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NXE:3400 OPC Process Monitoring: Model Validity vs. Process Variability

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ABSTRACT

As technology nodes shrink, OPC model accuracy needs to the fulfill tighter requirements. Those requirements can be met only under good process control. However, OPC model accuracy relies on the specific context. Ignoring the impact of process variation on OPC accuracy could lead to break edge placement error (EPE) budget. The OPC process monitoring project at imec is conducted on imec logic N7 M2 design at pitch 32nm use case and aims at quantifying long-term validity of the OPC model in the face of NXE:3400 scanner and process variations. To account and compensate for scanner and process variations impact, the ability of restoring OPC validity by OPC model dose tuning is tested.

Keywords: EUV Lithography, OPC Model, Edge Placement Error

1. INTRODUCTION

Edge placement error (EPE) has been known as a key driver of semiconductor technology node scaling.[1–4] The challenges are escalating and piling up at each node, the tighter requirements of EPE at advanced node can only be achieved by the stability of the scanner and process, together with accurate metrology and mask optimization (OPC, Optical Proximity Correction). However, model-based OPC accuracy fully relies on the validity and accuracy of the OPC model. The typical approach for calibrating an OPC model involves freezing the process and anchor wafers at "Best" Dose and "Best"Focus (BDBF), then collecting wafer CD data across the defined FEM (Focus Exposure Matrix) condition on a selected feature set representing a full range of the design rule and process proximity environments.[5] However, there is no real frozen process in the real production environment. All the processes can have slight variations through time. Therefore, the validity and accuracy of the calibrated OPC model relies on the specific context (measured dies, CD uniformity, wafer, lot, exposure tool and so on). Ignoring the impact of scanner and process variations on OPC accuracy could lead to break EPE budget. To quantify long-term validity of the OPC model in the face of those variations, the NXE:3400 scanner and process variations are monitored together with wafer CD variations. The impact of scanner and process variations on the model validity is quantified based on the calibrated baseline OPC model. At last, the baseline OPC model tuning based on multiple features is proposed to account and compensate for the impact of scanner and process variations.

The paper is organized as follows: Section 2 introduces OPC monitoring strategy. Section 3 shows the monitored scanner and process variations, and the impact of those variations on the model CDs and wafer CDs of monitored features through time. Section 4 analyzes the impact of scanner and process variations on the baseline OPC model error range. Section 5 proposes baseline model fine tuning based on all the monitored features to account and compensate for scanner and process variations. The last section will provide the summary.

2. OPC MONITORING STRATEGY

OPC process monitoring is conducted on imec N7 M2 design (foundry N5 equivalent)and process,[6,7] and was performed at imec from July 2019 to February 2020. Figure 1 shows an imec N7 design clip and the used pupil. The minimum metal pitch and trench CD on the design are 32nm and 17nm, respectively. The minimum Tip-to-Tip (T2T) is 25nm. A positive tone chemically amplified resist is used for the patterning. To quantify the

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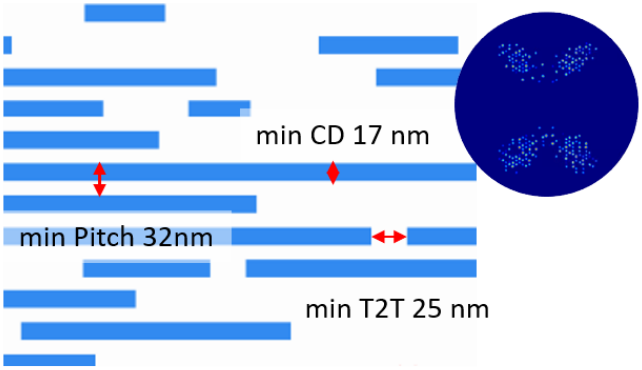

Figure 1: imec N7 M2 design and used pupil

impact of process and scanner variations on OPC EPE budget, the baseline OPC model was calibrated based on July 2019 wafer data.

Figure 2 shows the OPC process monitoring flow, which was performed on a monthly basis random FEM wafer exposed by NXE:3400 scanner. The random FEM wafer has 71 dies with three dose and seven focus steps variations (35 dies at the BDBF condition). As shown in the flow, HitaChi CD-SEM is used for image acquisition and ASML MXP tool is used for SEM contours and CD gauges extraction.[8, 9] The track variability is monitored by ASML YieldStar.[10]

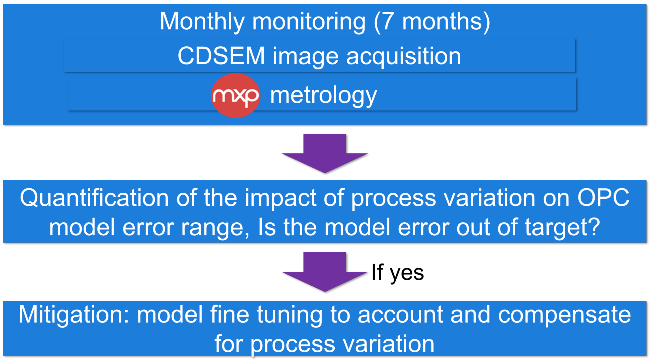

Figure 2: OPC monitoring flow

Figure 3 shows average SEM images of selected OPC-relevant features, which includes generic features (Line/Space without SRAF (sub-resolution assist feature), Line/Space with SRAF, Two-Bar with SRAF, Multiple-Bar without SRAF, 2D Multiple-T2T and elongated contact holes with OPC) and four design clips. The details of generic features are shown in Table 1. All the features are in the horizontal orientation and have very good printability, which are selected from the calibration set used for baseline OPC model calibration; the design clips are not included in the baseline model calibration set.

On the monthly exposed random FEM wafer, the measurements are performed die-to-die, wafer-to-wafer at center slit. To monitor aberrations variations, a few Line/Space and Two-Bar features are also measured through slit. The scanner log files (pupil, aberration, msd. etc) and resist thickness are collected and analyzed, the impact of these variations on the wafer CDs are investigated by the baseline OPC model. Therefore, the measured wafer data is compared to scanner and track variability to identify the root cause of those variations. It is also compared to the baseline OPC model prediction, to quantify the impact of scanner and process variability on OPC model accuracy. If the baseline model check error range is out of given target, model fine tuning will be

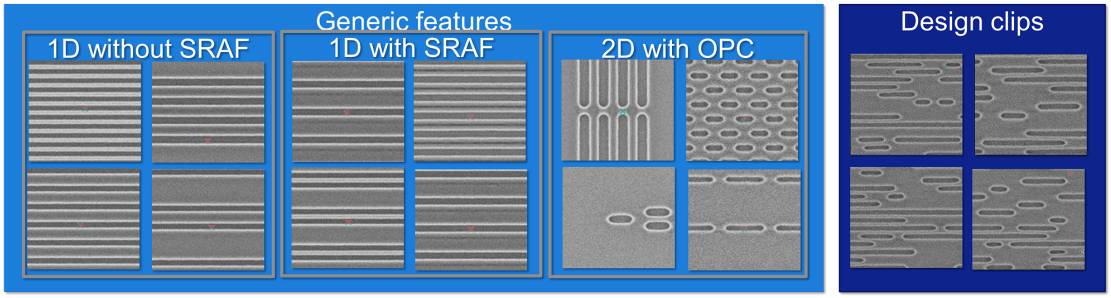

Figure 3: Average SEM images of the selected features relevant for imec N7 M2 design (foundry N5 equivalent) for OPC process monitoring

Table 1: Details of selected generic features relevant features for OPC process monitoring

Feature type	Module	Pitch(nm)	CD(nm)	SRAF distance to main(nm)
1D	Line/Space	32	15	na
		64	20	na
	Line/Space+SRAF	64	21	19
		96	21	47
		96	21	43
	Two-Bar+SRAF	32	17	25
		64	20	39
	Multiple-Bar	68	23	na
2D	Contact Hole Stag	100	24	na
	Contact Hole Regular	170	20	na
	Contact Hole Clust	600	24	na
	Multiple-T2T	64	22.5	na

carried out to test the ability of accounting and compensating for the scanner and process variations, to restore OPC validity.

3. SCANNER AND PROCESS VARIATIONS

OPC process monitoring is running monthly during a stable scanner period, which means that there has been no major update or maintenance during monitoring period. To identify the impact of scanner and track variability on the wafer CDs, scanner log files and resist thickness are collected and analyzed monthly, and compared to the measured wafer CDs. A new OPC model is generated from the baseline model by loading each variation (measured pupil, aberration), to identify the variation impact on the model prediction and assess OPC validity.

3.1 Scanner Variation

A) Pupil Variation

The pupil measured in July is used as the reference, Fig. 4 shows the measured pupil difference with respect to the reference through time. As shown in the figure, the measured pupils have slightly drifted through time, some pupil field facet mirrors are contaminated that lead to slightly affect the pupil shape. To quantify the pupil drift impact on the wafer CDs, the monthly measured pupil is loaded into the baseline OPC model, to generate a new OPC model that contains the pupil variation (monthly OPC model with updated pupil). Figure 5 shows the impact of the pupil drift on the model CDs of generic features for the BDBF through time at center slit, the model CD in July is used as the reference. The model CDs of generic features 1D have maximum variation of 0.2nm , while maximum 0.1nm variation observed for 2D features. Pupil drift has a minor contribution to the final wafer CDs.

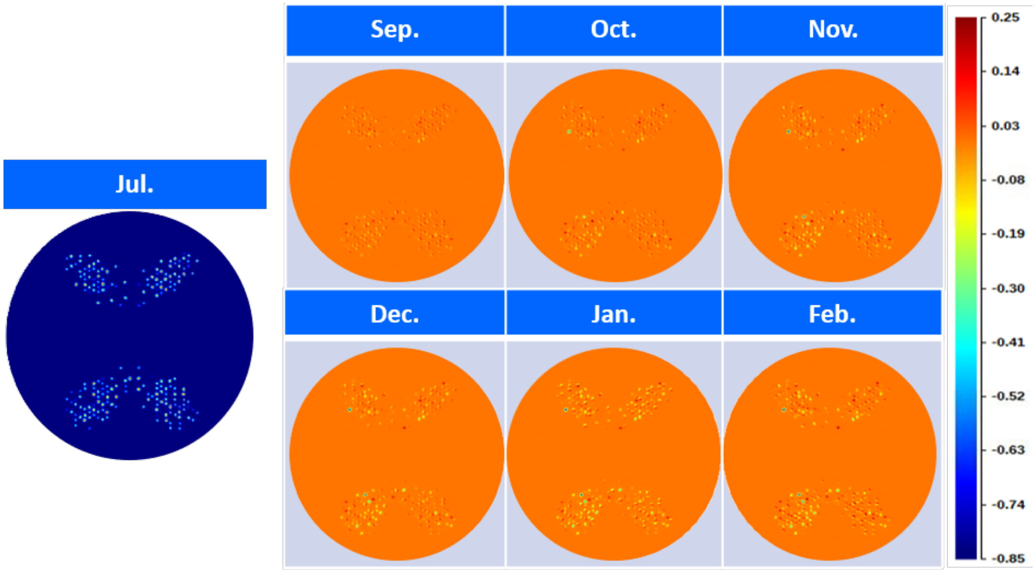

Figure 4: Scanner pupil variations through time (measured pupil difference with respect to July pupil)

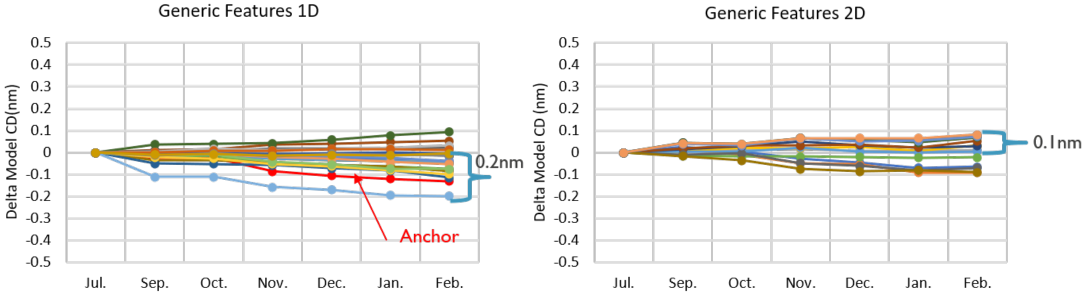

Figure 5: Pupil drift impact on the model CDs of generic features through time (Model CD in July is used as the reference; maximum 0.2nm variation on 1D features, and 0.1nm variation on 2D features)

B) Aberration Variation

Figure 6 shows through slit coma aberration variations (Zernike Z7, Z8, Z14, Z15) during the monitoring period. As shown in the figure, the aberration through slit signature is stable through time. To quantify the aberration impact on the wafer CD through slit, Two-Bar features are measured through slit. Figure 7 demonstrates that the wafer CD difference between top (left) bar and bottom (right) bar through slit is stable through time. A maximum delta of 0.43nm is observed for horizontal Two-Bar, which might be due to the coma aberration Z15 impact (as shown in the Fig. 6).

C) Best Dose Stability

The best dose stability is monitored by the process dose anchor feature, which is Line/Space pitch 32nm with mask CD 15nm (LS-P32CD15). To calculate the best dose, the linear interpolation between exposure dose and wafer CD is applied to get the wafer CD targeting 17nm (baseline OPC model wafer process anchor). Figure 8 shows the best dose stability with respect to the average resist thickness variation through time. The average resist thickness variation is measured after resist development by ASML YieldStar. The errorbar in the figure of resist thickness is resist thickness standard deviation across 71 dies on the wafer. As shown in the figure, the process best dose variation through time has a good correlation (coefficient is 0.8) with the average resist thickness, which means one of the key contributors to the wafer CD variations is the track stability. imec track has a good stability over the monitoring period except for the September wafer.

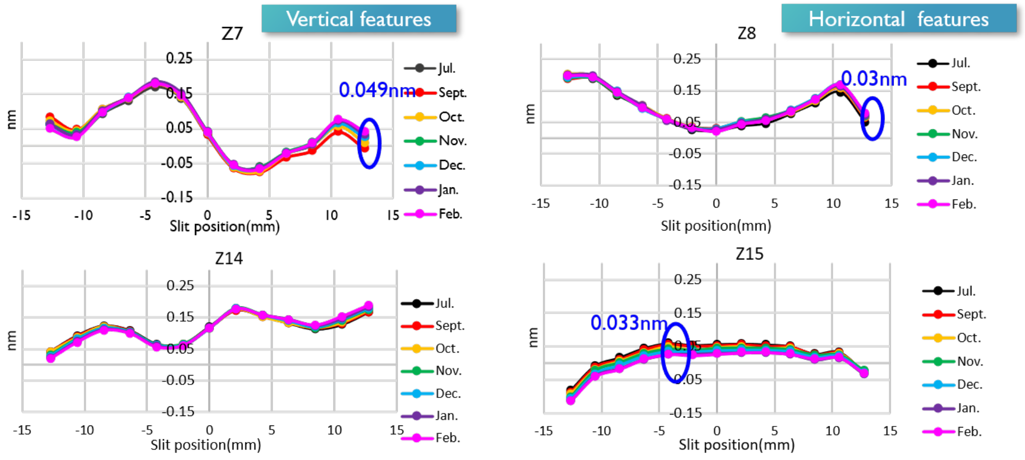

Figure 6: Through slit aberration variations during monitoring period (Z7 and Z8 impact on vertical features; Z8 and Z15 impact on horizontal features)

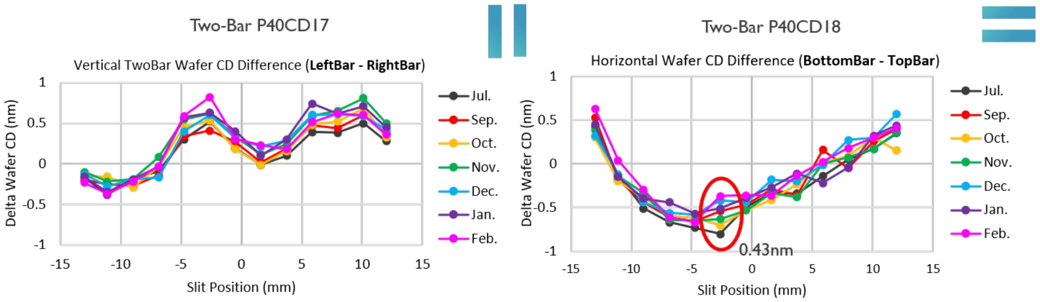

Figure 7: Through slit wafer CD difference of Two-Bar separation variations during monitoring period (maximum 0.43nm difference for horizontal Two-Bar)

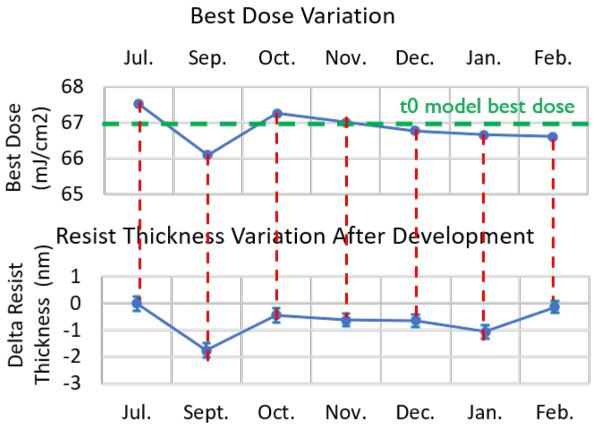

Figure 8: Best dose stability with respect to average resist thickness variation through time

D) Best Focus Stability

The best focus at center slit is monitored by three generic features that have good printability at best dose through focus, which includes Two-Bar with SRAF, Contact Hole and Multiple-T2T. The details of the features are shown in Table 1. Two gauges are measured for each feature. For each measured gauge, the wafer CD through focus is fitted by a parabola function, and the best focus is extracted from the fitted function. Figure 9 shows the best focus stability at center slit through time. The best focus variation of the monitored features is within the scanner focus specification (+/-6nm at center slit) during the monitoring period.

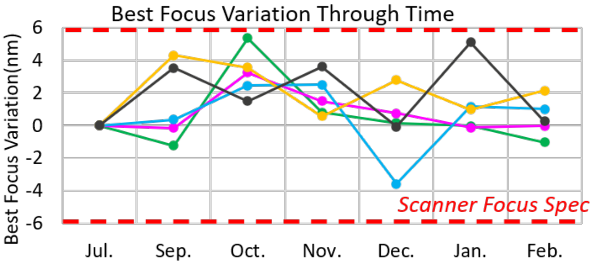

Figure 9: Best focus stability through time

3.2 Wafer CD Variation

Figure 10 shows the average wafer CDs variation of generic features at the BDBF condition through time. The CD measurement from the wafer exposed in July is used as a reference, an each colored line represents one wafer CD by averaging 35 dies measurement (at the BDBF condition). The shaded region of the line is the average standard deviation of the MXP CD measurement; Some of the 2D features have no measurement repetitions in the FoV (Field of View), this appears without shaded region in the plot. The errorbar is the wafer CD measurement standard deviation across all the 35 dies. As shown in the figure, the wafer CDs variation of generic features at center slit are stable through time. For 1D generic features, the delta wafer CDs increase in September is mainly attributed to track instability, which has a good correlation with resist thickness variation as shown in Fig. 8; For 2D generic features, the delta wafer CDs of some gauges that have no measurement repetitions in the FoV have a large deviation with respect to the reference point, which might be due to metrology error and process variations impact.

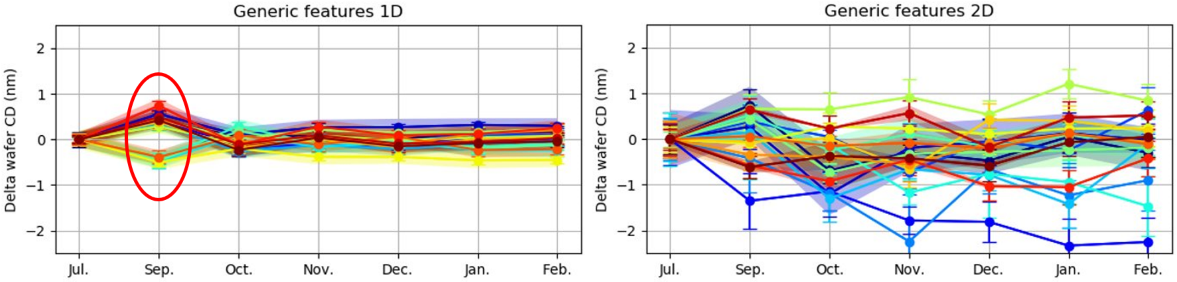

Figure 10: Generic features wafer CDs variation at center slit for BDBF through time

4. IMPACT OF PROCESS VARIATION ON OPC MODEL ERROR RANGE

To quantify the impact of process and scanner variations on OPC model accuracy, all the monitored wafer CDs of generic features are loaded in the baseline model. Since the monitored generic features are a down-sampling of the calibration set, the model error range must be within the target after running the baseline model check.

A) Generic features

Figure 11 shows the baseline model check result of monitored generic features at center slit for the BDBF condition during the monitoring period. As shown in the figure, the model error range of generic features is stable through time. For 1D generic features, the model error range is mainly within the target +/-0.75nm. The model error on September wafer is slightly out of target and on October wafer has a positive offset from zero; for 2D generic features, the model error is mainly within the target +/-1.5nm, however, the model errors of some gauges are slightly out of the given target.

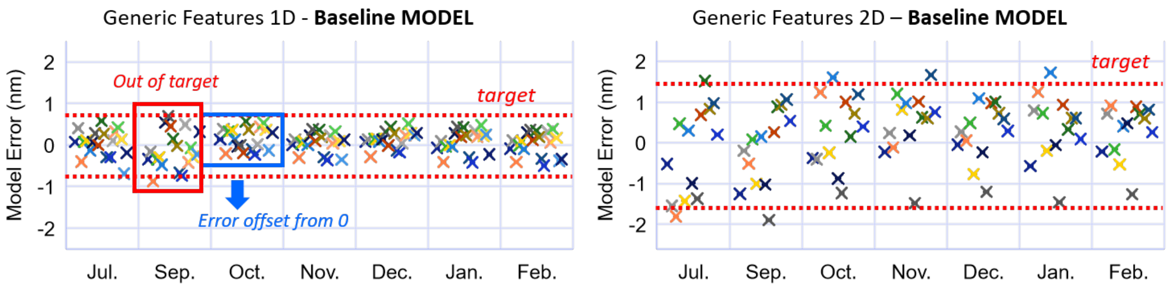

Figure 11: Baseline model check result of the monitored generic features at center slit for BDBF during the monitoring period (1D feature target+/-0.75nm, 2D feature target +/-1.5nm)

B) Two-Bar Through Slit

Figure 12 shows the baseline model check result of the monitored Two-Bar at BDBF through slit. For the vertical Two-Bar, the model errors have 0.75nm positive offset, and are varying between 0nm and 1.5nm; for the horizontal Two-Bar, the model errors of the Top-Bar and Bottom-Bar are slightly separated into two groups, and mainly varying between -0.5nm and 1nm. Compared to the coma aberration variations shown in Fig. 6, the Two-Bar model error separation might be due to coma aberration impact.

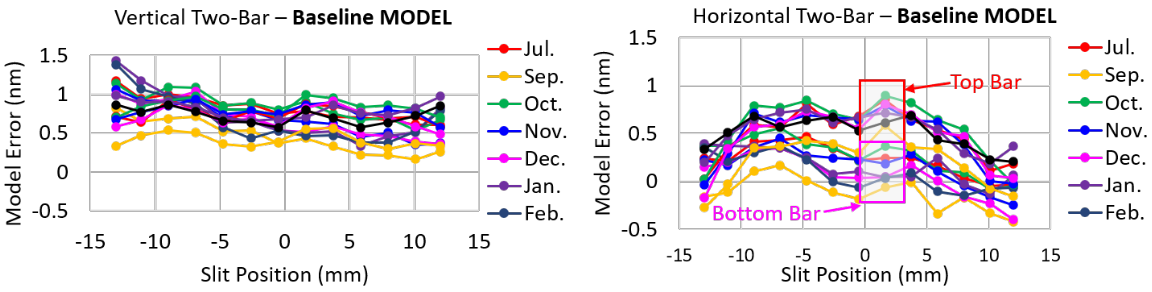

Figure 12: Baseline model check result of the monitored Two-Bar through slit at BDBF during the monitoring period

To identify the impact of aberrations on the Two-Bar through slit model error, new OPC models are generated by loading monthly new aberrations to baseline model, the models are not re-fitted. Table 2 shows the results of baseline model with monthly new aberrations. Compared to the baseline model, loading monthly aberrations into the baseline model does not help to reduce through slit model error. However,this eliminated the model error offset observed on the horizontal Two-Bar shown in Fig. 12.

C) Design Clips

The impact of scanner and process variations was also monitored on design clips. The cutlines considered are shown in Figure 13. The cutlines are placed across the whole design clip, to measure the CD of resist lines and

Table 2: Loading measured aberrations per month* at BDBF through slit

Orientation	Gauge	Average model error range Jul.-Feb. (nm)	
		Baseline model	Loading monthly aberrations
Vertical	left	0.70	0.70
	right	0.72	0.72
Horizontal	bottom	0.12	0.2
	top	0.46	0.37

***Note:** only update aberrations in the baseline model, NOT tuning.

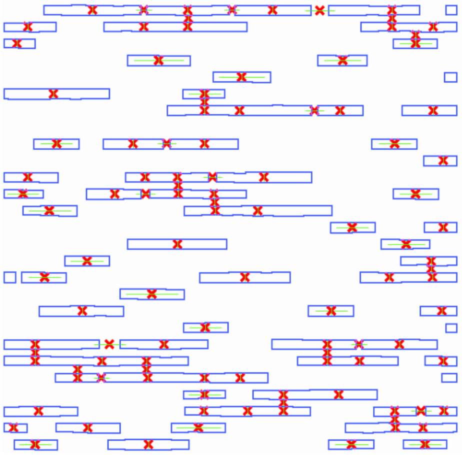

Figure 13: Cutlines considered in the design clips

trenches, T2Ts and Contact Holes. Figure 14 shows the baseline model check results at BDBF for center slit. As shown in the figure, design clips model check results in a larger model error range with respect to the generic features but stable through time. There are mainly three reasons: first, design clips are not included in the baseline model calibration, the larger model error might be due to model pattern coverage limitation; second, compared to generic features, design clips have slightly worse printability and more sensitive to the scanner and process variations; third, design clips CD gauges only have one repetition in the FoV, the metrology noise is higher with respect to generic features.

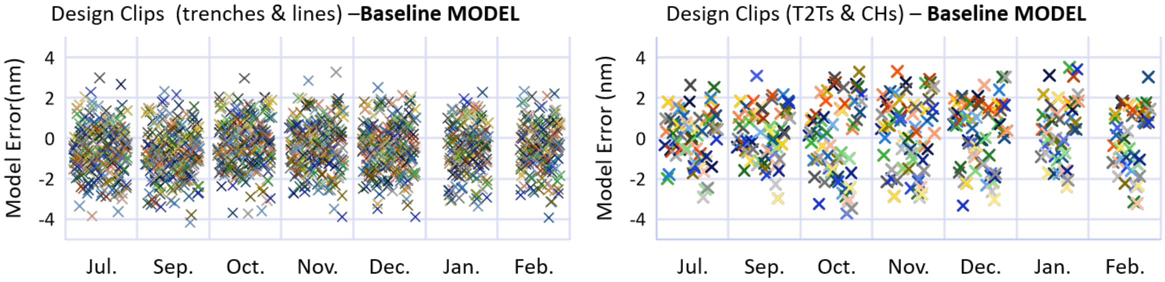

Figure 14: Baseline model check result of monitored design clips at center slit for BDBF during the monitoring period

5. MODEL FINE TUNING TO ACCOUNT AND COMPENSATE FOR SCANNER AND PROCESS VARIATIONS

As shown and discussed in Section 3, scanner variations from the source and aberrations slightly impacts the wafer CDs at center slit. The main contributor to the wafer CD variations is the track variability. To account and compensate for scanner and process variations, OPC model delta dose can be retuned. Typically, OPC model delta dose is tuned based on one feature, and the process dose anchor feature is often used to calculate the delta dose.

To come up with a good methodology, the OPC baseline model tuning based on all the monitored generic features is proposed in the paper. Figure 15 shows the baseline OPC model fine tuning flow. Firstly, all the monitored wafer CDs of generic features are loaded into the final calibration job for baseline model; secondly, freezing all the calibration variables in the job except for dose fine tuning. The re-anchoring is performed based on all the monitored generic features instead of one feature. The last step is a model check based on the baseline model with fitted delta dose. The model delta dose could also be dialed in the scanner to restore the OPC validity.

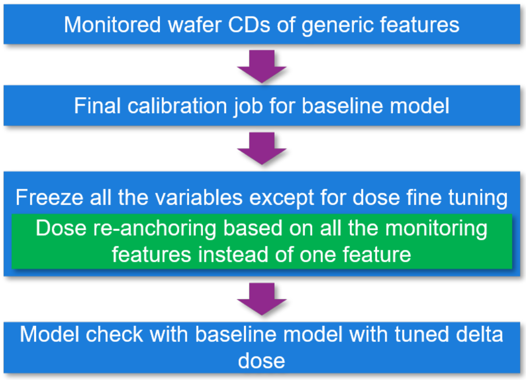

Figure 15: Model dose tuning flow

Figure 16 shows the tuned model error of generic features at center slit for the BDBF through time. Compared to the baseline model error shown in Fig. 11, for 1D generic features, the model error on September wafer can be pushed back into the target, and the model error on October wafer can be re-centered to zero after model dose fine tuning; for 2D generic features, all the model errors are within the target. Table 3 shows the model error range comparison between baseline and dose tuned OPC model. For 1D generic features, tuned OPC model can improve for the month with the worst model error range from 1.56nm to 1.28nm, while keep the similar average model error range; for generic features 2D, tuned OPC model can improve for the month with the worst model error range from 3.32nm to 2.47nm, and the average model error range can be reduced from 2.77nm to 2.23nm. Baseline model dose tuning based on multiple features can successfully reduce the scanner and process variations impact and restore OPC validity.

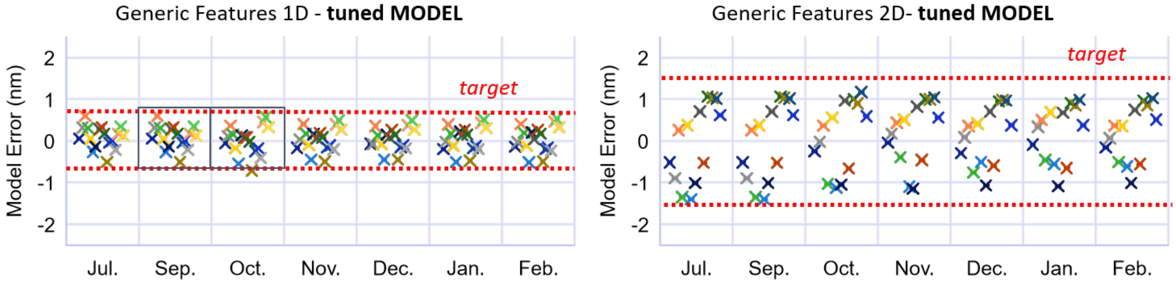

Figure 16: Tuned model error for center slit data at BDBF for generic features through time

Table 3: Model error comparison between baseline and tuned OPC model[a]

Features	Target (nm)	Case	Model error range Jul.- Feb.(nm)	
			Baseline model	Monthly tuned model
1D	1.5	Worst[b]	1.56	1.28
		Average[c]	0.99	1.07
2D	3	Worst	3.32	2.47
		Average	2.77	2.23

[a] **Note:** Dose tuning considers all monitored generic features gauges
[b] **Note:** Worst model error range among the monitored months
[c] **Note:** Average model error range among the monitored months

6. SUMMARY

EUV lithography is being introduced for manufacturing 7nm technology node and beyond. The stability of the scanner and process is a fundamental requirement to control EPE at advanced node. In this paper, imec N7 M2 process has been monitored with multiple features, and good scanner and process stability was observed during the monitoring period. To identify the scanner and process variations impact on the OPC validity, the baseline OPC model was calibrated at the beginning of the monitoring period. The validity of the model was evaluated on the new data acquired through the monitoring period. The model check results show that the monitored features model error mainly remained within the target during the monitoring period. The main contributor to the wafer CDs variations is the track variability. To account and compensate for the observed scanner and process variations impact, the model dose fine tuning based on all the monitored generic features was proposed. The tuned OPC model has the ability to restore the OPC model validity. The fitted delta dose can be fed to the scanner to improve the OPC validity.

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