APPLYING DIPOLE ILLUMINATION TO CHARACTERIZE THE IMAGING PERFORMANCE OF 193 NM PHOTORESISTS FOR THE 100 NM NODE

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This paper was first presented at the Arch Chemicals Seminar,
November 2000
San Diego, California, U.S.A.
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ABSTRACT

A comparison is made between state-of-the-art 193 nm photoresists in their ability to print 100 nm dense lines. To obtain an aerial image contrast suitable for imaging 100 nm dense lines (L:S=1:1), an ASML PAS 5500/950 with dipole illumination is used. The PAS 5500/950 has a maximum Numerical Aperture (NA) of 0.63. The combination of this NA with dipole illumination gives the same aerial image contrast as annular illumination with an NA of 0.75. In this way, it is now possible to test thoroughly the ability of a photoresist to print 100 nm dense lines, without the use of expensive and immature Phase Shift Masks (PSM).

By comparing the experimentally obtained exposure latitudes with the theoretical aerial image contrast, an indication of the maturity of the photoresists is obtained. This work will give the current status of the 193 nm photoresists in terms of readiness for the 100 nm node. In addition, this work shows that by using dipole illumination, it is possible to do these tests now, providing an opportunity for resist, etch and further process optimization.

1. INTRODUCTION

Over the last two years, there has been significant progress in 193 nm lithography. Currently, 193 nm resists exposed on 0.63 NA Argon Fluorine (ArF) Step & Scan systems have process windows comparable to, or larger than those of 0.7 NA, 248 nm lithography[2]. However, because of the maturity of the 248 nm lithography process, it is believed that for most applications of the upcoming 130 nm technology node, high NA KrF lithography using appropriate enhancement techniques will be the technology of choice.

Alternatively, for the 100 nm node, 193 nm lithography will be needed and it is therefore crucial to have 193 nm lithography ready in time.

The ITRS timetable shows that the 100 nm technology node should be in place on an R&D level in approximately six months. The development of high NA, Step & Scan 193 nm lithography tools is progressing rapidly and next year 193 nm exposure systems with 0.75 NA will be available in time to meet the needs of the 100 nm node. The 193 nm photoresists have been significantly improved over the last year, but it has not yet been proved that these photoresists will fulfill the requirements of the 100 nm node. While 100 nm isolated and semi-dense lines can be tested on the currently available, lower NA, 193 nm systems, a higher NA, or alternating PSM, are necessary to print 100 nm dense lines (L:S=1:1). Therefore, 193 nm photoresists were not tested so far in their ability to print these critical 100 nm dense lines (L:S=1:1).

Figure 1 (A) shows the Normalized Image Log Slope (NILS), simulated with ProLith (v.6.1.2.0.). It is shown as a function of linewidth for fully dense (L:S=1:1) lines for a 0.63 NA, 193 nm system in four different illumination modes. In decreasing order of Critical Dimensions (CD), the preferred illumination modes are: first conventional, then QUASAR, and, finally, annular illumination for the highest resolution[3]. In some applications, dipole illumination can be used to enhance the aerial image contrast. Dipole illumination shows similar characteristics to alternating PSM, with NILS being constant down to 100 nm dense lines. This can easily be understood from Figure 2, where the pupil fillings are shown for annular and dipole illumination[3]. The aerial image contrast is determined by the amount of first order diffracted light that is captured by the lens pupil. For dipole illumination, this is 100% for resolutions down to 100 nm dense lines. It is clear that for annular illumination, the reduction in aerial image contrast is more gradual. The shape of the NILS versus pitch plot makes dipole illumination suitable to investigate the imaging performance for 100 nm dense lines using a 0.63 NA exposure tool. An ideal resist should give a constant exposure latitude for dense lines down to 100 nm.

In Figure 1 (B), the NILS for a 0.75 NA system is shown for conventional, QUASAR and annular illumination. In this plot, the NILS for an 0.63 NA system with dipole illumination is added. It shows that for 100 nm dense lines, the combination of dipole illumination and 0.63 NA gives a similar contrast to that of QUASAR or annular illumination on a 0.75 NA system. This makes it possible to test photoresists in their ability to print 100 nm dense...
lines at the present time. Figure 3 shows the results of experiments and ProLith simulation for dipole and annular illumination for a 248 nm resist\(^3\). It is clear that for both illumination modes, experiment and theory coincide well. This illustrates that 248 nm resists are mature enough to push 248 nm lithography to its limits.

2. EXPERIMENTAL CONDITIONS

The experiments were done on an ASML PAS 5500/950 ArF Step & Scan system, which has a 0.63 NA Zeiss StarlithTM 950 projection lens\(^1\). The same exposure system was used for all experiments. A TEL Act 8 track and a FSI Polaris 2000 track were used.

CD measurements were done on a Hitachi S-8C40, top-down CD-SEM. Cross-sectional SEM pictures were made with a Philips XL30 SEM.

Data analysis of the CD measurements was done with FINLE ProData (v. 2.0.0b). FINLE ProLith (v.6.1.2.0) was used for aerial image simulations.

Three advanced, 193 nm resists were evaluated in Table 1. Resists A and B are single-layer resists on top of a thin organic BARC. These resists have been shown to have a good performance in the 0.13 mm node\(^2\). The difference between photoresists A and B is mainly in resist contrast. Resist B has an expected higher resist contrast and is designed for dense line applications. Photoresist C is a new bi-layer resist where the imaging takes place in a 265 nm thick top layer. In the experiments described here, the 400 nm thick underlayer was not etched, and only the results directly after development are shown. For all three resists, the process conditions used were those recommended by the applicable resist supplier.
3. EXPERIMENTAL RESULTS

Both annular and dipole illumination were used, with a maximum NA of 0.63 and maximum inner and outer sigmas of $\sigma_o=0.87$ and $\sigma_i=0.57$. This was done to get maximum aerial image contrast at the lower CDs. The same reticle was used for all experiments. This reticle, characterized by SEM, has several feature sizes for one point in the field. In addition, long cleavable lines are present.

Two different jobs were exposed. One was a Focus Exposure Matrix (FEM) for one point in the field. From this job, Exposure Defocus (ED) windows were measured. The second job is an FEM for the long cleavable lines. This job was used to get cross-sectional data.

ED windows were measured for 90, 100, 110, 120, 130 and 150 nm dense lines (L:S=1:1). After analysis with ProData, values for the Maximum Exposure Latitude (Max EL) and Maximum Depth Of Focus (Max DOF) were obtained. A summary of these results is given in Table 2.

Clear differences in Max EL between the three resists are observed. Resist B has the largest EL for features down to 110 nm with dipole illumination. It is not, however, able to resolve the small CDs achieved by the other resists. Resist C is even capable of printing 90 nm dense lines with dipole illumination. For dipole illumination, Max DOF is at a maximum for 110 nm dense lines, which can be seen from the pupil fillings shown in Figure 2. The DOF increases when the zeroth order light and first order light are more symmetrical with respect to the axis of the projection system[3].

From the exposures of the long cleavable lines, cross-sections have been made for different CDs at best focus and energy-to-size. Figure 4 shows cross-sectional pictures for photoresists B and C with dipole and annular illumination. It can be seen that with resist C and dipole illumination, it is possible to print 90 nm dense (1:1) lines. With annular illumination, it is possible to print 110 nm lines. Resist B had adhesion problems at the high resolutions. Pattern collapse occurred at 100 nm for dipole illumination and at 110 nm for annular illumination. It is possible that process optimization could improve the performance of resist B.

<table>
<thead>
<tr>
<th>Photoresist</th>
<th>Type</th>
<th>Substrate</th>
<th>Resist Thickness (nm)</th>
<th>Substrate Thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Single layer</td>
<td>Organic BARC</td>
<td>330</td>
<td>81</td>
</tr>
<tr>
<td>B</td>
<td>Single Layer</td>
<td>Organic BARC</td>
<td>330</td>
<td>81</td>
</tr>
<tr>
<td>C</td>
<td>Bi-layer</td>
<td>Underlayer</td>
<td>265</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 1: The photoresists that are investigated here.

<table>
<thead>
<tr>
<th>CD (nm)</th>
<th>Dipole NA 0.63, $\sigma_o 0.87$, $\sigma_i 0.57$</th>
<th>Annular NA 0.63, $\sigma_o 0.87$, $\sigma_i 0.57$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max EL (%)</td>
<td>Max DOF ((\mu m))</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>150</td>
<td>15.3</td>
<td>19.5</td>
</tr>
<tr>
<td>130</td>
<td>15.0</td>
<td>17.9</td>
</tr>
<tr>
<td>120</td>
<td>14.4</td>
<td>18.9</td>
</tr>
<tr>
<td>110</td>
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<td>19.9</td>
</tr>
<tr>
<td>100</td>
<td>11.5</td>
<td>0</td>
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<td>90</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2: Experimental results of maximum exposure latitude and maximum depth of focus versus CD for the three resists and two illumination modes.
Figure 4: Cross-sectional pictures of photoresist B and C at best focus and best energy for annular and dipole illumination.
To get a good comparison between the resists, the EL and the NILS were normalized to their respective values for 150 nm lines. The normalized EL and NILS are shown as a function of CD in Figure 5.

It can be seen that with dipole illumination, there are clear differences in the resolution of the resists. For annular illumination, the differences are less pronounced. This may be due to the fact that the energy steps in the FEM were too large to derive a finite value of EL at the smaller CDs. With annular illumination, the aerial image contrast becomes much smaller for the smaller CDs, in comparison to dipole illumination. As the simulations predicted, when dipole illumination is used, EL is almost constant for all three resists from 150 nm down to 110 nm. Below 110 nm, the behaviour of the three resists starts to deviate from the ideal. Resist B is not able to print 100 nm dense lines with a finite EL and DOF. For resists A and C, EL at 100 nm reduces by a similar amount, while NILS remains constant. Resist A does not print below 100 nm. Resist A has good adhesion, but it is not possible to open 90 nm fully dense lines. Resist C is the only resist that has a distinct EL for 90 nm dense lines. This is also shown in Figure 6 where CD is plotted as a function of energy at best focus for 90 nm dense lines. Figure 7 shows the corresponding EL as a function of DOF. The combination of the PAS 5500/950 lens and resist C is very similar to the theoretical NILS curve in Figure 1. From these data, it can be concluded that, of the three photoresists, resist C is the most promising material for 100 nm technology.

4. DISCUSSION

Based on the data presented in the previous section, it can be concluded that dipole illumination is a powerful tool for judging the imaging performance of photoresists for the 100 nm technology node. Clear differences in the performance of resists A, B and C are observed. Resist B, which is currently seen as an excellent resist for the 130 nm node[2], is not able to print 100 nm dense lines, even with an aerial image contrast which is suitable to image 100 nm fully dense lines. This shows that it is very important to expose current photoresists with a suitable aerial image contrast to investigate their imaging performance for the future 100 nm node.

The question arises which parameters contribute to the observed differences between the different resists. All three resists were exposed on the same tool and under the same conditions, so the parameters have to be found on the resist/processing side. For example, resist contrast, absorption, adhesion, line-edge roughness, substrate interaction and diffusion lengths may all have an impact on the resolution of the resist. The cross-sections shown in Figure 4 and the excellent EL for the larger features for resist B give the impression that resist B is able to print smaller features. However, adhesion problems degrade its performance. The cause of the failure of resist A is different. Here adhesion is not a problem, but at the smaller CDs, it is not possible to open the lines. Amongst other differences in the resist parameters, this may be due to the expected lower resist contrast for resist A when compared to the other two resists. The failure may also be caused by a premature close-up, due to, for example, “scumming” or substrate interaction.
Three state-of-the-art 193 nm photoresists have been evaluated in their capabilities to print 100 nm fully dense (L:S=1:1) lines. An ASML PAS 5500/950 with dipole illumination was used to get an aerial image contrast suitable for imaging 100 nm dense lines. It is shown that dipole illumination is a very powerful technique to do these tests when using the currently available 0.63 NA exposure systems. The possibility to do these tests at the present time provides an opportunity for resist, etch and further process optimization.

Clear differences in the performance of the three resists are observed. The exposure latitudes are measured for several feature sizes and then compared to the NILS simulated with ProLith. The combination of the ASML PAS 5500/950 and photoresist C approaches the ideal situation simulated with ProLith NILS. Of the three photoresists, resist C is the most promising for the 100 nm design rule. Resist C even resolved 90 nm fully dense lines with 8.4% EL and 0.3 µm DOF using dipole illumination. The other two resists have less resolution due to different failure mechanisms. Resist B has adhesion problems, which might be improved with process optimization. Resist A has no adhesion problems, but is not able to open up 90 nm dense lines with dipole illumination. This might have to do with the expected lower resist contrast of resist A.
6. ACKNOWLEDGEMENTS

The authors would like to thank Kurt Ronse, Geert Vandenberghe, Diziana Vangoidsenhoven and Peter de Bisschop from IMEC for the availability of the exposure tool, track and SEM and for assisting in the experiments. We thank Eddy van der Heijden and Yuri van Dommeleen for support in the experiments. The resist suppliers are thanked for the opportunity to use their resists. We thank Simon Duerden, Vivian Kim and the illustrators from ASML publications department for their assistance in the preparation of this manuscript.

REFERENCES
