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Particle contamination control by application of plasma

Job Beckers*[a], Boy van Minderhout[a], Paul Blom[b], Gerrit Kroesen[a], Ton Peijnenburg[b]

[a] Department of Applied Physics, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands; [b] VDL Enabling Technologies Group, PO Box 80038, 5600 JW Eindhoven, The Netherlands.

ABSTRACT

With the introduction of Extreme Ultraviolet (EUV) lithography, the control of contamination has become crucial. Sources for contamination in EUV lithography scanners are not limited to only particle generation and release inside the scanner environment but may be introduced from outside as well, e.g. through translational and/or rotational (robotic) feedthroughs.

In this contribution we highlight our joint (TU/e and VDL ETG) research efforts aimed at the development of plasma-enabled contamination control strategies. The focus in this research is on airborne particles immersed in a low pressure gas flow that interact with both the afterglow of a plasma and an externally applied electric field.

A flexible experimental setup has been developed and will be introduced which is able to study the interaction between contaminants, plasmas and externally applied electric fields. Our results show that the designed configuration allows to carefully control the residual charges of the particles as well as their positions and trajectories with respect to the gas flow in which they are immersed. These results, together with the understanding of the underlying principle processes, open-up various possibilities to achieve improved cleanliness of the mentioned systems.

Keywords: Plasma, EUV, EUV lithography, Particles, Contamination, Contamination control

*j.beckers@tue.nl; phone +31 40 247 4043

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1. INTRODUCTION

Since the introduction of Extreme Ultraviolet (EUV) lithography, cleanliness has become a crucial and hot-topic issue. With the eye on this topic, the situation inside an EUV scanner is represented by an extremely complex physical interplay between nano- to micrometer sized contaminants, ionizing radiation, (delicate) surfaces and highly transient plasmas, i.e. EUV-induced plasmas. These EUV induced plasmas are induced in the low pressure background gas which is partly ionized by irradiation with 13.5 nm (i.e. 92 eV) EUV photons.

Over the past decade, EUV-induced plasmas have been diagnosed extensively [1], not only experimentally by monitoring dynamics of electrons [2–6] and ions [7–9], but also by means of numerical simulations [10,11]. The interaction of those plasmas with contamination has been recently pinpointed as key by van de Kerkhof et al. [12].

Sources of contamination in EUV lithography scanners are not limited to only formation and release inside the scanner environment but may be introduced from its outside as well. Possible sources are for instance translational and/or rotational robotic feedthroughs. The sealing off of particle transport through these feedthroughs can be achieved by differentially pumped seals or by magnetic rotary seals. However, a solution based on plasma-filtering of contamination might result in enhanced suppression, lower costs and less volume claim.

The reason that application of plasma for contamination control is so promising is twofold. First, inside a plasma environment plasma-immersed particles may become charged due to the collection of charged plasma species, e.g. free electrons and ions. Second, everywhere plasma faces solid surfaces, strong electric fields – per definition directed from the plasma to the surface – are self-induced by the plasma. It is especially the interaction between the plasma-charged particles and the inevitably present plasma-induced electric fields that may levitate contaminants in the bulk of the plasma and prevent those to collide with or attach to crucial surfaces. This provides some freedom of operation to control the position and trajectory of plasma-immersed particles. Highly accurate position control can be achieved by for instance additional application of temperature gradients, gas flows, radiation pressure, surface biasing and/or external electric fields.

In this contribution we present our joint (TU/e and VDL ETG) research efforts with respect to the development of plasma-enabled contamination control strategies. Section 2 describes the Plasma Particle Charging Investigation (PCCI) setup developed in that framework to investigate fundamental plasma interaction with micrometer sized particles and to measure residual particle charges with a precision as good as a few elementary charges only. In section 3 we present some preliminary measurements on the particle charge under low pressure conditions. In section 4, we highlight the most important conclusions and provide future joint research plans.

2. EXPERIMENTAL

The experimental configuration – the Plasma Particle Charging Investigation (PCCI) setup [13] – is designed to enable investigations with respect to the physical interaction between particles, (the afterglow of) plasma, externally applied electric fields and plasma-facing surfaces (see Figure 1). As becomes clear from Figure 1 the setup consists of the following main elements.

The flow tube: a one meter long glass tube of which the cross sectional-shape is squared with inner dimensions of 100 x 100 mm. This cross-sectional shape is chosen to increase the accuracy of the optical detection system and to simplify data analysis. The pressure and the (in this case argon) gas velocity (directed from top to bottom) inside the tube can be controlled independently in the respective ranges of (1-100) Pa and (0.01 – 1) m/s by controlling the flow rate of the showerhead gas inlet at the top and the pumping capacity at the bottom of the tube. The base pressure of the system is ~5×10^{-5} Pa. Upon request, from the top micrometer sized particles can be injected by an in-house designed particle injection system. The shape, material and size (distribution) of these particles can be chosen as is appropriate for the specific research to be conducted. Under the configuration applied in this work, the terminal velocity of the particles is determined by the balance between gravity and drag forces exerted by neutral gas particles.

The Plasma: a five windings RF coil is wound around the glass tube approximately in the 'axial' middle, i.e. 45 cm below the shower head top. This coil is used to ignite and sustain an inductively coupled RF plasma (ICP) at low pressure inside the tube. This way of generating plasma is preferred because it does not obstruct the set gas flow, at least not from a flow dynamics point of view, and enables electrodeless operation of the plasma. The driving frequency of this plasma is 13.56 MHz and the deposited power can be set between 5 and 100 Watt.

Particle deflection and imaging: roughly 0.55 m below the center of the coil a potential difference between two Rogowski electrodes (diameter 70 mm and separation distance 40mm) induces a horizontal electric field (0 – 5 kV/m) that deflects the dispersed and plasma-charged particles. A high speed camera system (Photron Fastcam mini UX100) images the 447 nm diode laser irradiated particles' trajectories at a framerate of 3,200 fps. The field of view of this camera in the middle of the tube is 40 x 32 mm, resulting in an imaging resolution of 32 µm per pixel. From data post-processing, horizontal and vertical components of the velocity and acceleration of an ensemble of particles are deduced.

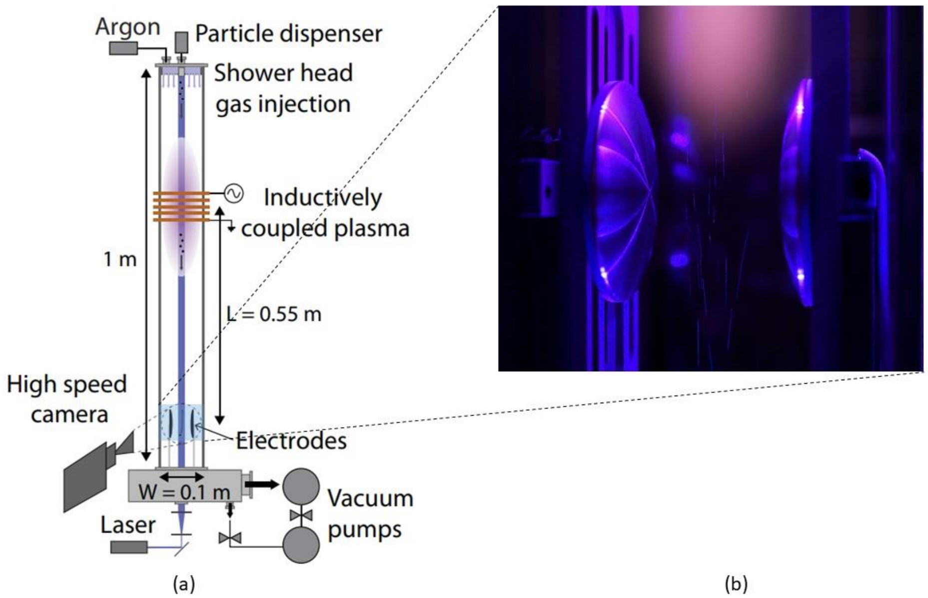


Figure 1. (a) Schematic overview of the experimental configuration developed. (b) zoom-in photograph of the laser illuminated region between the two Rogowski elements in which plasma-charged particles are deflected. Picture adapted from [13].

Although the experimental setup is designed such that maximum flexibility regarding the possible parameter space (pressure, gas flow velocity, gas type, plasma power, etc.) is achieved, the experimental results presented here have been generated under the following experimental conditions which were kept constant during the experiments: Particles: spherical monodisperse (4.76 ± 0.17 µm) silver-coated melamine-formaldehyde particles purchased from Microparticle GmbH, gas flow: 50 sccm argon resulting in a downwards laminar flow with center velocity of 0.36 m/s, plasma: 13.56 MHz, 15 Watt input power, externally electric field if applied: 4.3 kV/m.

3. RESULTS

Figure 2 demonstrates proof-of-principle of the mentioned technique, i.e. the ability of an externally applied electric field to deflect trajectories of plasma-charged particles by exerting an electric force F_{ext} – being the product of E_{ext} and local charge $Q_{particle}$ of the particle – on them. Even far in the spatial afterglow of the ICP plasma – where electrons have thermalized to room temperature and the plasma density has been depleted to low values – the particles apparently remain to be charged.

Moreover, the obtained trajectories can be fitted perfectly with a quadratic function indicating a spatially uniform acceleration. For densities below 10^{11} m^{-3} (as expected in this region), the typical particle decharging time is longer than the 'time of measurement' of τ_{meas}= 0.11 s. Therefore, the charge of the particles can be assumed to remain 'frozen' over the particles' trajectories displayed in Figure 2. This together with a constant particle charge during deflection (see derivation in [13]) hints towards a uniform horizontal electric field distribution in-between the Rogowski electrodes. This in turn indicates that indeed the plasma density has depleted to very low values.

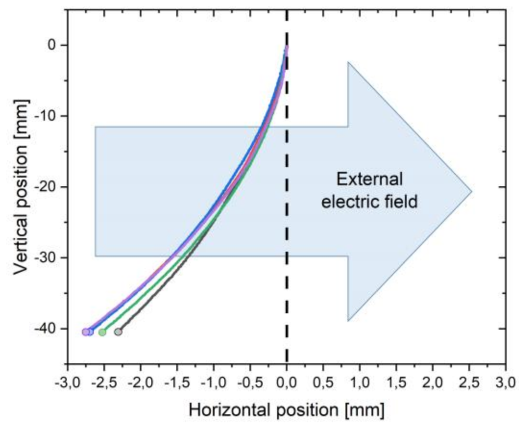
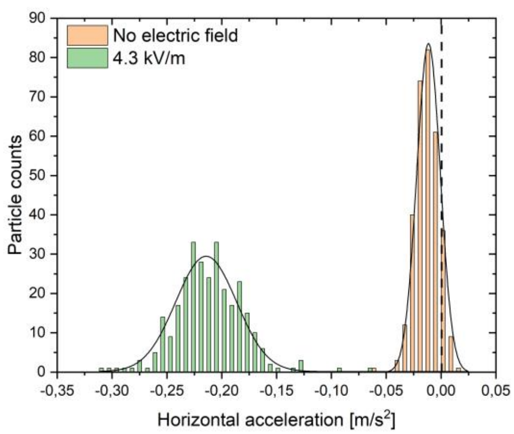


Figure 2. Trajectories of a set of microparticles in the spatial afterglow region of the ICP plasma after having traveled through the active plasma region being influenced by an externally applied electric field (directed horizontally from the left to the right). All data sets have can be perfectly fitted with a quadratic function.

Figure 3a shows measurements of the horizontal acceleration of particles after they have passed through the active ICP region and at the moment they are close to the middle in-between the Rogowski electrodes for situations with and without application of external electric field of 4.3 kV/m. As can be seen, for the case without electric field applied, measured accelerations are close to zero. However, when the electric field is switched on, the distribution is both broadened and shifted to higher values of the (negative) horizontal acceleration. As expected – and designed – the process manifesting itself here is the externally applied electric field interacting with the plasma-induced surface charge on the particles. The broadening of the distribution can be attributed to a charge distribution over the measured ensemble of particles instead of all particles in the ensemble carrying an identical charge.



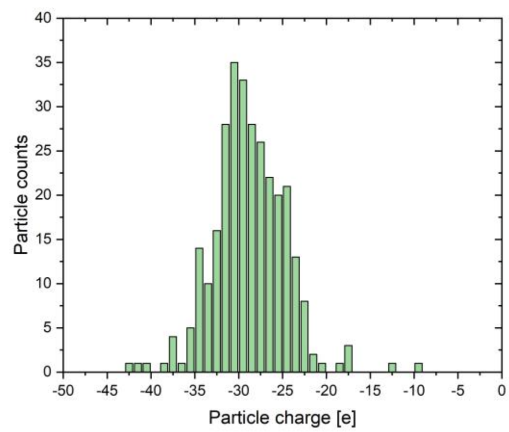


Figure 3. (a) Preliminary results demonstrating the effect of an externally applied horizontal electric field on the acceleration of the particles perpendicular to their vertical movement. (b) From the acceleration data - in (a) - one could deduce the resulting charge on the particles at the moment they have past the plasma and enter the detection volume.

From such measurements of the horizontal acceleration and by using supplier values for the particles' size and mass density, the net electric force on and thus charge of each individual particle can easily be obtained. This charge is given in Figure 3b. These spherical (4.76 ± 0.17 μm) silver-coated melamine-formaldehyde particles show a charge distribution with an average particle charge of ~30 (negative) elementary charges and a standard deviation of 7 elementary charges. It is clear that these values are a few orders of magnitude lower than values of 10^4-10^5 elementary charges which are typical values for the charge of equally sized particles in the active bulk of low pressure plasma regions [14].

4. CONCLUSIONS AND FUTURE RESEARCH

From the work presented, it can be concluded that:

- Experiments have demonstrated that the combination of plasma charging of particles and externally applied electric fields can be used as an effective mitigation strategy.
- The residual plasma-induced charge of particles in the spatial plasma afterglow is several orders of magnitude lower than would be the case in typical plasma bulk situations.
- The setup is able to measure residual particle charges with high accuracy (i.e. only a few elementary charges on the particle's surface can be detected), opening-up scientific possibilities to investigate for instance charge attachment and detachment on the most elementary level.

Overall, the setup enables to investigate elementary plasma-particle processes in a large parameter space especially relevant for application in EUV lithography.

Future joint applied research includes exploration of the charging and mitigation dynamics of non-spherical particles, i.e. clusters of particles, particles of different (compounds of) materials and particles in the nanometer range. Especially of interest will be adapted configurations in which the plasma can be additionally screened and initial plasma parameters (for instance density and temperature) can be tuned more effectively. Moreover, the effectiveness of the proposed strategy should be ensured in a relatively large pressure regime, bringing-up the necessity of measuring and predicting scaling laws with respect to primarily pressure but also with respect to gas flow and plasma power density.

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