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ABSTRACT

Extreme Ultraviolet (EUV) optical components used in EUV lithography tools are continuously impacted by an exotic and highly transient type of plasma: EUV-induced plasma. Such an EUV-induced plasma is generated in a repetitive fashion upon sending a pulsed beam of high energy (92 eV) photons through a low-pressure background gas. Although its formation occurs on a time scale of \( \sim 100 \text{ ns} \), it is the plasma’s decay dynamics on longer time scales that dictates the fluxes and energy distribution of the produced ions. Therefore, the plasma decay also determines the overall impact on plasma-facing EUV optical components. Enabled by electron density measurements using Microwave Cavity Resonance Spectroscopy at a much higher sensitivity, we clearly show the breakdown of the ambipolar field in an EUV photon-induced plasma below electron densities of \( 2 \times 10^{12} \text{ m}^{-3} \) and the—until now—unidentified transition from ambipolar diffusion-driven decay into a decay regime driven by free diffusion. These results not only further improve the understanding of elementary processes in this type of plasma but also have a significant value for modeling and predicting the stability and lifetime of optical components in EUV lithography.

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The multi-billion-dollar semiconductor industry is transitioning toward Extreme Ultraviolet lithography (EUVL) to produce cheaper and more energy-efficient integrated circuits. In EUVL tools, pulses of extreme ultraviolet (EUV) light with a wavelength of 13.5 nm are used to expose wafers for the production of integrated circuits. The high energy photons (92 eV) ionize the background gas (1–10 Pa) in these tools creating an EUV photon-induced plasma along the beam path. Due to the repetitive nature of the exposure, the plasma is highly transient. This plasma could affect the lifetime of the expensive and highly delicate multilayer EUV mirrors.1–3 A better understanding of the elementary processes in these plasmas could lead to improved operating conditions in EUVL tools and extend the lifetime by, e.g., cleaning of the mirror surfaces.4–6

Van der Velden et al. performed computer simulations7 and were the first to perform measurements using a Langmuir probe on an EUV photon-induced plasma in lithography tool conditions.8 These probes appeared to be unsuitable to investigate this type of plasma for mainly the following reasons: electromagnetic interference from the EUV discharge and the photo-electric effect when EUV photons hit the probe. Optical emission from an EUV photon-induced plasma was used to characterize the properties of such a plasma.9–11 The ions in EUV photon-induced plasmas were studied using an Electrostatic Quadrupole Plasma analyzer12–14 and a Retarding Field Energy Analyzer.15

The transient behavior of the plasma was explored non-intrusively by Van der Horst et al.9,16–18 employing Microwave Cavity Resonance Spectroscopy (MCRS) to probe the particles driving such plasmas, i.e., free electrons. In this method, the changes in the resonant behavior of a microwave field in a cavity are linked to the electron dynamics. A variant of MCRS, in which multiple resonant modes have been used sequentially to resolve the electron density spatially, was demonstrated as an effective EUV beam monitor.19 Two consecutive decay phases in EUV photon-induced plasmas were identified by Beckers et al.20 by applying the same diagnostic method. For pressures above 2.5 Pa, a transition from free to ambipolar diffusion occurs in
the first phase and the process of ambipolar diffusion continues during the second phase.

Ambipolar diffusion, the joint movement of ions and electrons driven by the Coulomb interaction, is one of the unique and striking processes in plasmas. This physical process underlies the fundamental property of plasmas: quasi-neutrality, i.e., the charge neutrality over length scales larger than the so-called electron Debye length $\lambda^e_D$,

$$\lambda^e_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}},$$

(1)

Here, $\varepsilon_0$ is the vacuum permittivity, $k_B$ is the Boltzmann constant, $T_e$ is the temperature of the electrons, $n_e$ is the electron density, and $e$ is the elementary charge. This characteristic length scale increases for decreasing electron densities up to the point that the diffusion length becomes dominant.\(^2\)\(^2\)\(^5\)\(^6\)\(^7\)\(^8\) Hitherto, little experimental data are available on plasma decay beyond the ambipolar regime due to the requirement of a very low detection limit in terms of the free electron density (typically $<10^{12}$ m$^{-3}$). This barrier complicates the progress in the fundamental understanding of plasmas and the processes inside them, e.g., (de)charging of macroscopic particles immersed in plasmas.\(^3\)\(^4\)\(^5\)\(^6\)

In this Letter, the MCRS method is applied to explore the physics in an EUV photon-induced plasma, which was not explored until now: the breakdown of the ambipolar field and the transition from ambipolar diffusion to free diffusion of the electrons. From an experimental perspective, this photon-induced plasma brings several advantages over the generally used electronic field excited plasmas to study this regime.\(^2\)\(^2\)\(^5\)\(^6\)\(^7\)\(^8\) This is because the source of the energy is directly absent after the EUV pulse and it is a very clean environment as there are no electrodes from which electrons need to be emitted. This investigation is enabled by the recent improvements of the diagnostic method.\(^9\)\(^2\)\(^8\)\(^9\)\(^3\)\(^0\) With this knowledge in mind, we add insights to the existing issues that impact the applications of EUV lithography, i.e., EUV beam monitoring and optics lifetime.

The experimental setup comprised a large vacuum system and electronics. The vacuum system was divided into three chambers based on functionality: radiation was generated in the source chamber, the light was focused in the collector chamber, and the EUV photon-induced plasma was probed in the measurement chamber. Each of these systems is discussed below and the authors refer the reader to more in-depth descriptions for more details. A schematic representation of the experimental setup is presented in Fig. 1.

A pulsed xenon pinch discharge produced EUV radiation with a pulse length of $\sim100$ ns, a repetition frequency of 497 Hz, and a pulse energy of $9 \pm 1 \mu J$ for the in-band (10–20 nm) radiation. This pulse energy was purposely reduced with respect to previous studies\(^9\)\(^16\)\(^17\) to reduce the maximum electron density and thereby the time from the pulse to the point of breakdown of the ambipolar field.

The second chamber contained seven nested grazing incidence Wolter collector mirrors. These mirrors focused the EUV light in the focal point, located in the measurement chamber. A spectral purity filter (SPF) was used to reject light with a wavelength larger than 20 nm. A cone with an opening of 2 mm diameter at the narrow end was used for two reasons. First, it prevents the creation of photoelectrons by EUV radiation hitting the cavity walls and second, it allows—as a restrictor—for differential pumping between the collector and the measurement chamber.

In the measurement chamber, argon at a base pressure of 5 Pa was used. This vacuum vessel contained a metal structure which formed the cylindrical pillow-shaped microwave cavity with a radius $r_{cav}$ of 33 mm and a height $h_{cav}$ of 16 mm. Two concentric holes with a diameter of 13 mm allowed the EUV radiation to pass through the cavity. The heart of the cavity was aligned with the focal point. The cavity had a TM$_{010}$ mode around 3.5 GHz with a quality factor $Q = 260$, which corresponded to a response time $\tau = 25$ ns.

A microwave generator was used to create a microwave signal with frequency $f = \omega / 2 \pi$. These microwaves traveled via a directional coupler to an antenna that protruded into the cavity. Depending on the applied frequency, the cavity was able to absorb a certain part of the power. The reflected microwaves returned to the directional coupler where -10 dB of it was directed to a logarithmic power detector. The output of the power detector was sampled at 25 MHz using a transient recorder. The measurements were synchronized with the EUV pulses. As the discharge dynamics were highly reproducible, this allowed the experiment to be performed in a frequency-resolved manner and under reduce noise by averaging the temporal response of 128 discharges. Computer code was used to scan the frequency domain within a range of 55 MHz around the resonance peak with a step size of 20 kHz. A fit function was used to determine the resonance frequency, i.e., the spectral position with the lowest reflected power, for each time step of the plasma initiation with 40 ns time resolution.

The change in resonance frequency $\Delta f$, in respect of the unperturbed cavity, was linked to the volume averaged electric-field-squared-weighted electron density $\bar{n}_e$ via the following relation:

$$\bar{n}_e = \frac{8 \varepsilon_0 m_e \pi^2 f^2 \Delta f}{e^2 f_0},$$

(2)

where $m_e$ is the electron mass, $f_0$ is the resonance frequency of the unperturbed cavity, and $f$ is the resonance frequency of the cavity filled with plasma. A moving average with a temporal width of 1 $\mu$s was used to further reduce the noise level in $\bar{n}_e$, except during the first decay phase to prevent loss of information regarding the electron density directly after the EUV pulse.

The measured $\bar{n}_e$ as a function of time after creation of the plasma by the EUV pulse is represented by the blue line in Fig. 2. In contrast to previous studies,\(^7\)\(^10\) where it was only possible to study the
FIG. 2. Squared-electro-field-weighted average electron density as a function of time for an argon plasma induced by EUV radiation with a pulse energy of 9 ± 1 μJ. The three distinctive decay phases are indicated by Roman numerals while the approximated positions of the transitions between the decay regimes are marked by vertical lines.

first two decay regimes of such a plasma, three decay regimes can be clearly distinguished in this work. Each of the phases is indicated by a Roman numeral (I–III). As the first two phases are already extensively described previously, the delineation of them will be brief.

In phase I, the initially created electrons will reach the walls within a few ns. The much slower ions will remain in the cavity and form a potential trap. Later created electrons will oscillate in the trap and lose energy by collisions with neutrals until the point of ambipolar diffusion. The expansion speed is governed by ambipolar diffusion for pressures above 2.5 Pa where the mean free path of the ions is shorter than the plasma radius. The plasma expands until it has reached the cavity walls.

In phase II, the transport of the species to the walls is still governed by ambipolar diffusion. Recombination of the plasma, and therefore depletion of the electrons, takes place at the walls. For this pressure, the electrons are at room temperature during this phase.

Most diagnostic methods have a lower detection limit which allows to explore plasma dynamics up to phase II. The setup and method used in this investigation had a detection limit of 4×10⁹ m⁻³, i.e., the standard deviation of nₑ over the period 1600–1800 μs in which the measured values were at the noise level. Hereewith, we enable the possibility to explore the behavior of the plasma beyond phase II.

In phase III, the decay rate of the electrons increases. This increase is attributed to the diminution of the role that the space charge plays in the transport of the electrons. Therefore, the electrons are slowed down to a lesser extent by the ions. Hence, the decay of the electrons is transitioning toward free diffusion in this phase.

The transition from ambipolar to free diffusion sets in at an electron density nₑ of approximately 2×10¹² m⁻³. In a prior work by Freiberg and Weaver, this point was generalized by postulating that if λ/λ₀ ≈ 100, the electrons start to diffuse faster than would be the case for ambipolar diffusion. Here, λ is the characteristic diffusion length for a finite cylinder in terms of this experiment,

\[
λ = \left[ \frac{2.405}{r_{cav}} \right]^2 + \left( \frac{π}{r_{cav}} \right)^2 \right]^{-1/2},
\]

which is 4.8 mm in this work. However, due to the presence of concentric holes on flat surfaces, this value is an underestimate.

In this experiment where the electrons are at room temperature in phase II, the transition starts at λ/λ₀ ≈ 6, which is significantly lower than the postulated ratio of approximately 100. A possible explanation for this difference in the critical point is that the free electrons disappears due to a lack of information concerning the location of the free electrons—based on an electric-field-weighted cavity averaged electron density. Following this, the inverse ratio of the effective (microwave-field-weighted) plasma volume and the effective (microwave-field-weighted) cavity volume \(V_{eff}\) should be 250, which is highly unlikely as the plasma has already reached the walls at the beginning of phase II. Calculations based on the effective electron-neutral collision cross sections for 5 Pa of argon and electrons at room temperature revealed that \(λ_{eff} = 26\) mm, which is, in contrast to the other studies, larger than \(λ\). As a consequence of \(λ_{eff} \gg λ\), due to evaporative cooling of the electrons, only the low-energy electrons remain in the plasma. Therefore, a delayed transition as measured here can be explained. Furthermore, Ar was used, while in the other experiments, He was the dominant gas and although the influence of metastables is investigated, excluding this mechanism as a cause of the difference seems perils.

Calculations of Gusinow and Gerber and experiments of Gerber and Gerardo and Gerber et al. showed that during the transition from ambipolar to free diffusion, the diffusion rate to the walls and recombination of the electrons and ions at the walls first accelerate. This is true up to the point that the ions can no longer follow. From this moment onward, the diffusion rate of the ions is lower than that of the electrons and a positive space charge region is formed. As the degradation of EUV mirrors is attributed to ions which are accelerated by plasma-induced electric fields toward the optical elements, the identification of the third decay phase—in which the electric fields collapse and the dynamics of the ions change—is of utmost importance for extending the lifetime of the optical systems. This would directly impact the stability of the output of EUV tools.

In conclusion, the improved lower detection limit of Microwave Cavity Resonance Spectroscopy enabled the identification and study of the transition from ambipolar to free diffusion in the afterglow of an Extreme Ultraviolet photon-induced plasma. This decay regime is not only interesting from a fundamental perspective but also contributes to a better understanding with a more accurate prediction of the interaction between EUV photon-induced plasmas with the optical elements in lithography tools. This could result in further optimization of the operational conditions in these tools and with that an increased lifetime of the delicate optical elements. Furthermore, the gained knowledge can be capitalized in tooling, such as a beam monitor for ionizing radiation.

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