Surveying Nanosize Particle and Flaw – Mask Defect Inspection System in Extreme Ultraviolet Lithography for Next-Generation Lithography –

Extreme ultraviolet lithography (EUVL) [1] is a most promising lithographic technology for the next-generation lithography of the 32 nm node around 2011. Defect-free mask fabrication is one of the critical issues in the use of EUVL technology in the high-volume production of semiconductor devices. According to the International Technology Roadmap for Semiconductors (ITRS) [2], a defect-free mask with no defect size greater than 25 nm is required for the 32 nm node. There are two types of EUVL mask defects. As shown in Fig. 1, one is an amplitude defect and another is a phase defect. Amplitude defects are either particles on the surface of a multilayer film or flaws in the multilayer film. These defects can be detected directly by measuring the reflected light intensity of deep ultraviolet (DUV) light from the mask surface. On the other hand, phase defects are produced when a multilayer film is deposited over a bump or pit on the substrate. The width (W) and height (H) of phase defects is shown in Fig. 1. Since these phase defects are swellings and depressions on the surface of the multilayer film, they cannot be inspected with a commercial tool using a DUV source. Thus, defect inspection can be carried out only by an inspection tool exposure using EUV light. As for defects on mask blanks, they can be detected using EUV dark-field actinic inspection systems at MIRAI and SEMATECH [3,4]; however, these systems cannot obtain an aerial image of mask absorber patterns because of its detection principle. Therefore, we developed an EUV microscope [5,6] that can observe an aerial image of mask absorber patterns for the criteria of defect size and height of multilayer phase defects to be printable.

Figure 2 shows the configuration and a photograph of the actinic EUV microscope installed at the BL-3 beamline in the NewSUBARU synchrotron radiation (SR) facility. It consists of Schwarzschild optics, a Mirau interferometer for phase-shift interference measurement, an X-Y sample stage, a focus detector, an X-ray zooming tube connected to a CCD camera, and an image processing computer. It was installed in a vacuum chamber evacuated to 1×10^{-5} Pa, and the vacuum chamber was set on a vibration isolation table.

The numerical aperture (NA) and magnification of Schwarzschild optics are 0.3 and 30, respectively. Our simulation predicted that the system can resolve a 10-nm-wide isolated line. The figure error and midfrequency surface roughness of the mirrors was less than 0.4 nm and less than 0.15 nm, respectively. The substrate material of the mirrors is Zerodur and is fabricated by ASML Tinsley. Mo/Si multilayer films were coated on these optics by an X-ray instrument company in Russia. A d-space matching of less than 0.01 nm was achieved at a wavelength of 13.5 nm. The wave-front error (WFE) of the Schwarzschild optics after assembly and alignment was measured by a Fizeau-type interferometer (ZYGO GPI) and found to be is approximately 2 nm (rms). The optics is installed in an optical housing made of invar to prevent the thermal expansion effect.

The mask image is projected to the X-ray zooming tube (Kawasaki Heavy Industries) with

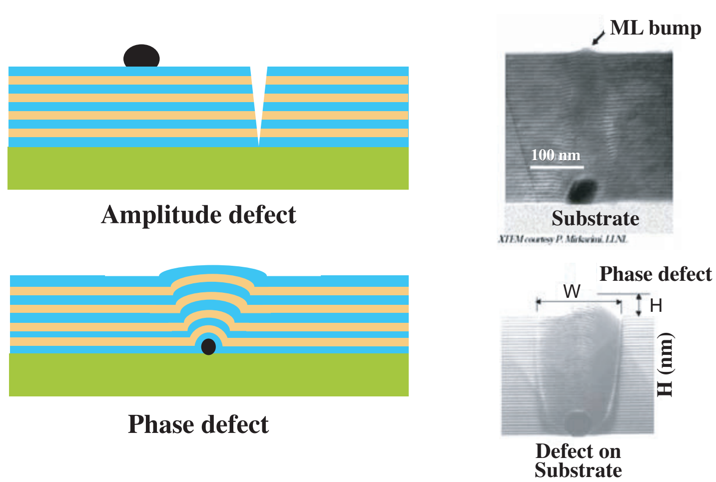

Fig. 1. Amplitude defect and phase defect of EUVL mask blanks.

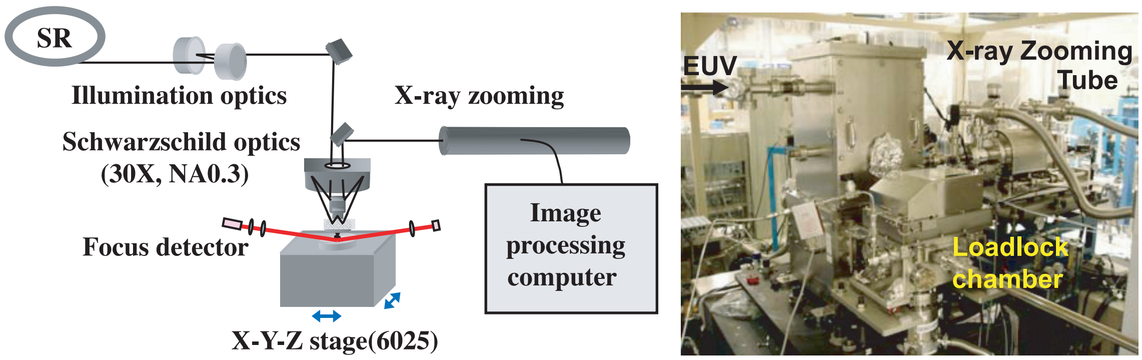

Fig. 2. Configuration and photograph of actinic EUV microscope.

electromagnetic lenses that can be adjusted to vary their magnification in the range from 10 to 200. Therefore, considering the magnification of the Schwarzschild optics, the total magnification range of the microscope system is from 300X to 6000X. The resolution of the X-ray zooming tube is 300 nm on a CsI photocathode. Defects of 10 nm size are magnified by the Schwarzschild optics to greater than

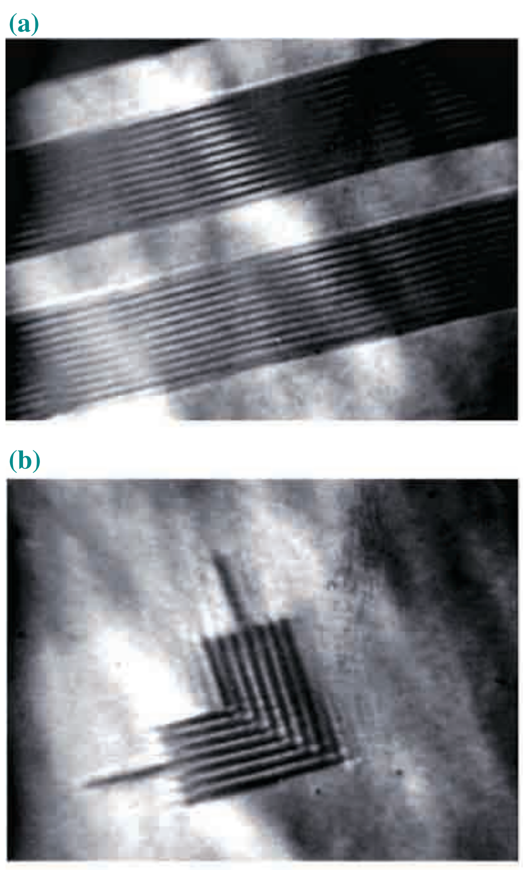

Fig. 3. EUVM images of mask with **(a)** 300-nm-wide isolated lines and **(b)** 400 nm-wide elbow patterns.

300 nm. Thus, the resolution of the X-ray zooming tube is sufficient to enable the detection of 10 nm defects and to produce resolution-limited Schwarzschild images of mask patterns. The X-ray zooming tube has a field of view of 1.5 × 1.5 mm^2 in the CsI photocathode, which corresponds to 50 × 50 μm^2 on the sample surface. The electron image generated by photoelectric transfer on the photocathode is magnified by the electrostatic lenses and focused on a microchannel plate (MCP). The magnified EUVM images are taken with the CCD camera and displayed on the screen of the image processing computer, and image data are stored in the computer.

A finished EUVL mask was observed using the EUV microscope. The mask with a 6025-format substrate (ULE glass, Corning) was fabricated by HOYA Corporation. Figure 3 shows EUVM images of the mask with a 300-nm-wide line and space (L&S) pattern and a 400-nm L&S elbow pattern. The white part is the Si surface of the Mo/Si multilayer film and the dark part is the absorber material of TaBN. The resolution of the observation system is determined by the NA of the optics and is determined by the magnifying power of the zooming tube used. Assuming a resolution rage from 25 to 75% of the slope of a light intensity profile at the knife edge the total resolution of EUVM was 50 nm.

The following is the fabrication process of programmed phase defects [7]: 1) The glass substrate was coated with ZEP520A resist and a coated charge-up preventer thin film was coated on the resist. 2) The substrate was subject to electron beam exposure using an electron beam writing tool, followed by development of the resist. 3) Selective dry etching of the glass substrate was carried out by masking a resist pattern. 4) The remaining resist was removed. Finally, a Mo/Si multilayer film was deposited using a DC or RF magnetron sputtering system, and programmed phase defects were formed on the glass substrate.

Figure 4 shows the observation result of a pit-patterned programmed defect with a shallow line pit. The pattern widths are 350 nm, 250 nm, 150 nm, 100 nm, and 75 nm. Programmed defects with a line width larger than 100 nm and a pit depth larger than 2.5 nm were clearly observed using the EUV microscope. However, no programmed defects with a 75 nm width and a 1.5 nm depth could be observed.

Figure 5 shows a summary of the printability results for pit line defects in both simulation and EUV microscopy. The horizontal axis is the width and the vertical axis is the depth of a pit line pattern. Star marks show the size of a pit line defect pattern observed using the EUV microscope. A printable region was calculated by computer simulation, which we previously reported. A programmed line pit phase defect with a 20 nm width and a 2 nm depth is the minimum printable size, as shown in the computer simulation. As observation results obtained using the EUV microscope, with a pit line depth of 2.5 nm, a line pit phase defect with a width larger than 100 nm is printable. Furthermore, a line pit with a 40 nm width and a 10 nm depth is also printable. Line pit phase defects could be observed here. Thus, we confirmed that this region is a printable region. However, no line pit defect with a 75 nm width and a 1.5 nm depth were observed using the EUV microscope. We thus confirmed that this area is unprintable.

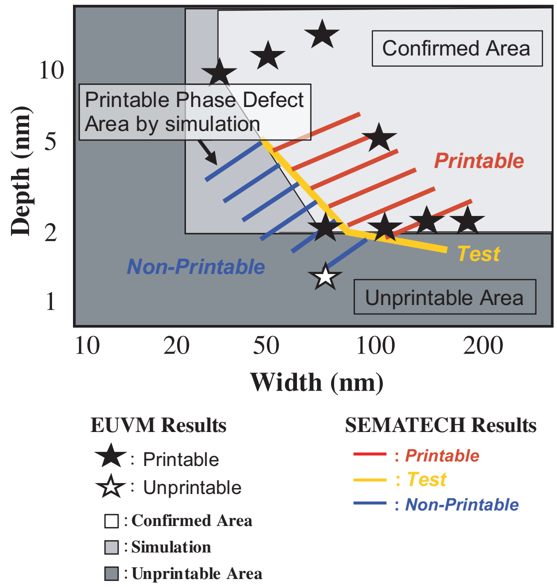

Fig. 5. Summary of printability results for pit line defects in both simulation and EUVM observation.

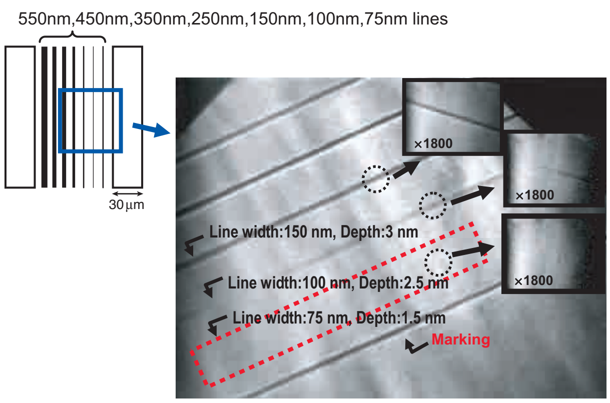

Fig. 4. EUVM image of pit defects.

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