Analysis of a radiofrequency plasma reactor for etching

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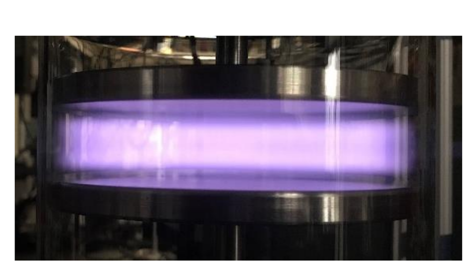
ABSTRACT

Microelectronics are a core component in many modern technologies. Production of microelectronics relies on plasma processing for etching of fine features in semiconductor material. While the technology is relatively mature, as structures are desired to be smaller, plasma properties that lead to non-uniformities in the etching process must be explored. To this end, a coupled experimental and modeling effort was undertaken to characterize an RF Argon plasma reactor operating in the 10 MHz regime with input power on the order of 100 W. Diagnostics of the experimental setup include Langmuir probe measurements, surface spectroscopy, tomography, and a retarding field analyzer to measure the ion energy distribution function (IEDF). A one-dimensional PIC/DSMC model was built to mimic the experimental configuration. Cross sections for electron-neutral collisions included elastic, excitation, and ionization. Elastic and charge exchange collisions for ions were also included. Analysis of the IEDF reaching the electrode surfaces as a function of pressure and input power were analyzed. Eventually, measured and simulated data will be used to train a machine learning model that may be able to predict optimized plasma parameters for other scenarios.

EXPERIMENTAL SETUP

An experimental RF plasma reactor will provide model validation for macroscopic plasma parameters. The coupled experimental modeling effort will allow for detailed analysis of the etching process.



Diagnostics to be developed

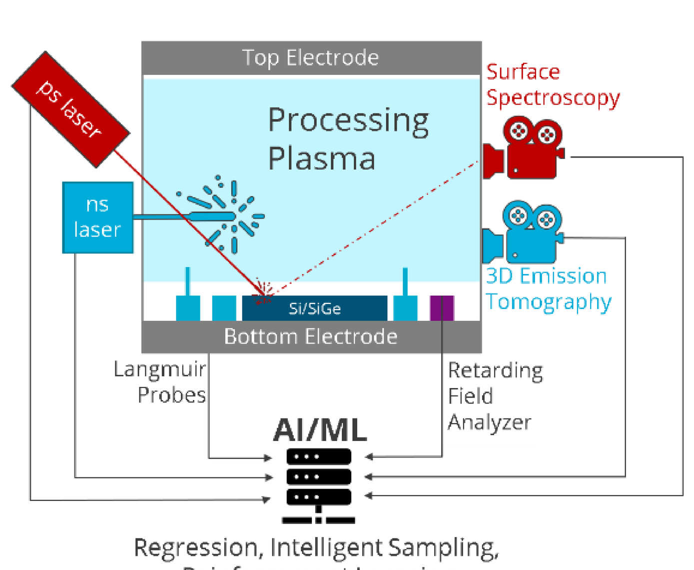
- Langmuir probe (EEDF)
- Laser-induced fluorescence (species densities)
- Optical tomography (3D information)
- Retarding field energy analyzer (IEDF)
- Surface spectroscopy (etch rates)

Operating conditions [2]:

- 1 – 300 Pa
- 3.39 – 13.56 MHz
- < 100 W
- ~ 330 V peak-to-peak
- Gas temperature range: 300 – 500 K

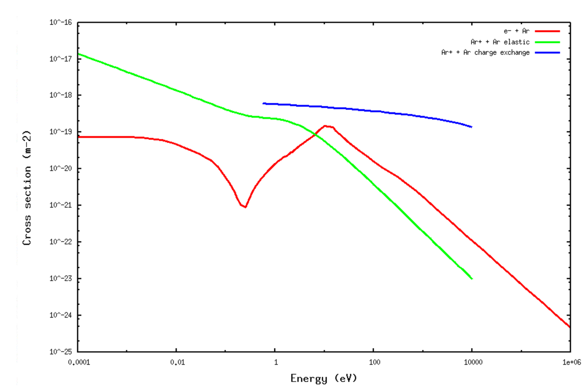
Plasma conditions:

- n_e range: 10^8 to 10^{11} cm^{-3}
- $T_e \sim 5$ eV

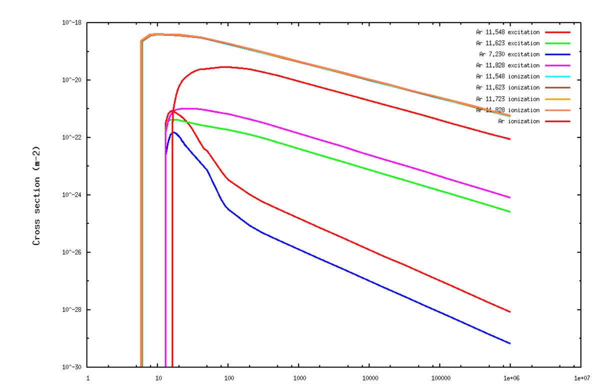


ARGON GAS MODEL

Cross sections for electron-neutral collisions include elastic, excitation, and ionization, as well as elastic and charge exchange collisions for ions



elastic + charge exchange

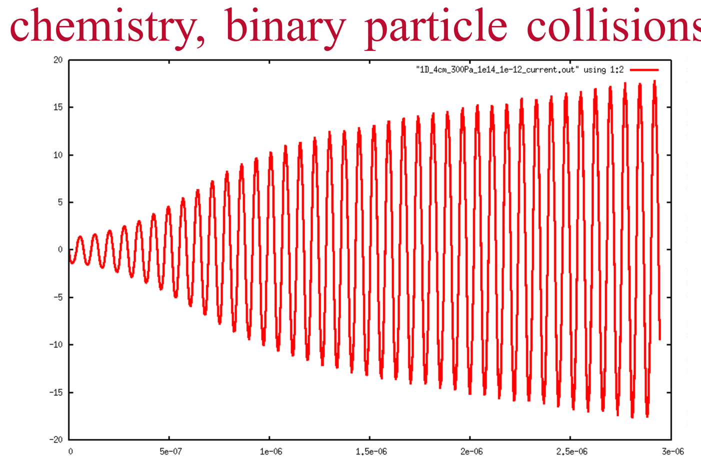


excitation and ionization

ALEPH MODEL

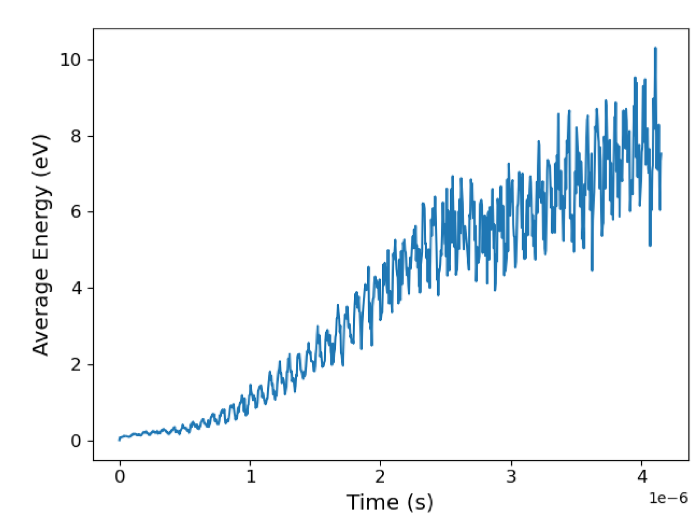
Aleph is a massively parallel particle-in-cell (PIC), Direct Simulation Monte Carlo (DSMC) code that includes physics for gas chemistry, binary particle collisions, photons, and surface physics.

- Numerical Parameters:
  - dt = 1 ps, dx = 5 μm
- 200 charged particles per element
- f = 13.56 MHz
- Pressure = 300 Pa

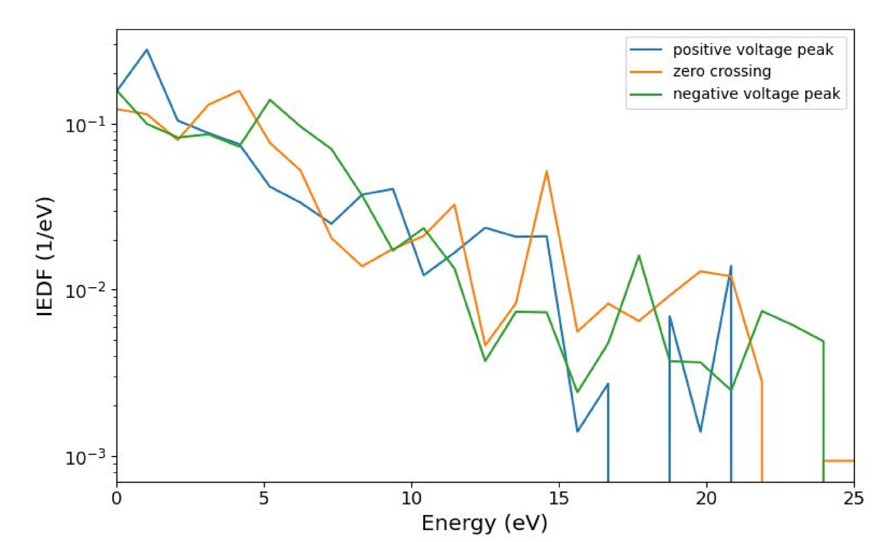


Current for a 300 Pa, Argon discharge operating at 13.56 MHz

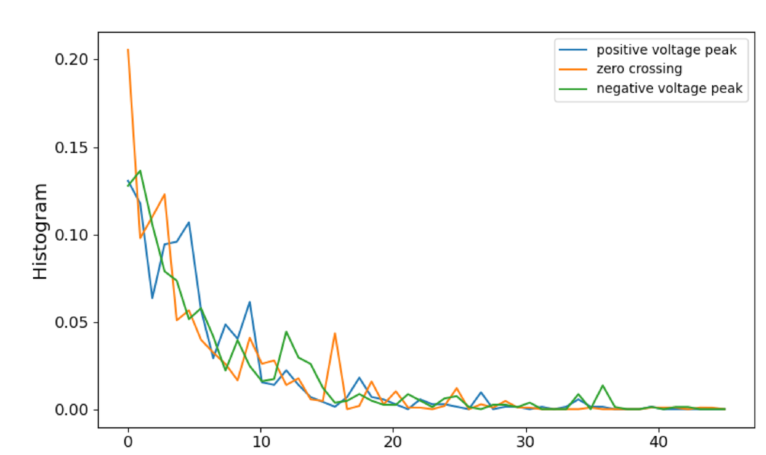
ION CHARACTERISTICS



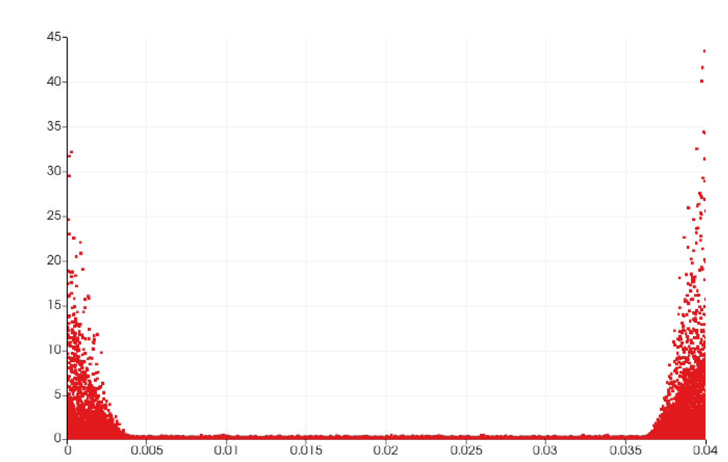
Average ion energy of ions impacting the cathode.



IEDF at different voltage points for ions impacting the cathode.



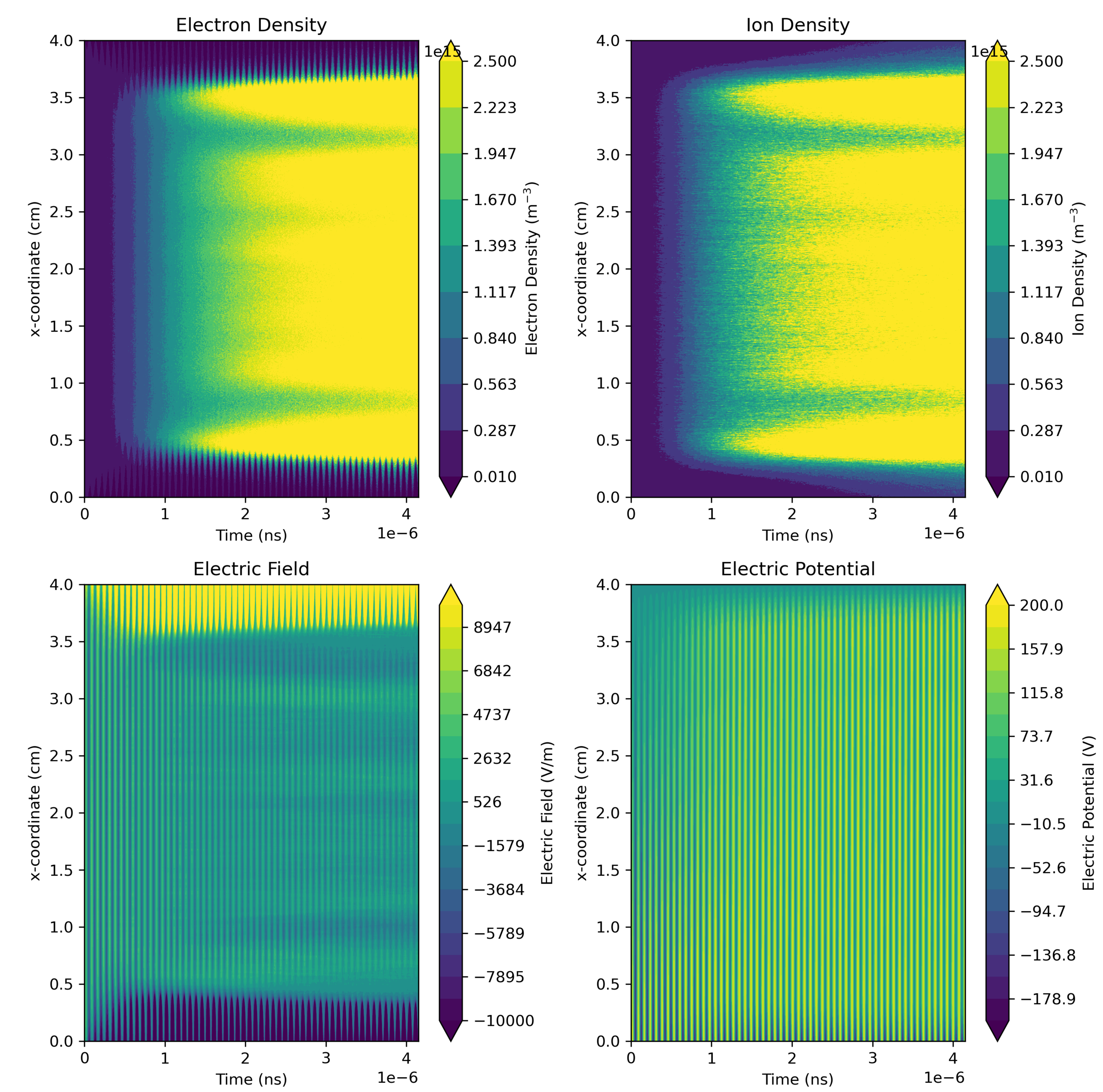
Angle of impact on cathode surface for positive ions.



Phase space plot for ion energy

SPATIO-TEMPORAL RESULTS

Spatio-temporal plots show the evolution of electron density (top left), ion density (top right), electric field (bottom left), and electric potential (bottom right). Sheath formation near the surfaces results in large electric fields that accelerate ions into the surfaces. Plasma appears to be non-uniform with structure over the initial plasma development period. Steady state not ret reached based upon structure observed in both one-dimensional and two-dimensional plots.



Spatial-temporal plots of plasma development over 4 microseconds

CONCLUSIONS

High-fidelity modeling of an RF plasma discharge has shown the capability to conduct detailed studies of ion energy distribution functions for an RF generated plasma operating in Argon at 13.56 MHz. Average ion energy and energy distribution functions follows the voltage driving frequency. Spatial-temporal analysis shows non-uniform plasma density distribution between the driven electrodes. Future work will involve comparison between modeling and experimental results. These results will eventually be incorporated into a machine learning model to predict IEDF's at other parameter regimes.

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