Featured Articles

Nanoscale Imaging, Material Removal and Deposition for Fabrication of Cutting-edge Semiconductor Devices

—Ion-beam-based Photomask Defect Repair Technology—

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OVERVIEW: FIB technology is applied to repair defects in lithography photomasks used in semiconductor device fabrication. Cutting-edge devices demand nanometer-scale minimum processing dimensions and precision for defect repair. To meet these scaling requirements, Hitachi has developed a novel gas field ion source. This breakthrough scaling technology replaces liquid metal ion sources, an area in which Hitachi has over 30 years of experience. It has been implemented into a defect repair system to confirm that it satisfies cutting-edge performance requirements such as minimum processing dimension, repair precision, and post-repair photomask optical properties.

INTRODUCTION

LITHOGRAPHY technology helps enable higher integration of semiconductor devices. It uses reduction projection exposure to repeatedly print the circuit pattern on a photomask onto a wafer. It is therefore vital that the photomask (which can be considered the circuit pattern original) be free of defects during semiconductor device fabrication. Since cutting-edge device pattern dimensions are scaled down to 20 nm or less, defect sizes on problem photomasks are also of a nanometer scale, and the defect repair technology must also be scaled.

A system using a focused ion beam (FIB) was developed to repair photomask defects. Over the 30 years since the release of the first unit in 1985, this technology has been used to repair defects in photomasks for ever more advanced cutting-edge semiconductor devices, helping improve semiconductor fabrication yields. The following describes the FIB-based photomask defect measurement/repair technology and the latest developments in this area.

FIB-BASED DEFECT MEASUREMENT/ REPAIR TECHNOLOGY

FIB technology was perfected in the early 1980s with the development of liquid metal ion sources, and subsequently came into widespread use. A major feature of FIB technology is its ability to achieve a small beam spot of 1 μm or less in diameter. By scanning a sample with an ion beam, the technology can be used as a scanning ion microscope, replacing the electrons of a scanning electron microscope (SEM) with ions. Moreover, using ion beam-based sputtering effects and surface reactions enables minute processing for localized etching and deposition. In other words, a single beam has three functions: imaging, material removal and deposition. These functions are used to implement photomask defect measurement and repair.

FIB-based Photomask Defect Repair System

Fig. 1 shows the composition of an FIB defect repair system. The major components include a high-brightness ion source, an ion optics system used to focus the ion beam on a minute spot and scan it, a charged particle detector used for ion image acquisition, an electron gun used to neutralize the charge on the photomask surface, a material gas injection system for localized etching and deposition, an XY stage used to mount and move the photomask, a vacuum evacuation system, and a mask transport system.

The general procedure for measuring/repairing photomask defects is as follows:

(1) Use defect coordinate data from the defect inspection device to move to the defect location.

(2) Acquire the scanned ion image of the area containing the defect.

(3) In the scanned ion image, determine the repair area

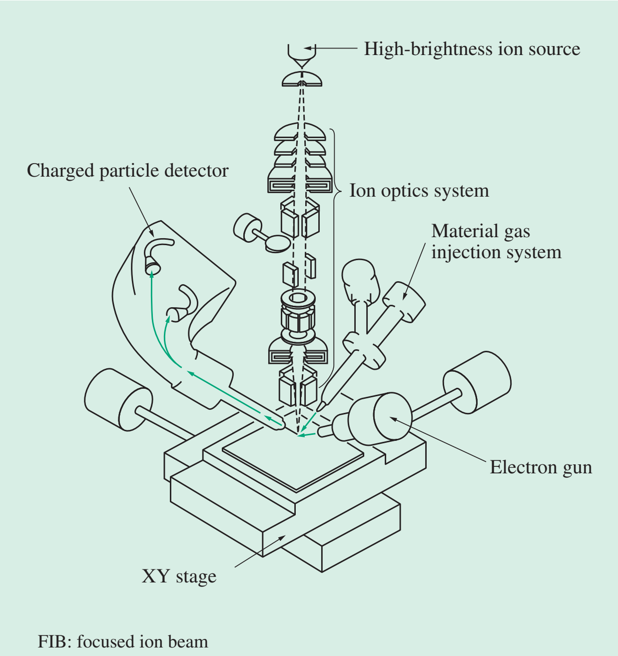


Fig. 1—Composition of FIB-based Defect Repair System.
This schematic diagram shows the relationships of the components placed in a vacuum.

and method according to the type of defect.
(4) Repair the defect by locally irradiating the photomask with the FIB while injecting gas.

Fig. 2 illustrates this defect repair procedure. Photomask defects can be classified into two types, (a) excess film defects caused by residual pattern film, and (b) missing film defects caused by lacking pattern film. Type (a) defects are called opaque defects since they block light, and type (b) defects are called clear defects since they allow light to pass through. The type of repair done depends on the defect type (opaque or clear). Opaque defects are repaired by etching done to remove the excess film, and clear defects by depositing material onto the area of missing film.

Performance Demanded of Cutting-edge Photomask Defect Repair Technology

As semiconductor devices become increasingly integrated, the following three capabilities are continually demanded for photomask defect repair:
(1) Support for narrow line widths
(2) Improved repair precision
(3) No change in the quality of the optical properties of photomask repair areas relative to normal areas

Defect repair technology for photomasks for cutting-edge devices needs to be able to handle narrow line-width patterns of 20 nm or less, and minimum repair dimensions of 10 nm or less. The shorter wavelengths and shorter focus depths of today’s lithographs create a need for very high repair precision, with reproducibility of 2 or 3 nm or less. Moreover, variations in the print dimensions of the repaired area caused by light transmittance or exposure focal-point drift need to be the same as for the normal (unrepaired) areas.

Major advances have been made in FIB technology to satisfy these demands. The following presents the technology used in the latest systems, and describes its performance.

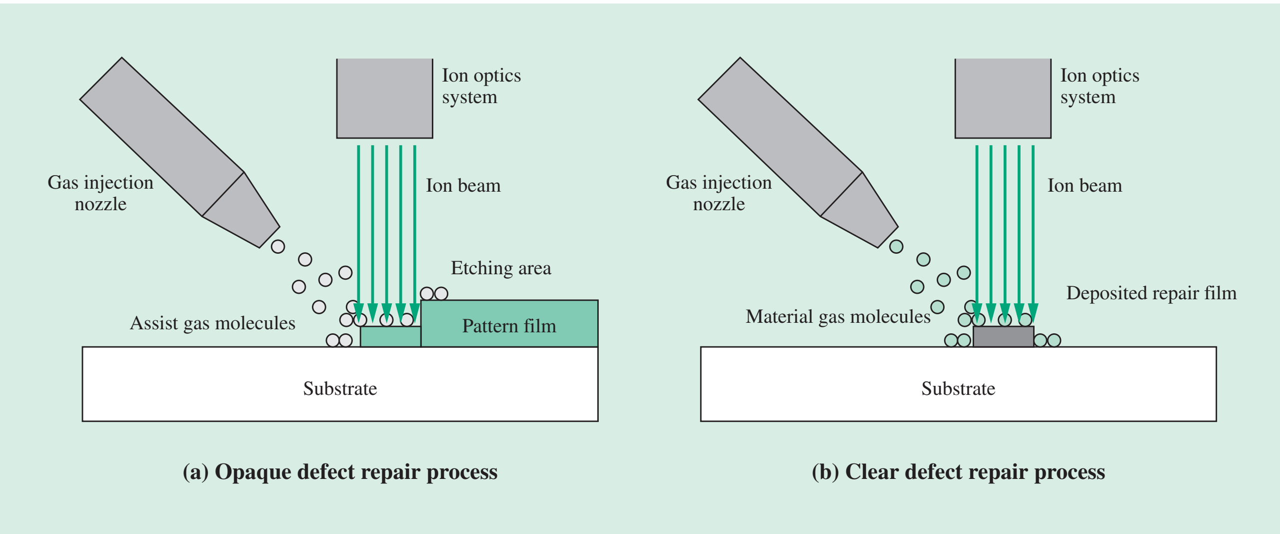


Fig. 2—Schematic Diagrams of FIB-based Defect Repair Procedures.
(a) is a schematic diagram showing the localized etching procedure for repairing opaque defects. (b) is a schematic diagram showing the localized deposition procedure for repairing clear defects.

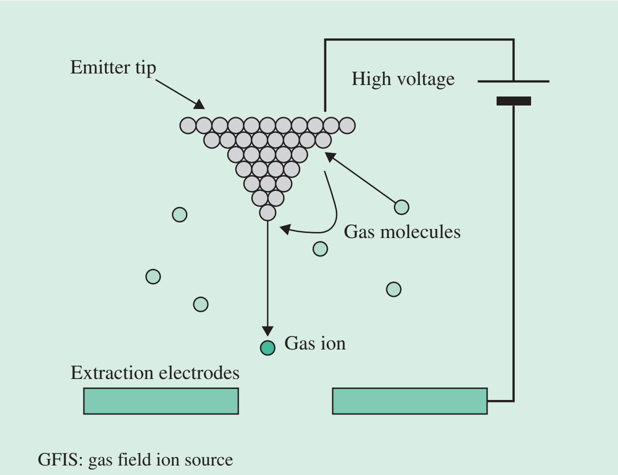


Fig. 3—Schematic Diagram of GFIS Structure.
A GFIS applies a high voltage between an emitter tip sharpened to the atomic level and opposing extraction electrodes to ionize gas molecules in the high electric field at the end of the tip.

OVERVIEW OF LATEST SYSTEM, PERFORMANCE EVALUATION RESULTS

System Overview

Hitachi's latest FIB defect repair system (GR3000) uses a new gas field ion source (GFIS) in place of the liquid metal ion sources Hitachi had worked with for over 30 years[(1), (2)]. The GFIS applies a high voltage to an emitter tip sharpened to the atomic level, forming a strong electric field at the tip, which is used to ionize gas molecules (see Fig. 3). As ionization occurs only in the strong electric field at the tip, the ion generation area is extremely small (only a few nanometers in size), making the energy distribution of the emitted ions very narrow. The system therefore has an outstanding capability to form ion beams with small spot diameters.

Mounting the GFIS reduces the ion beam spot diameter by at least 50% relative to conventional technology, improves the scanning ion microscope image resolution, and improves the visibility of minute defects. Fig. 4 shows an example scanning ion microscope image in which a defect of 4 nm in size is visible[(2)]. GFIS enables a repair process with a minimum dimension of 10 nm or less (see Fig. 5)[(2)]. Since the ion species has been changed from conventional metal ions to gas molecular ions such as nitrogen or hydrogen ions, there is a major improvement in the reduction of light transmittance caused by ion implantation, which is a problem when irradiating the quartz glass that photomask substrates are made of[(2), (3)].

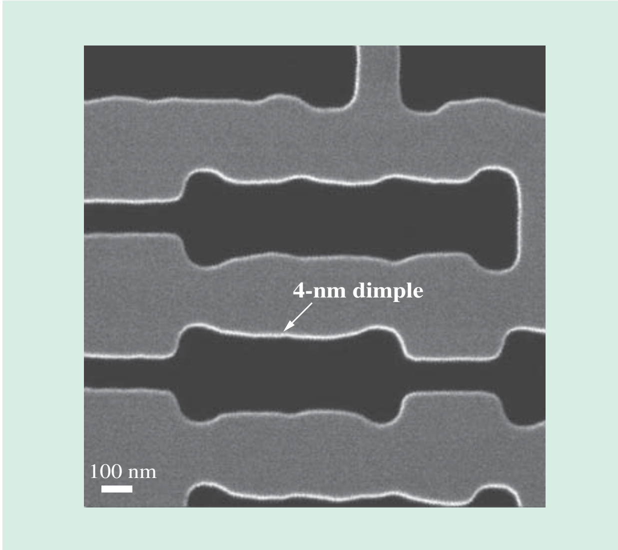


Fig. 4—Scanning Ion Microscope Image of Photomask Acquired by FIB System with GFIS Built-in.
The photo shows the image acquired by scanning a 25-keVN_2^+ beam on a photomask and detecting secondary electrons. A 4-nm defect is visible on the photomask.

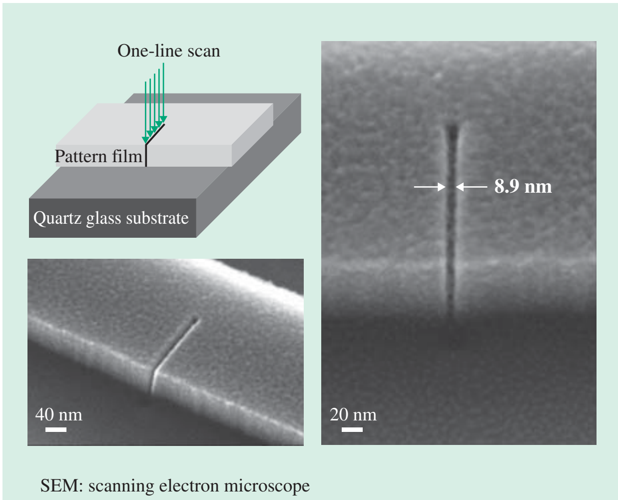
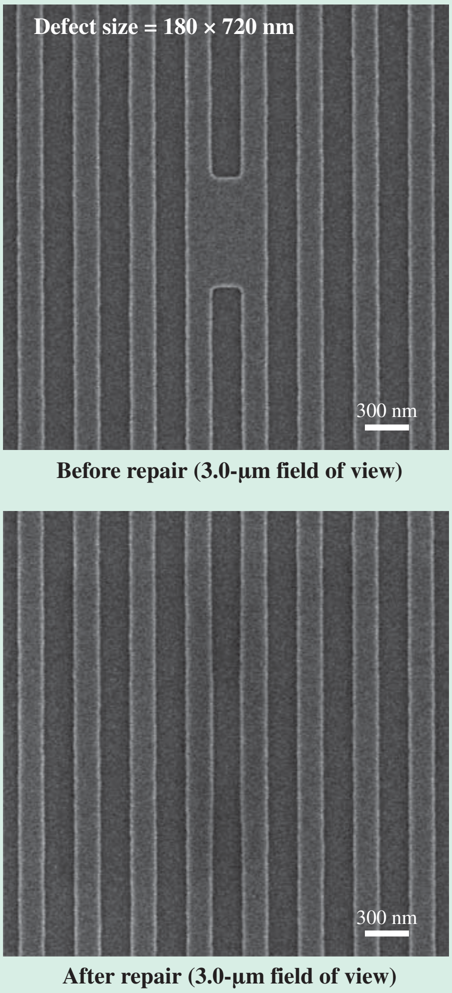


Fig. 5—Minimum Processing Dimension of GR3000.
A photomask pattern film that was line-processed with an ion beam was observed with an SEM.

Defect Repair Performance Evaluation Results

Fig. 6 shows an example of opaque defect repair by the GR3000. It shows the before and after SEM images for repair done by using etching to remove excess film from a bridging defect in a line and space pattern on a photomask. The pattern film is made of a molybdenum and silicon (MoSiON) compound phase shift mask*.

* Phase shift mask: A photomask that controls the phase and transmittance of light to improve characteristics during exposure and to improve resolution by drawing on the phenomenon of light interference.



MoSiON: molybdenum and silicon

Fig. 6—Example of Photomask Opaque Defect Repair Using GR3000 (Line and Space Pattern).
The photos show SEM images of the photomask before and after the repair. The pattern film is an MoSiON pattern film with a line width of 180 nm.

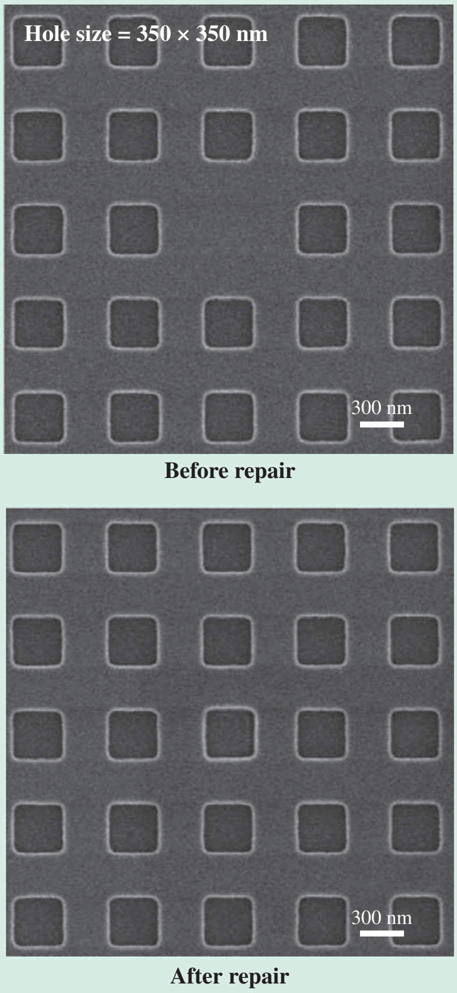


Fig. 7—Example of Photomask Opaque Defect Repair Using GR3000 (Hole Pattern).
The photos show SEM images of the photomask before and after the repair. The pattern film is an MoSiON pattern film with a hole width of 350 nm.

A 25-keV nitrogen ion (N_2^+) beam was used for the repair. As shown, there was no glass substrate damage in the repair area, and the pattern edge shape was repaired neatly. Fig. 7 shows before and after SEM images of a repair done to a minute hole pattern of the same material. A high-quality repair was also achieved in this case. Good optical property evaluation results were obtained for these repair areas at the photomask exposure wavelength[(2), (3)].

And, the defect repair performance was evaluated for masks used in extreme ultraviolet (EUV) lithography, a technology that is gaining attention as the next generation in lithography. A 15-keV hydrogen ion (H_2^+) beam was used for the repairs, which verified its practicality[(1)].

CONCLUSIONS

FIB technology enabling nanometer-scale imaging, material removal and deposition with a single system has been applied to repairing defects in lithography photomasks, helping make higher integration possible in semiconductor integrated circuits. To support cutting-edge minute patterns of 20 nm or less, Hitachi developed a mask defect repair system with a new GFIS built-in. This system was used to repair defects in photomasks and EUV masks for cutting-edge devices, confirming its practicality.

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REFERENCES

(1) F. Aramaki et al., "Development of New FIB Technology for EUVL Mask Repair," Proceedings of SPIE 7969, 79691C (2011).
(2) F. Aramaki et al., "Photomask Repair Technology by Using Gas Field Ion Source," Proceedings of SPIE 8441, 84410D (2012).
(3) F. Aramaki et al., "Performance of GFIS Mask Repair System for Various Mask Materials," Proceedings of SPIE 9235, 92350F (2014).

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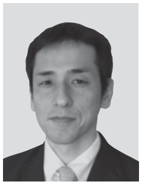

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