

RECENT PROGRESS ON THE PHYSICS OF CAPACITIVE DISCHARGES

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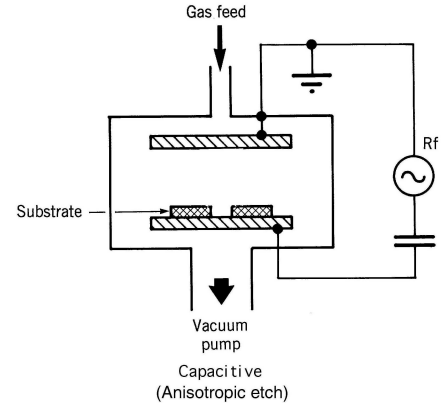
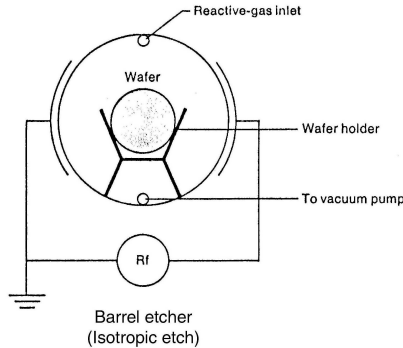
OUTLINE

- Dual frequency capacitive discharges
 - Stochastic heating
- Ion/neutral energy distributions on the substrate surface
- Dc/rf discharges
 - Electron flux and energy distribution at the substrate
- High frequency electromagnetic effects
 - Standing waves and their control
 - Skin effects
- Nonlinear effects and series resonance

EVOLUTION OF ETCHING DISCHARGES — FIRST AND SECOND GENERATIONS

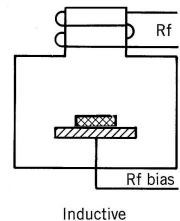
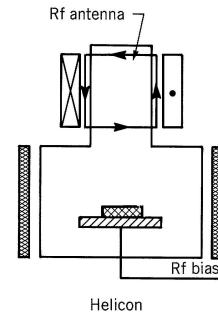
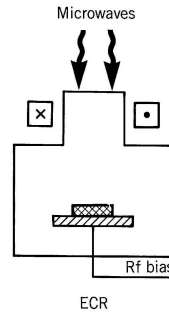
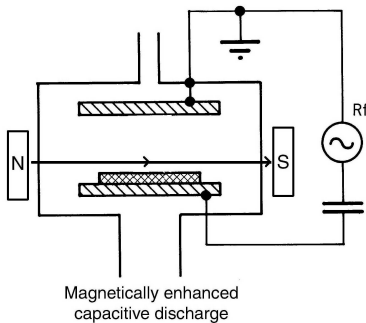
FIRST GENERATION

(1 rf source,
multi-wafer,
low density)



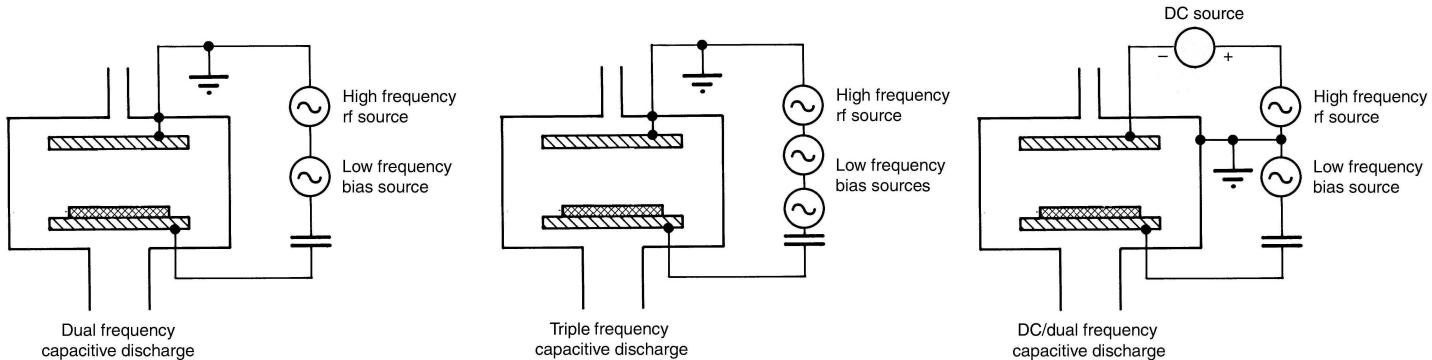
SECOND GENERATION

(2 sources,
single wafer,
high density)



THIRD GENERATION — INTER-DIELECTRIC ETCH

(Multi-frequency, single wafer, moderate density)



- In the year 2020
 - 6nm gate width, 6 billion transistors, 73 GHz on-chip clock
 - 14–18 wiring levels (dielectric layers)
- Why capacitive discharge?
 - low surface area seen by plasma (inexpensive)
 - silicon upper electrode (control of F/CF_x ratio)
 - robust uniformity over wide pressure range

DUAL FREQUENCY CAPACITIVE DISCHARGES

WHY DUAL FREQUENCY CAPACITIVE DISCHARGES?

- Independent control of ion flux and ion energy

High frequency power P_h controls ion flux
Low frequency voltage V_l controls ion energy

1. H.C. Kim, J.K. Lee, and J.W. Shon, *Phys. Plasmas* **10**, 4545 (2003)
2. M.A. Lieberman, J. Kim, J.P. Booth, J.M. Rax and M.M. Turner, SEMICON Korea Etching Symposium, p. 23 (2003)
3. P.C. Boyle, A.R. Ellingboe, and M.M. Turner, *J. Phys. D: Appl. Phys.* **37**, 697 (2004)

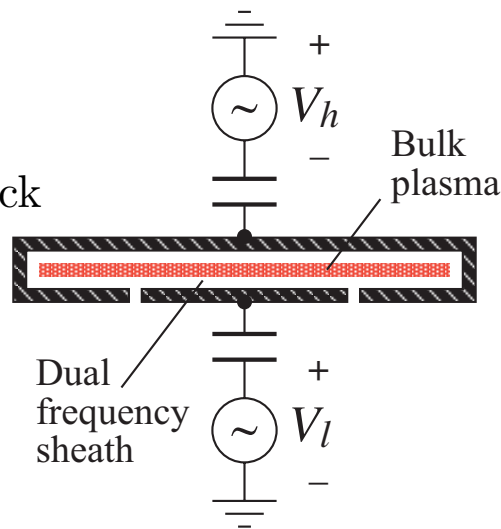
- $R \sim 15\text{--}30$ cm, $L \sim 1\text{--}3$ cm

$p \sim 30\text{--}300$ mTorr, $\text{C}_4\text{F}_8/\text{O}_2/\text{Ar}$ feedstock

$f_h \sim 27.1\text{--}160$ MHz, $V_h \sim 50\text{--}200$ V

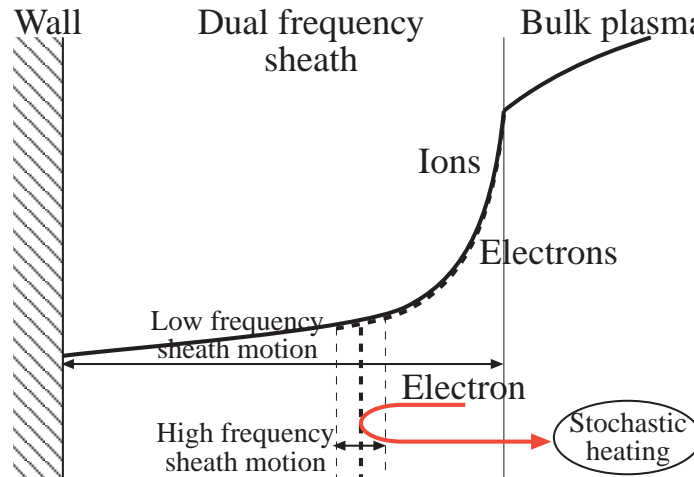
$f_l \sim 2\text{--}13.56$ MHz, $V_l \sim 500\text{--}1500$ V

Absorbed powers P_h , $P_l \sim 500\text{--}3000$ W



DUAL FREQUENCY STOCHASTIC HEATING

- An important electron heating process below 200 mTorr



- How are electrons heated by the high frequency oscillations?
 1. M.M. Turner and P. Chabert, *Phys. Rev. Lett.* **96**, 205001 (2006)
 2. E. Kawamura, M.A. Lieberman, and A.J. Lichtenberg, *Phys. Plasmas* **13**, 053506 (2006)
 3. I.D. Kaganovich, O.V. Polomarov, and C.E. Theodosiou, *IEEE Trans. Plasma Sci.* **34**, 696 (2006)

STOCHASTIC HEATING POWER

- Hard wall theory in dual frequency regime:

$$S_{\text{stoc}} = \underbrace{\frac{1}{2} m \bar{v}_e \frac{J_h^2}{e^2 n_s}}_{\text{High freq part}} \times \underbrace{\left(1 + \frac{\pi}{4} H_l\right) \left(\frac{H_l}{H_l + 2.2}\right)}_{\text{Low freq part } F(H_l)}$$

High freq part Low freq part $F(H_l)$

S_{stoc} = stochastic heating power per unit electrode area

m = electron mass

$\bar{v}_e = (8eT_e/\pi m)^{1/2}$ = mean thermal electron speed

J_h = high frequency current density

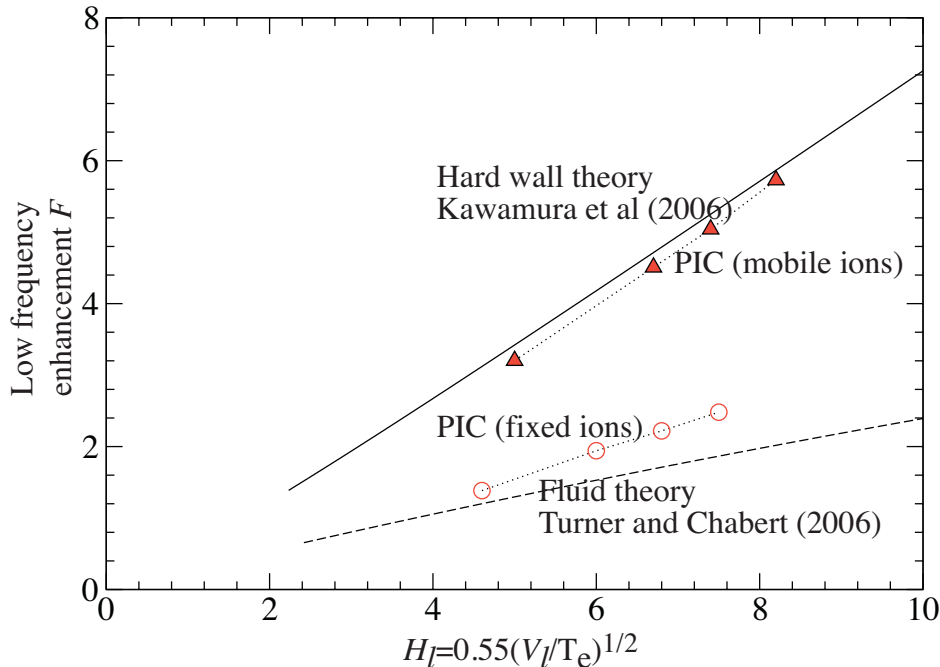
n_s = plasma density at bulk plasma–sheath edge

$H_l = 0.55(V_l/T_e)^{1/2}$ = low frequency enhancement factor

- Fluid theory gives similar result

PARTICLE-IN-CELL SIMULATIONS

- Dual frequency stochastic heating

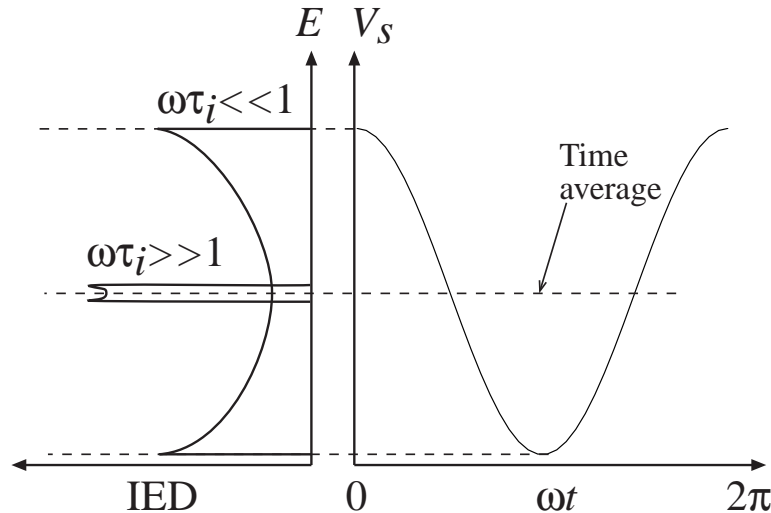


- Ohmic heating in the sheath shows similar behavior (M.M. Turner and P. Chabert, *Appl. Phys. Lett.* **89**, 231502, 2006)

ION/NEUTRAL ENERGY DISTRIBUTIONS ON THE SUBSTRATE SURFACE

1. T. Panagopoulos and D. Economou, *J. Appl. Phys.* **85**, 3435 (1999)
2. S. Shannon, D. Hoffman, J.G. Yang, A. Paterson, and J. Holland, *J. Appl. Phys.* **97**, 103304 (2005)
3. J.K. Lee, O.V. Manuilenko, N.Y. Babaeva, H.C. Kim and J.W. Shon, *Plasma Sources Sci. Technol.* **14**, 89 (2005)
4. A Wu, M.A. Lieberman and J.V. Verboncoeur, *J. Appl. Phys.* **101**, 056105 (2007)
5. T.V. Rakhimova et al, *IEEE Trans. Plasma Sci.* **35**, 1229 (2007)
6. Shuai Wang, Xiang Xu, and You-Nian Wang, *Phys. Plasmas* **14**, 113501 (2007)

FORMATION OF PERIOD-AVERAGED IED FOR SINGLE-FREQUENCY SHEATH



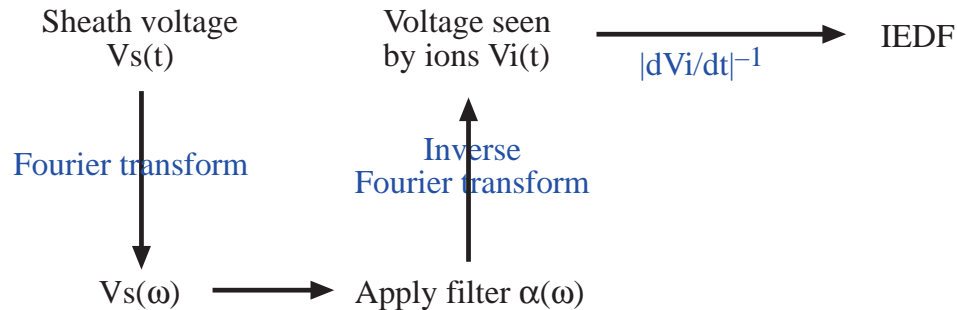
(τ_i = ion transit time across the sheath)

- For $\omega\tau_i \ll 1$, ions respond to the full time-varying sheath voltage
- For $\omega\tau_i \gg 1$, ions respond to the time-averaged sheath voltage

⇒ low-pass filter

FAST ALGORITHM TO CALCULATE ION ENERGY DISTRIBUTION (IED)

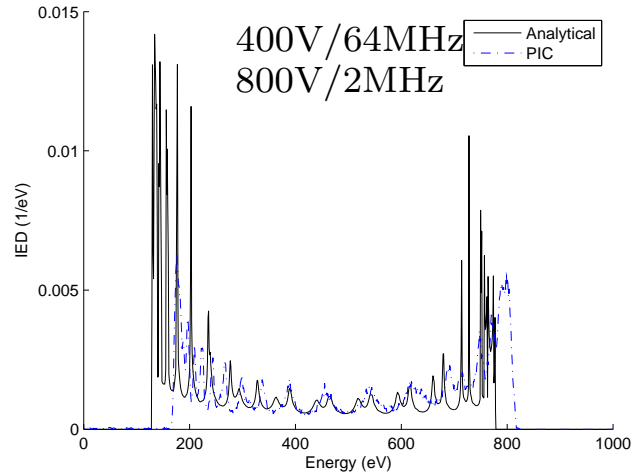
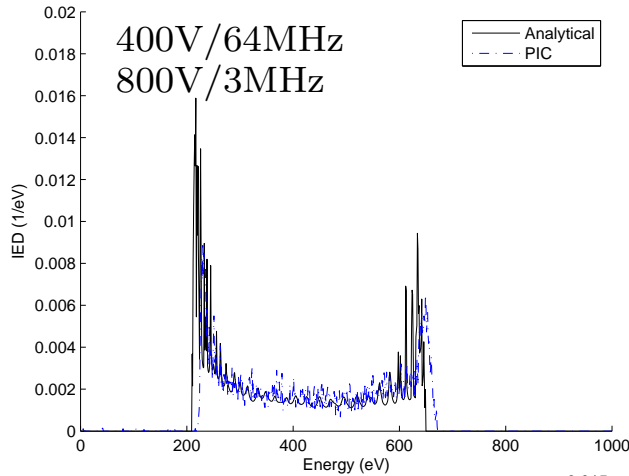
- What is energy distribution of ion flux incident on the substrate?
- Collisionless ions with two and three frequencies



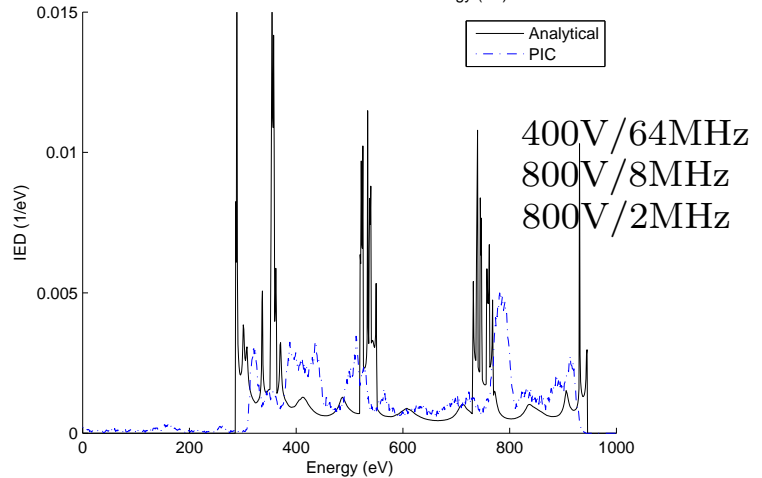
- Use filter $\alpha(\omega) = [(c\omega\tau_i)^p + 1]^{-1/p}$ with $c = 0.3$, $p = 5$, and $\tau_i =$ ion transit time across the sheath $= 3\bar{s}(M/2e\bar{V}_s)^{1/2}$

(A. Wu et al, 2007)

DUAL/TRIPLE FREQUENCY PIC SIMULATIONS



Gap=3 cm
p=30 mTorr
Collisionless ions

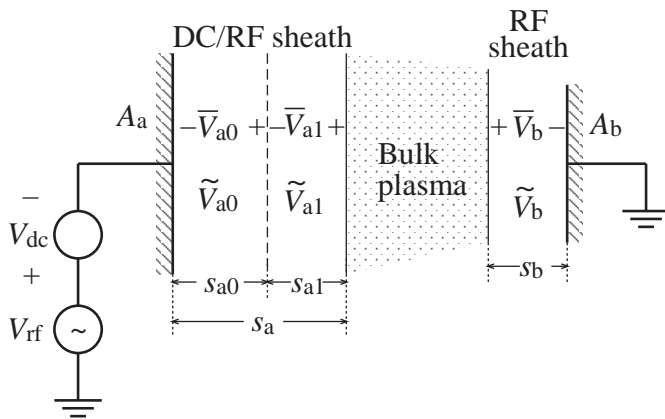


DC/RF DISCHARGES

1. W.T. Lai et al, “Etch Uniformity Control by Gap and DC Superposition at 65nm metal hard-Mask Dual Damescene”, *Proc. Int. Symp. Dry Process* (2006)
2. E. Kawamura, M.A. Lieberman, A.J. Lichtenberg and E.A. Hudson, *J. Vac. Sci. Technol. A* **25**, 1456 (2007)
3. Jiang Wei, Xu Xiang, Dai Zhong-Ling and Wang You-Nian, *Phys. Plasmas* **15**, 033502 (2008)
4. E. Kawamura, A.J. Lichtenberg, and M.A. Lieberman, *Plasma Sources Sci. Technol.* **17**, 045002 (2008)
5. V.A. Godyak and N. Sternberg, *Phys. Rev. A* **42**, 2299 (1990)

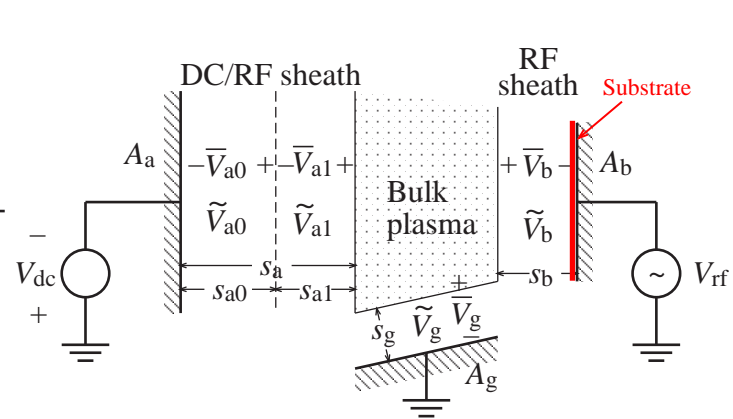
MOTIVATIONS FOR ADDING DC SOURCE

- “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)



DIODE

(for 1D PIC simulations)



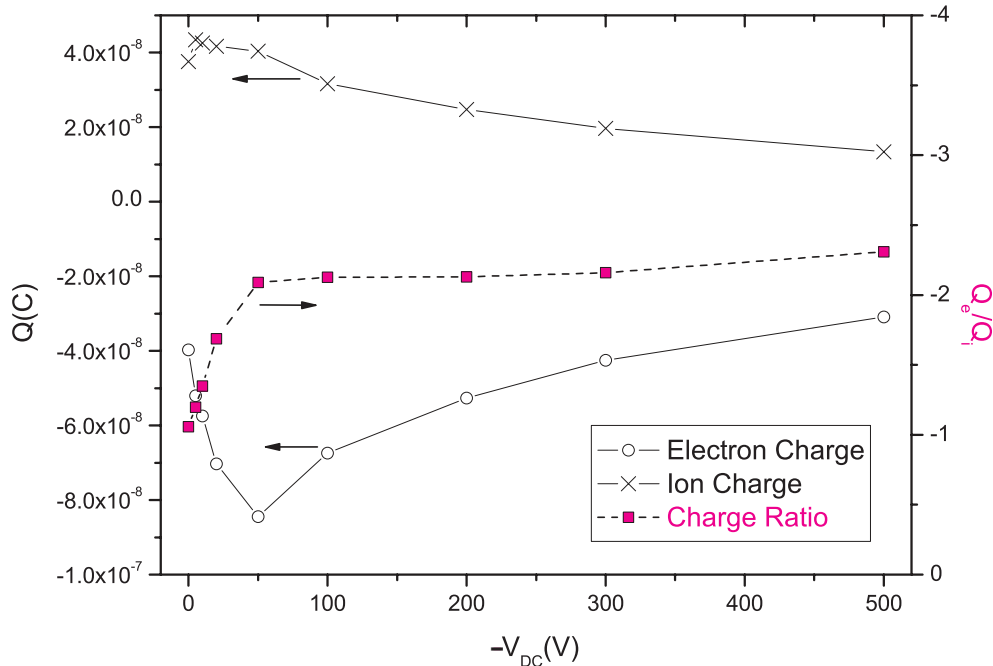
TRIODE

(for industrial use)

COMPARISON TO PIC SIMULATIONS

- Adding DC increases electron current to rf-powered substrate
⇒ significant changes in etch selectivities, charging damage

(Planar PIC, 50 mTorr argon, 3.5 cm, 13.56 MHz, 200 V)



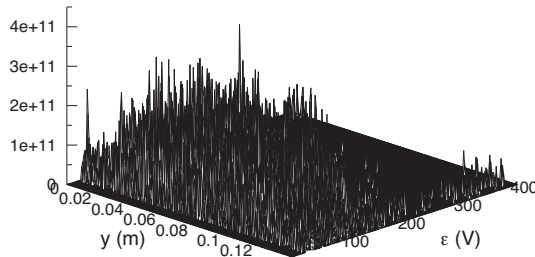
(Jiang Wei et al, 2008)

BALLISTIC SECONDARY ELECTRONS CREATED BY V_{dc}

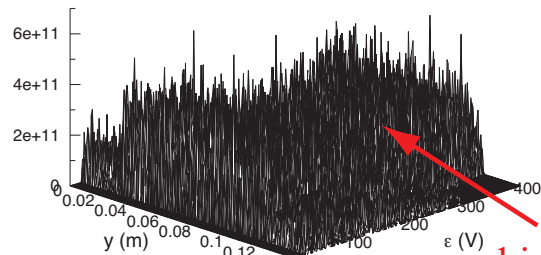
(30 mTorr argon, 3 cm gap, 0.2 secondary emission coefficient)

Rf only

Secondary energy distribution (arb units)

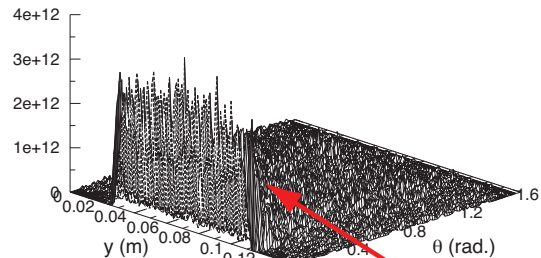
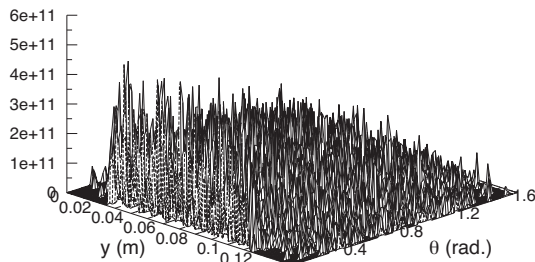


Dc/rf



high energy

Secondary angular distribution (arb units)



ballistic

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

(Kawamura et al, 2008)

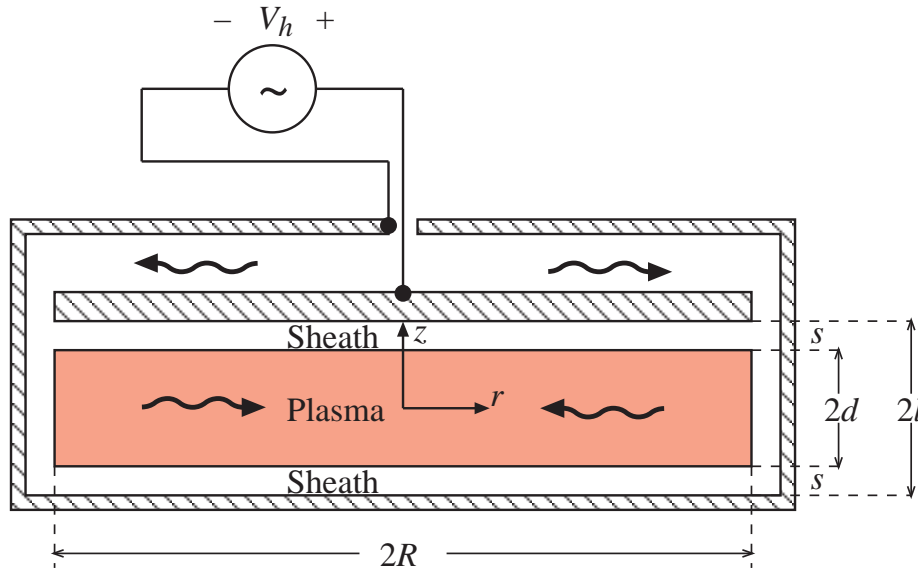
HIGH FREQUENCY ELECTROMAGNETIC EFFECTS

STANDING WAVE AND SKIN EFFECTS

- High frequency and large area \Rightarrow standing wave effects
 - High frequency \Rightarrow high density \Rightarrow skin effects
1. M.A. Lieberman, J.P. Booth, P. Chabert, J.M. Rax, and M.M. Turner, *Plasma Sources Sci. Technol.* **11**, 283 (2002)
 2. P. Chabert, *J. Phys. D: Appl. Phys.* **40**, R63 (2007)
 3. Insook Lee, D.B. Graves and M.A. Lieberman, *Plasma Sources Sci. Technol.* **17**, 015018 (2007)
 4. S. Rauf, K. Bera and K. Collins, *Plasma Sources Sci. Technol.* **17**, 035003 (2007)

CYLINDRICAL CAPACITIVE DISCHARGE

Consider only the high frequency source

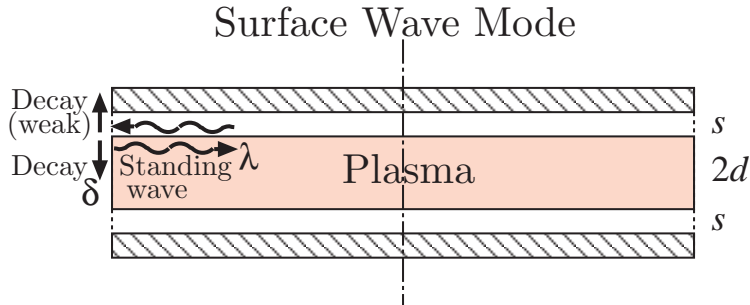


Fields cannot pass through metal plates

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

SURFACE WAVE MODE

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



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

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

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

- Axial skin depth for surface wave:

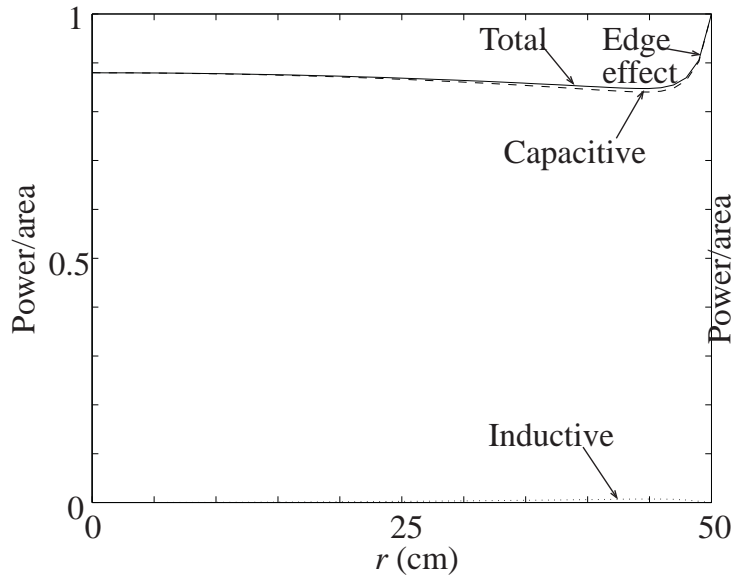
$$\delta \sim \frac{c}{\omega_p}$$

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

STANDING WAVE EFFECT — FIXED n_e AND s

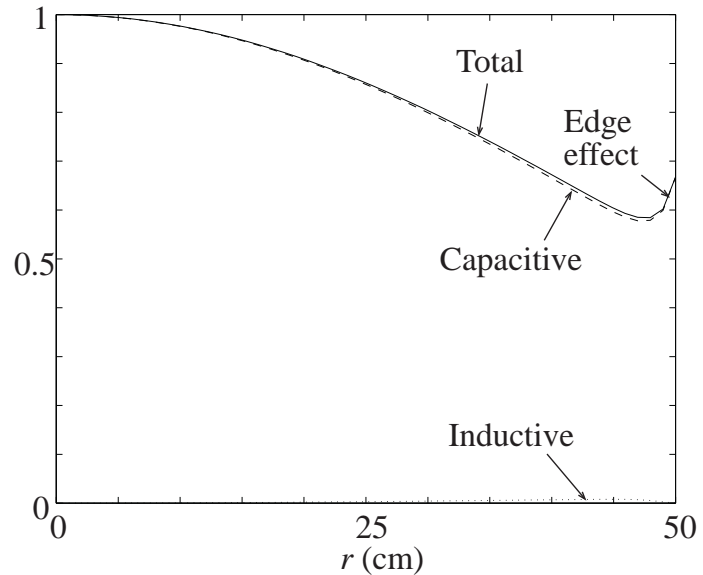
- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm, $n_e = 10^9$ cm $^{-3}$, $\delta \approx 16$ cm
- P_{cap} (dash), P_{ind} (dot) and P_{tot} (solid) as a function of r

13.56 MHz ($\lambda \approx 9\text{--}10$ m)



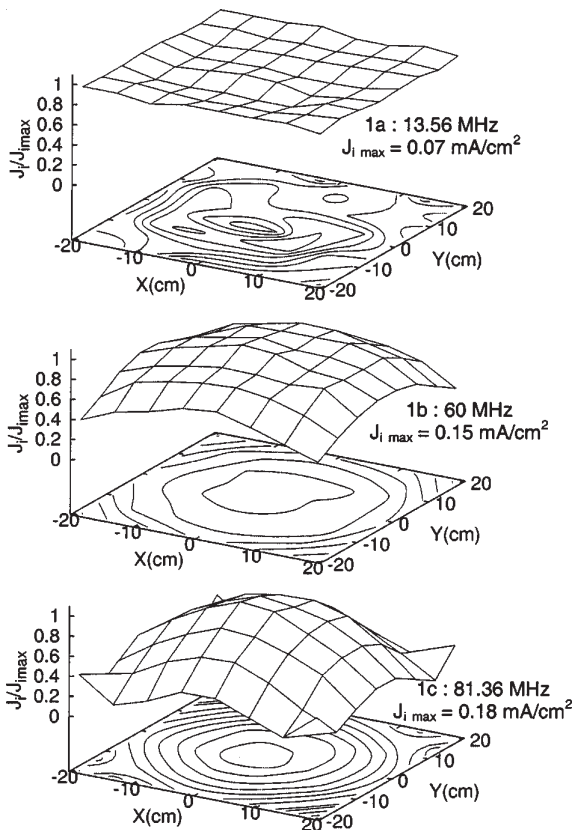
Small standing wave and skin effects

40.7 MHz ($\lambda \approx 3$ m)



Large standing wave effect;
center-high profile

EXPERIMENTAL RESULTS FOR STANDING WAVES



20×20 cm discharge
 $p = 150 \text{ mTorr}$
50 W rf power

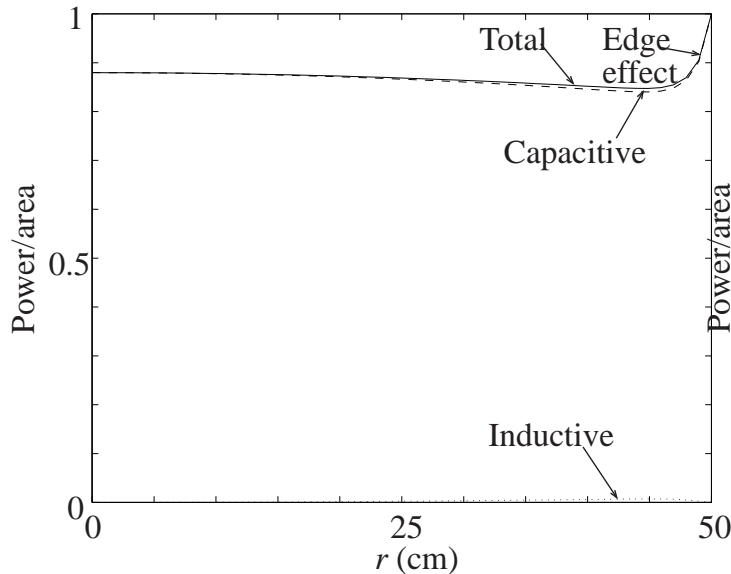
The standing wave effect is seen at 60 MHz and is more pronounced at 81.36 MHz

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

SKIN EFFECTS — FIXED n_e AND s

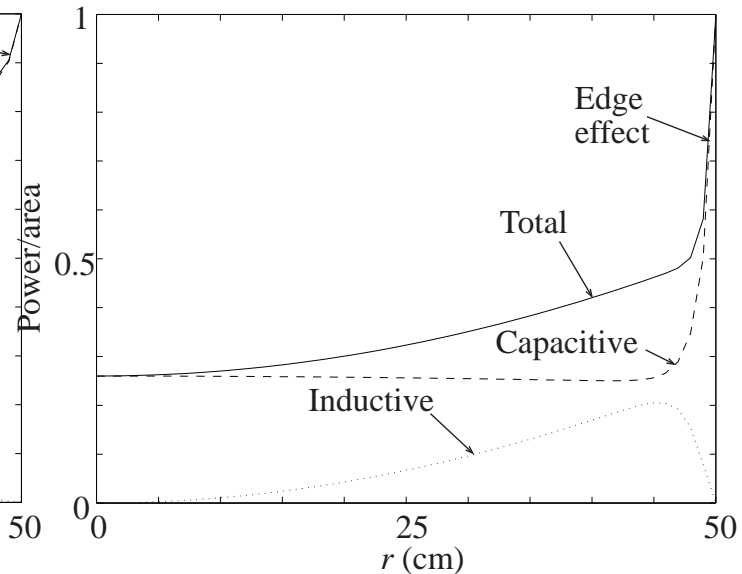
- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm, $f = 13.56$ MHz, $\lambda \approx 9$ m
- P_{cap} (dash), P_{ind} (dot) and P_{tot} (solid) as a function of r

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



Small standing wave and skin effects

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



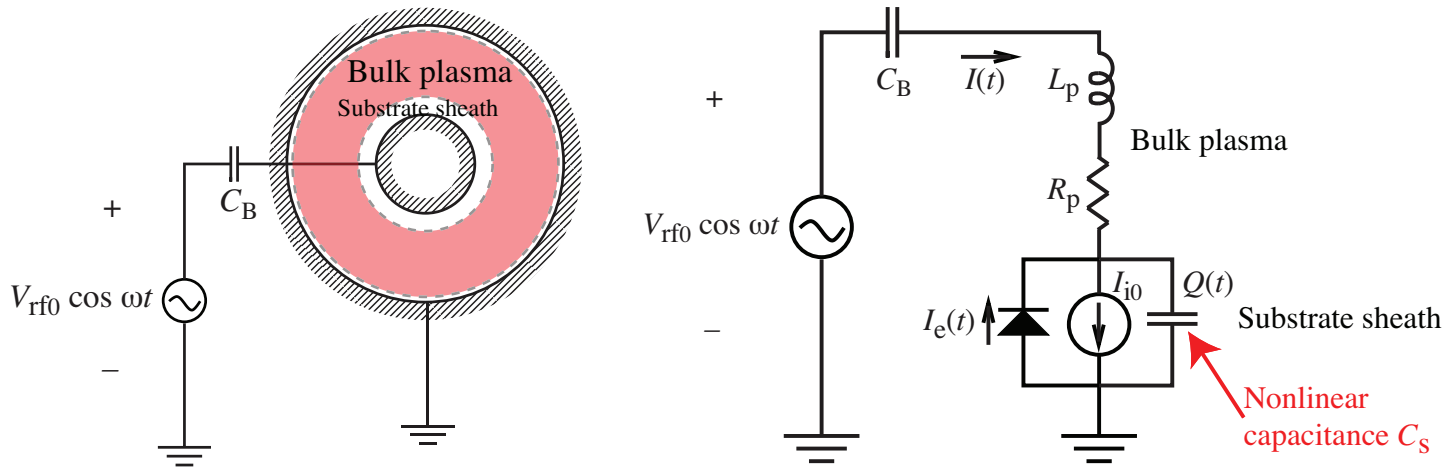
Large skin effects;
center-low profile

NONLINEAR EFFECTS IN CAPACITIVE DISCHARGES

1. P.A. Miller et al, *Plasma Sources Sci. Technol.* **15**, 889 (2006)
2. T. Mussenbrock and R.P. Brinkmann, *Appl. Phys. Lett.* **88**, 151503 (2006)
3. U. Czarnetski, T. Mussenbrock and R.P. Brinkmann, *Phys. Plasmas* **13**, 123503 (2006)
4. M.A. Lieberman, A.J. Lichtenberg, E. Kawamura, T. Mussenbrock and R.P. Brinkmann, *Phys. Plasmas* **15**, 063505 (2008)
5. D. Zeigler, T. Mussenbrock and R.P. Brinkmann, *Plasma Sources Sci. Technol.* **17**, 045011 (2008)

NONLINEAR EXCITATION OF SERIES RESONANCE

- Consider voltage-driven, highly asymmetric capacitive discharge

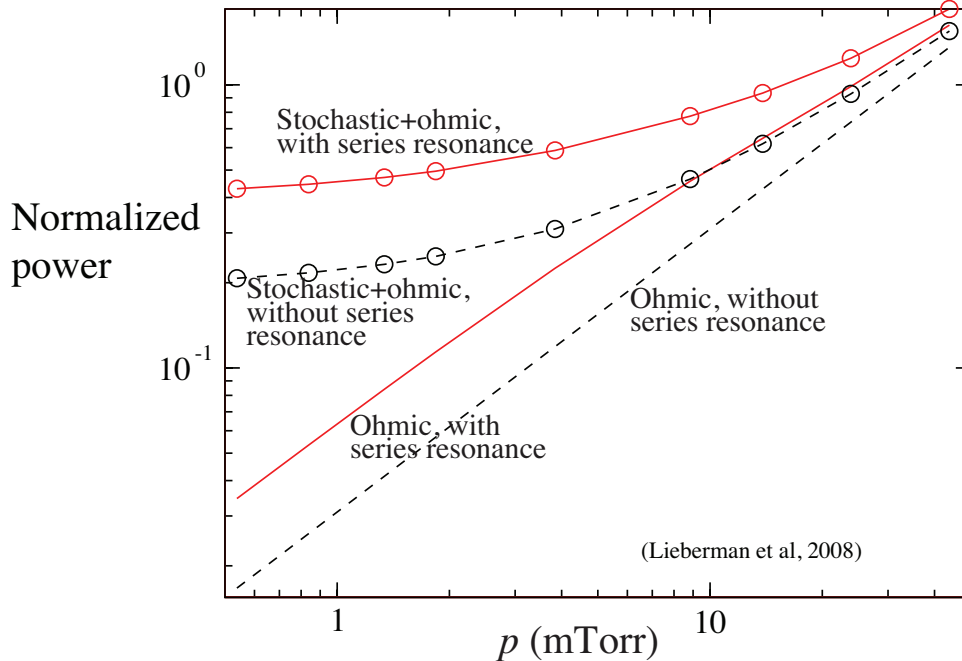
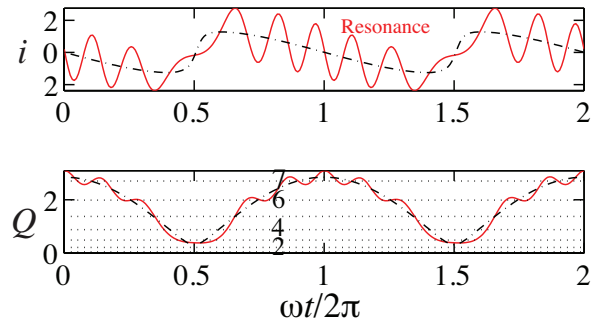


- Series resonance frequency $\omega_{\text{res}} = 1/\sqrt{L_p C_s}$
- RF voltage at frequency ω + nonlinear C_s excites the series resonance when $n\omega \approx \omega_{\text{res}}$

RF current harmonics near series resonance

ENHANCED OHMIC AND STOCHASTIC HEATING

- Series resonance effect increases the RMS rf current \implies enhanced electron heating



LiebermanAPCPST08

CONCLUSIONS

- CMOS microprocessors scale to 6 billion transistors, 6 nm (24 atom) gate lengths, and 14–18 wiring levels
- Third generation capacitive reactors for dielectric etch will dominate the plasma processing in the fab
- Exquisite control of plasma and etch uniformities, wafer-to-wafer reproducibilities, and energetic particle distributions on the substrate surface will be required
- There may be a transition from 300 to 500 mm wafers

⇒ A strong research and development program on capacitive discharges is needed

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