EUV photons induced plasma

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Creation, dynamics and decay of pulsed low pressure plasmas induced by photo-ionization by high energy (13.5 nm) Extreme Ultraviolet (EUV) photons is studied by means of microwave cavity resonance spectroscopy (MCRS) for various gas pressures and EUV pulse energies. The MCRS technique allows to monitor non-intrusively and with high temporal resolution the space-averaged electron density in a so-called cylindrical resonance cavity in which the plasma is created. Initial electron densities at the end of the EUV pulse in the order of 10^{14}-10^{15} m^{-3} were found. Our results also show that electrons cool rapidly and that expansion of the plasma at time scales larger than several microseconds - dependent on gas pressure - is dictated by mainly ambipolar diffusion. For this ambipolar diffusion phase, coupling the electron density measurements with a simplified ambipolar diffusion model gives useful information about the electron temperature of the expanding plasma.

1. Introduction

To enable successful employment of lithography on ever smaller length scales, the lithography industry uses Extreme Ultraviolet (EUV) light with a wavelength of only 13.5nm. This high energy radiation is partly absorbed by the low pressure background gas present in the scanner environment and, hence, a background plasma is created by photo-ionization. Everywhere this plasma is in contact with a surface strong electric fields are built up. These fields accelerate ionic plasma species towards the surface, possibly impacting long term operation of the lithography tool as a total. In order to understand and predict this long term impact, understanding fundamental mechanisms during and after the creation of an EUV-induced plasma is essential.

In previous studies, fundamental properties of EUV-induced plasmas have been studied using numerical simulations [1,2]. Also, in these studies the authors attempted to use Langmuir probes to experimentally determine the density of free electrons. Although measuring the electron density is – as being one of the key parameters – crucial to gain fundamental understanding with regards to EUV-induced plasmas, the authors claimed that the used method, i.e. utilizing Langmuir probes, appeared not feasible for application in these types of plasma. In previous work (see ref. [3]), we already demonstrated the possibility of measuring the electron density in an EUV-induced plasma both temporally resolved and non-intrusively.

Here, we present temporally resolved measurements of the electron density during and after a pulse of EUV light (produced by a Xe-based EUV source) was directed through a low pressure argon background gas. Parameters like gas pressure, EUV pulse energy and used spectral purity filter are varied. Combining the results with a simplified ambipolar diffusion model, enable to estimate the electron temperature.

2. Configuration

Figure 1 shows in schematic form the used experimental configuration consisting of three chambers.

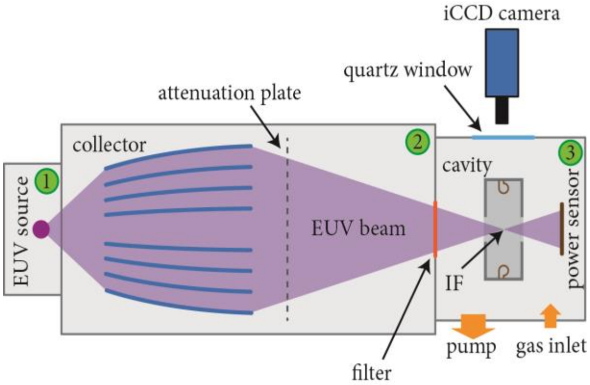

Fig.1: Schematic overview of the used experimental configuration with 1: the source chamber, 2: the collector chamber and 3: the measurement chamber housing the MCRS diagnostics and the EUV power sensor.

The source chamber houses a pulsed Xenon-based discharge produced plasma (DPP) source, generating pulsed EUV radiation with a pulse duration of 100 – 200 ns, a repetition rate of 500 Hz and with pulse energies to be varied between 1 and 150 µJ per pulse (in-band: 10-20 nm). The collector chamber houses a set of elliptic multilayer mirrors focussing the EUV light in the 'intermediate focus (IF)', located in the measurement chamber. The collector chamber and the measurement chamber are separated by a spectral purity filer (SPF) transmitting only in the 10-20 nm window and preventing out-of-band radiation. The measurement chamber with an argon background pressure between 0.5 Pa and 15 Pa houses an aluminum cylindrical resonance cavity with a radius of 33 mm and a height of 20 mm which is aligned around the IF. Top and bottom of the cavity contain holes for entrance and exit of the EUV light. During and after an EUV pulse, the resonant frequency of an excited resonant mode is monitored as a function of time. Since the presence of electrons shifts the resonant frequency of the individual resonant modes, the temporal shift in resonant frequency can be related directly to the space averaged and square electric field (of the resonant mode) weighted electron density. In the current work, we have used the TM_{010} mode with a resonant frequency around 3.482 GHz and a quality factor of 166. The latter means a fundamental time resolution of 15 ns.

3. Results and conclusions

The temporally resolved evolution of the space averaged and square electric field weighted electron density $\bar{n}_e(t)$ has been measured for various EUV pulse energies and background gas pressures and with different spectral purity filters. Figure 2 for instance, shows an example of a set of $\bar{n}_e(t)$ measurements at constant EUV pulse energy of (44±3) µJ and for several gas pressure.

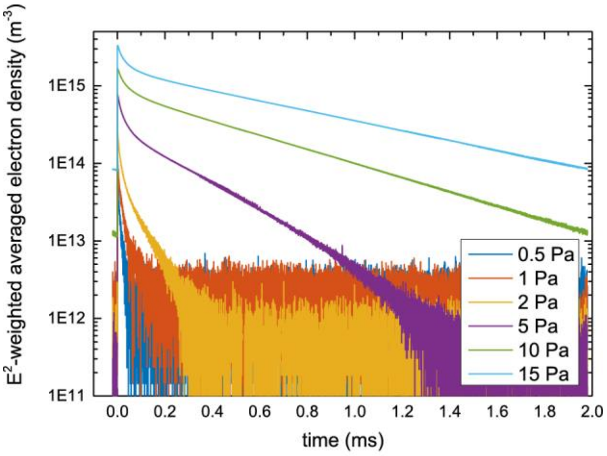

Fig.2: Space-averaged and squared electric field weighted electron density inside the resonance cavity for several values of the background gas pressure.

Almost instantaneous creation of electrons followed by a slower decay over several milliseconds can be observed. This latter decay can be fitted exponentially.

As can also be seen from this figure, the higher the pressure, the higher the initial electron density and the slower the plasma decay. The higher initial electron density can be explained by an increasing amount of photo-ionization events when the gas pressure and thus the gas density is increased. At the same time, electron impact ionization becomes more significant at higher pressures as the mean free path of the electrons created by photo-ionization becomes smaller. Of course the latter effect is even more enhanced by the first (i.e. increased number of initial photo-ionization events).

The slower decay of the plasma at higher gas pressures can be explained by considering ambipolar diffusion. Directly after the plasma is induced by EUV radiation, fast electrons run away towards the cavity wall leaving the positive ions behind. This creates a space charge and consequently an electric field from the cavity centre towards the wall. This plasma-induced electric field confines the remaining electrons and accelerates ions towards the wall.

The confined electrons cool down very rapidly on time scales shorter than 1µs due to a complex interplay between their interaction with the induced electric field and electron-atom collisions, having typical time scales of about 10-20 ns.

At longer time scales ambipolar diffusion sets in, dictating the expansion of the plasma and, hence, recombination of plasma species at the cavity wall. The higher the background density, the lower the ion mobility due to enhanced ion-neutral collisions and the lower the plasma expansion and plasma decay rate.

Assuming that indeed ambipolar diffusion dictates the plasma decay (for longer time scales), the decay time found after exponentially fitting the curves in Fig.2 is representative for the typical ambipolar decay time τ_{amb}, connected via the typical diffusion length Λ_{diff} to the ambipolar diffusion coefficient:

$$D_{amb} \approx \frac{\Lambda_{diff}^2}{\tau_{amb}}. \qquad (1)$$

D_{amb} can be approximated by the ion mobility μ_i and the temperatures $\widehat{T}_i$ and $\widehat{T}_e$ of ions and electrons respectively as $D_{amb} \approx \mu_i(\widehat{T}_i + \widehat{T}_e)$. Assuming that the ions remain at room temperature relates the measured plasma decay time to the electron temperature. Although this simplified model is a rough estimate, it delivers extremely useful information: the electron temperature during this expansion phase is close to room temperature.

4. Acknowledgements

The authors acknowledge and thank ASML for their financial support and source time on their Xe-DPP SoCoMo.

5. References

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