Importance of Electron drag force in EUV induced pulsed plasma

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The fabrication of semiconductor integrated circuits/chips involves a great variety of physical and chemical processes performed on a silicon substrate. Fundamental to all of these processes is the optical projection lithography through which almost aberration free and mainly diffraction-limited 3D image of the mask (pattern) are created on the substrate. The resolution of such images are determined by the Rayleigh resolution criterion which depends on the wavelength of the imaging light and numerical aperture of the projection optics. To obtain best possible resolution of nm scale features, the extreme ultraviolet (EUV) lithography has been introduced in recent times which uses highly energetic EUV photons (energy ~ 92 eV) with shorter illumination length (13.5 nm). One of the unavoidable side effect of this technological development is the generation of EUV photon induced plasma due to the interaction of such highly energetic photons with the low pressure (~ 1 – 10 pa) background hydrogen gas. The spatial and temporal characteristics of the EUV induced plasmas have been investigated by both experimentally and particle-in-cell (PIC) simulations. When the EUV pulse repetition time (20 μs) is much larger than the plasma decay time, the plasma evolution occurs through multiple stages: in the first stage, the EUV photons interact with background hydrogen gas which creates plasma containing highly energetic electrons with excess photon energy and non-Maxwellian energy distribution. A part of these electrons move towards the nearby surfaces/walls leaving behind a positive space charge region which confines the remaining electrons and allows positive ions to accelerate towards surfaces/walls. The confined electrons lose their energy within a short time (few tens of ns) due to electron impact ionization and increase the plasma density. After this stage, the plasma expands with rapid reduction of local electron density. During the last stage of the process, the plasma density continues to decrease due to ambipolar diffusion and recombination processes at surfaces/walls and the electrons are supposed to reach their equilibrium temperature. The energy is supplied during EUV ON within first few tens of ns within the pulse while it takes > 20 μs for the plasma to completely extinguish. This effect makes the highly transient pulsed plasma conditions which switches between nonthermal state ($T_e >> T_i$) and thermal states (T_e

~ T_i) within each pulse. Here $T_{e(i)}$ is the electron (ion) temperature. This effect leads to a build-up process over multiple pulses. Such transient plasmas generates an electric field (E) when it comes in contact with surfaces/walls and also responsible for charging mechanisms of nm-µm size particles which are present within the system as contaminations due to lack of sufficient cleanliness[1].

In presence of such transient electric fields, charge dependent volume forces such as electrostatic force (F_{el}), ion drag (F_{id}) and electron drag (F_{ed}) forces play important roles for nano particle transports. Electrostatic force is the direct manifestation of electric field interaction with the charge of the particle and it acts in the opposite direction of the electric field for a negatively charged particle. Ion drag force is associated with the momentum transfer of flowing ions to the particle and it acts in the direction of the electric field. Similarly, electron drag force is associated with the momentum transfer from flowing electrons to the particle and it acts in the opposite direction of the electric field. Earlier, the electron drag force was estimated for both collision less[2] and collisional[3] plasma regime. The goal of this work is to present the importance of electron drag force on small size (nm-µm) particle transport in transient pulsed hydrogen plasmas which is not negligible in comparison to electric force and ion drag force[4]. To do so, particle transport is considered within a single pulse duration in "steady state condition" where the plasma switches between nonthermal state and thermal states as mentioned before. The following parameters have been used for estimations: background hydrogen gas pressure at 5 pa, plasma density ~ 4 x 10^8/cm^3, E ~ 5 V/cm, T_e ~ 10 eV and T_i ~ 0.025 eV (room temperature). For the thermal state, T_e ~ T_i ~ 0.025 eV

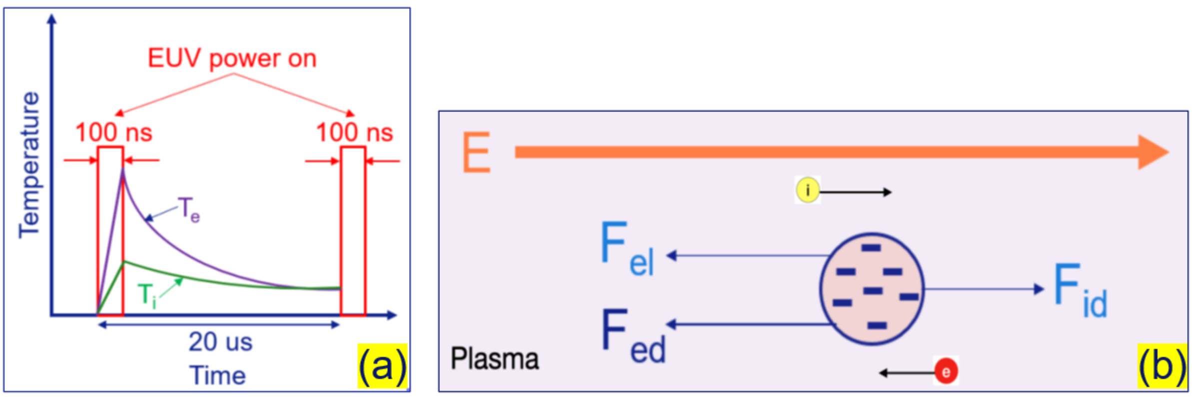

Figure 1: (a) An illustration of EUV pulsed plasma generation. (b) An illustration of the plasma induced volume forces acting on a negatively charged particle (outside EUV beam) in presence of an external electric field (E): electric force (F_{el}), ion drag force (F_{id}) and electron drag force (F_{ed}) .

For our estimation, we consider collision less electron drag force[2]:

$$F_{\text{ed}} = \frac{2}{3}\sqrt{\frac{2}{\pi}}\left(\frac{T_{\text{i}}}{e}\right)^2 \xi^{-2}\tau^2(1+\tau)^{-1}M_{\text{e}}\Phi(z,\xi).$$

Here $M_e = u_e/v_{Te}$ is the thermal Mach number for electrons where u_e and v_{Te} are the electron drift velocity and thermal velocity respectively. The parameter $\Phi(z, \xi)$ accounts for the electrostatic interaction between electrons and charged particles which can be estimated as contribution from direct collisions and from scattering. Here, $\xi = \lambda_D/a$ is the normalized particle size. However, for the ion drag force, the expression for weakly collisional regime has been taken into account[5]:

$$F_{\text{id}} = \sqrt{\frac{2}{\pi}}\left(\frac{T_{\text{i}}}{e}\right)^2 \ln\left(\frac{4M_{\text{i}}}{\eta\beta}\right)\frac{\beta^2}{M_{\text{i}}}.$$

Here $M_i = u_i/v_{Ti}$ is the thermal Mach number for ions where u_i and v_{Ti} are the ion drift velocity and thermal velocity respectively. The parameter β is the scattering parameter and η ($= \lambda_D/l_i$) is the collisionality index. Here, λ_D is the effective Debye length and l_i is the ion mean-free path.

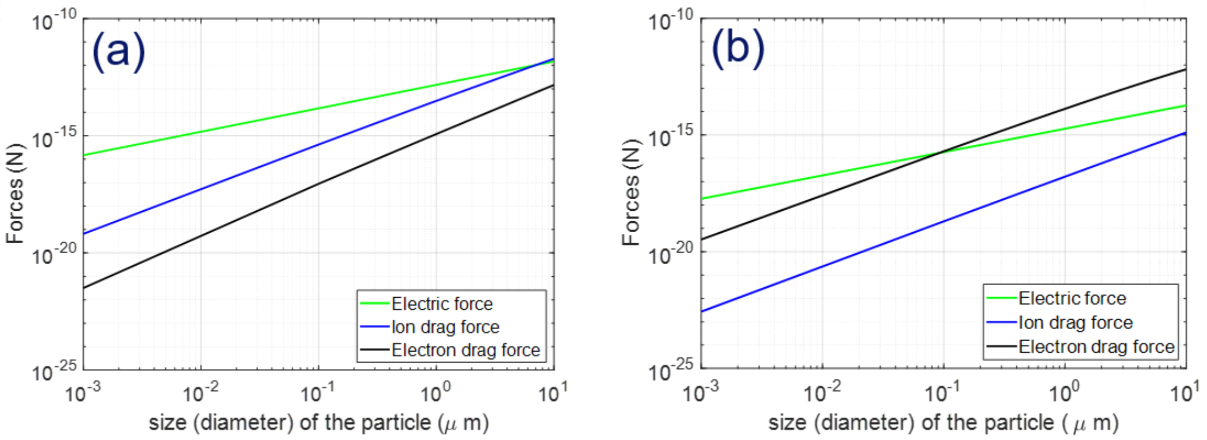

Figure 2: The variation of electric force, ion drag force and electron drag force with particle size in (a) non-thermal plasma and in (b) thermal plasma.

The variation of the electric, ion drag and electron drag forces with particle size ‘a’ is shown in Figure 2. At the beginning of the pulse, the plasma is nonthermal ($T_e/T_i \sim 400$) and the electric, ion drag forces dominate over the electron drag forces by 1-2 orders of magnitude. However, at the end of the pulse, the plasma is thermal ($T_e \sim T_i$), the electron drag force is always higher than the ion drag force. A cross-over between electric and electron drag forces is obtained at critical particle size $d_c \sim 100$ nm. The electric force dominates over electron drag force if the particle size is less than this critical size. The electron drag force dominates when particle size is bigger than this critical size. This is expected as $F_{el} \sim a$ and $F_{ed} \sim a^2$. Figure 3 shows the variation of d_c with pressure and electron-to-ion temperature ratio. From these plots it is possible to classify particle sizes for which electron drag force can dominate over electric force under typical operational conditions.

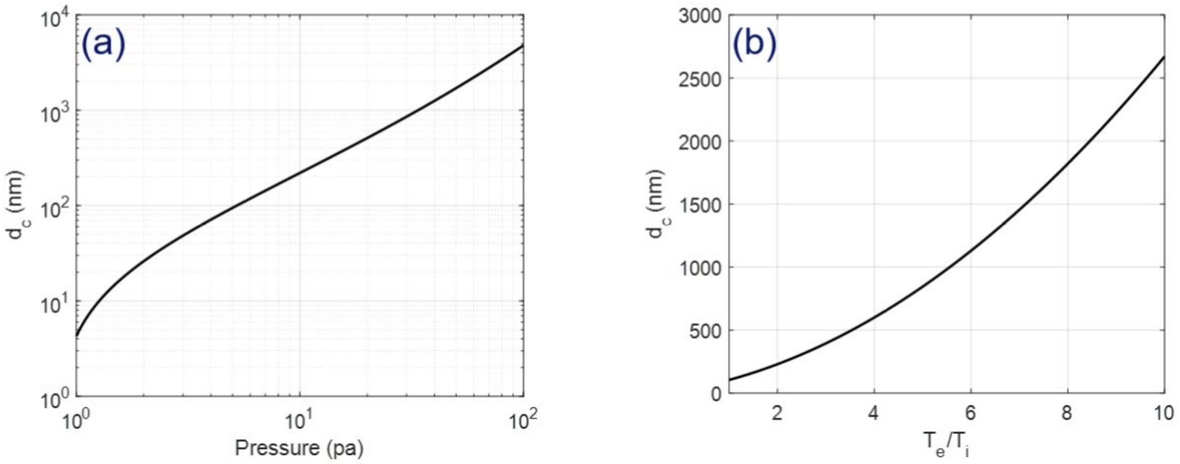

Figure 3: The variation of the cross-over particle size, d_c (when $F_{el} = F_{ed}$) with (a) pressure and (b) electron-to-ion temperature ratio (T_e/T_i).

To conclude, it is shown that particle transport within each EUV pulse strongly depends on the plasma regime. In case of multiple pulse scenario, residual charge may play an important role and its role on the steady state charge as well as drag force estimations should be performed self-consistently.

References:

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