SUPPRESSION OF STANDING WAVES IN HIGH FREQUENCY CAPACITIVE REACTORS

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OUTLINE OF TALK

- Introduction to high frequency/dual frequency capacitive discharges
- Standing wave and skin effects for high frequency
- Transmission line model for high frequency standing waves
- Suppression of standing wave effects

INTRODUCTION

WHY DUAL FREQUENCY CAPACITIVE DISCHARGE?

- Motivation for capacitive discharge
  - $\Longrightarrow$ Low cost
  - $\Longrightarrow$ Robust uniformity over large area
  - $\Longrightarrow$ Control of dissociation (fluorine)
- Motivation for dual frequency
  - $\Longrightarrow$ Independent control of ion flux and ion energy
  - $\Longrightarrow$ High frequency voltage controls ion flux
  - $\Longrightarrow$ Low frequency voltage controls ion energy
- A critical application for dielectric etch

TYPICAL OPERATING CONDITIONS

- $R \sim 15$–30 cm, $L \sim 1$–3 cm
- $p \sim 30$–300 mTorr, $C_4F_8/O_2/Ar$ feedstock
- High frequency $f_{\mathrm{rf}} \sim 27.1$–$160$ MHz, $V_{\mathrm{rf}} \sim 250$–1000 V
- Low frequency $f_B \sim 2$–13.56 MHz, $V_B \sim 500$–2000 V
- Absorbed powers $P_{\mathrm{rf}},\ P_B \sim 500$–$3000$ W

INDEPENDENT CONTROL

- Condition for independent control of ion flux and energy

$$\frac{\omega_{\mathrm{rf}}^2}{\omega_B^2} \gg \frac{V_B}{V_{\mathrm{rf}}} \gg 1$$

  (M.A. Lieberman, Jisoo Kim, J-P Booth, J-M Rax and M.M. Turner, SEMICON Korea Etching Symposium, p. 23, 2003)

- Effective frequency concept to describe transition
  (H.C. Kim, J.K. Lee, J.W. Shon, N. Yu. Babaeva, and O. Manuilenko, POSTECH, 2003)

ELECTROMAGNETIC EFFECTS FOR HIGH FREQUENCY

M.A. Lieberman, J.P. Booth, P. Chabert, J.M. Rax, and M.M. Turner

Plasma Sources Sci. Technol. **11**, 283–293 (2002)

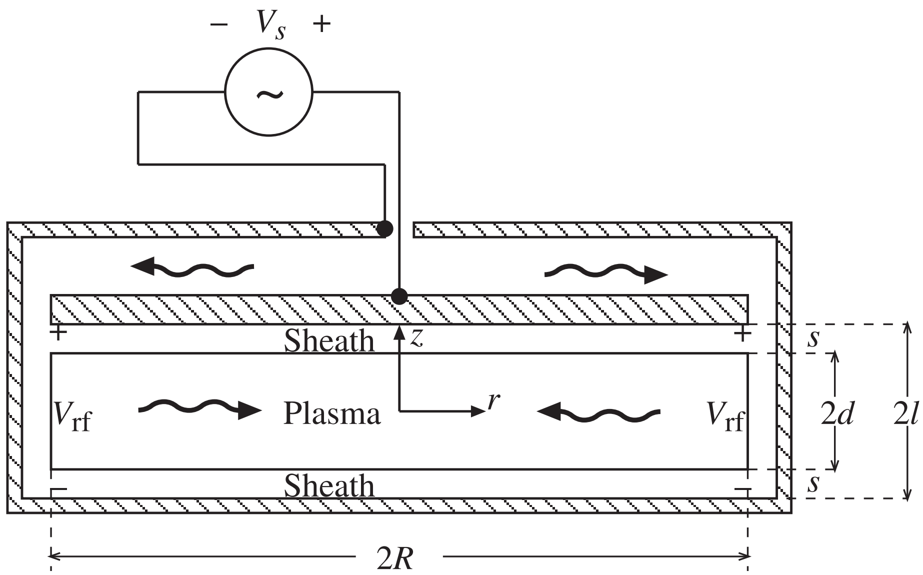
ELECTROMAGNETIC EFFECTS

- High frequency and large area $\Rightarrow$ $\boxed{\text{standing wave effects}}$
- High frequency $\Rightarrow$ high density $\Rightarrow$ $\boxed{\text{skin effects}}$
- Previous studies of capacitive discharges mostly based on electrostatics, not full set of Maxwell equations

$$\Longrightarrow \text{no standing wave or skin effects}$$

CYLINDRICAL CAPACITIVE DISCHARGE

Consider only the high frequency source



Fields cannot pass through metal plates

(1) V_s excites radially outward wave in top vacuum gap
(2) Outward wave excites radially inward wave in plasma

BASIC PHYSICS

- Plasma is (weakly) lossy dielectric slab

$$\kappa_p = 1 - \frac{\omega_p^2}{\omega(\omega - j\nu_m)}$$

where

$\omega_p = (e^2 n_e/\epsilon_0 m)^{1/2}$ = plasma frequency

ν_m = electron-neutral collision frequency

- TM modes with $H_\phi \sim \mathrm{e}^{j\omega t}$
- Maxwell's equations

$$\frac{\partial H_\phi}{\partial z} = -j\omega\epsilon_0\kappa_p E_r \qquad \text{(inductive field)}$$

$$\frac{1}{r}\frac{\partial(rH_\phi)}{\partial r} = j\omega\epsilon_0\kappa_p E_z \qquad \text{(capacitive field)}$$

$$\frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} = -j\omega\mu_0 H_\phi$$

- Choose uniform density n_e and sheath width s (arbitrary choice!)
- Solve with appropriate boundary conditions

FIELD SOLUTIONS IN PLASMA

$$E_r = -\frac{A\alpha_p \cosh \alpha_0 s}{j\omega\epsilon_0\kappa_p}\left(\sinh \alpha_p z\, \mathrm{J}_1(kr) + \sum_{q=1}^{\infty} C_q \sin k_q z\, \mathrm{I}_1(\alpha_q r)\right)$$

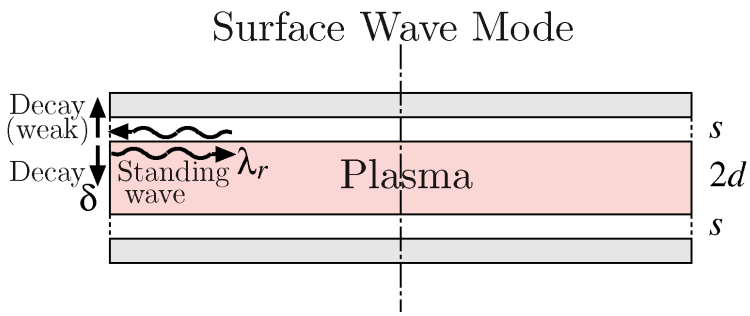
$$H_\phi = A\cosh \alpha_0 s\left(\cosh \alpha_p z\, \mathrm{J}_1(kr) - \sum_{q=1}^{\infty} C_q \frac{\alpha_p}{k_q} \cos k_q z\, \mathrm{I}_1(\alpha_q r)\right)$$

$$E_z = \frac{Ak \cosh \alpha_0 s}{j\omega\epsilon_0\kappa_p}\left(\cosh \alpha_p z\, \mathrm{J}_0(kr) - \sum_{q=1}^{\infty} C_q \frac{\alpha_p}{k}\frac{\alpha_q}{k_q} \cos k_q z\, \mathrm{I}_0(\alpha_q r)\right)$$

- First terms represent standing surface wave in the radial direction (k is radial wavenumber and α_p is axial decay constant)
- Second terms represent radially evanescent waves (C_q, $q = 1, 2, \ldots$ are amplitudes, k_q are axial wavenumbers, α_q are radial decay constants)
- Similar field solutions in sheath regions

SURFACE WAVE MODE

- Power enters the plasma via a *surface wave mode:*



- Radial wavelength for surface wave (low density limit):

$$\lambda_r \approx \frac{\lambda_0}{\sqrt{1 + d/s}} \sim \frac{\lambda_0}{3}$$

with $\lambda_0 = c/f$ the free space wavelength

- Axial skin depth for surface wave:

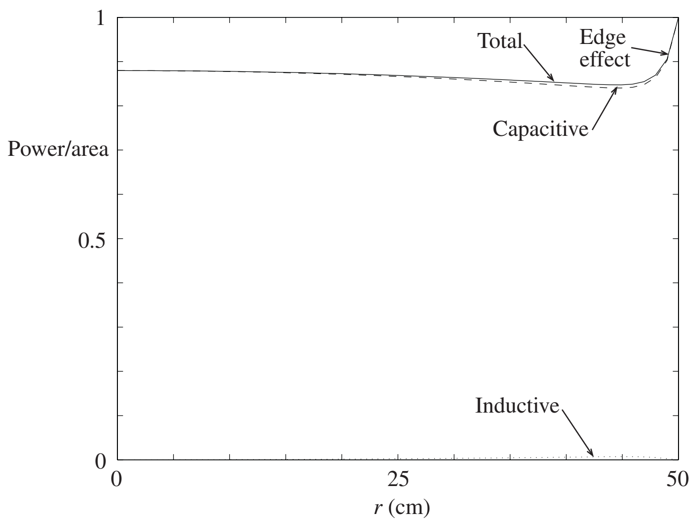
$$\delta \sim \frac{c}{\omega_p}$$

- There are also *evanescent modes* leading to edge effects near $r = R$

POWER DEPOSITION VERSUS RADIUS AT 13.56 MHz

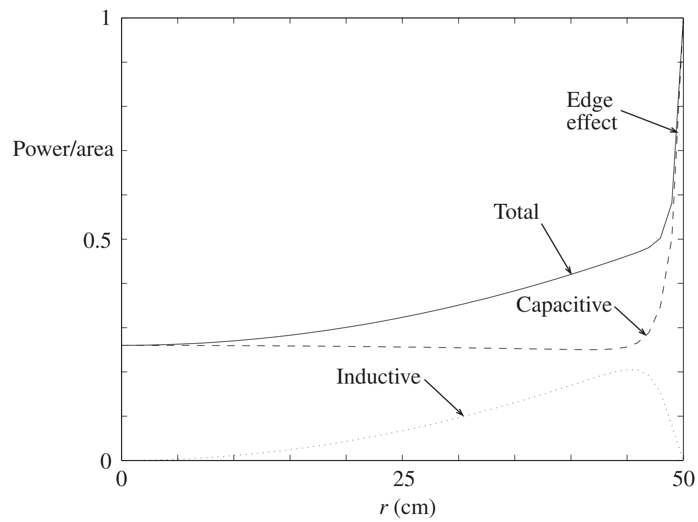
- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm ($\lambda_r \approx 9$–10 m)
- $P_{\rm cap}$ (dash), $P_{\rm ind}$ (dot) and $P_{\rm tot}$ (solid) as a function of r

$n_e = 10^9$ cm^{-3}
$\delta = 16.7$ cm



Small standing wave and skin effects

$n_e = 10^{10}$ cm^{-3}
$\delta = 5.3$ cm

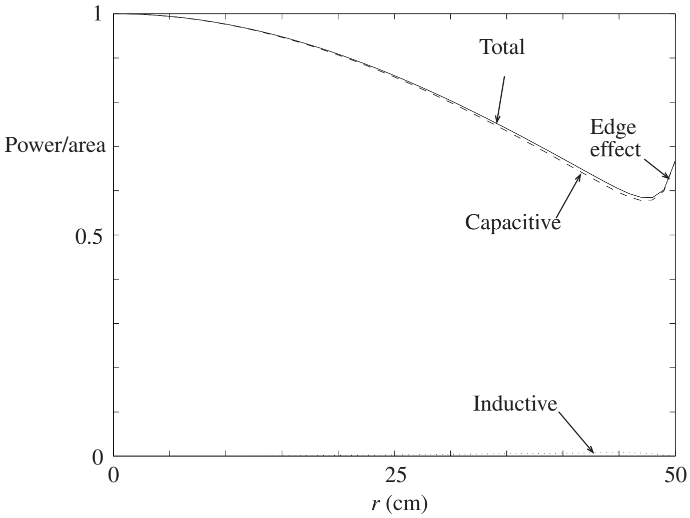


Large skin effect

POWER DEPOSITION VERSUS RADIUS AT 40.7 MHz

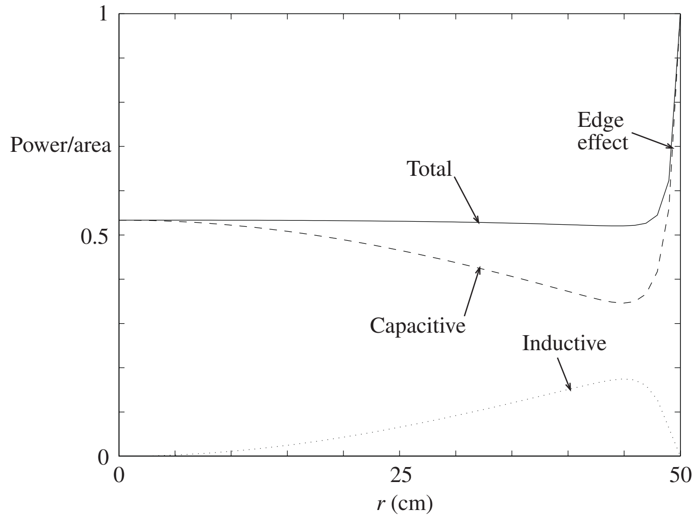
- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm ($\lambda_r \approx 3$ m)
- $P_{\rm cap}$ (dash), $P_{\rm ind}$ (dot) and $P_{\rm tot}$ (solid) as a function of r

$n_e = 10^9$ cm^{-3}
$\delta = 15.9$ cm



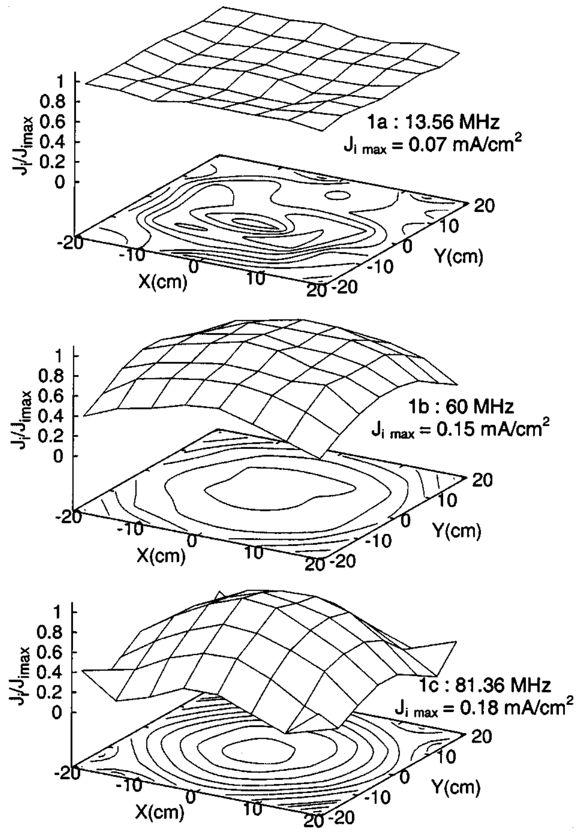
Large standing wave effect

$n_e = 7{\times}10^9$ cm^{-3}
$\delta = 6.3$ cm



Standing wave and skin effects cancel

EXPERIMENTAL RESULTS FOR STANDING WAVES



20×20 cm discharge
$p = 150$ mTorr
50 W rf power

The standing wave effect is seen at 60 MHz and is more pronounced at 81.36 MHz

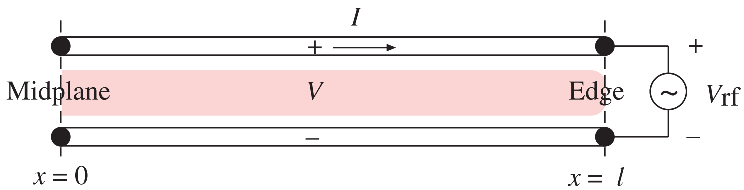
(A. Perret, P. Chabert, J-P Booth, J. Jolly, J. Guillon and Ph. Auvray, Appl. Phys. Lett. vol. 83, p. 243, 2003)

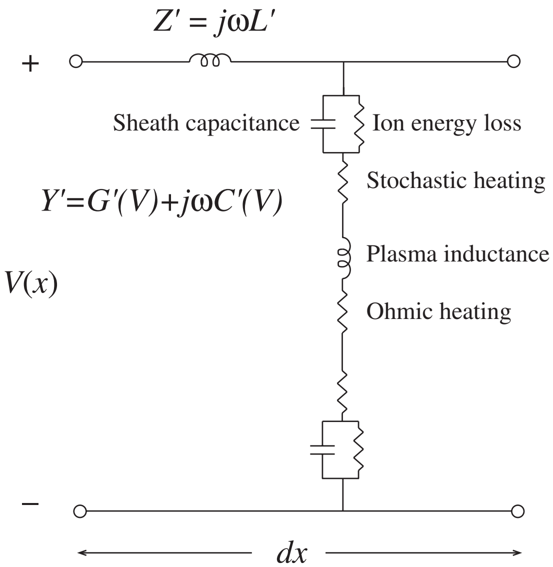
SELF-CONSISTENT STANDING WAVE MODEL

P. Chabert, J.L. Raimbault, J-M Rax and M.A. Lieberman,
to appear in Physics of Plasmas, 2004

TRANSMISSION LINE MODEL

- Parallel plane transmission line model with local (in x) particle and energy balance to determine density $n_e(x)$ and sheath width $s_m(x)$





- Transmission line admittance per unit length, Y', is a function of the voltage $V(x)$ on the line through electron power balance

$$V \Rightarrow \text{electric fields} \Rightarrow n_e \Rightarrow \kappa_p,\, s_m \Rightarrow Y'(V)$$

TRANSMISSION LINE EQUATIONS

- Transmission line equations are nonlinear:

$$\frac{dV}{dx} = -Z' I$$
$$\frac{dI}{dx} = -Y'(|V|)\, V$$

- Small losses ($G' << \omega C'$) $\Longrightarrow$ Hamiltonian form

$$H(I', V) = \frac{1}{2}\omega L' I'^2 + \int_0^V \omega C'(V') V'\, dV'$$

with $I' = -jI$ = "canonical momentum", V = "canonical coordinate", x = "time", and Hamilton's equations

$$\frac{dV}{dx} = \frac{\partial H}{\partial I'}$$
$$\frac{dI'}{dx} = -\frac{\partial H}{\partial V}$$

- Hamiltonian $\Longrightarrow$ dependence of the standing wave wavelength λ on the voltage, frequency, and gap length

SCALING OF WAVELENGTH WITH REACTOR PARAMETERS

- Most important nonlinearity in C' = sheath variation with voltage
- Example of collisionless sheath with stochastic heating

$$\Rightarrow C'(V) \propto V^{-1/4}$$

- Hamiltonian has the form

$$H_0 = \frac{1}{2}X'I'^2 + \frac{4}{7}aV^{7/4} = \frac{4}{7}aV_{\rm rf}^{7/4}$$

- Solving for I'

$$I'(V) = \frac{8a}{7X'}\left(V_{\rm rf}^{7/4} - V^{7/4}\right)$$

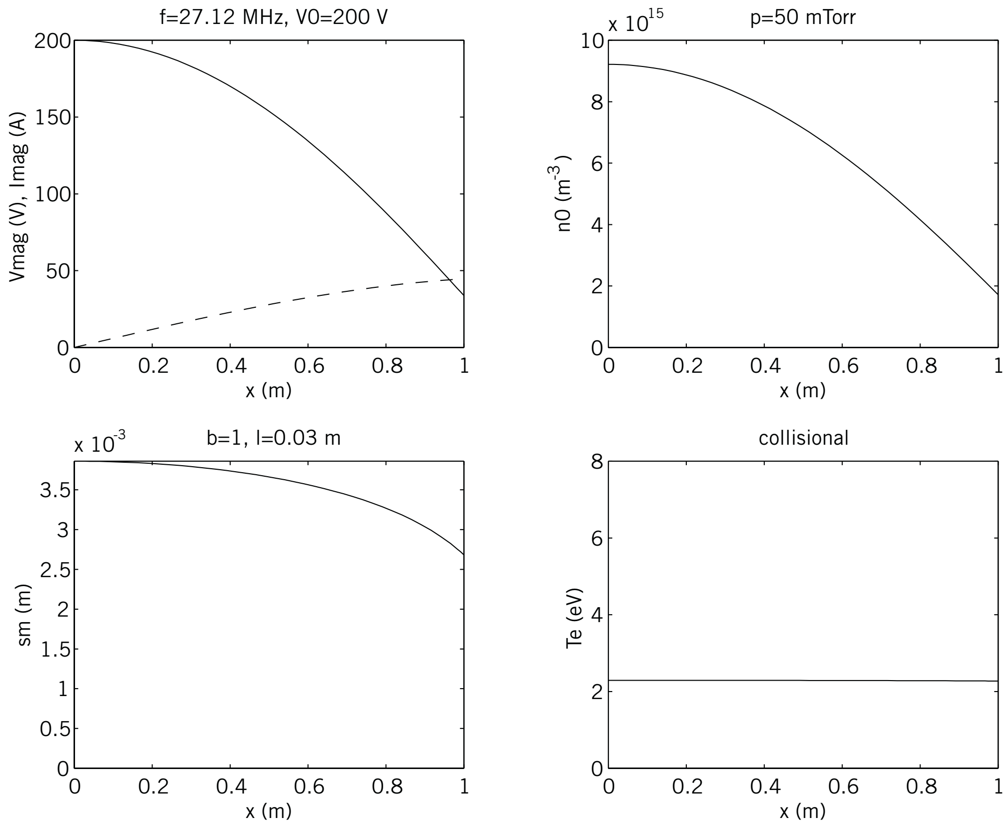
- Integrate TL equation from $V = V_{\rm rf}$ at $x = 0$ to $V = 0$ at $x = \lambda/4$

$$\frac{\lambda}{4} = \frac{1}{X'}\int_0^{V_{\rm rf}} \frac{dV'}{I'(V')}$$

- We find

$$\boxed{\lambda \propto \frac{V_{\rm rf}^{1/8}}{\omega^{3/2}\, l^{1/2}}}$$

TRANSMISSION LINE MODEL RESULTS



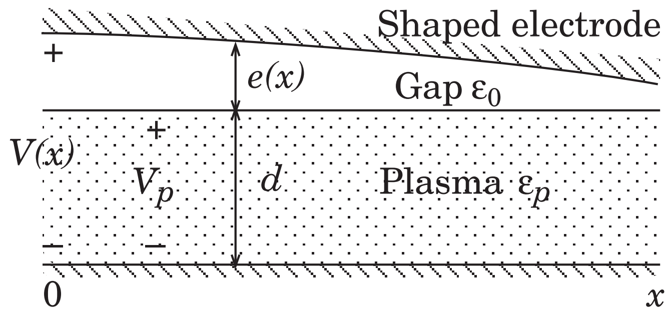
SHAPED ELECTRODE TO SUPPRESS STANDING WAVE EFFECTS

L. Sansonnens and J. Schmitt, *Appl. Phys. Lett.* **82**, 182, 2003

P. Chabert, J.-L. Raimbault, J.-M. Rax, and A. Perret,
to appear in *Appl. Phys. Lett.*, 2004

TRANSMISSION LINE WITH SHAPED ELECTRODE

- Transmission line consisting of plasma and variable gap $e(x)$



- Transmission line equations are

$$\frac{dV}{dx} = -Z'I; \qquad \frac{dI}{dx} = -Y'V$$

with

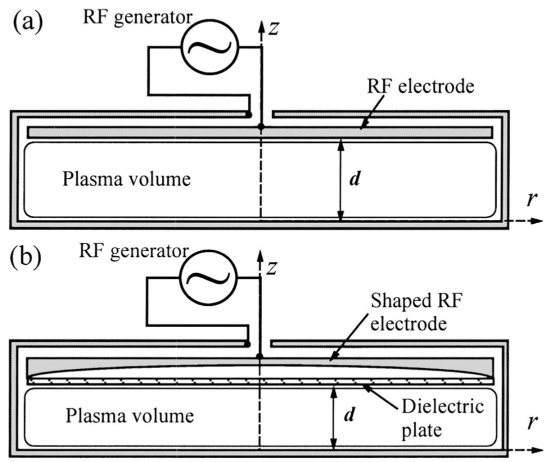
$$Z' = j\omega\mu_0 \frac{d+e}{w}; \qquad \frac{1}{Y'} = \frac{d}{j\omega\epsilon_p w} + \frac{e}{j\omega\epsilon_0 w}$$

$$V = V_p\left(1 + \frac{e\epsilon_p}{d\epsilon_0}\right)$$

- Substitute into TL equations to find an equation for V_p
- Set $dV_p/dx \equiv 0 \Longrightarrow$ equation for $e(x)$

SUPPRESSING STANDING WAVE EFFECTS

- Solution is Gaussian shape
$$e(x) = A\mathrm{e}^{-\frac{1}{2}k_0^2x^2} - B$$
with $k_0 = \omega/c = 2\pi/\lambda_0$
- Shaped electrode (and diel plate) eliminate standing wave effects



- Increased overall thickness in center compared to edge keeps voltage across discharge section constant
- The electrode shape is *independent* of the plasma properties

CONCLUSIONS

- Capacitive reactors with one high frequency drive are good candidates for next-generation etching

- Electromagnetic theory reveals reactor nonuniformities due to standing wave, skin, and edge effects

- Self-consistent transmission line models determine the plasma nonuniformity

- Standing wave effects can be suppressed using a Gaussian-shaped electrode