

CAPACITIVE DISCHARGES DRIVEN BY COMBINED DC/RF SOURCES

Emi Kawamura, M.A. Lieberman, and A.J. Lichtenberg

**Department of Electrical Engineering and Computer Sciences
University of California
Berkeley, CA 94720**

E.A. Hudson

**Lam Research Corporation
Fremont, CA 94538**

Download this talk:

<http://www.eecs.berkeley.edu/~lieber>

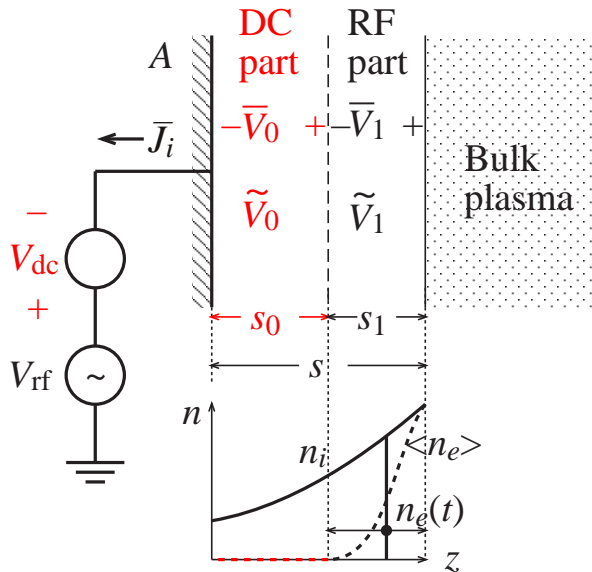
MOTIVATIONS FOR ADDING DC SOURCE

- “Tune” discharge particle and energy balance
($\Rightarrow T_e \downarrow, n_e \uparrow$, radial uniformity)
- “Tune” secondary electron bombardment of substrate
(etch selectivities, charging damage)

OUTLINE

- Structure of DC/RF sheaths — theory
- Equal area diode discharges — theory and 1D PIC simulations
- Asymmetric diode discharges — theory and 1D PIC simulations
- Secondary electrons — timescales and energy deposition
- Triode discharges — theory and 2D PIC simulations

STRUCTURE OF A DC/RF SHEATH



$$\text{DC voltage } \bar{V} = \bar{V}_0 + \bar{V}_1$$

$$\text{RF voltage } \tilde{V} = \tilde{V}_0 + \tilde{V}_1$$

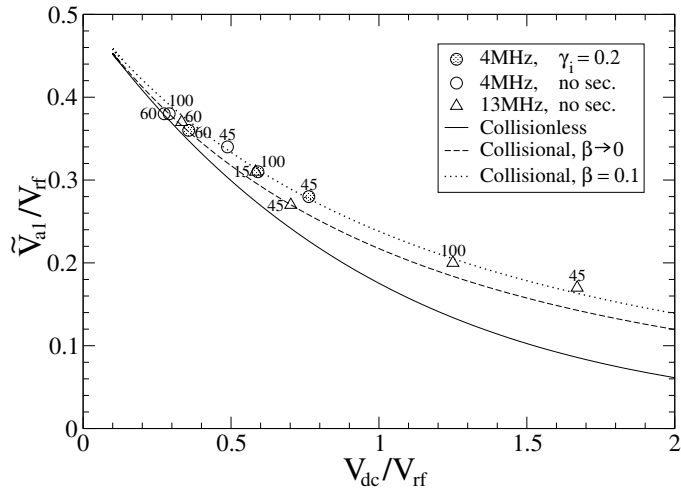
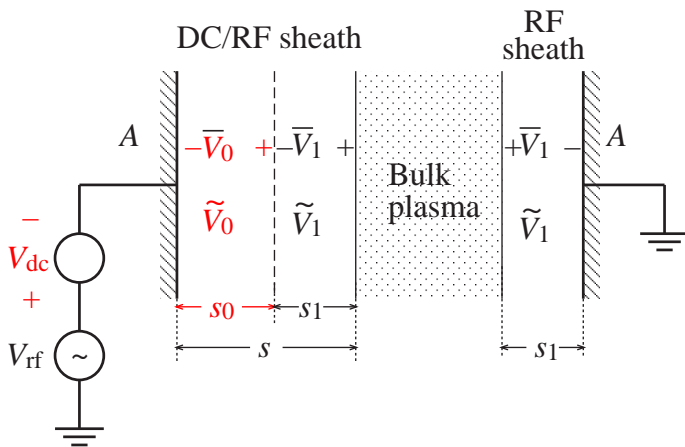
- New result for Child law for collisionless ions:

$$\bar{J}_i = \frac{4}{9} \epsilon_0 \left(\frac{2e}{M} \right)^{1/2} \frac{(\bar{V}^{1/2} - \frac{1}{3} \bar{V}_1^{1/2})(\bar{V}^{1/2} + \frac{2}{3} \bar{V}_1^{1/2})^2}{s^2}$$

- New result for Child law for collisional ion sheath also obtained

EQUAL AREA DIODE DISCHARGE

- Comparison of theory with 1D particle-in-cell (PIC) simulations

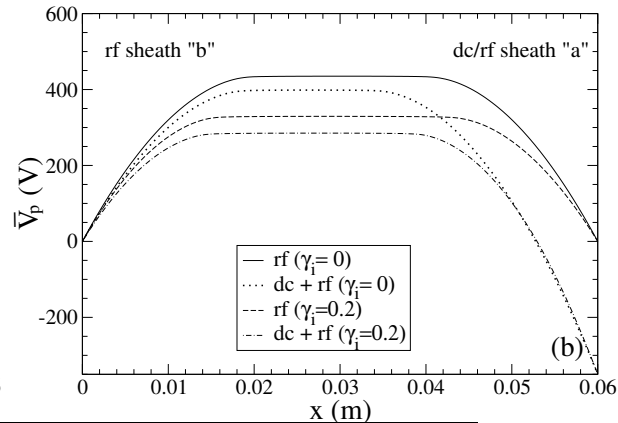
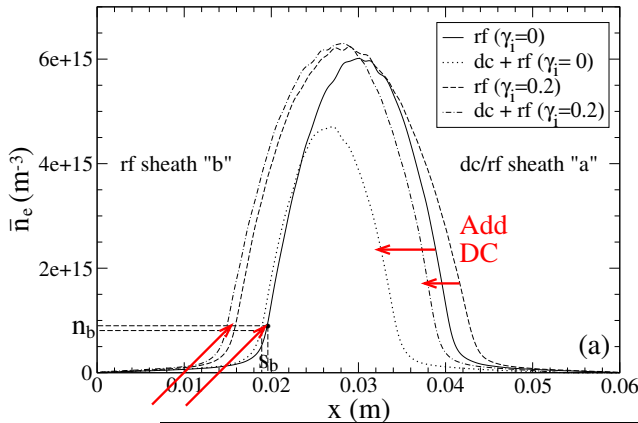


(Symbols: PIC with argon pressure in mTorr;
 lines: theory; $\beta \propto \lambda_D/\lambda_i =$ collisionality;
 $\gamma_i =$ secondary emission coefficient)

- Excellent agreement of PIC with collisional Child law

DENSITY AND VOLTAGE AT CONSTANT P_{rf}

(60 mTorr, 6 cm gap, 4 MHz, 0.017 W/cm^2 , $V_{dc} = 350 \text{ V}$)



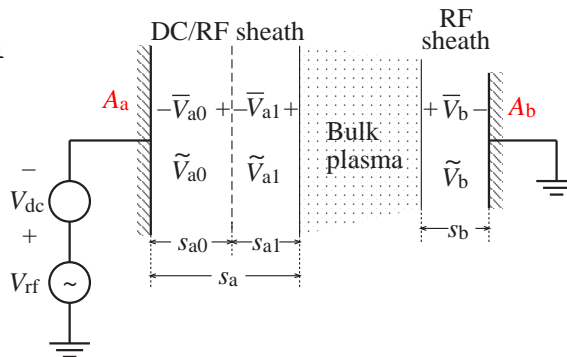
	γ_i	V_{rf} (V)	\bar{V}_b (V)	\mathcal{E}_{ceff} (V)
Rf only	0	1064	436	64
Dc+rf	0	1277	398	60
Rf only	0.2	805	330	53
Dc+rf	0.2	980	283	46

(\bar{V}_b = plasma potential; \mathcal{E}_{ceff} = collisional energy loss/electron-ion pair)

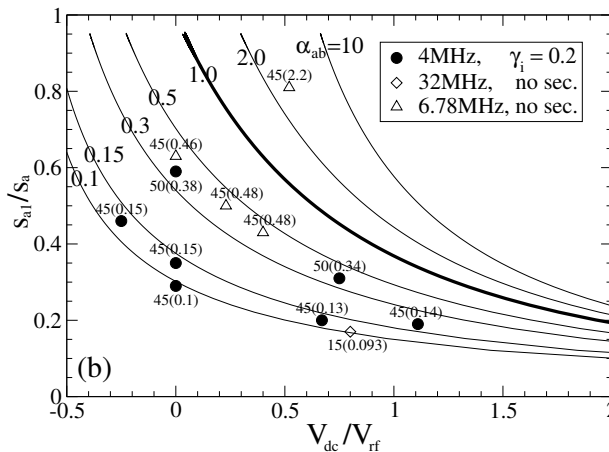
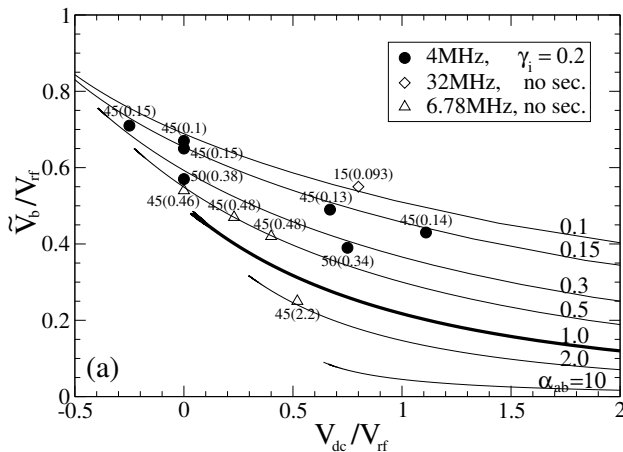
- Plasma potential \bar{V}_b and sheath width s_b independent of V_{dc}
- Secondary electrons increase discharge efficiency
- V_{dc} reduces bulk plasma thickness

ASYMMETRIC DIODE RESULTS

- Excellent agreement between 1D (cylindrical) PIC and collisional CL theory



- Introduce rf voltage asymmetry ratio $\alpha_{ab} = \tilde{V}_{a1}/\tilde{V}_b$



Numbers near each symbol: mTorr (α_{ab})

SECONDARY ELECTRON LOSS PROCESSES

- Surface losses to substrate and walls:
 - Transit time across gap $\tau_{\text{fr}} = d/v_h$ at low pressures
 - Diffusion time $\tau_{\text{diff}} = d^2/2D_h$ at higher pressures ($D_h = \lambda_h \bar{v}_h/3$)
 - Trapping time $\tau_{\text{trap}} = \delta/f$ (favorable configuration of rf voltages can trap secondaries for a fraction δ of the rf period $1/f$)

$$\tau_{\text{lh}} = (\tau_{\text{fr}}^2 + \tau_{\text{diff}}^2 + \tau_{\text{trap}}^2)^{1/2} = \nu_{\text{lh}}^{-1}$$

- Volume losses: secondary electrons lose energy and join the thermal population

$$\tau_{\text{izh}}^* = \frac{\mathcal{E}_h}{\nu_{\text{izh}} \mathcal{E}_{\text{ch}}}$$

(\mathcal{E}_h , ν_{izh} are secondary energy and ionization frequency;

$\mathcal{E}_{\text{ch}} \approx 20$ V is secondary collisional energy loss/e-i pair created)

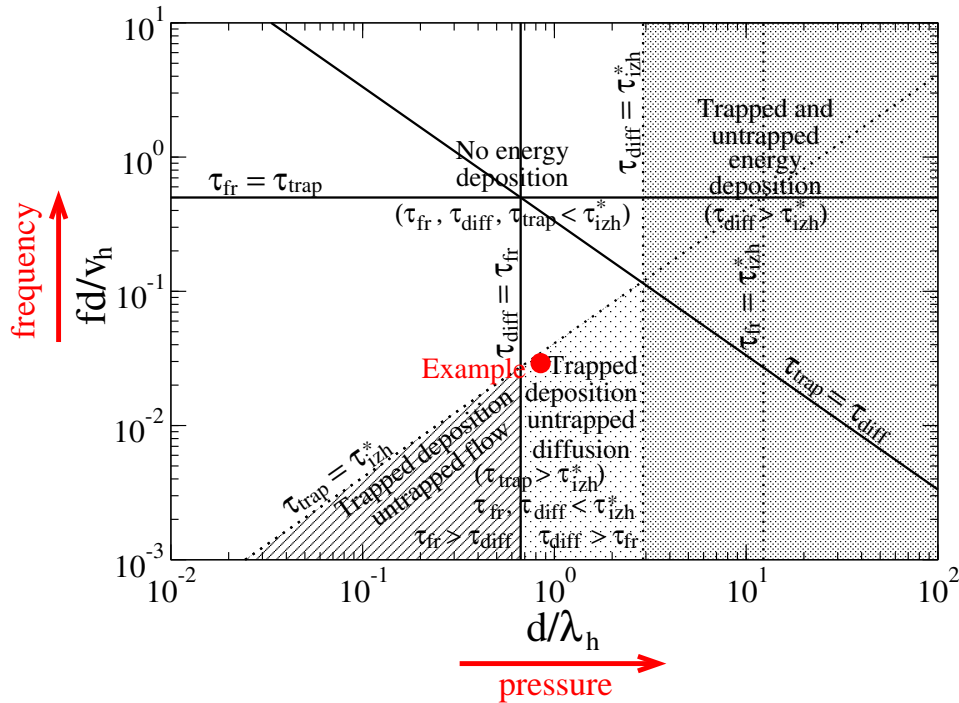
- Total loss frequency is $\nu_h = \nu_{\text{lh}} + \nu_{\text{izh}}^*$

If $\nu_{\text{izh}}^* \gg \nu_{\text{lh}}$, secondary electrons efficiently produce e-i pairs

If $\nu_{\text{lh}} \gg \nu_{\text{izh}}^*$, secondary electrons efficiently bombard the substrate

ENERGY DEPOSITION REGIONS

$$\epsilon_h = 70 \text{ V}, \delta = 0.5$$

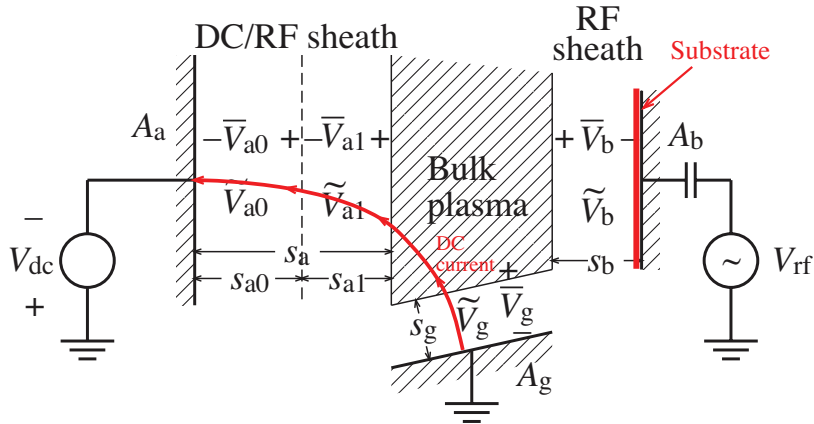


- Most interesting regions are where trapped and untrapped electrons behave differently

TRIODE DC/RF DISCHARGE

- Substrate can have a dielectric layer which cannot draw dc current

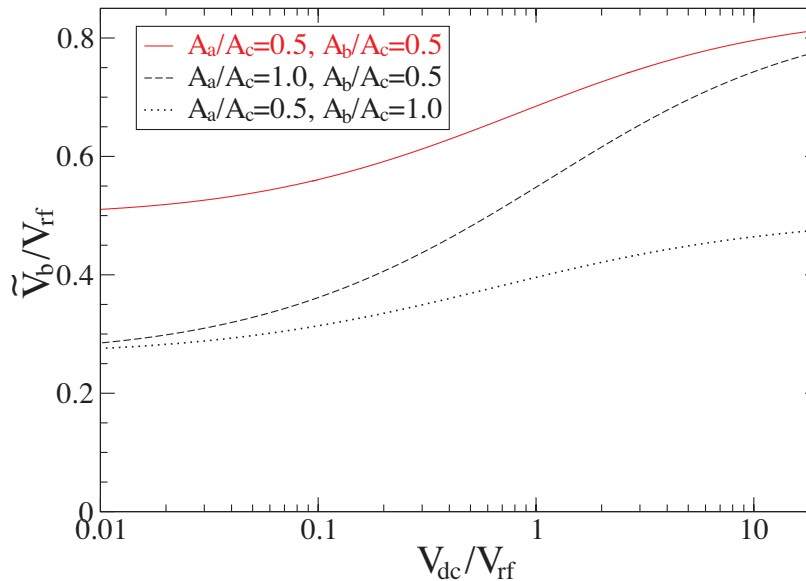
A triode configuration is necessary



- A global model incorporating the collisional dc/rf sheath is used to determine the voltages, currents, and sheath widths

TRIODE RF PLASMA POTENTIAL \tilde{V}_b VERSUS V_{dc}

- Collisional theory results for triode



- Example (red solid line):

DC electrode area = ground electrode area = $\frac{1}{2} \times$ RF electrode area

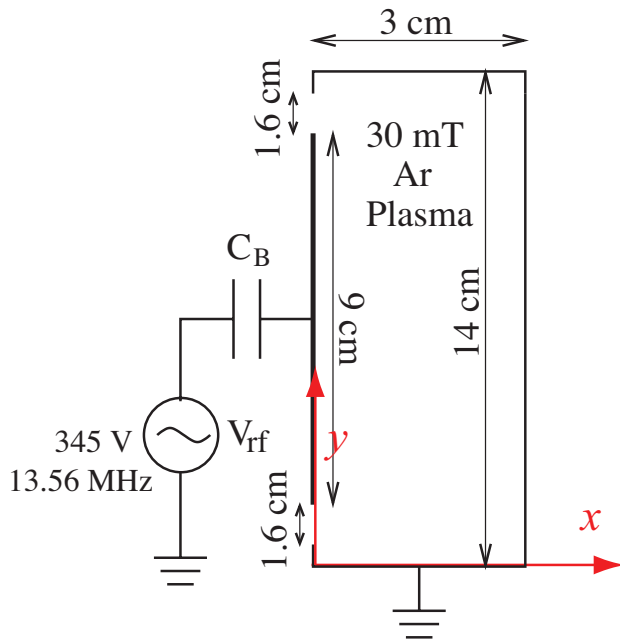
For $V_{dc} \rightarrow 0$, equal area diode and $\tilde{V}_b/V_{rf} = 0.5$

For $V_{dc} \rightarrow \infty$, asymmetric diode and $\tilde{V}_b/V_{rf} = 0.86$.

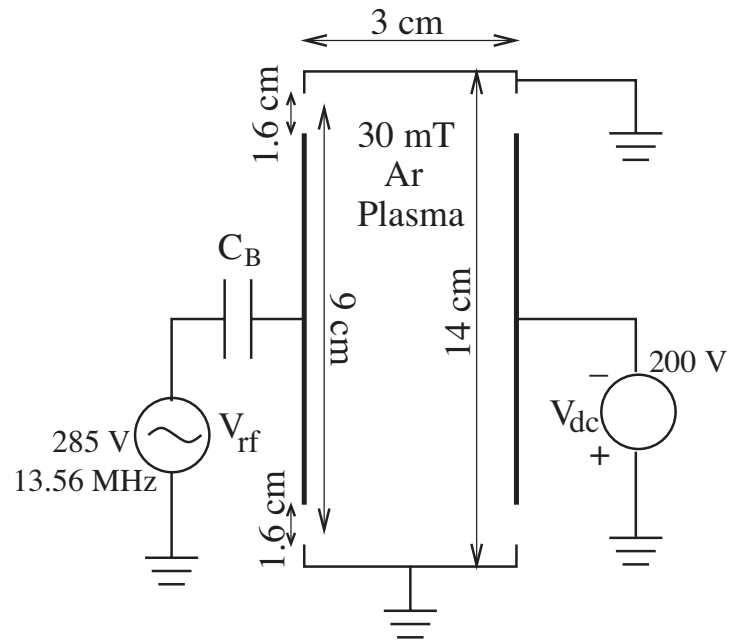
2D PIC SIMULATION BASE CASE

- $p = 30$ mTorr, $P_{\text{rf}} = 2.2$ W, $\gamma_i = 0.2$ at all surfaces
- Secondaries in “trapped deposition, untrapped diffusion” regime

RF only



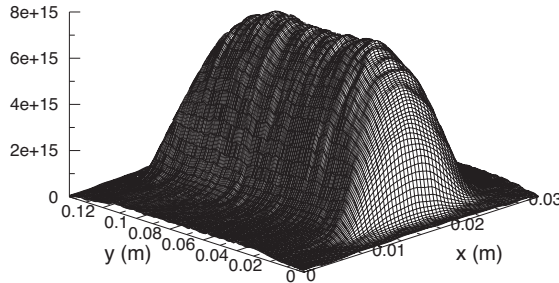
DC/RF triode



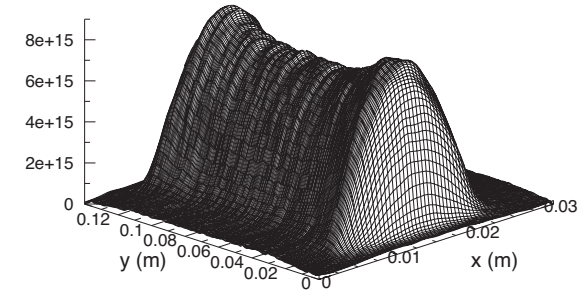
UNIFORMITY IS MODIFIED BY V_{dc}

Rf only

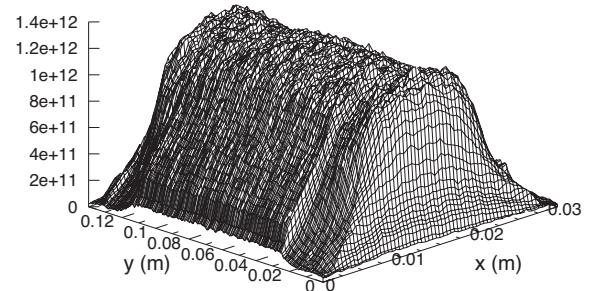
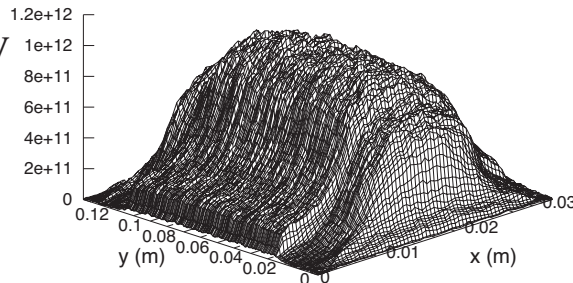
Plasma density (m^{-3})



Dc/rf



Secondary density (m^{-3})



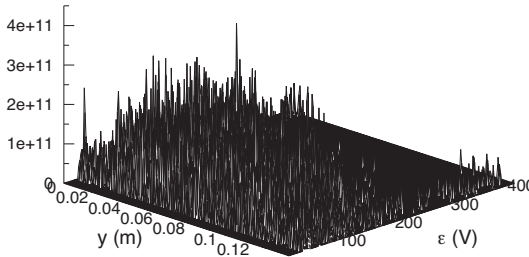
- Thinner bulk plasma near midplane ($y = 0.06$ m) for DC/RF case

\Rightarrow center-low plasma density profile

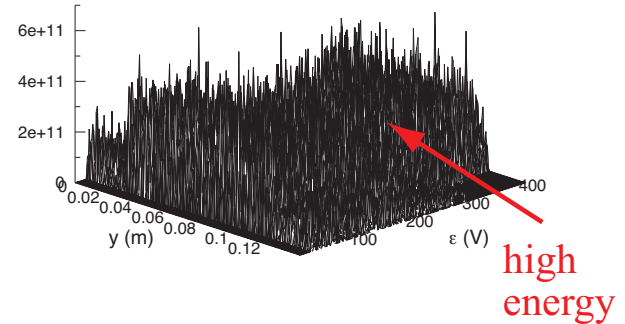
BALLISTIC SECONDARY ELECTRONS CREATED BY V_{dc}

Rf only

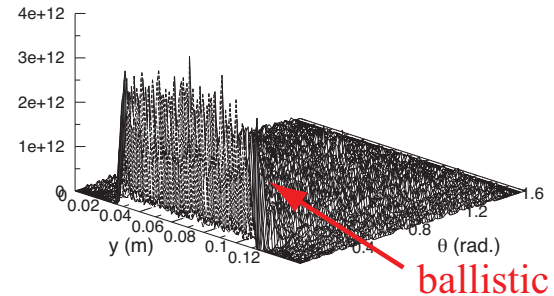
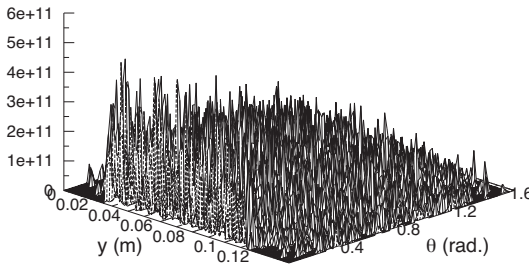
Secondary energy distribution (arb units)



Dc/rf



Secondary angular distribution (arb units)



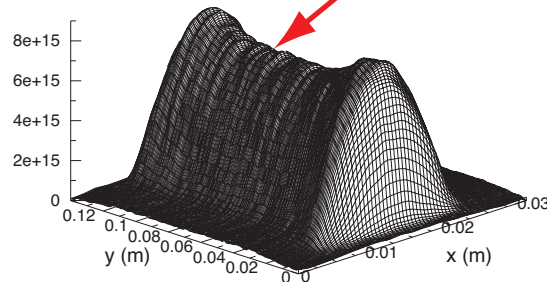
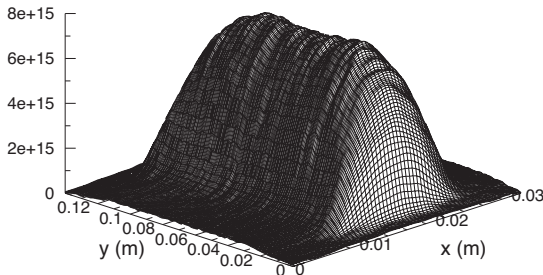
- Secondary electrons are ballistic and have high energies for DC/RF case

PLASMA DENSITY PROFILES VERSUS PRESSURE

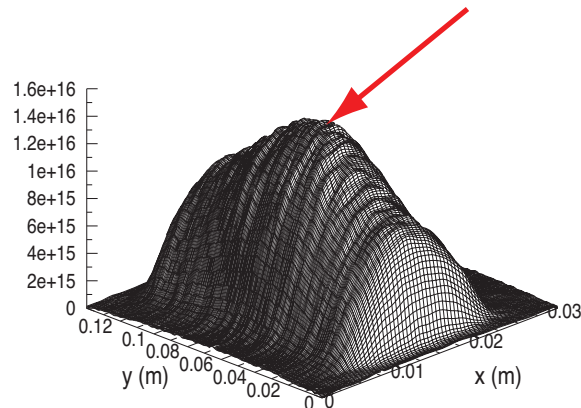
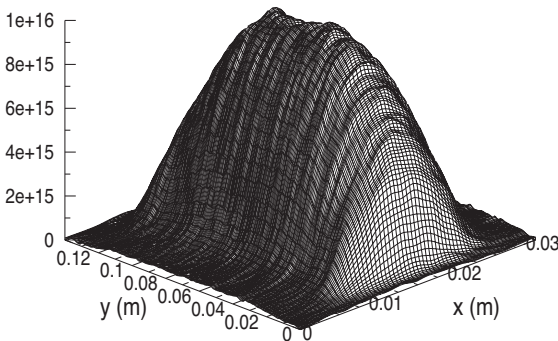
Rf only

Dc/rf

30 mTorr



45 mTorr



- Effects of V_{dc} on profile:
Thinner bulk plasma \Rightarrow center-low profile
Increased secondary ionization \Rightarrow center-high profile

CONCLUSIONS

- Collisionless and collisional DC/RF Child laws determined
- DC voltage can control the discharge asymmetry
- DC voltage increases secondary electron ionization
- DC voltage reduces bulk plasma thickness
- DC voltage promotes the formation of ballistic electrons
- DC voltage modifies the plasma density profile

Download this talk:

<http://www.eecs.berkeley.edu/~lieber>

Ref: E. Kawamura, M.A. Lieberman, and A.J. Lichtenberg, “Capacitive Discharges Driven by Combined DC/RF Sources”, *J. Vac. Sci. Technol. A*, **25**, 1456–74, Sept. 2007