Particle charging by EUV and EUV-induced plasma

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EUV light (Extreme Ultra-Violet; 13.5 nm) is used extensively in advanced manufacturing and metrology of semiconductor devices. An unavoidable side effect is the generation of EUV induced plasma by the photons (energy ~ 92 eV) interacting with the low pressure hydrogen gas in typical EUV lithography tools[1]. The EUV induced plasma is modelled in the lithography tools by Particle In Cell (PIC) simulation, as for example shown in Figure 1a for the area around the reticle[1].

In semiconductor manufacturing, submicron particles must be controlled and kept away from critical surfaces to be imaged, exposed or measured. The force balance on these particles, is often dominated by coulomb forces due to the presence of EUV induced plasma. Therefore, understanding and control of particle charge is crucial. Typically, the particle charge is determined by the flux balance conditions of different plasma components: electrons, ions and photons, as shown in Figure 1b. The charging strongly depends on the location, time and size of the particles.

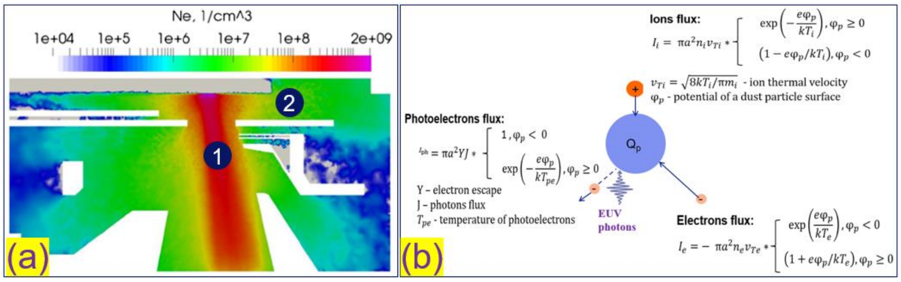
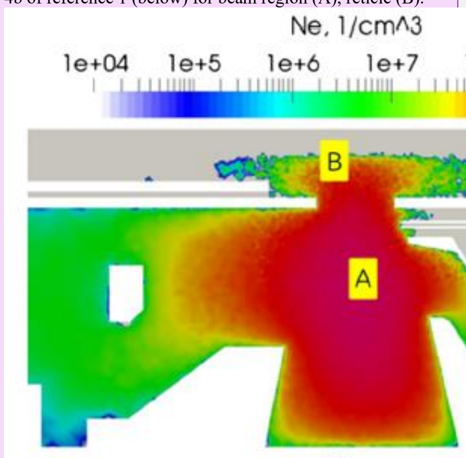


Figure 1: (a) EUV induced plasma accumulation over single pulse: inside (1) and outside (2) of EUV beam. See further details in ref 1. (b) The particle charging mechanisms as the balance between electron flux, ion flux and photoelectric effects.

The EUV photons charge particles positive by expelling electrons from it. The EUV beam is pulsed in typical EUV photolithography tools with a period of 20 µs. This causes a periodic oscillation of the charge on a particle inside the EUV beam region (Figure 2a). The particle

Commented [LH1]: Figure 1a needs more annotation of the various pieces that are visible. As e.g. is done in figure 4b of reference 1 (below) for beam region (A), reticle (B).



Commented [MC2R1]: I used this figure initially where A,B,C represent respectively (multipulse) beam area, floating reticle surface and grounded ReMa. But in this work our primary focus is to explain charging mechanism inside and outside EUV beam. That's why I used this figure

Commented [LH3]: Is this figure the average over the 20µs period? It seems only the plasma during the EUV-pulse, not between pulses. Can you specify?

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charges positively during an EUV pulse due to photo-electric effect . It charges negatively between pulses due to the EUV-induced plasma.

Particles outside of the EUV beam have the traditional charging mechanisms with a balance between electron and ion fluxes making it negative due to higher mobility of electrons. The particle charge only slightly oscillates with the EUV pulses, due to the changing plasma parameters. In the vicinity of the surfaces, the photoelectric effect of the surface may dominate and significantly contribute to the incoming electron flux to the particle, as illustrated for a 100 nm particle in Figure 2b.

Figure 2a shows that, the particle acquires positive steady state charge in one single pulse inside EUV beam; whereas outside EUV beam (figure 2b), the same particle acquires negative steady state charge through multiple pulses. In both cases, the dynamics of the particle charge was fitted as $Q(t) = Q_s + Q_0 * e^{(-t/\tau)}$. Here Q_s is the stationary charge, ($Q_s+Q_0=0$) is the initial charge and τ is the characteristic charging time. The fitted curves are shown by the dashed line.

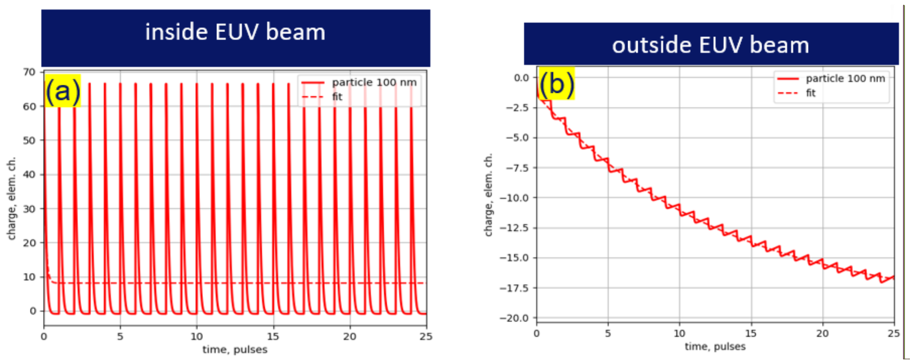

Figure 2: Particle (100 nm diameter) charge evolution with time (a) inside and (b) outside EUV beam. The particle charge acquire steady state in a single pulse within EUV beam. However, the particle charge takes multiple pulse to acquire steady state when they are outside of EUV beam

Commented [LH4]: Can you add a label to the vertical axes in the right graph and an (a) and (b) label to reference the two graphs?

Commented [MC5R4]: done

Commented [LH6]: Why does the particle outside the beam get much more negative than the one inside the beam between pulses?

Commented [MC7R6]: My explanation would be inside EUV beam there are significant photoelectrons coming from particle surface which makes the sheath surrounding the particle double layer type. It creates the potential barrier for incoming electrons from bulk. Only very few electrons can overcome this pot barrier which makes the charge less negative. Outside EUV plasma, the bulk electrons do not see such potential barrier and hence more electrons contribute to charging.

The particle charge and charging time for 100 nm particles at different locations (inside and outside of EUV beam) are shown in Figure 3. The figure shows that the equilibrium particle charge varies throughout the volume. Particles are negative in most of the volume, but get positively charged inside the beam area due to the photo-ionisation. The charging time is much shorter inside the beam than outside the beam; as anticipated in Figure 2. This implies that the particle charge is influenced by its trajectory-history, especially for particles outside the beam, as they might not be in equilibrium with their surrounding yet.

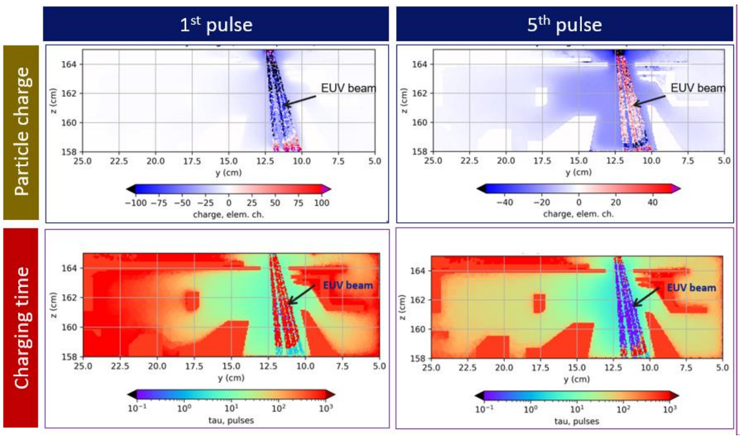

Figure 3: The upper panel shows the simulation results on spatial distribution of particle (100 nm diameter) charge over multiple pulses. The lower panel represents the spatial distribution of particle charging time over multiple pulses.

The charging mechanisms depends strongly on particle size. Considering OML theory[2], it can be shown that $dQ/dt \sim r^2$ where r is the radius of particle. On the other hand, the equilibrium potential depends only on plasma conditions, not particle size so that $Q_s \sim r$. Therefore, the time required to come to this charge scales as $\tau \sim Q_s/(dQ/dt) \sim 1/r$. This implies that larger particles charge more quickly. This is illustrated in Figure 4 for both inside and outside of EUV beam. The charging is faster inside the EUV beam as anticipated above; e.g. the 1 um particle reaches steady state in a single pulse whereas outside of EUV beam, it takes multiple pulses (~ 7-8 pulses). In both locations the 1 µm particle charges approximately 100 times faster than the 10 nm particle, as expected from the 1/r-scaling.

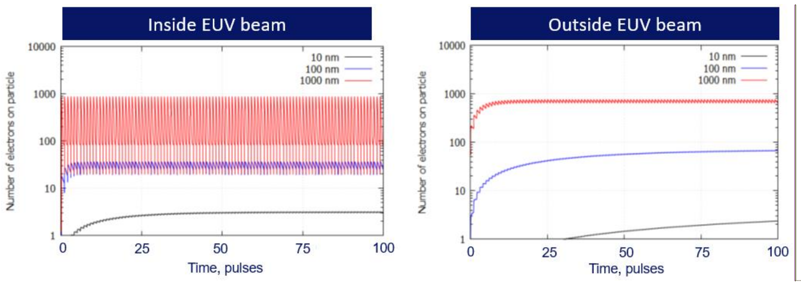

Figure 4: The steady state particle charge number strongly depends on particle size: bigger (10 um diameter) particles acquire steady state charge faster than smaller size (10 nm diameter) particles.

Commented [LH8]: I don't understand why the charging time changes for pulse nr 1, 2 and 5. Shouldn't this be the same value?

Commented [LH9]: I would suggest using only 2 figures: one with equilibrium charge (Qs) and one with charging time (τ). This also allows them to be bigger, which will benefit readability.

Commented [MC10R9]: Indeed. Good suggestion

Commented [LH11]: Can we make the axes (label) the same as figure 2 and figure 5 for consistency? All horizontal axes should either be in pulses (as fig 2) or µs (as fig 4 and 5). And the vertical axes should be either negative (as figure 2 and 5) or positive (as figure 4).

Commented [MC12R11]: Good point. Changed to pulses time unit. I changed to charge number.

The particle charging is strongly influenced by the background neutral gas pressure: the plasma parameters (density, temperature) are affected and the ion angular momentum is lost due to collisions with neutrals. This effect significantly enhances ion flux to the particle and therefore the charge of the particle decreases. This effect is shown in Figure5 for both cylindrical[3] (blue curve) and spherical probe[4] (black curve) correction, along with collision less OML estimation (red curve).

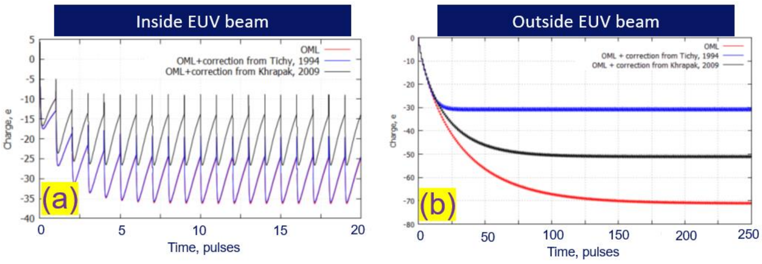

Figure 5: The influence of ion-neutral collisions on charge dynamics for the 100 nm particle. (a) The particle charge is for a directly irradiated particle within the EUV beam. (b) The particle charge outside of EUV beam.

The variation of steady state charge for 100 nm particle with pressure is shown in Fig 6. The slope of the curve provides the pressure sensitivity of particle charge. It is found that pressure sensitivity of particle charge outside of EUV beam is higher than that inside EUV beam.

Commented [LH13]: I don't see this statement in the graph. The relative scaling is virtually the same.
Outside: 72 to 41 is factor 0.57
Inside: 36 to 23 is factor 0.64
For all pressures, the charge outside the beam is twice that inside the beam, so the scaling with pressure is the same.

Commented [MC14R13]:

Commented [MC15R13]: I just checked in the report D001160338. Inside EUV sensitivity 0.536 and outside it is 1.397 which were obtained from this linear fit

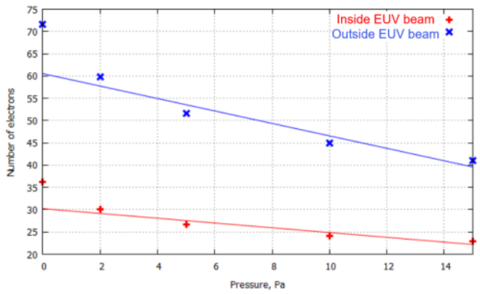

Figure 6: Steady state charge variation of 100 nm particle with pressure for both inside and outside of EUV beam

References:

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