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Characterization of carbon contamination under ion and hot atom bombardment in a tin-plasma extreme ultraviolet light source

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ABSTRACT

Molecular contamination of a grazing incidence collector for extreme ultraviolet (EUV) lithography was experimentally studied. A carbon film was found to have grown under irradiation from a pulsed tin plasma discharge. Our studies show that the film is chemically inert and has characteristics that are typical for a hydrogenated amorphous carbon film. It was experimentally observed that the film consists of carbon (~70 at.%), oxygen (~20 at.%) and hydrogen (bound to oxygen and carbon), along with a few at.% of tin. Most of the oxygen and hydrogen are most likely present as OH groups, chemically bound to carbon, indicating an important role for adsorbed water during the film formation process. It was observed that the film is predominantly sp^3 hybridized carbon, as is typical for diamond-like carbon. The Raman spectra of the film, under 514 and 264 nm excitation, are typical for hydrogenated diamond-like carbon. Additionally, the lower etch rate and higher energy threshold in chemical ion sputtering in H_2 plasma, compared to magnetron-sputtered carbon films, suggests that the film exhibits diamond-like carbon properties.

1. Introduction

The phenomenon of the contamination of optics under the action of EUV radiation is a known problem that is actively studied. Even in vacuum conditions, carbon atoms are deposited onto a surface when residual hydrocarbons dissociate during interaction with energetic photons [1]. The carbon atoms can then accumulate on surfaces, which is undesirable for reflective optics because the carbon layer absorbs radiation. For instance, EUV-induced carbon contamination of grazing incidence optics in synchrotron beam lines is one of the major reasons for the optics' reduced reflectivity. The study of this problem began a few decades ago [2], and several cleaning mechanisms have since been investigated [3–5].

Extreme ultraviolet lithography (EUVL) is currently the most advanced technology for the fabrication of integrated circuits with characteristic half-pitch ≤22 nm. In modern 13.5 nm EUV lithography, the main contaminant on optics is carbon. Even at pressures as low as 10^{-5}–10^{-6} Pa, the C film deposition rate can be as high as 0.01–1 nm/h for an average EUV-radiation intensity of about 0.1–1 W/cm^2. A carbon film will cause a reflectivity loss of about 1%/nm per mirror, which is especially critical for optical systems that have multiple reflecting surfaces.

Off-line removal of EUV-induced carbon contamination also reduces the duty cycle of EUVL, which is undesirable [1,6,7], and ultimately, increases the operating cost of the EUVL process. However, with the use of fluxes of ions or neutral reactive species to restore reflectivity, the lifetime of a standard Mo/Si MLM system can be extended to several thousand hours [8]. A new cleaning strategy that uses the plasma, induced by EUV ionization of the low-pressure gas (usually H_2) over the mirror surface, was recently proposed [9]. This inline cleaning process has the potential to increase the duty cycle of EUVL.

Until recently, magnetron deposited carbon was frequently used as a model for EUV-induced carbon growth. However, the characteristics of a carbon film depend on the deposition conditions. In practice, this means that the optics located close to the EUV light source (i.e., collector mirrors) could be coated with a significantly denser carbon film, due to the presence of a broad spectrum of high energy photons and ions. The structure of EUV-induced carbon films determines the reflectivity losses of the mirror. For instance, the denser structure of diamond-like carbon (DLC) film leads to more EUV absorption compared to a polymeric layer or "soft"

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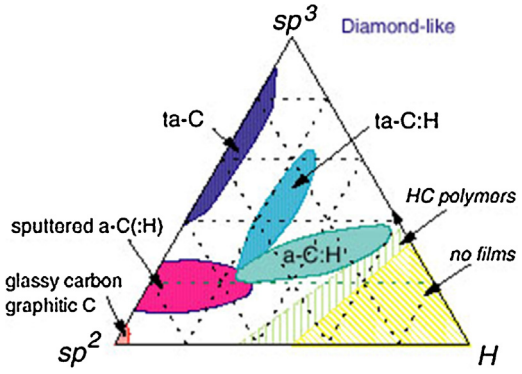

Fig. 1. Phase diagram of hydrogenated amorphous carbon films.

amorphous carbon layer of the same thickness. Furthermore, because the carbon in DLC films is more tightly bound, the films are likely to be more difficult to clean. Hence, it is necessary to know how the phase of carbon may vary depending on the growth conditions.

In the presence of water and heavy hydrocarbons, a carbon film is likely to be hydrogenated. Typically, hydrogenated amorphous carbons are classified into four classes, illustrated by the phase diagram shown in Fig. 1 [10].

All a-C:H films have a specific hydrogen content and properties that are revealed by applying a combination of different diagnostic techniques, such as X-ray photoelectron spectroscopy (XPS), Raman spectroscopy (RS), energy-dispersive X-ray (EDX) spectroscopic analysis, electron energy loss spectroscopy (EELS), transmission electron microscopy (TEM), and others.

In this paper, we report the experimental study of carbon-based films, deposited on the collector mirror of an EUV source. The condition under which the film was grown will be described, as well as analysis showing that the film has DLC characteristics.

2. Experiment

2.1. Film deposition

The experimental set up is schematically shown in Fig. 2. A *Z*-pinch discharge in Sn vapour is used as a source of pulsed EUV emission. The discharge is initiated using an Nd:YAG laser pulse to evaporate Sn from the surface of a liquid tin cathode. The Sn vapour short circuits the 3 mm gap to the anode, which is biased at high voltage (3–4 kV). A few nH inductance of the discharge circuit allows a highly ionized Sn (Sn^{8+-11+}) plasma to be produced, which with further pinching leads to a powerful shot of EUV emission being generated. The energy input into the discharge is 1–2 J, while CE (conversion efficiency) to 13.5 nm emission in a 2% spectral band is about 1%. The shot repetition rate of the EUV source is 1.5 kHz, which allows a high photon fluence for a period of ~3 h with 3–5% stability.

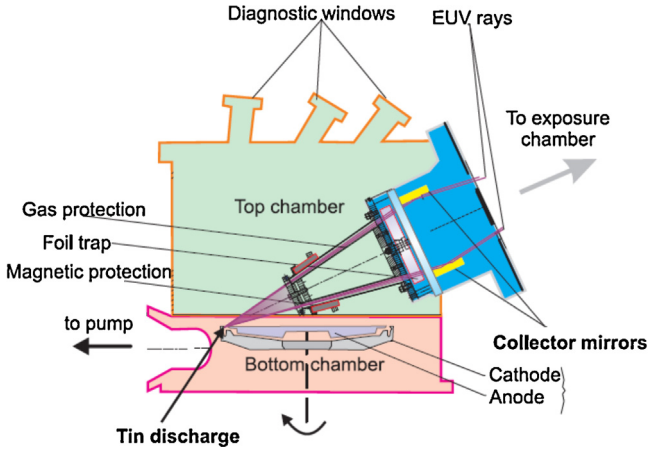

Fig. 2. EUV tin plasma source for direct reproducing EUV-lithography tool conditions.

The *Z*-pinch emission is collected by a set of grazing incidence cylindrical Mo mirrors, called the EUV collector. Our test bench collector consists of six mirrors, located at a distance of 48 cm from the source of radiation. Each mirror consists of a curved glass-ceramic substrate with an ultra low coefficient of thermal expansion (sitall) that is 45 mm × 60 mm square, and has a thickness of 6 mm. High reflectivity EUV range is achieved by coating the substrate with 50 nm of Mo.

To protect the collector from the products of the Z-pinch discharge, a series of traps are located between the discharge and the mirrors. The debris mitigation system consists of a magnetic field to defect most ions with an energy less than 100 keV and rotating foil trap, which effectively collects all micron-sized tin droplets moving at speeds of less than 500 m/s. Thus, the collector is exposed to radiation (both in-band EUV, and deep ultraviolet), high energy ions, and high velocity Sn debris during source operation.

Before the experiments, the source chamber was evacuated to 3–5 × 10^{-6} Torr. The partial pressures of the background gases were: water ~10^{-7} Torr, nitrogen ~10^{-7} Torr oxygen ~10^{-9} Torr, and residual hydrocarbons 10^{-9} Torr. The experimental set up is schematically shown in Fig. 2. During operation, H_2 is fed into the vacuum channel, where the collector mirrors are located. The hydrogen flows in the direction of the EUV source chamber, slowing down and scattering energetic ions and small Sn droplets in collisions with neutral and charged particles of H_2 plasma formed in the collector optics channel. The presence of H_2 over the collector mirrors notably decreases the contamination rate of the mirrors by carbon. The H_2 pressure in the channel is ~10^{-3} Torr and does not influence on EUV source operation [11].

3. Analysis

Our contamination film was gray-brown in color, and transparent in the visible region. The films, which were still attached to the collector mirror, were placed in 65% HNO_3 acid. It was noticed that, even after the underlying molybdenum was etched away (~20 s) with nitric acid, the carbon film remained on the sital substrate. The undamaged carbon film flakes were then removed from the substrate and transferred to a copper support grid with a 1 × 1 mm mesh, and then sandwiched in a slotted copper envelop grid to provide mechanical stability.

The total thickness of the film was found to be of the order of 150 nm after few hundreds millions EUV shots. The thickness was measured by EELS, in the energy-filtered transmission electron microscopy (EFTEM) mode. At this thickness, a film of magnetron sputtered carbon would be expected to be completely etched away within 10 s in 65% HNO_3 acid.

To understand the atomic composition of the film, EDX was used. According to EDX results (see Table 1) the film is, on average, composed of the order of approx. 72 at.% C, and approx. 18 at.% O. In addition, trace elements from the EUV source fuel (Sn), electrodes (Fe, Ni, and Mg), and the collector mirror (Mo, and Si) were also found. The sample was also slightly contaminated by the attempts to chemically etch it (Cr, P, and others). Despite these low levels of various elements, the film is predominantly carbon, oxygen and tin, which is expected. We assume that the carbon and oxygen content of the film comes from background gases and adsorbed water.