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Creating new multistep etch and deposition processes with recycled etch data using SandBox Studio AI™

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ABSTRACT

Identification of optimal recipes for multi-step and cyclic etch processes where the outcome of each step depends on the progression of the previous steps is a major challenge. Selecting the order and duration of each step is typically performed by a tedious trial and error process where the number of experimental trials scales exponentially with process complexity. Here we present a simulation-based methodology that significantly accelerates the process. We use limited experimental data taken at various process conditions, which may include pressure, gas type, gas flow rate, power, bias, and time to calibrate a step-aware reduced-order physics-based etch and deposition model. This model is used to generate predictions with steps permuted in any desired order and duration. The calibrated model predicts ordering, timing, and possible cycling of each step to achieve desired etch targets. The methodology is demonstrated on a multilayer stack with three possible steps, including etch and deposition. It is shown that the total number of experiments required for the proposed methodology is significantly less than that required by standard methods like full-factorial design of experiment. We also demonstrate how the etch data and the resulting calibrated model can be used to determine the optimal etch recipe for different aperture and/or mask geometries without having to perform further experiments.

Keywords: Etch, etch recipe creation, multi-step etch, deposition, experimental design, modeling

1. INTRODUCTION

EUV photomasks achieve smaller node features by using multiple alternating layers of Mo and Si to reflect light. Etch processes of the multilayer introduce defects such as bowing, absorber overhang, and surface roughness [1,2]. These defects diminish reflectance of the substrate, increase susceptibility to breakage and particle debris, and diminish wafer printability. Determining the process recipe required to eliminate defects is difficult due to the complex multistep processes used with the outcome of each step depending on the outcomes of the previous steps.

Most challenging is the determination of the order, timing, and cycling of each processing step [3,4]. Currently, this is largely done by time-consuming and expensive trial and error experiments. However, significantly improved design of experiment is possible by combining physics-based models of each process with experimental data for model calibration. The resulting deterministic model can be used to efficiently search over the parameter space to identify the optimal etch conditions, including ordering, timing, and cycling of the various processing steps to achieve the desired critical dimensions.

Here we present an automated, efficient, and accurate methodology to identify an optimal etch recipe for a multilayer EUV photomask. The process engineer only provides the experimental data and the model build, calibration, and subsequent optimization of the process is done automatically. We apply SandBox Studio™ AI to synthetic experiments to demonstrate the effectiveness of the method at identifying an optimum process window for an etch recipe that achieves the target critical dimensions. Most importantly, we demonstrate how etch data and the resulting calibrated model can be used to determine an optimal etch recipe for different aperture and/or mask geometries *without* having to perform further experiments. This greatly improves the value of the original experimental data through a modeling framework.

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2. METHODOLOGY AND MODEL CALIBRATION

The first aim is to predict an optimized process recipe of a three-step process for etching a MoSi multilayer with a 200 nm opening for maximized vertical etching and minimized surface roughness. The process flow is illustrated in Figure 1. It consists of three steps of etch, deposition and clean. The second aim is to take the results of this optimization using the calibrated model for the 200 nm opening to determine the optimal recipe for a 50 nm opening.

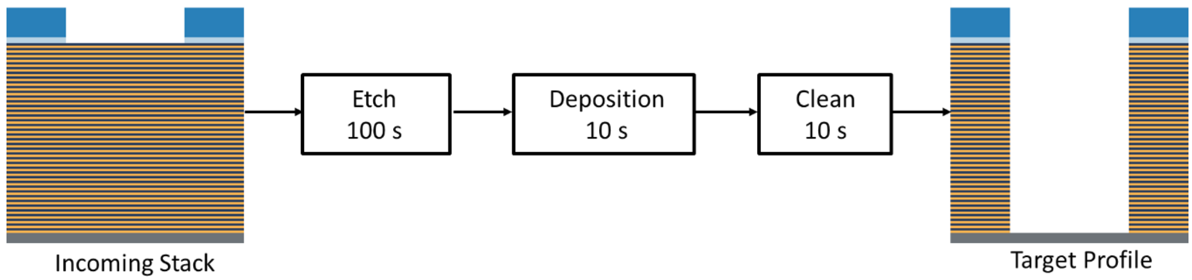


Figure 1. A three-step process is modeled. The objective is to achieve a vertical etch with a width uniformity of +/- 10 nm.

For the first aim, the incoming stack is illustrated in Figure 2. It consists of a 50 nm thick chromium mask with a 200 nm opening and 10 nm of ruthenium under the chromium. The stack consists of 40 alternating layers of molybdenum (3 nm thick) and silicon (4 nm thick) with a 20 nm thick stop layer at the bottom.

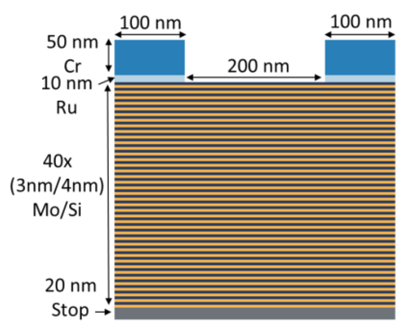
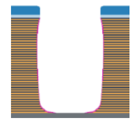
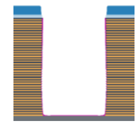
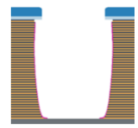
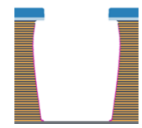
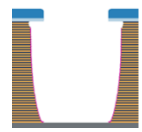
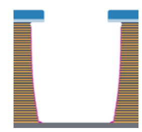
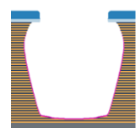
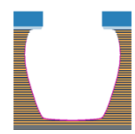
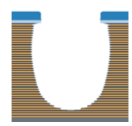
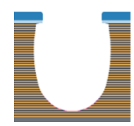
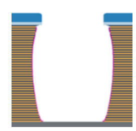
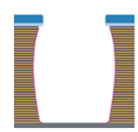
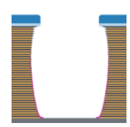
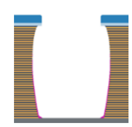
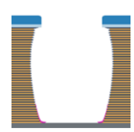
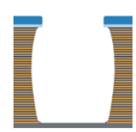


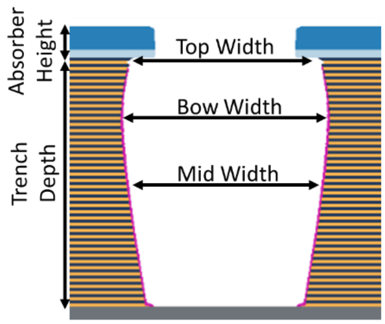
Figure 2. The materials and dimensions of the 400 nm wide x 164 nm tall EUV photomask.

We calibrate a physics-based model described elsewhere [5, 6] using eight synthetic experiments with varying process parameters. The normalized values for the process parameters, the synthetic experimental profiles and the predicted profiles from the calibrated model are shown in Table 1. The comparison between the experimental and predicted profiles is very good, indicating the model has successfully selected the key governing mechanisms of the etch and deposition behavior.

Table 1. Process parameter trends and experimental vs predicted profile comparisons.

Exp	Etch				Depo		Clean		Experimental Profile	Predicted Profile
	P1	P2	P3	P4	P5	P6	P7	P8		
1	1.0	0.0	0.0	0.0	1.0	0.8	0.0	0.0		
2	1.0	0.0	0.5	0.5	1.0	0.8	0.5	0.5		
3	1.0	0.0	1.0	1.0	1.0	0.8	1.0	1.0		
4	1.0	1.0	0.5	0.5	1.0	0.8	0.5	0.5		
5	0.0	0.0	0.0	1.0	0.0	0.8	0.0	1.0		
6	1.0	0.0	0.0	1.0	1.0	1.0	0.0	1.0		
7	1.0	0.0	0.0	1.0	1.0	0.4	0.0	1.0		
8	1.0	0.0	0.0	1.0	1.0	0.0	0.0	1.0		

A summary of the model calibration statistics is listed in Figure 3. The model was calibrated with five critical dimensions: absorber height, trench depth, top width, bow width and mid width as marked in the schematic within Figure 3. Mean prediction errors for these five CDs range from 1.3 to 7.6 nm.

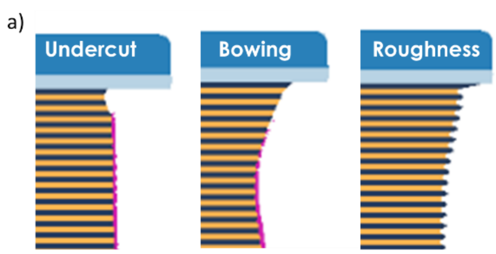


Critical Dimension	Mean Prediction Error (nm)
Absorber Height	7.6
Trench Depth	7.0
Top Width	5.5
Bow Width	6.9
Mid Width	1.3

Figure 3. Mean prediction error of the calibrated model for the five key critical dimensions.

3. MODEL PREDICTIONS AND PROCESS OPTIMIZATION

The calibrated model captures key defects that can occur in EUV masks, namely undercuts, bowing, and surface roughness as illustrated in Figure 4. These features arise from insufficient surface passivation during the deposition step. We can now use the calibrated model to identify the optimal process recipe (OPR). To do so we select the target criteria for the five CDs listed in Figure 4b.

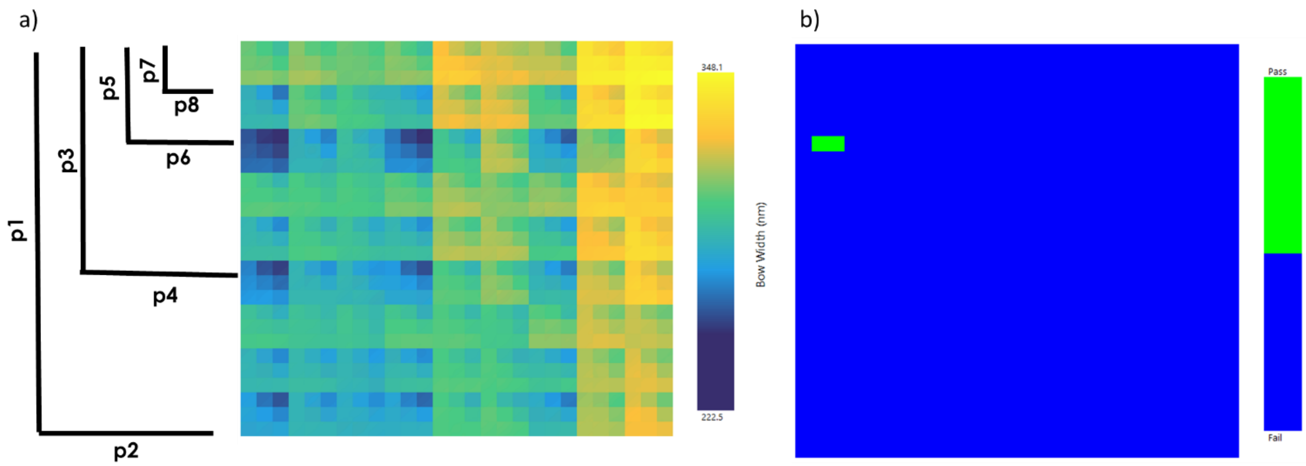


b)

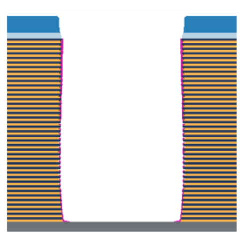
Critical Dimension	Target Criteria (nm)
Absorber Height	30 +/- 10
Trench Depth	320 +/- 10
Top Width	210 +/- 10
Bow Width	210 +/- 10
Mid Width	210 +/- 10

Figure 4. a) Undercut, bowing, and roughness are defects observed in the experimental data set used in model calibration. b) Target critical dimensions used to achieve a desirable defect free, vertical etch.

The next step is to search through the parameter space using a version of the calibrated model that can be evaluated rapidly (see Refs. [5,6] for details). Because there are eight parameters (P1 through P8) we present the results in terms of a flattening of the eight-dimensional space as a Quilt®. An example of the results is illustrated in Figure 5a for the bow width. In Figure 5a, blue corresponds to low widths and yellow to high (undesirable) bow widths. For example, the Quilt® displays that large values of P2 lead to large undesirable bow widths. The Quilt® in Figure 5a can be created for the other four CDs. One can then combine them computationally to look for the largest window in terms of the eight-dimensional parameter space that achieves the target CDs. This is shown in the pass/fail Quilt® shown in Figure 5b. The region of the process space where target criteria are not met is shown in blue and the region where they are all met is shown in green. As seen in Figure 5, a defect-free multilayer etch requires high values of P1, P5 and P6 and low values of P2, P3 and P4. The target criteria depend negligibly on P7 and P8. The process window for the OPR is shown in Figure 5c along with specific values of the optimized CDs. All CDs are within the tolerances listed in Figure 5b. Although the target CDs were achieved, surface roughness was observed for the OPR. Therefore, to investigate other options to further reduce this defect, different step times and cycles were simulated. Surface roughness was minimized by optimizing etch and deposition times and increasing the number of cycles from one to four (1x, 2x, and 4x).



	P1	P2	P3	P4	P5	P6	P7	P8
Min	0.96	0.00	0.00	0.00	0.96	0.50	0.00	0.00
Max	1.00	0.04	0.04	0.04	1.00	1.00	1.00	1.00



CD	Target Criteria (nm)
Absorber Height	30
Trench Depth	320
Top Width	203
Bow Width	217
Mid Width	212

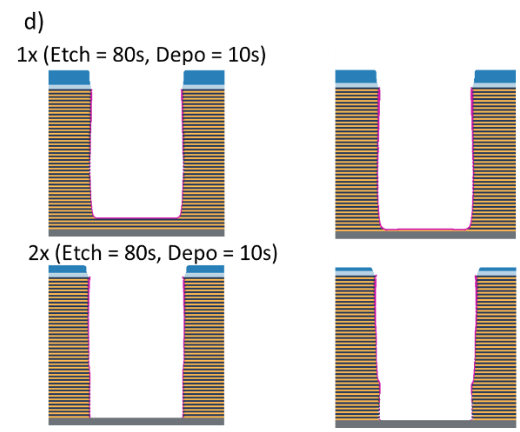
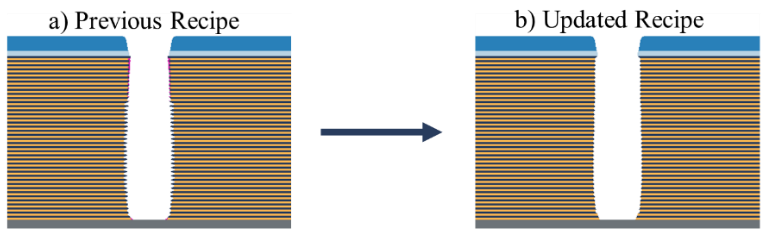


Figure 5. Simulation results obtained using Sandbox Studio™ AI simulations. (a) axis labels and sample quilt plot for bow width, (b) pass/fail plot to satisfy all etch criteria, (c) optimal process recipe (OPR), and (d) OPR modified with different etch and deposition times. The number of cycles (1x, 2x, or 4x) was adjusted to meet the target criteria and etch to the stop layer.

4. RECYCLING DATA FOR NEW NODES

The optimal recipe was computed using data from a 200 nm node. When the recipe is run on a 50 nm aperture, four times smaller than the original experiments, a severe amount of surface roughness is observed. However, the calibrated model in Sandbox Studio™ AI can be used to recompute an OPR for the new, narrower aperture without any additional experimental data. A new recipe was optimized, and surface roughness was mitigated, as shown in Figure 6.



c) Updated Optimal Process Recipe

	P1	P2	P3	P4	P5	P6	P7	P8
Min	0.98	0.00	0.00	0.00	0.00	0.00	0.00	0.98
Max	1.00	0.02	0.02	0.02	1.00	1.00	0.02	1.00

Figure 6. a) Forward simulation of the OPR computed for the 200 nm aperture on a 4x reduced node, b) the 200 nm model was recycled and used to compute an updated OPR for the reduced node, and c) forward simulation of the updated OPR.

5. CONCLUDING REMARKS

Sandbox Studio™ AI was used to build a hybrid physics and machine learning-based computational representation of a multilayer EUV photomask etch using synthetic experimental data from a 200 nm node. An optimal process window was determined which minimized undercut, bowing, and surface roughness. The model was used to experiment with different recipe times and number of processing cycles. Surface roughness was suppressed further by lowering etch times and increasing the number of cycles. The model was used to compute a new optimal process window for a stack with a 4-fold smaller aperture width without any additional experimental data.

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REFERENCES

[1] Christina T., Ravi B., Emily G., Jonathan G., Masayuki K., Louis K., Eisuke N., Steven N., Yoshifumi S., "EUV mask black border evolution," Proc. SPIE 9235, Photomask Technology, 2014, 923513.

[2] Lin, C., Chen. C., Lee, H., Chen, C., Hsu, P., Su, Y,. Lee, G., Shen, T. “Lithography Mask With a Black Border Region and Method of Fabricating the Same”. United State Patent, 2020, US 10,866,504 B2.

[3] Letzkus, F., Butschke, J., Irmscher, M., Kamm, F., Koepernik, C., Mathuni, J., Rau, J., Ruhl, G. “Dry Etch Processes for the Fabrication of EUV Masks”. Microelectronic Engineering, 2004.

[4] Abe, T., Sasaki, S., Mohri, H., Hayashi, N., Shoki, T., Yamada, T., Nozawa, O., Ohkubo, R., Ushida, M. “Process Development for EUV mask Production”. Photomask Technology, 2006, 63493G.

[5] Ban, Y., Kearney, K., Sundahl, B., Leandro, M., Bonnecaze, R., Chopra, M. “Fast Etch Recipe Creation with Automated Model-Based Process Optimization”. Advanced Etch Technology and Process Integration for Nanopatterning, 2021, 116150L.

[6] Kearney, K., Chopra, S., Zhu, X., Ban, Y., Bonnecaze, R., Chopra, M. “Accelerated Optimization of Multilayer Trench Etches Using Model-Based Experimental Design”. Advanced Etch Technology for Nanopatterning IX, 2020, 11329OZ.