Self-healing in extreme UV lithography collector mirrors

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An intrinsic mechanism peculiar to tin-based plasma radiator sources mitigates damage from debris, preserving reflectivity and extending the lifetime of condenser optics.

Extreme UV lithography (EUVL) has been identified as a viable technology for the manufacture of advanced nanoscale integrated circuits with feature sizes (such as the width of a channel) below 45nm. As the size of features we can achieve is now primarily defined by the wavelength of the light source, EUV at 10–14nm is an obvious choice. However, while it may seem a simple process to switch to an EUV source, in reality the properties of materials in the extreme portion of the electromagnetic spectrum are very different from those in the visible and UV ranges. This poses a unique set of problems that must be overcome to produce an efficient system for high-throughput manufacture of components.

Systems currently being developed employ a high-density plasma radiator source (a laser is targeted at a substrate to produce a plasma that emits visible and EUV radiation). The resultant EUV emission is passed through a collector/condenser module designed to collect 13.5nm light and focus to an intermediate point in the optical path. This light is reflected from the mask and then passes through a reducing optics module to a wafer coated with an EUV-sensitive resist (see Figure 1).

Of particular interest are problems associated with the plasma radiator section and collector/condenser module. EUVL high-density plasma sources induce an enormous amount of debris at the electrode surface onto the nearby collector mirror optics. Debris can be divided into various types, including metal clusters, fast ions, thermal particles, and off-band and in-band radiation. The collector mirror must be able to reflect as much EUV light as possible. Technically, the loss of reflectivity must be kept under 5–10% over the course of operation. This is a daunting challenge given that collector mirrors can lose as much as 50% of reflectivity with only a small amount of debris deposited on the mirror surface. For example, tin (Sn) is known to be an optimal radiator for metal radiators used for 13.5nm light. When in operation, both Sn ions and thermal atoms reach the collector optical mirror surface and cause damage.

Mitigation systems are designed to reduce and minimize this debris. However, under certain conditions such systems can enhance damage to the mirror and not effectively eliminate all the debris. Separating the module into three major components makes it possible to derive solutions based on each section (see Figure 2). The debris flow can be alleviated by a variety of protection tools, including flowing gas, physical shields, and magnetic fields (for ion debris). The effectiveness of these approaches can be studied with computational modeling and experiments that yield data on gas pressure and flow rate for mitigation, optimal shielding, and material and magnetic field strength/configuration. Our work has identified a regime by which one can control damage to the collector optics and thus maintain little loss in EUV reflectivity while keeping the mirror protected from excessive erosion and surface modification.

Figure 1. Schematic illustration of the various components of an extreme UV lithography (EUVL) system. EUV emissions from a metal source are collected and condensed into a beam that is reflected from the mask through reducing optics and finally to the wafer. The mask and wafer are timed to move across the EUV beam in concert. (Image courtesy ASML.)

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Studies conducted in our facilities at Argonne National Laboratory and Purdue University have measured in situ the combined energetic ion and thermal atom interaction of Sn on candidate EUV optical mirror material surfaces, including ruthenium, rhodium, and lead. We measured, as a function of incident Sn fluence (both from energetic ions and thermal atoms), the behavior of the Sn surface concentration on the EUV collector mirror correlated to the relative reflectivity loss at 13.5nm. Off-line experiments corroborated this data when we conducted absolute at-wavelength reflectivity for exposed and nonexposed mirror samples. Ex situ x-ray fluorescence spectroscopy measurements confirmed the absolute amount of Sn present in the samples. Loss of reflectivity depends greatly on the ratio of ion to atom interaction with the EUV collector optic surface.\textsuperscript{1,2} For example, for lead collector mirrors, the reflectivity was maintained at losses of only 2–5% when combining energetic Sn ions at fluxes ~30% higher than thermal Sn fluxes on the mirror surface. Consequently, even though the surface concentration at the top one to two reflective layers remained about 80%, the self-limiting surface concentration due to preferential sputtering of Sn over lead led to a self-protecting coating that ‘healed’ the eroded surface and did not compromise the at-wavelength 13.5nm EUV reflectivity.

We are continuing to investigate this phenomenon with particular focus on understanding the large fluence (or long time dependence) effect of the self-protecting mechanism. Since the in situ experiments were conducted under ideal and controlled conditions, more work is necessary to understand the effect of other debris types that may work to disrupt the balance between incident ions and thermal atoms on the collector optical mirror surface.

Complementing in situ experiments, we developed a number of plasma and surface chemistry models in the past five years to elucidate the physical mechanisms responsible for the low loss of 13.5nm reflectivity in the presence of Sn on the collector mirror surface. The current conjecture is that preferential erosion combined with near-surface segregation is responsible for maintaining a controlled amount of Sn at the surface while inducing a highly dense and compact layer capable of reflecting 13.5nm with very little loss. Our ongoing work will also attempt to confirm this.

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