The temporal evolution of electrons in EUV-induced plasmas

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We studied the temporal evolution of the electron density in a low pressure pulsed plasma induced by high energy photons (92 eV) by means of microwave cavity resonance spectroscopy (MCRS). Although MCRS generates space averaged information about the electron density, we demonstrate here the possibility to obtain spatial information by combining different resonant modes. The results show that the plasma expands to the wall of the cavity on a time scale of tens of microseconds. The speed of this expansion depends on the gas pressure; the higher the gas pressure, the slower the expansion. This effect is explained by ambipolar diffusion, which is inversely proportional to the gas pressure.

1. Introduction

There is an increasing global demand for more computational power and memory capacity at higher energy efficiency. To achieve further miniaturization of semiconductors, the next logical step is to use lithography based on Extreme Ultra-Violet (EUV) radiation at 13.5nm (92 eV). These high energy photons are partially absorbed by the background gas, which leads to the generation of a background plasma. The formation of this kind of plasma is of significant importance for the lithography industry since in the vicinity of surfaces (e.g. EUV mirrors) strong electric fields are induced. These fields accelerate ions from the plasma towards the mirrors which could have an impact on the long term operation of the lithography tools. To predict this impact, it is essential to understand the physics of EUV-induced plasmas.

In previous work numerical calculations were used to study the influence of EUV-induced plasmas on the optical elements in lithography tools [1,2]. These authors also attempted to determine the electron density with Langmuir probes; however, they concluded that these probes are not feasible [2]. Recently, we reported the first time resolved non-intrusive measurements of the electron density in EUV induced plasmas using microwave cavity resonance spectroscopy (MCRS) [3].

In this contribution we will study the expansion of the electrons in an EUV-induced argon plasma temporally after the EUV pulse and as a function of the gas pressure.

2. Experimental set-up and method

The experimental set-up which we used in our experiments is shown in Figure 1. It basically consists of 3 different chambers. The source chamber contains the EUV source, which is a xenon-based discharge produced plasma source [4]. This source generates an EUV pulse with a repetition rate of 500 Hz, a typical duration of 100-200 ns and a pulse energy of 44 µJ. The collector chamber contains a set of elliptic mirrors, which focus the EUV beam in the intermediate focus (IF) located in the measurement chamber and an attenuation plate to vary the EUV energy. Between the collector and measurement chamber we placed a spectral purity filter (SPF), which only transmits between 10 and 20 nm. The argon pressure in the measurement chamber is varied between 0.5 Pa and 15 Pa. A cylindrical microwave cavity is centred around the IF to measure the electron density.

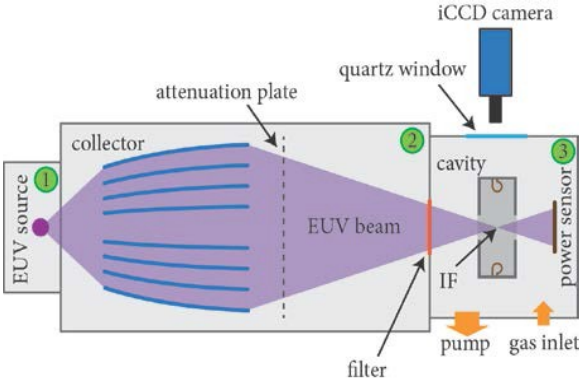

Figure 1: Schematic overview of the experimental set-up. Number 1 denoted the source chamber, 2 denotes the collector chamber and 3 denotes the measurement chamber which contains all diagnostics. The iCCD camera is not used in the current work.

During a measurement we continuously monitor the resonant frequency of the excited mode in the microwave cavity. When the EUV pulse generates a plasma, the permittivity of the medium inside the cavity and, hence, the resonant frequency changes. This change in resonant frequency is directly related to the square electric field (of the resonant mode) weighted space averaged electron density. In our work we used two resonant modes (TM_{010} and TM_{110}) with a different spatial dependence of their electric fields. The resonant frequency of the modes is respectively 3.482 GHz and 5.419 GHz. The quality factor of the cavity is 166, which means that the fundamental time resolution is 15 ns.

3. Results

We measured the temporally resolved electron density as a function of pressure with the TM_{010} and TM_{110} mode. As an example the square electric field weighted averaged electron density at 5 Pa argon as function of time for both modes is shown in Figure 2. It is clear that the temporal behaviour of the E^2-weighted averaged electron density is different for both modes.

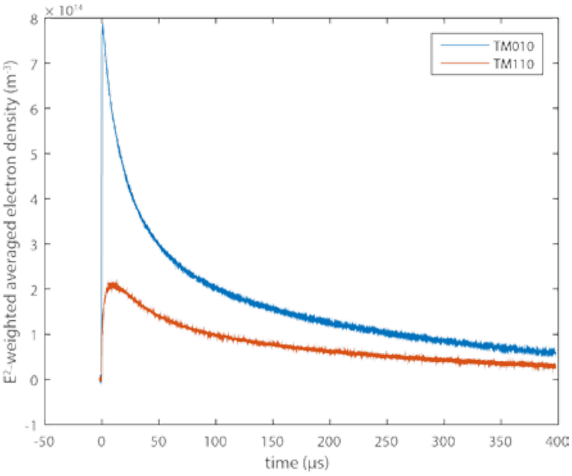

Figure 2: The square electric field weighted average electron density evolution in a 5 Pa argon plasma measured with two different resonant modes (TM_{010} and TM_{110}).

When we combine the measurements of these two modes with a simplified diffusion mode, i.e. we assume that the plasma expands as a whole and ignore the individual effects of the electrons and ions, we can obtain the radial width of the electron density distribution. The full width at half maximum (FWHM) evolution of radial electron density distribution is shown in Figure 3 for various pressures.

There are two effects visible in Figure 3. First, the plasma expands on a time scale of tens of microseconds and the FWHM reaches an asymptote at about 16 mm. From our diffusion model we know that a FWHM of 16 mm corresponds to a total width of the density distribution of about 63 mm. This corresponds very well with the diameter of our cavity (66 mm). So, in the end, the electrons are distributed over the entire cavity.

A second effect is that the expansion rate increases if the pressure decreases. This can be explained as follows. The decay of the plasma is governed by ambipolar diffusion, which has a typical diffusion speed v_{amb} of

$$v_{amb} = \frac{D_{amb}}{\Lambda_{diff}} \qquad (1)$$

where D_{amb} is the ambipolar diffusion coefficient and Λ_{diff} is the typical diffusion length. The ambipolar diffusion coefficient can be approximated by $D_{amb} = \mu_i(\hat{T}_e + \hat{T}_i)$, with μ_i the ion mobility and $\hat{T}_e$ and $\hat{T}_i$ the electron and ion temperature respectively. Since the ion mobility is inversely proportional to the gas pressure, the expansion speed will decrease if the pressure increases. From Figure 3 we find that the expansion speed during the first microsecond is 200-1800 m/s (depending on pressure). If we assume a reasonable electron temperature of 1 eV, we obtain from our ambipolar diffusion model an ambipolar diffusion speed of 100-1000 m/s (depending on pressure). This is in good agreement with the experimental results.

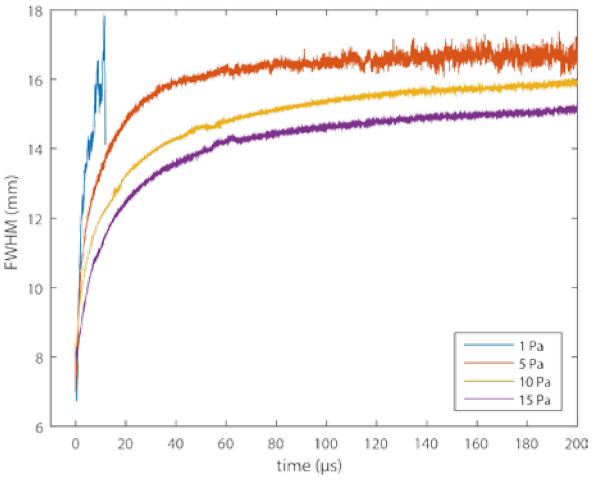

Figure 3: The evolution of the FWHM of the radial electron density distribution for various pressures.

3. Conclusions

We determined the FWHM of the radial electron density distribution in EUV-induced plasma with MCRS by combing the measurements of two different modes with a simplified diffusion model. The expansion rate depends on the pressure of the background gas, which can be explained by ambipolar diffusion.

3. Acknowledgements

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3. References

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