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# Particle-in-Cell Modeling of Low Pressure Capacitively Coupled Plasmas for High Aspect Ratio Etching

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Plasma etching of semiconductors is an essential process in the production of microchips which enable nearly every aspect of modern life. Two frequencies of applied voltage are often used to provide control of both the ion fluxes and energy distribution.

One particularly challenging process is high aspect ratio (HAR) etching, which often pushes the limits of controlling the plasma ion energy distributions delivered to surfaces to etch features that are as much as 100 times as deep as they are wide. Low pressures (< 10 mTorr) and high voltages (> 2 kV) are used to produce narrow ion angular distributions with high energies. In this regime, fluid and many hybrid models are no longer valid, and a fully kinetic approach is necessary. The kinetic approach is computationally intense due to the small Debye length (requiring a dense mesh) and high energy electrons (requiring a small timestep). Aleph, a particle-in-cell direct simulation Monte Carlo model (PIC-DSMC), has been used to model a 1-dimensional plasma in this regime, and analyze some of the basic plasma dynamics for a 4 mTorr argon plasma in a 4 cm gap. 1 kV at 40 MHz was applied to the upper electrode, and 3 kV at 2 MHz was applied to the lower electrode. The mesh resolution was 10 μm and the timestep was 95 fs.

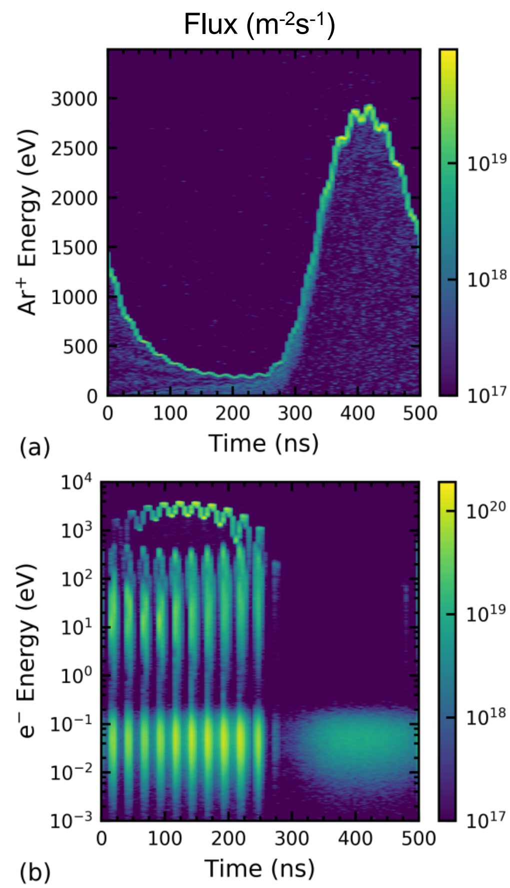


Fig. 1 – (a) The energy distribution of $Ar^+$ ions and (b) electrons reaching the lower electrode as a function of time in the low frequency cycle.

The time-dependent ion and electron energy distributions at the lower electrode (i.e., the wafer) are shown in Fig. 1. At higher pressure, collisions of ions as they are accelerated through the sheath result in lower energy ions at the surface. At these low pressures, the effect of collisions is much less significant, and at any time the ions are nearly mono-energetic. While the contribution of the high frequency voltage to the ion energy is often assumed to be negligible, in this case some modulation of the ion energy is visible (fluctuations on 10 ns timescales). The electron energy distributions, which impact charging within HAR features, provide more insight to the plasma dynamics. The highest energy electrons (> 1 keV) originate from ion-induced secondary electron emission at the upper electrode.

The effects of pressure, voltage, and gap size on the distributions of ions and electrons and the plasma dynamics were also explored. This improved understanding of the plasma dynamics will help inform recipe development in the more complex HAR etching reactors containing complex gas mixtures.

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