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Advanced processes in metal-oxide resists for high-NA EUV lithography

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ABSTRACT

One of the key steps in the pattern formation chain of extreme ultraviolet (EUV) lithography is the development process to resolve the resist pattern after EUV exposure. The traditional development process might be insufficient to achieve the requirements of ultra-high-resolution features with low defect levels. The aim of this paper is to establish a process to achieve a good roughness, a low defectivity at a low EUV dose, and capability for extremely-high-resolution for high numerical aperture (NA) and hyper-NA EUV lithography. A new development method named ESPERTTM (*Enhanced Sensitivity develoPER Technology*TM) has been introduced to improve the performance of metal oxide-resists (MOR). ESPERTTM as a chemical super resolution technique effectively apodized the MOR chemical image, improving chemical gradient (higher exposure latitude (EL)) and reducing scums (fewer bridge defects). This new development method can also keep the resist profile vertical to mitigate the break defects. The performances of the conventional development and ESPERTTM were evaluated and compared using 0.33 NA EUV, 0.5 NA EUV, and electron beam (EB) exposures, for all line-space (LS), contact hole (CH), and pillar (PL) patterns. Using 0.33 NA EUV scanners on LS patterns, both bridge and break defects were confirmed to be reduced for all 32-nm-pitch, 28-nm-pitch, 26-nm-pitch LS patterns while reducing the EUV dose to size (DtS). In the electrical yield (1 meter length) test of breaks/bridges of 26-nm pitch structures, ESPERTTM reduced EUV dose while its combo yield was almost 100% over a wide dose range of 20 mJ/cm². For CH patterns, in the case of 32-nm-pitch AEI (after etch inspection), EL was increased 7.5% up to 22.5%, while failure free latitude (FFL) was widened from 1 nm to 4 nm. A 16-nm-pitch LS pattern was successfully printed with 0.5 NA tool, while a 16-nm-pitch PL and an 18-nm-pitch CH patterns were also achieved with an EB lithography by ESPERTTM. With ESPERTTM, there was no pillar collapse observed for 12-nm half-pitch PL by 0.5 NA and 8-nm half-pitch PL by EB. With all the advantages of having a high exposure sensitivity, a low defectivity, and an extremely-high-resolution capability, this advanced development method is expected to be a solution for high-NA EUV towards hyper-NA EUV lithography.

Key words: EUV resist, MOR, contact hole, electrical yield, defects, high-NA EUV, hyper-NA EUV.

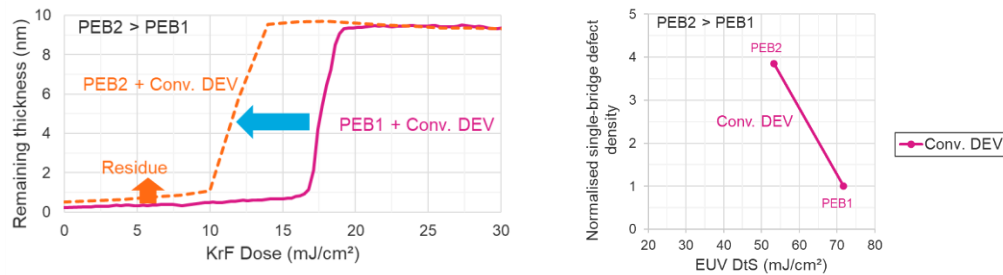
* ESPERTTM and *Enhanced Sensitivity Developer Technology*TM are trademarks of Tokyo Electron Ltd.

1. INTRODUCTION

Chemically amplified resists (CAR) have been used widely for many years in optical lithography. On the other hand, currently metal oxide resists (MOR) are among the leading candidates for EUV lithography at future nodes thanks to its simplicity, small building blocks, and a high etch resistance¹. Thanks to the high etch resistance, it is possible to use a thinner resist with MOR than with CAR, which will be beneficial in pattern collapse mitigation and in high-NA EUV lithography where the depth of focus is smaller. Nevertheless, when developing MOR with the conventional development method, there are still challenges such as the well-known RLS trade-off and defectivity for all types of patterns (LS, CH, PL).

1.1 The dose-residue and dose-defect trade-off relationships

Figure 1 displays the contrast curves and single-bridge defect density of MOR with different PEB temperatures PEB1 and PEB2 (PEB2 is higher than PEB1). When increasing PEB temperature, exposure sensitivity can be improved but at the expense of higher residue (remaining thickness) at low dose area (from 0 to 10 mJ/cm²), as shown in Fig. 1a, and a higher number of single-bridge defects, as shown in Fig. 1b. It is therefore extremely challenging to have both a higher sensitivity and a lower number of defects, simultaneously, using the conventional development.



a) Contrast-curves with two different PEB temperatures b) AEI single-bridge defects of 32-nm-pitch LS

Figure 1. Dose-residue and dose-defect trade-off relationships in MOR.

1.2 The pattern profile challenge

Not only the avoidance of residue (scums), the shape of the pattern profile is also very important factor for good performance. It is normally difficult to obtain vertical pattern sidewalls. Because of the residue (or defect) problem, which is discussed in Sect. 1.1, a strong developer can be used to remove the scums for a low defectivity. But it can also remove the desired resist at exposed areas, so higher exposure doses are required. A high PEB temperature can be used to compensate for the loss in exposure sensitivity, but, due to the high absorption coefficient in MOR, the exposed area will tend to have a reverse tapered shape as displayed in Fig. 2. Having a reverse tapered pattern shape can cause pinching defects, as well as difficulties in etch transfer, reducing DtS, and forming extremely-high-resolution patterns.

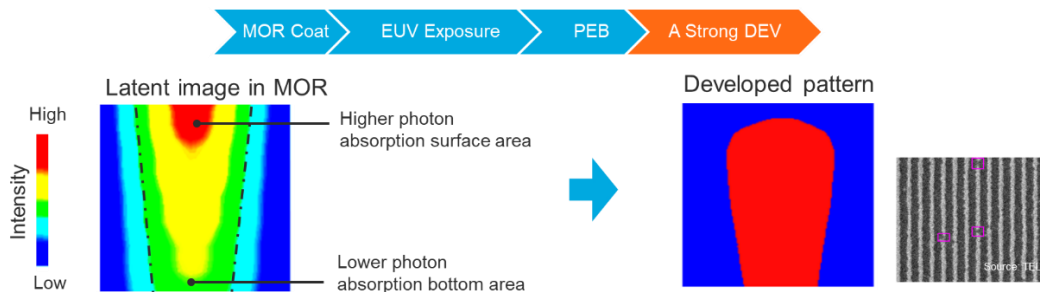


Figure 2. The pattern-profile challenge.

High-NA EUV lithography will require low roughness and defect levels, due to small feature sizes and expected high levels of integration. To achieve these requirements while avoiding large losses of productivity, it is necessary to break the dose-residue trade-off relationship and to obtain a vertical shape of the pattern profile. In this paper, a new advanced development system is used to fulfil the requirements.

2. NEW WET DEVELOPMENT METHOD

In prior papers, a development method named ESPERT™ has been introduced to improve the performance of MOR for both 0.33 NA EUV lithography and 0.55 NA exposure tools²⁻¹⁰. It has proven possible to break the dose-roughness trade-off and reduce defects. The new method was reported to improve the DtS of 32-nm-pitch LS patterns by 36%, while the single-bridge defects were reduced by half⁴. In the case of 36-nm-pitch CHs, the new development method had the capability to remove scums, thus lowering missing defectivity². Meyers et al. also proved ESPERT™ as a chemical super resolution technique¹¹. They used chemical measurements and simulations of ESPERT™ to show that ESPERT™ effectively apodized the MOR chemical image, improving chemical gradient and reducing scums. In this work, this development technique was optimised for tighter-pitch LS, CH, and PL patterns.

The hydrophilicity map of MOR after PEB process, as in Fig. 3, has been reported in our prior literature^{2,4} as in Fig. 3. In the non-exposed area (left side of the figure), most of the hydrophobic ligands are intact and still connected to the core. In the highly exposed area (right side of the figure), the ligands are cleaved, and the resist is hydroxylated. After PEB, there are enough condensed tin-oxides in the highly exposed area, making it insoluble in the developer. In the intermediate region between the non-exposed and fully exposed areas, not all the hydroxy groups are condensed, making it a hydrophilic region.

The conventional development can effectively dissolve the hydrophobic area, but only partially dissolve the hydrophilic area, leaving scums or defects. Using ESPERT™, the removal capability of hydrophobic area is kept unchanged, but the removal capability of the hydrophilic area is promoted, giving it the capability to dissolve the unexposed area completely, i.e., less defects and a higher development contrast.

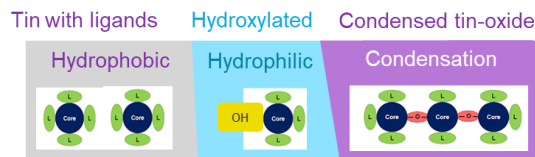


Figure 3. Hydrophilicity map of MOR after PEB^{2,4}.

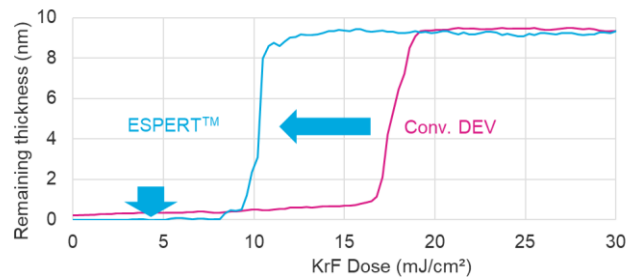


Figure 4. Contrast curves with ESPERT™ and conventional development².

Figure 4 shows the contrast curves when using ESPERT™ and conventional development. It displays that ESPERT™ has both a higher sensitivity and lower residue simultaneously, which was not possible with the conventional development. It also confirms that ESPERT™ has a higher contrast even though the sensitivity is higher. It means ESPERT™ breaks the dose-residue trade-off relationship. Lower residues will result in fewer defects, while a higher contrast can produce a higher EL.

3. EXPERIMENTAL

The performances of the conventional development and ESPERT™ were evaluated and compared using 0.33 NA EUV, 0.5 NA EUV, and EB exposures, for LS, CH, and PL patterns.

For 0.33 NA EUV exposures, 32-nm-pitch, 28-nm-pitch, and 26-nm-pitch LS patterns were exposed using an ASML NXE:3400B EUV exposure tool at imec, unless described otherwise. The bridge defects were inspected by a KLA optical inspection tool. The 32-nm-pitch and 36-nm-pitch hexagonal CH patterns were exposed on a 0.33 NA EUV exposure system at the Albany Nanotech Complex in Albany. The stacks of ADI (after development inspection) and AEI of CH are illustrated in Fig. 5.

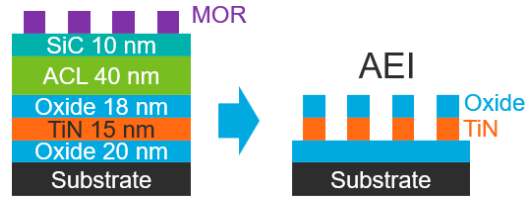


Figure 5. Stack of hexagonal CH patterns by 0.33 NA EUV exposure.

In 0.5 NA EUV evaluation, wafers were exposed by a EUV light from one of the Advanced Light Source (ALS) beamlines at Lawrence Berkeley National Laboratory. The stack was illustrated in Fig. 6. MOR thickness was 12 nm for LS, and it was 16 nm for CH and PL patterns.

The EB evaluation of PL and CH were exposed by an Elionix ELS-BODEN 150 kV beam writer on a 300 mm wafer. 22-nm-thick MOR was spin-coated on a 10-nm-SiC underlayer as illustrated in Fig. 7.

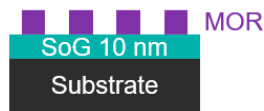


Figure 6. Stack of 0.5 NA EUV samples.

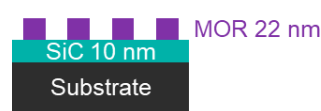


Figure 7. Stack of EB samples.

All SEM images were obtained by Hitachi High-Tech Corp. CD-SEM CG6300. For data analysis, CD, LCDU, and fraction defect were measured by MetroLER software (MetroLER version 3.2, Fractilia, LLC). LCDU was the unbiased value.

4. RESULTS AND DISCUSSION

The results of ESPERT™ are compared with data from conventional development method using 0.33 NA EUV exposure (for LS and CH) and 0.5 NA EUV exposure. The resolution capability of ESPERT™ is also demonstrated using EB lithography.

4.1 LS patterns by 0.33 NA EUV

4.1.1 ADI pattern profiles of ESPERT™

After being developed by ESPERT™, we have confirmed the desired resist profile of a vertical shape. Figure 8 displays the straight resist profile of 26-nm-pitch LS patterns at ADI. Being a straight profile can help to reduce defects (especially breaks), to reduce EUV dose, and to form extremely tight patterns, which will be discussed in the coming sections.

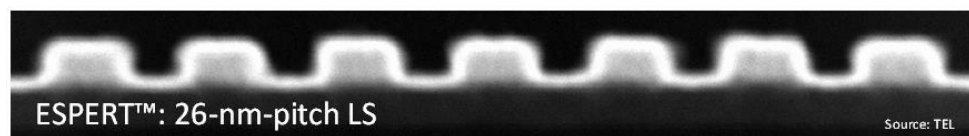
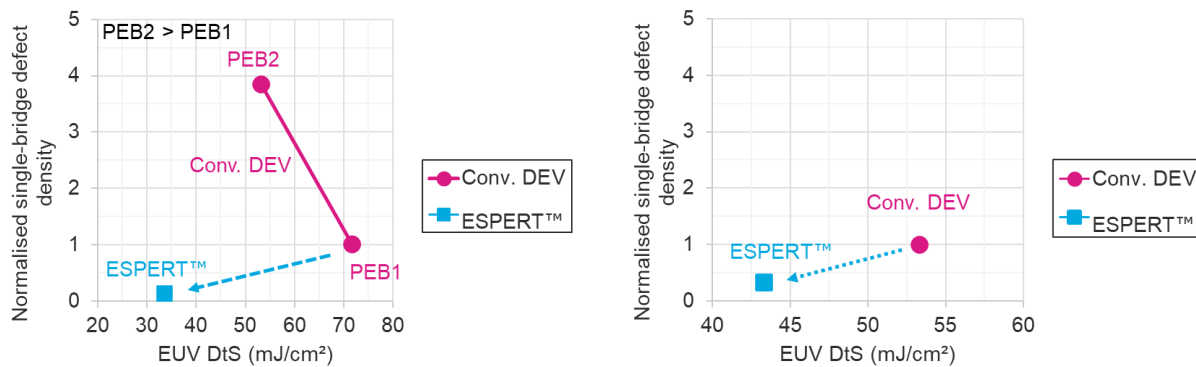


Figure 8. Resist profile of 26-nm-pitch LS pattern developed by ESPERT™.

4.1.2 The dose-defect trade-off relationship

ESPERTTM can effectively remove residues as shown in its contrast curve (Fig. 4). This section shows how this could transfer into a lower defectivity at a higher EUV sensitivity.

Since the single-bridge type of defects is not easily captured by the optical inspection tool at ADI, they were inspected at AEI after being etched into the TiN layer. Figure 9 shows the AEI single-bridge defect density of conventional development and ESPERTTM for both 32-nm-pitch LS (Fig. 9a) and 28-nm-pitch LS (Fig. 9b). The inspection area was 98.4 cm² for 32-nm-pitch LS and it was 238.5 cm² for 28-nm-pitch LS. Unlike conventional development where the single-bridge defects increase when reducing EUV dose, ESPERTTM reduced EUV DtS while single-bridge defects were also reduced for both 32-nm-pitch and 28-nm-pitch LS. For instance, in the case of 32-nm-pitch, EUV DtS was reduced by more than half (from 71.7 mJ/cm² to 33.5 mJ/cm²) while the single-bridge defect density was also reduced by a factor of approximately 7, thus breaking the dose-defect trade-off relationship.



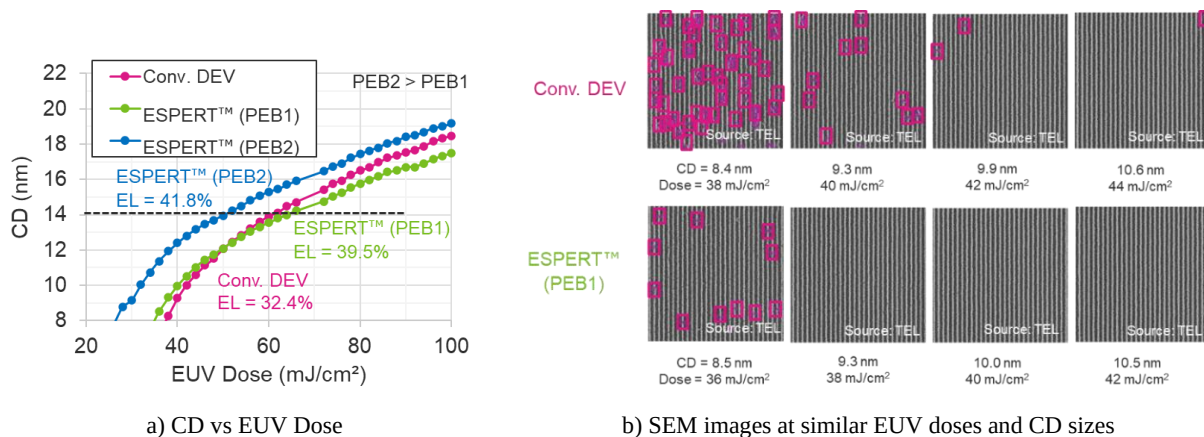
a) AEI single bridge defects of 32-nm-pitch LS

b) AEI single bridge defects of 28 nm pitch LS

Figure 9. ESPERTTM breaks dose-defect trade-off relationship.

4.1.3 The EL and the break defects

Thanks to the high development contrast of ESPERTTM as shown in its contrast curve (Fig. 4), the EL was also higher than that of conventional development. Figure 10 displays the data of 28-nm-pitch LS patterns exposed by the 0.33 NA EUV exposure system at the Albany Nanotech Complex in Albany. With similar EUV DtS (62 mJ/cm² for conventional development and 64 mJ/cm² for ESPERTTM), EL of ESPERTTM was 39.5%, while that of conventional development was 32.4%. Even when DtS of ESPERTTM was reduced to 50 mJ/cm² by using a higher PEB temperature, EL was still maintained high at 41.8%. The minimum CD without collapsing or pinching (break) defects was smaller in case of ESPERTTM which was approximately 9 nm, as shown in Fig. 10b.



a) CD vs EUV Dose

b) SEM images at similar EUV doses and CD sizes

Figure 10. Conventional development vs ESPERTTM for 28-nm-pitch LS (ADI).

4.1.4 26-nm-pitch LS breaks/bridges (combo) electrical yield

Section 4.1.2 shows that ESPERT™ greatly improved the single-bridge defects using the KLA optical inspection tool and Sect. 4.1.3 shows that it also had many fewer break defects using MetroLER software. The electrical test was also conducted for the purpose of verifying the total process performance. An electrical yield of both ESPERT™ and the reference process were also evaluated on 26-nm-Pitch LS using fork-fork (FF) and meander (MN) structures. The electrical yield (in Fig. 11) was measured as a combination of both breaks and bridges from FF and MN structures respectively on 1 meter length. ESPERT™ reduced EUV dose while its combo yield was also higher than the reference. The reference is the current best process in imec. The yield was almost 100% over a wide dose range of 20 mJ/cm² (from 72 to 92 mJ/cm²) for ESPERT™, compared to a dose range of 6 mJ/cm² (from 91.5 to 97.5 mJ/cm²) with a yield higher than 90% for the reference, but still lower than that for ESPERT™. The maximum yield of reference was 92.9% while it was 98.8% in the case of ESPERT™.

The high residue-removal capability of ESPERT™ (desirable for a low bridge defectivity) combined with its vertical resist profile (desirable for a low break defectivity) are possibly the reasons giving ESPERT™ superiority in this combo electrical yield test.

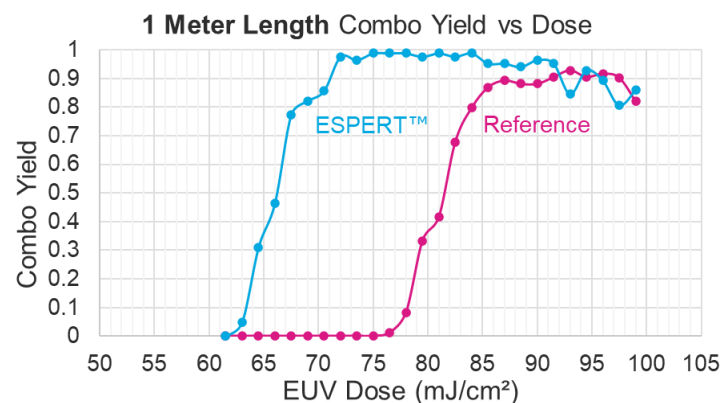


Figure 11. 26-nm-pitch LS combo electrical yield.

4.2 CH patterns by 0.33 NA EUV

The results of ESPERT™ and conventional development method for 36-nm-pitch and 32-nm-pitch CH using 0.33 NA EUV are discussed and compared in this section.

4.2.1 The advantages of CH patterning by negative tone MOR with bright-field masks

Using the negative tone MOR, PL patterns are created by a dark-field mask while CH can be created by a bright-field mask. Figure 12 displays the CD of 36-nm-pitch patterns on a 0.33 NA EUV exposure system for both PL and CH as a function of EUV dose using the conventional development process. With the same resist process conditions, such as PEB temperature, CH patterns require less EUV dose to form the same target CD of 18 nm as compared to PL patterns. The EUV DtS of PL was 65 mJ/cm², while that of CH was only 37 mJ/cm², approximately. This also means that CH created by a bright-field mask could have a lower exposure dose compared to CH created by pillars and tone reversal. Another advantage of CH patterning is that CH are less prone to collapsing, unlike in PL patterning. Despite those advantages, if the CH patterns are developed by the conventional method, there are challenges which are discussed in Sect. 4.2.2 and Sect. 4.2.3. Besides, it is also necessary to keep the blank mask defects low, which is beyond the scope of this paper.

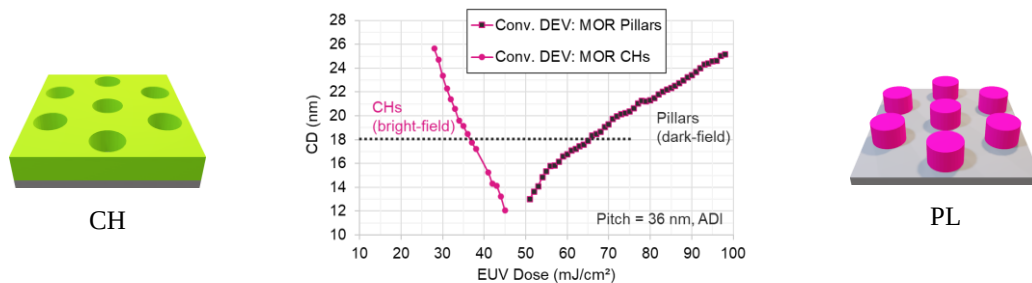


Figure 12. CD as a function of EUV dose for PL created by a dark-field mask and CH created by a bright-field mask using the same process conditions.

4.2.2 ESPERT™ vs conventional development for 36-nm-pitch CH

In a prior paper², ESPERT™ was shown to out-perform the conventional development for 36-nm-pitch CH patterns using bright-field masks. With ESPERT™, EL was increased from 21.1% to 35.5%, LCDU was reduced to approximately 3 nm at target-CD of 18nm, while FFL was extended to target-CD $\pm 10\%$, as shown in Fig. 13.

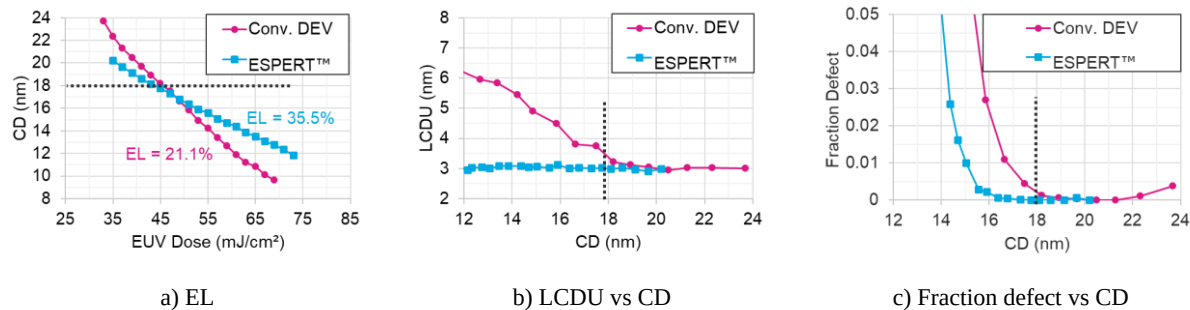


Figure 13. ESPERT™ vs conventional development for 36-nm-pitch CH at ADI.

The same wafers, which were measured at ADI in Fig. 13, were etched through the TiN layer for AEI. Figure 14 displays that there were big improvements in performance when developing by ESPERT™ at AEI also². EL by ESPERT™ was 45.4%, compared to only 24.6% by conventional development. TEM images of AEI samples were also obtained to confirm the changes when using ESPERT™ visually. Figure 14b displays the TEM images at both near target-CD of 18 nm and a small CD near 14.6 nm by both types of development. Using ESPERT™, CH patterns were nicely transferred to TiN layer for both target CD and the small CD. The TiN profiles by ESPERT™ were also straighter, more uniform, and without any missing holes, especially in case of small CD sizes.

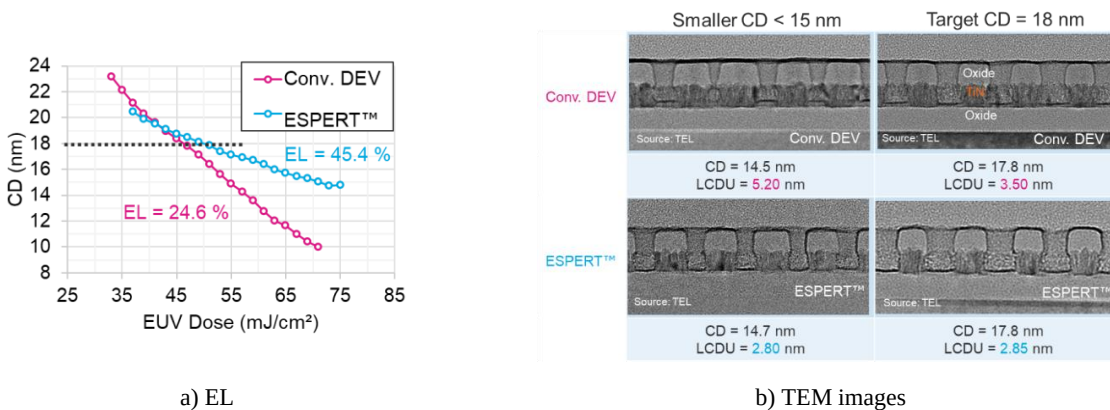


Figure 14. ESPERT™ vs conventional development for 36-nm-pitch CH at AEI.

4.2.3 32-nm-pitch CH patterning by conventional development

Figure 15 shows the differences between 36-nm-pitch vs 32-nm-pitch CH patterning using conventional development. When changing from 36-nm-pitch to 32-nm-pitch, EL was significantly reduced from 21.1% to 9.7% as shown in Fig. 15a. It could be explained by the reduction of NILS which was simulated by PROLITH software (KLA Corporation).

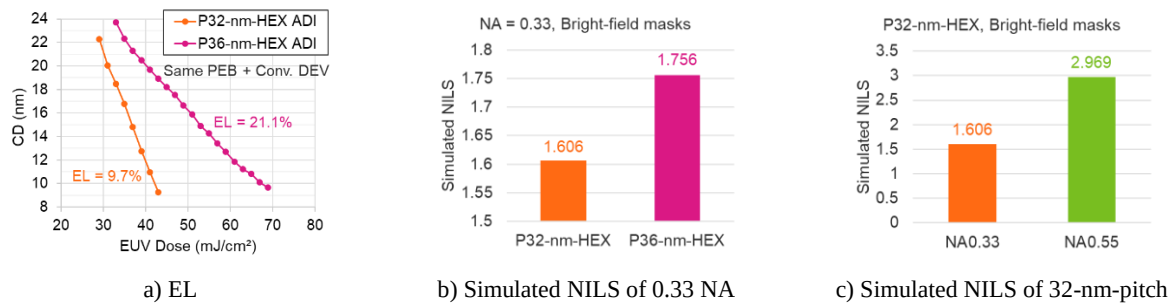


Figure 15. 36-nm-pitch vs 32-nm-pitch CH of bright-field masks.

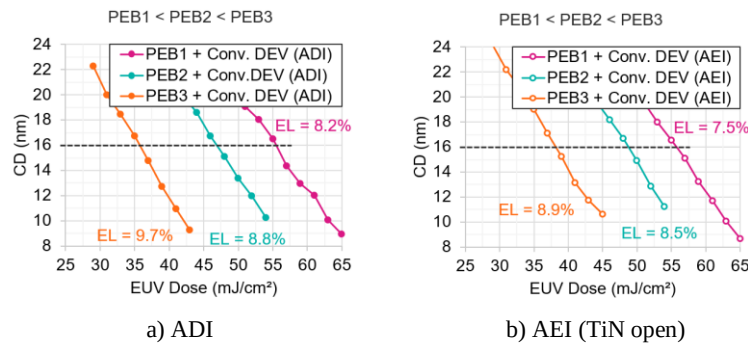
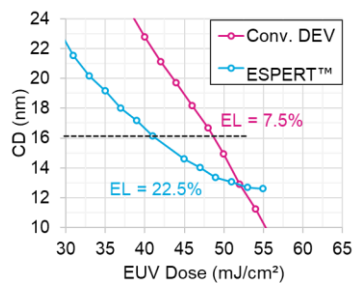


Figure 16. ADI & AEI Data of 32-nm-pitch CH using conventional development with 0.33 NA EUV.

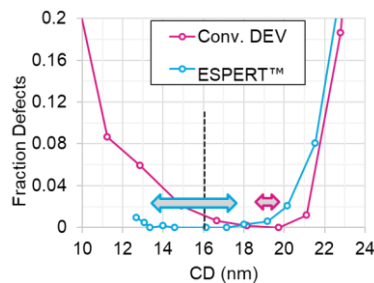
Figure 16 shows that with conventional development, EL did not improve by changing PEB temperature nor through etch. All EL values were less than 10%. The NILS is simulated to be increased from 1.6006 up to 2.969 if a 0.55 NA EUV is used, as shown in Fig. 15c. Using 0.33 NA EUV, it is therefore very challenging to increase EL with conventional development. Section 4.2.4 will show that EL can, however, be increased by ESPERT™.

4.2.4 ESPERT™ vs conventional development for 32-nm-pitch CH

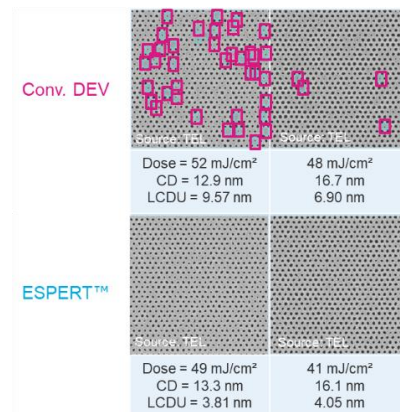
Figure 17 displays the data of 32-nm-pitch CH developed by both ESPERT™ and conventional development at AEI. With ESPERT™, EL was increased 7.5% up to 22.5% at a lower EUV Dts (Fig. 17a), while FFL was widened from 1 nm to approximately 4 nm (Fig. 17b). There were no missing holes detected by MetroLER even at CD of 13.3 nm (Fig. 17c). Therefore, the superiorities of ESPERT™ over the conventional development have been confirmed for 32-nm-pitch CH patterning also.



a) CD vs EUV dose



b) Fraction defects vs CD



c) SEM images

Figure 17. Conventional development vs. ESPERT™ for 32-nm-pitch CH (AEI).

4.3 High-NA (BMET 0.5 NA EUV)

LS data illustrated in Fig. 18 from the 0.5 NA exposure tool has also confirmed the advantages of ESPERT™ as reported^{4,11}. The exposure dose and roughness were improved 30% and 21%, respectively. A 16-nm-pitch LS pattern was clearly resolved without pinching defects.

	20-nm-pitch LS	18-nm-pitch LS	16-nm-pitch LS
Conv. DEV	 Dose = 88 mJ/cm² CD = 9.8 nm, LWR = 3.61 nm	 Dose = 88 mJ/cm² CD = 8.5 nm, LWR = 3.74 nm	NA
ESPERT™	 Dose = 62 mJ/cm² CD = 9.9 nm, LWR = 2.85 nm	 Dose = 67 mJ/cm² CD = 9.0 nm, LWR = 2.63 nm	 Dose = 72 mJ/cm² CD = 7.7 nm, LWR = 3.02 nm

Figure 18. ADI SEM images exposed by 0.5 NA EUV.

CH and PL patterns were also exposed by 0.5 NA EUV. Figure 19 shows the data of 44-nm-pitch CH patterns, ESPERT™ reduced EUV DtS and LCDU by 27% and 16%, respectively. Data of 28-nm-pitch PL and 24-nm-pitch PL patterns were displayed in Fig. 20. There was no collapsing pillar observed at both target-CD of 14 nm and 12 nm with ESPERT™. These data of LS, CH, and PL patterns show the capability of ESPERT™ for extremely-tight-pitch patterns in high-NA EUV lithography.

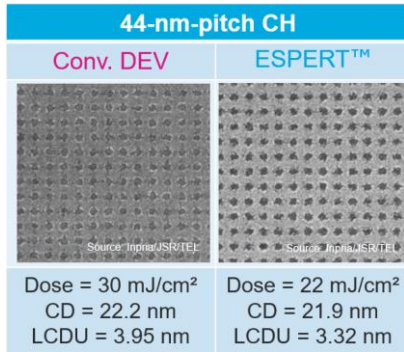


Figure 19. CH patterns exposed by 0.5 NA EUV.

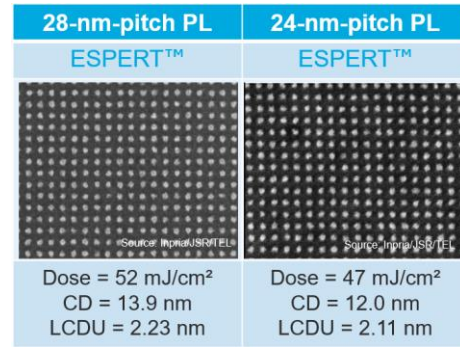


Figure 20. PL patterns exposed by 0.5 NA EUV.

4.4 ESPERT™ towards hyper-NA EUV (EB demonstration)

The data in the earlier sections have shown the superiorities of ESPERT™ in 0.33 NA and 0.5 NA EUV lithography. Instead of a commercial hyper-NA exposure tool, which currently does not exist, an EB lithography system was used to demonstrate that ESPERT™ can also work for extremely tight patterns towards hyper-NA EUV. Figure 21 displays the ADI SEM images of different pitches of PL and CH patterns. Due to that fact that the EB exposure was not stable over the course of exposure, some dislocations of the patterns could be observed. It was, however, not likely to related to the development process. The resist thickness was 22-nm. There was no pattern collapse observed for PL and clear holes could be resolved in CH patterns with sizes down to 16-nm-pitch and 18-nm-pitch for PL and CH, respectively. These results demonstrate the full capabilities of ESPERT™ for not only high-NA but also hyper-NA EUV in the future.

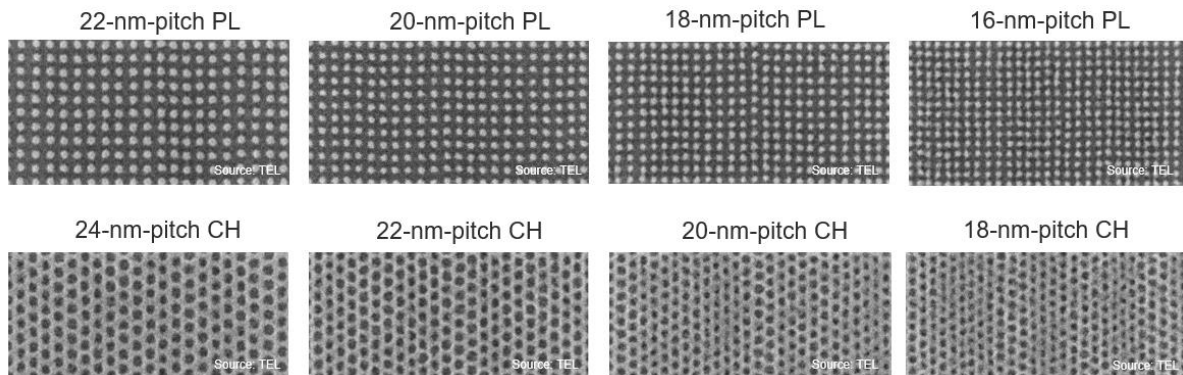


Figure 21. ADI SEM images of extremely tight PL and CH patterns developed by ESPERT™.

5. CONCLUSIONS

This paper has described a robust development method ESPERT™ to improve the performance of MOR. The data confirmed that the new development methods had superiorities over conventional methods. ESPERT™ can be used as a chemical super resolution technique, effectively apodized the MOR chemical image. This results in a high capability to remove scums at low exposure dose regions while enhancing the developing contrast. Consequently, EUV sensitivity and EL are both enhanced while the defectivity is reduced simultaneously.

Using 0.33 NA EUV scanners on 32-nm-pitch LS, EUV DtS was reduced by more than half (from 71.7 mJ/cm² to 33.5 mJ/cm²) while the single-bridge defect density was also reduced by a factor of approximately 7. In addition to the high residue-removal capability of ESPERT™, its resist profile is also vertical, which is generally not possible with conventional development. Thanks to the vertical resist profile, break defects could also be mitigated. In the combo electrical yield test of both breaks and bridges for 26-nm pitch, 1 meter length, ESPERT™ reduced EUV dose while its

combo yield was almost 100% over a wide dose range of 20 mJ/cm² (from 72 to 92 mJ/cm²). For the future work, EB inspection tools will also be used to capture SEM images of locations where the break defects occurred.

Using 0.33 NA EUV scanners on both 36-nm-pitch and 32-nm-pitch CH patterns, ESPERT™ enhanced all EUV sensitivity, EL and FFL. In the case of 32-nm-pitch AEI, EL was increased 7.5% up to 22.5%, while FFL was widened from 1 nm to 4 nm approximately. There were no missing holes observed even at CD of 13.3 nm.

Using this new development method on the 0.5 NA exposure tool, the sensitivity and LWR were both improved by 30% and 21%, respectively. A 16-nm-pitch LS pattern was successfully printed by this high NA tool. For PL patterns, there was no collapsing pillar observed at both target-CD of 14 nm and 12 nm with ESPERT™.

Using a 150 kV EB lithography system, extremely-high-resolution patterns of a 16-nm-pitch PL and an 18-nm-pitch CH patterns were successfully printed on a 22-nm-thick MOR resist by ESPERT™.

With all the advantages of having a high exposure sensitivity, a low defectivity, and an extremely-high-resolution capability, this advanced development method is expected to be a solution for high-NA EUV towards hyper-NA EUV lithography.

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