Energy and Angular Distributions of Ions and Neutrals Extracted From a Slot in Contact With a High-Density Plasma

Doosik Kim and Demetre J. Economou

***Abstract*—The energy and angular distributions of ions and neutrals extracted from a two-dimensional slot in contact with a high-density Ar plasma were investigated. A combined fluid/Monte Carlo simulation was developed to follow the trajectories of ions and fast neutrals through the sheath and out the slot. The energy and angular distributions reflect the strong disturbance of the sheath when the slot size is comparable to the sheath thickness.**

***Index Terms*—Fluid/Monte Carlo simulation, plasma molding, sheath simulation.**

PLASMA interaction with an opening occurs in ion extraction through a grid [1], in applications ranging from thin-film etching and deposition to neutral beam sources and ion thrusters. Also, in MEMS fabrication, the plasma often interacts with features that are comparable to, or larger than the local sheath thickness. In such circumstances, plasma "molding" over the opening or the feature influences the energy and angular distributions of energetic ions and neutrals impinging on the substrate. In this work, plasma molding over a two-dimensional (2-D) slot was investigated computationally with a combined fluid/Monte Carlo simulation.

The compressible fluid equations for ions (momentum and species balance) coupled with Poisson's equation for the electric potential, and Boltzmann's relation for the electron density were employed. A finite-difference scheme using the donor cell method was implemented to solve the ion continuity and momentum equations. At each time step, Poisson's equation was solved to update the electric potential profiles. The simulation evolved until a steady state was achieved. Based on the electric field profiles obtained by the fluid simulation, trajectories of ions and fast neutrals (resulting by charge exchange or ion neutralization on the walls) were followed in order to calculate their energy and angular distributions. During their transit, ions could suffer elastic scattering or charge exchange collisions with the background neutral gas. Collisions with the wall were treated as specular reflections, with an energy loss calculated based on the binary collision approximation [2]. When an ion collided with the wall, the ion was neutralized and the resulting hot neutral was followed through. Both dc- and RF-modulated cases were calculated, but only a dc case is shown below. Results were visualized on a Dell workstation running Windows NT by using Tecplot (Amtek Engineering, Inc., Bellevue, WA).

The specified plasma parameters at the upper boundary of Fig. 1(a) were: electron temperature $T_e = 3$ eV, ion density $n_o = 2.59 \times 10^{16}$ m^{-3}, and potential $\Phi_o = 20$ V. The wall (blackened block) was grounded, and the background Ar gas pressure and temperature were set at 20 mtorr and 580 K (0.05 eV), respectively. The bottom of the domain (dashed line) was also set at ground potential, while both sides were symmetry planes. The slot width and thickness were 508 and 254 μm, respectively. The sheath thickness (defined as the position where the relative net charge $\rho \equiv (n_i - n_e)/n_i = 0.01$) was found to be ~500 μm, which is comparable to the width of the opening. As a result, there is significant disturbance of the plasma near the opening (Fig. 1). The ion density profiles [Fig. 1(a)] show the presence of "ears" right behind the opening, reflecting the divergence of the ion trajectories by the horizontal electric field [Fig. 1(b)]. The ion density behind the slot is one-order-of-magnitude smaller than the "bulk" value. The electric field is higher near the upper corners of the slot (as opposed to the downstream corners) where the charge density is higher. The strong horizontal component of the electric field is evident from the vector plot in Fig. 1(b). This is due to a "hole" in the potential profile [also Fig. 1(b)] owing to the fact that the slot opening is comparable to the sheath thickness. Within the slot, the horizontal electric field is stronger than the axial field over a significant fraction of the slot width. Thus, ion trajectories can be strongly deflected with ions striking the vertical walls of the slot at relatively large angles.

Fig. 2 depicts the energy and angular distributions (log scale) of ions [Fig. 2(a)] and fast neutrals [Fig. 2(b)], calculated by Monte Carlo simulation, sampled at the bottom of the domain [dashed line in Fig. 1(a)]. The ion energy is around 20 eV, equal to the sheath potential. The energy spread is due to the energy distribution of ions entering the sheath [3] (of the order of T_e). Due to the low gas pressure and the short transit time, ion flow is nearly collisionless. The angular distribution of ions is also shown in Fig. 2(a). The peak on axis corresponds to ions traveling on or around the plane of symmetry; these ions are not affected by the horizontal fields. The ion angles [with respect to the normal on the dashed line at the bottom of Fig. 1(a)] extend to ~50° reflecting the strong bending of ion trajectories by the horizontal fields. (Ions exiting through the vertical symmetry planes were accounted for.)

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The authors are with the Plasma Processing Laboratory, Department of Chemical Engineering, University of Houston, Houston, TX 77204-4004 USA (economou@uh.edu).

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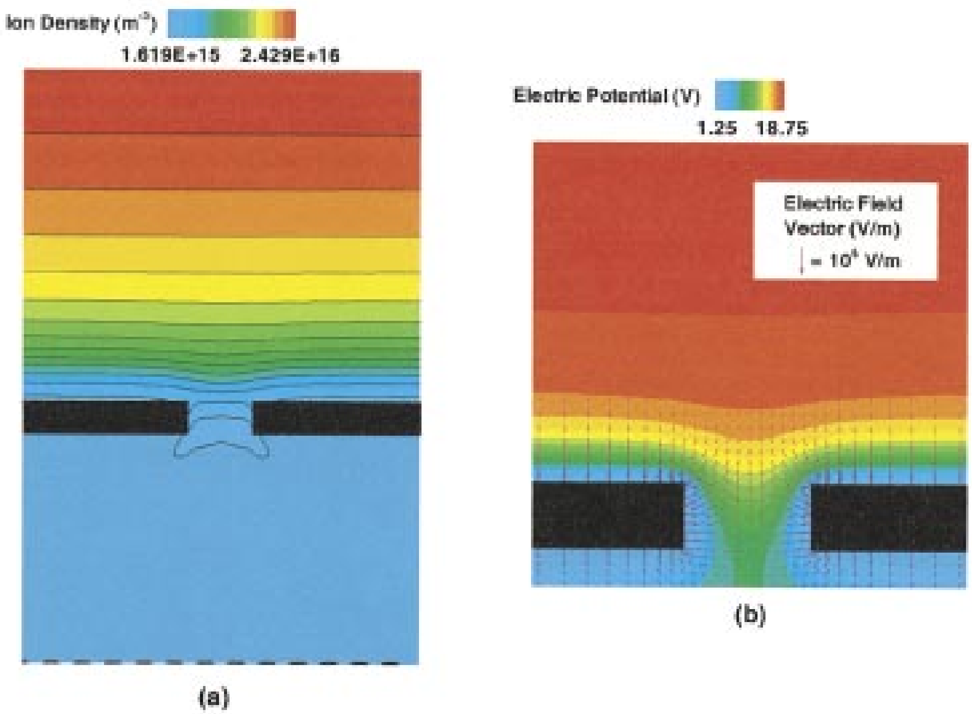

Fig. 1. Ion density (a), and potential distribution (b), near a 2-D slot. Electric field vector is also shown in Fig. 1(b). The slot width is 508 μm. The blackened block represents the solid electrode. The dashed line at the bottom of (a) is the position where the distributions of Fig. 2 were recorded.

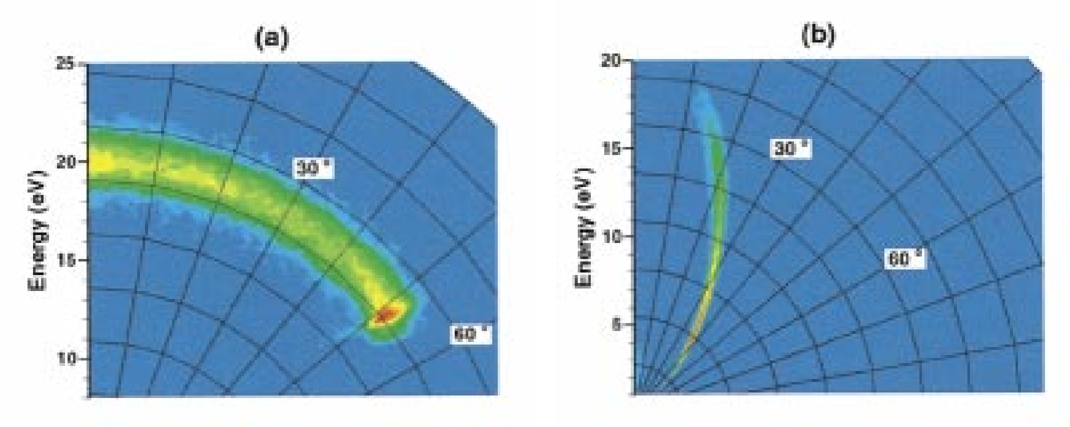

Fig. 2. Energy and angular distributions of ions (a), and fast neutrals (b) recorded at the position of the dashed line of Fig. 1(a).

In contrast to ions, the energy distribution of fast neutrals [Fig. 2(b)] is wide. The vast majority of neutrals are formed by ions neutralized on the side (vertical) walls of the slot. Since the energy of the emerging neutral depends on the impact angle of the parent ion, and ions strike the sidewall at varying angles, a wide energy distribution of neutrals results. Fig. 2(b) suggests that most neutrals result from ions striking the sidewalls at smaller angles (most strongly affected by the horizontal fields). Ions striking at these smaller angles (with respect to the normal on the *vertical* sidewall) loose a larger fraction of their energy, and the resulting neutrals populate the lower energy, larger angle (with respect to normal on the *horizontal* collecting surface), segment of their distribution function.

In conclusion, when the sheath thickness is comparable to the opening size, the angular distributions of extracted ions and fast neutrals reflect the significant disturbance of the plasma near the opening. Distributions from RF modulated plasma potential show richer behavior, due to periodic collapse of the sheath into the slot.

References

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