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

THE NANOELECTRONICS REVOLUTION

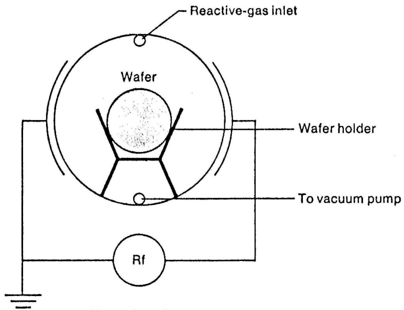
- Transistors/chip doubling every $1\frac{1}{2}$–2 years since 1959
- 1,000,000-fold decrease in cost for the same performance in the last 30 years

EQUIVALENT AUTOMOTIVE ADVANCE

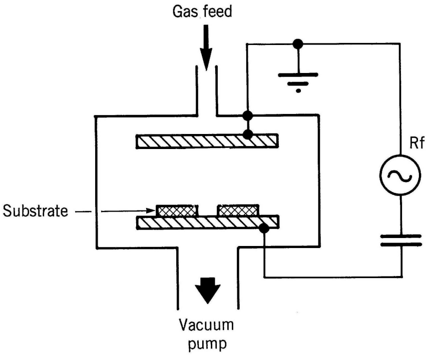
- 60 million miles/hr
- 20 million miles/gal
- Throw away rather than pay parking fees
- 3 mm long × 1 mm wide
- Crash 3× a day

EVOLUTION OF ETCHING DISCHARGES — FIRST AND SECOND GENERATIONS

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

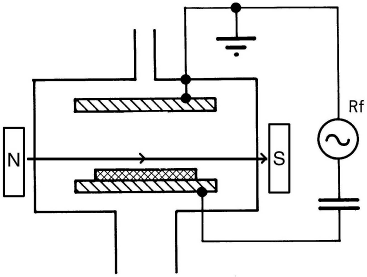


Barrel etcher
(Isotropic etch)

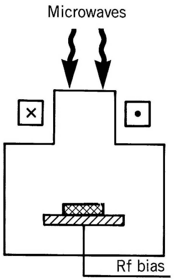


Capacitive
(Anisotropic etch)

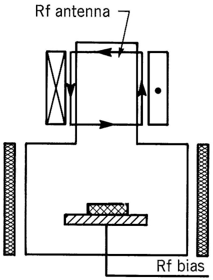
SECOND GENERATION
(2 sources, single wafer, high density)



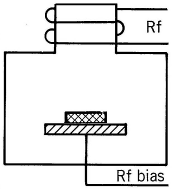
Magnetically enhanced capacitive discharge



ECR



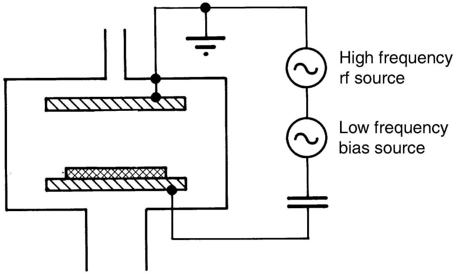
Helicon



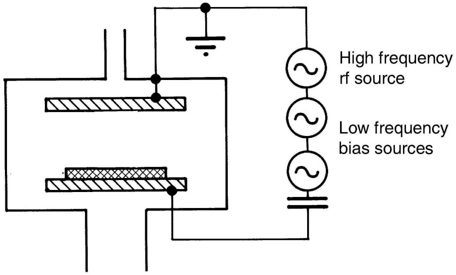
Inductive

THIRD GENERATION — INTER-DIELECTRIC ETCH

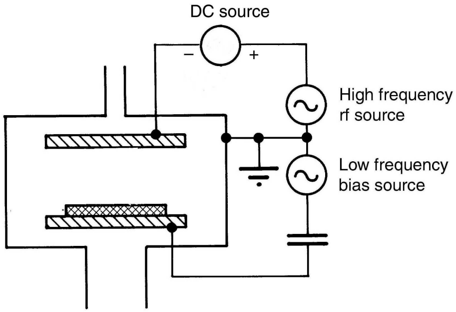
(Multi-frequency, single wafer, moderate density)



Dual frequency capacitive discharge



Triple frequency capacitive discharge



DC/dual frequency capacitive discharge

- 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)

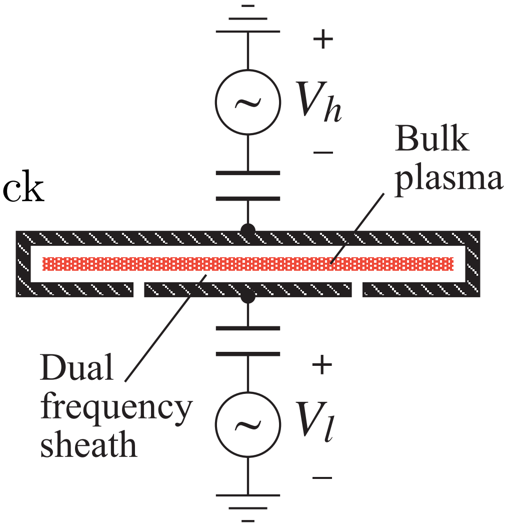
- $R \sim$ 15–30 cm, $L \sim$ 1–3 cm

$p \sim$ 30–300 mTorr, $C_4F_8/O_2/Ar$ feedstock

$f_h \sim$ 27.1–160 MHz, $V_h \sim$ 50–200 V

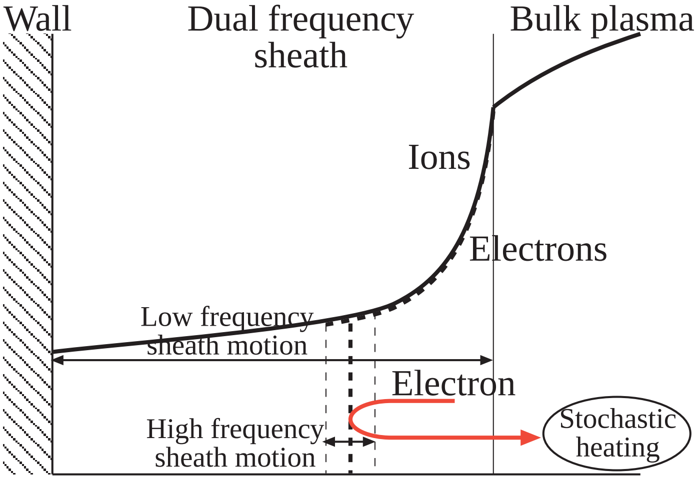
$f_l \sim$ 2–13.56 MHz, $V_l \sim$ 500–1500 V

Absorbed powers P_h, $P_l \sim$ 500–3000 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:

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

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

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

m = electron mass

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

J_h = high frequency current density

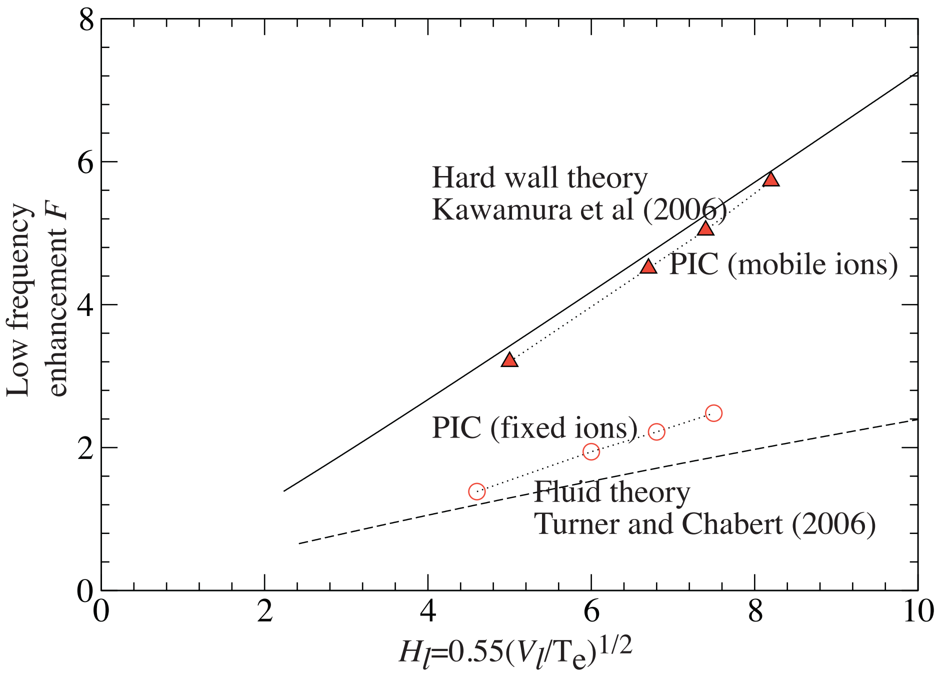
n_s = plasma density at bulk plasma–sheath edge

$H_l = 0.55(V_l/\mathrm{T}_e)^{1/2}$ =low frequency enhancement factor

- Fluid theory gives similar result

PARTICLE-IN-CELL SIMULATIONS

- Dual frequency stochastic heating

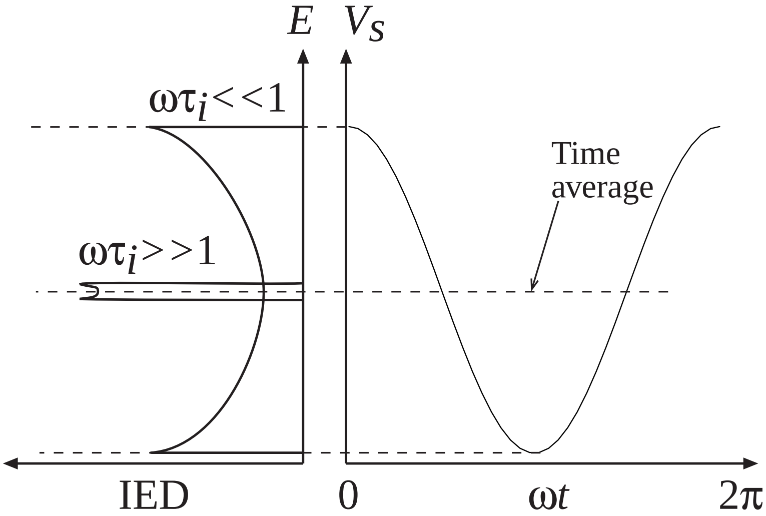


- Ohmic heating in the sheath shows similar behavior
  (M.M. Turner and P. Chabert, *Appl. Phys. Lett.* **89,** 231502, 2006)

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



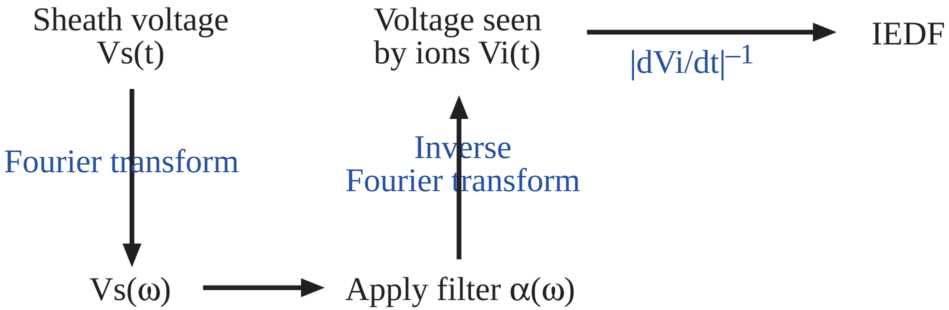
(τ_i = ion transit time across the sheath)

- 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-average sheath voltage

$$\boxed{\Rightarrow \text{low-pass filter}}$$

FAST ALGORITHM TO CALCULATE ION ENERGY DISTRIBUTION (IED)

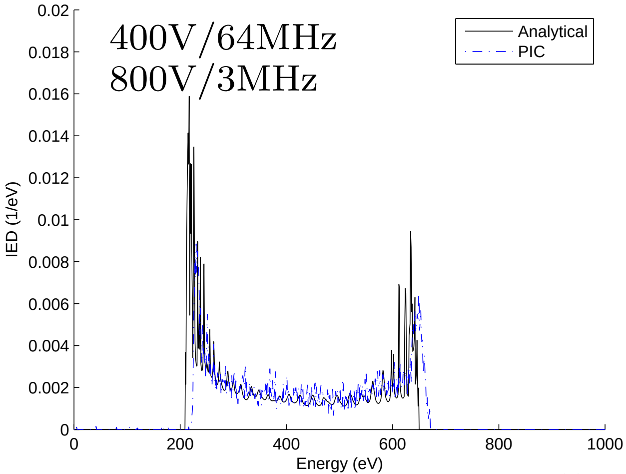
- What is energy distribution of ion flux incident on the substrate?
- Collisionless ions with two and three frequencies

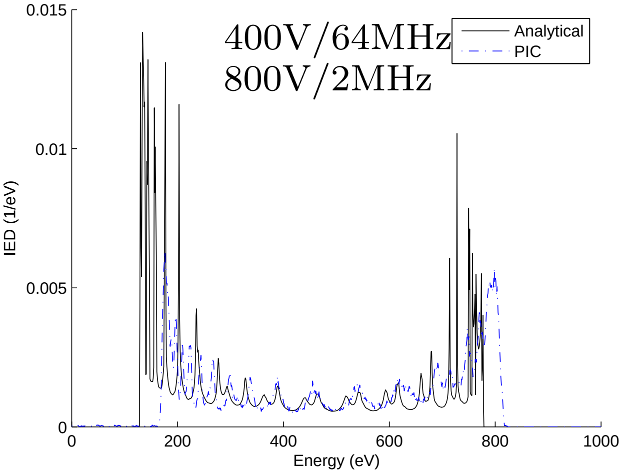


- Use filter $\alpha(\omega) = [(c\,\omega\tau_i)^p + 1]^{-1/p}$ with $c = 0.3,\ p = 5$, and $\tau_i =$ ion transit time across the sheath $= 3\bar{s}(M/2e\overline{V}_s)^{1/2}$

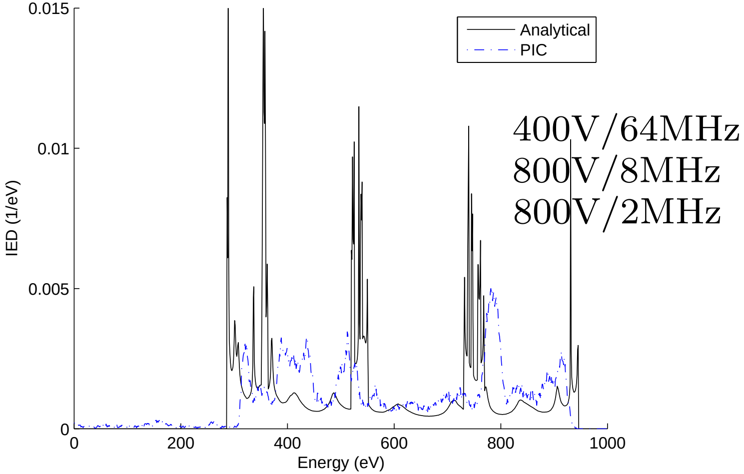
(A. Wu et al, 2007)

DUAL/TRIPLE FREQUENCY PIC SIMULATIONS





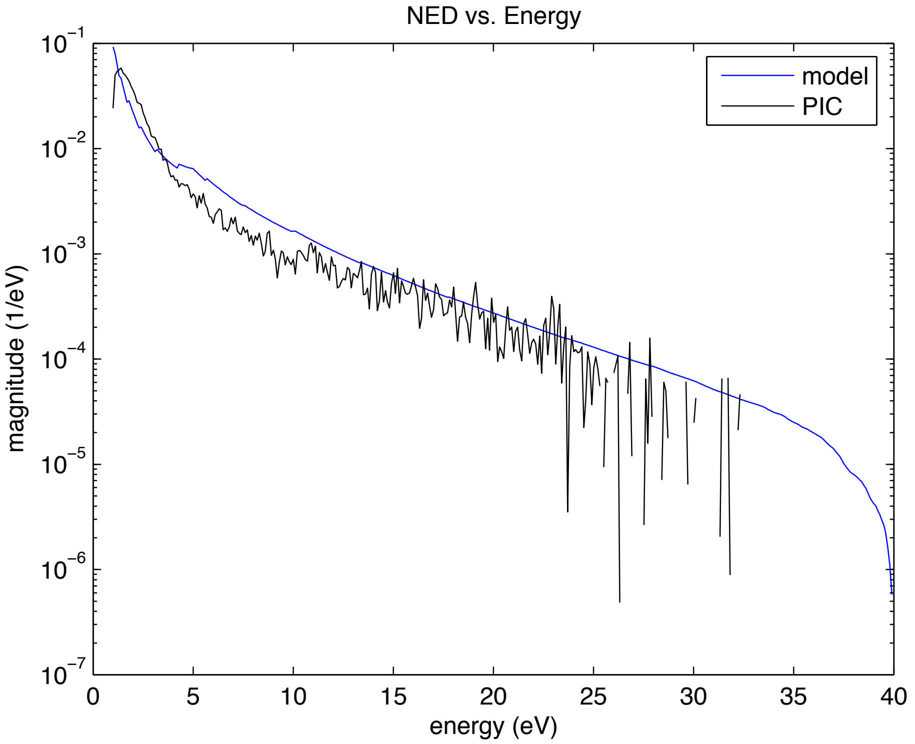
Gap=3 cm
p=30 mTorr
Collisionless ions



COLLISIONS WITH/AMONG NEUTRALS

(40 V at 64 MHz, 50 mTorr argon, 3 cm gap)

- Fast computational model for neutral energy distribution (NED)



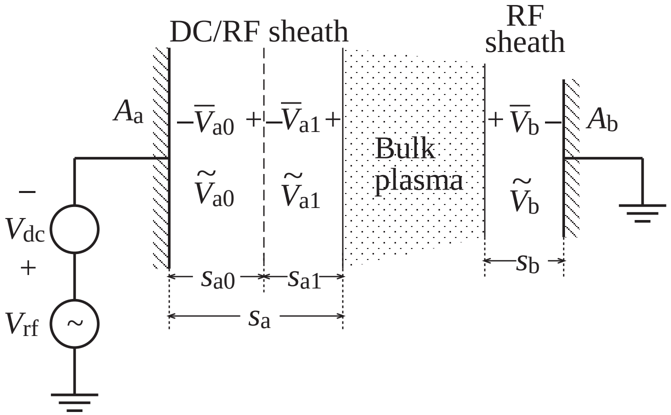
(A. Wu Ph.D. Thesis, 2007)

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)

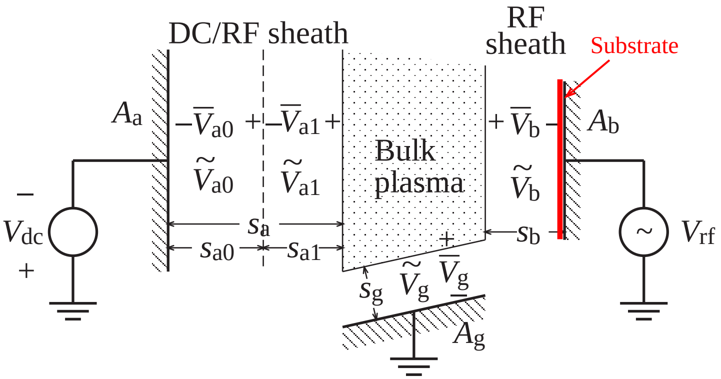
MOTIVATIONS FOR ADDING DC SOURCE

- “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)



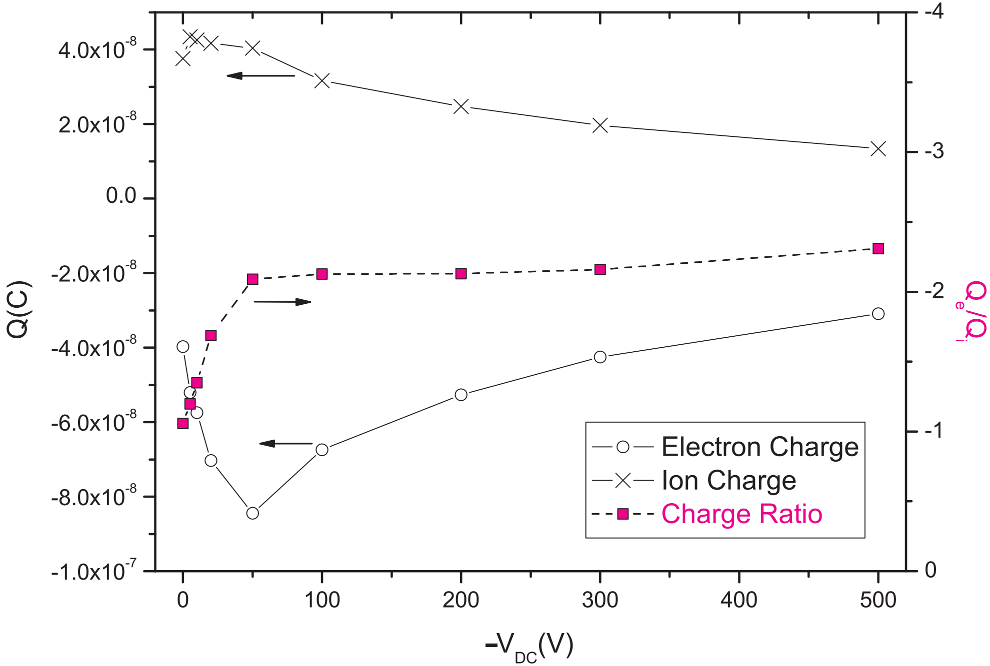
TRIODE

(for industrial use)

COMPARISON TO PIC SIMULATIONS

- Adding DC increases electron current to rf-powered substrate $\Longrightarrow$ 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}

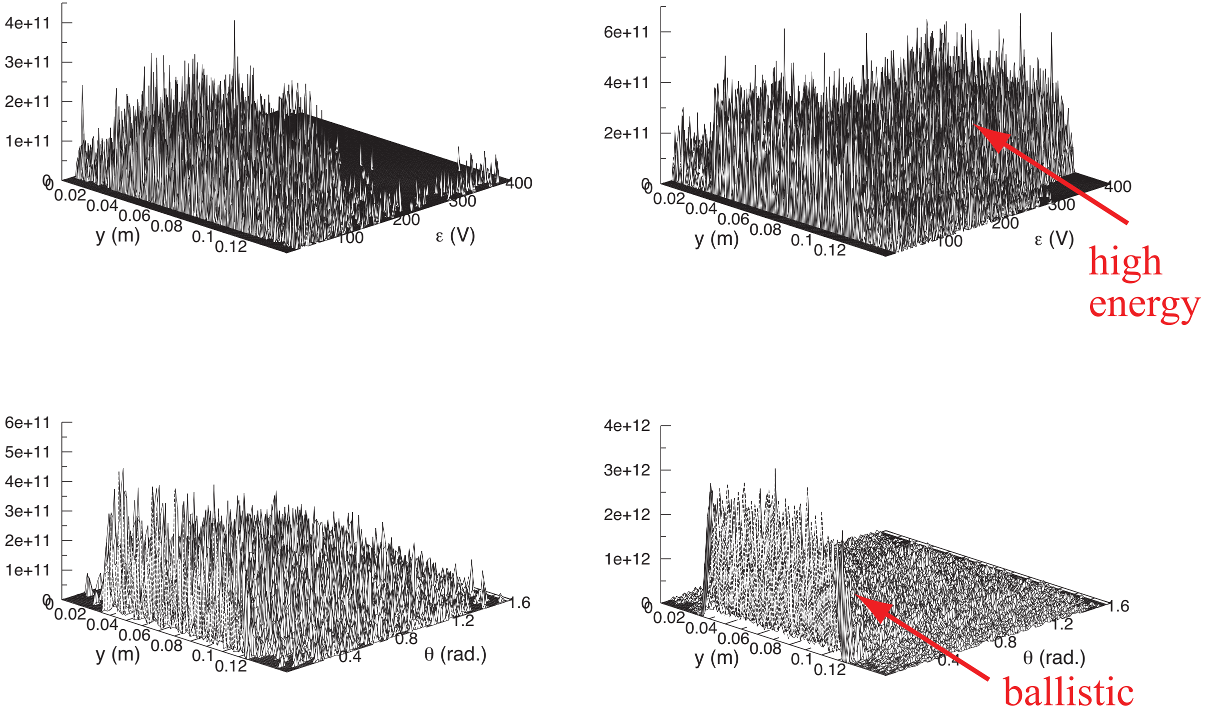
(30 mTorr argon, 3 cm gap, 0.2 secondary emission coefficient)

Rf only

Dc/rf

Secondary energy distribution (arb units)

Secondary angular distribution (arb units)



high energy

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

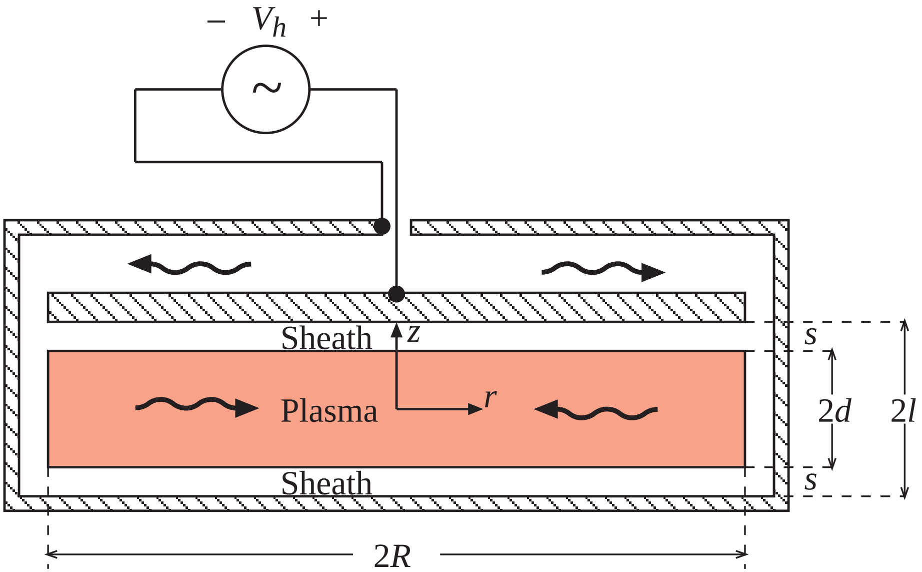
- High frequency and large area ⇒ $\boxed{\text{standing wave effects}}$

- High frequency ⇒ high density ⇒ $\boxed{\text{skin effects}}$

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



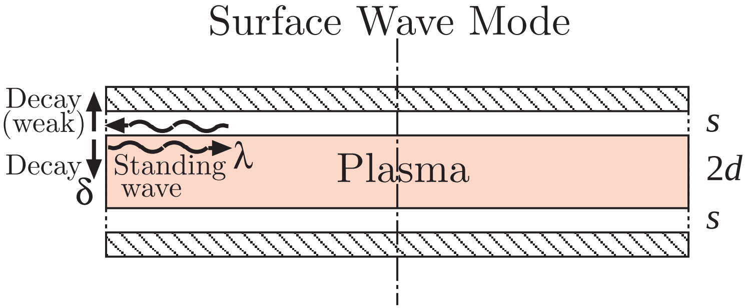
Fields cannot pass through metal plates

(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):

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

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

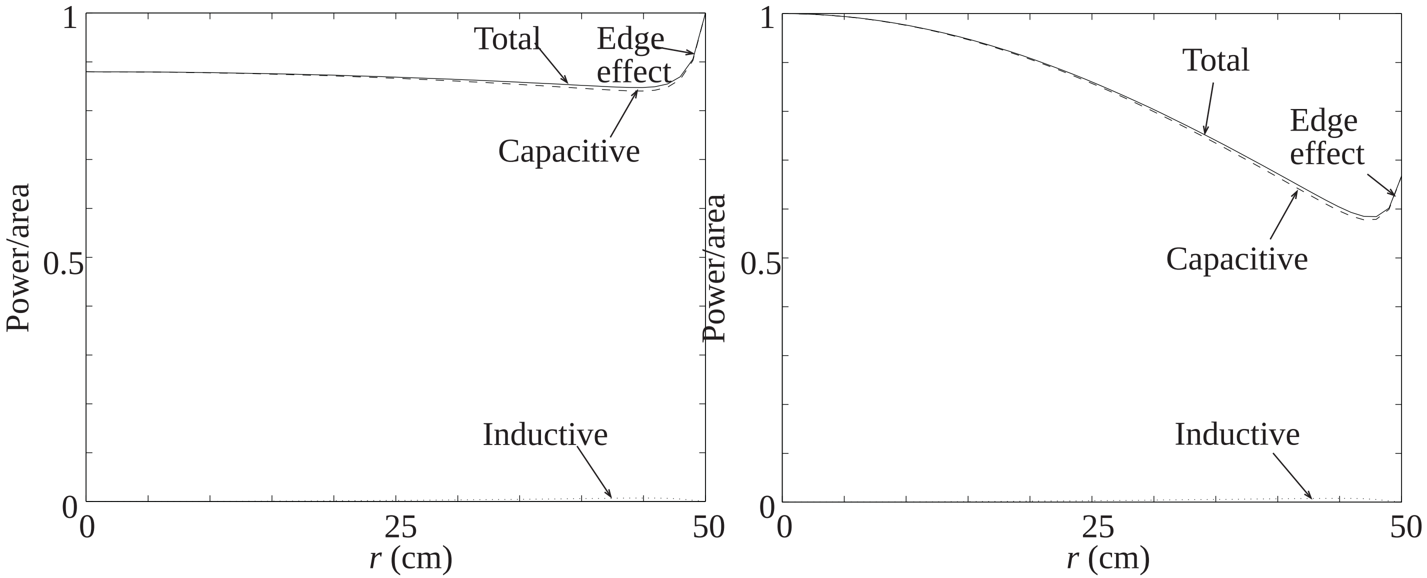
- Axial skin depth for surface wave:

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

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

STANDING WAVE EFFECT — FIXED $\mathbf{n_e}$ AND $\mathbf{s}$

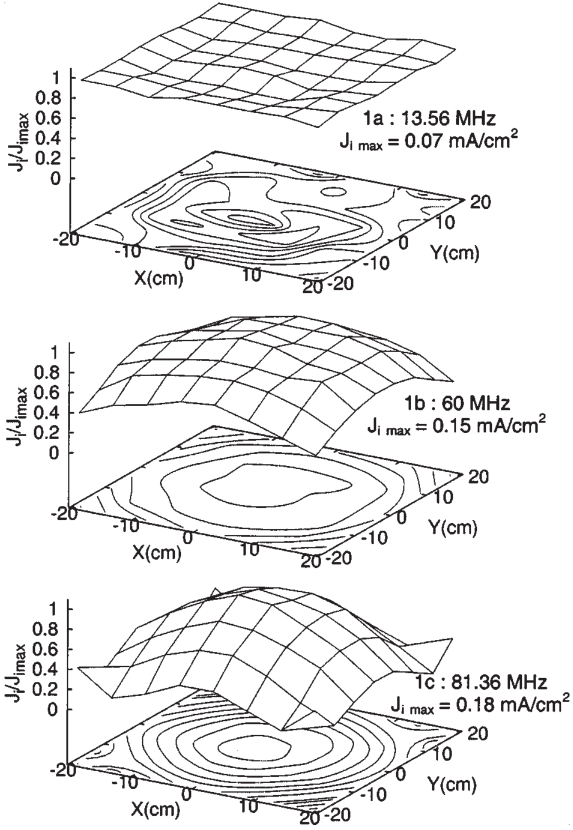
- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm, $n_e = 10^9$ cm^{-3}, $\delta \approx 16$ cm
- P_cap (dash), P_ind (dot) and P_tot (solid) as a function of r



Small standing wave and skin effects

Large standing wave effect; center-high profile

EXPERIMENTAL RESULTS FOR STANDING WAVES



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

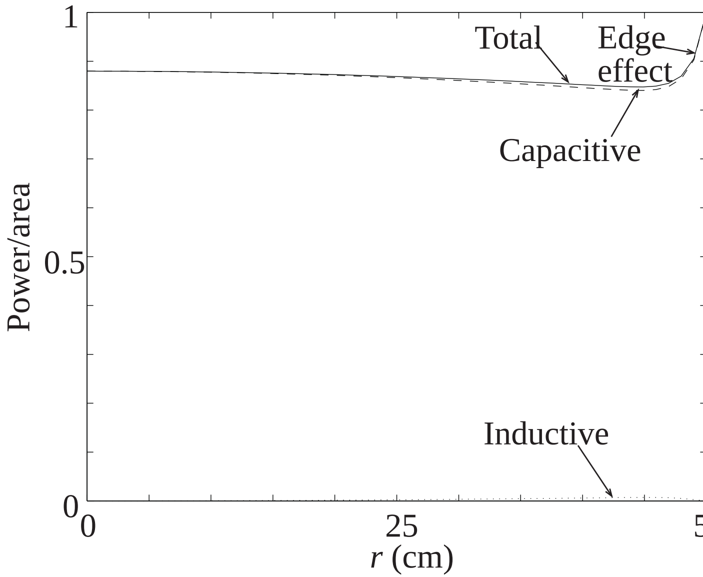
The standing wave effect is seen at 60 MHz and is more pronounced at 81.36 MHz

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

SKIN EFFECTS — FIXED n_e AND s

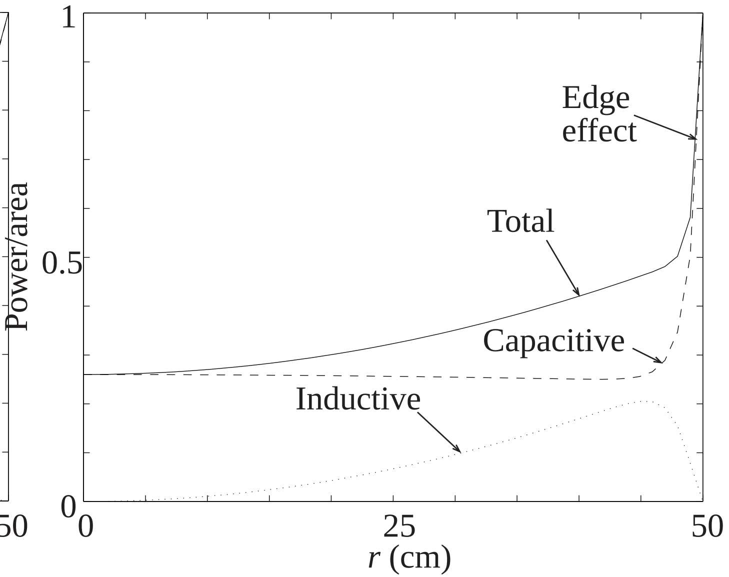
- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm, $f = 13.56$ MHz, $\lambda \approx 9$ m
- P_{cap} (dash), P_{ind} (dot) and P_{tot} (solid) as a function of r

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



Small standing wave and skin effects

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

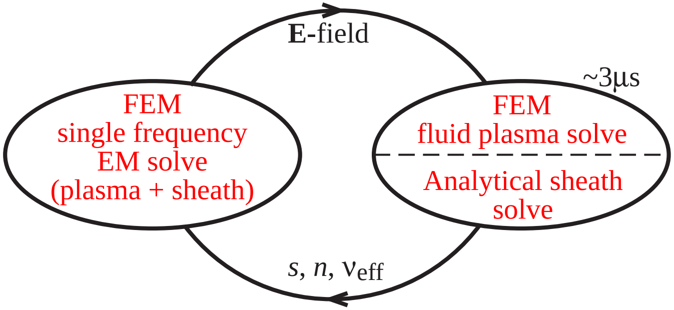


Large skin effects; center-low profile

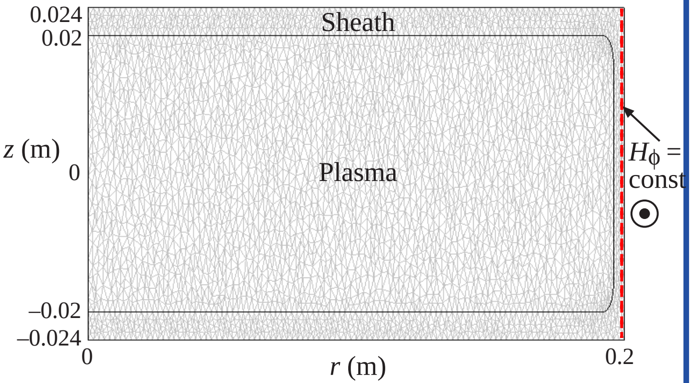
FINITE ELEMENT METHOD (FEM), 2D EM SOLUTIONS

(Insook Lee et al, 2007)

- Arbitrary (asymmetric) discharge geometries and materials
- Transition from global to local power balance
- Distinguish edge effects (electrostatic) versus EM effects
- Series resonance stop band



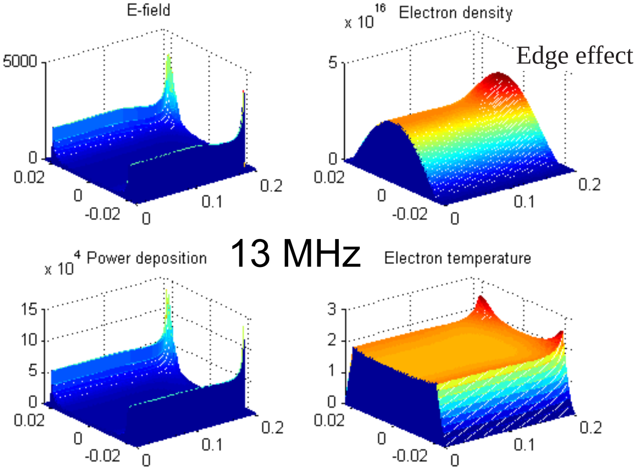
Solution Procedure



FEM Mesh (6252 elements)

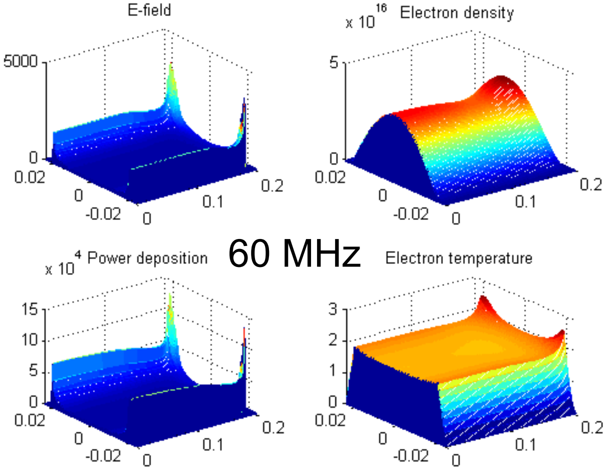
(Analytical model: collisional Child law, variable sheath width, stochastic and ohmic heating in the sheath)

STANDING WAVES — 40 W, 150 mTORR

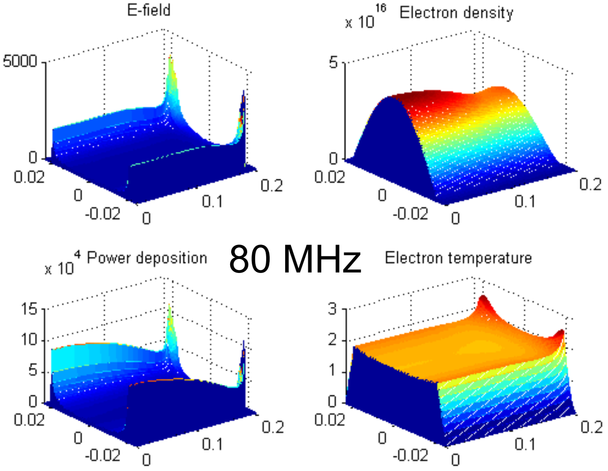


Edge effect

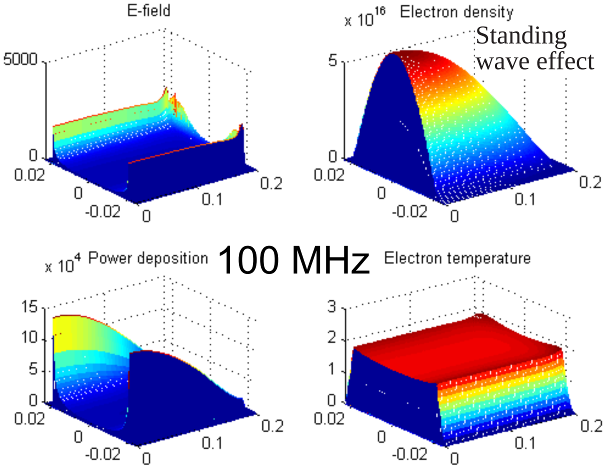
13 MHz



60 MHz



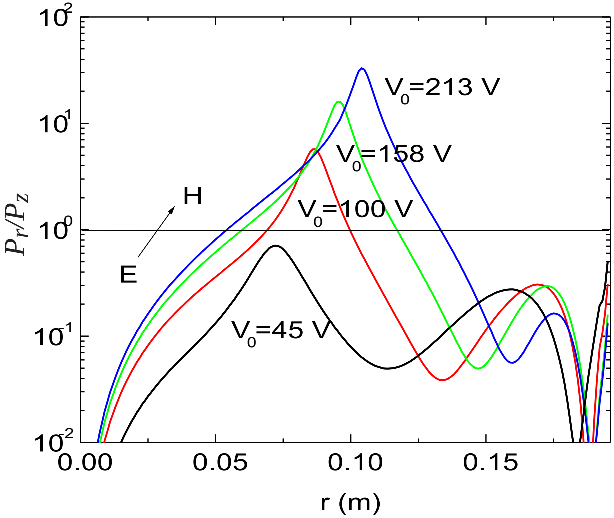
80 MHz



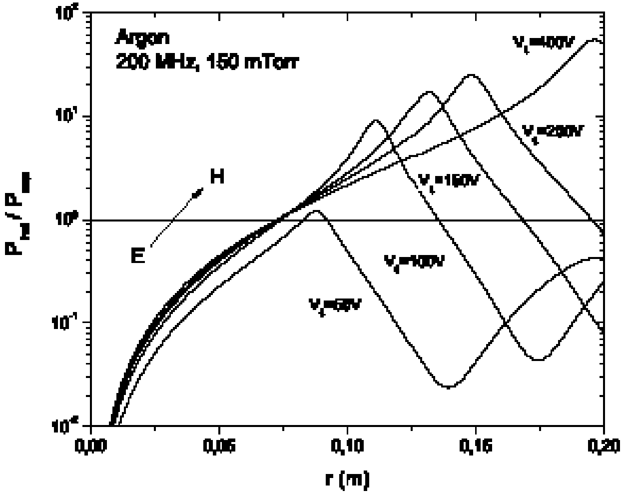
Standing wave effect

100 MHz

SKIN EFFECTS — 150 mTORR



FEM model
(Insook Lee et al, 2007)



Transmission line model
(P. Chabert et al, *Plasma Sources Sci. Technol.* **15,** S130, 2006)

- Transmission line model: collisionless sheaths, no edge effects, purely local power deposition

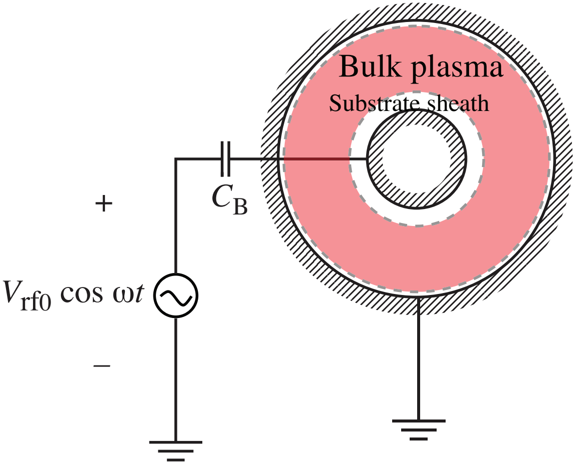
In both cases spatial E to H transitions are seen

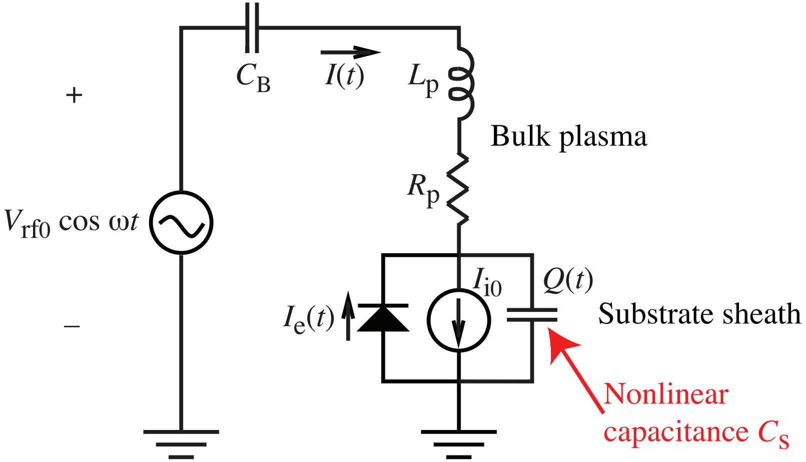
NONLINEAR EFFECTS IN CAPACITIVE DISCHARGES

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



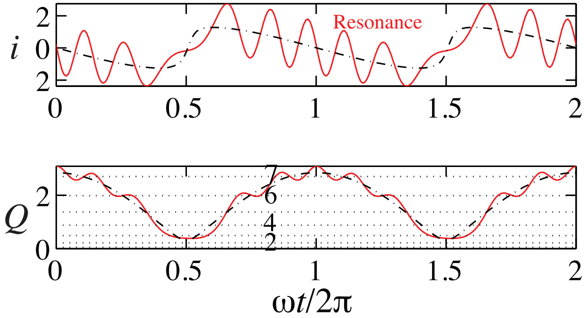


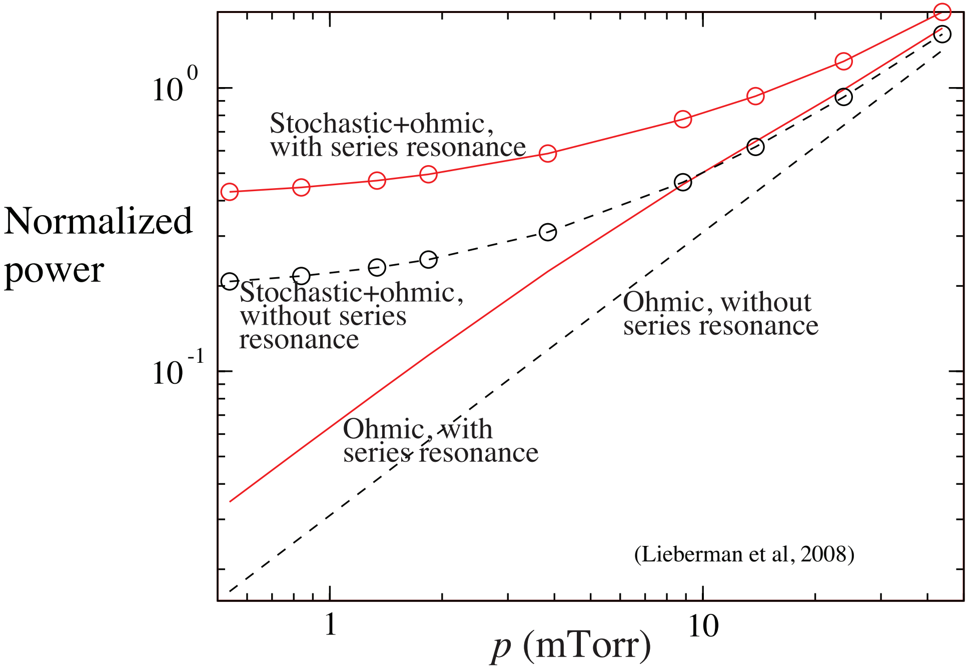
- Series resonance frequency $\omega_{\rm res} = 1/\sqrt{L_p C_s}$
- RF voltage at frequency ω + nonlinear C_s excites the series resonance when n$\omega \approx \omega_{\rm res}$

$$\boxed{\text{RF current harmonics near series resonance}}$$

ENHANCED OHMIC AND STOCHASTIC HEATING

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

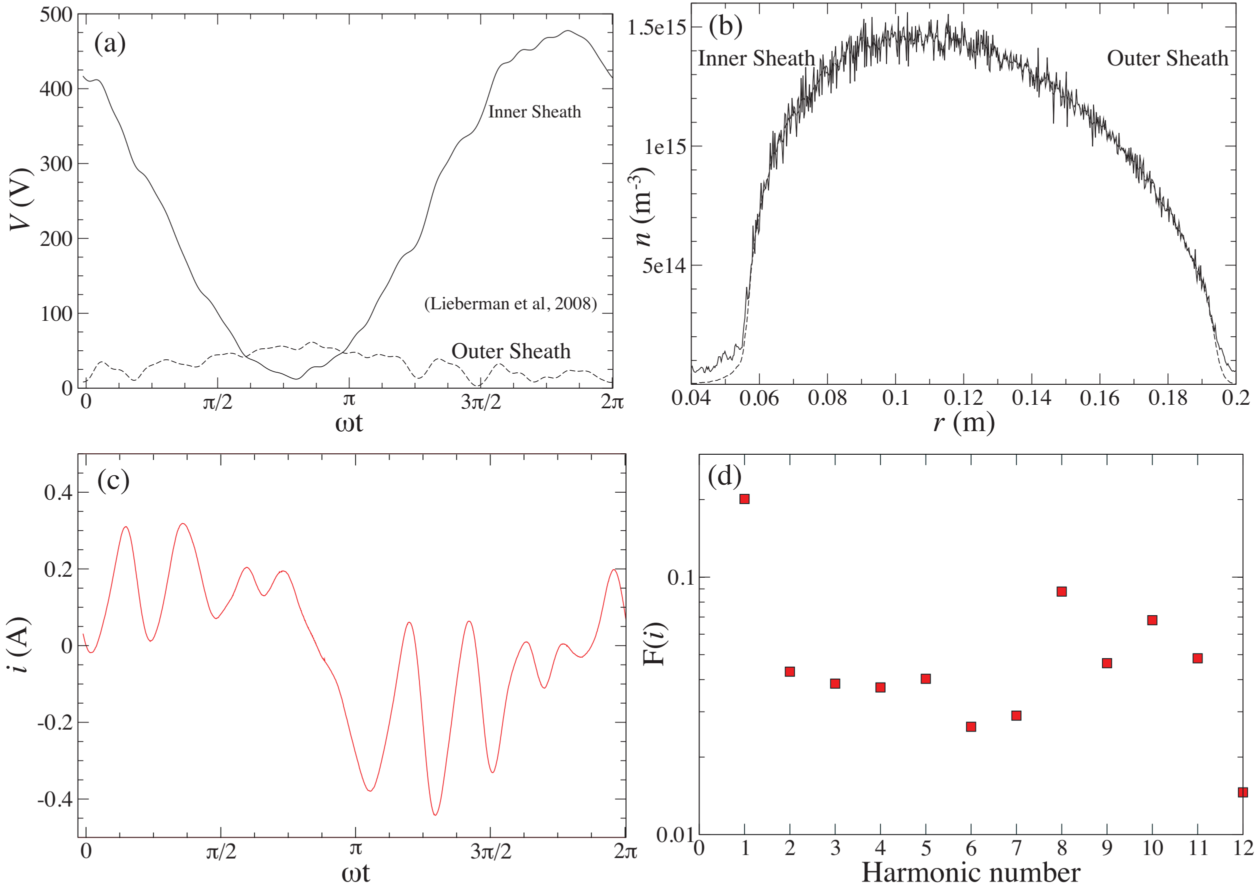




(Lieberman et al, 2008)

CYLINDRICAL PIC SIMULATION

(13.56 MHz, 250 V, 3 mTorr argon, 4 cm inner radius, 20 cm outer radius)



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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