Defects, Overlay and Focus Performance Improvements with Five Generations of Immersion Exposure Systems

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ABSTRACT

This paper discusses the current performance and the evolution of five generations TWINSCAN immersion scanning exposure tools. It is shown that production worthy overlay and focus performance can be achieved at high scan speeds. The more critical part for immersion tools is related to defects, but also here improvements resulted in production worthy defect levels. In order to keep the defect level stable special measures are needed in the application of wafers. Especially Edge Bead Removal (EBR) design and wafer bevel cleanliness are important.

1. INTRODUCTION

The history of microlithography teaches us that the full integration of new lithography technologies into volume production takes about 10 years. Immersion lithography however, is currently being brought to manufacturing in less than 5 years. The early availability of immersion exposure tools has been one of the key enablers for this fast introduction. The learning done with these early immersion exposure tools resulted in fast and gradual improvements of the immersion technology.

Since 2003 we have been shipping five generations of immersion scanners with maximum NA starting from 0.75 up to 1.35 for the latest tool [1,2,3,4]. Over time we have been improving the specific immersion modules in the scanners, resulting into improvements in defects, overlay and productivity. In this paper we will review the learning we did on these critical performance items. It will be discussed how improvements in water containment and improvements in immersion resist processing lowered the defect numbers to levels as required for volume manufacturing. On overlay and focus performance it will be discussed how the thermal management of immersion water and wafer can bring overlay down to numbers comparable as seen on dry exposure systems.

Data will be presented representing the performance of more than 30 immersion systems and for a variety of user conditions.

2. BUILDING BLOCKS IMMERSION EXPOSURE SYSTEMS

The immersion performance of a lithographic exposure system is reflected in defects, overlay and productivity. As figure 1 illustrates, the fluid containment is at the center of immersion performance triangle. The fluid containment is done with an immersion hood (IH) which controls the meniscus of the local water puddle under the lens. When a wafer is scanned under the water volume, viscous forces start to pull the film and affect the meniscus. Above a certain speed,
the containing meniscus becomes unstable and a water film is pulled out of the water volume, and later breaks up into droplets. The water droplets can evaporate and the evaporation heat will cool down the wafer locally. Consequently the wafer will be distorted eventually leading to overlay errors. Looking to defects, the droplets on the wafer may form drying stains or may form water-mark of defects [5]. The challenge of the design of the immersion system now is to maximize scan speed and minimize the impact on defects and overlay.

Figure 1: The immersion system design triangle of overlay, defects and productivity.

Besides the specific design of the Immersion Hood (IH) also the surface properties of the resist stack have a major influence on the meniscus stability and hence water containment. The two main factors are the surface hydrophobicity and topography. Different resist and top coats have different contact angles with water, and thus the design of the IH should enable a wide operating range, covering the range between more hydrophilic surfaces (receding contact angle of 40 degrees or less) to more hydrophobic surfaces (receding contact angle of 70 degrees or more). To maximize the operating range at high scan speeds, ASML immersion scanners employ an IH based on a double fluid containment concept. An illustration of this is given in figure 2.

Figure 2: ASML immersion hood concept with double containment concept

The first and main containment mechanism controls the meniscus of the puddle. The meniscus stability of the water film is affected by the scan speed (v), the viscosity and surface tension of the water, the contact angles on the resist side and the IH side, the water flow inside the puddle and the gap (h) between the wafer and the IH. The IH used in ASML systems have an actuator on the gap height. The second added containment method is based on an air curtain. In practice the air curtain increases the critical speed up to which water can be contained within the IH especially for more hydrophilic surfaces.
Next to the IH, the wafer stage (WS) is an important building block for immersion systems. The WS holds the wafer and the structure that holds the wafer is designed such that the wafer deformation is minimized. Evaporation effects of water on the wafer can be counter acted by thermal conditioning of the wafer. The WS also includes solutions for water containment at the edge of the wafer, the bevel edge seal (BES).

![Diagram of Wafer Stage](image)

**Figure 3: The Wafer Stage (WS) for immersion systems including Wafer Table (WT), Closing disk and Bevel Edge Seal (BES).**

In table 1 we summarize the design steps of IH and WS for the five different generations of immersion tools. The different IH types improve gradually on water containment and critical speed at which droplets are lost, whereas the different steps in WS design show improvements on thermal control of the wafer.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Lens NA</th>
<th>Scan Speed</th>
<th>IH design</th>
<th>WS design</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT:1150i</td>
<td>0.75</td>
<td>360 mm/s</td>
<td>Proto type</td>
<td>Proto type</td>
</tr>
<tr>
<td>XT:1250i</td>
<td>0.85</td>
<td>500 mm/s</td>
<td>Actuated type</td>
<td>conditioned WS</td>
</tr>
<tr>
<td>XT:1400i</td>
<td>0.93</td>
<td>500 mm/s</td>
<td>Actuated type</td>
<td>Bevel Edge Seal (BES)</td>
</tr>
<tr>
<td>XT:1700i</td>
<td>1.20</td>
<td>550 mm/s</td>
<td>Adapt 1.2 NA with improved flow</td>
<td>Improved thermal design</td>
</tr>
<tr>
<td>XT:1900i</td>
<td>1.35</td>
<td>600 mm/s</td>
<td>Adapt 1.35 NA with improved flow</td>
<td>Improved material</td>
</tr>
</tbody>
</table>

3. DEFECTS CLASSIFICATION AND PERFORMANCE

Defect inspection of patterned wafers is normally done with optical inspection tooling, subsequently followed by a SEM review of the found defects. The measured defects are classified into types which relate to their root causes. Defect categories also known in conventional “dry” lithography are those linked to the resist coating step and development steps. For immersion lithography not only the known defect types can be found, but additionally new types have been identified. In table 2 we give an overview of the classes we use in our immersion tool qualification process. In figure 4 we present a comparison data set of defects measured on a dry XT:1400 tool and a wet XT:1400i tool. The measurements are based on an annular exposure with 0.93 NA, a 100nm LS reticle, BARC 1c5d (AZ-Clariant), resist Tarf6111 (TOK) and top coat TCX041 (JSR). The KLA 2365 is used for defect inspection. Looking to the results presented in figure 4 and the classification in table 2, we distinguish between immersion related defects and immersion doubtful defects. The immersion related defects include pattern expansion, drying stains, attenuations and printed particles, whereas the immersion doubtful defects are bridges between two lines, u-bridges and missing pattern. From a scanner design perspective, the defect root causes can be droplet related (pattern expansions, drying stains or inverted attenuations), bubble related (attenuation) or particle contamination related.
Table 2: Defects classes and root causes

<table>
<thead>
<tr>
<th>Class</th>
<th>Pattern expansion</th>
<th>Drying stains</th>
<th>Inverted attenuation</th>
<th>Pattern attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>examples</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure Size</td>
<td>Circular or irregular</td>
<td>0.1 – 10 µm</td>
<td>Narrower pitch 1 – 1000 µm</td>
<td>Circular shape Wider pitch 0.1 – 2 µm</td>
</tr>
<tr>
<td>Root Cause</td>
<td>Droplet interaction with resist</td>
<td>Droplet drying after resist leaching</td>
<td>Droplet swelling topcoat/resist before exposure</td>
<td>Bubble on topcoat/resist</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class</th>
<th>Printed particle</th>
<th>Bridge</th>
<th>Micro Bridge</th>
<th>Missing Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>examples</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure Size</td>
<td>Irregular; Particle affecting pattern 0.1 – 5 µm</td>
<td>Bridge between 2 lines &lt; 0.5 µm</td>
<td>hair-like bridge between 2 lines &lt; 0.2 µm</td>
<td>Circular, resist is gone 0.1 – 5 µm</td>
</tr>
<tr>
<td>Root Cause</td>
<td>Particles exposed</td>
<td>Resist process or small particle</td>
<td>Incomplete develop rinse or small particle</td>
<td>solvent splash back in track</td>
</tr>
</tbody>
</table>

Figure 4: Defect classification measurement comparison between dry XT:1400 and wet XT:1400i

The immersion defect performance for XT:1700i exposure system is evaluated prior for system shipment. The processing for the wafers exposed is done either with the SCREEN RF3 track or the TEL Lithius i+ track. The tracks are
not linked to the systems. The defects are analyzed on the KLA 2365 (UVBF mode, threshold 15) with SEM review on a Hitachi SEM, and based on 100nm LS exposure using, BARC 1c5d (AZ-Clariant), resist Tarf6111 (TOK) and top coat TCX041 (JSR). In figure 5 we present the results on total defects count (immersion related including particles) and in figure 6 we present a breakdown of all measurements into the different classes.

![First systems vs Latest systems](image1)

**Figure 5:** Total defects count per wafer measured for multiple XT:1700i systems.

![Breakdown of defect data](image2)

**Figure 6:** Breakdown of all defect data on XT:1700i into the different classes.

The results of figure 5 show that the average total defects count for the latest systems is 15 defects per wafer. The best result is 2 defects per wafer. Figure 6 shows that the majority of the immersion defects originate from particles which are printed during the exposure. A smaller significant part (<10%) of the defects is pattern expansion, coming from residual droplets. In few cases (<2%) attenuations are observed. Looking to the performance on immersion specific defects, the results of three XT:1700i production systems are presented in figure 7. The results show that immersion defects are significantly lower than 5 defects per wafer, with zero defects per wafer as best result. In figure 8 we present
through batch performance for one of the XT:1700i machines. It is shown that for all batch defect performance can be well below 5 defects per wafer.

Figure 7: Defect wafer map of three different XT:1700i production systems showing immersion specific defects.

Figure 8: Through batch defects performance of showing immersion specific defects on XT:1700i system.

4. IMMERSION CLEANLINESS

Whereas the initial defects performance for immersion systems is low, the challenge with immersion is to keep the level low and constant. In contrast with dry exposure systems, the immersion exposure process is very sensitive for contamination because the water is a good transport medium for cross contamination. Especially the edge of the wafer can be a potential source for particle contamination. The strategy for keeping the defects level low is threefold:

1) Use clean wafers and resist process → immersion specific Edge Bead Removal (EBR) design, and cleaning of wafer bevel

2) Active removal of particles at wafer edge and automated cleaning during system idle time
3) Periodical cleaning of the immersion hardware (IH and WS)

Starting with clean EBR design, we evaluated different EBR layouts and their impact on pattern defects counts. In figure 9 we present the summary results. It is shown that with the wrong EBR layout the resist or the top coat can be flushed away from the wafer, thus causing a huge amount of particle defects. The best EBR strategy is to put the resist and the top coat both on the BARC. This assures the best adherence to the wafer. Possibly HMDS can be used to promote the adherence of the BARC to the wafer as well.

![EBR-1, EBR-2, EBR-5, EBR-7 layouts]

**Figure 9: Patterned defect results for 4 different EBR strategies, wafer map represents result of 4 stacked wafers**

In the ASML scanners there is an active bevel edge seal (BES). The BES removes particles on the bevel of the wafer. For comparison reasons we performed an experiment in which bare Si wafers are cycled through an immersion system, once with BES on and once with BES off. The added particles per wafer (top side) are measured with KLA SP2 surface scan system. In figure 10 the results are presented. It is shown that the particle count without active BES increases significantly, up to factor 7. Next to the active BES, automated in-line cleaning (AutoFlush) is implemented. The AutoFlush function becomes active during idle time of the machine and automatically cleans the critical areas of the WS and the IH. In figure 11 we present results of the AutoFlush functionality. It is shown that without AutoFlush the defect can increase with factor 4 or more, whereas with AutoFlush the defect level stays low and more constant.

The clean wafer process, optimized EBR, active BES and AutoFlush functionality should keep the defects level constant. However, incidents still may contaminate the scanner significantly. Especially for these incidents, more aggressive cleaning tooling is needed. For both IH and WS megasonic supported cleaning tools are developed. These tools are used on periodic basis.
Figure 10: Impact Bevel Edge Seal (BES) on/off of particles (>120nm) added to bare Si wafer;

Figure 11: Impact of AutoFlush on defects count.

5. OVERLAY AND FOCUS PERFORMANCE

Compared to dry exposure systems, the heat load caused by water evaporation is the main disturbing factor overlay and focus of immersion systems. The heat load may depend on time and position of the wafer. Reduction and control of the evaporation is driving in lowering the immersion overlay penalty. By using a so-called reversed overlay test, the thermal overlay penalty can be quantified. This test exposes 10 wafers with a layer 1 using wafer following order 1, 2, 3, ..., N, and layer 2 in wafer following order N, N-1, ......, 1. Possible time dependent thermal distortions of the wafer are so magnified. From the first generation of immersion tool (AT:1150i) up to the fifth generation tool (XT:1900i), continuous design improvements have been implemented. In figure 12 the improvements in reversed overlay are shown. It is demonstrated that current performance is well below 3 nm.
In figure 13 we present the results of a 3-day single machine overlay stability test. The results are shown from an XT:1700i production system at 550 mm/s and a XT:1900i proto system at 600mm/s. It is demonstrated that current long term single machine overlay is below 6-nm.

**Figure 12:** (Upper) Reversed overlay for 5 generation immersion tools, (Lower) Reversed overlay results for the latest (5th generation) immersion system.

**Figure 13:** Single machine overlay 3-day stability test results for XT:1700i production system and XT:1900i proto system.
The focus performance of immersion systems is measured with a full wafer focus uniformity test (LVT) and a full wafer focus stability test based on FOCAL. The improvements for the five generations immersion systems are shown in figure 14. It is shown that current focus performance is below 25nm.

![Figure 14: Focus uniformity (LVT) and 3-day focus stability performance for four generations immersion tools](image)

### 6. CONCLUSIONS

In this paper we discussed the improvements achieved on five generations of TWINSCAN immersion scanners. Between 2003 and 2007 we introduced systems with NA increasing from 0.75 up to 1.35. The scan speed was increased from 360 mm/s to 600 mm/s, while defects overlay and focus errors have been reduced dramatically.

On defects we discussed the different classes and related root causes for immersion defect formation. Residual water droplets play a role in the defect formation, and the droplet loss can be controlled in the scanner immersion hood (IH). The IH used in ASML scanners actuates the air gap and uses an air curtain to clean-up possible droplets leaving the meniscus. With the latest IH a scan speed of larger than 0.6 m/s can be obtained, with immersion specific defects lower than 5 defects per wafer over the full lot. To keep the defect level constantly low clean resist processes including EBR and in-situ cleaning is needed.

On overlay and focus performance we discussed the improvements on thermal design of the wafer stage. With the latest generation immersion technology, we achieve overlay numbers smaller than 3-nm (chuck dedicated overlay) and smaller than 6-nm dual chuck 3-day overlay. The focus uniformity is improved to <25nm. Overlay and focus performance are maintained even at high scan speeds of 600 mm/s.
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