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Resist parameter sensitivity analysis based on calibrated simulation for understanding resist limitations in next generation lithography

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Abstract

Simulations for predicting resist effects in the sub 50 nm resolution regime are strongly requested today, as well as for improvement of present resolution and CD control. Therefore this letter reports about a simulative resist parameter sensitivity analysis with help of calibrated resist models, based on Sigma-C's SOLID software. Target of the study was to learn about the impact of resist parameters on practical resolution limits and to derive specific process and material change proposals. After resist model calibration for 90 nm design rules, process window, mask error enhancement factor, linearity, line end shortening etc. were investigated. The main influencing resist parameters were determined with two independent methodologies: Single-and multiparameter variation, which showed good agreement. Further, the sensitivity analysis was expanded to feature sizes down to 20 nm halfpitch. To decouple all optical influences from the resist, ideal rectangular aerial images were generated and used for simulation. The simulation reveals that an ArF resist might be capable of 40 nm resolution with sufficient exposure dose latitude, comparable to today's 90 nm design rule. On the other hand even optimized exposure tools can't provide such ideal rectangular aerial images and there is no commercial resist known today that shows a process window at 40 nm resolution today. Therefore, the main key resist parameters, which are responsible for resolution enhancement, were identified out of this simulation study and proposals for improved processes are given.

Keywords: Lithography simulation; Resolution limits; Sensitivity analysis; Calibrated resist models

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1. Introduction

Today's lithography roadmap targets design rules down to 32 nm halfpitch and below. To resolve these small structures there is still no consensus whether 193 nm immersion or EUV lithography will be used. Beside challenges regarding light source, optics, mask, immersion liquid and defectivity it is also still unclear, whether the resist material will be able to meet resolution requirements [1]. The best reported resolution of dense lines/spaces is about 40 nm using EUV or water based 193 nm immersion lithography. In both cases, exposures were carried out under reasonable photospeed conditions below 20 mJ/cm^2 [2]. Additionally, it has to be considered that all experimental work on resist and process screening has to be performed on the few, worldwide available 193i and EUV exposure tools. To effectively plan today's resist experiments, it is recommended to evaluate material effects in the sub 50 nm resolution regime also by simulations. Subsequently, simulated results can be verified using appropriate experiments.

Therefore, this letter reports a simulative resist parameter sensitivity analysis evaluating important lithography effects. Simulations were performed using calibrated models at a feature size of 90 nm. In a second step, the investigations were expanded down to minimal feature sizes of 20 nm with help of idealized rectangular aerial images. For all simulations, Sigma C's SOLID and process window analyzer (PWA) software was used.

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2. Calibration of resist models

Resist model calibration for the two examined commercial ArF resists was carried out partly semi-automized with help of Matlab based scripts. Simulations were done based on full resist models with the "Meta post exposure bake model" in Sigma C's SOLID C software. Basis for calibration were 90 and 70 nm DRAM printing results, regularly processed within the Infineon production site in Dresden, Germany. Silicon wafers with organic BARC and chemically amplified ArF positive resists were processed with an ASML 1100 Scanner at $NA = 0.75$, using annular illumination and half tone phase shift masks. Post exposure bake (PEB) conditions were adjusted as recommended by the resist supplier. Development was carried out with standard TMAH developer. Testpatterns for process window determination (focus exposure matrix, FEM), mask error enhancement factor (MEEF, CD variation with constant pitch), Optical proximity correction (OPC, pitch variation with constant CD) and linearity (CD and pitch variation) were printed. Resist A was exposed with a 90 nm, resist B with a 70 nm design rule. CD data were obtained with help of inline-scanning electron microscopy (SEM), resist profiles were investigated by cross-section SEM.

Calibration procedure was to fit simultaneously FEM, MEEF, OPC and linearity CD data, to obtain one single parameter set that describes all these effects with good accuracy. The error range was not accepted to be larger than 5 nm absolute CD error. Fine tuning of resist profiles was carried out mainly by adjustment of Solid C's delay module parameters.

3. Sensitivity analysis for a 90 nm DRAM layout

Target of our sensitivity analysis was to learn about the impact of each single resist parameter on the production relevant printing behavior. Based on a 90 nm design rule we investigated exposure sensitivity, process window, MEEF, OPC and linearity behavior, beside of line end shortening and iso-focal point. We used a method, known as "one-factor-at-a-time" analysis [3]. In all calculations always only one resist parameter was increased and decreased by typically 20%, while all other parameters were kept constant according to their original resist model settings. Simulations of the examined lithography effect (process windows, MEEF, etc.) were carried out for variations of each of the 24 resist parameters, with the exposure doses adjusted. This resulted in more than 1000 single simulations. The results were generated and compared as follows:

MEEF: Slope of MEEF graph of the original model was set to 1. Changed resist models gave new MEEF values smaller or bigger than 1.

Iso-dense bias: Dose adjustment was carried out on the target CD of 70 nm and pitch of 900 nm (isolated pattern). Slope of the graphs between 250 and 400 nm mask CD was taken as measure for iso-dense biasing.

Non-linearity: The curvature in the minimum point of the obtained typical linearity curves was taken as measure.

Iso-focal point position: Percentage shift of iso-focal point CD in the different models was compared.

Line end shortening (LES): Percentage amount of line end shortening differences were compared.

Process window: Focus exposure matrices were calculated and evaluated with Solid™ and PWA™ software. The percentage changes were compared.

The quantification of resist parameter impact was classified as follows: negligible (less than 2% change of the lithography effect), weak (more than 2%), moderate (more than 5%), and strong impact (more than 20% change). The overall result of the sensitivity analysis is shown in Table 1. In the first row the desired direction of the lithography effect is shown. The first column contains all resist parameters, which show an effect larger than 2% (out of 24 examined parameters).

For improvement of the lithography properties, shown in the columns, the key parameters can be adjusted in the following way:

Table 1
Result of 90 nm DRAM layout resist parameter sensitivity analysis

⇊ or ⇈ Strong impact (>20% change) ↓ or ↑ Medium impact (>5% change) (↓) or (↑)Weak impact (>2% change)	Low MEEF	Low iso/dense bias	Low non linearity	Iso-focal point at large CD	Small LES	Process window: large focus latitude	Process window: large EDL	Low dose-to-size
Acid diff length	⇊	⇊	⇊	↓	↓	(↓)	↓	↑
Dill b	(↑)	(↑)	(↑)		(↓)			↓
Dill c								⇈
k_1 (deprotection)	(↓)	(↓)	↓		(↓)			↑
k_2	↓		(↓)					
k_4 (neutralization)								⇈
Quencher amount		(↓)	↓					⇊
Quencher diff length								
Development N	↑	↑	↑	↑	(↑)	(↑)	(↑)	↓
Development $R_{\min}$	↑	(↓)	(↓)	(↓)	(↓)	(↓)	(↓)	(↑)
refractive index n	↑	⇈	↑	(↑)		(↑)	↑	⇊
Resist thickness					(↓)			↓
BARC thickness	(↓)		(↓)					(↑)

Litho effect is improved if resist parameter is increased (Arrows up) or decreased (Arrows down), respectively.