Prolith simulations were conducted to determine approximately how much each resist parameter (R*max*, R*min, n, Mth* and B) changes dose to size, DOF, SWA, PAC gradient, linearity and iso-dense bias. The ranges for the parameter settings were: R*max* (200-600nm/sec), R*min* (0.2-0.8nm/sec), *mth* (0.5-0.7), *n* (15-25), B (0.7-1.4).

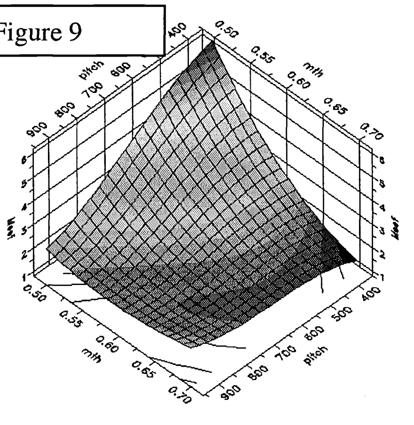
Using LMS-Optimus we created a latin-hypercube and 3-way full factorial DOE with the following input variables: pitch, R*max,* R*min*, Mth, *n* and B. The following output variables were calculated using the Prolith simulation results and LMS Optimus: MEEF, nominal CD, and iso-dense bias. Before the final simulations were performed, the authors needed to obtain a final NA-σ optimization (*EL & DOF*) using the extreme values of the input variables. For our case here, the original NA-σ settings were fairly robust to changes in the various input variables.

Figure 8



The authors calculated a nominal CD and MEEF response surface for each of the input variables listed above. Interpolating, 2nd and 3rd order polynomial fits were used with good success (R^2 values of 0.95 for the 2nd and 3rd order fits). The response surfaces for iso-dense bias through focus will be discussed at a later time.

Figure 9



The authors have generated several response surface plots to demonstrate that for a calibrated resist model certain resist parameters can reduce MEEF through pitch. In figure 10 we have plotted MEEF as a function of pitch and R*max.* There is a clear indication that there can be a reduction in MEEF with an increase in R*max.* Large changes in the photoresist dissolution rates created large changes in R*max* and R*min* but not significant changes in DOF and iso-dense bias however, as expected, there were large

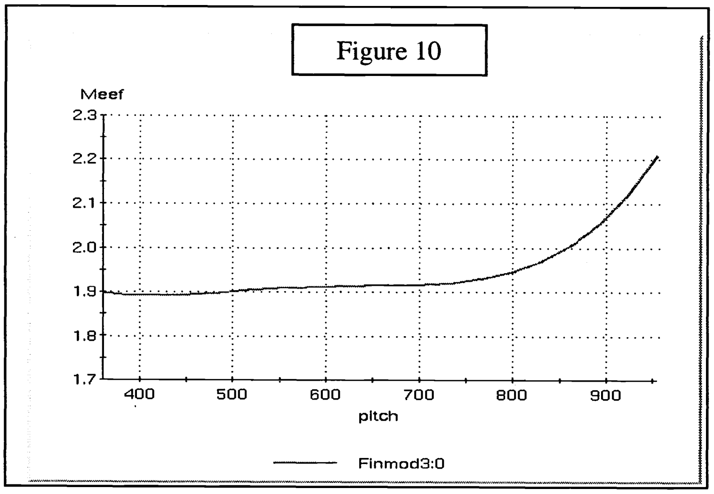


Figure 10

changes in feature size and resist loss. In figure 11 the authors have plotted *n* or the contrast of the photoresist system vs pitch vs. MEEF. In has been known that photoresists can be optimized for pitch *ie:* nested photoresist vs an isolated line resist system, however, here we see that MEEF can be taken into consideration and improvements can be realized. Furthermore, contrast (*n*) changed dose to size rather dramatically, smaller *n* equal bigger spaces.

In figure 12 the threshold and deprotection or the *mth*, is a very powerful knob, this resist "turn-on" parameter can really change MEEF, which may be both good and bad news. So then, the good news is that changing the "turn on" position can significantly reduce MEEF through pitch. The bad news is this is difficult to do and more experiments are required to understand the impact.

The authors would also like to make a few comments regarding absorption, the B parameter. This changes the gradient (both before and after PEB) so much so that it can act like an optical resist lever, which might be a good since it is the only resist "optics" knob. A question to ask is can we change B by 20% while keeping the resist index of refraction within +/- 5% of nominal?

Early in this section the authors plotted MEEF through pitch with our "old" resist parameters and in fugure 13 have plotted MEEF through pitch with our new parameters. Let's focus not on the absolute numbers but the relative difference of MEEF through pitch in figure 13 vs. MEEF through pitch plotted in figure 8. This reduction is over 2X for the nested pitch and some reduction for the more isolated pitch, however, further refinement might be required to achieve additional MEEF reduction in the more isolated pitches.

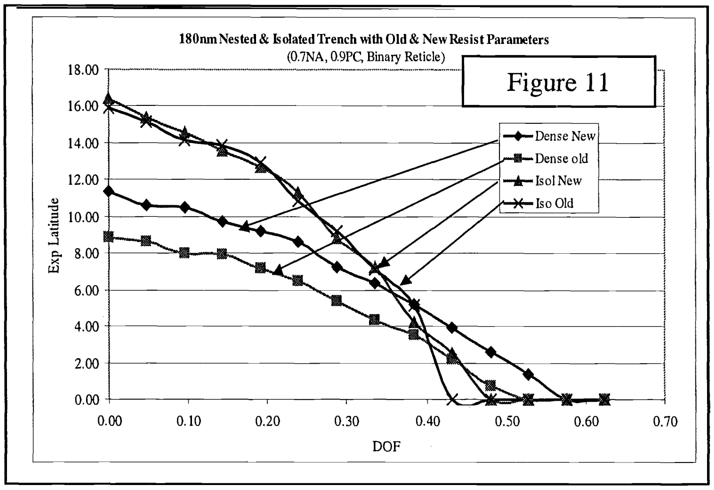


Figure 11

Our final experimental confirmation was to simulate ED process windows with the old and new resist parameters shown in figure 14. Interestingly, there is no degradation in the isolated line process window, moreover, there is an increase in the nested imaging process window demonstrating not only reductions in MEEF but slight improvements in process windows.

3.4 MEEF Correct ED Process Windows.

The obvious effect of a greater than one MEEF is the impact on the mask CD requirement as discussed by Wong et al (5). The authors have taken this a step further in developing a correction to the ED process window once a given MEEF is known. In our example we have generated a process window along with MEEF data on 180nm nested and isolated trenches with 0.7NA and 0.9σ using a binary reticle. Figure 15 is a plot of MEEF through focus for 180nm nested imaging and will serve as our *"MEEF Through Focus Calibration Curve"* . Based on this initial curve the authors have extrapolated MEEF through focus to greater than 1 for the purposes of correcting a more complete ED process window. This is done by the equation below (figure 16) where the old exposure latitude is multiplied by one minus the ρCD on the mask multipled by the MEEF at the focus position and divided by the CD specification. Figure 17 are simulated ED windows for 180nm nested and isolated trenches with 0.7NA and 0.9σ in 400nm of photoresist. There are two series of graphs which represent an ED window with a *"prefect reticle"* and an ED window once the known reticle error is factored in via the equation in figure 16. Let's look at the nested ED window with a perfect reticle and the corrected nested window once a known reticle variation is calculated in. First there is a large reduction in the exposure latitude which is understandable, however, let's further look at the reduction in DOF which is equally as significant and in this case represents a nearly 33% reduction in overall process window reduction. Furthermore, if we look at the isolated trench it already has a small ED window, however, with the correction taken into account it becomes even smaller.

$$New\ Exp\ Lat = Old\ Exp\ Latitude\ \frac{(1-(\Delta CDmask * MEEF)}{CDspec}$$

Figure 12

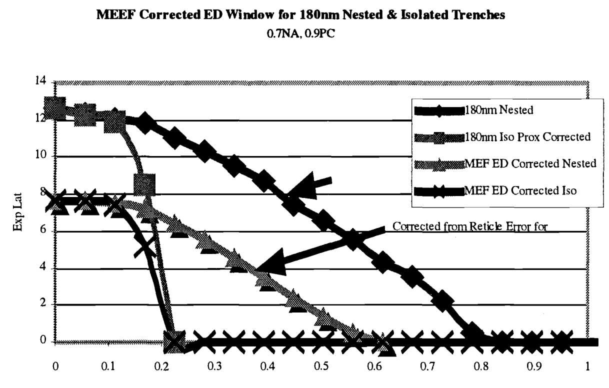


Figure 13

(4.) Conclusion

The authors have discussed recent work to investigate how the choice of illumination conditions can significantly influence MEEF through pitch. Data based on simulation and experiment was collected with high numerical aperature 248nm (KrF) imaging using binary reticles and conventional illumination. We have discussed the MEEF impact on total CD control and the influence on the imaging budget for 0.18μm lithography. Significant enhancements can be realized based on photoresist attributes, as well as choice of illumination, reticle bias/enhancements and numerical aperature. Finally, we have discussed the impact MEEF has on the ED process window and that when taken into consideration a dramatic impact on the process window is realized.

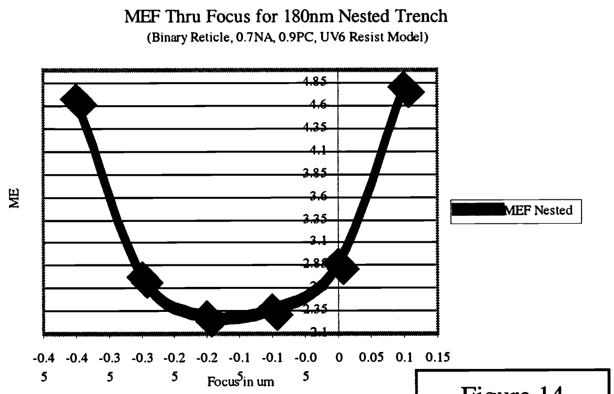


Figure 14

(5.) Acknowledgements

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(6.) References:

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