Complex Shape EUV Extreme-Ultraviolet Patterning – EUV Resist Process Optimization and Dry Etch Solutions for Defect Reduction and Cross-Wafer Uniformity Improvements

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Silicon surface area enhancement and preservation is imperative for chip scaling. Existing challenges of defects generated during EUV lithography process and challenges of pattern control of novel complex geometric shapes through dry etch and EUV process, needed to enhance silicon surface area have been discussed in the paper. The solutions proposed for EUV track developer optimization through new developer nozzle is critical for any memory technology pursuing EUV process. Dry etch solutions proposed to improve cross wafer pattern uniformity and integrity are fundamental to advance high aspect ratio tight pitch EUV etches for complex patterns. In this paper we provide three mechanisms to achieve large surface area while maintaining cross wafer uniformity of the complex pattern.

Index Terms: **Complex EUV pattern, CDU, Dry Etch, Descum step, Descum time, Defects, EUV Resist, HAR, Track Developer**

I. INTRODUCTION

For device scaling in memory industry, silicon surface area preservation is paramount. We need to find creative and unique ways of increasing the surface area as the pitch shrinks sub 10 nm. Simple line and space patterns may no longer be conducive to deliver memory needs of the future. Hence, we need to overcome the drawbacks of current EUV (extreme ultra-violet) lithography and dry etch technology to provide solutions for complex patterns with low defectivity, cross wafer uniformity and lower process variability.

In this paper, we discuss New Developer Nozzle for Positive Tone Developer (PTD) that significantly improves Center of wafer (CoW) defects generated during EUV photolithography. We provide solutions to etch complex pattern namely combinations of rectangular and spherical geometry simultaneously Fig. 1 which is first of a kind in the industry.

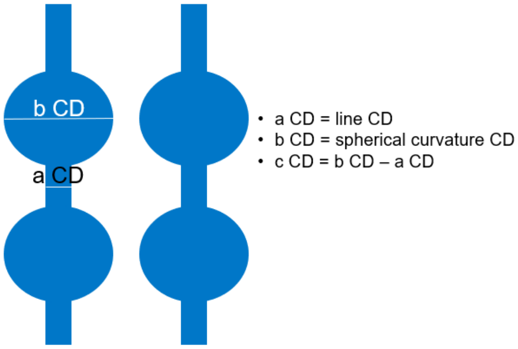


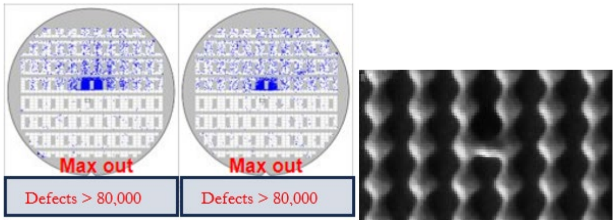
Fig. 1 Complex pattern discussed in the paper with dimension specifications.

We also discuss mechanisms to enable device feature uniformity for features a and b from center to edge of the wafer locally within few microns of Field of View (FoV) also called Local Critical Dimension Uniformity (LCDU) to maintain good overall CD imbalance for the device fabrication. We delve into solutions to have the largest c CD to optimize surface area.

II. METHODOLOGY AND RESULTS FOR DEFECT REDUCTION AND CROSS-WAFER UNIFORMITY

A. Defect Reduction in Complex Patterns through EUV Track Developer Optimization

As the photolithography specifications get tighter the defectivity requirement become more stringent to prevent yield loss in complex patterns. Historically static mode Multiple Good Performance Developer Nozzle Arm (GP/MGP) has exhibited low levels of defectivity [1] however complex line and sphere pattern show heavy CoW bridging defects possibly caused by bubble generation due to cavitation effects during first developer in the photolithography process [2]. Photo Track Monitor which is a defect monitoring device showed that the **New Developer Nozzle** for PTD was a breakthrough to significantly improve defectivity.



(a) (b)

Fig. 2 a) Post Hardmask Etch Transfer Bright Field Defects Maps for Fab4 and Fab16 b) Post Hardmask Etch Transfer CoW bridging defects on the complex pattern originating at photolithography.

Fig.3 shows the difference between conventional - dynamic and static mode nozzles with the new developer nozzle. By optimizing the new developer nozzle dev mode, the defect count can be reduced by 99%. The following parameters were optimized to achieve the desired results:

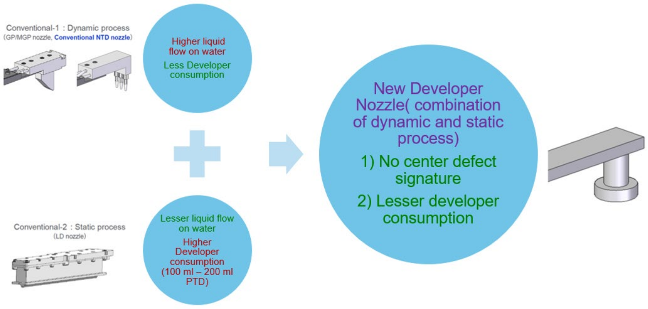


Fig. 3 Conventional nozzle: dynamic process, Conventional nozzle: static process and new developer nozzle

- Developer parameter: To make sure developer is evenly distributed across wafer the spin time & spin speed were increased.
- Addition of Dynamic Puddle: More developer reaction time was added to infiltrate hole pattern.
- Defect Reduction Rinse Control: Spin speed during scan rinse was made same as the centrifugal force which helps the EUV resist to maintain hydrophobicity.

Below Fig.4. describes the process flow of the new developer nozzle. One of the main differences between the conventional nozzle and the new developer nozzle is that in the new developer nozzle a puddle of dispense is formed with lower spin speed application and the CD profile can be controlled through the scan process. This puddle enables uniform distribution of developer across the wafer.

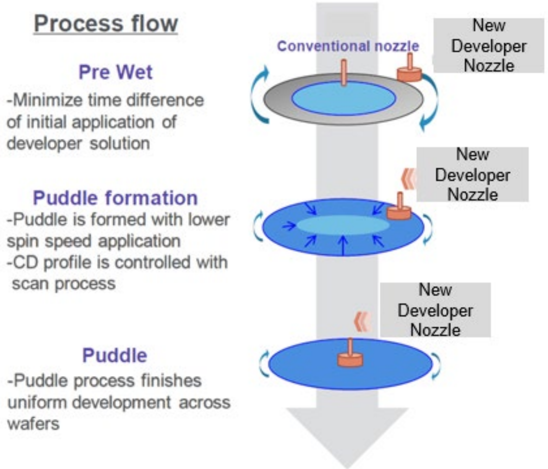


Fig. 4 Process flow of the new developer nozzle

Thus, new developer nozzle's developer recipe was able to reduce the defect count from over 80,000 to < 400 CoW bridging defects post hardmask etch transfer shown in Fig.5.

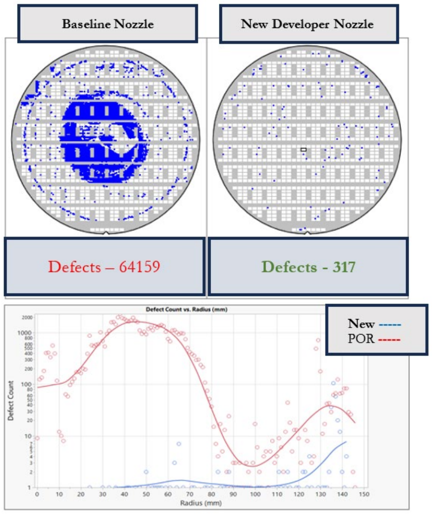


Fig. 5 CoW defectivity progression at Post Hardmask Etch Transfer Bright Field Defects Maps for Baseline-MGP nozzle wafer vs New Developer nozzle wafer.

B. *Dry Etch Optimization and Uniformity Tuning for Complex EUV Pattern*

The current challenges of Dry Etch includes aspect ratio dependent etch (ARDE) effect, ion reflection effect and cross wafer loading effect when etching a complex combination of geometric pattern such as sphere and rectangle, simultaneously. In Fig. 6 b CD erodes faster than a CD causing high c CD loss (c CD = b CD- a CD, i.e., lesser overall surface area), especially at the wafer edge. Since we see an edge roll- off signature at the photolithography step and the current EUV photo resist has an inherently tapered and footed profile, we need a solution to control the uniformity of a CD and b CD independently across the wafer while etching a and b features simultaneously. Etching rates in silicon deep reactive ion etching (RIE) of rectangular trenches are sensitive to width while ring trenches are sensitive to both width and area [3].

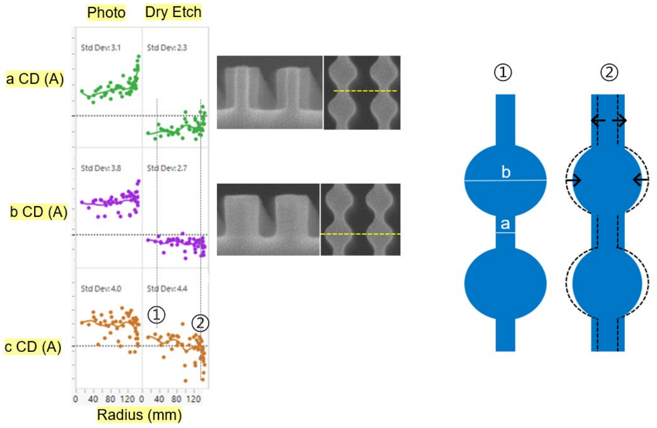


Fig. 6 Complex EUV pattern cross wafer profile for a CD, b CD, c CD= (b CD – a CD) and CD erosion during etch.

Conventional Dry Etch industry tuning parameters are electrostatic chuck (ESC) temperature, inductively coupled plasma etching which includes a power input circuit and an RF supply unit, and gas injection. These knobs affect a CD and b CD simultaneously. For cross wafer uniformity and improvement in the edge of the wafer roll-off signature of c CD, we need knobs that can independently control a CD and b CD.

Thus, through Dry etch DOE (design of experiments) Fig.7, we identified that the **Descum Step (DS)** is the main step to enable good uniformity of c CD from wafer center to edge, which is the novel part for DE in the paper. The main parameters under descum step in order of priority are **descum time** and **N_2/CH_2F_2 gas flow rate**. Out of the various gas chemistries evaluated such as CH_3F, CH_4, $SiCl_4$, it was found that the **N_2 and CH_2F_2** gases play a critical role in determining the process window for ultra-high etch selectivity of Film1 and EUV resist shown in Fig.8 due to disproportionate changes in the degree of polymerization on these two surfaces. Increasing the CH_2F_2 flow rate results in a smaller steady state CH_xF_y thickness on the Film1, and in turn, enhances the Film1 etch rate due to enhanced resultant formation. CH_xF_y layer is deposited on the EUV resist surface which protects the resist under certain N_2 flow conditions [5]. At the descum (DS) step, by toggling the time of N_2 and CH_2F_2 gas flow, we can simultaneously deposit different amounts of polymer and etch the feature, depending on the device requirements. Through this technique, we can independently control b CD and achieve similar a CD and b CD cross wafer signature and hence get flat c feature CDU while maintaining low levels of defectivity.

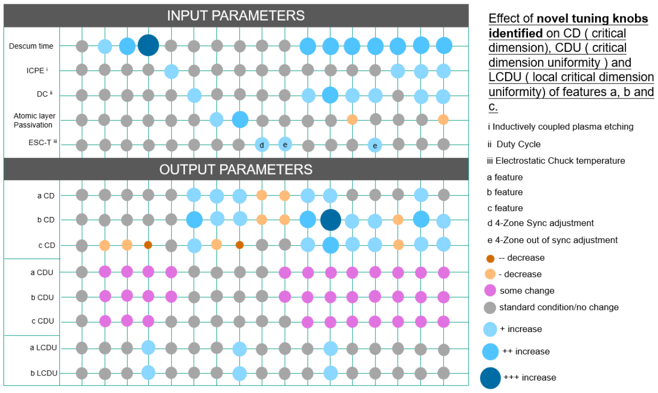


Fig. 7 Design of Experiment DOE- Sensitivity of Dry Etch Parameters

Mechanism 1: Descum Time impact on c CD

Descum time is the key step for tuning Mean a CD and Mean b CD values. In Fig.8 ①: Tapered b CD profile → Smaller b CD → Smaller c CD where as ②: Squared b CD profile → Larger b CD → Larger c CD.

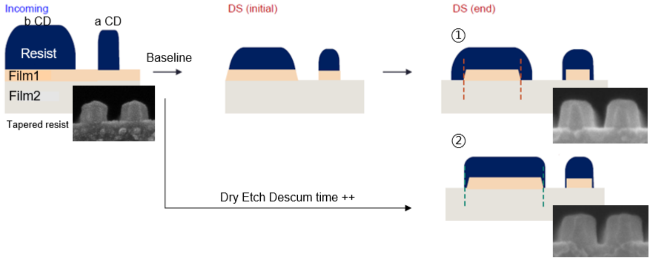


Fig. 8 Impact of descum time on c CD ① Low Descum time, low c CD ② Higher Descum time, higher c CD

Table I
The SEM data of incoming EUV Photo Resist and movie etch at wafer edge.

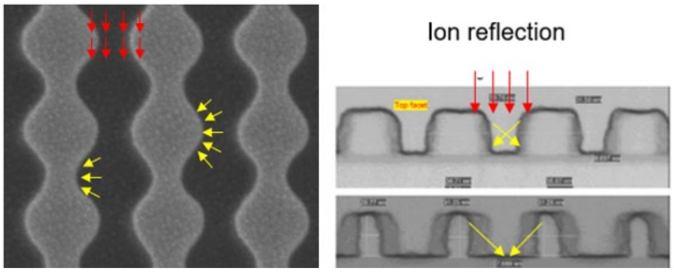
Angle of b CD	**POR**	**Longer Descum Time**	**Delta** [a]
Incoming Photo Resist	119.14°		
Post 1st phase Film1 Dry Etch	101.85°	94.12°	7.8°(↓)
Post 2nd phase Film1 Dry Etch	97.26°	92.34°	4.9°(↓)
Post Film2 Dry etch	94.8°	90.52°	4.3°(↓)
Post Full Dry Etch	89.9°	90.2°	0.3° (~)

a: Delta b CD between POR and Longer Descum Time, ↓: Improved, ~: Comparable.

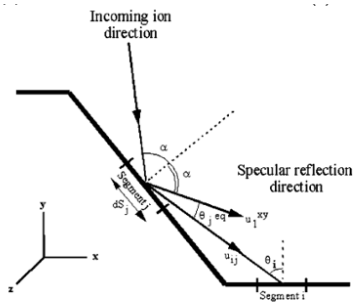
Through lean fluorine etch chemistry and more polymer deposition we can achieve larger b CD and c CD. Less fluorine helps in lesser Film1 lateral etch during mask open step. More polymer deposition helps with squared resist and Film1 profile even with tapered and footed incoming resist profile. Table I shows that longer descum time (40s longer than POR (process on record: baseline), helps to make the DE profile straighter by ~5° on the hard mask and underlayer mandrel, which should protect c CD from erosion.

Mechanism 2: Cross wafer c CDU improvement through Descum Time

The tighter spaces between c CD experience enhanced ion reflection effect Fig.9 which causes higher CD degradation of c feature, decreasing overall surface area.



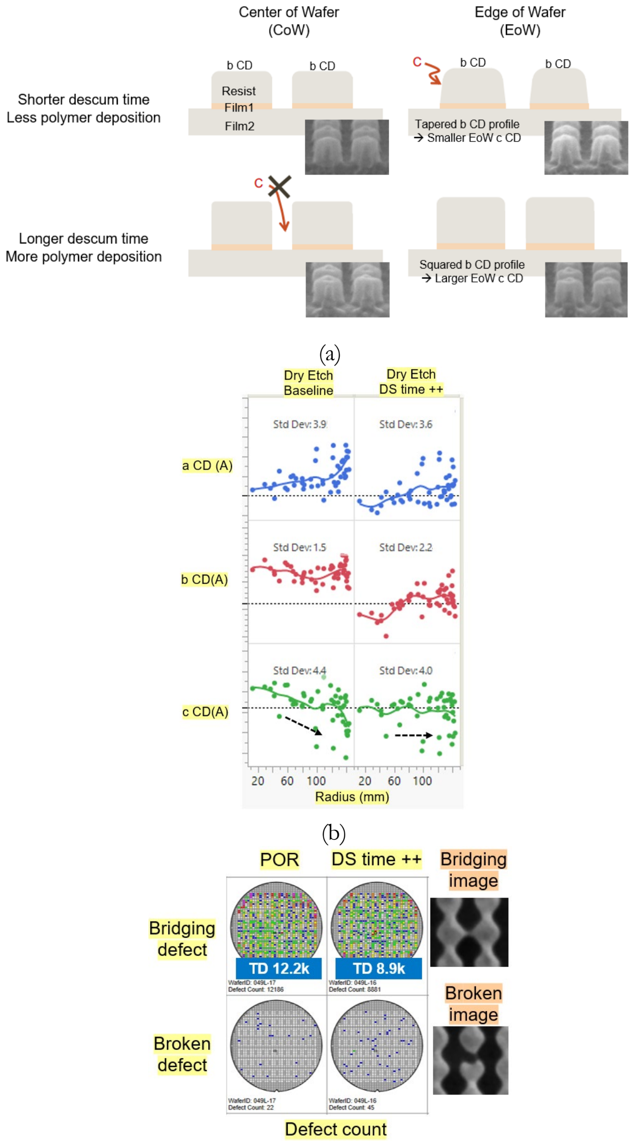
(a)



(b)

Fig. 9 (a), (b) Incoming and reflected ion fluxes for the sidewall of a trench, projected to x–y plane [4].

Shorter descum time results in less polymer deposition. The wafer edge roll-off signature is from less polymer deposition and faster b CD erosion caused by ion reflection effect. Longer descum time provides more deposition to protect resist and mitigate roll-off signature as shown in Fig 10.



(a)

(b)

(c)

Fig. 10 (a), (b) Cross wafer uniformity through shorter and longer descum times (c) Defectivity comparison

Mechanism 3: Polymer deposition amount tuning at descum step to enable more uniform and larger c CD cross wafer.

As shown in Fig 11, in case 1, we know that shorter descum time results in lesser polymer deposition causing small and non -uniform: a CD, b CD and c CD. In case 2, Longer or sufficient descum time helps with optimized polymer deposition resulting in straight etch profile for uniform a, b, and c CD. However, polymer deposition saturates after a certain point. In case 3, even though longer descum time helps to make the edge of wafer (EoW) profile straighter with no negative impact such as clogging, taper etc. compared to CoW profile, it's been observed that the overall Mean c CD is lower compared to case 2.

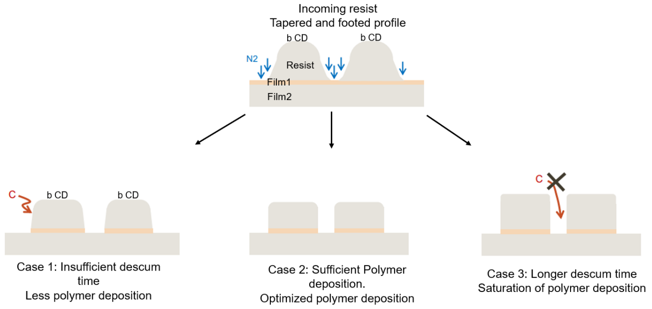


Fig. 11 Polymer deposition amount tuning at descum step to enable more uniform and larger c CD cross wafer through descum time.

Based on DOE in Fig.12, the c CD can be brought to target by changing the **Radio Frequency (RF) Pulsing Duty Cycle** shown in Table II and Fig.12. We also observe that by adjusting the percentage of RF duty cycle we can increase the c CD post hardmask etch transfer. Increasing DS time improves LCDU of a and b CD while keeping other parameters constant and increasing DS N_2 flow rate helps improve LCDU of b CD with slight impact to a LCDU and no impact to a, b, c CD.

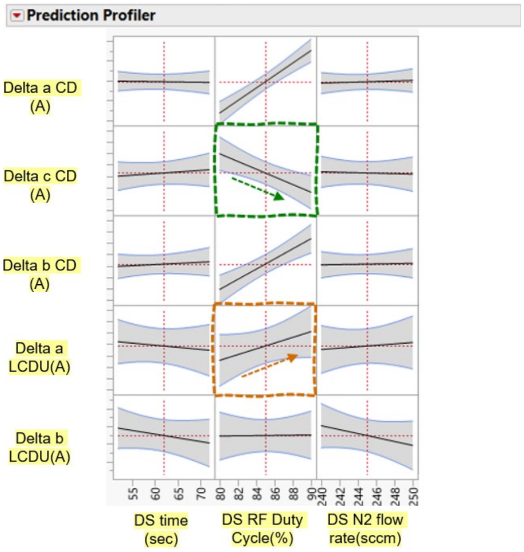


Fig. 12 Prediction Profiler of DS step DOE Prediction Profiler (Delta: Resist CD minus post etch CD)

Table II. Parameters effect summary of DS step DOE, Duty Cycle shows significant linearity with delta c CD, P-value < 0.005

Source	LogWorth	PValue
DS Duty Cycle	3.273	**0.00053**
DS N2 flow rate	0.744	0.18014
DS time	0.603	0.24932
DS Duty Cycle*N2 flow rate	0.524	0.29937
DS time*N2 flow rate	0.316	0.48252
DS time*Duty Cycle	0.183	0.65588

N_2/CH_2F_2 gas flow rate adjustment in the descum step which is the 1st step post EUV lithography can also be used to achieve desired polymer deposition amount and uniform c CD. We observe cleaner post etch bridging bright field maps with low CH_2F_2 and N_2 flow rate without impacting the broken defects. Based on the bright field defect recipe sensitivity, we observe that a CD thins, or thinning defects get worse as a CD reduces, however the process window for a CD is large enough that it doesn't translate to actual broken defects post hardmask etch.

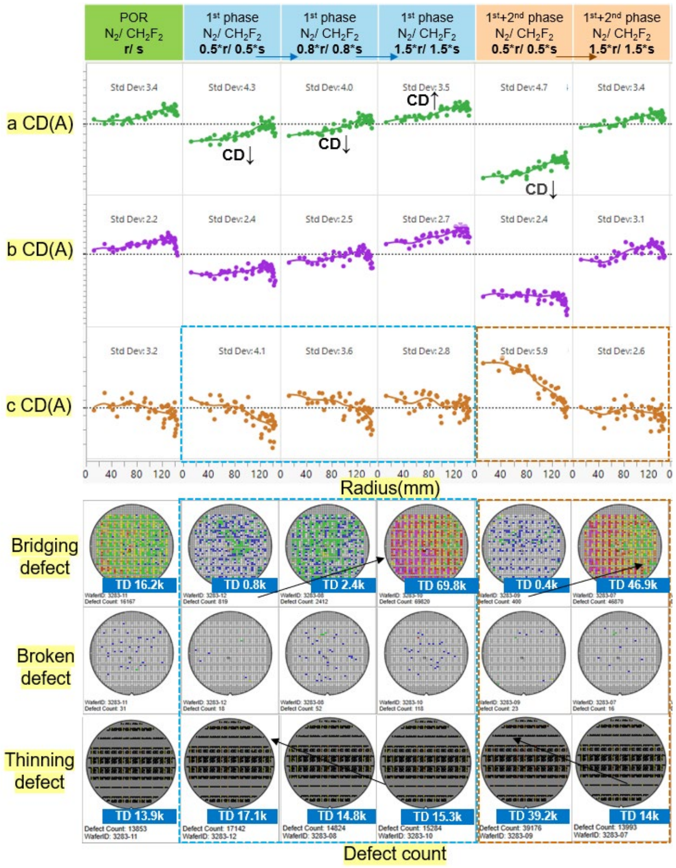


Fig. 13 a CD, b CD and c CD uniformity N_2/CH_2F_2 gas flow rate skew without a CD compensation. (r: N_2 flow rate, s: CH_2F_2 flowrate, ↓: smaller a CD, ↑: larger a CD, TD: Total defects)

At lower flow rates we also observe that, the c CD standard deviation became slightly worse predominantly at the wafer edge. The higher CDU for a and c features at lower gas flow rate can be mitigated with trim time adjustment during 1st phase Film1 Dry Etch discussed in Fig.8 and Table I. At trim step we trim the Resist and etch Film1, and by increasing trim capability we can mitigate micro-bridging defects caused by polymer deposition at the descum step, where we etch Film1 and deposit polymer on Resist to preserve mask shape.

Table III. Bridging and Broken EDL comparison of DS gas skew. (^{a}: POR)

N_2/ CH_2F_2 (sccm)	a CD & b CD	EDL % (Bridging)	EDL % (Broken)	EDL % (Thinning)
1.5*r/ 1.5*s	↑	73.7 (50%↑)	0.12	100%
r/ s^a	-	24	0	100%
0.8*r/ 0.8*s	↓	0.7 (23%↓)	0	100%
0.5*r/ 0.5*s	↓	0.3 (24%↓)	0	100%

EDL: Estimated Die Loss

From Fig.13, we observe that c CD edge roll off is lower with higher flow rate, suggesting that polymer has higher impact on etching the chamber wall film compared to fluorine chemistry (F). On the contrary, with lower flow rate, ($poylmerF_x$) etches hard mask and clears some oxide films on the chamber wall. Under low CH_2F_2 and N_2 gas flows, at the CoW, polymer deposits more enabling the mask to be more squared. Under high flow rate, it gets more difficult to deposit polymer at the CoW into the small space between c CD and hence we still have a squared and straight mask with no significant increase in c CD or additional bridging of pattern keeping a CD on target as shown in Fig.14. Defects are sensitive to CDs, especially Bridging Defects to b CD and Broken Defects to a CD. We compared defect counts under similar a CD shown in Fig.14.

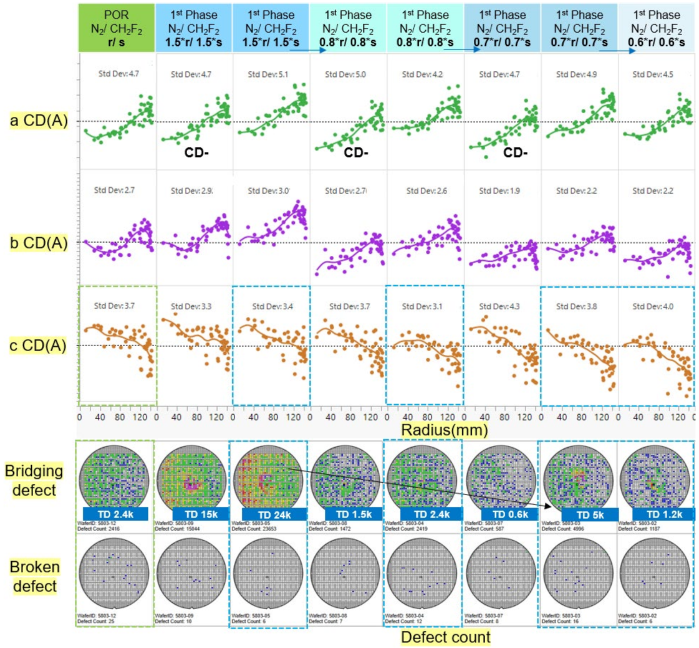


Fig.14 a CD, b CD, c CD and bridging, broken bright field defect maps with DS N_2 /CH_2F_2 gas flow skew, combined with a CD compensation and skew. (TD: Total Defect count)

Based on the technology curve, 48 sccm is the saturation point for the CH_2F_2 gas flow rate shown in Fig.15.

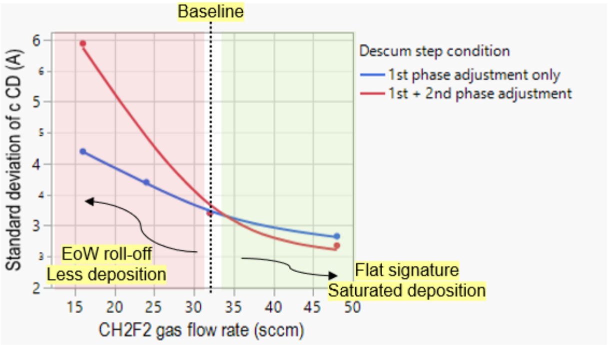


Fig.15 N_2/CH_2F_2 gas flow rate vs standard deviation of c CD (A)

III. CONCLUSION

In this paper we discuss the process of the new developer nozzle for PTD that significantly improves CoW defects generated during EUV photolithography. We highlight the existing challenges of dry etch technology when etching a complex pattern - combination of spherical and rectangular geometry simultaneously. We propose three mechanisms to enable critical dimension uniformity (CDU) for features a and b from center to edge of the wafer while maintaining large surface area c CD. Mechanism 1: Descum Time impact on c CD, Mechanism 2: Cross wafer c CDU improvement through Descum Time and Mechanism 3: Polymer deposition amount tuning at descum step to enable more uniform and larger c CD cross wafer.

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