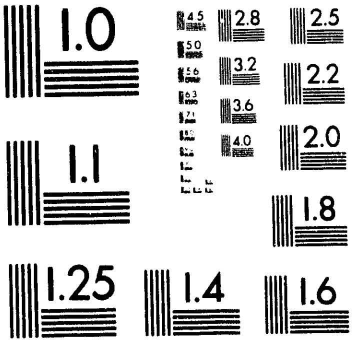
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Characterization and Possible Repair of Defects in Soft X-ray Projection Lithography Masks

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Abstract

Soft X-ray Projection Lithography (SXPL) is one promising technique for the mass production of integrated circuits with minimum feature sizes below 100 nm. Mask fabrication, inspection and repair processes are critically important to all forms of lithography, including SXPL which requires a reflection mask (a substrate coated with a x-ray multilayer coating and patterned with a thin metallization layer). Processes for the repair of defects in the metallization patterns have been developed, but at present, there exist no processes for the repair of defects in the multilayer coating. In this paper, we characterize the density and size distribution of defects in multilayer coatings deposited in LLNL's magnetron sputter deposition facility, which produces state of the art x-ray multilayer mirrors. We also propose one possible process for the repair of defects in these multilayer coatings.

Introduction

Modern integrated circuits are fabricated by replicating a master pattern (i.e., a mask or reticle) onto a resist coated wafer. In this procedure, a great deal of effort is dedicated towards producing a defect-free mask that can be copied many thousands of times. In mass production, it is impractical to replicate a mask with known defects and attempt to repair these replicated defects on the exposed wafer. Mask fabrication, inspection and repair processes are critically important to all forms of lithography including soft x-ray projection lithography (SXPL).

Masks for SXPL are used in reflection. These masks consist of a thin (< 100 nm) metallized pattern (the x-ray absorber) on a state-of-the-art x-ray multilayer mirror (the x-ray reflector) deposited onto a substrate. A mask used in production must be free of all defects in both the metallization pattern and in the multilayer mirror. A mask fabrication and repair process cannot tolerate reduced mirror reflectivity. A defect-free mask with low mirror reflectivity will reduce system throughput and is not acceptable. Previously, the repair of SXPL metallization patterns has been addressed(ref), but the repair of (or recovery of mirror reflectivity from) defects in the SXPL multilayer coating have not been discussed.

State-of-the-art multilayer mirrors are fabricated at LLNL using magnetron sputter deposition. SXPL masks are fabricated by lithographically defining a thin metallization pattern on the mirror. Fig. 1 illustrates a scanning electron micrograph of a SXPL mask consisting of a thin (50 nm gold) metallization pattern on a molybdenum-silicon x-ray mirror designed to operate near $\lambda = 13$ nm. In this micrograph, a defect in the multilayer coating is clearly visible; however, it is not clear if this defect was generated by the deposition system or by the lithographic process defining the metallization pattern. Defects in mirrors that have not undergone subsequent lithographic processing have also been observed, (Fig. 2) and appear similar to those defects detected on the SXPL mask (Fig. 1). Both defects appear as (approximately) micron-sized particles surrounded by regions without any multilayer coating.

Defect Characterization

We prepared several samples to characterize the number and size of defects generated by our state-of-the-art multilayer deposition system. We prepared SXPL mask blanks that were multilayer mirrors deposited onto 100 mm diameter, (100) silicon wafers, and SXPL masks, which were masks blanks patterned (by liftoff) with a 5 nm Cr, 50 nm Au metallization layer. We prepared reference wafers for the mask blanks and the patterned masks so as to monitor the defects generated by our wafer handling and processing equipment. In our procedure, the reference wafers experienced the <u>exact</u> same

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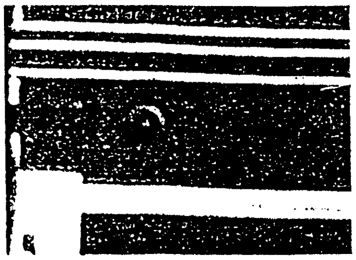


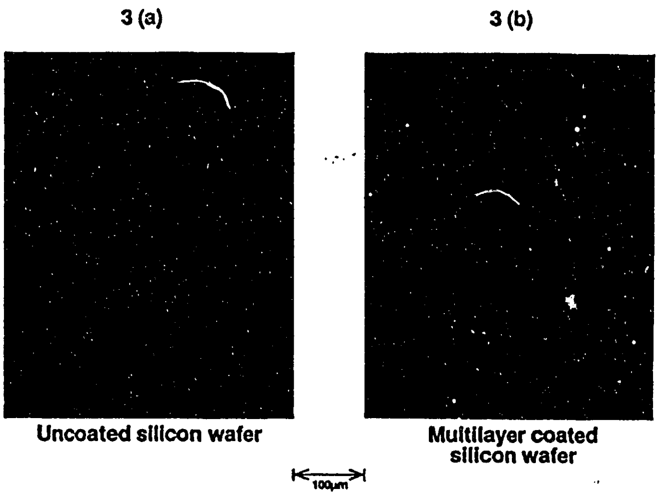
SemSpec Image

Figure 1
A scanning electron micrograph of a mask for SXPL. The bright lines are 50 nm thick gold on a siliconwafer coated with an x-ray multilayer. A large defect is clearly visible.

Figure 2
A scanning electron micrograph of a multilayer coated wafer. This wafer has not undergone any processing subsequent to the multilayer deposition. The defects on this sample appear similar to those observed in Fig. 1.

processing as the mask blanks or the patterned masks. For example, a reference wafer for the mask blanks was physically inserted into the deposition system, removed (without depositing a multilayer coating) and stored in a similar, flouroware wafer holder. The reference wafer for masks was also inserted into the deposition system and underwent identical wafer cleaning, lithographic processing and storage as the masks. In this way, we could distinguish between the defects generated by the deposition process from defects generated by handling.

Optical inspection of the mask blanks was performed using both dark field imaging and inspection with an industrial inspection tool. Fig. 3a is an optical photograph of the dark field image from a reference wafer for a mask blank and Fig. 3b is an optical photograph of the dark field image for a mask blank. Both photographs were taken at the same microscope magnification, exposure and development conditions and are representative of the samples. Upon inspection of the uncoated silicon wafer (the reference wafer) very few defects were detected. However, inspection of the multilayer coated wafer illustrated many surface defects. Inspection of the photograph reveals approximately 15 surface defects in an area 400 µm x 500 µm, implying 7,500 defects/cm^2.



Uncoated silicon wafer

Multilayer coated silicon wafer

Figure 3
(a) Dark field inspection of a reference silicon wafer. (b) Dark field inspection of a multilayer coated silicon wafer. Both samples were handled and stored identically and the photographs taken under identical illumination conditions. The multilayer coated wafer shows many more defects (approxmately 7500/cm^2) than the reference wafer (approximately 4/cm^2).

Further optical inspection was performed at Optical Specialties, Inc. (OSI, Fremont, California) on their IQ-165 automated wafer defect detection system. This industrial tool utilizes optical pattern filtering to locate random defects on both patterned and unpatterned wafers. Tests by OSI indicated that the tool is capable of detecting < 100 nm latex spheres on silicon wafers, but no sensitivity tests on multilayer coated silicon wafers were performed. Inspection of reference wafers for mask blanks detected approximately 4 defects/cm^2 that we attribute to our wafer handling and storage processes. However, inspection of multilayer coated mask blanks detected in excess of 6500 defects/cm^2 in the regions of lowest defect density. We attribute these defects to the magnetron sputtering multilayer mirror deposition process.

We inspected SXPL masks (i.e., mask blanks with a metallization pattern) in the KLA SemSpec tool and detected over 9000 defects/cm^2. (Note: This defect density should not be used as a comparison against the defect density measured by the OSI tool because the OSI tool measured defects in mask blanks and the KLA tool was used to measure processed, metallized masks). The SemSpec uses a scanning electron beam to serially inspect individual pixels on the mask and make a high resolution, "die-to-die" comparison. This tool has been used to inspect masks for proximity print x-ray lithography and is capable of detecting defects as small as 50 nm. At present, the SemSpec requires a pattern on the mask for electron beam focusing and is not well suited to inspect unpatterned mask blanks. Future improvements under consideration include focal plane mapping by an optical technique that should permit inspection of mask blanks. A useful feature of the SemSpec is that it is capable of measuring the dimensions of detected defects, Fig. 4. From this information, we determined that a majority of the defects are submicron in size, and the defect distribution closely follows a "*1/x*" curve.

To complete the characterization of defects in multilayer coatings and to begin the process of fabricating near "defect-free", state-of-the-art multilayer coatings, further work is required. Specifically, it is necessary to measure the defect density of coatings produced in other deposition systems and by other techniques and then to correlate these defects with printed x-ray images.

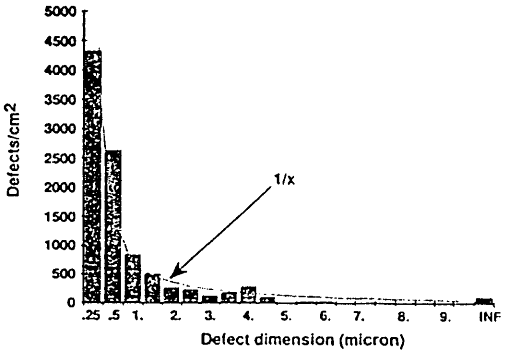


Figure 4
Defect-size histogram for a multilayer coated silicon wafer. Notice that the defect distribution closely matches a "1/x" curve.

Mask Blank Reflectivity Recovery

As a practical matter, it will be impossible to routinely fabricate defect-free SXPL masks without a mask repair process. In an industrial setting, one can expect that masks will be fabricated with a small number of defects and that an inexpensive process will be needed to repair the defects. Repair of metallization patterns on x-ray multilayer mirrors has been demonstrated(1,2), but the repair of defects in the multilayer coating has not been addressed.

We propose redundant multilayer coatings separated by a spacer layer for the SXPL mask blank, Fig. 5. The mask blank contains multiple x-ray reflectors and only those portions of each mirror that are defect-free are used, Fig. 6. An essential element is to develop a process where the defects in the redundant multilayer coatings are spatially uncorrolated. To achieve this, we plan to planarize the spacer layer between the redundant coatings and to develop an etch process to selectively remove the defective portions within the top multilayer (and the spacer material directly below it) and thereby expose the undamaged coating in the bottom multilayer. The total thickness of the redundant multilayer coatings and the planarized spacer layer is much less than the depth of focus of the imaging system at the mask.

We have begun theoretical calculations to simulate the effect of the "repaired" mask blank, Fig. 5, in an imaging system. These calculations will study the effects of varying the spacer layer thickness, the area of the etched region and the angle of the incident radiation. Preliminary indications indicate that the low numerical aperture (NA<0.02) and the large depth of focus (> 25 μm) at the mask are important features for the success of this process.

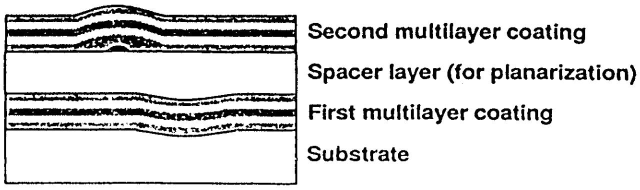


Figure 5
Mask blanks with redundant multilayer coatings seperated by a planarized spacer layer may be used for SXPL masks. This figure illustrates uncorrolated defects in each multilayer coating.

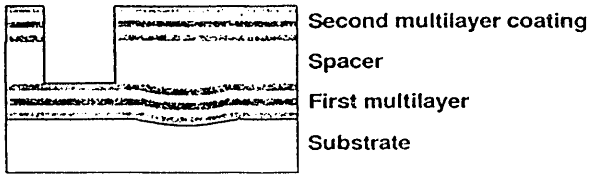


Figure 6
A mask blank with a defect in one multilayer coating could have the defect and planarization layer removed to expose (and use) the defect-free multilayer region below.

Conclusion

Defect densities on SXPL mask blanks and patterned masks have been quantified and shown to be much greater than the number of surface particles on similarly handled and stored reference wafers. The SXPL mask blanks and masks were fabricated using LLNL's magnetron sputter deposition system and it is believed that magnetron sputtering is the cause of these high defect densities. We plan to study the defect densities of multilayer coatings fabricated using other deposition tools and deposition processes. Ultimately, a deposition process capable of producing high reflectivity x-ray mirrors with few (or no) defects must be developed.

We have proposed one possible technique for the repair (or recovery) of a mask blank with a small number of defects utilizing redundant multilayer coatings. A key ingredient to this process is producing coatings with uncorrelated defects through the use of a planarization layer between the coatings. Additionally important is the large depth of focus and low numerical aperture of the imaging system at the wafer plane. We have begun calculating the effect of these repaired mask blanks on the imaging performance of an optical system as a function of planarization layer thickness, the width of the etched region and the angle of the incident radiation.

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