Recent Advancements in EUV Resist Materials and Process Performance

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Resist ability to simultaneously meet the requirements for Resolution, LER and Sensitivity (RLS) remains one of the critical issues EUV Lithography is facing. As good progress in resolution and sensitivity have been made, nowadays LER and pattern collapse are considered as the two main items requiring improvement. In this paper, the current performance of EUV resist on the ASML ADT is reviewed and the effectiveness of process improvements for pattern collapse and LER reduction has been investigated. Results are presented of EUV resist screening for sub-28nm LS and 30nm contact holes on the ASML ADT to prepare for a resist process on the pre-production tool NXE:3100, currently under installation at imec. Acceptable resist performance was obtained for 28nm LS with some of the new resist materials outperforming the current imec reference resist in terms of LER. By applying a 20% mask bias, imaging of 30nm contacts at $<14\text{mJ/cm}^2$ with wide processing latitudes was achieved. Local variation of contact CD however is a serious limitation at smaller contact sizes. The use of TBAH developer and the application of FIRM rinse were found to be effective to reduce pattern collapse and to extend processing windows. With the FIRM rinse in addition LER was improved. Finally the feasibility of printing 22nm LS at 13mJ/cm^2 with 4.7nm LER have been demonstrated on the NXE:3100 using dipole illumination.

Keywords: EUV lithography, EUV resists, TBAH, pattern collapse, rinse, LER

1. Introduction

Extreme Ultraviolet (EUV) lithography is a key lithography option for sub-22nm device manufacturing. Resist ability to meet the requirements for Resolution, LER and Sensitivity (RLS) remains one of the critical issues EUV Lithography is facing, as confirmed at the 2010 EUVL symposium. Several publications [1-4] have assessed the performance and readiness of EUV resists towards 22nm. Line width roughness (LWR) and pattern collapse were identified as the main items requiring improvement and several solutions were proposed.

At imec we have been methodically evaluating the performance of different resists from various vendors since 2008, using the

ASML ADT full field scanner. At its introduction the ASML ADT was specified for 40nm LS imaging [5-6].

Fig. 1 : Resist progress with regard to sensitivity and LER on the ADT at imec

Resolution at which good imaging performance was obtained on the ADT gradually improved from 40nm in 2008 to 28nm HP in 2010 by the improvement in resist materials. Indeed, steady progress in resist was made for both resolution and sensitivity (Fig.1) and to a lesser extent on Line Edge Roughness (LER). To meet the stringent requirements on LER, post-litho smoothening techniques might need to be applied [7].

In this paper, the current status of EUV resist performance at imec is reviewed. We report our findings with regard to resist screening for Line Space performance at 28nm and below and 30nm HP contact holes. Process improvements in the form of alternative developer and surfactant rinse are applied to the selected resist to cope with pattern collapse and improve on LER.

By mid 2011, the ASML NXE:3100 pre-production exposure tool [8], with off axis illumination capability, will be operational at imec. We plan to extend the current resist work towards 22nm and 16nm HP, with this tool.

2. Experimental conditions

2.1 Exposure and outgassing tool

Exposures have been carried out on an ASML EUV Alpha Demo Tool (ADT) full field scanner, installed at imec, using conventional illumination with NA=0.25 and $\sigma=0.5$. A TEL Clean Track ACTTM12 interfaced to the ADT was used for resist processing.

Before exposure on the ADT, the resists are tested for outgassing in a dedicated set-up, supplied at the end of 2008 by EUV Technology (Martinez, US). This set-up has the capability of RGA based outgassing testing as well as witness plate based contamination testing. Details of the tool set-up and procedures have been previously described [9-10]. Only resists passing the outgassing criteria are allowed to be exposed on ADT.

2.2 Resist materials and processing

All experiments were carried out using EUV resists samples and organic underlayers (UL) supplied by commercial vendors. Chemically amplified resists were coated at 50-60nm film thickness on 300mm wafer silicon wafers or on top of an organic UL. Vendor recommended settings for post-apply bake and post-exposure bake temperature and time were used.

All resist screening/benchmarking work was carried out on 20nm thick organic underlayer plumed on the track (referred to as std UL). The experimental resist samples were hand dispensed using pipets. Development was done in-line, standardly in TMAH (0.26N) without surfactant. The alternative developer TBAH (0.26N) as well as the surfactant rinse FIRMTM Extreme material has been installed on the track.

2.3 Metrology and analysis

For critical dimension (CD) and LWR measurements a Hitachi CG4000 scanning electron microscope (SEM) was used. In case of contact holes, the local variation in CH dimension, which can be considered as the equivalent of LWR, has been determined. The CD of 25 contacts in each field of view are measured on Hitachi SEM and 1 sigma standard deviation of the 25 measurements is calculated. This measurement is repeated at 10 different locations and the average of these 10 measurement is reported as local contact hole CD variation.

Process windows for LS and CH have been analysed with the Klarify Prodata software from KLA-Tencor. Processing latitude determination is based on CD measurement as well as visual inspection of the quality of the printed images. Elliptical process windows were used to calculate exposure latitude (EL) and depth- of- focus (DOF) values.

3. Resist performance for lines/spaces

3.1 Resist material screening for 28nm HP

Screening of resist materials is carried out at imec on the ADT, mainly with regard to the RLS performance. We have previous reported [11] that by the application of an underlayer an improvement in LER with 15-20% could be obtained and that a reduction in resist thickness to 50nm was needed to print feature sizes at 28nm HP and below. Therefore all resist screenings in the last year were carried out in 50nm thickness on the std UL in 20nm thickness at imec. Screening of new Underlayers was also undertaken in thicknesses of 10nm and 5nm but no significant improvement was seen compared to this std UL [11].

Figure 2 shows the dose-to-size versus LER for several resists in 2010. Resists A,B and C were installed on track and benchmarked in detail [11], resulting in a best overall performance for resist B and as such resist B is the reference resist

Fig. 2: Dose-to-size vs. LER for 28nm LS for various resists

to judge the progress in performance in 2011. No resist meets the LER target of 3.5nm. Only few resist material (Fig. 2) are achieving a lower LER than the reference resist B and this is even at the expense of a higher dose.

Fig. 3 : Dose-to-size vs. LER for 28nm LS with advanced resists and new test mask (2011).

In 2011 a new test reticle was introduced for resist screening. Figure 3 shows the dose versus LER plot for the reference resists as well as for the latest resist sample exposed in 2011 with the new reticle. Exposure dose drops with about 2 mJ/cm² and LER decreases with 0.2-0.3nm for the reference resist B. This might be attributed to a better quality of the new mask, resulting in a decrease in the contribution of the mask line roughness to the LER in resist [12]. One new material (resist F) is simultaneously meeting both the LER (3.5nm) and sensitivity target (15mJ/cm²) for 28nm LS. The overall performance of this material F with regard to

processing windows and ultimate resolution is of course also important (Table I).

Resist	DTS 28nm L/S (mJ/cm ²)	LER 28nm LS (3σ nm)	28nm L/S		27nm L/S		MEEF 30nm	ultimate resol.
			Max EL	Max DOF	Max EL	Max DOF		
target	15	3.5	10%	100nm	10%	100nm		26
Resist B	12.1	4	18%	120nm	0%	0nm	1.4	26
Resist C	13.2	4.1	18%	120nm	9%	40nm	1.3	26
Resist D	14.7	3.9	21%	160nm	17%	80nm	1.3	26
Resist E	14.4	3.8	12%	120nm	4%	40nm	1.5	26
Resist F	15.4	3.5	17%	120nm	11%	80nm	1.5	27

Table I: Performance overview (on the ADT) of the promising resist materials to date.

	28nm HP	27nm HP	26nm HP	25 nmHP
Resist B				
Resist C				
Resist D				
Resist E				
Resist F				

Fig. 4: Resolution pictures (NA=0.25, σ=0.5)

A comparison of the better performing resist samples, is illustrated in Table I. Good processing windows are obtained for both 28nm and 27nm LS for resist F, outperforming the reference resist B. Resist D is the champion with regard to process windows. While all resists are clearly resolving 26nm and only minor bridging/necking is keeping them from resolving 25nm (Fig. 4), pattern collapse is limiting the usable resolution of resist F to 27nm.

The resist performance on actual 2-dimensional device patterns are of great interest to IC manufacturers. A device type pattern with 28nm HP features was exposed on ADT using resists B,C,D, and E. Figure 5 shows the printed wafer results, in addition to the original mask design pattern and the results of simulation with the calibrated resist model for imec's baseline

process. All four resist resolved the pattern reasonably well with good match to simulation.

Fig.5 : 2 dimensional device patterns

3.2. Resolution towards <22nm node imaging

Resolution capabilities of chemically amplified resist at 22nm HP and below have already been demonstrated on micro-exposure tools [4, 13] and were recently reported also on the ASML NXE:3100 pre-production tool [8] using dipole illumination. Screening of resist materials for 22nm HP and below will start at imec on the NXE:3100 in the 2nd half of 2011.

In preparation for the 22nm resist screening, a wafer was exposed on a NXE:3100 (NA=0.25) at the ASML facilities with Resist B on std UL using 60 degree dipole ($\sigma=0.81/0.43$) illumination. Process windows at 28nm showed a significantly larger DOF (200nm) than the conventional illumination on ADT. Reasonable process windows on 25nm LS were also obtained: 12.2 mJ/cm² DTS, 4nm LER and 13% exposure latitude. 22nm lines were well resolved with a LER of 4.7nm and sub-20nm resolution was demonstrated as illustrated in Fig.6. This holds promise with regard to the performance of the newer advanced resists on the NXE:3100.

Fig. 6 : 22nm down to 19nm HP resolution in resist B (40nm thick) using dipole illumination on NXE:3100.

4. Resist performance for contact hole

With regard to contact hole performance, besides processing windows, the main important parameters are the dose-to-size and the Local Critical Dimension variation of the contact holes (LCDU) within an array of contacts. This LCDU parameter behaves in a similar way as LWR in case of lines/spaces. The imec internal target value for dose-to-size is 15 mJ/cm² and for LCDU is 1nm (1 σ) for 30nm contacts. A lowering of the dose-to-size can be realised either by enhancing the sensitivity of the resist through chemical modifications (e.g. by PAG, Quencher optimization) or by applying a mask bias.

Fig. 7 : Dose-to-size for 30nm contact holes versus designed CD on mask for resist B at 2 different PEB temperatures and for resist CH1.

Several dedicated contact hole resists were initially screened at a film thickness of 60nm on the ADT for their performance at 32nm (64nm pitch). This screening resulted in the identification of a resist CH1 having wide processing latitudes at low dose to size. This resist has been further tested in more detail, targeting 30nm CH (60nm Pitch) and its performance was compared to the reference resist B on track, using different mask biases. The contact hole reticle has several biases. For the nominal 30nm (pitch 60nm) contacts, biases of respectively +3nm,+6nm,+8nm corresponding to 10%,20%,25% were applied.

Performance results of resist B and CH1 are summarized in Figure 7 and Figure 8 for 30nm contacts at several mask biases. Dose-to-size linearly decreases with increasing mask CD (mask bias) for both resists (Fig.7 and 8), but this was found at the expense of a higher local CDU. Possible contributors to the LCDU are expected to be : image contrast, mask quality, shot noise, acid diffusion etc. Resist B was processed at two

	Resist B			Resist CH1		
Mask CD	C33P60(+10%)	C36P60(+20%)	C38P60(+25%)	C33P60(+10%)	C36P60(+20%)	C38P60(+25%)
Dose-to-size	17.6mJ/cm2	13.7mJ/cm2	12.3mJ/cm2	12.7mJ/cm2	9.8mJ/cm2	8.8mJ/cm2
1 sigma LCDU	1.4nm	1.5nm	1.5nm	1.5nm	1.7nm	1.7nm
Max Exp latitude ($\geq 15\%$)	19.1%	21.0%	18.8%	13.7%	15.0%	16.7%
Max DOF ($\geq 120\text{nm}$)	160nm	160nm	150nm	160nm	120nm	80nm
DOF at 10% EL	160nm	160nm	120nm	130nm	90nm	80nm
Exp Latitude at 150nm DOF	18%	14.0%	1.0%	6%	0.0%	0.0%

Fig. 8 : Performance data of 30nm contacts (pitch 60nm) in resist B and resist CH1 exposed on the ADT (NA=0.25, $\sigma=0.5$) for 3 different

28nm HP contacts				
	Resist B		Resist CH1	
Mask CD	C34P56	C35P56	C34P56	C35P56
Dose-to-size	14.6mJ/cm2	13.4mJ/cm2	10.5mJ/cm2	9.5mJ/cm2

Fig. 9 : 28nm contact holes performance

Fig. 10 : 26nm LS patterns in 60nm (left) and in 50nm (right) thick resist B.

different PEB temperatures to check a possible impact of acid diffusion on the LCDU. At 20% mask bias (Fig.7) indeed a lower LCDU value was found at low PEB conditions, but lower PEB temperature also increased the dose to size. Lowering the sensitivity of the resist either by chemical changes or by processing conditions (e.g. PEB temp. variation) obviously has led to better LCDU. The clear trade-off between dose and LCDU leads to the conclusion that shot noise is probably the main contributor to LCDU. Optimum mask bias is about 10-20% for largest processing latitudes (Fig. 8). The mask error enhancement factor (MEEF) was measured as 1.5 to 1.6 for 30nm HP contacts for both resists and independent of the mask bias.

Overall, resist B is better performing than the resist CH1. Resolution of 28nm HP contacts is feasible (Fig. 9) but no usable process window is

	30nm HP	28nm HP	26nm HP
TBAH
	CD=30.1nm Dose 11.8 mJ/cm ²	CD=26.9nm Dose 13 mJ/cm ²	CD=26.3nm Dose 14.2 mJ/cm ²
TMAH

Fig. 11 : Resolution pictures of resist B (60nm thickness) on UL, developed in TBAH and in TMAH.

obtained due to unacceptable high variation of contact size.

5. Resist process improvements

At (sub)-28nm feature sizes pattern collapse limits the ultimate resolution and the process windows. A reduction in aspect ratio by thinning the resist from 60nm to 50nm thickness (Fig. 10) solves the collapse issue but resulted in higher LER [11]. Therefore two modification in the processing of resist at the development step have been investigated to reduce pattern collapse: the use of an alternative developer TBAH [14-16] and the use of a surfactant rinse [3,17].

5.1 TMAH versus TBAH development

Development using 0.262N tetra-butyl ammonium hydroxide (TBAH) instead of conventional 0.262N tetra-methyl ammonium

Fig. 12 : Effect of developer on LER for 30nm and 28nm LS on Si substrate and on UL.

Fig. 13: 28nm LS through dose for resist B and C (60nm FT) with and without the FIRM rinse

hydroxide (TMAH) has been proposed for pattern collapse mitigation by researchers at Selete. [14,15]. Reduction of resist swelling during development in the bulkier TBAH has been originally proposed as the operating mechanism. An alternative mechanism based on surface modification by the developer has been proposed by imec [16]. The latter explains also why the pattern collapse improvement works with certain resist chemistries and not with others.

The performance of (TBAH) was compared to TMAH, both at a 0.262N concentration. The resist B was used in a thickness of 60nm on Si substrate and on Underlayer. A clear improvement in resolution is illustrated in Figure 11 with the development in TBAH. With TMAH, pattern collapse limits the resolution to 30nm LS, while the use of TBAH resolves the 26nm LS. Development with TBAH results in more top rounded resist profiles. A 6% improvement in sensitivity was noticed with TBAH. No beneficial effect on LER was found (Fig. 12). The LER is increasing by the use of TBAH on both Si and UL substrate. The beneficial effect of an underlayer on LER is illustrated.

Fig. 14 : Exposure latitude of 28nm LS for resist B and C with and without FIRM rinse.

Resolution	Resist B (60nm) DI-water	Resist B (60nm) FIRM
28nm HP	28nm	28.3nm
26nm HP	27nm	26.4nm
25nm HP	14.2mJ/cm2	25.7nm 14.8mJ/cm2

Fig. 15 : Effect of FIRM on resolution limit of resist B

5.2 Application of FIRM rinse

A well know method to mitigate pattern collapse includes the use of surfactant rinses. These are applied after the development step and the final DI water rinse, before spin drying.

The FIRMTM Extreme rinse has been applied to resist B and resist C in 60nm thickness on organic UL. A clear improvement in pattern collapse margin without any impact on sensitivity is seen for both resists by the use of FIRM rinse (Fig. 13). The minimum standing CD at 56nm pitch (Fig. 13) is reduced with 3nm by FIRM. Resist B is suffering more from pattern collapse than resist C. The minimum standing CD at 56nm Pitch is 29.4nm which means that basically resist B does not resolve 28nm LS and has no process window.

Fig. 16 : LER on 28nm LS for resist B and C with and without FIRM rinse

A clear improvement in resolution and exposure latitude for resist B by FIRM is shown in Fig. 14-15. Process window for both resists B and C is significantly increased. A further increase in process window could be achieved by combining a thickness reduction to 50nm and the use of FIRM rinse (Fig.14). Additionally, FIRM rinse resulted in a 7% LER reduction (Fig.16).

Due to its simultaneous improvement in pattern collapse and LER, its ease of application (simple in track processing), and compatibility with different resist types, this rinse process is very attractive to be implemented for 22nm node resist processing.

6. Summary and conclusions

In this paper the current status of the resist performance was reviewed. Reasonable resist performance for 28nm LS and 30nm contact holes have been demonstrated on the ASML ADT exposure tool. While no resist meets all the RLS requirements at 28nm and below simultaneously, there has been a slow march of improved performance towards the target by most resist vendors in the last couple of years. Resolution capability of 26nm LS was shown in several resists but in some cases was limited by pattern collapse. Improvement in pattern collapse was demonstrated with FIRM rinse and TBAH developer. The FIRM rinse also provided the added benefit of lower LER.

For contact holes, by applying mask biasing, the sizing dose could be lowered to a value comparable as for LS. This was however achieved at the expense of a higher local CD variation of the contacts. Keeping the LCDU

under control remains the main challenge for contact hole performance.

With the availability of NXE:3100 preproduction exposure tool at imec, with off-axis illumination capability, we plan on continuing the resist process characterization and development effort towards 22nm and below.

Initial results with Dipole illumination on NXE:3100 looks encouraging. The reference resist B shows 22nm LS at 13mJ/cm² with 4.7nm LER and sub-20nm features show clear modulation.

It is expected that to meet the performance targets for 22nm, we may have to adopt all possible process improvements such as FIRM Rinse or Alternative developer chemistries, and other available post-litho smoothing processes [7].

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