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Low-Frequency Ionization Oscillations in Hall Thruster Discharge Plasma

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Ionization oscillations in Hall effect thrusters (HETs) have been observed using numerical simulation and experiments. We have been developing a hybrid-direct kinetic (DK) simulation to study the excitation and stabilization of such plasma oscillations in the range of 10-30 kHz, which affect the performance of HETs. In a DK simulation, the kinetic equations are solved to obtain the velocity distribution functions (VDFs) directly on a discretized phase space.

We have previously reported that the results obtained from a hybrid-DK simulation are in good qualitative agreement with experimental data.[1] This study suggests that electron transport plays an important role in plasma oscillations whereas the common understanding was that heavy species transport is the main contributor for such oscillations.

In addition to the numerical simulations, we developed a perturbation theory including the perturbations of electron energy as well as the heavy species.[2] The main observations include that: (1) the ionization oscillation is unconditionally damped when the electron energy perturbation is neglected and (2) unstable modes appear when including the electron energy perturbation. As shown in Fig. 1, the growth rate of the ionization oscillation increases as the electron mean speed increases. In addition, the oscillations are stabilized when the electron temperature and the wall heat flux increase as the electron cooling due to plasma-wall interaction balances the Joule heating. These theoretical observations support the numerical results that are compared with experiments.

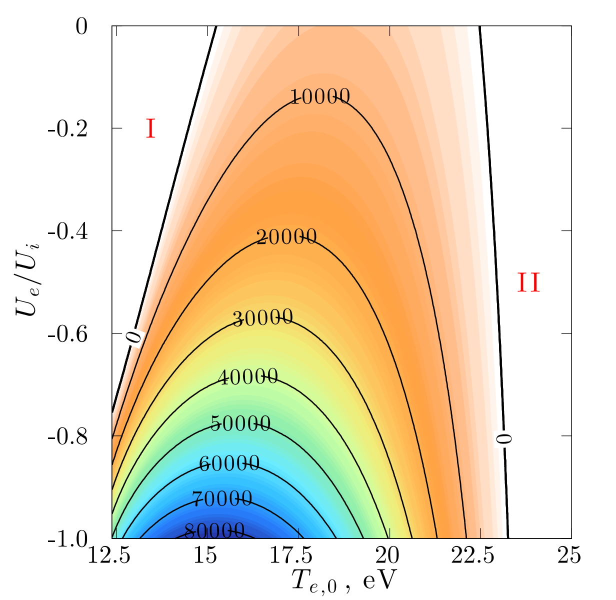
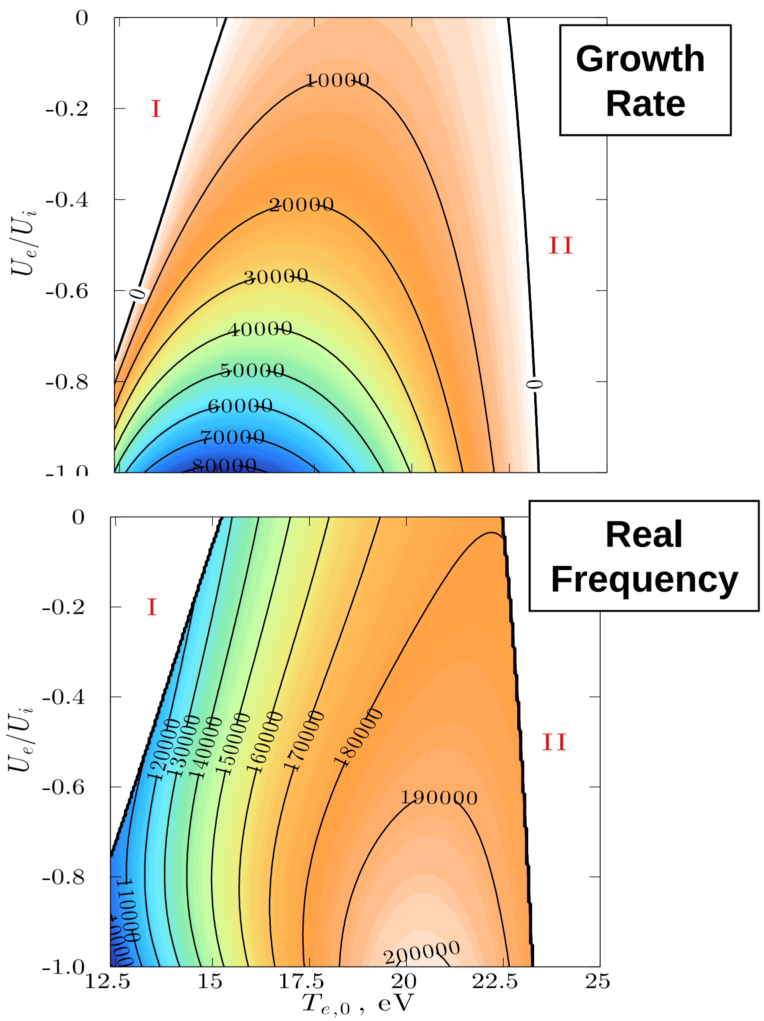


Figure 1 - Growth rate of ionization oscillations as a function of equilibrium electron temperature and electron mean velocity. The white regions show stable modes. The perturbations of ion and neutral atom continuity, ion momentum, and electron energy equations are taken into consideration.

References

[1] K. Hara, M. J. Sekerak, I. D. Boyd, and A. D. Galimore, J. Appl. Phys., **115**, 203304 (2014).
[2] K. Hara, M. J. Sekerak, I. D. Boyd, and A. D. Gallimore, Phys. Plasmas, **21**, 122103 (2014).

LOW-FREQUENCY IONIZATION OSCILLATIONS IN HALL THRUSTER DISCHARGE PLASMAS



- Results from the perturbation theory of ionization oscillations

- The results obtained from a 1D hybrid-direct kinetic (DK) simulation code suggest that electron transport and heating/cooling mechanisms play an important role in ionization oscillations of Hall effect thrusters.
- A perturbation theory is developed to investigate the ionization oscillations.
- We found that ionization oscillations are unconditionally damped when the perturbation of electron energy is neglected.
- Unstable solutions (positive growth rates) are found depending on the electron temperature and electron mean velocity. The theoretical results support previous numerical observations.

HIGHLIGHT

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Massively Parallel Writing of Nano-Patterns as Small as 3 nm Using a Highly Monoenergetic Ion Beam Extracted from a Pulsed Plasma with Pulsed Bias

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Lithography at the sub-10 nm scale is essential for the fabrication of future integrated circuits, as well as many other nanodevices. For example, quantum and single electron devices require a critical dimension (e.g., dot, wire or ribbon) < 10 nm to enhance quantum effects, leading to greatly improved or totally new device characteristics. While serial methods such as scanning probe or electron beam writing have been demonstrated for forming patterns at such small scales, no large scale rapid fabrication method has emerged for large scale fabrication of such devices.

Previously, we demonstrated a method that has the potential to meet this need: nanopantography. Billions of electrostatic lenses are first fabricated on top of a wafer using conventional semiconductor manufacturing processes. A broad area, collimated, monoenergetic ion beam is then directed towards the wafer surface. By applying an appropriate DC voltage to the lens array with respect to the wafer, the ion beamlets entering each lens converge to a fine spot focused on the wafer surface that can be 100 times smaller than the diameter of the lens. By controlling the tilt of the substrate with respect to the ion beam, the focused ion beamlets can "write" a desired pattern in a massively parallel fashion in selected areas of the substrate.

Nanopantography was previously used to etch ~10 nm-dia. holes in Si, by exposure to a monoenergetic Ar^+ ion beam and Cl_2 gas. Etching of trenches was also demonstrated, with 15 nm resolution. Using the pulsed plasma-pulsed DC bias method developed in the DoE Plasma Science Center for creating monoenergetic ion energy distributions, along with an improved design for creating a high density plasma, and space-charge neutralization without filaments, we were able to extract an ion beam with an extremely monoenergetic IED and achieve a "world-record" resolution of 3 nm in a single spot etched into Si, as shown in Fig. 2. Simulations indicate that sub 1-nm resolution should be possible.

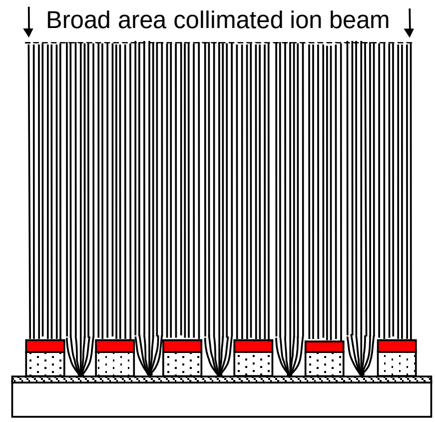


Figure 1 – Schematic of nanopantography method. DC bias is applied between top (red) and bottom (cross hashed) conductor layers with an insulating layer (dotted) between, causing ion beamlets to focus at the bottoms of these electrostatic lenses.

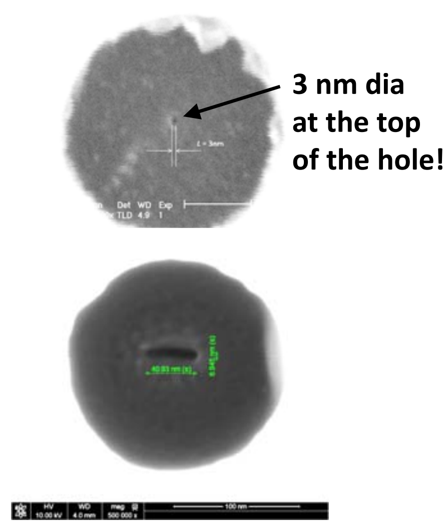
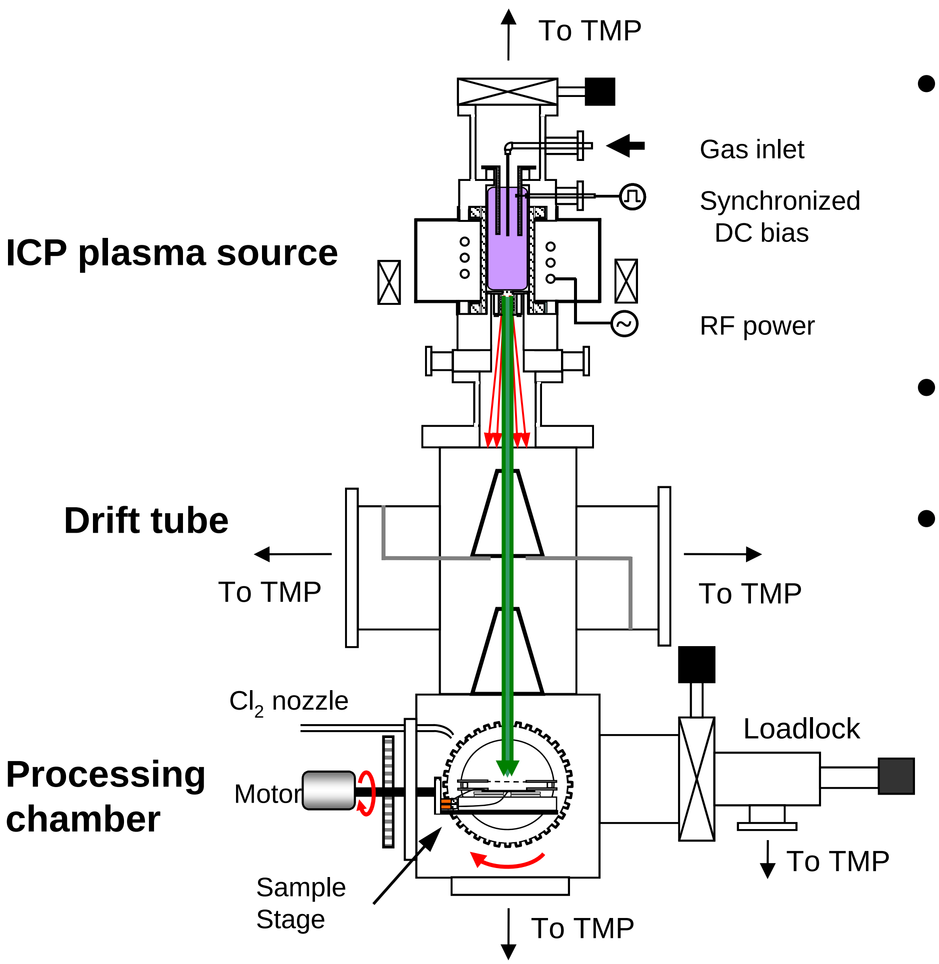


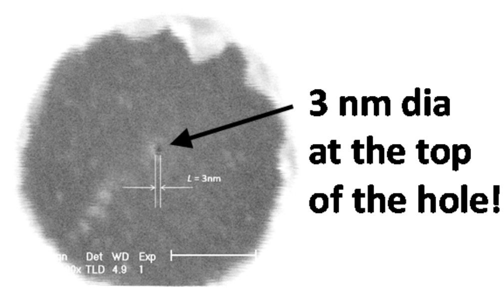
Figure 2 – (top): Hole with 3 nm top dia., and (bottom) trench with 6.9 nm top width etched in Si by nanopantography.

MASSIVELY PARALLEL 3 NM NANO-PATTERNS USING A MONO-ENERGETIC ION BEAM EXTRACTED FROM A PULSED PLASMA



- Experimental setup

- **A pulsed ICP with pulsed DC biased boundary electrode in the afterglow is used here to create space-charged neutralized ion beam with a monoenergetic ion energy distribution.**
- **This ion beam enables the previously reported "nanopantography" method.**
- **Here we use the ion beam to create the smallest pattern ever written (array of 3 nm dia. holes) in a massively parallel manner.**



- 3 nm dia. hole formed in Si.

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