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Hydrogen radical production from laser produced plasmas emitting extreme ultraviolet light

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This work consists of the first results in optimizing the drive laser conditions for efficient hydrogen radical production for debris cleaning in reflective optics used in extreme ultraviolet lithography. Extreme ultraviolet light and vacuum ultraviolet light are produced from a laser produced plasma, which are employed to produce hydrogen radicals via photodissociation and photoionization processes. Hydrogen Balmer-alpha and beta lines corresponding to excited state radical emissions are measured by optical emission spectroscopy. Hydrogen radical emission increased when the laser intensity is decreased down to 3×10^9 W/cm^2.

1. Introduction

Extreme ultraviolet lithography (EUV: Extreme Ultraviolet) is, by far, the most effective method to produce the next generation semiconductor chips.[1] EUVL utilizes laser ablation of tin to produce EUV light (13.5 nm wavelength at 2% bandwidth) in the scanner. Along with EUV light, the emission also consists of soft x-ray light (XUV: 13 nm $< \lambda <$ 20 nm), vacuum ultraviolet (VUV: 15 nm $< \lambda <$ 200 nm), as well as visible (VIS) and infrared (IR) light. The EUV light is reflected to a series of multilayer mirrors and a mask and is focused on the semiconductor wafer which is etched to nanometer-sized dimensions. The entire process of laser ablation, light reflection, and light focusing occurs for about 50000 times a second inside scanners. During EUVL, the ablated tin contaminates these multilayered mirrors as they deposit on the surface.[2] Mirror contamination results to lowering the through put and duty cycle. This results to scanner downtimes, thus leads to higher operation costs. This is a major factor which hinders the high-volume semiconductor manufacturing using EUV light. To resolve this problem, an in-situ method of optics cleaning must be developed.

The key mechanism of cleaning these multilayer mirrors involves production of hydrogen radicals (atoms) from hydrogen gas. This is performed by introducing hydrogen gas into the vacuum chamber. These hydrogen radicals chemically react with tin, forming volatile stannane (SnH_4), which can then be evacuated inside the vacuum chamber.[3-4] Therefore, to achieve efficient cleaning, increased number of hydrogen radicals are desired. To optimize the generation of radicals, the hydrogen photoionization and photodissociation cross-sections are examined, in which these radicals are efficiently formed from 70 to 110 nm, which is within VUV wavelengths.[5] In EUVL, the emission is dominant in the XUV region. Therefore, a scheme to decrease the photon energy to VUV is sought. In a laser produced plasma, the ion population is dependent on the drive laser parameters such as intensity and wavelength. At a constant wavelength and pulse duration, ion energies can be controlled by changing the laser intensity. Keeping the laser energy constant, the plasma optical emission efficiencies are proportional to the detected signal. In measuring hydrogen radicals, optical emission spectroscopy (OES) is employed, where excited state hydrogen emits at 656.3 and 486.1 nm wavelengths, corresponding to n=3 and n=4 quantum states, respectively. In this work, we demonstrate the first results of increased hydrogen radical production by decreasing the laser intensity.

2. Materials and methods

Experiments are performed inside a stainless steel vacuum chamber maintained at a base pressure of 10^{-1} Pa. A neodymium-YAG laser (0.6 J laser energy, 1064 nm wavelength, 10 ns pulse width) is incident on a layer of xenon frost, which is solidified by liquid nitrogen at -190°C. The xenon gas is solidified on a copper drum target which is rotated at a 191 revolutions per minute, forming a thin layer and continuously providing fresh surface. The laser is focused on the layer with a focusing lens at a focal distance of 300 mm, where the spot diameter of 300 μm. The lens is attached to a linear motor which moves the lens towards the target, increasing the spot size up to 3 mm. The laser incident on the xenon target produces plasma, which emit XUV and VUV radiation. The emission from the laser produced plasma is collected by a photodiode designed for XUV collection (AXUV100G). The photodiode is equipped with a 200 nm thick zirconium filter which collects only XUV radiations with wavelengths from 12-25 nm. VUV radiation was detected by placing a silicon carbide mirror in front of the photodiode entrance aperture. Since the laser produced plasma consists of visible and infrared light apart from the desired XUV and VUV light, IR light-pass filters as well as VIS-pass filters (fused silica) are placed in front of the aperture while collecting the signal from the plasma, which act as the background signal. The photodiode is connected to a 1 GHz oscilloscope.

The VUV and XUV emission are focused on a stainless steel gas cell containing hydrogen gas maintained at 5 Pa pressure by two ellipsoidal mirrors with a focal length of 150 mm.

The focused XUV and VUV light injected inside the gas cell generates a plasma with an emission at 656.3 nm and 486.1 nm, corresponding to Balmer Hα and Hβ lines, respectively. The light emission image is transferred in a 1:1 relay by several mirrors and convex lenses towards a spectrometer located outside the chamber towards a spectrometer with 2 mm slit which is equipped with an intensified charge coupled (ICCD) camera. The CCD detects the emission image at a specified wavelength at a 20 ns gate width.

3. Results and discussion

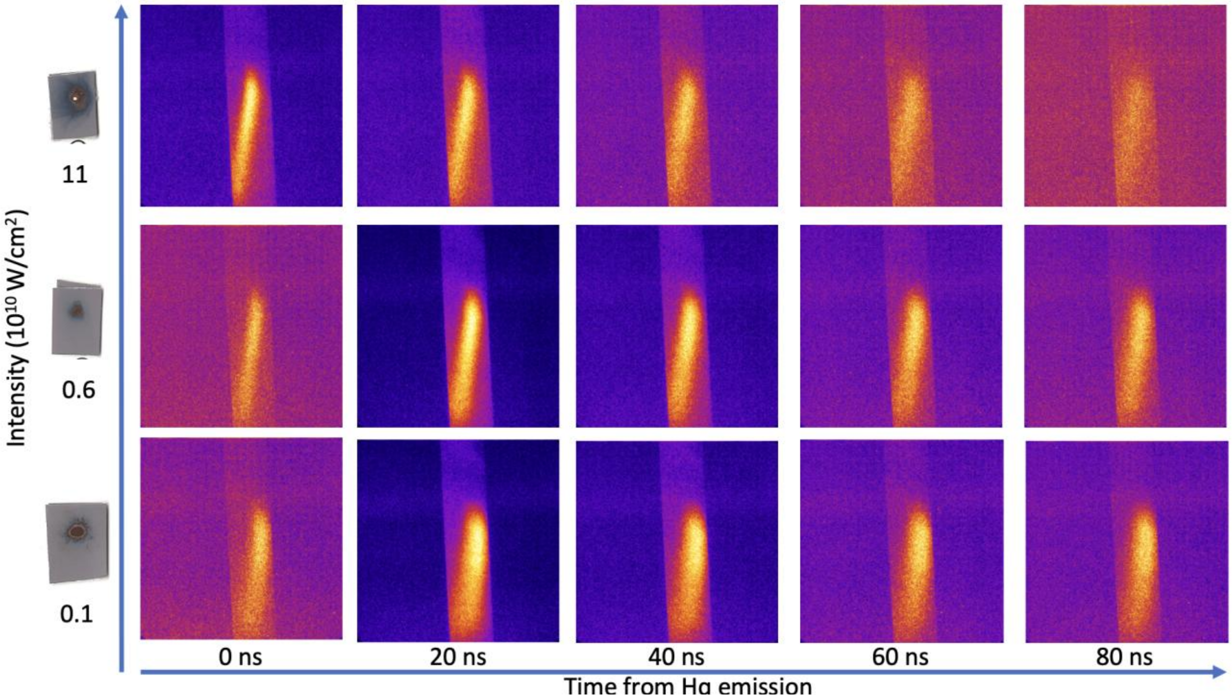

Figure 1. Hα emission images for varying laser intensity and timing from the VUV and XUV injection. Left side shows the burn pattern caused by the laser on a photographic film, showing the spot size

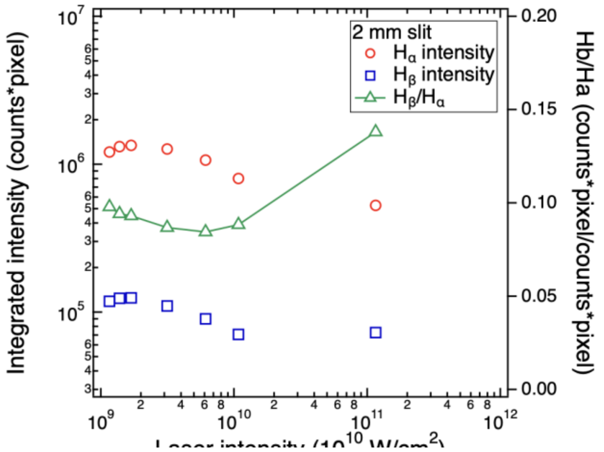

Figure 2. Integrated Hα and Hβ emission signals for varying laser intensity

Figure 1 shows the emission signals observed from the spectrometer for varying laser intensity and timing from the XUV and VUV injection. A higher emission is observed after 20 ns from the XUV and VUV injection timing. This shows the behavior of the XUV and VUV-induced plasma expansion, where the fast electrons correspond to several eV to excite the ground state hydrogen atom. A higher emission signal is observed when the laser intensity is lowered. This indicates the lower electron temperature from the Xe plasma source leads to increased excitation. Note that the dominant mechanism for XUV production is photoionization, whereby at lower photon energies, excitation is preferred. When the drive laser intensity on the Xe target is lowered, the electron temperature from the plasma also decreases, which leads to an increase in higher wavelength VUV radiation. The VUV radiation then excites, rather than ionizes the hydrogen atoms to a higher state, forming radicals which correspond to visible light emissions. Figure 2 shows the integrated signal from Hα and Hβ emissions from the obtained images for varying laser intensities. Both Hα and Hβ emission signals increase with the decrease in laser intensity, due to the transition from XUV to VUV radiation, as explained above. The signal ratio of Hβ/Hα also decreases which shows, qualitatively, a decrease in temperature from the emissions down to 6×10^9 W/cm^2 laser intensity. Therefore, optimizing the laser intensity for hydrogen radical production is crucial to achieve an efficient cleaning rate towards the implementation of this scheme to lithography optics cleaning.

4. Conclusion

A scheme is developed for optimizing hydrogen radical production is developed for in-situ cleaning of optics employed in extreme ultraviolet light lithography. XUV and VUV light were produced from Xe plasma and were focused on hydrogen gas to generated radicals. Optical emission images of H radicals corresponding to Balmer Hα and Hβ emission show the optimized XUV and VUV injection timing at 20 ns. A drive laser intensity of 6×10^9 W/cm^2 was found to be optimal in producing of these radicals.

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