Recent advancements in 193 nm step and scan lithography

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With the introduction of full field step&scan systems, 193 nm technology development is currently being accelerated and resists are used closer to their final area of application, i.e. under realistic conditions of lens aberrations, stray-light and wafer coverage. In this paper, the lithographic performance of advanced 193 nm resist materials has been evaluated on a full field step&scan system. Single layer and bi-layer resist processes are compared in terms of performance and complexity. Very similar lithographic performance is observed for both the single layer and the bi-layer approaches at 130 nm. Optimization of illumination conditions (NA, sigma) is investigated as a way to enlarge processing windows and to reduce iso-dense bias. The application of a PSM illustrates the extendibility of 193 nm lithography for the 100 nm technology node. In general, significant progress in resist performance has been made but further improvements are needed before 193 nm resists will reach the maturity level of today's state-of-the-art 248 nm resists.

Keywords : ArF lithography, step&scan system, ARC, 193 nm resists, bi-layer resist, CD control

1. Introduction

In 1997, 248 nm lithography has been inserted in the volume manufacturing of integrated circuits. Development of the next lithography wavelength has been slow and 248 nm is being pushed to its limits. The current belief is that 193 nm will be inserted in manufacturing with the 130 nm technology node, which is predicted between 2001 and 2003. This is only about 10 years after the first published¹⁻³ research on polymers for 193 nm. Compared to 248 nm technology development, the development of 193 nm will be at least a factor of two faster.

Return of investment of the 193 nm development efforts will only be possible if this technology can be pushed one generation further, to the 100 nm node. Calculating the k_1 -factors to print 100 nm in 193 nm, strong resolution enhancement techniques like alternating phase shifting masks,

quadrupole illumination and aggressive illumination will be unavoidable.

Photoresist development is, along with optical materials, exposure tools and lasers, one of the key components in the success of 193 nm. In the last year, significant progress has been made in all of these areas. As a result first generation 193 nm full field exposure tools⁴⁻⁶ as well as new advanced resist materials are becoming available.

The major challenge in the resist development is to combine high transparency and good dry etch resistance with good lithographic performance. Several resist approaches⁷ are considered for 193 nm today including single layer resists⁷⁻¹⁵, bi-layer resists¹⁶⁻¹⁸ and top surface imaging (TSI)^{1,19-20}. Single layer resist materials are preferred by the industry because of their limited complexity. However, bi-layer resist schemes are becoming more accepted as bi-layer resists can be

competitive with single layer resists plus BARC in terms of complexity. Until recently, 193 nm resist samples have been primarily evaluated on micro-steppers. These small field systems were very valuable to identify good candidate chemistries and to evaluate lithographic performance. With the advent of full field scanners, it is expected that 193 nm process development will be accelerated. Full field scanners allow the resist process performance to be tested over the full field including real life aberration and stray light levels. Pattern transfer can be checked using representative resist wafer coverage. Additionally the illumination conditions can be adjusted to improve CD control.

In this paper, the lithographic performance in terms of resolution, processing latitudes, linearity, proximity effects of several advanced single layer resist in combination with organic and inorganic ARC²¹⁻²⁵ as well as bi-layer resists are evaluated on a full field 193 nm scanner from ASML.

2. Experimental conditions

2.1 Step&Scan exposure tool

The exposure tool used in this work is the ASML PAS5500/900 first generation 193 nm step and scan tool. The system is based upon the proven PAS5500 step and scan body. The key features and 193 nm specific features of the /900 with respect to the 248 nm DUV Step & Scan tool, are the AERIAL™ II illuminator, the Zeiss Starlith™ 900 lens, the ArF laser source and the beam delivery system. The ArF laser is operating at 1 kHz, 5 W and is line narrowed to a bandwidth smaller than 0.7 pm. The beam delivery system allows the laser to be positioned up to 20 m from the scanner.

The efficiency is optimized by minimizing the amount of optics in the light path. The AERIAL II illuminator, developed by Zeiss and ASML, is a redesign of the AERIAL I and contains CaF₂ to minimize the 193 nm radiation damage. It features the established variable pupil optics functionality which enables high intensity levels at conventional and annular settings. The Starlith™ 900 4x double telecentric lens has a variable NA from 0.45 to 0.60. To minimize the ozone formation and contamination of the optical surfaces, most of the optical path is purged with non-oxygen gases. The laser, beam delivery and illuminator are purged with nitrogen, the lens

contains an inert gas. Other innovations in the /900 are advanced off-axis alignment system (ATHENA) and the Transmission Image Sensor (TIS). The specifications of the PAS5500/900 are summarized in Table 1. Further details on the system performance are described in other papers⁴⁻⁶.

Parameter	Specification
Resolution	<0.15 μm
Field size	26 mm x 33 mm
NA range	0.45-0.60
Sigma range (conventional)	0.35-0.85
Sigma range (annular)	0.35-0.85 (outer)
Annular ring width	≥ 0.30
Integrated Uniformity	< 1.2%
Intrafield CD uniformity range @ best focus @ 0.4 μm focus range	< 22 nm < 32 nm
Image distortion	< 25 nm
Image Plane deviation	< 200 nm
Overlay (single machine)	< 40 nm
Overlay matched to /500	< 60 nm
Throughput (at 10 mJ/cm ² , 46 exp)	> 40 wph

Table 1: Main specifications PAS5500/900.

2.2 Resist processing conditions

Several resist materials have been evaluated and as starting point the processing conditions as recommended by the resist manufacturers have been used. All experiments have been carried out at the ASML application lab using 200 mm Si substrates. Resist processing was carried out on an FSI Polaris DUV cluster and/or on a MTI track. Exposures have been carried out on a ASML PAS5500/900 Step & Scan tool. The specifications and performance of this tool are described in section 2.1. Track and scanner were not interfaced and were located in different areas of the ASML development facility. This distance has an impact on the delay between exposure and PEB and might influence the obtained results for some of the resists which are more sensitive to airborne contamination. In general delay between exposure and PEB was kept shorter than 3 minutes. A number of photo resists were too sensitive to be processed under these conditions. Therefore, a detailed evaluation was carried out only for 2 single layer resists and one bi-layer material.

A first single layer resist sample from JSR was manually coated on a MTI track to a thickness of

392 nm and soft-baked for 90 sec at 140 °C. After exposure, further resist processing consisted of a PEB of 140 °C /90 sec followed by a 60 sec puddle development using OPD262 on a FSI Polaris DUV cluster.

The second single layer resist, Sumitomo PAR101A4 was processed on an organic BARC. Shipley D3 BARC was spin coated on the MTI track and baked at 215 °C. The resulting BARC thickness is 68 nm. The Sumitomo PAR101A4 resist was spin coated and soft-baked at 130°C /60 sec resulting in a thickness of 450 nm. After exposure, resist processing consisted of a PEB of 130 °C /60 sec followed by a 60 sec puddle development using OPD262 on a FSI Polaris DUV cluster.

The bi-layer resist process from ARCH chemicals consisted of a 250 nm thin silicon containing wet developable resist (193ARCH 410) on top of a DUV cured layer of 450 nm 193ARCH 510 material. The 193ARCH 510 layer was spin coated to a thickness of 500 nm and soft-baked at 120 °C. This layer was cured on a Fusion Semiconductor 200 PCU Photostabilizer. After curing, the resulting thickness is 440 nm. The top resist has been spin coated to a thickness of 250 nm. The resist processing consists of 100°C /90 sec soft-bake and 100°C /90 sec PEB followed by 30 sec puddle development in OPD262 on a FSI Polaris DUV cluster. Dry development of the undercoat layer is done in a LAM TCP9400SE etcher using O₂/SO₂ chemistries.

CD measurements were carried out on a Hitachi S-8C40 and a Hitachi S-7800H tiltable CD SEM. Inspection (tilted view) has been done on a Philips XL810 SEM. For cross-sectional SEM evaluation a Philips XL30 analytical SEM has been used.

2.3 Etch equipment/process

For the bi-layer resist, dry development of the bottom layer has been optimized in a LAM alliance TCP9400SE reactor. The TCP reactor provides flexibility with regard to process optimization by its independent control of plasma generation and ion energy. Variables in the optimization of the process in the LAM TCP9400 system are : TCP power, the chuck power, the O₂ flow, the SO₂ flow. Pressure was kept constant at 5 mTorr and electrode temperature at -12°C. For

details on the process optimization we refer to previous publications ^{16,20}. The final optimized process used in this work has the following settings : TCP power = 500W, chuck power = 200 W, SO₂ flow = 25 sccm, O₂ flow= 100 sccm, He flow = 50 sccm, pressure = 5 mTorr and chuck temperature = -10°C. The etch rate for this process is 785 nm/min and selectivity between top and bottom resist is 1:7. With the optimized process vertical profiles down to 0.12 µm are demonstrated.

Etching of a 200 nm P-doped Polysilicon layer has been carried out in a LAM TCP9400 PTX reactor using a three step process (breakthrough etch, main etch and overetch). The main etching step was based on an HBr/Cl₂ chemistry. Typical etch time for a full process is 110 sec.

3. Resist performance evaluation

3.1 Introduction

The strategy for the development of a resist process consists of several steps. First of all the basic lithographic performance of the resist is tested including : resolution, linearity, processing windows, proximity, delay stability, line edge roughness, etch resistance. Bottom anti-reflective coatings are needed for implementation in device production in order to achieve adequate CD control. Therefore the compatibility of the resist with ARCs is evaluated. Both inorganic (SiON) and organic ARCs are considered. After selecting the appropriate ARC, the resist process is further optimized. Illumination conditions (NA/sigma, conventional, annular) as well as resist baking conditions are optimized towards process windows. Finally the use of resolution enhancement techniques such as PSM is applied in order to extend 193 nm to sub-100 nm resolution. In this work, a detailed evaluation of the performance of 2 single layer resists and one bi-layer resist has been carried out. The resists have been processed according to the conditions as described in section 2. The results are described in the following sections.

3.2 Resolution and latitudes

Resolution, linearity and processing latitudes have been determined for both conventional and annular illumination using a binary mask. The standard ASML ATP settings have been used :
- Setting #1, NA=0.60 σ=0.85 (conventional)

- Setting #2, NA=0.58 σ =0.8/0.5 (annular)
Linearity and processing windows have been measured top/down using a low voltage SEM for 0.15 and 0.13 μ m feature sizes. From these process windows, the maximum depth-of-focus and maximum exposure latitude have been determined. An overview of the major results for all 3 resists can be found in table 2 and table 4.

Fig. 1 : Linearity/resolution of ARCH bi-layer resist after wet development of the top resist. (conventional ill., NA=0.60, σ =0.85).

Fig. 2 : Linearity/resolution of ARCH bi-layer resist after dry development of the bottom layer. (annular illumination, NA=0.63, σ =0.8/0.5).

Fig. 1-2 show the profiles of the ARCH bi-layer resist after wet development of the top resist (Fig.1) using conventional illumination and after dry development into the bottom layer using annular illumination (Fig.2). The profiles are straight. With the bi-layer resist an ultimate resolution of 0.12 μ m L/S is achieved both by conventional and annular illumination. The isolated line resolution is 0.10 μ m. The resist process is linear down to 0.15 μ m for the dense features and down to 0.11 μ m for the isolated lines. Excellent results are obtained with the bi-layer which is not so surprising as bi-layer resist schemes are making use of the principle of surface imaging. However single layer resists are nowadays catching up with the bi-layer resist and

are now also demonstrating high resolution. With conventional illumination, the JSR ArF resist on silicon demonstrates an ultimate resolution down to 0.12 μ m L/S (Fig.3) and Sumitomo PAR101A4 resist on organic BARC shows an ultimate resolution down to 0.13 μ m L/S (Fig.4). Both resists show straight profiles. By applying annular illumination, 0.12 μ m L/S are also resolved by the PAR101 resist. Isolated line resolution goes down to 0.10 μ m. For both single layer resists, a linear resolution down to 0.14 μ m L/S has been measured.

Fig. 3 : Resolution of JSR ArF single layer resist (NA=0.60, σ =0.85).

Fig. 4 : Resolution of Sumitomo PAR101A4 (NA=0.60, σ =0.85).

Processing windows have been measured for 0.15 and 0.13 μ m CD's. The maximum depth of focus and maximum exposure latitude as determined from these windows are summarized in table 2. From analysis of the results in table 2, the following can be concluded. All resists show acceptable latitudes for 0.15 μ m dimension. The latitudes for 0.13 μ m CD are rather limited with

conventional illumination. Annular illumination typically increases the DOF especially for the dense lines while exposure latitude is not affected. As the ED-window does not contain any information on profile or possible resist thickness loss, cross-sectional SEM pictures through focus have been made. Profiles through focus are shown in Fig. 5 and 6 for 0.13 μm dense lines in Sumitomo PAR101 respectively for conventional and for annular illumination. An increase of DOF from 0.4 μm to > 0.6 μm is achieved by the use of annular illumination. A similar DOF of 0.60 μm is achieved for the ARCH bi-layer and for the JSR ArF resist (Fig.7) as determined from cross-sectional SEM pictures.

Fig. 5 : Profiles of 0.13 μm L/S in Sumitomo resist using conventional illumination (NA=0.60, σ =0.85).

Fig. 6 : Profiles of 0.13 μm L/S in Sumitomo resist using annular illumination (NA=0.58, σ =0.5/0.8).

Fig. 7 : Profiles of 0.13 μm L/S in JSR resist using annular illumination (NA=0.58, σ =0.5/0.8).

Resist	CD [μm]	NA=0.60, σ =0.85		NA=0.58, σ =0.5/0.8	
		DOF [μm]	EXP [%]	DOF [μm]	EXP [%]
Sumitomo PAR101	0.15 dense	0.75	14	1.05	12.3
Sumitomo PAR101	0.15 isol	0.65	12	0.61	13.3
Sumitomo PAR101	0.13 dense	0.60	12.3	0.85	10
Sumitomo PAR101	0.13 isol	0.40	12.3	0.50	9
JSR ArF resist	0.15 dense	0.65	12.4	0.85	15.4
JSR ArF resist	0.15 isol	0.4	14.7	0.45	14.2
JSR ArF resist	0.13 dense	0.45	10	0.85	11
JSR ArF resist	0.13 isol	0.45	9	0.6	12
ARCH bi-layer	0.15 dense	0.8	10	0.90	8.9
ARCH bi-layer	0.15 isol	0.75	9	0.65	9.2

Table 2 : Overview of maximum Depth-of-focus (DOF) and maximum exposure latitude (EXP) for different critical dimensions (CD) , for different illumination settings (conventional and annular settings) and for the 3 different resists.

3.3 Proximity effect

Good individual processing latitudes have been seen (table 2) for 0.15 μm lines however no overlap is seen between the windows for dense and isolated lines, as the isolated lines require a much lower dose to be printed on target as compared to the dense lines. In Figure 8, the line width of a nominally 0.16 μm line is plotted as a function of the space/line ratio for the ARCH bi-layer resist. In Fig. 9, the line width of a nominally 0.14 μm line is plotted as a function of the space/line ratio for the Sumitomo PAR101 resist.

Fig. 8 : CD versus space/line ratio for nominally 0.16 μm features in ARCH bi-layer resist for different PEB temperatures.

Fig. 9: CD versus space/line ratio for nominally 0.14 μm features in Sumitomo PAR101.

A large difference in CD between dense and isolated lines or a large iso-dense bias is seen. Values for the iso-dense bias are listed in table 4 for the 3 resists for the standard illumination condition. Values up to 65 nm have been measured for the bi-layer resist. This proximity effect or iso-dense bias is an issue that needs to be solved. Several factors are contributing to the proximity effect : aerial image, reticle errors,

resist and resist processing effects. Optimizing the resist processing conditions is one way to reduce iso-dense bias. For example lowering the PEB temperature (90 °C) results in a lower proximity effect as shown in Fig. 8. Another way to reduce proximity is to adjust the illumination conditions. Optimization of the illumination settings has been investigated as well and is described in section 4. Profiles as a function of pitch are shown in Fig. 10 under more optimized conditions.

Fig. 10: Profiles of 0.15 μm lines for different line/space ratios.

3.4 Full field CD control

For device production, CD control over the full field and from wafer to wafer is crucial. In general, acceptable production yields are obtained with CD variations over the scanner field smaller than 10% of the nominal CD. ASML's step and scan systems, as a standard, are tested using :

- six fields
- three focus steps
- 20 points in the field

The horizontal and vertical features are analyzed to produce a distribution through focus, averaged over the six fields. The CDs are measured with an automated top/down SEM. Full field (scanning) CD uniformity measurements were done at one conventional (NA 0.6, σ 0.85) and one annular setting (NA 0.58, σ 0.8-0.5) using the Sumitomo PAR101A4 resist. For 0.15 μm dense lines and spaces, intrafield CD range of 15 nm at Best Focus and 18 nm over a 0.4 μm focus range were obtained with the annular setting. For the conventional setting the CD uniformity of isolated 0.15 μm lines were 15 nm at BF and 32 nm over 0.4 μm DOF. These CD uniformity values are well within the system specifications. The root causes of the observed CD spread have been analyzed⁵. For isolated lines, the higher

values of CD uniformity over 0.4 μm focus as compared to the dense features is attributed the limited DOF for isolated lines.

3.5 Etch resistance

Combining good lithographic performance with good dry etch resistance has been a real challenge in the development of 193 nm resist materials. The etch rate of several resists has been tested in a typical polysilicon etch process in a LAM Alliance TCP9400PTX etcher. A polysilicon etch process consists of a breakthrough step using CF_4 chemistry, a main etch step using HBr/Cl_2 chemistry and finally an overetch step. The etch rate has been measured for two processes : for a full poly etch process including all 3 steps and for an etch process consisting only of the main etch. The values for the etch rates relative to the novolac etch rate are listed in table 3. Typical etch rates are a factor of 1.5 to 1.8 higher than novolac. In a pure HBr/Cl_2 chemistry a factor of 2 in etch rate is found between 193 nm resists and novolac. Etch resistance still needs to be improved.

Resist	Full poly etch	Poly main etch
Novolac	1	1
JSR ArF	1.76	2.07
PAR101	1.51	2.19
Resist X	1.66	
Resist Y	1.8	

Table 3 : Relative etch rate in a polysilicon etch process.

Fig. 11 : 150 nm etched polysilicon lines before stripping of the resist

Patterned polysilicon wafers have also been etched using Sumitomo PAR101 in combination with an organic BARC and using JSR resist without ARC as mask. Successful pattern transfer into a 200 nm thick amorphous Silicon layer is demonstrated in Fig. 11 for both resist materials. Fig. 11 shows 150 nm amorphous Silicon lines after etch and before stripping of the resist. We can conclude that the resist thickness and the etch resistance are sufficient for pattern transfer into a 200 nm polysilicon layer.

3.6 Performance overview

A summary of the performance of the three resists is listed in table 4. In general the performance of the 3 resists is pretty comparable. Both single layer resists fulfil the requirements for sensitivity being below 10 mJ/cm^2 . The bi-layer resist has a somewhat lower sensitivity. Linear resolution down to 0.15-0.14 μm and ultimate resolution down to 0.13-0.12 μm for conventional illumination have been demonstrated. Also in terms of processing latitudes no major differences are seen. All resists showed sensitivity to contamination resulting in severe T-top formation after 10 min post-exposure delay (PED) in 20 ppb NH_3 environment. Also the delay effect in the stepper (in filtered environment) has been tested. This is important because for some specific system test such as for example CD uniformity, the exposure times can go up to more than 30 minutes. Both single layer resists were found to be very stable showing only a few nm line width change for PED up to 40 minutes. The bi-layer resist had a rather limited stability and could not be used for long exposure times. The compatibility with SiON was found to be fine for the JSR resist as illustrated by the profiles in Fig. 12. The Sumitomo resist however showed sloped profiles and more footing. Footing is a well known issue in case of SiON and might be reduced by giving an appropriate pre-treatment of the SiON wafer and/or by using an oxide cap on the SiON. This needs further investigation.

Fig. 12 : JSR resist on SiON

Line edge roughness is another well known critical issue for 193 nm resist. The line edge roughness has been measured on a KLA8100ER. No significant difference has been seen between the resists. For the bi-layer resist, the line edge roughness (LER) after dry development is influenced by the dry development conditions. A clear correlation has been seen between the selectivity of the etch process and the LER.

Resist name	JSR ArF resist	Sumitomo PAR101A4	ARCH bi-layer
Resist thickness	392 nm	450 nm	250 nm
ARC thickness	None	68 nm D3 BARC	450 nm
Sensitivity	6.5 mJ/cm ²	7 mJ/cm ²	20 mJ/cm ²
Linearity for dense lines	0.14 μ m	0.14 μ m	0.15 μ m
Linearity for isolated lines	0.12 μ m	0.11 μ m	0.11 μ m
Ultimate resolution L/S	0.12 μ m	0.13 μ m	0.12 μ m
Ultimate resolution IL	0.10 μ m	0.11 μ m	0.10 μ m
DOF 0.15 L/S (X-section)	0.60 μ m	> 0.60 μ m	0.50 μ m
DOF 0.13 L/S conventional (X-section)	No data	0.40 μ m	0.40 μ m
DOF 0.13 L/S annular (X-section)	0.60 μ m	0.60 μ m	0.60 μ m
Iso-dense bias on 0.15 μ m	55 nm	45 nm	65 nm
Max DOF/EL 0.15 L/S	0.65 μ m / 12%	0.75 μ m / 14 %	0.80 μ m / 10 %
Max DOF/EL 0.15 μ m IL	0.40 μ m / 14 %	0.65 μ m / 12 %	0.75 μ m / 9 %
Max DOF/EL 0.13 μ m L/S	0.45 μ m / 10%	0.6 μ m / 12 %	No data
Max DOF/EL 0.13 μ m IL	0.45 μ m / 9 %	0.40 μ m / 12 %	No data
Contamination sensitive	Yes	Yes	Yes
Delay sensitive in stepper	OK > 40 min	OK > 40 min	sensitive
SiON compatibility	OK	Footing, profile slope	OK
Line edge roughness	8 nm (3 σ)	8.9 nm (3 σ)	6.8 nm (3 σ)
Etch rate (HBr/Cl ₂)	2.1 x novolac	2.2 x novolac	
Etch rate (full poly process)	1.8 x novolac	1.5 x novolac	1 x novolac

Table 4 : Overview of the resist performance

Finally the etch resistance of the single layer resists is limited and some further improvements are needed. The bi-layer resist has an etch rate which is comparable to novolac.

To summarize, significant progress has been made in terms of resist performance. Bi-layer and single layer resists are comparable in terms of process performance and complexity. Still a number of improvements are needed before the 193 nm resists will reach the maturity level of the 248 nm resists. Critical issues which need improvement are SiON compatibility, LER, etch resistance, proximity effect and depth of focus especially of isolated lines.

4. Effect of the illumination conditions

Iso-dense bias is a critical issue as already shown in paragraph 3.3. Iso-dense bias is partly due to the resist chemistry and processing and is partly due to the aerial image. Indeed, as was seen in table 2 the iso-dense bias for Sumitomo resist was lower as compared to JSR resist and to the bi-layer resist. Optimization of the illumination conditions is evaluated in this work as a way to improve the overlapping processing windows for

dense and isolated lines. It was found that the effect of the NA and sigma settings on the ultimate resolution and on the iso-dense bias have an opposite trend. The smallest feature sizes are resolved under the conditions of high NA in combination with high sigma values. For minimum iso-dense bias however, low sigma values are beneficial. As such, the standard illumination conditions used in this work (NA=0.60 and $s=0.85$) are indeed optimum to achieve the highest resolution but are not ideal with regard to iso-dense bias.

Fig. 13 : Top/down photos of 0.15 μ m L/S and IL for low partial coherence (left) and for high partial coherence factor (right).

Fig. 13 shows top/down pictures of 0.15 μ m dense and isolated lines for two different values

of partial coherence. The low partial coherence factor results in the lowest iso-dense bias. Fig. 14 shows the processing window for 0.15 μm lines and spaces (L/S) and for 0.15 μm isolated line (IL) for different illumination conditions. At the highest sigma value of 0.85, no overlap is seen for the L/S and the IL windows. Decreasing the sigma to 0.7 or 0.55 results in a good overlap for the processing windows.

The overlapping processing windows have also been measured for logic design rules. In case of logic design rules the most dense features (equal lines and spaces) are not present in the design.

The process windows have been measured for line/space ratios of 1:1.5, 1:2, 1:3 and a fully isolated line. For 0.15 μm CDs a large overlapping processing window is obtained for all pitches especially at low $\sigma=0.55$ (Fig. 15). The overlapping DOF is 0.8 μm and overlapping exposure latitude is 12% for the $\sigma=0.55$, while for the higher $\sigma=0.85$ the overlapping DOF is only 0.35 μm and overlapping exposure latitude is 3%. For the 0.13 μm dimensions no overlap is seen for all pitches (Fig. 16). The use of higher NA or the application of optical proximity correction will be required for 0.13 and sub-0.13 μm feature sizes.

Fig. 14 : Processing windows for 0.15 μm dense and isolated lines for 5 different illumination conditions.

Fig. 15 : Processing windows for 0.15 μm features for 4 different line/space ratios at two illumination settings

Fig. 16 : Processing windows for 0.13 μm features for 4 different line/space ratios at two illumination settings.

5. PSM results

The use of alternating PSM was investigated as a way to further improve resolution and processing latitudes.

Fig. 17 : 90 nm isolated line in ARCH bi-layer resist after wet development (left) and after dry development (right), exposed with an alternating PSM.

Fig. 18 : DOF of 70 nm lines in PAR101 resist (PSM, NA=0.63, $\sigma=0.35$).

Exposures with an alternating PSM using an NA=0.60 and a $\sigma=0.35$, resulted in an isolated line resolution down to 60 nm for the bi-layer resist. However significant resist thickness loss was seen at these small dimensions. Practical

resolution for the bi-layer resist with PSM was 90 nm isolated lines. The profile of a 90 nm isolated line, after wet development of the top layer and after dry development, is shown in Fig. 17. With the Sumitomo PAR101 resist a resolution down to 70 nm IL was demonstrated in a 450 nm thick layer (Fig. 18). Depth of focus on the 70 nm line was $>0.5 \mu\text{m}$ both by profile as well as by CD criterion (Fig. 18).

6. Conclusions

The performance of advanced 193 nm resists has been studied on a full field scanner. Significant progress in resist development has been made in the last year resulting in a performance of single layer resists being comparable with bi-layer resist. Excellent resolution down to 0.12 μm L/S and 0.10 μm IL has been demonstrated with binary masks. Acceptable processing latitudes have been achieved. Some critical issues which need further improvement are : proximity effects, etch resistance, line edge roughness and ARC compatibility and depth-of-focus of isolated lines. The optimization of the illumination conditions was investigated as a possible way to reduce proximity effects. Exposure at low $\sigma=0.55$ resulted in large overlapping windows for 0.15 μm features. 0.13 μm lithography without strong enhancements looks feasible but might require higher NA and/or the use of OPC in order to enlarge the overlapping processing windows. The use of strong enhancement techniques (PSM) resulted in 70 nm line resolution with 0.5 μm depth-of-focus and as such holds promise for the 100 nm technology node.

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