Application of a wafer development process to mask making

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ABSTRACT

Recently, the design of integrated circuits has become more and more complicated due to higher circuit densities. In particular for logic applications, the design is no longer uniform but combines different kinds of circuits into one circuit resulting in stringent criteria for both wafer and photomask manufacturing. Photomask CD uniformity control and defectivity are two key criteria in manufacturing today's high-end reticles, and they are both strongly impacted by the mask developing process.

A new photomask develop tool (ACT-M) designed by Tokyo Electron Limited (TEL) has been installed at the Advanced Mask Technology Center (AMTC) in Dresden, Germany. This ACT-M develop tool is equipped with a standard NLD nozzle as well as an SH nozzle which are both widely used in wafer developing applications. The AMTC and TEL used the ACT-M develop tool to adapt wafer puddle develop technology to photomask manufacturing, in an attempt to capture the same optimum CD control enjoyed by the wafer industry. In this study we used the ACT-M develop tool to examine CD uniformity, local loading and defect control on P-CAR and N-CAR photomasks exposed with 50keV e-beam pattern generators. Results with both nozzle types are reported. CD uniformity, loading, and defectivity results were sufficient to meet 65-nm technology node requirements with these nozzles and tailored made develop recipes for photomask processing.

Keywords: Photomask, LD nozzle, SH nozzle, develop, puddle process, CD uniformity, local loading, E-beam CAR

1. INTRODUCTION

Recently, the design of integrated circuits has become more and more complicated due to higher circuit densities. In particular for logic applications, the design is no longer uniform but combines different kinds of circuits into one circuit resulting in stringent criteria for both wafer and photomask manufacturing. Photomask CD uniformity control and defectivity are two key criteria in manufacturing today's high-end reticles, and they are both strongly impacted by the mask developing process.

The ACT-M is equipped with a standard new linear drive (NLD) nozzle as well as a super H (SH) nozzle, both widely used in wafer developing applications. A previous collaboration between TEL and the AMTC using an alpha photomask develop tool concluded the transfer of wafer puddle develop technology to photomask processing was not a simple, straightforward process [1]. Additionally, several other studies report the local loading (also called microloading) effect on CARs is more pronounced when single puddle develop processes are employed [2, 3]. In this study we applied the ACT-M and wafer puddle develop technology to photomask developing and gauged the performance by examining CD uniformity and local loading behavior on a special test mask design. Additionally, N-CAR and P-CAR product reticles designed at the 65nm technology node and exposed with 50keV e-beam pattern generators were processed with the ACT-M and examined for CD uniformity, local loading and defect control. Results indicate the ACT-M is capable of meeting photomask requirements at the 65nm technology node with tailor made develop recipes culled from wafer puddle develop technology.

2. EXPERIMENTAL

2.1. Experimental pattern

The AMTC used a special layout mask to evaluate the overall CD uniformity and local loading behavior. The mask was a 12 by 14 array of dies (168 total dies) covering 108x126mm, each with a background pattern and CD cell. The background pattern varied in pitch to create different local loading conditions. We selected four dies in close proximity to one another with 50%, 0%, 100% and 50% local loading in order to observe the local loading behavior (Figure 1). Each of these four dies contained 41 CD cells and we measured clear and dark 500nm features in every CD cell in order to quantify the CD change as local loading is varied. For N-CAR the same pattern was inverted so that local loading was equivalent between P-CAR and N-CAR. The overall CD uniformity was measured on four different 300nm features (Iso-Dark, Iso-Clear, Dense-Clear and Dense-Dark) in all 168 dies on this test reticle. The radial and linear (side-to-side) contributions to CD uniformity were also analyzed to observe the systemic CD error. Lastly, several 65-nm design DRAM customer patterns were also developed on the ACT-M to verify CD uniformity and defect control.

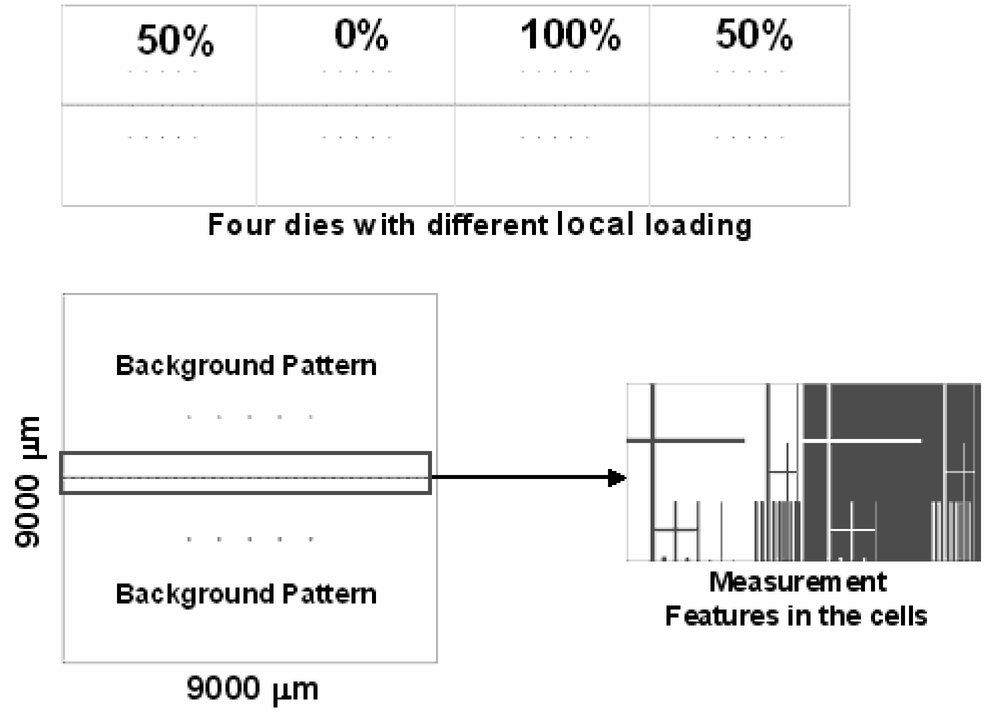

Figure 1: Description of the pattern for local loading behavior measurement

2.2. Experiment conditions

All experiments were done with 6 inched 250 mil chrome blanks. Tests on FujiFilm Arch FEP171 P-CAR and Sumitomo NEB22 N-CAR were written using 50keV e-beam pattern generators. Optimized dose and proximity effect correction (PEC) were specific for each resist. Post Exposure Bake was performed on STEAG Hamatech APB5000. Resist and chrome CDs were measured using HOLON CD-SEM, EMU-220. Chrome etching was performed on an Applied Materials Tetra Etch system.

2.3. Description of the tests

Table 1 lists the develop recipes used in this study, along with the nozzle type and total develop time. TEL-A and TEL-B recipes were both single puddle processes using the NLD and SH nozzles. Both of these recipes are widely used in wafer developing processes. The remaining recipes in Table 1 (Mask 1, 2, 3) are multi-puddle develop recipes created specifically for CAR photomask processing.

Table 1 Description of recipes

Recipe Name	Nozzle Type	Concept	Total Developing Time
TEL-A	LD	Single Puddle	60 sec
TEL-B	SH	Single Puddle	60 sec
Mask-A	LD	Multi-Puddle	60 sec
Mask-B	SH	Multi-Puddle	60 sec
Mask-C	LD, SH	Multi-Puddle	60 sec

3. RESULTS & DISCUSSION

3.1. Development local loading on FEP171

The local loading behavior of FEP171 has been reported in several studies [4, 5]. The CD error due to local loading on FEP171 is lower than on Novolak type resists [6] (*e.g.,* IP3600 or IP3500), but needed improvement in order to meet 65-nm technology node requirements. The test masks were written without fogging effect correction (FEC). Figure 2 displays results of FEP171 local loading measurements in resist, so that chrome etch effects are excluded. CD deviation is plotted on the Y-axis and was calculated by subtracting the measured CD from target for iso-line features. Conversely, iso-space features were calculated by subtracting the target CD from measured CD values. The X-axis represents the change in die local loading on this test reticle layout.

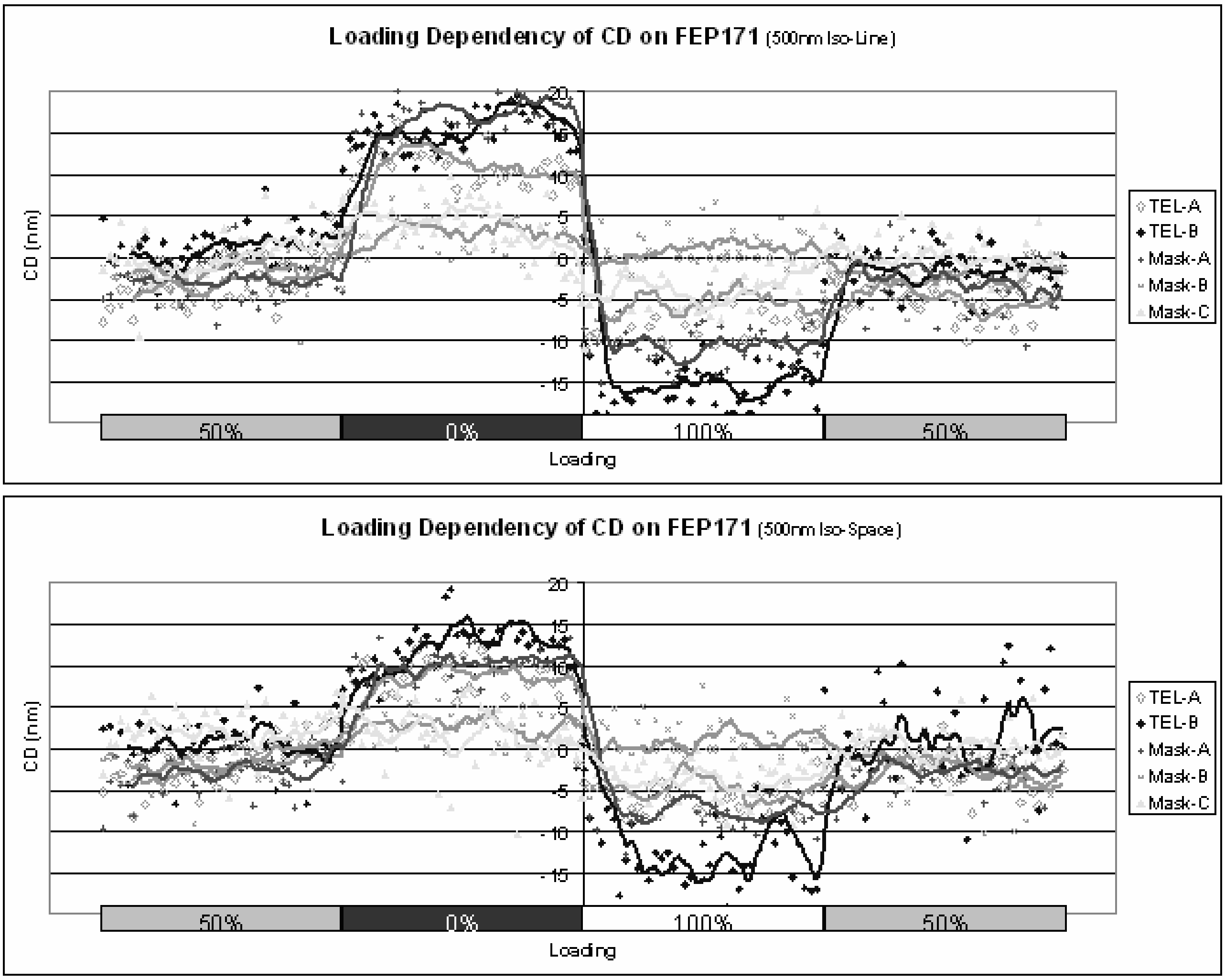

Figure 2 Loading dependency of resist CD on FEP171

Multi develop puddle processes have proven effective in reducing the loading effect on FEP171 [5] however, simply adding an additional puddle into the develop recipe did not significantly improve the loading effect in this study (recipe Mask A). Reasons for this lack of improvement were believed to originate from the slow development rate of FEP171 [5] coupled with the inefficient removal of by products when using the NLD nozzle, even with multiple dispenses. Other studies report enhancing the developer exchange rate using higher flow rates, PGSD, and MID are also effective in reducing loading effects [4, 6, 7]. In the next multiple puddle develop recipes (Mask-B & Mask-C), we utilized the high impact dispensing SH nozzle, which can dispenses developer at a much higher pressure than the NLD nozzle, and observed significant reductions in FEP171 loading effect. The loading effect was more pronounced on iso-line than iso-space features however, using the Mask-B recipe, this difference can be virtually eliminated.

3.2. Overall CD uniformity on FEP171

The table 2 presents results of overall CD uniformity on FEP171. Test masks were written without fogging effect correction (FEC), and resist CD was measured on 300nm isolated and dense space features. Linear and radial contributions to CD uniformity were also analyzed in order to gauge the systematic CD error in the process. The recipe TEL-A was evaluated in a previous study [1], and showed promising performance on PEK130 resist exposed with a DUV pattern generator. However, the loading effect achieved with the TEL-A recipe was too high on FEP171 resist (Figure 2). Of all the recipes examined in this portion of the study, Mask-B showed the best combination of overall CD uniformity and local loading effect however, some systematic CD errors were still present. We believed these errors were due to the absence of a fogging correction during exposure and also due to some resist instability during CD SEM measurement. This same develop recipe was investigated further applying a FEC, and Table 3 and Figure 3 display the resist and chrome CD uniformity results of 300nm features.

Table 2 Resist CD uniformity (nm) on FEP171

Recipe		**CD Uniformity (3σ)**	**CD Range**	**Linear Contribution (3σ)**	**Radial Contribution (3σ)**
TEL-A	Iso-Space	6.2	10.2	0.8	3.9
	Dense-Space	7.2	12.0	0.2	5.8
TEL-B	Iso-Space	9.5	20.7	1.8	6.3
	Dense-Space	8.7	15.6	1.1	7.7
Mask-A	Iso-Space	8.7	15.2	2.4	4.5
	Dense-Space	7.4	11.0	2.2	5.8
Mask-B	Iso-Space	6.4	12.0	2.0	2.1
	Dense-Space	5.8	9.0	2.6	2.7
Mask-C	Iso-Space	7.9	12.5	2.5	4.9
	Dense-Space	8.2	14.4	1.1	5.9

Comparing resist and chrome measurements we observed larger changes in space features than we did for lines or dark features. Additionally, the radial contribution to CD uniformity for space features was an order of magnitude larger in resist than in chrome. We propose these differences for space features were due to resist charging during CD SEM measurements. Indeed in chrome CD measurements, the radial CD uniformity contribution of space features was very low and similar to those of line features. For all feature types measured in chrome, the systematic CD errors were within the requirements for 65-nm DRAM reticles based on ITRS 2004 [8] requirements.

Table 3 CD uniformity (nm) on resist and Cr with FEC applying

Recipe: Mask-B		**CD Uniformity (3σ)**	**CD Range**	**Linear Contribution (3σ)**	**Radial Contribution (3σ)**
Resist CD	Iso-Line	6.1	10.7	1.5	2.0
	Iso-Space	5.6	8.6	0.6	**4.8**
	Dense-Space	4.2	8.8	0.7	**2.8**
	Dense-Line	4.3	7.4	0.6	1.9
Cr CD	Iso-Line	5.9	10.3	1.8	1.3
	Iso-Space	3.0	5.2	0.6	**0.6**
	Dense-Space	3.5	5.5	1.0	**0.4**
	Dense-Line	4.1	7.3	1.2	0.7

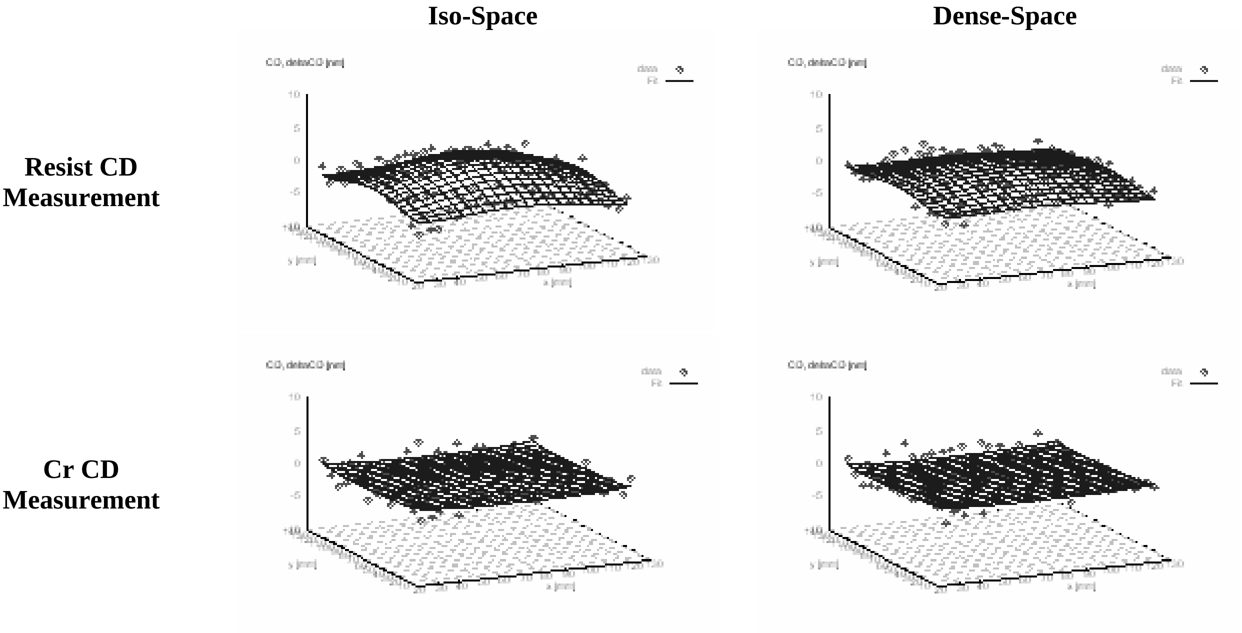

Figure 3 CD uniformity (nm) on resist and Cr with FEC applying

The local loading effect was also measured on this mask in resist and chrome and results are presented in Figure 4. For both feature types, the loading effect measured in chrome is lower than in resist, which could indicate the develop and etch steps in our process contribute to loading in opposing ways.

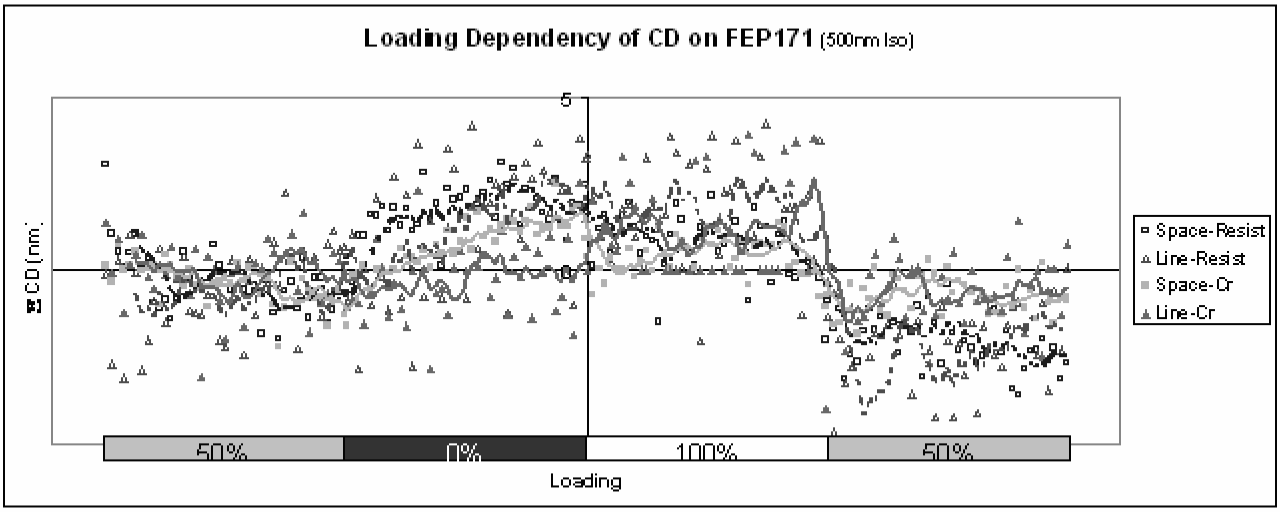

Figure 4 Loading dependency on resist and Cr using Mask-B recipe on FEP171 with FEC

To verify performance of the Mask-B develop recipe, we processed two 70-nm DRAM HTPSM masks, and the chrome CD uniformity results are presented in Table 4. The overall CD uniformity fulfilled the requirement of 70-nm DRAM mask as well.

Table 4 CD uniformity (nm) on 70-nm DRAM masks

Mask#	CD Uniformity (3s)	CD Range	Linear Contribution (3s)	Radial Contribution (3s)
1	4.0	7.9	1.3	1.6
2	4.3	8.6	0.6	1.3

3.3 Defect control on FEP171

The 70-nm DRAM masks mentioned in Table 4were also used to verify the defect control. Defect inspections were performed in chrome on a KLA-Tencor TeraScan DUV reticle inspection tools with high sensitivity and the results are listed in Table 5. Total defect levels represent not only the develop step but all steps in HTPSM fabrication and was acceptable for this technology node..

Table 5 Defect inspection results

Mask#	Opaque Defects	Clear Defects	Un-repairable Defects	Total Defect Count
1	9	1	0	10
2	4	0	0	4

3.4 Development local loading on NEB22

The local loading effect on NEB22 was studied with the same test pattern used with FEP171, and the test masks were written without FEC. Figure 5 displays NEB22 local loading using different develop recipes. NEB22 has a lower local loading effect compared to FEP171, even with a single puddle develop process (Figure 2). Measurements were made in resist in order to exclude the loading effect contributions from chrome etch. As with FEP171, we observed the non-direct written feature (in this case clear or space) had a higher loading effect than the direct written feature (dark or line), most likely due to fogging effect. Fogging correction might be responsible for the difference in loading effect between non-direct and direct features.

Figure 5 shows all of the multi-puddle develop recipes reduced the loading effect on NEB22, but unlike FEP171, the LD nozzle, multi puddle develop recipe (Mask-A), provided the largest loading effect reduction. When the high impact, SH nozzle was added to the develop recipe (Mask-C) further reduction in NEB22 loading effect was not observed, leading us to conclude high impact dispensing is not necessary for NEB22. This observation was counter intuitive because NEB22 dissolves at a much faster rate than FEP171, which would require a faster removal rate of reaction by products which, in turn, would should require a faster refresh rate of fresh developer. Explanation for this observed behaviour is not clear.

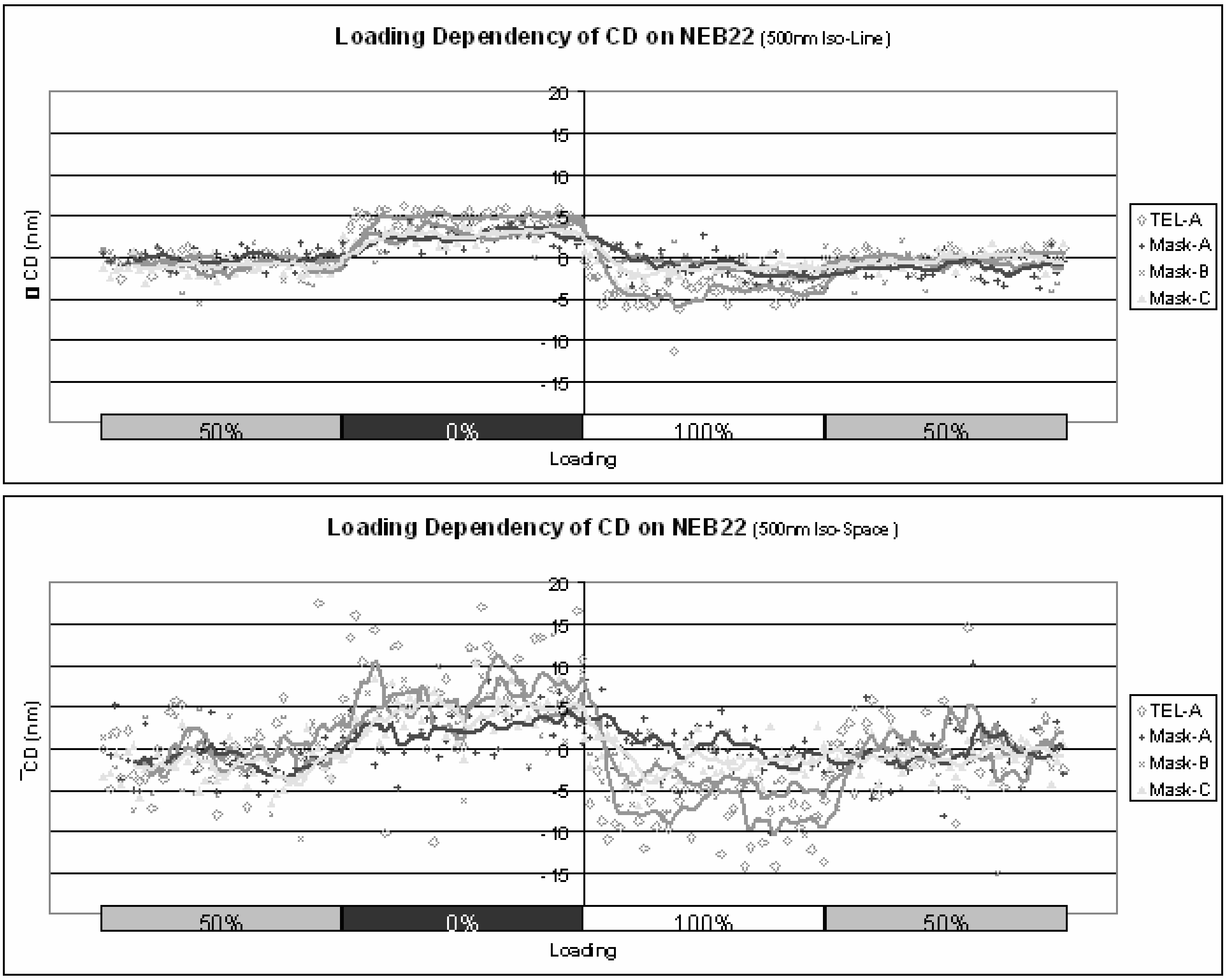

Figure 5 Loading dependency of resist CD on NEB22

3.5 Overall CD uniformity on NEB22

Table 6 presents overall CD uniformity results for NEB22. The test masks were written without FEC, and resist CDs were measured on 300nm isolated and dense line features. The radial and linear error contributions to CD uniformity are also presented. The TEL-A recipe provided acceptable CD uniformity, however the local loading effect was too high. The Mask-A recipe provided a low local loading effect, but the linear contribution from this recipe was too high. It might be due to the scan speed, and the fast dissolving rate of NEB22 would cause the strong side-to-side CD signature The recipe Mask-C has a comparable loading effect to Mask-A, as well as provides better CD uniformity. As in the case of FEP171, the best develop recipe was used to process another test reticle written with FEC, and Table 7 displays CDs measured in both resist and chrome for this experiment.

Table 6 Resist CD uniformity (nm) on NEB22

Recipe		**CD Uniformity (3σ)**	**CD Range**	**Linear Contribution (3σ)**	**Radial Contribution (3σ)**
TEL-A	Iso-Line	4.5	9.3	1.8	1.8
	Dense-Line	6.3	11.2	1.7	2.6
Mask-A	Iso-Line	9.6	18.8	4.9	2.0
	Dense-Line	7.6	14.6	4.1	2.4
Mask-B	Iso-Line	8.6	16.2	1.5	4.2
	Dense-Line	7.7	13.3	1.5	4.7
Mask-C	Iso-Line	4.7	9.8	2.6	1.4
	Dense-Line	5.7	9.1	3.7	1.8

Table 7 CD uniformity (nm) on resist and Cr with FEC applying

Recipe: Mask-C		**CD Uniformity (3σ)**	**CD Range**	**Linear Contribution (3σ)**	**Radial Contribution (3σ)**
Resist CD	Iso-Line	4.5	9.1	0.8	1.4
	Dense-Line	3.8	7.1	1.0	1.9
Cr CD	Iso-Line	3.9	7.7	0.2	1.2
	Dense-Line	4.8	8.8	0.3	2.9

The use of FEC lowered the linear contribution to CD uniformity but not the radial CD error. This indicates error contributions are introduced from other lithography processes, and the most likely source is the post exposure bake tool (PEB). The PEB process is normally set up to achieve the best possible temperature uniformity across a photomask. However, this approach does not consider the reaction mechanism nor solvent evaporation during the PEB process. We believe further CD uniformity on NEB22 can be achieved by optimizing the PEB process.

The loading effect in resist and chrome were also measured and the results are plotted in Figure 6. The use of FEC made almost no difference in loading between non-direct written and direct written features on NEB22.

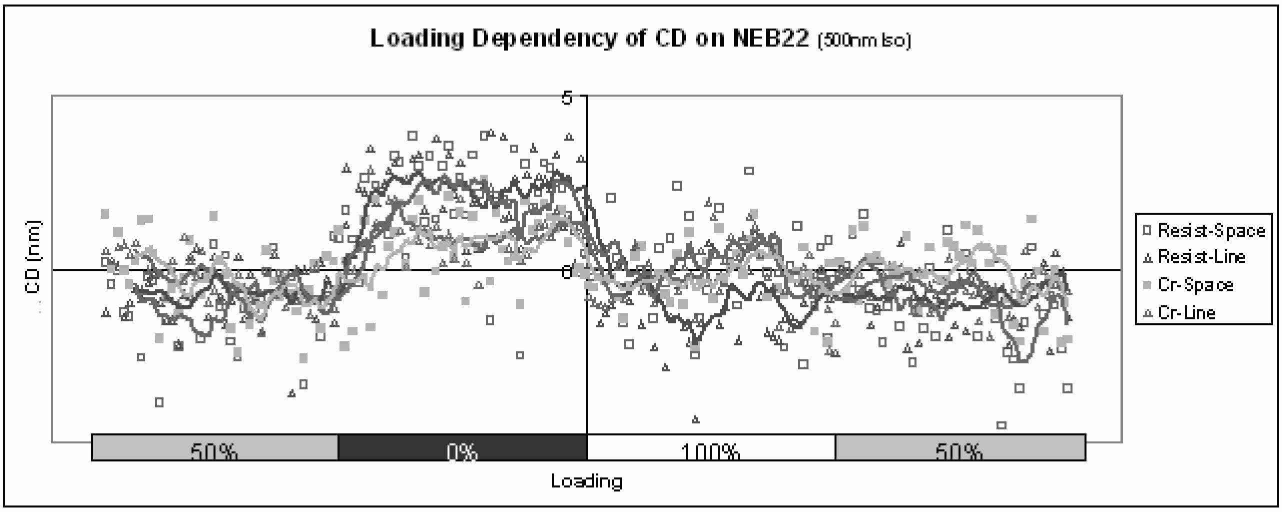

Figure 6 Loading dependency on resist and Cr using Mask-C recipe on NEB22 with FEC

4. CONCLUSION

Our study demonstrated typical wafer developing processes could provide good CD uniformity on CAR photomasks exposed with 50keV pattern generators. However, the local loading effect was not so easily reduced via the develop step. Tailor made develop recipes were able to lower the local loading effect while simultaneously achieving good CD uniformity on both P-CAR and N-CAR photomasks. Results fulfil the 65nm technology node requirements using the TEL CLEAN TRACK ACT-M develop tool at the AMTC. Lastly, the ACT-M develop tool demonstrated good defect control on 70nm DRAM customer patterns.

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