Current Status and Future Direction of EUV Resists

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Current status of EUV resists including imaging performance and resist out-gassing were described. As a result of resist benchmarking using small field exposure tool that has stand alone EUV source and 0.3 numerical aperture projection optics, resolution limit of 25nm was obtained in certain resist material. This is potential candidate for below 32nm node devices fabrication. On the other hand, sensitivity of 20-30mJ/cm² and line width roughness of 4-7nm should be improved. Moreover, as a result of resist out-gassing analysis using originally designed out-gassing evaluation tool, the resist out-gassing was not large for initial exposure tool, but it should be minimized for volume manufacturing exposure tool. In the near future, completely new resist material and/or new resist processing are strongly expected. Furthermore fundamental research such as understanding reaction mechanism of resist pattern formation and synthesis of new resin and photo-acid generator are still needed to realize 22nm node device manufacturing.

Keyword: EUV resist, sensitivity, resolution limit, line width roughness (LWR), resist out-gassing

1. Introduction

These past few years have seen significant progress in the field of optical lithography. This in turn may be highly attributed to the implementation of 193nm immersion lithography and related resolution enhancement technologies. However, as pattern dimensions continue to become smaller than the 32nm node, achieving a stable process for volume-production may prove to be difficult, even with the aforementioned technology. To provide new answers to this challenge, extreme ultraviolet lithography (EUVL) comes out as the strongest possible solution [1-5].

In EUVL, resists are one of the most critical issues in its realization for use in actual semiconductor device manufacturing below the 32nm node [6-9]. This is due to the fact that at present, no resist concurrently meets the targets for sensitivity, resolution limit, and line width roughness (LWR). Another concern for EUV resists is out-gassing at these highly energetic wavelengths under high vacuum [10-14]. At the estimated throughputs of volume manufacturing (~100 wafers per hour), there is a huge concern about contamination of the exposure tools. In EUV resist research and development, three factors; sensitivity, resolution limit and LWR have been known to have trade-off relationships. Besides these, the suppressing of resist out-gassing resulting from EUV irradiation is also becoming a big factor. We have been developing and evaluating EUV resist materials and processing using small field exposure tool (SFET), collaborating with major resist manufactures. EUV resist out-gassing has been evaluated using originally developed resist out-gassing evaluation tools. In this paper, current status of EUVs resists including
imaging performance and resist out-gassing are described. Furthermore, future directions for realizing EUV resist to volume production of below 32nm semiconductor devices are discussed.

2. Experimental

2.1. Small field exposure tool

Figure 1 shows SFET which has 0.3 numerical aperture projection optics and 10W discharge produced plasma stand alone light source. Exposure field size is $0.6 \times 0.2 \text{mm}^2$. Also, the SFET is linked with coater/developer track system (TEL ACT-12) under a chemically controlled environment. The illumination condition used for imaging evaluation of resist materials was an annular illumination of $\sigma$-outer 0.7/$\sigma$-inner 0.3 [1, 7].

2.2. Out-gassing evaluation tool

Figure 2 shows resist out-gassing evaluation tool. This evaluation tool is unique with the application of a number of analysis methods [12]. In the out-gassing quantitative experiments performed, the pressure rise method (using PKR251 ion gauge by Pfeiffer Vacuum Technology AG) was used. For mass spectrum analysis, the QMS (Prisma QMS200M3 by Pfeiffer Vacuum Technology AG) was applied. For the light source, a discharge produced plasma EUV source (EQ-10MR by Energetiq, Inc.) was utilized. Exposure dose conditions were kept constant at 30mJ/cm$^2$ that is corresponding to about 3 times the clearing dose ($E_0$). [13].

2.3. Materials and processing

Various kinds of chemically amplified positive EUV resist including conventional polymer type as well as newly developed low-molecular type resist were obtained from major resist manufactures. For the detail analysis of resist out-gassing, tert-butoxy carbonyl (t-BOC) protected polyhydroxy-styrene (PHS) based chemical amplified positive EUV model resist was utilized [14].

3. Results and Discussion

3.1. Resist bench marking

Table 1 summarizes results of resist benchmarking, such as sensitivity, resolution limit, LWR and resist out-gassing amount [7]. Figure 3 shows top-sown SEM micrographs of various kinds of resists obtained from major resist manufactures [7]. The sensitivity that is defined as sizing exposure dose of 45nm lines and spaces (L&S) are 20-30mJ/cm$^2$. Sample G shows relatively higher sensitivity of 16.6mJ/cm$^2$. These are still larger than that of target value of below 10mJ/cm$^2$. Further improvement is strongly needed to minimized exposure time. The resolution limit that is defined as separation of minimum feature size of L&S pattern is 25 to 28nm. These are almost within the target of 32nm L&S. The LWR that is defined as short-range (measurement length = 461nm) LWR at 45nm L&S pattern is still very large of 4-7nm that is more than three times of target value of below 1.7nm. However, Sample G shows relatively lower LWR of 4.1nm. Resist out-gassing amount that is defined as total amount of out-gassing under
the 30mJ/cm² exposure dose is $10^{13}$ to $10^{14}$ molecules/cm² level [13]. These are acceptable level for initial exposure tool (alpha-tool). Future limitation value for volume production exposure tool should be discussed with exposure tool manufacturers.

Table 1. Results of resist benchmarking.

<table>
<thead>
<tr>
<th>Resist Sample</th>
<th>Sensitivity @45nm L&amp;S (mJ/cm²)</th>
<th>Resolution limit @45nm L&amp;S (nm)</th>
<th>LWR @45nm L&amp;S (nm)</th>
<th>Out-gassing amount (molecules/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>19.3</td>
<td>26</td>
<td>7.0</td>
<td>(No data)</td>
</tr>
<tr>
<td>B</td>
<td>29.3</td>
<td>26</td>
<td>5.4</td>
<td>$4.4 \times 10^{13}$</td>
</tr>
<tr>
<td>C</td>
<td>20.2</td>
<td>26</td>
<td>6.1</td>
<td>(No data)</td>
</tr>
<tr>
<td>D</td>
<td>32.7</td>
<td>25</td>
<td>5.8</td>
<td>(No data)</td>
</tr>
<tr>
<td>E</td>
<td>26.9</td>
<td>26</td>
<td>5.3</td>
<td>(No data)</td>
</tr>
<tr>
<td>F</td>
<td>18.1</td>
<td>28</td>
<td>5.6</td>
<td>$1.7 \times 10^{14}$</td>
</tr>
<tr>
<td>G</td>
<td>16.6</td>
<td>26</td>
<td>4.1</td>
<td>$1.2 \times 10^{14}$</td>
</tr>
<tr>
<td>H</td>
<td>26.5</td>
<td>26</td>
<td>6.1</td>
<td>$1.1 \times 10^{14}$</td>
</tr>
</tbody>
</table>

![Top-down and cross-section of SEM images for different resists](image)

Fig. 3. Top-down SEM of various kinds of resists.

3.2. Current status of “SSR2” & beyond

Figure 4 shows top-down and cross-section of SEM images for (a) Selecte standard resist (SSR2) and (b) Sample G. Resolution limit are almost the same as 25-26nm L&S and the resist pattern profiles of Sample G shows much rectangular comparing with SSR2. This is the results of optimization of resist formulations, but it is not enough performance for actual semiconductor device fabrication. Figure 5 shows relationship between (a) sensitivity - resolution, (b) sensitivity - LWR, and (c) LWR - resolution for various resist samples, indicating with the target values of both 32nm and 45nm nodes. Currently no resist sample is found to satisfy simultaneously the target values of sensitivity, resolution limit and LWR, however, some improvement could be obtained from SSR2 to Sample G. Further improvement, especially sensitivity and LWR are strongly needed.

![Top-down and cross-section of SEM images for different resists](image)

Fig. 4. Top-down and cross-section of SEM images for (a) Selecte standard resist (SSR2) and (b) Sample G.

![Graphs showing sensitivity vs resolution and sensitivity vs LWR](image)

(a) Sensitivity - resolution

(b) Sensitivity - LWR
exposure dose of 30mJ/cm². For only the base resin of PHS and solvent, a negligible amount of resist out-gassing was found. For the PHS having protecting group of t-BOC, there is an increase in total resist out-gassing amount. A large resist out-gassing amount was observed with the PHS having t-BOC with photo-acid generator (PAG). It is also interesting to note that the pressure rise reached maximum at a lower dose compared to the sample of all resist components were present. The PHS having t-BOC with PAG and acid quencher, also showed some resist out-gassing but is comparatively smaller than the resist out-gassing from the PHS having t-BOC. It is interesting to see how resist out-gassing has decreased due to the presence of quenchers. These results show that resist out-gassing release characteristics vary drastically depending upon the resist formulation.

3.3. Resist out-gassing benchmarking

Figure 6 shows resist out-gassing amount for various resist samples obtained from major resist manufactures. Some resists show higher out-gassing amount of 10¹⁵ molecules/cm² level, other resists show lower out-gassing amount of middle 10¹³ molecules/cm² level. The out-gassing level of 10¹⁴ molecules/cm² is currently acceptable that means most of current resist sample can be proceed to imaging evaluation on alpha-exposure tool [13]. Future limitation value for volume production exposure tool should be defined based on these data.

3.4. Resist out-gassing dependence on resist formulation

Figure 7 shows resist out-gassing analysis for the model resists; (a) exposure dose dependence of total pressure rise and (b) resist out-gassing amount based on an

Fig.6. Resist out-gassing amount for various resist samples obtained from major resist manufactures.

Fig.7. Resist out-gassing analysis for the model resists; (a) exposure dose dependence of total pressure rise and (b) resist out-gassing amount.

3.5. Resist out-gassing dependence on protecting ratio and quencher concentration

Figure 8 shows resist out-gassing amount for
the model resists: (a) protecting ratio dependence and (b) quencher concentration. As protecting ratio was increased the amount of released resist out-gassing increased. On the other hand, as quencher concentration was increased, resist out-gassing decreased. It should be noted that protection ratio is largely affected to resist out-gassing, however, acid quencher can suppressed resist out-gassing [14].

![Resist out-gassing amount vs Protecting ratio](image1)

(a) Protecting ratio dependence

![Resist out-gassing amount vs Quencher concentration](image2)

(b) Quencher concentration dependence.

Fig. 8. Resist out-gassing amount for the model resists; (a) protecting ratio dependence and (b) quencher concentration dependence.

4. Conclusions

Current status of EUV resists including imaging performance and resist out-gassing were described. Resolution limit of 25nm was obtained in certain resist material. This is potential candidate for below 32nm node devices fabrication. On the other hand, sensitivity of 20-30mJ/cm² and LWR of 4-7nm should be improved aggressively by developing resist materials as well as resist processing. Resist out-gassing was not large for initial exposure tool, but it should be minimized for volume manufacturing exposure tool. In the near future, completely new resist material and/or new resist processing are strongly expected. Furthermore fundamental research such as understanding reaction mechanism of resist pattern formation and synthesis of new resin and PAG are still needed to realize 22nm node device manufacturing.

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References