Advanced Mask Inspection and Metrology

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Abstract. Lithography is one of the most important semiconductor micro-fabrication technologies that form mask pattern images onto the substrate. Since a mask is the original edition of semiconductor patterns, precise control of the mask aperture size becomes critical. The masks have to be made up in the accurately controlled patterns and zero defects. Therefore, mask inspection and metrology that guarantee the mask qualities are important key technologies for realizing the semiconductor production with high reliability and high yield. The advanced inspection and metrology are being developed. The requirements, technical issues, and current status of these technologies are reported. Mask inspection technologies for next generation lithography such as electron projection lithography (EPL) and extreme ultraviolet lithography (EUVL) are also reported.

INTRODUCTION

Reduction projection optical lithography is now widely used for semiconductor micro-fabrication, and is expected to be used in the 65 nm technology node with the short exposure wavelength, a large numerical aperture (NA) lens, and several resolution enhanced technologies. Since the masks have the original patterns to be projected onto the wafer, it must be made up in the accurately controlled pattern generation and the zero defects.

Figure 1 indicates trends of lithography wavelength, a minimum feature size required for lithography, and mask inspection wavelengths. It is clear from the figure that the minimum feature size has become smaller than exposure wavelength. This sub-wavelength lithography has now become a common technique. In such lithography, proximity effects and bias problems become much larger than those that would be expected from the normal reduction ratio of an imaging system. This means that mask pattern errors are amplified at the wafer. The ratio of this amplification is called the MEEF (mask error enhancement factor) and the MEEF equals 1 for ideal linear imaging. Therefore, precise control of the mask aperture size becomes critical. Nevertheless, mask inspection wavelengths always stay behind to the lithography wavelength.

On the other hand, electron projection lithography (EPL) and extreme ultraviolet (EUV) lithography have been developed by consortia and several companies as the next generation lithography (NGL). These NGL technologies also use the masks whose structures are different from those for optical lithography.

These progresses in optical lithography and NGLs require the infrastructures for making, inspecting, and repairing masks with further accuracy. Mask inspection and metrology that guarantee the mask qualities are important key technologies for realizing the semiconductor production with high reliability and high yield.

In this paper, the requirements, technical issues and current status of mask inspection and metrology technologies are described. Mask inspections for next generation lithography such as EPL and EUVL also are shown.

REQUIREMENT OF PHOTOMASK FOR RESOLUTION ENHANCEMENT

Schematic structure of photomask and defects on the mask are shown in Fig. 2. The photomask consists of a
FIGURE 2. Schematic structure of photomask and defect.

A quartz substrate, a Cr opaque film which has pattern apertures, and a pellicle as shown in this figure. While conventional binary mask basically uses the transmitted light intensity, phase-shift mask introduces optical phase difference to enhance a resolution by using interference effects. For attenuated phase shift mask, MoSiON film is an example of attenuated layer which acts as the phase-shifted region with respect to the mask apertures. Although weak light passes through the attenuated region, its intensity is insufficient to develop the photoresist on the wafer. Alternate phase shift mask has non-planar structure to create the 180-degree phase difference of light passing through adjacent apertures on the mask.

Pin holes or pin dots on the mask shown in the figure cause CD variation in projected image. Therefore these defects must be detected and repaired. Precise control of the mask aperture size becomes also critical.

The 2002 ITRS (International Technology Roadmap for Semiconductors) of photo mask technology is shown in Table 1[2]. The required defect size specifications decrease with a progress of the technology generation. In the case of 65nm technology node, the requirement of defect detection sensitivity is 52nm. Placement and phase errors, higher accuracies also are required for 65 nm nodes to keep a required CD accuracy. To meet the aggressive requirements, high accuracy mask inspections and metrologies in addition to the mask fabrication processes are necessary.

TABLE 1. ITRS of photomask technology [2].

<table>
<thead>
<tr>
<th>Year of Production</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer minimum half pitch (nm)</td>
<td>100</td>
<td>90</td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td>Mask minimum image size (nm)</td>
<td>260</td>
<td>212</td>
<td>180</td>
<td>160</td>
</tr>
<tr>
<td>Mask OPC feature size (nm)</td>
<td>130</td>
<td>106</td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td>CD uniformity: Isolated lines (MPU gates)</td>
<td>5.1</td>
<td>4.2</td>
<td>3.7</td>
<td>3.4</td>
</tr>
<tr>
<td>CD uniformity: Dense lines (DRAM half pitch)</td>
<td>8.0</td>
<td>7.2</td>
<td>6.4</td>
<td>5.6</td>
</tr>
<tr>
<td>Defect size of ITRS (nm)</td>
<td>80</td>
<td>72</td>
<td>64</td>
<td>56</td>
</tr>
<tr>
<td>Cr dot (nm)</td>
<td>1:1 pitch</td>
<td>103</td>
<td>96</td>
<td>91</td>
</tr>
<tr>
<td>Cr extension (nm)</td>
<td>1:2 pitch</td>
<td>109</td>
<td>100</td>
<td>93</td>
</tr>
<tr>
<td>Oversize defect (nm)</td>
<td>1:1 pitch</td>
<td>80</td>
<td>76</td>
<td>65</td>
</tr>
<tr>
<td>Oversize defect (nm)</td>
<td>1:2 pitch</td>
<td>85</td>
<td>89</td>
<td>91</td>
</tr>
<tr>
<td>Undersize defect (nm)</td>
<td>1:1 pitch</td>
<td>35</td>
<td>29</td>
<td>19</td>
</tr>
<tr>
<td>Undersize defect (nm)</td>
<td>1:2 pitch</td>
<td>40</td>
<td>36</td>
<td>30</td>
</tr>
<tr>
<td>Defect size of ITRS (nm)</td>
<td>25</td>
<td>21</td>
<td>14</td>
<td>17</td>
</tr>
<tr>
<td>Defect size of ITRS (nm)</td>
<td>30</td>
<td>27</td>
<td>23</td>
<td>16</td>
</tr>
</tbody>
</table>

In general, mask inspection is performed by obtaining the magnified mask aperture images and by image data processing. Examples of mask apertures and simulated images for several inspection wavelengths (364 nm, 266 nm, and 198 nm) are shown in Fig. 3. It is clear that short inspection wavelength provides clear image.

OPC (Optical Proximity Correction) technology is currently used as a key technology of resolution enhancement. Fig. 4 shows the dependence of defect position on defect printability of patterns with assist

FIGURE 3. Examples of mask aperture and simulated images for several inspection wavelengths (364nm, 266nm and 198nm).

DETECT INSPECTION FOR PHOTOMASK

Trend of defect inspection

The defect size requirements for down to 70 nm technology node were simulated for several kinds of defects with 1:1 and 1:2 pitches assuming ArF lithography. The simulation results are shown in Table 2[3]. It is suggested that the requirement of defect detection is higher than that of ITRS. Therefore, it can be understood that the higher sensitivity of defect inspection tool is required.
This means that the defect sensitivity and defect distinction requirements for photomask with OPC patterns become complex.

**FIGURE 4.** Dependence of defect position on defect printability of mask patterns with assist bar [4], reprinted with permission from SPIE, ©2002.

Trends of mask defect sensitivity and inspection wavelength are summarized in Fig. 5, with indicating the schematic illustrations of inspection tools for both transmission and reflective masks. Current advanced mask inspection system has 100 nm-size defect detection capabilities with UV light illumination with the wavelength of around 260 nm. An example of mask defect inspection tool with 266 nm wavelength is shown in Fig. 6[5]. This system has been developed by joint work with NEC and Selete. This system has the beam scan type optics with two beams, and has both Die to Die and Die to data inspection modes. Though a target sensitivity of defect detection is 80 nm, progress results of sensitivity were obtained for several defect types as shown in the figure.

**FIGURE 5.** Trends of mask defect sensitivity and inspection wavelength.

To satisfy the mask inspection requirement for 65 nm technology node and beyond, the light source with short wavelength in the region of 200–160 nm is required. It is well known that a DUV pulse laser had already been developed for the lithographic usage, but the mask inspection system requires the continuous-wave (CW) laser light source. Therefore, such DUV-CW laser source must be developed. A new DUV sensitive sensor device capable for inspection speed will also be needed.

Table 3 summarizes the photomask inspection optics parameters and also shows a ratio of mask defect size to the optical resolution based on the prediction of current and future mask inspection tool. A 200 nm inspection wavelength is required for 65 nm technology node and 160 nm inspection wavelength will also be required for 45 nm technology and beyond.

**TABLE 3.** Trends of photomask inspection technology.

<table>
<thead>
<tr>
<th>Technology node</th>
<th>65 nm</th>
<th>45 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection sensitivity (D) *</td>
<td>104 nm</td>
<td>72 nm</td>
</tr>
<tr>
<td>Inspection wavelength (λ)</td>
<td>257 nm</td>
<td>257 nm</td>
</tr>
<tr>
<td>Numerical Aperture</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Nominal resolution (R) **</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td>Ratio of sensitivity and resolution (D/R)</td>
<td>0.27</td>
<td>0.32</td>
</tr>
</tbody>
</table>

*Minimum defect size which can be detected

**Development of 198.5nm wavelength inspection tool**

To achieve the CW oscillation in the UV region, the wavelength conversion of the long-wavelength lasers is essential. A sum-frequency generation (SFG) can be
realized by using the actively controlled cavity[6]. For the case shown in Fig. 7, with one cavity, a 1064 nm light from a CW-Nd:YAG laser was resonated and a 244 nm light which is a doubling output of a single frequency Ar ion laser was passed just once at the CLBO crystal. Using the SFG technique, CW 198.5 nm light with the output power of 50 mW has been generated at MIRAI project[7]. The output power will be increased to meet the requirement of mask inspection tool.

FIGURE 8. Novel backside thinned TDI (Time Delay and Integration) sensor device for 200 nm inspection wavelength.

The sensor technique is also important for DUV inspection wavelength. The performance requirement for the sensor device is very high sensitivity for the DUV wavelength and high image acquisition speed such as 400M or 800M pixel/second. To satisfy the sensitivity requirement for the wavelength of 200nm, a novel backside thinned TDI (Time Delay Integration) sensor device which has multiple linear array rows and time delay integration mechanism has been developed shown in Fig. 8 [8]. Backside thinned technique is very important because the conventional TDI sensor absorbs the DUV light incident at the front layer of the sensor device. By illuminating from the backside of the sensor device, the high conversion ratio from DUV photons to electrons is achieved for high DUV sensitivity.

Figure 9 shows a schematic structure of 198.5 nm wavelength inspection tool[5]. The laser and the TDI sensor are for 198.5 nm inspection wavelength. Inspection optics, mask stage system, and image processing unit are developed by Selete, NEC and Toshiba. The target specification is 60nm. This system is also a new platform for 65 nm technology node.

**METROLOGY FOR PHOTOMASK**

Table 4 shows the optical lithography mask metrology technology requirements. Since the resolution enhanced technology will be commonly used, mask metrology requirements become severe. In particular, achievement of phase metrology precision is very difficult. According to the ITRS 2001-2002, it is difficult to find the manufacturability solution for CD metrology tools.

<table>
<thead>
<tr>
<th>Year of production</th>
<th>2003</th>
<th>2004</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mask minimum image size (at 4X, nm)</td>
<td>260</td>
<td>220</td>
<td>160</td>
</tr>
<tr>
<td>Minimum OPC size (opaque 4X, nm)</td>
<td>130</td>
<td>110</td>
<td>80</td>
</tr>
<tr>
<td>Mask image placement technology</td>
<td>21</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>Mask CD metrology tool precision</td>
<td>1.3</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Mask CD metrology tool precision</td>
<td>1.75</td>
<td>1.6</td>
<td>1.15</td>
</tr>
<tr>
<td>Mask CD metrology tool precision</td>
<td>1.6</td>
<td>1.45</td>
<td>0.65</td>
</tr>
<tr>
<td>Mask CD metrology tool precision</td>
<td>1.2</td>
<td>1.05</td>
<td>0.65</td>
</tr>
<tr>
<td>Phase metrology precision (P/T=0.2)</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

As the photomask CD measurement tool, optical type with UV light and SEM (Scanning Electron Microscope) type measurement tools are used. Currently, optical aerial image monitor type has been paid attention, since a transmitted light image through the mask can be measured. By using the optical aerial image monitor tool, we can look the pattern image CD on the wafer and the defect printability of photomask. Fig. 10 show the optical aerial image monitor system with 157nm laser for restricted area inspection. This system is being developed by Carl Zeiss[9].

**TABLE 4. Requirements of photomask metrology technology.**

**FIGURE 10.** Optical aerial image monitor system with 157nm laser (Carl Zeiss AIMS-157). The photograph with permission from Carl Zeiss.

Phase error measurement is also important, because phase shift mask is a strong resolution enhancement method, and the phase accuracy influences the lithographic performance. An example of phase metrology for attenuated and alternate phase-shift masks has been proposed by Lasertec in Japan. This phase...
measurement system for 157nm lithography is shown in Fig. 11 [5]. This system also has a transparency measurement function.

**FIGURE 11.** Phase measurement system with 157nm laser (Lasertec MPM-157). The photograph with permission from Lasertec.

**ACTIVITY OF INSPECTION FOF NGL MASK**

Since the structure of NGL mask is different from that of photomask, new system for NGL mask inspection are required. The R & D activities of inspection tools for EPL and EUVL masks are introduced in the following.

**EPL mask inspection**

Figure 12 shows the comparison of stencil type EPL mask and photomask. As shown in Fig.12, pattern thickness of EPL stencil mask is 2000 nm though that of photomask is about 100 nm. Therefore EPL stencil mask has very high aspect ratio (greater than 7 in 65-nm node) as compared with the aspect ratio (approximately 0.5) of photo mask. EPL mask patterns are not supported by substrate though photomask patterns are supported by thick quartz substrate. It is seen that EPL stencil mask has the three-dimension structure that is different from that of photomask.

**FIGURE 12.** Comparison of stencil type EPL mask and photomask

Imaging evaluation results of EPL stencil mask by usual DUV light and transmission electron beam are shown in Fig. 13. Comparing the reflection image and transmission image by DUV microscope with the inspection wavelength of 266 nm, clear image of EPL mask can be obtained by transmission electron beam. Therefore, the EPL mask inspection system with EB transmission optics has been proposed by Seleite, HOLON and Tokyo Seimitsu [10].

**FIGURE 13.** Comparison of DUV optical microscope image and SEM image for stencil type EPL mask patterns [10], reprinted with permission from SPIE, ©2003.

Figure 14 shows the EPL mask inspection system with EB transmission optics. The system consists of illumination lenses to converge the electrons onto the mask, projection lenses to form transmitted EB image of the mask, transducer to convert the electron image into an optical image, and multi-line TDI-CCD sensor of which pixel size is 50nm. The electron acceleration voltage is 5KV. The system has die to die and die to data

**FIGURE 14.** Development of EPL mask inspection tool with electron optic system [10], reprinted with permission from SPIE, ©2003 except upper right photograph.

**FIGURE 15.** EB transmission image of a stencil mask captured by TDI-CCD camera [10], reprinted with permission from SPIE, ©2003.
inspection mode. Fig. 15 shows the EB transmission image of a stencil mask captured by the TDI-CCD camera. The pictures of 70 nm logic EPL mask patterns of which the width and pitch are 280 nm and 560 nm on mask, respectively, had been obtained by using this system.

**EUVL mask inspection**

The EUV lithography mask fabricating process is illustrated in Fig. 16. The process includes a preparation of glass substrate, multi-layer deposition, buffer layer and absorber layer deposition and absorber pattern fabrication. Critical defects can occur either in the absorber pattern, the multilayer reflecting coating, or due to contamination of the finished masks. In particular, phase defect due to the particle residing on the mask blank substrates are critical[11,12]. Current laser-based inspection tool has very low sensitivity of the phase defect when the size becomes smaller than 100 nm.

The effects of phase defects on projected patterns and a schematic structure of at-wavelength inspection tool proposed by MIRAI project are shown in Fig. 17 [13,14]. From the mask pattern image simulation, it becomes clear that critical phase defect size that causes 10% CD variation is approximately 25-30 nm on the 4X EUVL mask for 45 nm technology node. The inspection tool shown in the figure is capable of detecting such phase defects. When an EUV beam from the laser produced plasma (LPP) EUV light source is incident on a defect, photons are scattered into non-specula directions or dark field. A magnifying optics located to collect only scattered EUV constructs a dark field image on the image plane, where an EUV-sensitive CCD is set to detect the image.

**CONCLUSIONS**

The minimum feature size of ULSI devices has become smaller than the wavelength of exposure light used in optical lithography. The mask technology for resolution enhancement such as OPC and phase-shift mask provides fine features with approximately a half of exposure wavelength. Since a mask is an original edition of semiconductor patterns, precise control of the mask aperture size becomes critical. Many types of inspection and metrology for those masks are reviewed.

Inspection with short wavelength is one of the key issues to improve the resolution of inspection/metrology optics. To obtain a CW-DUV laser source, sum-frequency generation technique has been investigated and CW 198.5 nm laser source has been developed. To obtain a high efficiency sensor for 19.5nm wavelength, the backside thinned TDI sensor device has been developed. The mask inspection system using 198.5nm wavelength technologies is being developed.

The metrology tools that can assure the quality items such as CD and phase error are required. Currently, an aerial image monitor tool and a phase measurement tool with 157nm wavelength are being developed.

Mask inspection technologies for next generation lithography such as EPL and EUVL are also reported. Electron beam imaging system for EPL, and at-wavelength phase defect detection for EUVL are under development. Effective use of mask inspection/metrology technologies will extend the practical resolution limit of mask projection lithography.

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