SCALING OF MICROWAVE DISCHARGE DEVICES: PYRAMIDAL STRUCTURES*

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AGENDA

- Introduction of pyramidal microdischarge devices.
- Description of model.
- Fundamental properties of MDs sustained in neon.
- Transition from Townsend to negative glow.
- Scaling of MDs
- Concluding remarks.
MICRODISCHARGE PLASMA SOURCES

- Microdischarges are plasma devices which leverage pd scaling to operate dc atmospheric glows 10s –100s µm in size.
- MEMS fabrication techniques enable innovative structures for displays and detectors.
- Although similar to PDP cells, MDs are dc devices which largely rely on nonequilibrium beam components of the EED.
- Electrostatic nonequilibrium results from their small size. Debye lengths and cathode falls are commensurate with size of devices.

\[
L_{\text{cathodeFall}} = \left( \frac{2V_c \varepsilon_0}{(qn_I)} \right)^{1/2} \approx 10 - 20 \mu m
\]

\[
\lambda_D \approx 750 \left( \frac{T_{eV}}{n_e (cm^{-3})} \right)^{1/2} \quad cm \approx 10 \mu m,
\]

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PYRAMIDAL MICRODISCHARGE DEVICES

- Si MDs with 10s µm pyramidal cavities display nonequilibrium behavior: Townsend to negative glow transitions.
- Small size also implies electrostatic nonequilibrium.

2-D MODELING OF MICRODISCHARGE SOURCES

• Charged particle continuity (fluxes by Sharfetter-Gummel form)
  \[
  \frac{\partial N_i}{\partial t} = -\nabla \cdot \left( qN_i\mu_i(-\nabla \phi) - D_i \nabla N_i \right) + S_i
  \]

• Poisson’s Equation for Electric Potential
  \[
  -\nabla \cdot \varepsilon \nabla \phi = \rho_v + \rho_s
  \]

• Bulk continuum electron energy transport and MCS beam.
  \[
  \frac{\partial (n_e \varepsilon)}{\partial t} = \vec{j} \cdot \vec{E} - n_e \sum_i N_i \kappa_i - \nabla \left( \frac{5}{2} \varepsilon \phi - \lambda \nabla T_e \right), \quad \vec{j} = q \vec{\phi}_e
  \]

• Neutral continuity and energy transport.
  \[
  \frac{\partial N_i}{\partial t} = -\nabla \cdot \left( \vec{v} - D N_o \nabla \left( \frac{N_i}{N_o} \right) \right) + S_i, \quad \frac{\partial (\rho c T)}{\partial t} = -\nabla \cdot \kappa \nabla T + P_g
  \]
DESCRIPTION OF MODEL: MCS AND MESHING

- Transport of energetic secondary electrons is addressed with a Monte Carlo Simulation.

- Superimpose Cartesian MCS mesh on unstructured fluid mesh. Construct Greens functions for interpolation between meshes.

- Electrons and their progeny are followed until slowing into bulk plasma or leaving MCS volume.

- Electron energy distribution is computed on MCS mesh.

- EED produces source functions for electron impact processes which are interpolated to fluid mesh.
MODEL GEOMETRY: Si PYRAMID MICRODISCHARGE

- Investigations of a cylindrically symmetric Si pyramid microdischarge were performed.

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MODEL GEOMETRY: Si PYRAMID MICRODISCHARGE

- Meshing is absolutely critical to resolve small structures and distant boundaries.
- Typical Mesh: 5,000-10,000 nodes, $10^2$-$10^3$ dynamic range
BASE CASE: Ne, 600 Torr, 50 µm DIAMETER

- Optimum operation produces large enough charge density to warp electric potential into cathode well.

- Inspite of large $T_e$, ionization is dominated by beam electrons

- Ne, 600 Torr, 50 µm, 200 V, 1 MΩ
BASE CASE: Ne, 600 Torr 50 µm DIAMETER

- There is essentially no region of quasi-neutrality or which is positive column-like.
- Monomer and dimer ions are segregated.
- Excited state densities > $10^{15}$ cm$^{-3}$ rival macroscopic devices

- Ne, 600 Torr, 50 µm, 200 V, 1 MΩ

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TRANSITION TO NEGATIVE-GLOW BEHAVIOR

- Although geometry precludes true hollow cathode behavior, negative glow behavior sets in at lower pressures.
- Characterize negative glow by \( \frac{S[\text{Ne}^2^+]}{(S[\text{Ne}^+] + S[\text{Ne}^2^+] )} \)

- Ne, 50 µm diameter, 200 V, 1 MΩ
SCALING WITH PRESSURE: PASCHEN BEHAVIOR

- With $pd=1-10$ Torr-cm, these microdischarge devices display Paschen behavior.

- Although sensitive to ballasting and current density, lower pressures requiring larger applied voltages also produce large plasma densities.

- Ne, 50 $\mu$m diameter, 1 M$\Omega$
SCALING WITH PRESSURE: PLASMA PROPERTIES

- Over a range of pressures that V(applied) and R(ballast) can be constant, confinement at higher pressures produces higher peak plasma densities.

- $[e] \times 10^{12} \text{ cm}^{-3}$

- 550 Torr
  - $[2.1 \times 10^{13} \text{ cm}^{-3}]$

- 650 Torr
  - $[3.9 \times 10^{13} \text{ cm}^{-3}]$

- 750 Torr
  - $[5.6 \times 10^{13} \text{ cm}^{-3}]$

- Ne, 50 µm diameter, 200V, 1 MΩ

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SCALING CONSIDERATIONS: CATHODE FALL THICKNESS

- In MDs, the cathode fall thickness may be commensurate with cavity size. Current density is therefore critical to scaling.

• -210 V, 1 MΩ
  \[ [e] = 4.9 \times 10^{13} \text{ cm}^{-3} \]

• -200 V, 1.75 MΩ
  \[ [e] = 5.3 \times 10^{12} \text{ cm}^{-3} \]

- Low j (and \([e]\)) may result in cathode fall not being conformal to cathode.

- Ne, 50 μm diameter, 600 Torr
SCALING WITH SIZE: \( pd, \) BALLAST = CONSTANT

- Scaling while maintaining \( pd, V(\text{applied}) \) and \( R(\text{ballast}) \) constant results in a reduced \( j \) and \( [e] \) in the larger device. The plasma is not conformal to the cathode.

\[ [e] \text{ (Max} = 1.7 \times 10^{14} \text{ cm}^{-3}) \]

\[ [e] \text{ (Max} = 3.3 \times 10^{12} \text{ cm}^{-3}) \]

- Ne, -200 V, 1 M\( \Omega \)
SCALING WITH SIZE: pd, j = CONSTANT

- Scaling while maintaining pd and j constant produces similar plasma densities and conformality to the cathode.

- 400 Torr
- 600 Torr
- 1000 Torr

- Ne, -200 V

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CONCLUDING REMARKS

• MDs differ from macroscopic devices in that plasma scale lengths are commensurate with device dimensions.

• Scaling of MDs with pressure (traditionally “pd”) likely also required $\lambda/L$ to remain constant or less than a critical value.

• Scaling with complex shapes must consider all dimensions.

• The transition from Townsend to negative glow is largely geometrically dependent, and can be controlled to some degree by shape.