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Optical degradation issues for xuv projection lithography systems*

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ABSTRACT

We review the degradation susceptibility of the various optical components proposed for use in XUV projection lithography systems at 13-20 nm. Contamination by laser plasma target debris and carbonaceous films are two primary hazards that must be essentially nullified. Pertinent experimental results of a number of researchers illustrate the present status.

Key Words: contamination; extreme-ultraviolet; laser plasma; oxidation; photolithography; plasma debris; projection lithography; soft-x-ray.

I. INTRODUCTION

Optical projection lithography using extreme-ultraviolet (XUV) exposure wavelengths from 13 to 20 nm is being developed to produce gigabit integrated circuits with feature sizes less than 0.2 μm while providing a total depth of focus (DOF) of $\geq 1 \mu\text{m}$.¹⁻⁴ Projections of the process wavelength needed for photolithographic production of consecutive generations of DRAM microchips are shown in Fig. 1. With such short wavelengths, all-reflective condenser and imaging systems with reflective masks will be required. Since seven to eight reflections at normal incidence appear to be necessary to attain diffraction-limited images of the 5-10 cm^2 size of future gigabit chips, high mirror reflectance is very important for transmission of a practical fraction of the exposure source power to the wafer. As a result, present attempts to develop soft-x-ray projection lithography are focused mainly around 13 nm where relatively high reflectance up to 65% has been attained with Mo/Si multilayer mirrors.^{6,7}

The essential components of an optical projection lithography system include: 1) photon source (preferably cw), 2) condenser optics for providing uniform illumination on a 3) reticle patterned with the desired circuit features, 4) imaging optical system, typically with 5:1 demagnification, 5) resist-coated silicon wafers currently up to 20-cm diameter, and 6) precision wafer alignment and translation stage. For XUV wavelengths, it will be necessary to operate in a high vacuum, both for efficient transmission of the light and to minimize surface contamination of the optical surfaces. The design concept for one such XUV lithography system is shown in Fig. 2.

Potential threats to reliable operation of XUV lithography systems are progressive deterioration and thermal distortion of the optical surfaces. Mirror reflectance can be degraded by contamination by exposure source-generated particulates and carbon epilayers, and chemical changes at the multilayer reflector interfaces due to thermal annealing. Likewise, contamination of the several vacuum isolation windows, used to separate the illumination and imaging optics from the patterned mask and the photoresist, will reduce the system throughput. Also, XUV flux absorbed by the mirrors must be restricted to minimize source-induced thermal distortion of the surface figure that can result in significant wavefront distortion and degraded lithographic images.

2. TYPES OF DEGRADATION TO LITHOGRAPHIC OPTICS

For convenience, we separate the various manifestations of optical degradation to lithographic optics into three categories: 1) surface contamination, 2) permanent, radiation induced degradation, and 3) operational, radiation induced degradation. After a brief summary of each, the remainder of this paper will be concerned only with surface contamination which we consider as the primary hazard.

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Surface contamination: Contamination layers of concern are metal debris from a laser plasma target, carbonaceous compounds from the residual vacuum atmosphere, and to a much lesser degree at ~13 nm, oxide films. Layers of these materials reduce the mirror reflectance and window transmittance, thereby attenuating the radiation flux incident on the wafer. To compensate, either the lithographic exposure time must be increased (lower wafer throughput) or the exposure source power must be augmented (additional thermal distortion).

Permanent radiation-induced degradation: The structure of multilayer-mirror material combinations is affected adversely by the exposure radiation flux, causing migration of film materials across mutual interfaces when at elevated temperatures, chemical reactions between layer components induced by heating or high-energy photons, and crystallinity changes. Mirror reflectance decreases due to lowering of the refractive-index discontinuity, progressively leading to lower system light throughput and thermally induced surface distortion.

Operational radiation-induced degradation: Source-induced thermal distortion of the optics can sufficiently aberrate the wavefront to degrade the quality of the image. With pulsed exposure sources, the peak-to-peak temporal distortion exacerbates the problem. For a given source average source power requirement, quasi-cw sources are preferred.

3. SURFACE CONTAMINATION

The subject of surface contamination is itself separated here into several topics: laser plasma debris contamination of condenser mirrors, carbonaceous film contamination of multilayer reflectors, carbon contamination of vacuum isolation windows, and particulate contamination of patterned reflection masks.

3.1. Laser plasma debris contamination of condenser mirrors

U.S. and European funded programs to develop XUV projection lithography systems at 13-20 nm are currently based on laser-induced plasma sources. The potential Achilles heel of this approach is mirror contamination produced by debris ejected from the metal (Sn, Au, or Fe) targets. Using a KrF laser output of 1.25 J per 25-ns pulse focused to a spot size of 150 μm on a rotating gold target, Kubiak et al.² at Sandia National Laboratories measured the target debris deposition rate in high vacuum to be 0.02 $\text{\AA}/\text{laser shot}$ at a distance of 0.175 m. In agreement with previous workers, Kubiak et al.² determined that introduction of He gas at a pressure near 200 mTorr essentially eliminated the deposition of the uniform component of the gold plasma debris, albeit with a 50% attenuation of the 136 $\text{\AA}$ XUV flux after traveling 1 meter (see Fig. 3). At this pressure, however, the He gas does not block enough of the discrete gold particles (1-10 μm diam), the so-called "hot rocks." Figure 4 shows the multiple-shot, integrated degradation in spectral reflectance caused by the buildup of the larger particles on a Mo/Si multilayer mirror at a distance of 0.25 m and 45° angle to the target normal. Further reduction in debris accumulation has been attained at Sandia Labs by the use of thin tape targets, but not yet enough for practical application.⁸

M. Richardson et al.⁹ have also evaluated the methods to reduce debris accumulation on the mirrors (He gas, thin tape targets, rotating apertures) with the goal of a three-month operating time before mirror replacement. The cost of the high speed (24 m/s for 400-Hz laser irradiation) tape target motivated them to consider cryogenic Xe as an alternative. A more optimistic prognosis for debris mitigation has been presented by F. Bijkerk et al.¹⁰ They assert that flowing He buffer gas across the target to block diffuse particulates (<0.3 μm dia.) and orienting the first collection mirror at the angle where cluster debris ejection is a minimum will reduce the debris accumulation rate to a practical level without significant attenuation of the XUV beam. U. S. researchers have not attained similar results.

3.2. Carbonaceous film contamination of multilayer reflectors

Numerous experimenters have reported that optical surfaces contained in a vacuum while exposed to intense XUV and X-radiation become contaminated by carbon deposits.¹¹ For example, Yamamoto, et al.¹² have measured a substantial decrease in the reflectance of a Mo/Si multilayer reflector after exposure to undispersed synchrotron radiation for only 26 hours (see Fig. 5). The carbon films derive from partial pressures of carbon containing gases, such as CO, CO₂, and CH₄, that are cracked by photon induced, secondary electrons emitted from the adjacent

optical surfaces. Using Auger electron spectroscopy, Scott et al.¹³ observed that the growth rates of carbon contamination layers depend on the substrate material. As seen in Fig. 6, carbon films grow rapidly on Rh, but not on Ag surfaces. Another observation was that ionizing sources, including ion gauges and ion pumps (and high-energy photons), greatly increase the rate of carbon film accumulation on Rh, Al, Si, but again not on Ag. Since some materials such as Ag attract carbon contamination layers much less than others, it is possible that thin overcoats of these films will protect other films that have superior optical properties.

Johnson and Garrett¹⁴ have developed an effective method of cleaning carbon-contaminated optics *in situ* using reactive oxygen from a rf glow discharge at a pressure of 0.1-0.5 Torr for a period of up to 24 hours. This process converts the surface carbon compounds to gaseous forms that are pumped away. In an industrial lithography system, it might be possible to avoid periodic shutdowns for cleaning by running the discharge at a very low oxygen pressure to avoid substantial absorption of the 13-nm beam.

3.3 Carbon contamination of vacuum isolation windows

As shown in Fig. 2, several transmitting windows will be needed to separate the vacuum chambers containing the reflective imaging mirrors (in $\sim 10^{-9}$ Torr) from the reflective mask, the condenser mirrors, and the photoresist-coated silicon wafers (in $\sim 10^{-4}$ Torr vacuum). Due to its high transmittance near 13 nm, a thin ($\sim 0.3 \mu\text{m}$) membrane of silicon is the leading window candidate. The photoresist will probably emit gaseous contaminants, such as carbonaceous compounds, so that some method may well be needed (like an ion gun) to continuously clean one side of that silicon window. The contamination of the other Si surfaces will be less rapid, but will require periodic or continuous cleaning similar to that of the multilayer reflectors. Without some provision for removing the carbon films, the transmittance of the Si windows would gradually deteriorate as shown in Fig. 7.

3.4 Particulate contamination of patterned reflection masks

Reflection masks, being developed for use at 13-20 nm wavelengths, consist of patterned multilayer reflectors of Mo/Si deposited on polished silicon substrates. One practical design, shown in Fig. 8, uses an absorbing layer of Go (or Au) to obtain a reflection contrast of 200-300 between absorbing and reflecting areas.^{7,18} Silicon is an attractive substrate material because of its high thermal conductivity and the very smooth polished surface that can be achieved ($\sim 1 \text{ \AA}$ rms), which minimizes light scattering. Use of a relatively thick ($\sim 1 \text{ cm}$) substrate avoids the thermal distortion and fragility problems inherent with the transmission mask alternative which would use a very thin ($\sim 1 \mu\text{m}$) Si membrane.

The outstanding issue is whether the multilayer reflective coatings can be fabricated essentially defect free, that is, with not a single high-contrast scattering or absorbing site that, when imaged by the $\sim 5:1$ reduction optics, would produce an imperfection in the photoresists larger than about one-fifth the minimum circuit feature dimension. This is truly a major challenge! To avoid producing these "killer defects" in the multilayers over areas as large as 100 cm^2 will require use of a near-defectless coating deposition procedure. This might be attained using layer-by-layer optical monitoring with an *in situ* scatter detector with subsequent coating repair with a focused ion beam. Otherwise, post-deposition repair of defects *within* a multilayer structure would appear to be improbable.

4. SUMMARY

A number of optical degradation issues confront the eventual successful application of XUV projection lithography systems being developed for commercial production of future 256 Mb and 1 Gb computer chips. Among the most serious concerns are mirror contamination by target debris from laser plasma sources, XUV beam induced carbon contamination of mirrors and windows, and manufacture of defect free reflection masks. Clever but practical designs will be required to attain sufficiently long operating times between optics cleaning or replacement.

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Figure 1. XUV exposure wavelengths will be needed to produce future generations of gigabit DRAM chips. First introduction into the commercial market assumes a continued progression of a new chip generation every three years.⁵ Wavelength requirements for gigabit-chip lithography were determined for $\text{DOF} \geq 0.8 \mu\text{m}$ with process parameters $k_1 > 0.7$ and $k_2 = 0.5$, except for 256 Mb chips where a 193-nm laser will limit DOF to $0.66 \mu\text{m}$. Extended use of each wavelength is possible with phase-shift masks or off-axis illumination characterized by $k_1 > 0.4$.

Figure 2. Design concept for an XUV projection lithography system based on a laser plasma source. Condenser mirrors: C_1, C_2, C_3 ; Imaging mirrors: M_1, M_2, M_3, M_4 ; Different vacuum environments: P_1, P_2, P_3, P_4 . Silicon vacuum windows: W_1, W_2, W_3 . After N. M. Coglio and A. M. Hawryluk (with C_3 added).³

Figure 3. Deposition rate of the uniform component of the gold plasma debris film and the monochromatized flux near 13.6 nm transmitted through 1-m of He buffer gas. (See text). After G. Kubiak et al.²

Figure 4. Spectral reflectance measured at 3° incidence angle for a Mo/Si multilayer mirror at 0.25 m distance from a gold cylinder target and exposed to the following integrated number of laser plasma pulses: (a) 0, (b) 10,000, (c) 30,000, (d) 70,000, (e) 150,000, (f) 310,000, and (g) 630,000. (See text). After G. Kubiak et al.²

Figure 5. XUV reflectance of a Mo/Si multilayer mirror at three angles of incidence measured: - - - - - before irradiation; - · - · - · after irradiation, but outside irradiated area; — after irradiation and inside the irradiated area for 26 hours irradiation by undispersed synchrotron radiation at beam current of 175 mA (4×10^{20} photons/cm²). After M. Yamamoto et al.¹²

Figure 6. Surface carbon film accumulation rate on four substrate materials as determined by Auger electron spectroscopy in a UHV system (10^{-9} Torr) with no ion gauges or Auger filaments operational. After M. L. Scott et al.¹³

Figure 7. Influence of carbon film accumulation (0, 0.01 μm , and 0.05 μm) on the transmittance of a 0.3- μm -thick Si window (with 10- $\text{\AA}$ thick SiO_2 on both sides). Transmittance was computed using the optical constants for Si,¹⁵ $\text{SiO}_2(\text{glass})$,¹⁶ and carbon.¹⁷

Figure 8. Potential coating defects within and outside a multilayer reflection mask with Ge absorber pattern.