Measuring resist-induced contrast loss using EUV interference lithography

Andreas Langner^{a,*}, Harun H. Solak^{a,b}, Roel Gronheid^c, Eelco van Setten^d, Vaida Auzelyte^a,
Yasin Ekinici^{a,c}, Koen van Ingen Schenau^d, Kees Feenstra^d

^aPaul Scherrer Institut, 5232 Villigen PSI, Switzerland

^bEulitha AG, 5232 Villigen PSI, Switzerland

^cIMEC vzw, Kapeldreef 75, B-3001 Leuven, Belgium

^dASML Netherlands B.V., De Run 6501, 5504 DR Veldhoven, The Netherlands

^eETH Zürich, 8093 Zürich, Switzerland

*andreas.langner@psi.ch; phone +41 56 310 2543; <http://lmn.web.psi.ch/>

ABSTRACT

In this paper the contrast behavior of photoresists upon EUV exposure is addressed. During a lithographic exposure, the intended shape undergoes contrast loss which can be divided into two portions. One part is assigned to exposure tool induced contrast loss (e.g. aberrations of the exposure optics, mechanical stability of the system), while the other part is due to chemical processes in the resist during exposure and development. Both contributors have to be decoupled from each other in order to solely analyze the resist contrast loss. The method presented here is based on an experimental evaluation of dense line/space patterns obtained from EUV exposures. For decoupling of the resist induced contrast loss from the exposure tool contrast, the aerial image has to be determined. As an alternative EUV exposure tool the EUV interference lithography (EUV-IL) beamline at Paul Scherrer Institute is applied for resist qualification. The theoretical description of the sinusoidal aerial image of the EUV-IL tool is presented as well as the experimental method applied to analyze resist patterns in terms of resist contrast. Finally, the results are compared with data obtained from ASML's ADT EUV scanner.

Keywords: EUV, interference lithography, resist contrast loss

1. INTRODUCTION

One of the main issues in EUV lithography is the photoresist-induced contrast loss. In case of chemically amplified (CA) resists, the acid diffusion during post-exposure bake is the main factor contributing to image blur. For example, a conventional EUV CA photoresist with a typical value of 15 nm acid diffusion length would lead to approximately $1\sigma = 10$ nm Gaussian image blur. Especially for small pitches as targeted by EUV lithography the image blur limits the contrast which can be achieved in resist [1]. However, the resulting image contrast is not only impacted by the photoresist-induced contrast loss but also by the exposure tool contrast loss. For photoresist performance testing as well as for exposure tool qualification it is necessary to decouple both portions leading to image contrast loss. Since only the printed pattern in resist is available for analysis, e.g. via determination of the exposure latitude, the aerial image as delivered by the exposure tool has to be determined theoretically. In this paper a method is presented which uses EUV interference lithography (EUV-IL) as an independent exposure tool for EUV CA photoresist qualification. Furthermore, the results are compared with data obtained from exposures on the ADT EUV scanner from ASML. In this section the theoretical description of the sinusoidal aerial image of the EUV-IL tool will be presented as well as the method applied for resist contrast analysis.

1.1 EUV interference lithography

In interference lithography two or more beams are coherently superimposed to produce a periodic aerial image used for the exposure of photoresists. Fig. 1 shows the scheme of the grating-based EUV-IL setup installed at the Swiss Light

Source (SLS), Paul Scherrer Institute [2]. A coherent beam of 13.5 nm wavelength which is generated by the synchrotron source is used. Mirrors and pinholes are used to coherently and homogeneously illuminate the grating mask. The gratings consisting of Cr lines are written with e-beam lithography on Si₃N₄ membranes of about 100 nm thickness. The sinusoidal aerial image leading to dense line/space pattern necessary for resist analysis is produced by two gratings of equal period. The period of the interference pattern is half the period of the gratings if the first order diffracted beams are used for interference. This method has been shown to enable patterning of photoresists down to 11 nm half-pitch and has been applied for numerous applications in the field of nanopatterning as well as for EUV resist characterization [3].

Figure 1. Scheme of grating-based interference with two (left) and four (right) beams using two and four gratings with the same period, respectively. The corresponding SEM images show 11 nm half-pitch lines in case of the two beam interference and 19 nm half-pitch dots for the four beam exposure in HSQ [3].

1.2 Aerial image

Considering a one-dimensional image modulation along x-axis, the aerial image of an exposure tool can be characterized using the Normalized Image Log-Slope (NILS), defined via the slope of the intensity distribution $I(x)$:

$$NILS = L \frac{\partial \ln I(x)}{\partial x} \quad (1)$$

where L is the linewidth of the patterned lines. An aerial image produced by two interfering beams has a sinusoidal intensity distribution of

$$I(x) = M \left(\frac{\cos(kx) + 1}{2} \right) + B \quad (2)$$

with M the modulation amplitude, B the background intensity, and $k = 2\pi / p$ with p the period (see Fig. 2). Combining Eq. 1 and Eq. 2 $NILS$ can be expressed as

$$NILS = \frac{M}{M + 2B} \pi = \mu \pi \quad (3)$$

with μ between 0 and 1. In an ideal aerial image without any additional level of background ($M = 1$, $B = 0$), $NILS$ is equal to π for a nominal linewidth L equal to half-pitch at ideal threshold. However, flare levels other than zero as well as blur result in a reduced intensity modulation of the aerial image and add an additional background which will reduce $NILS$ to values less than π .

Figure 2. Sinusoidally shaped aerial image with period p , modulation M and background B . At ideal threshold, the linewidth L is equal to half-pitch.

1.3 Resist contrast

For the resist characterization dense line/space patterns with various pitches are analyzed with top down SEM imaging. The analysis of the critical dimension (CD) through dose is used to determine the exposure latitude (EL) for each pitch [4]. The EL is defined via the dose range for $\pm 10\%$ change in CD around half-pitch (hp) as target CD:

$$EL = 0.2 \frac{CD_{size}}{Dose_{size}} \left. \frac{\partial(Dose)}{\partial(CD)} \right|_{Dose_to_size} \quad (4)$$

In case of a resist without contrast loss the EL is equal to 10π in interference-based lithography. However, for resist-induced contrast loss the EL will decrease. The ratio $EL/(10\pi)$ gives a number between 0 and 1 which describes the contrast of the resist. This resist contrast is derived by experimentally determine the developed resist image as described by EL and correct it for the optical contrast delivered by the tool as given by NILS. Therefore, resist contrast loss is equal to $1-EL/(10\pi)$. It should be stressed that this definition of resist contrast is different from the commonly known resist development contrast as given by γ .

In Ref. [4] a Modulation Transfer Function (MTF) is proposed describing the evolution of resist contrast through pitch p :

$$MTF = \frac{p^2}{2\pi^2 L_d^2} \left[1 - \exp\left(-\frac{2\pi^2 L_d^2}{p^2}\right) \right] \quad (5)$$

The only free parameter in this equation is the resist blur length L_d . It has been proposed that this parameter constitutes all the factors contributing to image blur [5]. For chemically amplified resists (CARs) the main contribution to this length comes from the acid diffusion. This is the reason why L_d is often referred to as acid diffusion length in the context of CARs. The MTF model, however, can be applied to non-CARs as well. For non-CARs other mechanisms than acid diffusion are main contributors to image blur. Therefore, L_d will be more generally referred to as resist blur length within the scope of this paper. It should be stressed that there is a difference between Gaussian image blur and this resist blur length L_d . In the limit of resist blur lengths much smaller than the pitch, L_d is larger by a factor of $\sqrt{2}$ compared to 1σ Gaussian image blur. This factor increases with decreasing ratio of resist blur length to pitch [5]. According to the model above, MTF for all resists goes to zero as p approaches zero while MTF is unity as p goes to infinity, meaning that for periods p much larger than the resist blur length L_d an ideal contrast value of one is obtained. In this work, we use Eq. 5 for EUV-IL results as a best-fit model for the analysis of measured contrast curves of different pitches and their comparison.

2. EUV-IL EXPOSURE AND RESULTS

As discussed in Section 1, resist pattern characterization is done via determination of the exposure latitude. Furthermore, the analysis of resist behavior through pitch yields information about the capability of the resist to resolve small pitches. Therefore it is necessary to expose and analyze line/space patterns through dose as well as through pitch. In this section the experimental conditions for the EUV-IL setup are described and then the resist contrast and resist blur lengths obtained from EUV-IL exposures of different resists are presented.

2.1 Mask design for EUV-IL

The masks which are used for the exposures in the EUV-IL setup are written with electron beam lithography in PMMA and subsequently etched into a 15 nm thick Cr layer. At 13.5 nm wavelength material absorption is high. Therefore, the masks are fabricated on free-standing Si_3N_4 membranes with 100 nm thickness and with an area of a few mm^2 , supported by silicon frames. The mask designed for the necessary line/space exposures through pitch and dose features several grating pairs with grating periods between 88 and 400 nm which equates half-pitches on wafer between 22 and 100 nm. For the interference pattern first order diffraction is used. The grating pairs are arranged in a way which excludes the overlap of higher orders (up to third) with the first order interference pattern. The advantage of having several grating pairs on a single mask is that a number of different pitches can be exposed within a single exposure dose. All areas outside the gratings on the mask are coated with a thick polymer film which completely absorbs the direct (zero order) beam.

2.2 Resists

Two CARs and one non-CAR (Hydrogen Silsesquioxane, HSQ) were chosen for EUV-IL exposure and analysis. The CARs are positive tone resists with a well balanced trade-off between resolution, line edge roughness and sensitivity. In contrast, HSQ is a negative tone resist with very high resolution but at the cost of sensitivity. Table 1 shows some process parameters for the used resists.

Table 1. Process parameters of the used resists including post-apply bake (PAB) and post-exposure bake (PEB).

Resist name	Substrate	Spinning	PAB	Thickness	PEB	Developer / Time
Fujifilm FEVS-P1101	Si/HMDS	1500 rpm / 45s	120°C / 90s	70 nm	110°C / 90s	TMAH 0.26N / 60s
Shin-Etsu SEVR-40	Si/HMDS	1500 rpm / 45s	110°C / 60s	63 nm	90°C / 60s	TMAH 0.26N / 30s
Dow Corning XR-1541 (HSQ)	Si	2000 rpm / 45s	70°C / 60s	50 nm	--- / ---	TMAH 2.6N / 60s

2.3 Exposure and analysis

The EUV-IL exposures were done on 4" silicon wafers in a dose meander. The distance between grating mask and wafer surface was $800 \pm 20 \mu\text{m}$. In contrast to exposure tools based on projection optics the gap between wafer and mask does not affect the quality of the exposed pattern as long as the gap is within the overlapping region of the two interfering beams. However, there is an optimum gap defined by the grating geometry at which the interference pattern has the largest possible width. After developing, the resulting line/space patterns were imaged with Scanning Electron Microscopy (SEM) in top down configuration. Subsequently, CD analysis was done offline with the software LWR_Demokritos [6].

2.4 Results

Several through-dose exposures were done using the resists listed in Table 1. The CD of the line/space patterns was analyzed through dose and pitch and fitted with a second order polynomial. Half-pitch was taken as target CD and with Eq. 4 EL was calculated from the fitted second order polynomial. For the calculation of the pitch-dependent resist contrast, an ideal sinusoidal aerial image was assumed, i.e. $NILS = \pi$ for all pitches. This implies that there is no contrast loss due to the exposure tool itself. This assumption will be discussed more in detail in the next section.

In Fig. 3 the measured resist contrast as a function of half-pitch is plotted for different resists. Although more pitches were resolved in the exposures only data points are plotted which were obtained from uniform CD images with a statistical relevant number of working doses. All three resists show a decrease in contrast towards smaller half-pitches. Furthermore, it can be seen that HSQ possesses the highest contrast values followed by FEVS-P1101 and SEVR-40. In case of HSQ and FEVS-P1101, half-pitches down to 25 nm were resolved. For SEVR-40 only half-pitches down to 40 nm showed sufficient performance for analysis.

Figure 3. Resist contrast over half-pitch is plotted for the resists exposed with EUV-IL. The data points represent the evaluated resist contrast at given half-pitch while the solid lines represent the corresponding MTF fits obtained from Eq. 5. The resulting resist blur lengths L_d are given in the key.

For all three resists the corresponding MTFs (Eq. 5) were calculated and plotted in Fig. 3. The corresponding resist blur lengths L_d obtained from the MTF fits are listed in the key of Fig. 3. The two CARs have resist blur lengths of 14.5 nm and 17.5 nm, respectively, which are typical values for acid diffusion in EUV CARs. In contrast, the non-CAR resist HSQ features a considerably lower resist blur length of approximately half the value of the CARs. However, with respect to the agreement between measured resist contrast and fitted MTF, the behavior of CARs seems to be better reproduced than the behavior of the non-CAR.

3. DISCUSSION

The resist blur lengths in the last section were derived from the resist contrast behavior through pitch. The resist contrast, in turn, is proportional to the ratio of EL and NILS. While EL is an experimentally derived number which describes the resist exposure and development, NILS is based on theoretical considerations and describes the aerial image of the exposure tool. In this section both contributions to resist contrast will be treated individually and their impact on the resist blur length will be discussed.

3.1 Exposure latitude

The resist blur lengths L_d given in the key of Fig. 3 indicate the resolution capability of the corresponding resist. Although the underlying single parameter model is a rather simple model to describe the performance of a resist, the results are in good agreement with experimental observations. For example, with FEVS-P1101 dense L/S patterns down to 20 nm half-pitch were obtained in EUV-IL while it was only 27 nm half-pitch for SEVR-40. However, it has to be stressed that this parameter does not solely characterize the resist resolution itself but rather the performance of the whole resist processing including exposure and development. For example, alternative developers can be used to improve the resist contrast. In the case of HSQ it has been shown that using a salty NaOH solution as developer can significantly increase the resolution [7]. Similarly, the contrast and resolution for CARs can be improved by optimization of post-exposure steps. For instance, an increased performance of CARs has been reported by replacing the developer TMAH with TBAH [8]. Although for both CARs studied in this work a higher EL and a higher resist contrast, thereby a lower resist blur length L_d can be obtained, an elaborative process optimization is out of scope of this work.

Further difficulties in quantitative analysis of the contrast curves come from the CD imaging and analysis itself. The interaction of imaging electrons with the resist during SEM inspection modifies the morphology of the resist. This effect can be minimized (though not absolutely be avoided) by using SEM settings with low energy deposition. In addition, in an analysis with top-down SEM imaging, significant information such as the top loss of the resist during processing and

the slope of the resist edges cannot be determined. In our analysis 90° resist line edges and absence of resist top loss during development is assumed.

Finally, the results of the CD analysis are very sensitive to threshold settings during the analysis of the resist SEM images. A change in the threshold setting results in a shifted position of the detected edge and thus the measured CD value will change as well. In order to make the data from different resists comparable to each other, the SEM was operated with a fixed set of parameters for image recording and a fixed threshold for edge detection in the offline CD analysis. Nevertheless, these parameters rely, to a certain amount, on subjective human perception and vary within a small range without a severe change in the detected resist edge position. For the presented procedure this range was estimated to be about $\pm 4\%$ of the analyzed pitch. If the analyzed CD data is biased within this range, the corresponding EL and thus the resist contrast will change. For the two CARs this effect is shown in Fig. 4. The resist blur lengths for each MTF fit are given in Table 2.

Figure 4. Comparison of the contrast values over half-pitch for differently biased CD data. The red curves represent the non-biased data as shown in Fig. 3. The green and blue curves are derived from biased CD values of plus and minus 4% of the corresponding pitch, respectively.

For both CARs the non-biased MTF resist contrast fits (red curves in Fig. 4) are located between the biased ones. However, the effect of biasing on the resist contrast shows an opposite behavior for the two CARs. In case of FEVS-P1101 a positive bias of the measured CD data leads to a slightly higher resist blur length of 15.7 nm compared to the non-biased value of 14.5 nm. In contrast, a negative bias results in a significantly smaller resist blur length of 10.7 nm. For SEVR-40 the situation is vice versa. The negative bias shows only a small increase in resist blur length while the positive bias leads to a clearly decrease of the resist blur length.

Table 2. Overview of the resist blur lengths L_d obtained from the biased CD data for the two CARs. The non-biased experimentally determined CD values have been biased with $\pm 4\%$ of the corresponding pitch and the resulting resist blur lengths are compared to each other.

Resist name	L_d [nm] -4% bias	L_d [nm] no bias	L_d [nm] +4% bias
Fujifilm FEVS-P1101	10.7	14.5	15.7
Shin-Etsu SEVR-40	19.5	17.5	13.3

The conclusion from this section is that the resist performance measurement via EL determination can be applied to compare the performance of different resists to each other. However, the method is quite sensitive to the applied analysis parameters, e.g. applied parameters during SEM imaging and threshold setting for line edge detection in the CD analysis. This has been shown by the bias analysis. In order to make the procedure more reliable it is important to obtain a statistical relevant amount of data for the analysis. This can be achieved, for instance, by exposing and analyzing small dose steps per pitch and several pitches per exposure dose.

3.2 Normalized image log-slope

So far, for the analysis and the discussion NILS was assumed to be at its ideal value of π for an aerial image produced by two interfering beams. However, several parameters impact NILS which will be discussed in this section.

Since NILS is a number describing the aerial image of the exposure tool, it is sensitive to the mask with its diffraction gratings used for the generation of the interference image. Therefore, the mask itself was imaged with SEM and grating linewidth and line edge roughness have been analyzed. The exposed line/space patterns are generated by a pair of identical gratings. The ratio of line to space determines the diffraction efficiency of a grating. For first order diffraction from an amplitude grating, highest diffraction efficiency is obtained for equally-sized lines and spaces, i.e. 1:1 duty cycle. During mask fabrication this ratio is not always obtained. However, NILS is only affected if there is a difference between the gratings which belong to the same grating pair. In that case the diffracted amplitudes from each grating would differ and thus the minimum intensity in the interference pattern does not vanish anymore. The aerial image would still be sinusoidally shaped but with a decreased modulation and an additional background (see Fig. 2 and Eq. 3). For the used mask the measured deviation of the line/space ratio between the two gratings of each grating pair is less than 1 nm. This deviation can be assigned to measurement errors produced by SEM and CD analysis and thus there is no correction on NILS necessary for that case.

Another issue is the line edge roughness (LER) of the grating lines of the mask. For this mask a LER of $3\sigma = 4.3 \pm 0.5$ nm was obtained. This value is quite independent of the analyzed pitch. LER marks a deviation from the assumption of an ideal grating. A rough grating edge introduces additional scattering points for the transmitted light. Simulations have been performed to estimate the impact of rough grating edges. The interference pattern of a 100 nm period grating with LER $3\sigma = 4.3$ nm was calculated with Huygens-Fresnel wave propagation and normalized with the interference pattern of an ideal grating without LER. For that case a scattering-induced background of maximum 3% was obtained. With Eq. 3 the according NILS value is calculated to be 0.94π for 3% background intensity. Due to the constant LER the produced background will be less significant for larger pitches. A 100 nm pitch on mask exposes a 25 nm half-pitch pattern in resist. Since none of the tested resists showed sufficient resolution performance at half-pitches below 25 nm, the corrected NILS of 0.94π provides a maximum correction value for mask-produced background intensity.

NILS is not only affected by the design and the properties of the mask. Mechanical and thermal instabilities have to be considered as well because they lead to image blur. Relevant contributions are only expected to arise from the relative motion between mask and substrate during exposure. Although vibration measurements were conducted for the whole setup, their meaning is quite limited because they describe the vibrations of the setup as a whole. The distance between wafer and mask during the exposure is typically in the range of a few hundreds of micrometers only. Reliable precision measurements on a nanometer scale, e.g. by interferometric means, are not available for this setup. Therefore, a maximum estimate based on the tool performance is presented instead. As shown in Ref. [3], 11 nm lines could be exposed in HSQ using the EUV-IL setup. Assuming this value as the vibration-induced limit of resolution for the EUV-IL exposure tool, a Gaussian image blur of $\sigma = 4$ nm (i.e. $\approx 50\%$ image modulation at 11 nm hp) is used to describe the vibration behavior.

Both estimates, the pitch-independent background and the pitch-dependent Gaussian image blur, are used to correct the ideal NILS of π . The resulting pitch-dependent NILS is plotted in Fig. 5. For large half-pitches the correction to NILS is only on the order of a few percent and mainly caused by the background intensity. The smaller the half-pitch the more pronounced the impact of the Gaussian image blur becomes. At 22 nm half-pitch, for example, the tool-induced contrast loss in this maximum estimate is 20%.

Figure 5. Plot of NILS versus half-pitch with for the EUV-IL tool with a maximum background of 3% and an assumed Gaussian image blur of $\sigma = 4$ nm.

This pitch-dependent NILS can now be used to normalize the EL measurements with a background- and mask roughness-corrected aerial image. Due to the lower NILS which is a result of the tool-induced contrast loss, the resist contrast values increase. The resulting resist blur lengths for that corrected NILS are listed in Table 3 and compared to the values obtained from an assumed ideal NILS of π . For the two CARs the decrease in L_d is on the order of 20% of the uncorrected L_d . However, in case of HSQ the corrected L_d of only 0.1 nm implies that there is virtually no resist contrast loss in the HSQ exposure process. This clearly indicates that the EUV-IL tool-induced contrast loss resulting from mask roughness and image blur has been overestimated. In future, further experiments will be conducted to explore the limits of the factors which may contribute to the tool-induced contrast loss of the EUV-IL exposure tool.

Table 3. Comparison of resist blur lengths L_d assuming an ideal NILS value of π (L_d uncorrected) and a pitch-dependent NILS corrected by 3% background and $\sigma = 4$ nm Gaussian image blur (L_d corrected).

Resist name	L_d [nm] uncorrected	L_d [nm] corrected
Fujifilm FEVS-P1101	14.5	11.8
Shin-Etsu SEVR-40	17.5	14.3
Dow Corning XR-1541	7.7	0.1

4. COMPARISON WITH EUV SCANNER DATA

4.1 ADT exposures and results

For both CARs exposures were done also on the ADT EUV scanner at IMEC, Belgium. For EL determination CD-SEM (half-pitches 30, 32, 35, 40 nm) and scatterometry (half-pitches 40 and 50 nm) was used and the NILS factors were provided by simulation. The resulting contrast values over half-pitch are shown in Fig. 6 for HMDS primed silicon and organic underlayer substrates. For the required EL determination calibration measurements were undertaken to ensure comparability of the ADT and PSI data.

FEVS-P1101 gives very similar performance on underlayer and HMDS-primed Si. The results from the contrast loss test are very similar for both processes. The contrast loss is quite constant through pitch at 0.35-0.40. For SEVR-40 the performance on underlayer is clearly better than on primed Si substrate. It is known for this material that it forms a foot on primed Si, which potentially affects the top down CD measurements, resulting in an apparently increasing resist

contrast with decreasing feature size on Si substrate. Compatibility between SEVR-40 and the organic underlayer is much better. This results in higher overall contrast and a stable signature through pitch. The contrast loss for this material is determined at ~10%. It should be noted that the MTF model (Eq. 5) is not valid for multiple orders as with ADT for $k_1 > 0.5$ and thus it does not give a very good fit to all data sets in Fig. 6. The MTF always rises to a value of 1 at high pitches which is clearly not the case for the P1101 data sets. This will be further discussed based on simulation results in the next section.

Figure 6. Resist contrast as a function of imaged half-pitch for FEVS-P1101 and SEVR-40 exposed on ADT on HMDS primed Si and organic underlayer (UL) substrates.

4.2 Discussion

Determination of the resist contrast loss requires not only accurate (experimental) determination of EL, but also accurate determination of NILS through simulation. NILS simulations have been performed using Prolith and included the following scanner imperfections: flare (calculated from the pattern density on the reticle layout and the point spread function for the optics of ADT2 as provided by Zeiss), aberrations and estimates on the stage vibrations (estimated to be $MSD_{xy} = 3 \text{ nm } 1\sigma$). In addition to the NILS calculations, simulations have been done to understand the differences in response of the resist contrast test between PSI and the ADT. The simulated response of $EL/(10 \text{ NILS})$ versus pitch for a default resist model is given in Fig. 7. For this model the acid diffusion length was set at 15 nm, which is a typical value for a conventionally blended EUV CAR. It is notable to see that the apparent resist contrast is lower for the ADT settings than it is for the PSI. The background is that the very high NILS on the ADT (due to the fact that multiple diffraction orders are captured by the pupil at sufficiently large dimensions) is impacted more by the acid diffusion than the lower NILS at PSI. Indeed when the acid diffusion length is reduced the two curves move closer together (data not shown).

The simulations also show that the expected behavior of the resist contrast test is either a fairly constant response of $EL/(10 \text{ NILS})$ through pitch or a monotonous decay of the resist contrast towards tighter pitches. Except for the process of SEVR-40 on Si substrate, the experimental results in Fig. 6 indeed demonstrate this behavior. For the case of SEVR-40 on Si substrate exposed on the ADT, specific resist substrate interactions probably cause metrology artifacts leading to anomalous behavior. These results can therefore not be used.

Figure 7. Simulated response of resist contrast through pitch for a resist with an acid diffusion length of 15 nm using typical illumination settings for the ADT and for PSI.

The resist modeling has been used to extract a resist-dependent blur length from the experimental ADT data presented in Fig. 6. In case of SEVR-40 on underlayer it is about 10 nm and for FEVS-P1101 it is about 15 nm. These values can now be compared to the resist blur lengths obtained from the EUV-IL exposure. Since there is no HSQ data from the ADT only the CARs can be compared to each other. For FEVS-P1101 the resist blur length of 15 nm from ADT exposure corresponds perfectly with the resist blur length of 14.5 nm obtained from the EUV-IL exposure with an assumed ideal NILS of π (see Table 3). However, as discussed in the last section mask roughness and Gaussian image blur will lead to a reduced NILS value for the EUV-IL exposure. The result is a decreased resist blur length if the corrections are applied. In case of FEVS-P1101 the corrected L_d is 11.8 nm (third column Table 3). With the data available for the EUV-IL tool, this 20% range between 11.8 nm and 14.5 nm resist blur length marks the confidence region for the resist blur length of FEVS-P1101. If the EUV-IL tool is taken as a reference system, then this 20% range in L_d translates into a maximum variance of 14% for resist contrast determination at 27 nm line/space patterns on the ADT.

In case of SEVR-40 there is a significant difference between the ADT and EUV-IL exposure. While the 10 nm resist blur length from ADT was derived from the SEVR-40 exposure on organic underlayer, the EUV-IL exposure for that resist has been done on bare silicon. As mentioned before metrology issues are thought to be the reason why the SEVR-40 on silicon exposure leads to inconsistent results.

5. SUMMARY

A method has been presented which is capable of characterizing EUV resist contrast loss upon EUV exposure. The method relies on a careful analysis of dense line/space patterns via their pitch-dependent exposure latitude. For decoupling resist-induced contrast loss from exposure tool contrast loss, an accurate determination of the aerial image quality of the tool is required. The EUV-IL tool at PSI delivers a very well defined sinusoidal aerial image with a pitch-independent ideal NILS equal to π . Parameters which affect NILS have been discussed and their contribution to resist contrast has been shown for the EUV-IL setup. In case of the EUV-IL data, a resist-dependent resist blur length based on an MTF is extracted, which qualifies the resolution capability of the resists.

In addition to examining resist contrast at PSI, the applied CARs were also exposed on ASML's ADT EUV scanner. In accordance with the PSI exposure FEVS-P1101 showed the same resist performance as characterized by the resist blur length L_d . In case of SEVR-40 the results cannot be compared between ADT and EUV-IL exposures. The reason for that is that the ADT exposure with a resist blur length of approximately 10 nm has been derived from SEVR-40 on underlayer. The metrology problems when SEVR-40 on Si is analyzed will also apply for the EUV-IL results. Therefore, the SEVR-40 exposure at PSI has to be repeated on organic underlayer for a reliable comparison to ADT data.

In future, this resist contrast test will be extended to other resists to further improve the reliability of this method. This will finally allow establishing the test as a EUV resist characterization method for tool-independent resist contrast characterization.

REFERENCES

- [1] K. van Ingen Schenau, S. Hansen, B. Pierson and J. van Schoot. Proc. SPIE 6923 (1), 692314 (2008).
- [2] H. H. Solak. J. Phys. D: Appl. Phys. 39 (10), R171-R188 (2006).
- [3] V. Auzelyte, C. Dais, P. Farquet, D. Grützmacher, L. J. Heyderman, F. Luo, S. Olliges, C. Padeste, P. K. Sahoo, T. Thomson, A. Turchanin, C. David and H. H. Solak. J. Micro/Nanolith. MEMS MOEMS 8 (2), 021204 (2009).
- [4] D. V. Steenwinckel, J. H. Lammers, L. H. A. Leunissen and J. A. J. M. Kwinten. Proc. SPIE 5753 (1), 269-280 (2005).
- [5] D. V. Steenwinckel, R. Gronheid, F. V. Roey, P. Willems and J. H. Lammers. J. Micro/Nanolith. MEMS MOEMS 7 (2), 023002 (2008).
- [6] Purchased from National Center for Scientific Research, Athens, Greece.
- [7] J. K. W. Yang and K. K. Berggren, J. Vac. Sci. Technol. B 25 (6), 2025-2029 (2007).
- [8] T. Itani and J. J. Santillan. J. Vac. Sci. Technol. B 27 (6), 2986-2989 (2009).