THE MICROELECTRONICS REVOLUTION

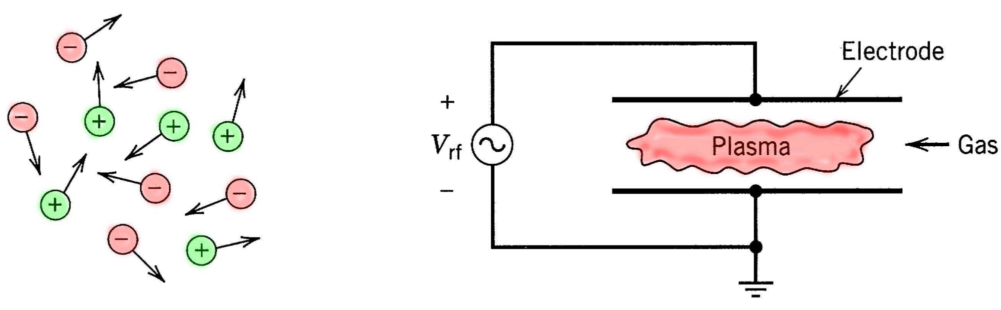
- Transistors/chip doubling every $1\frac{1}{2}$–2 years since 1959
- 500,000-fold decrease in cost for the same performance
- In 20 years one computer as powerful as all those in Silicon Valley today
- CMOS transistors with 4 nm (16 atoms) gate length

EQUIVALENT AUTOMOTIVE ADVANCE

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

PLASMAS AND DISCHARGES

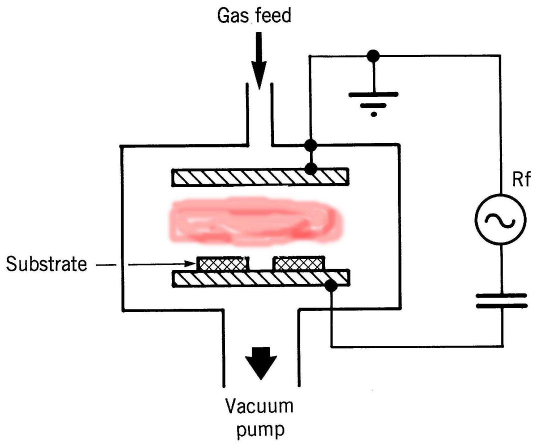
- Plasmas
  A collection of freely moving charged particles which is, on the average, electrically neutral
- Discharges
  Are driven by voltage or current sources
  Charged particle collisions with neutral particles are important
  There are boundaries at which surface losses are important
  The electrons are not in thermal equilibrium with the ions



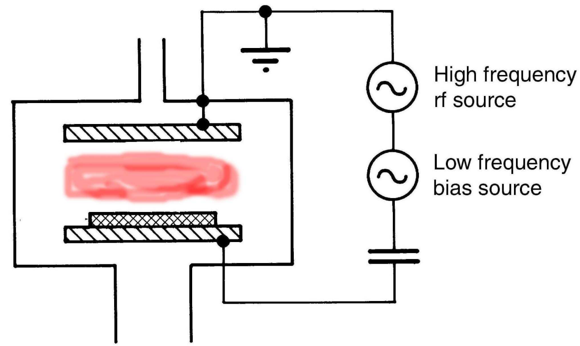
(a) (b)

- Device sizes ∼ 30 cm – 1 m
- Frequencies from DC to rf (13.56 MHz) to microwaves (2.45 GHz)

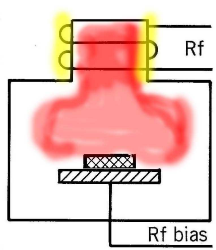
EVOLUTION OF ETCHING DISCHARGES



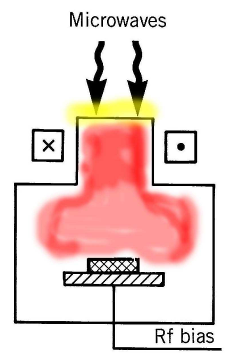
Capacitive
(Anisotropic etch)



Dual frequency capacitive discharge



Inductive

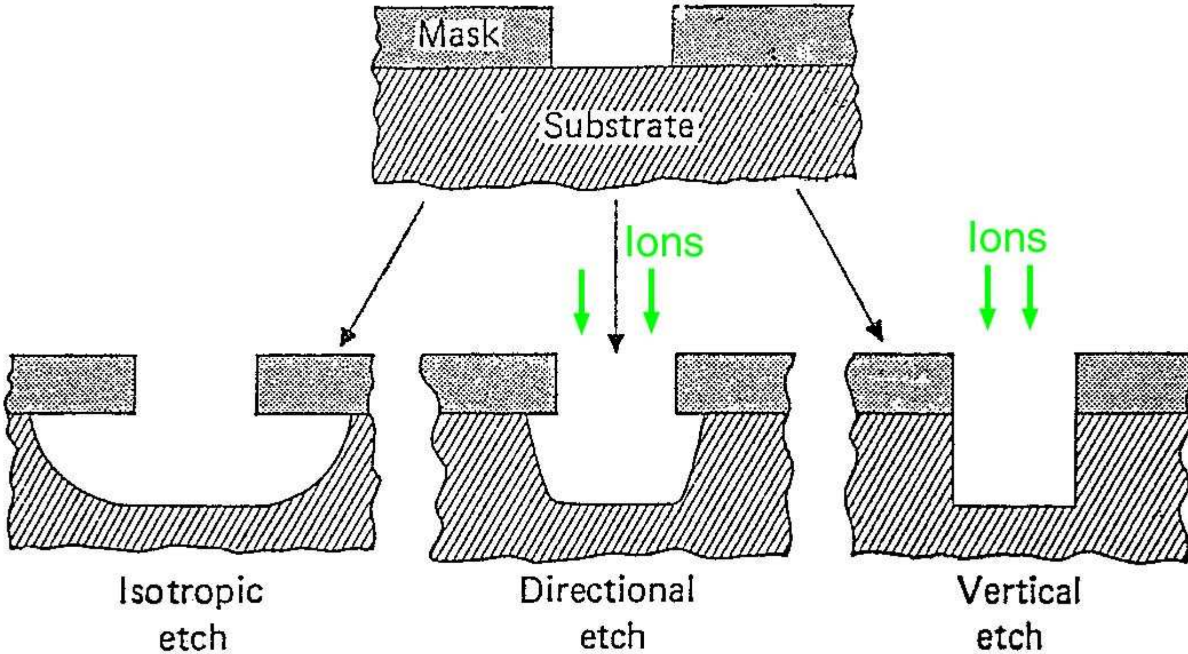


ECR

RANGE OF MICROELECTRONICS APPLICATIONS

- Etching
  Si, a-Si, oxide, nitride, III-V's
- Ashing
  Photoresist removal
- Deposition (PECVD)
  Oxide, nitride, a-Si
- Oxidation
  Si
- Sputtering
  Al, W, Au, Cu, YBaCuO
- Polymerization
  Various plastics
- Implantation
  H, He, B, P, O, As, Pd

ANISOTROPIC ETCHING



Wet Etching
Plasma Etching

Ion Enhanced Plasma Etching

ISOTROPIC PLASMA ETCHING

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

$$CF_4 \longrightarrow CF_3 + F$$

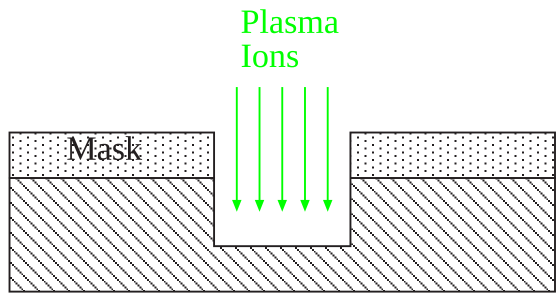
3. Species reacts with material, yielding volatile product

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

4. Pump away product
5. CF_4 does not react with Si; SiF_4 is volatile

ANISOTROPIC PLASMA ETCHING

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



UNITS AND CONSTANTS

- SI units: meters (m), kilograms (kg), seconds (s), coulombs (C)
  $e = 1.6 \times 10^{-19}$ C, electron charge $= -e$
- Energy unit is joule (J)
  Often use electron-volt

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

- Temperature unit is kelvin (K)
  Often use equivalent voltage of the temperature

$$\boxed{\mathrm{T}_e(\text{volts}) = \frac{kT_e(\text{kelvins})}{e}}$$

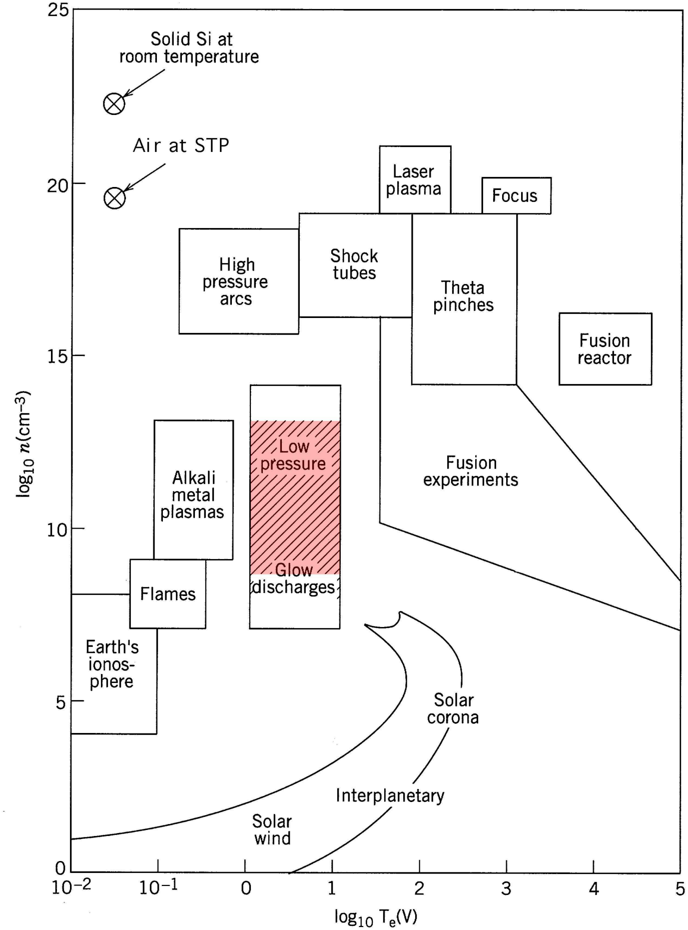
where k = Boltzmann's constant $= 1.38 \times 10^{-23}$ J/K

$$\boxed{1 \text{ V} \Longleftrightarrow 11,600 \text{ K}}$$

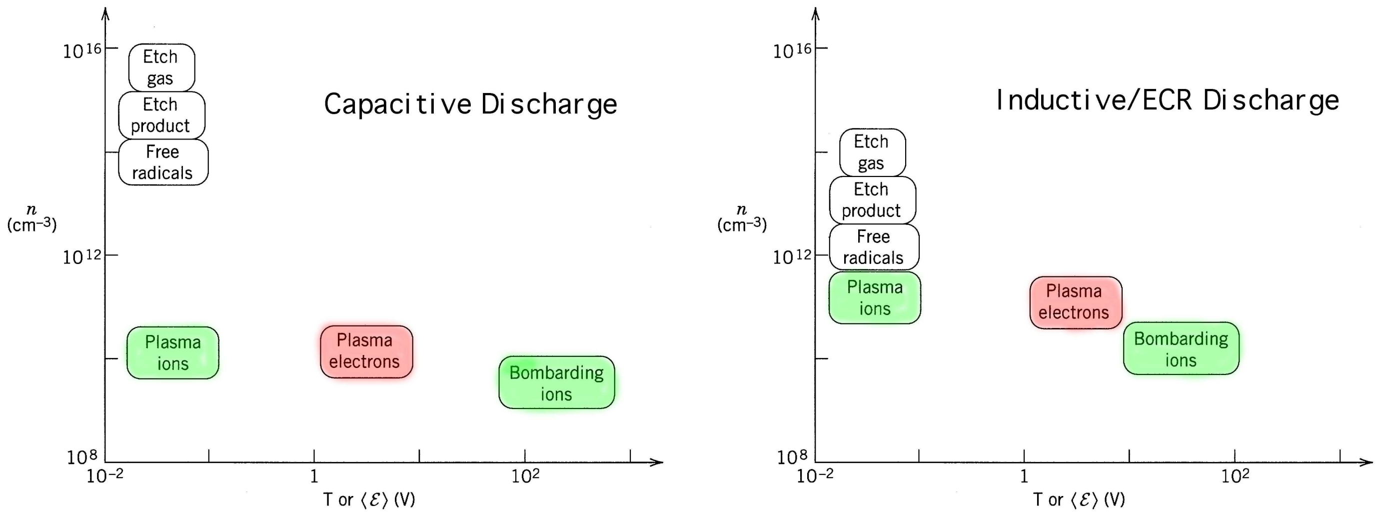
- Pressure unit is pascal (Pa); 1 Pa = 1 N/m^2
  Atmospheric pressure $\equiv$ 1 bar $\approx 10^5$ Pa $\approx$ 760 Torr

$$\boxed{1 \text{ Pa} \Longleftrightarrow 7.5 \text{ mTorr}}$$

PLASMA DENSITY VERSUS TEMPERATURE

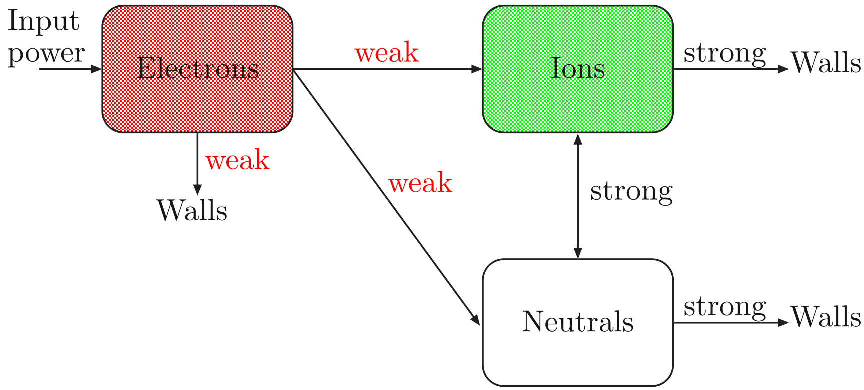


RELATIVE DENSITIES AND ENERGIES



NON-EQUILIBRIUM

- Energy coupling between electrons and heavy particles is weak



- Electrons are *not* in thermal equilibrium with ions or neutrals

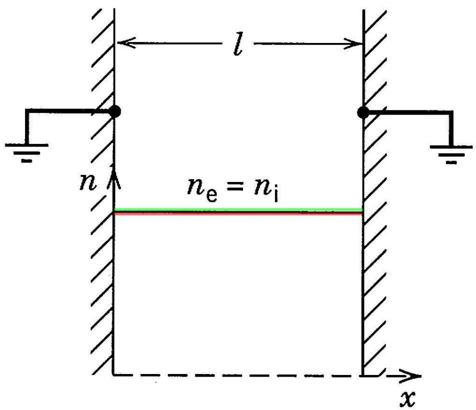
$$T_e \gg T_i \quad \text{in plasma bulk}$$

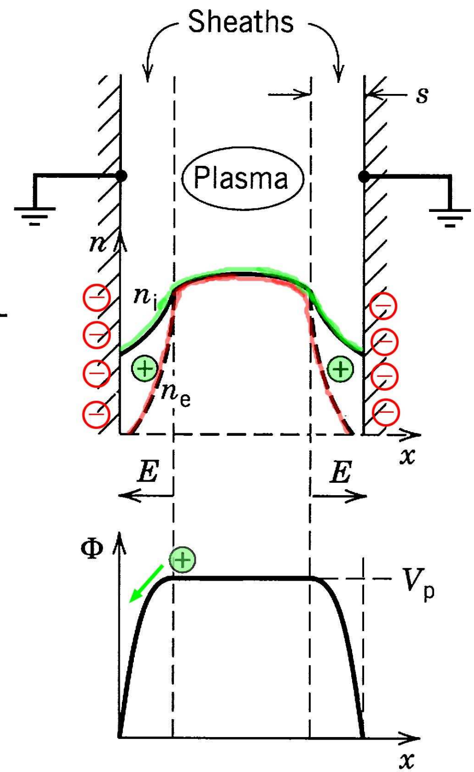
$$\text{Bombarding ion } \mathcal{E}_i \gg T_e \quad \text{at wafer surface}$$

- "High temperature processing at low temperatures"
  1. Wafer can be near room temperature
  2. Electrons produce free radicals $\Longrightarrow$ chemistry
  3. Electrons produce electron-ion pairs $\Longrightarrow$ ion bombardment

ELEMENTARY DISCHARGE BEHAVIOR

- Uniform density of electrons and ions n_e and n_i at time $t = 0$
- Low mass warm electrons quickly drain to the wall, forming sheaths

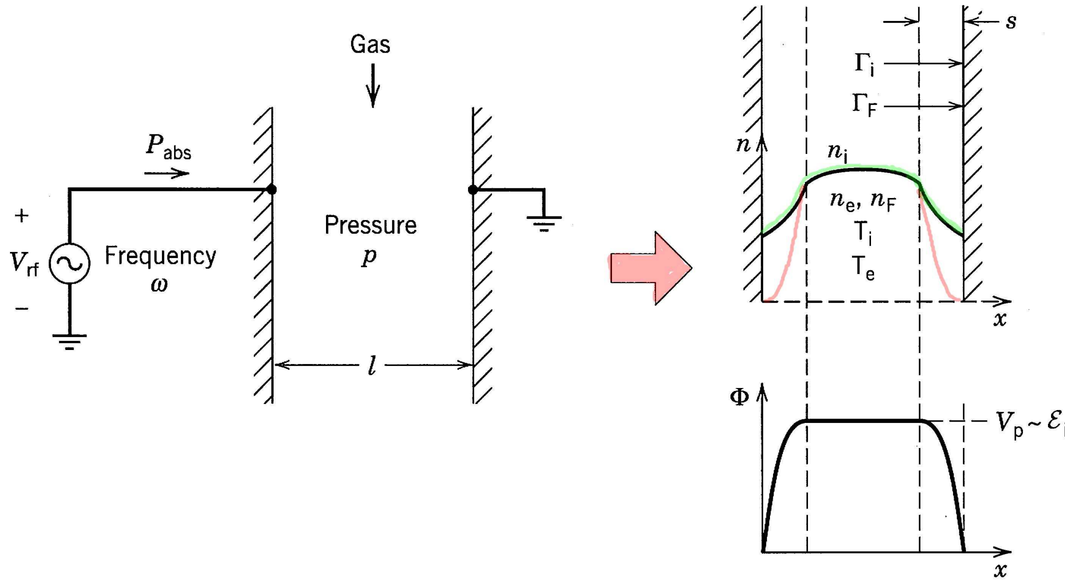




- Bulk plasma is quasi-neutral
  $\Longrightarrow n_e \approx n_i$

- Ions accelerated to walls; ion bombarding energy $\mathcal{E}_i$ = plasma-wall potential V_p

CENTRAL PROBLEM IN DISCHARGE MODELING



- Given V_{rf} (or I_{rf} or P_{rf}), ω, gases, pressure, flow rates, discharge geometry (R, l, etc)
- Find plasma densities n_e, n_i, temperatures T_e, T_i, ion bombarding energies $\mathcal{E}_i$, sheath thicknesses, neutral radical densities, etc
- Learn how to design and optimize plasma reactors for various purposes (etching, deposition, etc)