PLASMA PROCESSING IN THE 21ST CENTURY

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OUTLINE

- The nanoelectronics revolution
- Plasma etching
- Dual frequency capacitive discharges
- Decoupling high and low frequencies
- Standing wave and skin effects
- Conclusions

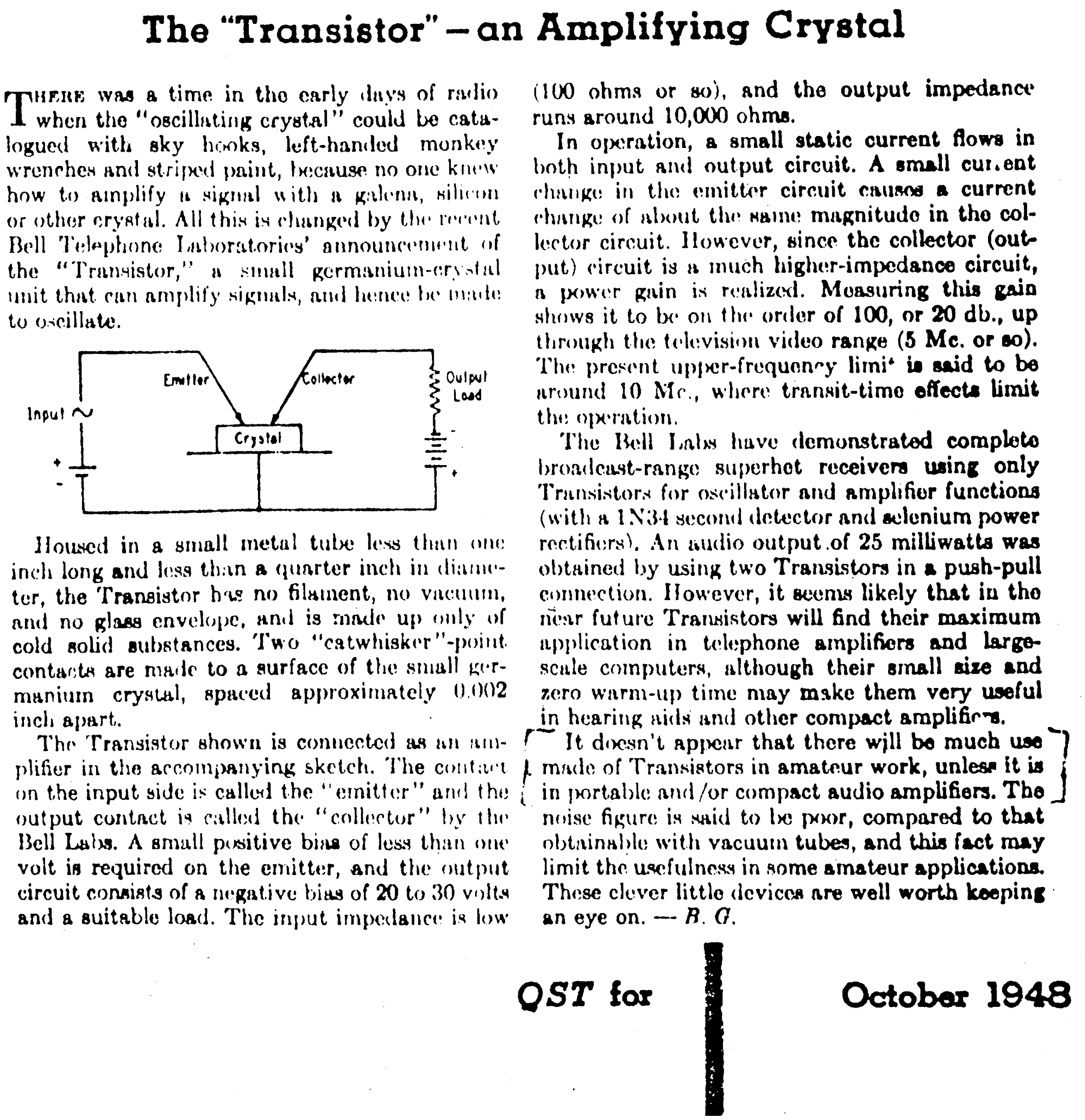
THE NANOELECTRONICS REVOLUTION

- Transistors/chip doubling every 2 years since 1959
- 500,000-fold decrease in cost for the same performance
- In 20 years one computer as powerful as all those in Silicon Valley today

EQUIVALENT AUTOMOTIVE ADVANCE

- 4 million km/hr
- 1 million km/liter
- Never break down
- Throw away rather than pay parking fees
- 3 cm long × 1 cm wide
- Crash 3× a day

THE INVENTION OF THE TRANSISTOR



The "Transistor" – an Amplifying Crystal

There was a time in the early days of radio when the "oscillating crystal" could be catalogued with sky hooks, left-handed monkey wrenches and striped paint, because no one knew how to amplify a signal with a galena, silicon or other crystal. All this is changed by the recent Bell Telephone Laboratories' announcement of the "Transistor," a small germanium-crystal unit that can amplify signals, and hence be made to oscillate.

Housed in a small metal tube less than one inch long and less than a quarter inch in diameter, the Transistor has no filament, no vacuum, and no glass envelope, and is made up only of cold solid substances. Two "catwhisker"-point contacts are made to a surface of the small germanium crystal, spaced approximately 0.002 inch apart.

The Transistor shown is connected as an amplifier in the accompanying sketch. The contact on the input side is called the "emitter" and the output contact is called the "collector" by the Bell Labs. A small positive bias of less than one volt is required on the emitter, and the output circuit consists of a negative bias of 20 to 30 volts and a suitable load. The input impedance is low (100 ohms or so), and the output impedance runs around 10,000 ohms.

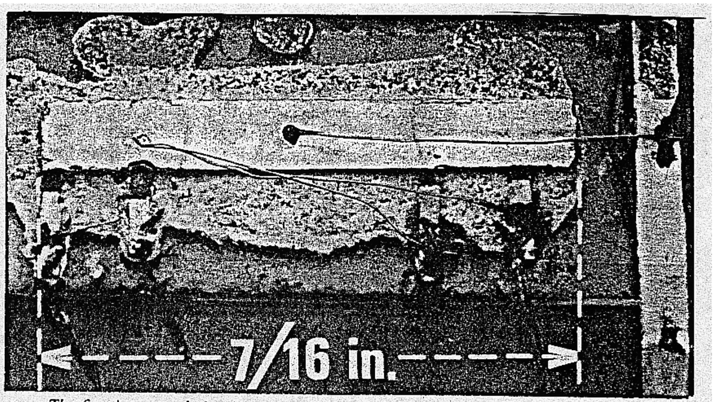
In operation, a small static current flows in both input and output circuit. A small current change in the emitter circuit causes a current change of about the same magnitude in the collector circuit. However, since the collector (output) circuit is a much higher-impedance circuit, a power gain is realized. Measuring this gain shows it to be on the order of 100, or 20 db., up through the television video range (5 Mc. or so). The present upper-frequency limit is said to be around 10 Mc., where transit-time effects limit the operation.

The Bell Labs have demonstrated complete broadcast-range superhet receivers using only Transistors for oscillator and amplifier functions (with a 1N34 second detector and selenium power rectifiers). An audio output of 25 milliwatts was obtained by using two Transistors in a push-pull connection. However, it seems likely that in the near future Transistors will find their maximum application in telephone amplifiers and large-scale computers, although their small size and zero warm-up time may make them very useful in hearing aids and other compact amplifiers.

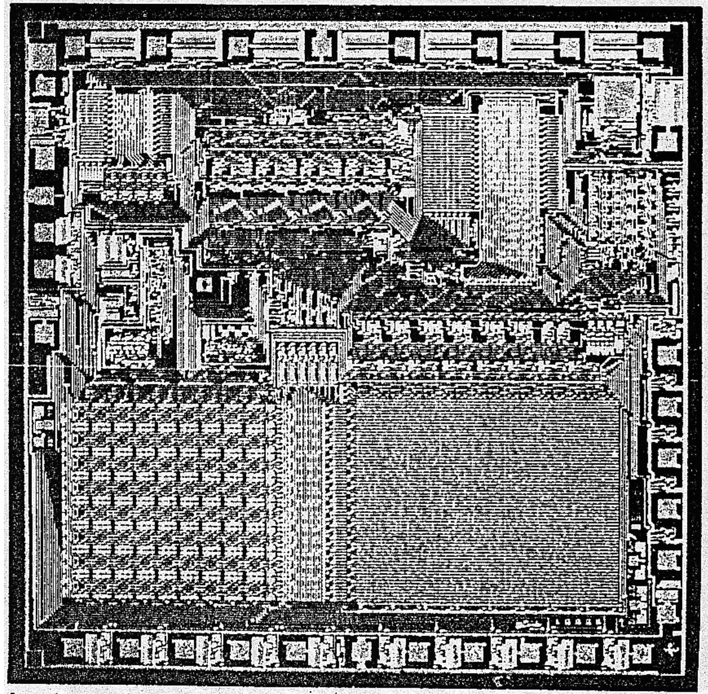
It doesn't appear that there will be much use made of Transistors in amateur work, unless it is in portable and/or compact audio amplifiers. The noise figure is said to be poor, compared to that obtainable with vacuum tubes, and this fact may limit the usefulness in some amateur applications. These clever little devices are well worth keeping an eye on. — *B. G.*

QST for October 1948

FIRST INTEGRATED CIRCUIT AND MICROPROCESSOR



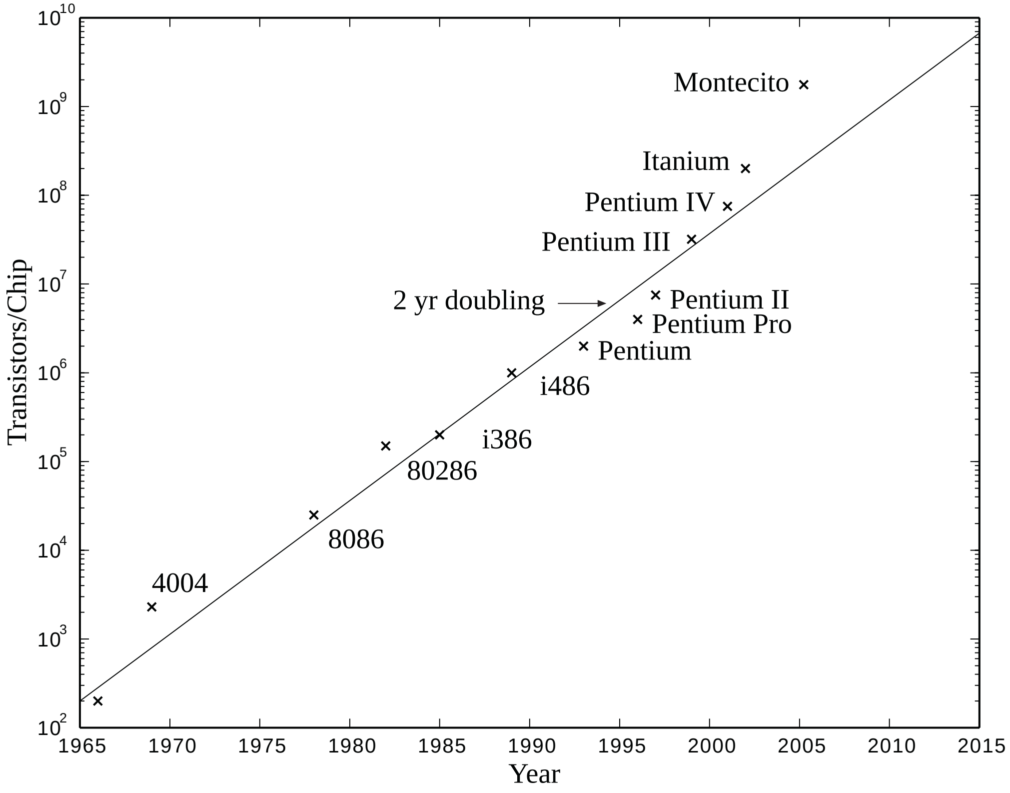
The first integrated circuit was made in 1958 by Jack Kilby of Texas Instruments.



Less than two decades later, engineers put a complete microcomputer on a chip. [Source: Texas Instruments, Inc.]

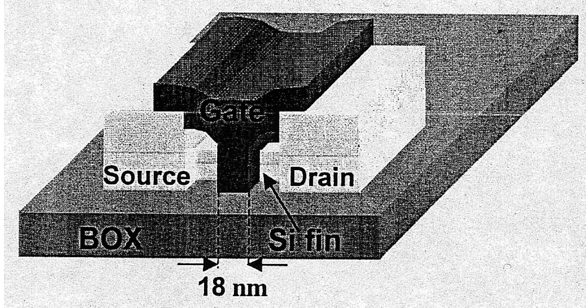
MOORE'S LAW

- "Transistors/chip double every 18 months" — Gordon Moore (1965) (Transistor size shrinking; chip size growing)
- Now a self-fulfilling prophecy

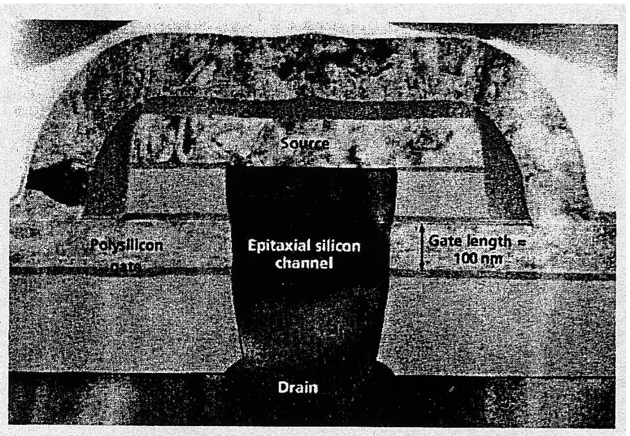


- "No exponential is forever. . . but we can delay 'forever"' (Gordon Moore, 2003)

DOUBLE/TRI GATE TRANSISTORS



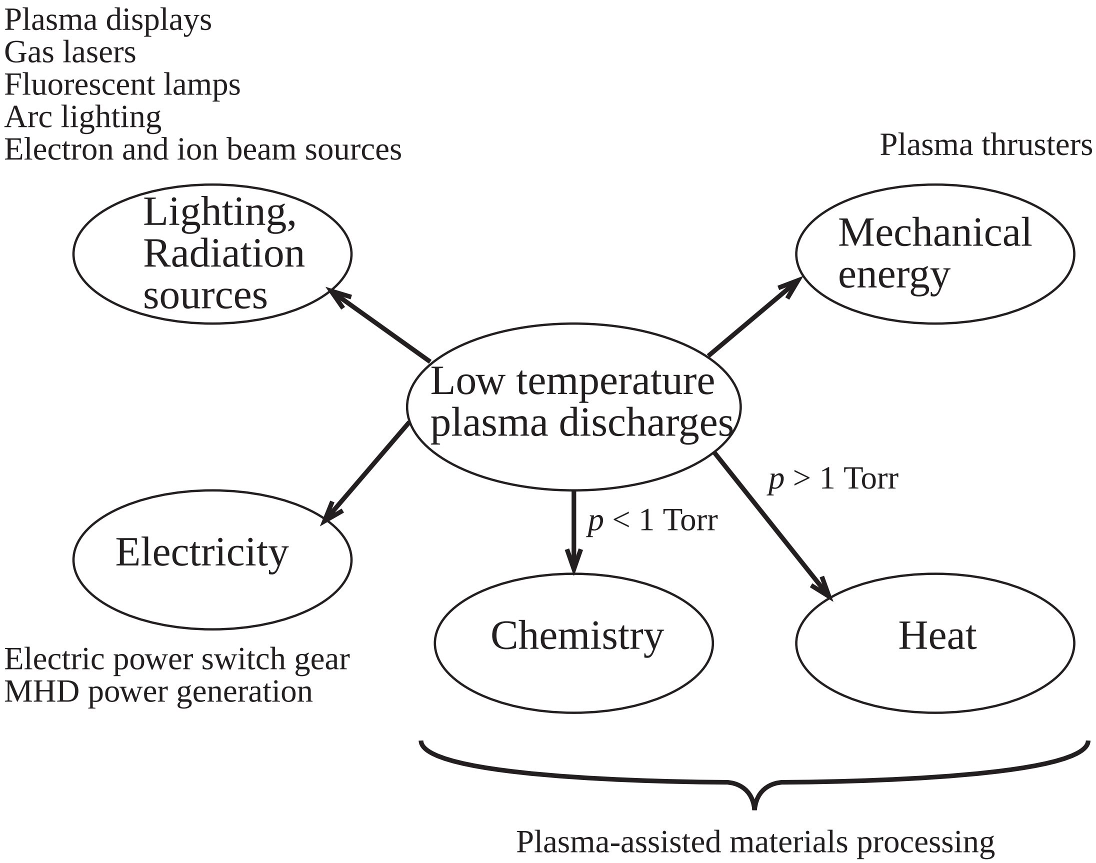
FinFET (UC Berkeley)



Vertical Transistor (Lucent)

- Both structures can be built with current ic fabrication techniques
- CMOS can be scaled another 20 years!
- State of the art (2005):
  - In manufacture:
    50 nm (200 atoms) gate length
    1.5 nm (5 atoms) gate oxide thickness
  - Smallest fabricated CMOS transistor (FinFET, UC Berkeley):
    12 nm (48 atoms) gate length
  - Limiting gate length from simulations (desktop ic):
    4 nm (16 atoms) gate length

LOW TEMPERATURE INDUSTRIAL DISCHARGES



Plasma displays
Gas lasers
Fluorescent lamps
Arc lighting
Electron and ion beam sources

Lighting, Radiation sources

Plasma thrusters

Mechanical energy

Low temperature plasma discharges

$p > 1$ Torr

$p < 1$ Torr

Electricity

Chemistry

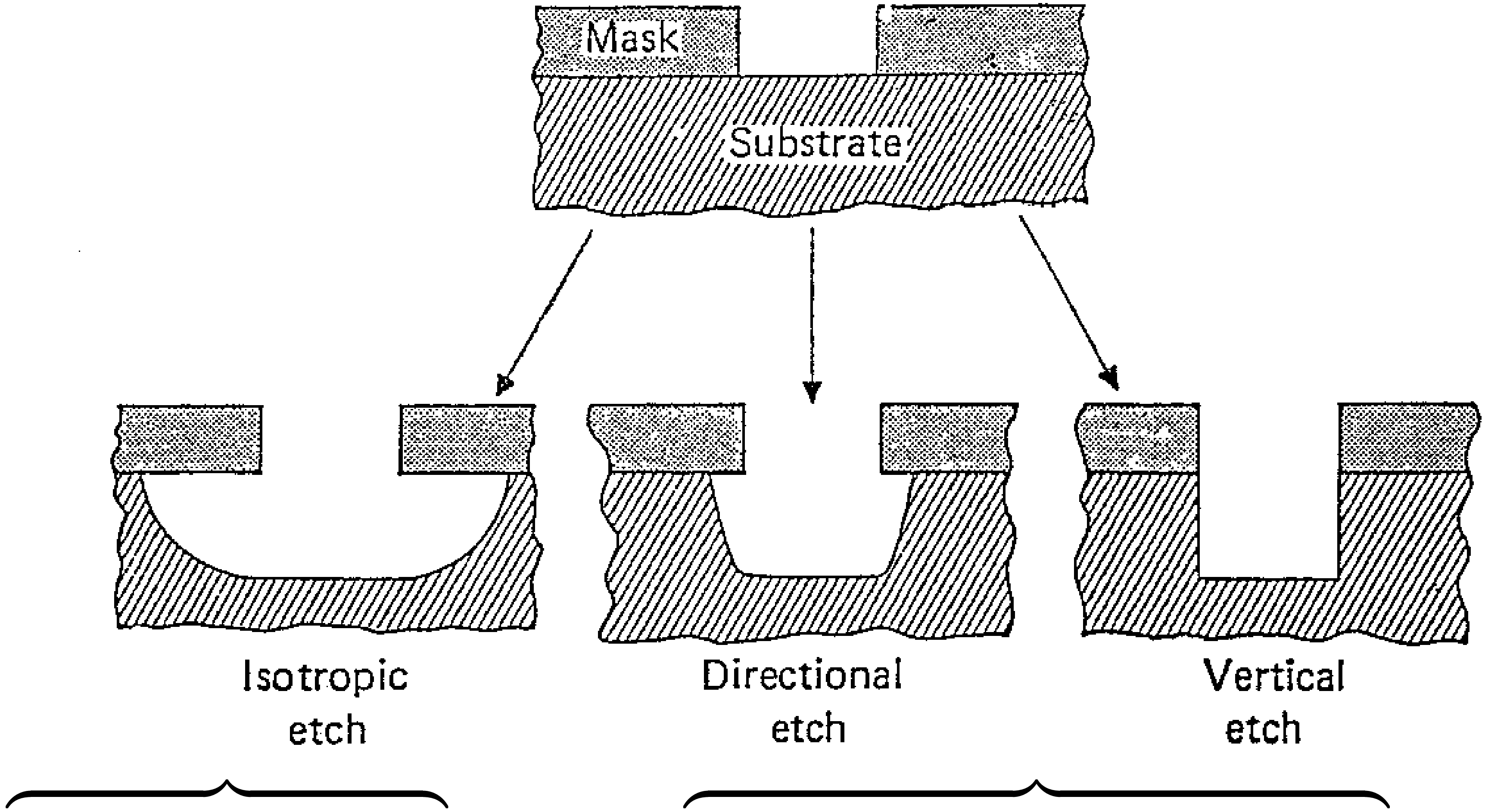
Heat

Electric power switch gear
MHD power generation

Plasma-assisted materials processing

Microelectronics etching, deposition, oxidation, implantation, passivation
Liquid crystal display and solar cell depositions
Aerospace and automotive ceramic and metal coatings, films, paints
Metallurgical melting, refining, welding, cutting, hardening
Ceramics synthesis, ultrapure powders, nanopowders
Food packaging permeability barriers
Textile adhesion treatments
Medical materials bio-compatibility treatments, sterilization, cleaning
Architectural and automotive glass coatings

ANISOTROPIC ETCHING



Wet etching

Ion-enhanced plasma etching

RECIPE FOR PLASMA ETCHING

1. Start with inert molecular gas CF_4
2. Make discharge to create reactive species:

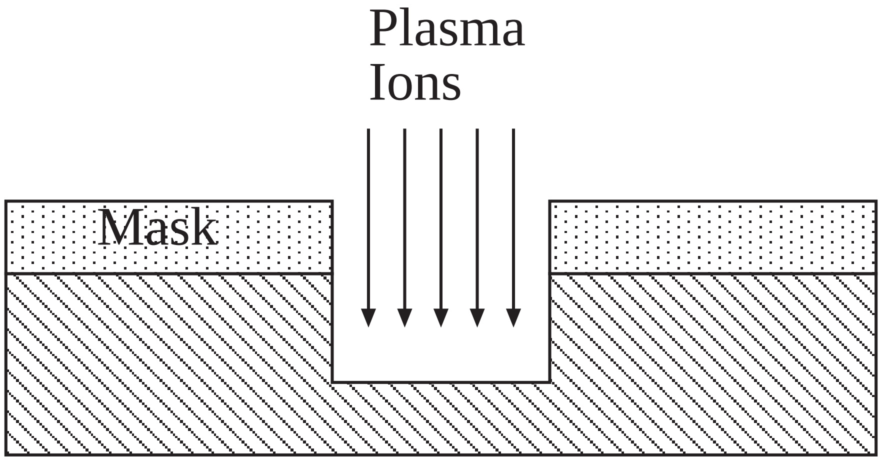
$$CF_4 \longrightarrow CF_3 + F$$

3. Species reacts with material, yielding volatile product:

$$Si + 4F \longrightarrow SiF_4 \uparrow$$

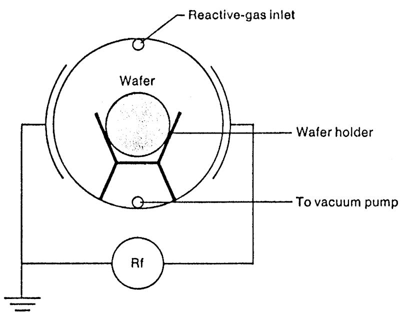
4. Pump away product
5. Source of anisotropy:

   Energetic ions bombard trench bottom, but not sidewalls:
   - (a) Increase etching reaction rate at trench bottom
   - (b) Clear passivating films from trench bottom

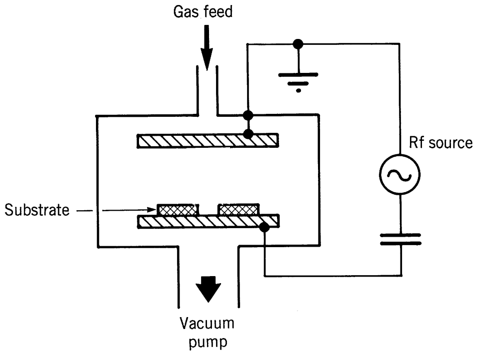


EVOLUTION OF ETCHING DISCHARGES

FIRST GENERATION

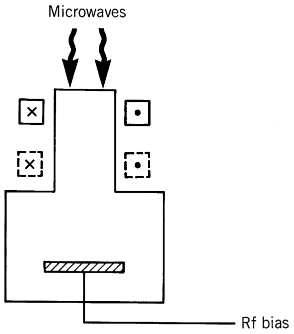


Barrel etcher
(Isotropic etch)

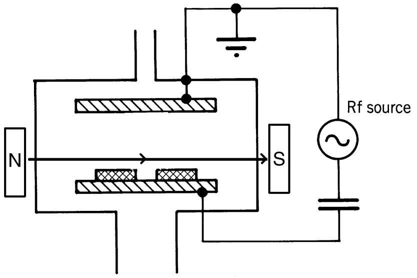


Capacitive
(Anisotropic etch)

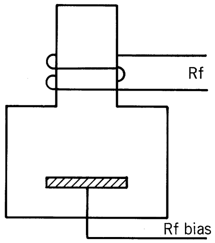
SECOND GENERATION



ECR



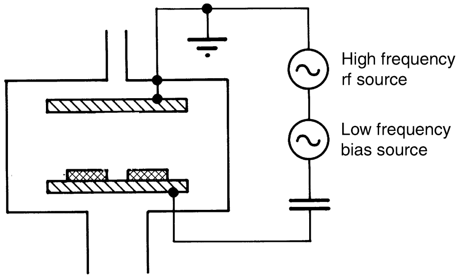
Magnetically enhanced
capacitive discharge



Inductive

THIRD GENERATION

?



Dual frequency
capacitive discharge

?

WHY DUAL FREQUENCY CAPACITIVE DISCHARGES?

- Motivation for capacitive discharge
    - Low cost
    - Robust uniformity over large area
    - Control of dissociation (fluorine)

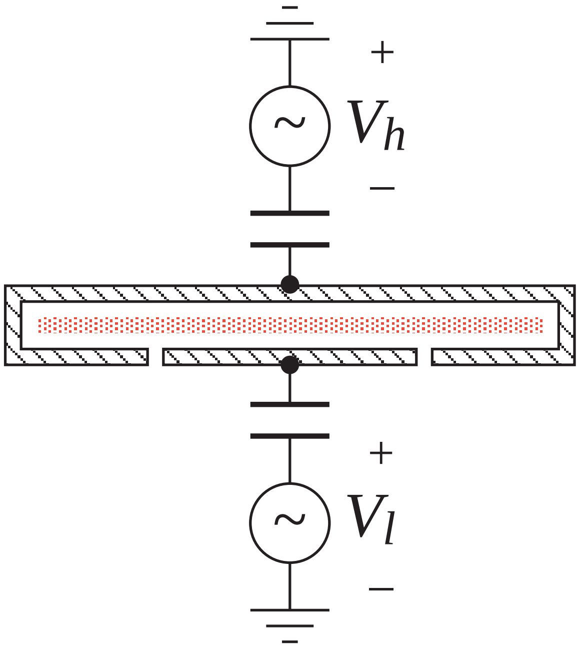
- Motivation for dual frequency
    - Independent control of ion flux and ion energy

High frequency voltage controls ion flux
Low frequency controls ion energy

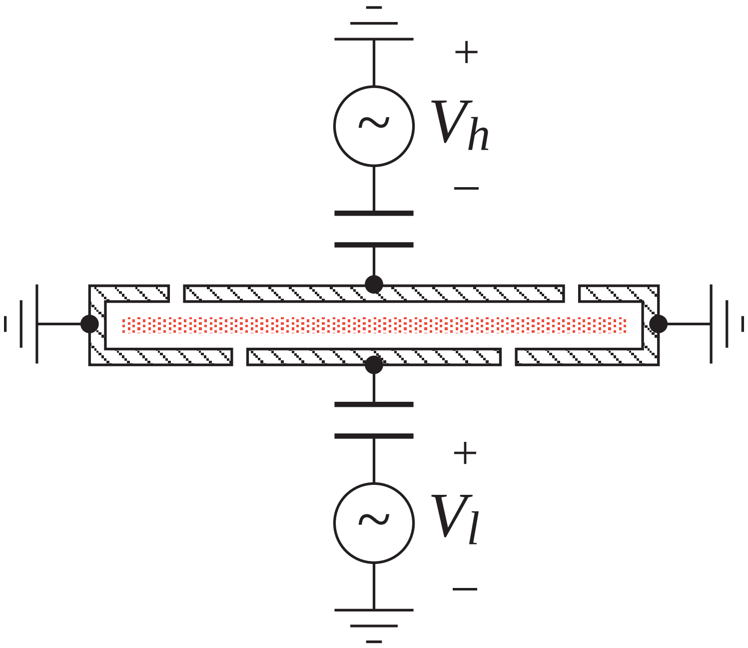
- A critical application for dielectric etch

TYPICAL OPERATING CONDITIONS

- $R \sim 15\text{–}30$ cm, $L \sim 1\text{–}3$ cm
- $p \sim 30\text{–}300$ mTorr, $C_4F_8/O_2/Ar$ feedstock
- High frequency $f_h \sim 27.1\text{–}160$ MHz, $V_h \sim 200\text{–}500$ V
- Low frequency $f_l \sim 2\text{–}13.56$ MHz, $V_l \sim 500\text{–}1500$ V
- Absorbed powers P_h, $P_l \sim 500\text{–}3000$ W



Diode (2 electrodes)



Triode (3 electrodes)

CONTROL OF PLASMA DENSITY

- Particle balance $\Longrightarrow$ electron temperature T_e (independent of plasma density)

$$\Longrightarrow \mathrm{T}_e \sim 2\text{–}6 \text{ eV}$$

- Electron power balance $\Longrightarrow$ plasma density n (once electron temperature T_e is known)

$$n \ \propto \ P_e$$

- In these discharges

$$P_e = \ \text{power absorbed by electrons} \ \propto \ \omega^2 V_{\mathrm{rf}}$$

$$\Longrightarrow n \ \propto \ \omega^2 V_{\mathrm{rf}}$$

- Make $\omega_h^2 V_h \gg \omega_l^2 V_l$

$$\boxed{V_h \text{ controls plasma density (ion flux)}}$$

CONTROL OF ION ENERGY

- Ion bombarding energy is total dc bias voltage across sheath

$$\mathcal{E}_i \sim |V_h + V_l|$$

- Make $V_l \gg V_h$

$$\boxed{V_l \text{ controls ion energy}}$$

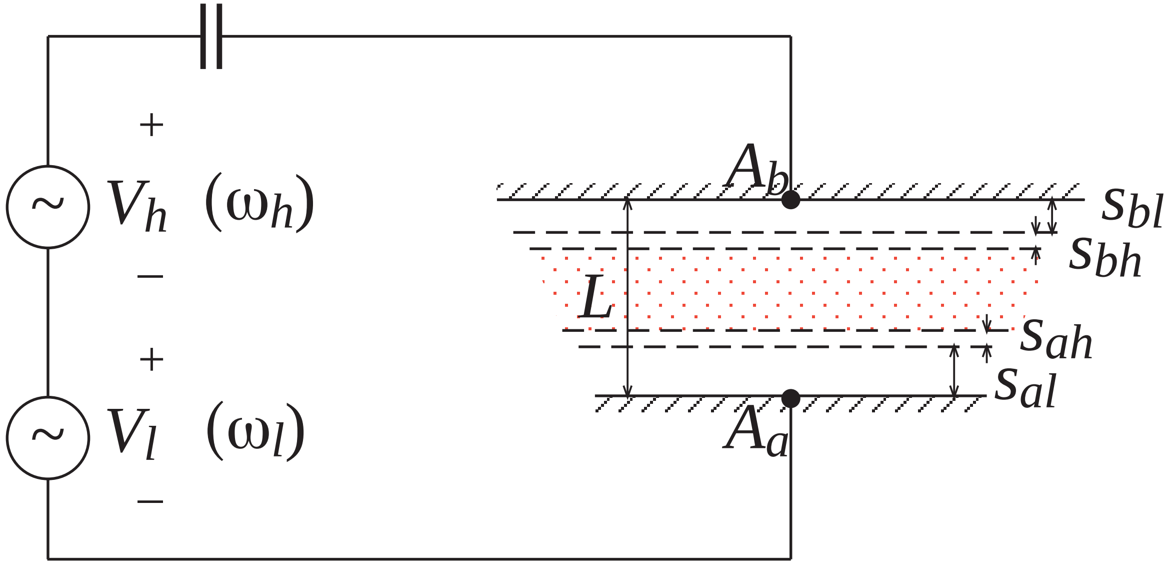
- Combined condition for independent control of ion flux and energy

$$\boxed{\frac{\omega_h^2}{\omega_l^2} \gg \frac{V_l}{V_h} \gg 1}$$

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

GLOBAL MODEL OF DISCHARGE

- Asymmetric diode (plate areas A_a and A_b)

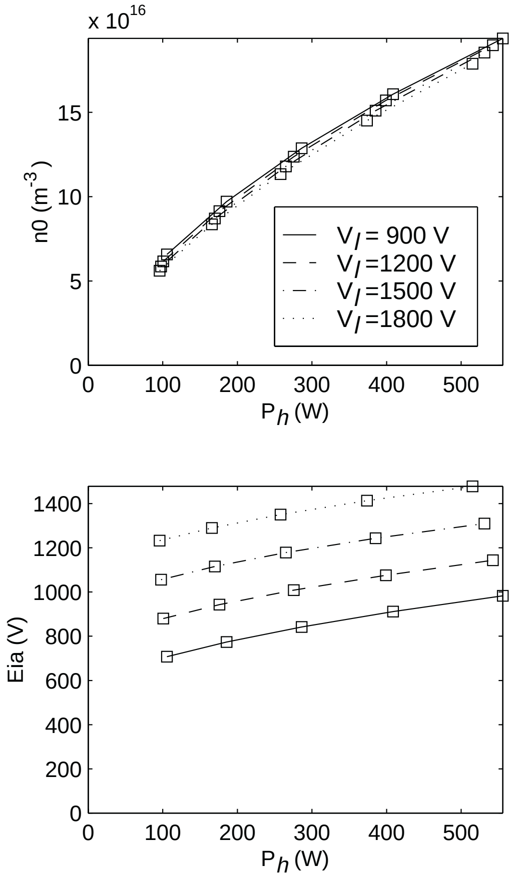


- Low frequency Child law sheaths
- High frequency homogeneous sheaths
- Ion particle balance, and electron and ion power balance
- All high and low frequency heating terms

RESULTS FOR 27.1/2 AND 60/2 MHz

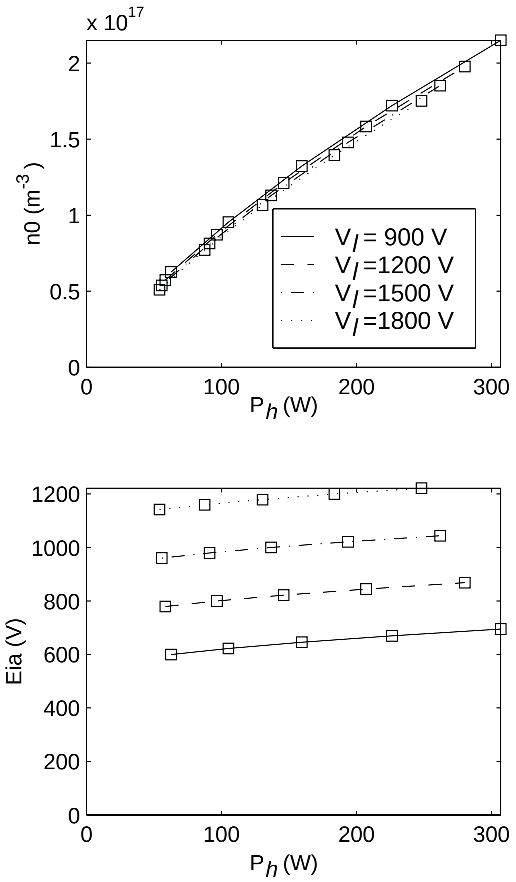
- $A_a = 544\ \text{cm}^2$, $A_b = 707\ \text{cm}^2$, $L = 1.6$ cm, $p = 190$ mTorr argon

$f_h = 27.1$ MHz



The high/low frequency decoupling is good but not perfect

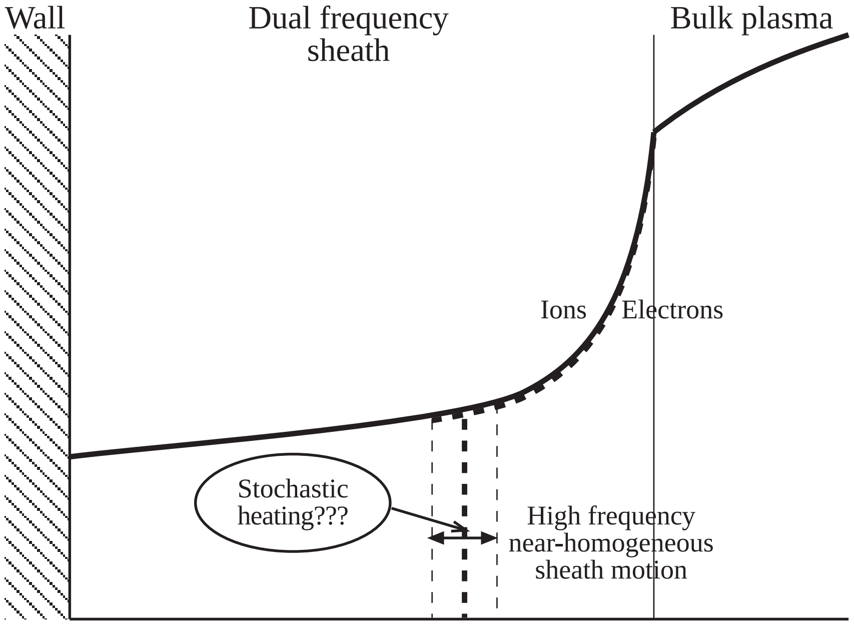
$f_h = 60$ MHz

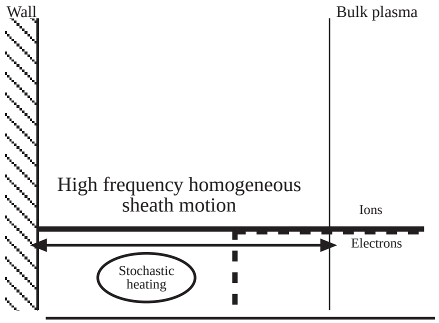


The high/low frequency decoupling is better but not perfect

1. DUAL FREQUENCY STOCHASTIC HEATING?

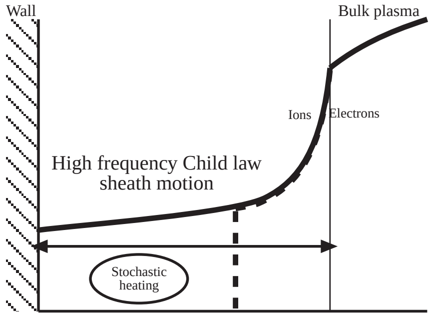
- High frequency sheath oscillates over nearly uniform ion density





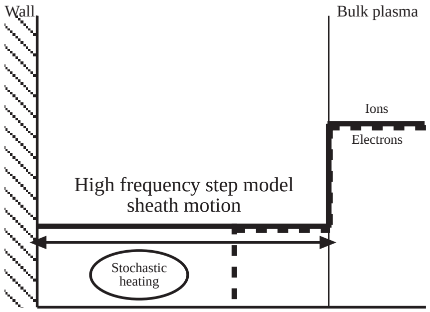
(Lieberman, 1988)

$S_{\text{stoc}} = 0$



(Lieberman, 1988)

$S_{\text{stoc}} \neq 0$



(Kaganovich, 2002)

$S_{\text{stoc}} \neq 0$

2. COUPLING OF VOLTAGES?

- Additive assumption?

$$\mathcal{E}_i \approx 0.41\,(V_l + V_h)$$

- Current-driven homogeneous model gives

$$\mathcal{E}_i = \frac{3}{8}\left(V_l + V_h - \underbrace{\frac{2}{3}\,\frac{V_l V_h}{V_l + V_h}}_{\text{cross term}}\right)$$

  Worst case for crossterm is $\frac{1}{6}(V_l + V_h)$ when $V_l = V_h$

- Cross term for Child law sheaths?
  Voltage-driven discharges?
  Real systems driven through matching networks?

3. ION POWER SUPPLIED BY SOURCES?

- For single frequency capacitive discharges

$$\text{Electron power} = P_e \propto \omega^2 V_{\text{rf}} \propto n$$

$$\text{Ion power} = P_i \propto \omega^2 V_{\text{rf}}^2 \propto n V_{\text{rf}} \gg P_e$$

$\Rightarrow$ RF power source supplies P_e and P_i

- For dual frequency discharges

$$\text{Electron power} = P_e \propto \omega_h^2 V_h \propto n$$

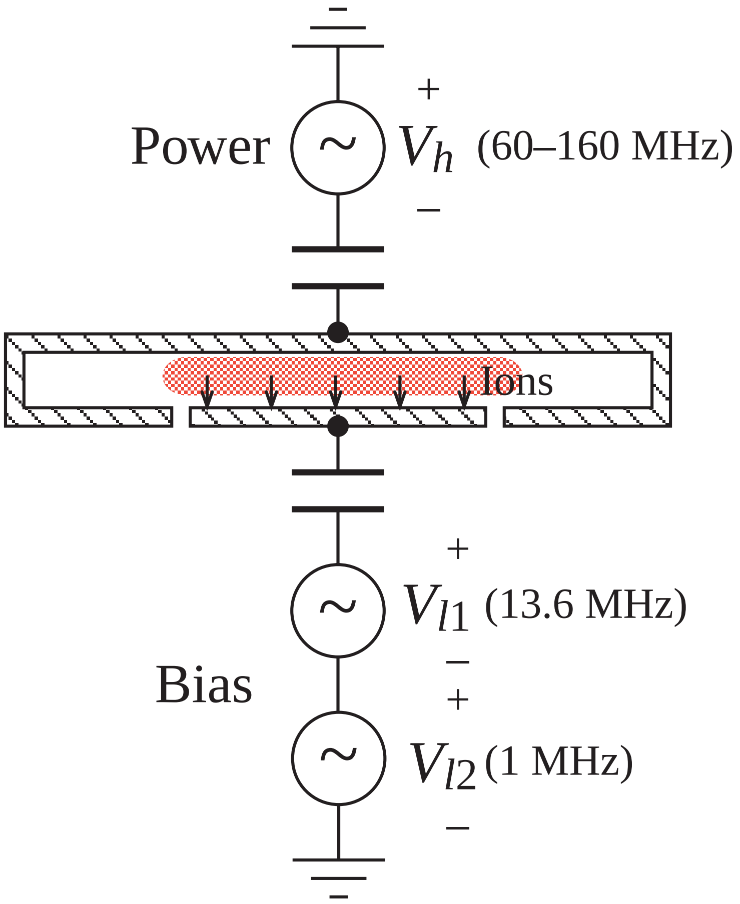
$$\text{Ion power} = P_i \propto \omega^2 V_h \left(V_l + V_h\right) \gg P_e$$

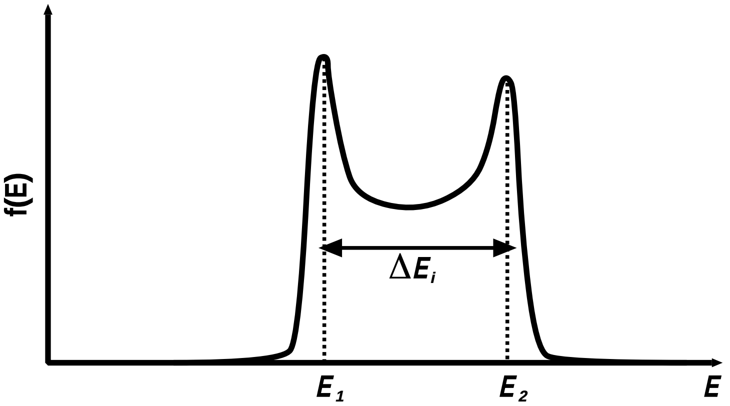
High frequency source supplies P_e

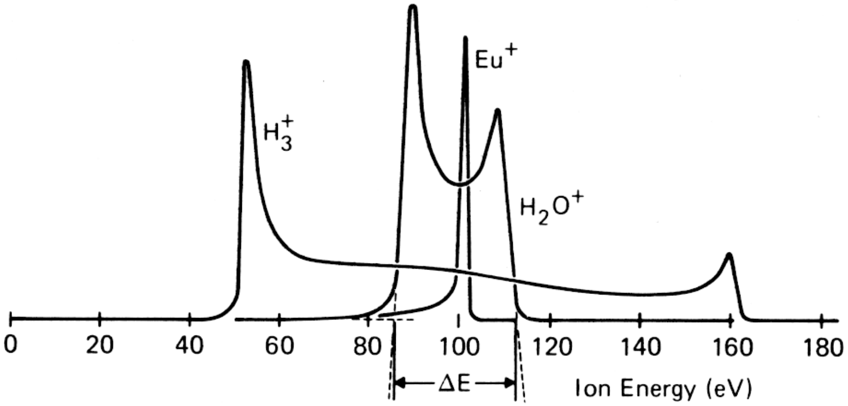
Which sources supply the ion power? Is $P_{il}/P_{ih} = V_l/V_h$?

TRIPLE FREQUENCY RF DISCHARGE

- IEDF depends on rf bias period/ion transit time across sheath



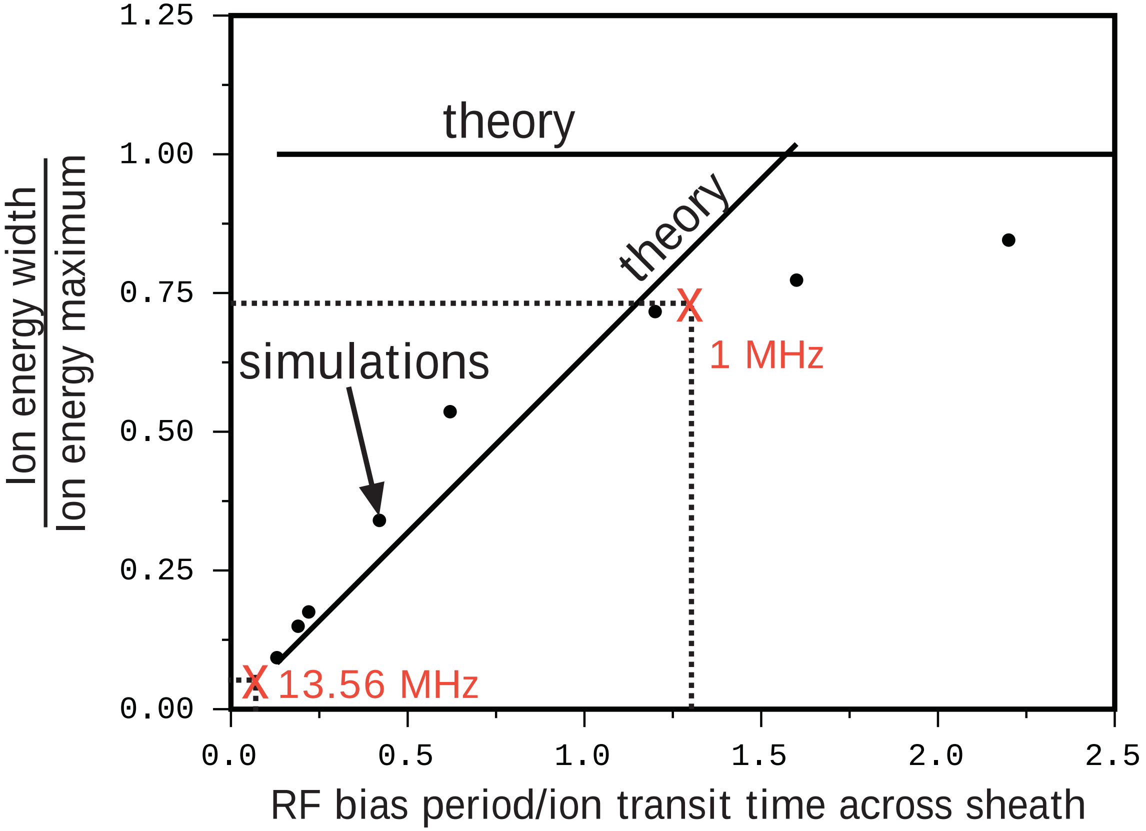




Coburn and Kay (1972)

WIDTH OF ION ENERGY DISTRIBUTION

(Argon, 600 V rf bias, 10^{11} cm^{-3} density)



1. V. Georgieva, A. Bogaerts, and R. Gijbels, *Phys. Rev. E* **69**, 026406 (2004)
2. J.K. Lee, O.V. Manuilenko, N.Y. Babaeva, H.C. Kim, and J.W. Shon, *Plasma Sources Sci. Technol.* **14**, 89 (2005)
3. S. Shannon, D. Hoffman, J.G. Yang, A. Paterson, and J. Holland, submitted to *Journal of Applied Physics* (May 2005)

HIGH FREQUENCY ELECTROMAGNETIC EFFECTS

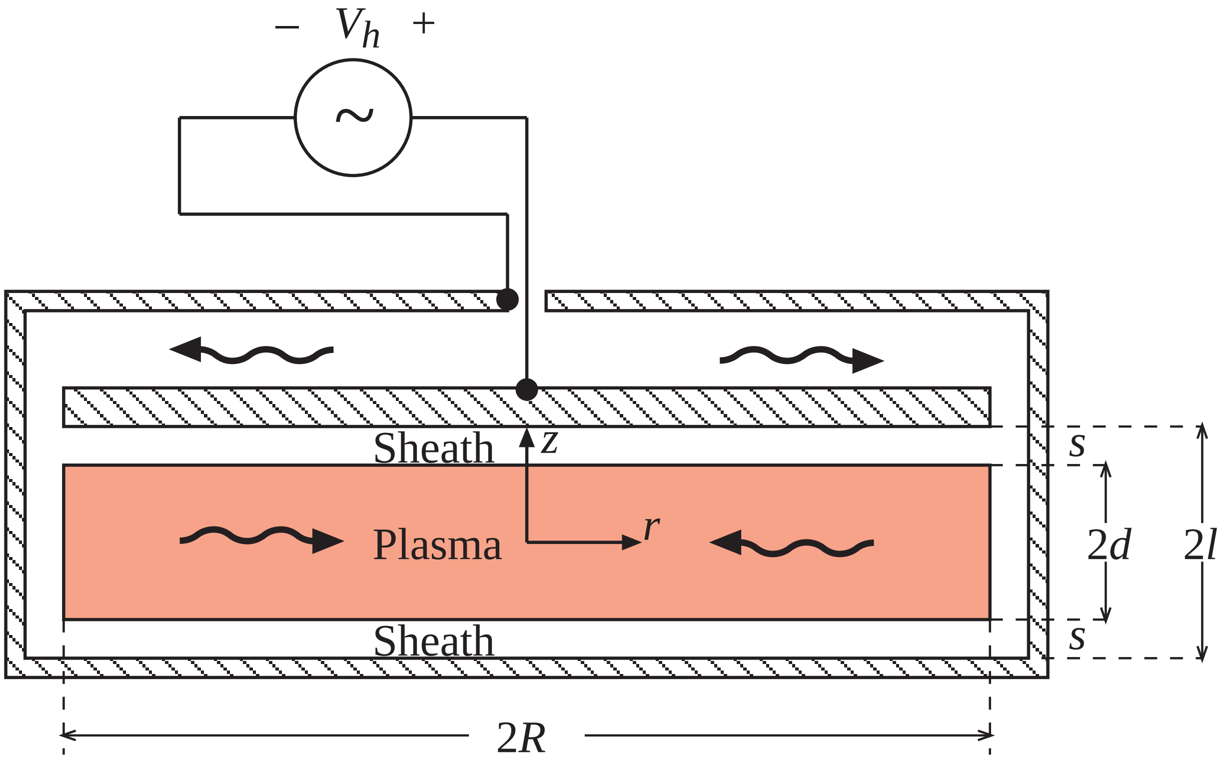
- High frequency and large area ⇒ $\boxed{\text{standing wave effects}}$
- High frequency ⇒ high density ⇒ $\boxed{\text{skin effects}}$
- Previous studies of capacitive discharges mostly based on electrostatics, not full set of Maxwell equations

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

M.A. Lieberman, J.P. Booth, P. Chabert, J.M. Rax, and M.M. Turner, *Plasma Sources Sci. Technol.* **11**, 283 (2002)

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

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

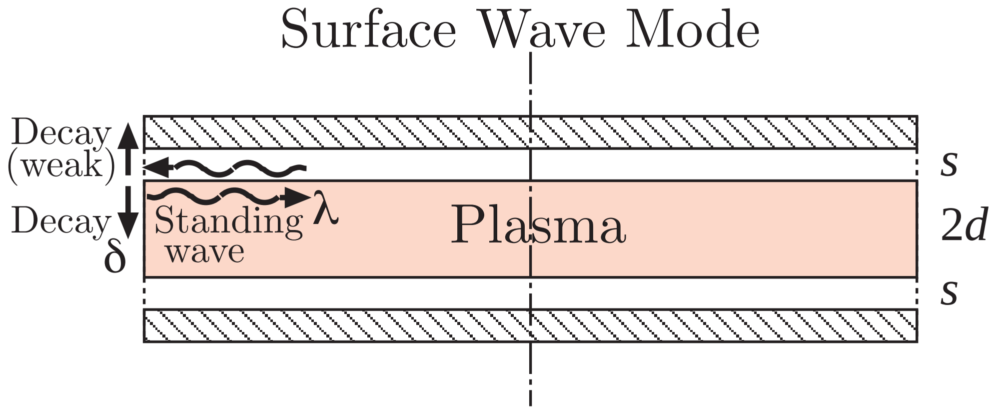
$$\frac{1}{r}\frac{\partial(rH_\phi)}{\partial r} = j\omega\epsilon_0\kappa_p E_z \qquad \text{(capacitive field)}$$

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

- Choose some uniform density n_e and sheath width s
- Solve with appropriate boundary conditions

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:

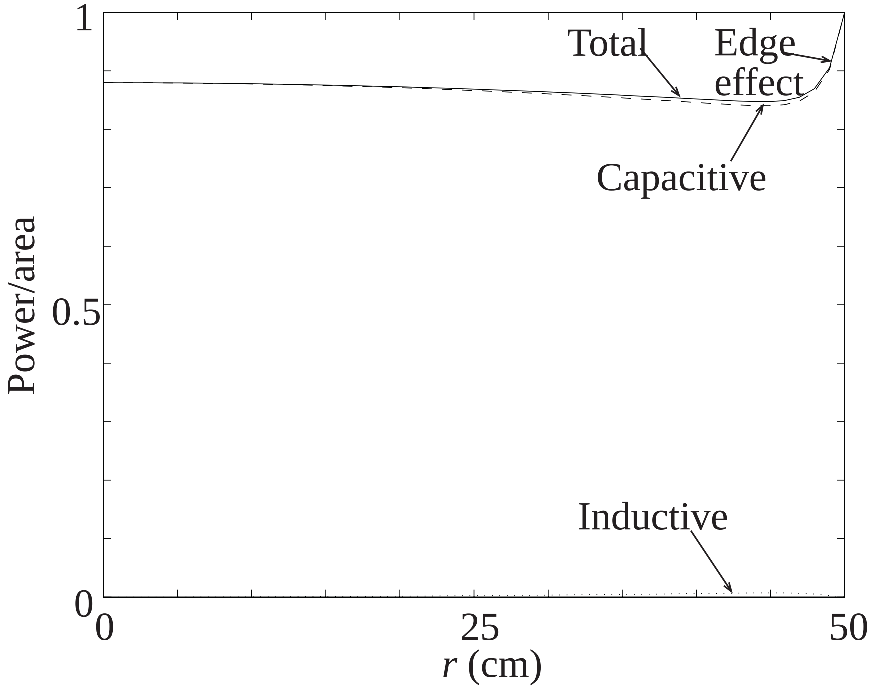
$$\boxed{\delta \sim \frac{c}{\omega_p}}$$

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

POWER DEPOSITION VERSUS RADIUS AT 13.56 MHz

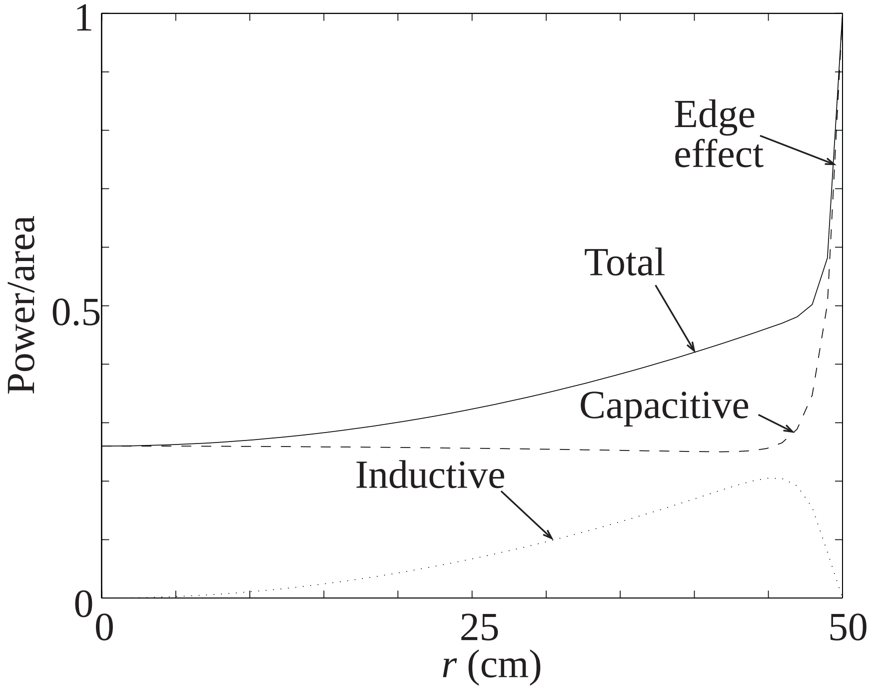
- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm ($\lambda \approx 9$–10 m)
- $P_{\rm cap}$ (dash), $P_{\rm ind}$ (dot) and $P_{\rm tot}$ (solid) as a function of r

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



Small standing wave and skin effects

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

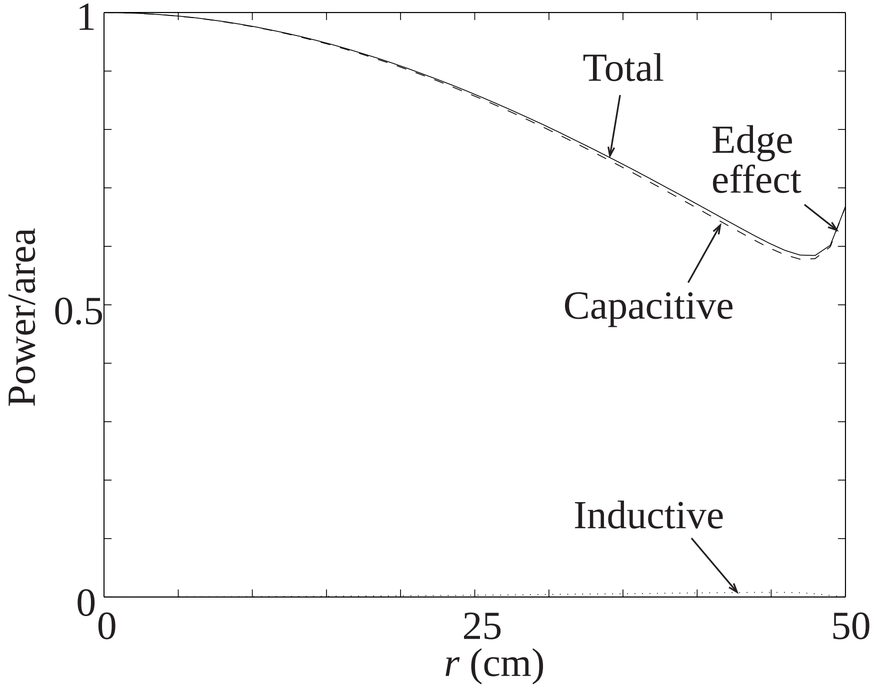


Large skin effect

POWER DEPOSITION VERSUS RADIUS AT 40.7 MHz

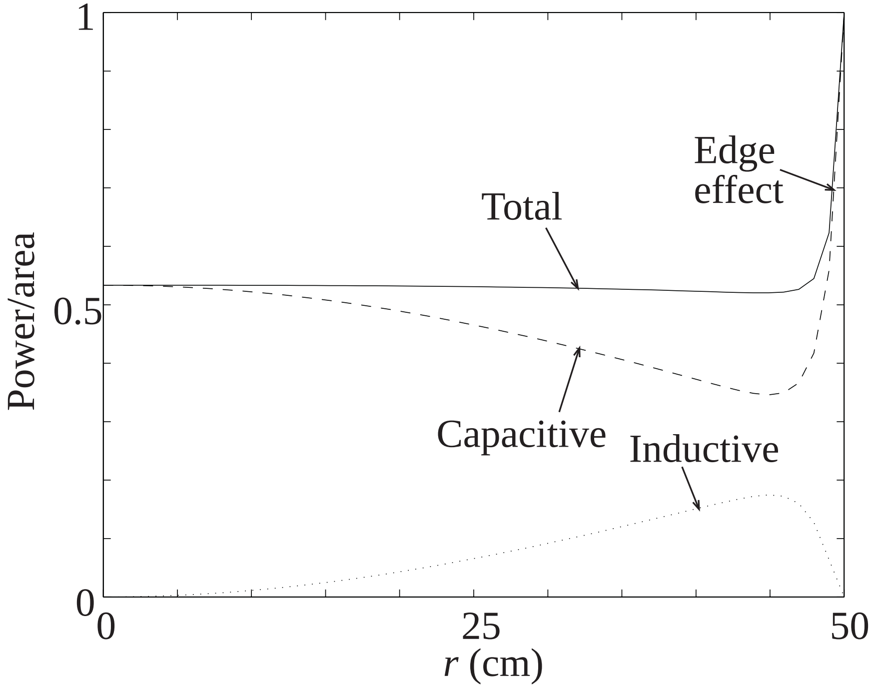
- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm ($\lambda \approx 3$ m)
- $P_{\rm cap}$ (dash), $P_{\rm ind}$ (dot) and $P_{\rm tot}$ (solid) as a function of r

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



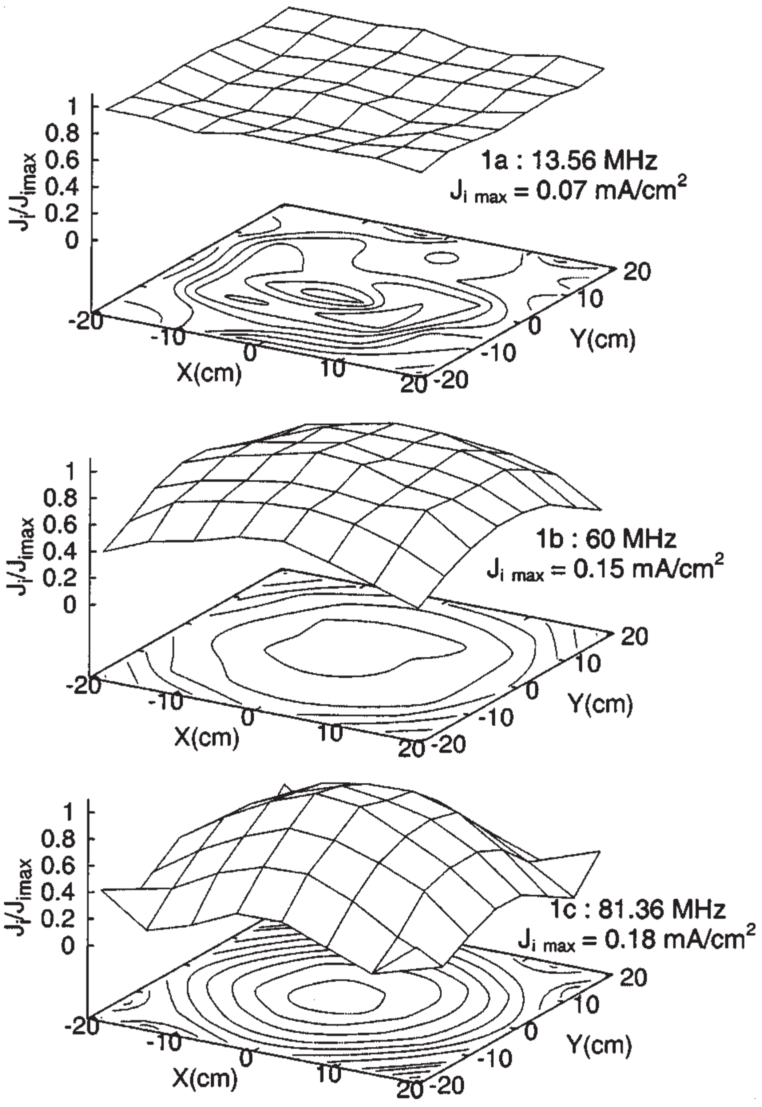
Large standing wave effect

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



Standing wave and skin effects cancel

EXPERIMENTAL RESULTS FOR STANDING WAVES



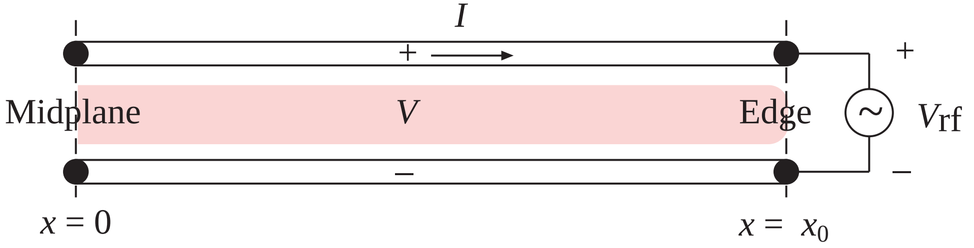
20×20 cm discharge
$p = 150$ mTorr
50 W rf power

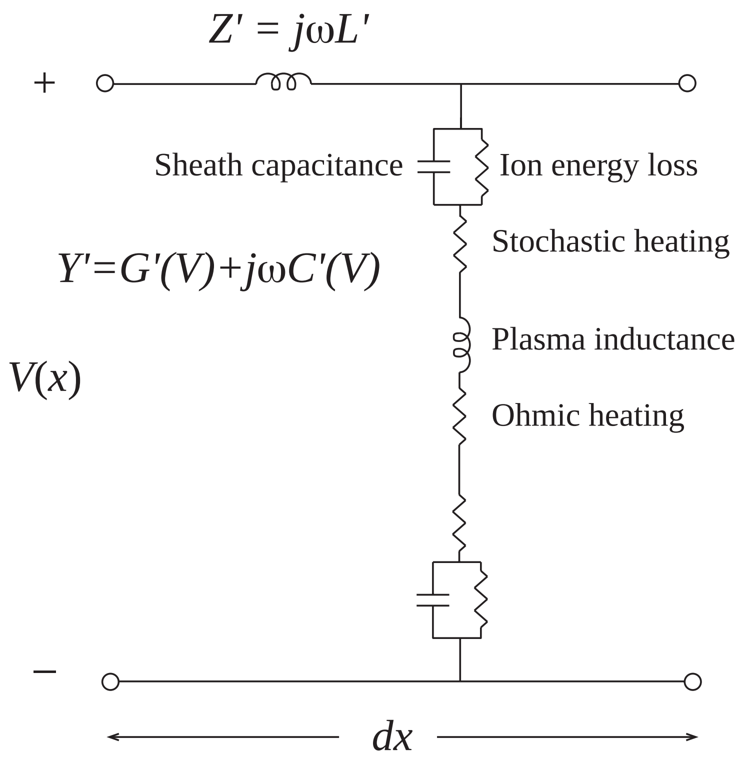
The standing wave effect is seen at 60 MHz and is more pronounced at 81.36 MHz

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

TRANSMISSION LINE MODELS

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



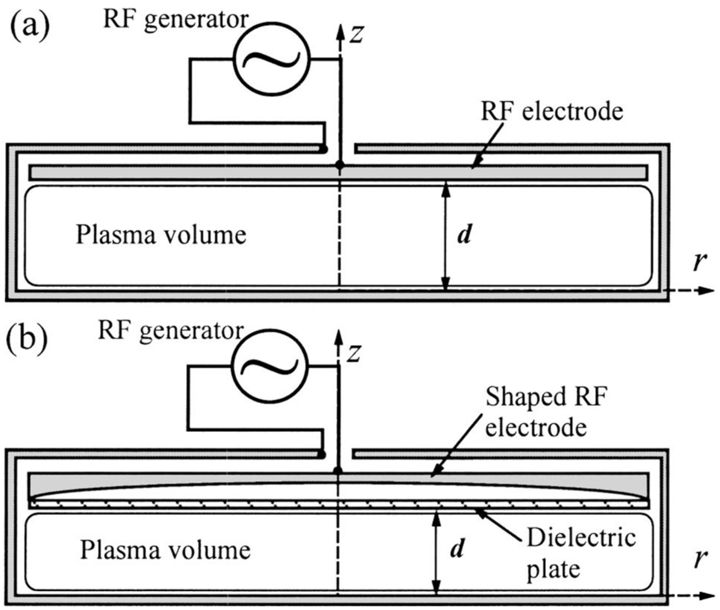


$$\boxed{\lambda/\lambda_0 \approx 40 V_{\rm rf}^{1/10} L^{-1/2} f^{-2/5}}$$

P. Chabert, J.L. Raimbault, J.M. Rax, and M.A. Lieberman,
Phys. Plasmas **11**, 1775 (2004)

SUPPRESSION OF STANDING WAVE EFFECTS

- Shaped electrode (and diel plate) eliminate standing wave effects



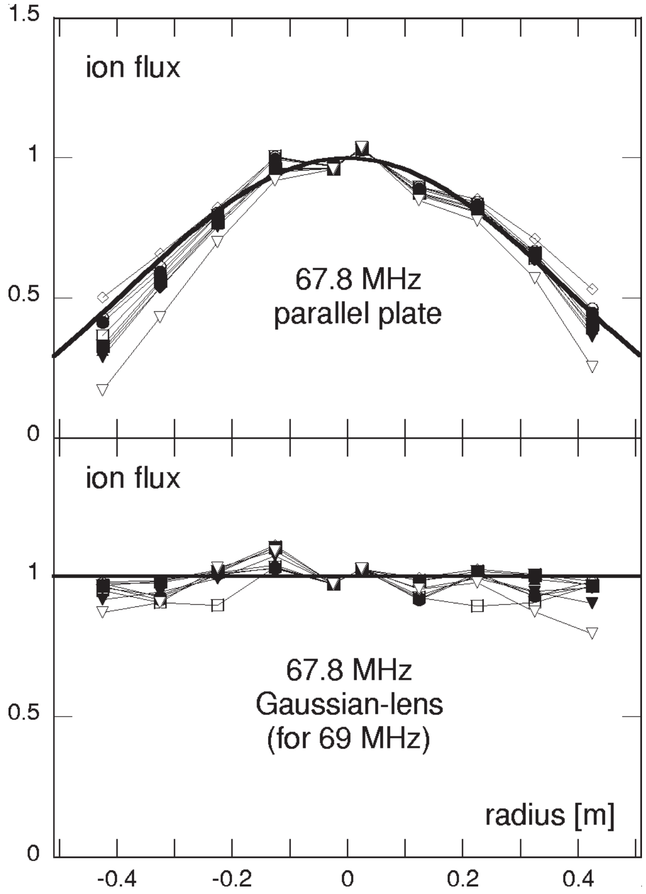
- Increased overall thickness in center compared to edge keeps voltage across discharge section constant
- The electrode shape is a Gaussian, independent of the plasma properties

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

P. Chabert, J.L. Raimbault, J.M. Rax, and A. Perret, *Phys. Plasmas* **11**, 4081 (2004)

EXPERIMENTAL CONFIRMATION

- 5–250 mTorr argon, 50–300 W



H. Schmitt et al, *J. Appl. Phys.* **95**, 4559 (2004)

SKIN EFFECTS?

- Skin effects $\Longrightarrow$ radial nonuniformities at high densities when

$$\delta \lesssim 0.45\,\sqrt{d\,R}$$

$\delta \propto \dfrac{1}{\sqrt{n}}$ = collisional or collisionless skin depth
d = bulk plasma half-thickness
R = discharge radius

- Control of 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.L. Raimbault, P. Levif, J.M. Rax, and M.A. Lieberman, submitted to *Physics of Plasmas*, May 2005

CONCLUSIONS

- Transistors will scale to nano-sizes — 4nm–12nm gate lengths
- Nanoelectronics drives the development of processing discharges
- Dual frequency capacitive reactors are increasingly important for next-generation dielectric etching
- The high and low frequencies can be well-decoupled
- Standing wave effects can be controlled
- Plasma processing has a bright future in the 21st century!