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Reticle Blanks for Extreme Ultraviolet Lithography: Ion Beam Sputter Deposition of Low Defect Density Mo/Si Multilayers

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Abstract

We report on the growth of low defect density Mo/Si multilayer (ML) coatings. The coatings were grown in a deposition system specifically designed for EUVL reticle blank fabrication. Complete, 81 layer, high reflectance Mo/Si ML coatings were deposited on 150 mm diameter (100) oriented Si wafer substrates using ion beam sputter deposition (IBSD). Added defects, measured by optical scattering correspond to defect densities of $2x10^{-2}/cm^2$. This represents a reduction in defect density of Mo/Si ML coatings by a factor of 10^5.

Key Words Thin films, Deposition and fabrication, X-ray mirrors, X-ray imaging.

Introduction

Extreme ultraviolet lithography (EUVL) requires the development of diffraction limited imaging systems utilizing reflective optical components. High reflectance is achieved with resonant multilayer (ML) coatings deposited on the optical surfaces. Mo and Si offer the best optical performance at 13 nm and normal incidence reflectivities of 65% have been demonstrated.

An EUVL reticle consists of a high reflectance ML coated substrate (the reticle blank) and a patterned absorbing overlayer. The ML coating that forms the reticle is situated at one of the conjugate points of the imaging system. Consequently, any significant variation in the phase or amplitude of the field reflected from the reticle has the potential of being replicated in the lithography process and could print as a killer defect. Defect densities of order $10^{-3}/cm^2$ will be required for production reticles.

There are highly developed techniques for repairing defective regions in the absorber, including selected area deposition and selected area milling; however, at present there is no satisfactory strategy for repairing ML defects.[1] Consequently, the economic viability of EUVL is contigent upon the ability to produce essentially defect free Mo/Si ML coated reticle blanks. A defect is any imperfection in the coating that results in variation in either the amplitude or phase of the reflected field. The study of "printable" defects in the ML structure, and their influence on lithographic reproduction will require high spatial resolution, "at wavelength" inspection of the ML coated substrate. This is beyond the current state of the art. We have concentrated on reducing process generated particulate material, realizing that the elimination of particulates represents a necessary, not sufficient, condition for the production of EUVL reticle blanks. Particulates as small as

0.13 μm can be readily detected using light scattering techniques.

A Mo/Si ML for EUVL applications at 13 nm will consist of 81 thin film layers; 40 layer pairs of Mo and Si with a bilayer period of 7 nm and individual Mo and Si layer thicknesses of 3 and 4 nm respectively. A 4 nm Si capping layer is added to minimize oxidation of the Mo on exposure to the atmosphere. Optimum optical properties are obtained when the individual layers are smooth, the transition between the different materials is abrupt and the layer to layer thickness variation is maintained within 0.01 nm. The favored technique for Mo/Si ML deposition is magnetron sputtering and the method is very successful in producing coatings meeting these specifications.

Typically, Mo/Si MLs are fabricated in dual source rf, or dc magnetron sputtering systems. Substrate motion is used to effect layering of the constituents and improve coating uniformity. A common scheme that has been employed by several groups is to fix the substrate to a rotating table which alternately transits each source. Layer thickness control is achieved by stabilizing both the magnetron source power and the table rotation rate.

Historically, the experimental emphasis in ML development for EUVL applications has been on the attainment of high EUV reflectance. Little attention has been given to the number and nature of the defects in the ML coatings. Optical scattering from the defects degrades the throughput of the condenser and imaging camera; however, for a high quality ML, the losses due to defect scattering are insignificant compared to the optical absorption of the ML, which is of order 28%.

Unfortunately, several of the techniques used to fabricate the high reflectance ML stack are incompatible with low defect thin film growth. For example, in-vacuum motions are known to generate particulates and should be minimized; however, the ML has 81 layers which requires relative motion of the source and substrate. Additionally, the presence of electrostatic fields within the deposition environment can trap and transport particulate material generated in the deposition process.[2] These problems can be particularly severe in magnetron sputtering where the substrate and target serve as the discharge anode and cathode, respectively.

A survey of high reflectance Mo/Si ML coatings fabricated using a variety of deposition techniques at several laboratories engaged in EUV experiments exhibited defect densities of order 10^4/cm^2.[3] The 7 order of magnitude discrepancy between the specification and the current state of the art provided a daunting technical challenge.

We have achieved a 5 order of magnitude reduction in defect density using a low particulate, ultra-clean ion beam sputter deposition (IBSD) technique to fabricate high reflectance Mo/Si ML coatings suitable for EUVL reticle blanks. The tool employs 150 mm Si wafers as substrates, standard mechanical interface (SMIF) modules for wafer introduction and wafer transport, robotic handling and *in-situ* particulate monitors[4] to ensure low defect density deposition. Coatings exhibit defect densities as low as $2\text{x}10^{-2}$/cm^2, with an EUV reflectance in excess of 60%, with a reflectance uniform to better than 5% across the wafer.

System Design

The deposition system pictured in Fig. 1 includes four separate vacuum modules a load-lock, degas chamber, robot and deposition chamber all isolated by high vacuum gate valves. We utilize 150 mm diameter, epitaxial grade, (100) oriented, single crystal Si wafers as substrates. Si wafers are used because they are readily available, clean and have a surface roughness compatible with the requirement for high EUV reflectance. In addition, the selection of Si wafer substrates (1) permitted us to utilize semiconductor standard wafer handling tools in the design of the system and (2) permitted us to use semiconductor standard diagnostic tools to characterize system operation.

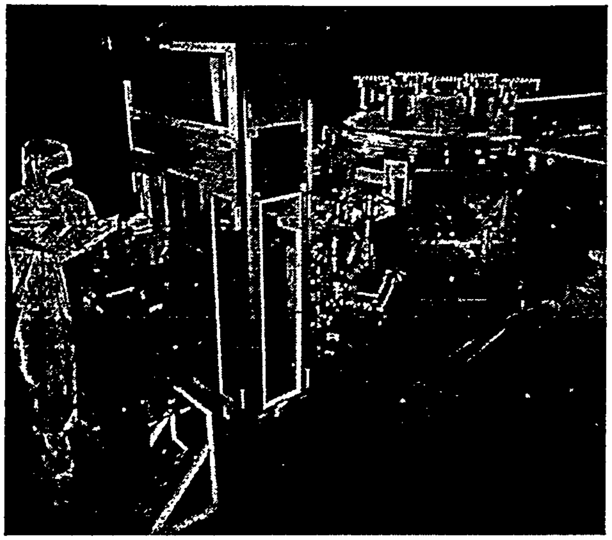

Fig 1. IBSD system for EUV reticle blank fabrication.

The system and defect diagnostic (Tencor Surfscan 6420)[5] are configured for single cassette operation. Wafer ingress and egress is accomplished with ASYST standard mechanical interface (SMIF) pods[6]. Class 1 minienvironments are used for wafer insertion and removal. Once the wafers are loaded into the SMIF pod they are continuously maintained in either vacuum, a mini-environment, or a pod. This approach allows us to maintain a wafer environment of better than Class 1 while situating the tool in a Class 1000 area.

In-situ particle monitors are located within the load-lock, robot and main chamber vacuum roughing lines.[4] These monitors are used to establish pump-vent protocols and provide real-time particle counts of each vacuum enclosure during system operation and during pump-purge cleaning of each of the vacuum modules. *Ex-situ* diagnosis is accomplished with a Tencor Surfscan 6420. The instrument can detect particulates as small as 0.13 μm in diameter at greater than 95% efficiency.

The deposition module utilizes sequential ion beam sputter deposition from elemental Si and Mo sputtering targets to grow the ML. Ar ions are generated in an rf plasma discharge and extracted and focused with gridded ion optics to form a focused beam. The extracted beam is transmitted at electrical ground potential. Electrostatic neutralization of the beam is accomplished with a plasma bridge neutralizer (PBN). The sputtering targets are mounted back-to-back on a water-cooled, rotary stage. ML deposition is effected by rotating the stage from target to target. The ion beam angle of incidence at the sputtering target can be continuously varied. Substrates are mechanically clamped to a three axis rotary stage. The stage permits single axis rotation and dual axis oscillation of the substrate during deposition.

Experimental Procedure

For the MLs fabricated in this study the focussed ion beam angle of incidence was 55 degrees from the target normal. The substrate and the sputtering target surfaces were parallel and the only substrate motion was a simple rotation at 0.5 Hz about the substrate normal. The ion source was operated at 780 V with an extracted current of 400 mA and a source target distance of 40 cm at a total Ar flow rate of 15 sccm. The ion source requires an Ar flow of 13 sccm, the PBN uses 2 sccm. This produced Mo and Si deposition rates of order 1Å/sec at a deposition pressure of order 10^{-4} Torr and a target substrate distance of 40 cm. The deposition system base pressure is $3x10^{-9}$ Torr. Individual layer thicknesses were selected by adjusting the deposition time. The ion source was electrostatically gated during sputtering target rotation. This approach permits interruption of the extracted ion beam (and interruption of IBSD) during continuous operation of the rf plasma discharge and avoids the use of mechanical shutters.

The following protocol was rigorously adhered to in the fabrication of the ML films. The as-received substrates were transferred from their shipping containers to cassettes in a filtered laminar-flow enclosure and loaded into a SMIF pod. The surface defect densities were measured and recorded with the Tencor 6420. The cassette was transferred into the load-lock and the load-lock was evacuated. The wafers were processed serially in a sequence that involved wafer transfer from cassette to deposition module, ML deposition and transfer from deposition module back to the wafer cassette. The load-lock was vented and the cassette was returned to the SMIF pod. The surface defect densities were remeasured using the Tencor Surfscan and the defect maps were recorded. Deposition times for the 81 layer ML structures were of order 100 min. As an additional diagnostic particle counts were measured on bare wafers that had been moved through the sample transfer cycle (wafer walk) prior to the initiation of depositions each morning. Random wafer walks were performed during the deposition phase to determine the cleanliness of the system following ML deposition.

Results

Initially, a set of depositions was undertaken to evaluate the cleanliness of the deposition system and ascertain the defect density of IBSD ML films. The first films had defect densities of order $10^2/cm^2$. However, the defect density decreased exponentially as the protocols improved. In Figure 2, we show the measured defect density for a series of 27 ML deposition runs that occurred over a period of 2 weeks.

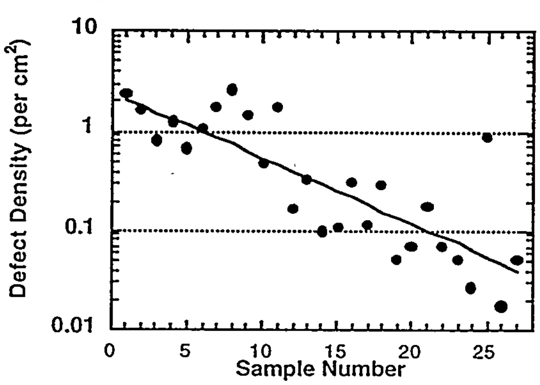

Fig 2. Defect density vs. sample number for a series of 27 EUVL reticle blanks.

Densities were measured over a 113 cm^2 circular aperture centered on the 150mm diameter wafer - this corresponds to an exclusion zone of 15 mm from the edge of the wafer. Note that the defect density, on average, decreases with increased operation time (number of cycles) and that the best results correspond to a defect density of $2x10^{-2}/cm^2$. This corresponds to a total of 2 particles added during the full 81 layer ML deposition. The wafer defect map is shown in Figure 3.

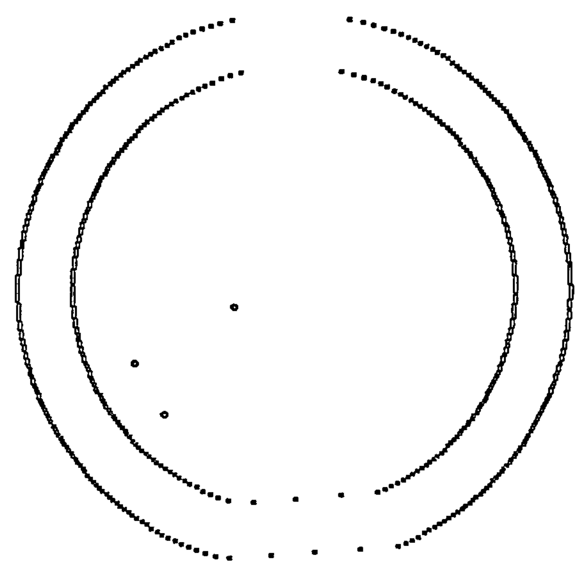

Figure 3. Defect map of the wafer illustrating a added defect density of $2x10^{-2}/cm^2$.

In Figure 4, we show the measured near normal incidence reflectance (NIR) of one of the IBSD Mo/Si MLs. The sample was measured at 6 degrees from normal incidence, near the center of the wafer. The ML achieved greater than 60% reflectance at 14.13 nm, indicating a high structural quality of the ML.

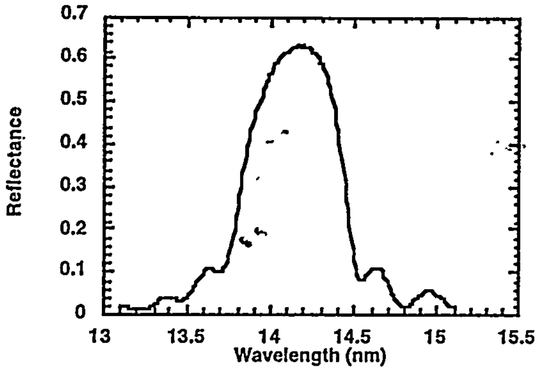

Fig 4. NIR of a typical low defect density IBSD Mo/Si ML.

Conclusion

We have designed and built a deposition system specifically to produce low defect EUV reticles. The system utilizes an IBSD technique to deposit complete, 81 layer high reflectance Mo/Si MLs on 150mm diameter (100) oriented silicon substrates. The system produced MLs with 5 orders of magnitude fewer particles than typical multilayers, with the best samples achieving defect densities of $2x10^{-2}/cm^2$. This reduction of defect levels has not come at the price of a reduction in multilayer quality as the resulting mirrors have near normal incidence reflectivities of greater than 60%.

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