Pattern Transfer I

- Subtractive
  - —Dry etching
    - Physical Etching
    - Chemical Etching
    - Physico-Chemical Etching
  - —Wet Etching
    - Chemical
    - Electrochemical
    - Photochemical
    - Electrophotochemical
- Additive

Dry etching advantages:
- Reduced undercut of resist/hardmask features
- Scalable to nanometer feature sizes
  - Controllable rates
  - No wetting/surface tension issues
  - Real-time monitoring
- Reduced waste disposal requirements
- Reduced corrosion issues
- Improved surface cleanliness

Fun damentals of Microfabrication , M. Madou, CRC Press, Boca Raton (1997)

Glow Disch arge Processes , B. Chapm an, John Wiley and Sons, New York (1980)

Overview

- Dry etching techniques
- Plasma Physics
  - —DC plasmas
  - —RF plasmas
  - —Other plasma sources
- Physical Etching
- Dry Chemical Etching
- Physical-Chemical Etching
- Chemistries

Dry Etching Techniques

Glow Discharge Methods Diode Type				Ion Beam Methods Triode Type	
		Physical Etching			
Plasma Etching	Reactive Ion Etching/sputtering	Sputter Etching	Ion Milling	Ion Beam Assisted Chemical Etch	Reactive Ion Beam Etching
Reactive Plasma	*Reactive Plasma*	*Inert Plasma*	*Reactive Ion Beam*	*Inert Ion Beam*	*Reactive Ion Beam*

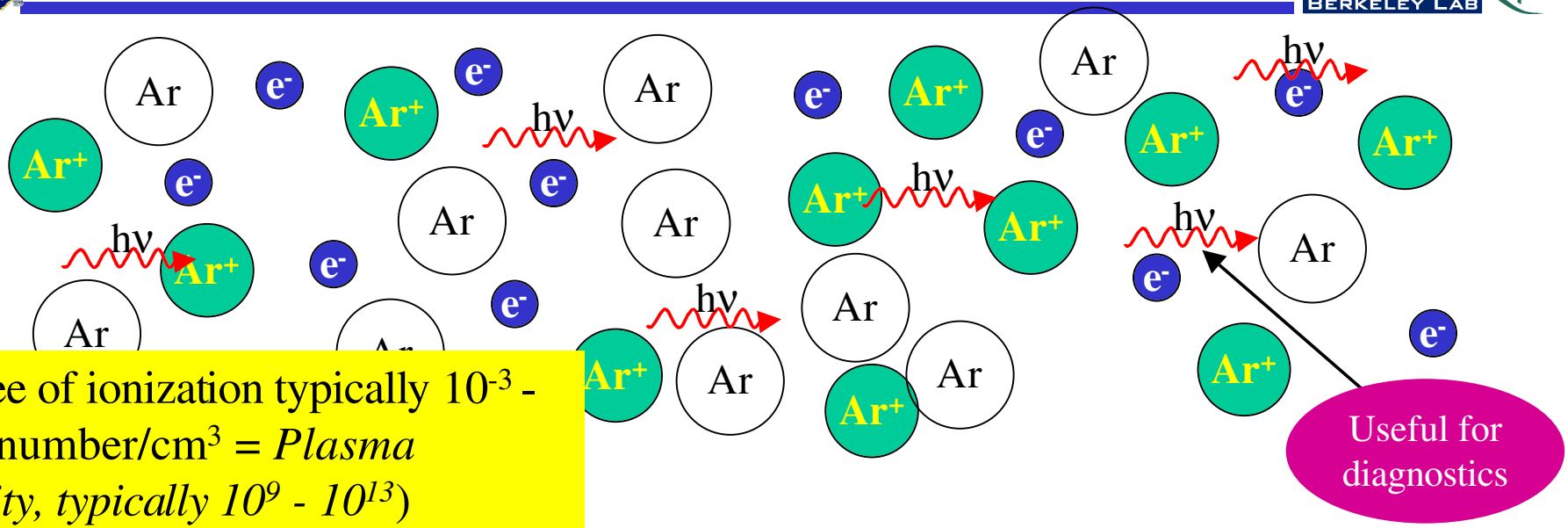
0.2 - 2 Torr

0.01 - 0.2 Torr

10^{-3} - 10^{-4} Torr

Low Energy Bombardment	High Energy Bombardment	High Energy Bombardment	No Reactive Neutrals	Reactive Neutrals Added	Some Reactive Neutrals

Plasma Components



Degree of ionization typically 10^{-3} - 10^{-6} (number/cm^3 = *Plasma Density, typically 10^9 - 10^{13}*)

$$e^- + Ar \Rightarrow 2e^- + Ar^+$$

Impact ionization

$$Ar \overset{h\nu}{\Rightarrow} e^- + Ar^+$$

Photoionization

$$e^- + Ar \Rightarrow e^- + Ar^*$$

Excitation

$$e^- + O_2 \Rightarrow e^- + \cdot O + \cdot O$$

Dissociation

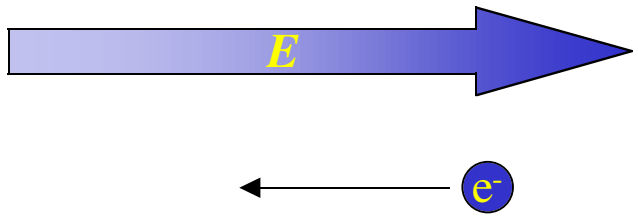
$$e^- + CF_4 \Rightarrow e^- + \cdot CF_3 + \cdot F$$

Dissociation

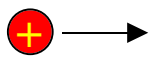
$$e^- + CF_4 \Rightarrow 2e^- + CF_3^+ + \cdot F$$

Dissociative ionization

Plasma Temperatures



$$a = \frac{Ee}{m_e} \quad , \quad K.E. = \frac{(Ee\tau)^2}{2m_e} = \frac{m_e \overline{v_e^2}}{2} = \frac{3kT_e}{2}$$



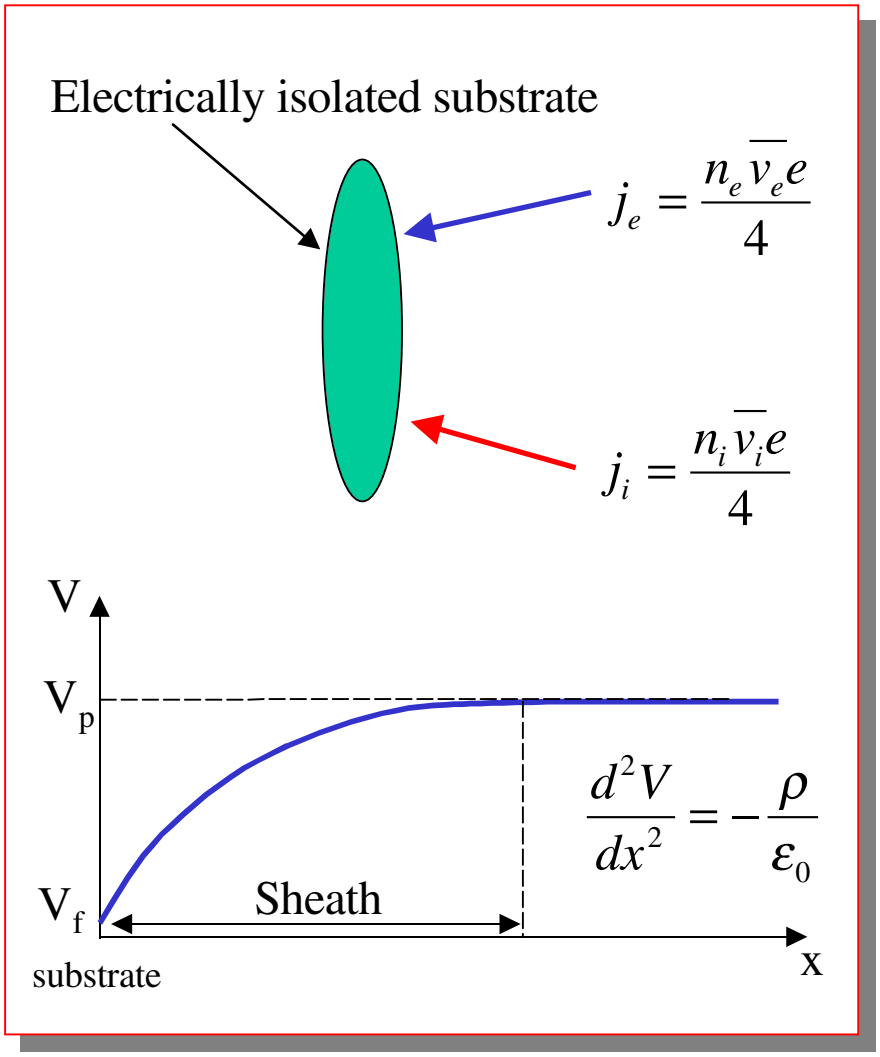
$$a = \frac{Ee}{m_i} \quad , \quad K.E. = \frac{(Ee\tau)^2}{2m_i} = \frac{m_i \overline{v_i^2}}{2} = \frac{3kT_i}{2}$$

$$\frac{m_n \overline{v_n^2}}{2} = \frac{3kT_n}{2}$$

τ = mean time between collisions

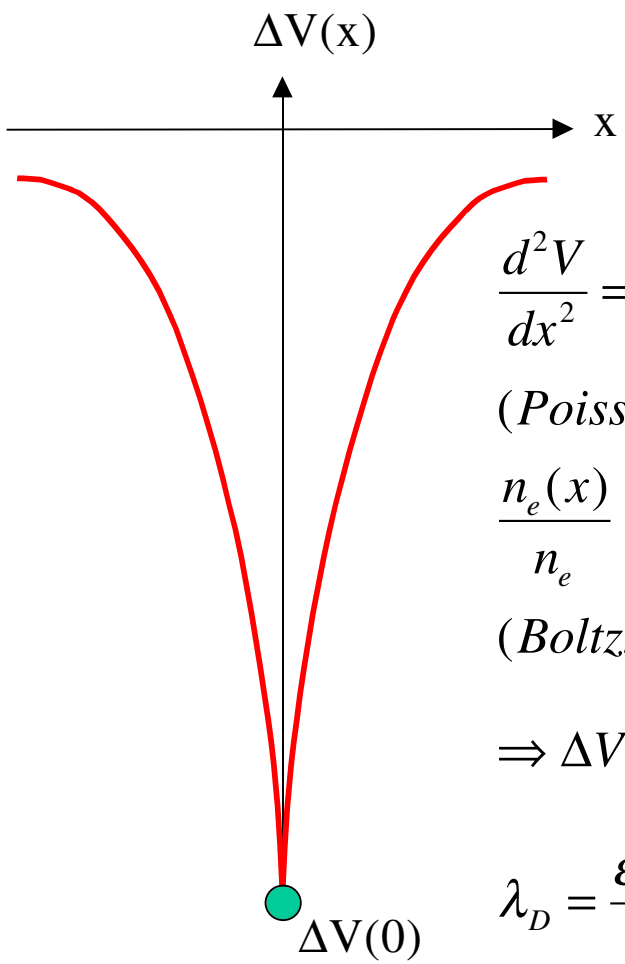
- Electrons, ions and neutrals are affected differently by applied fields
- Ions and neutrals exchange energy efficiently - similar masses, numerous collisions
- Electrons accelerate very quickly and cannot transfer energy efficiently through collisions with ions/neutrals
- Representative values for T and K.E. are
  - —Neutrals: T = 293 K, K.E. = 1/40 eV, v = 400 m/s
  - —Ions: T = 500 K, K.E. = 0.04 eV, v = 520 m/s
  - —Electrons: T = 23 000 K, K.E. = 2 eV, v = 950000 m/s

Plasma Potential



- Electron speed is >> ion speed (10^5 x)
- Electron current density ∴ >> ion current density
  - Negative charge builds on substrate until difference between floating potential (V_f) of substrate and plasma potential (V_p) equalizes electron and ion current densities
- Negative substrate potential repels electrons from vicinity of substrate, creating net positive charge distribution (*space-charge or sheath*)
- V_p-V_f = 10 - 15 V
- Ions are accelerated across sheath by (V_p—V_f) for an isolated substrate
- Reduced number of electrons makes sheath appear dark

Debye Shielding



$$\frac{d^2V}{dx^2} = -\frac{e}{\varepsilon_0}(n_i - n_e(x))$$

$(Poisson)$

$$\frac{n_e(x)}{n_e} = \exp-\left(\frac{\Delta V(x)e}{kT_e}\right)$$

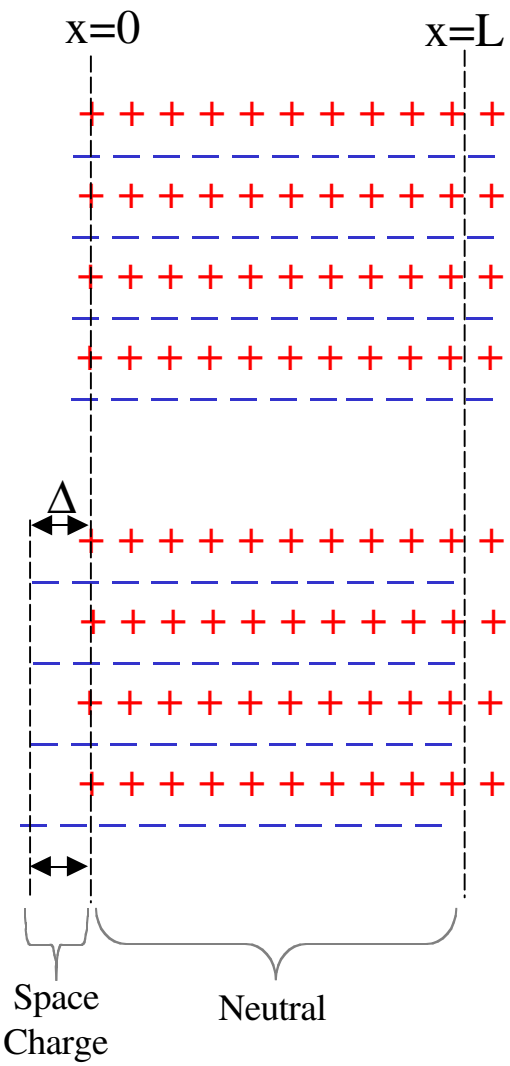
$(Boltzmann)$

$$\Rightarrow \Delta V(x) \approx \Delta V_0 \exp-\frac{|x|}{\lambda_D}$$

$$\lambda_D = \frac{\varepsilon_0 kT_e}{e^2 n_e} \; (Debye\ length)$$

- Number of ions, n_i, assumed constant for short times
- $n_i = n_e$ in the undisturbed plasma
- Perturbations to the potential do not extend beyond a few λ_D
- For $n_i = n_e = 10^{10}$ cm^{-3} and $kT_e = 2$ eV, $\lambda_D = 100$ μm

Plasma Oscillations



$$\frac{dE}{dx} = \frac{ne}{\varepsilon_0} \quad (Poisson)$$

$$Integrating:$$

$$E = \frac{ne\Delta}{\varepsilon_0}$$

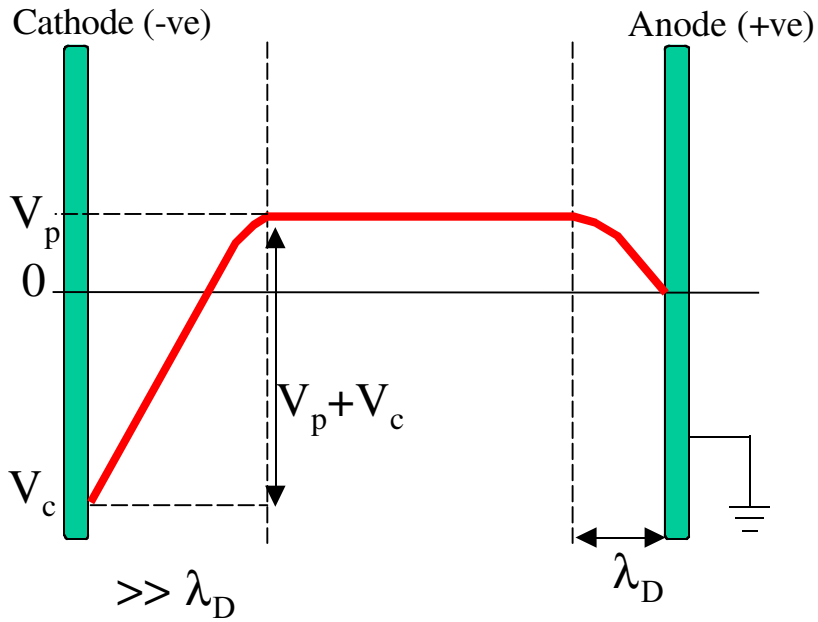
$$m_e \frac{d\Delta}{dt} = -eE = \frac{ne^2\Delta}{\varepsilon_0} \quad (SHM)$$

$$\omega_e = \left(\frac{ne^2}{m_e\varepsilon_0}\right)^{1/2}$$

$$\lambda_D\omega_e = \left(\frac{\varepsilon_0 kT_e}{ne^2}\right)^{1/2}\left(\frac{ne^2}{m_e\varepsilon_0}\right)^{1/2} = \left(\frac{kT_e}{m_e}\right)^{1/2} \approx \overline{v_e}$$

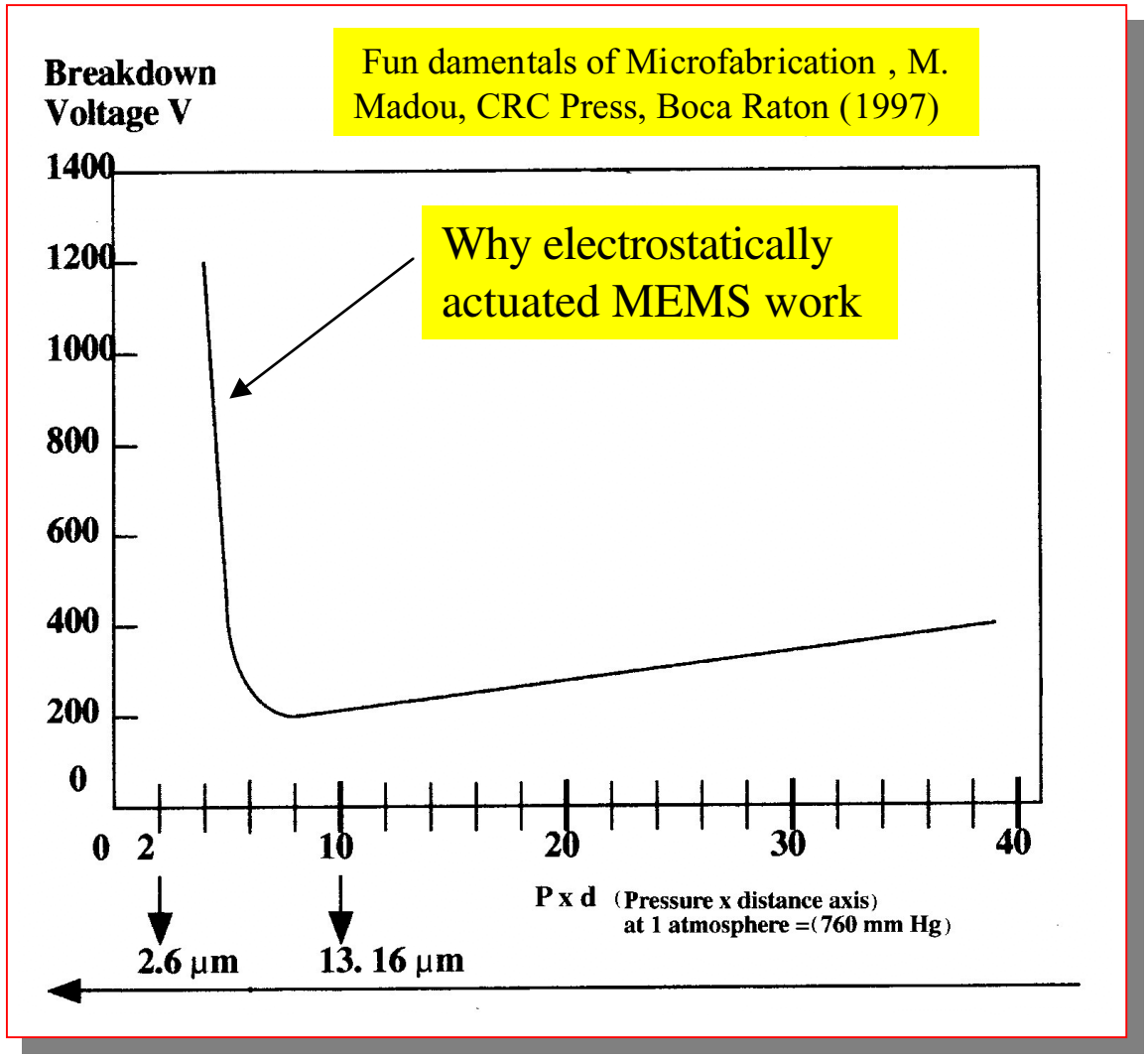
- Electrons displaced by external force gives rise to space charge
- Field created creates restoring force
- Electrons oscillate at ω_e
- For $n_i = n_e = 10^{10}$ cm^{-3} and $kT_e = 2$ eV, $\omega_e = 9.10^8$ Hz
- Electrons respond in ns, i.e. GHz

DC Glow Discharge



- Plasma is always most positive body in discharge and is essentially field free
- Electric fields restricted to sheaths at electrodes
- Sheath fields repel electrons at both electrodes
- Cathode sheath is large because large negative potential creates positive space charge sheath (i.e. positive ion density distribution) of varying density

Paschen Curve

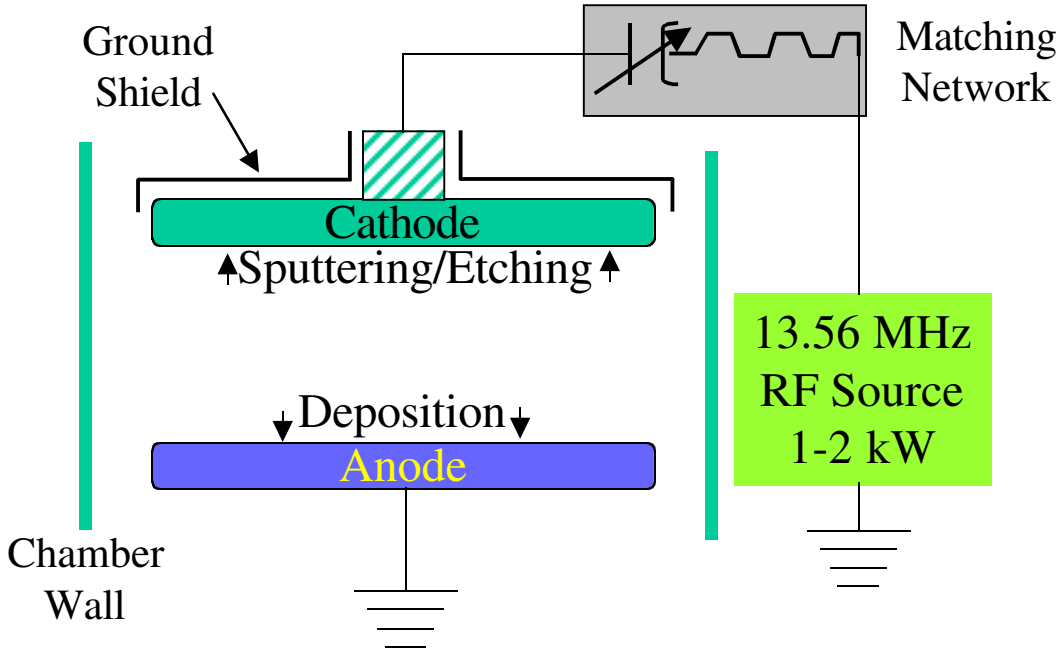


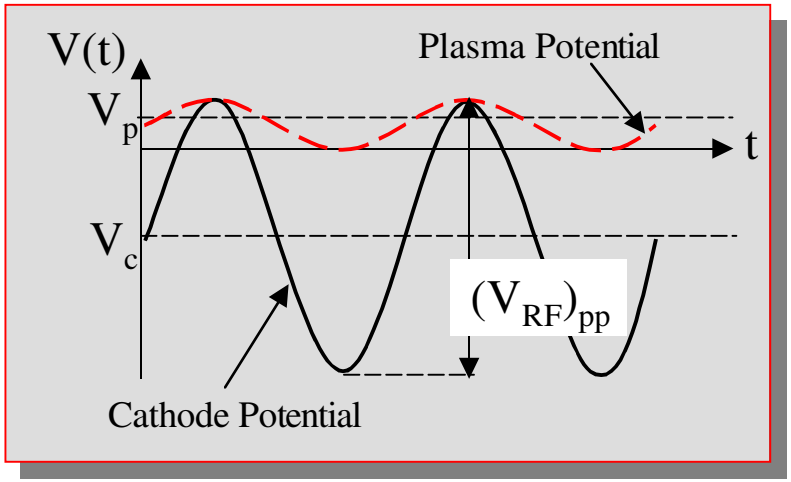
- Degree of ionization depends on ionization rate and loss of charged particles by recombination or collision with walls
- Breakdown cannot occur unless each electron produces 10 - 20 additional electrons thorugh collisions
  - Rise on left hand side occurs because electrode/gas atom spacing is comparable to electron mean free path
  - Rise on right hand side occurs because mean free path becomes so short electrons cannot acquire enough energy to ionize gas atoms when they collide

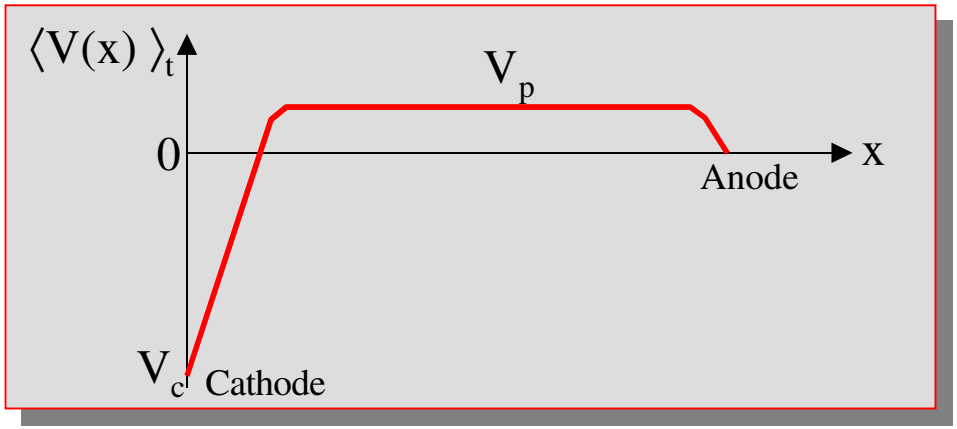
RF Discharge

- Net charge flow to both electrodes is zero
  - ➢ Enables etching/sputtering of insulators
- Discharges can be continuous at > 1 MHz (capacitative time constant)
  - — Secondary electron avalanches not required ➢ low pressure plasmas
  - — 13.56 MHz chosen to avoid radio interference
- Electrodes self-bias because of different electron and ion mobilities
  - ➢ Ion bombardment almost continuous
  - ➢ Sheath voltages can be very large
- Sheath voltage is larger at the smaller electrode: voltage ratio $\propto$ (area ratio)^n
  - ➢ Target area < electrode+walls

RF System







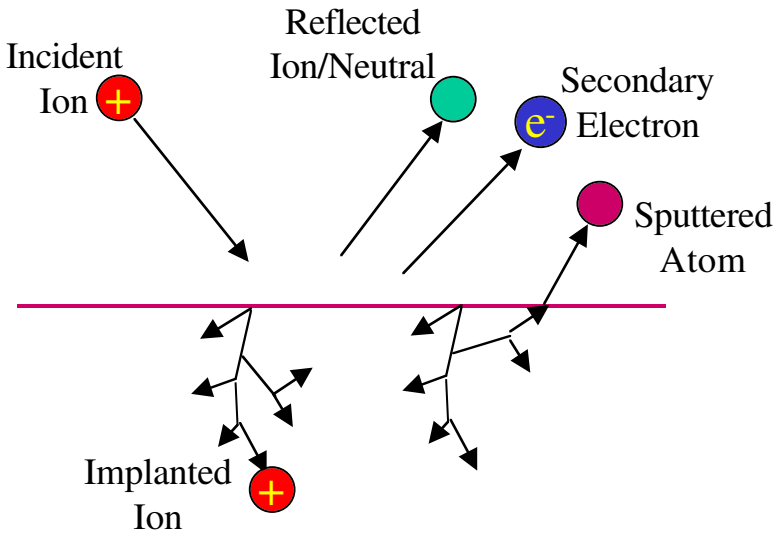
$$2V_p \approx \frac{(V_{RF})_{pp}}{2} - |V_c|$$

$$E_{\max} = e(|V_c| + V_p), \quad (Cathode)$$

$$E_{\max} = eV_p, \quad (Anode)$$

Ion Energy

Sputtering



Sputter Yield

$$S = \frac{3\alpha}{4\pi^2} \frac{4 m_i m_t}{(m_i + m_t)^2} \frac{E}{U_0}$$

U_0 = Binding Energy

E = Incident Ion Energy

m_i / m_t = Ion/Target Mass

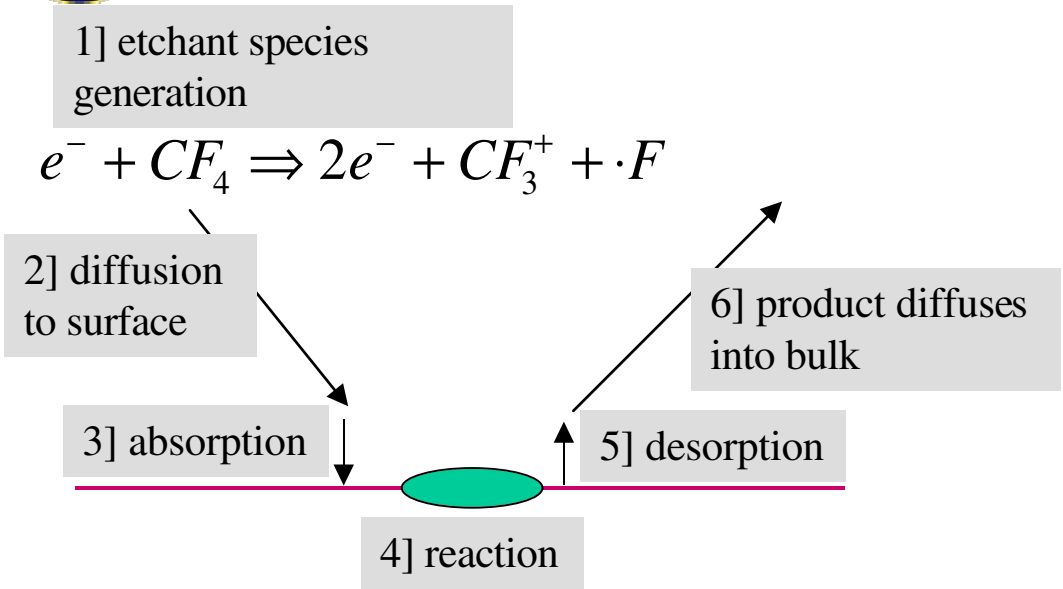
$\alpha = \mathrm{f}(m_t / m_i)$

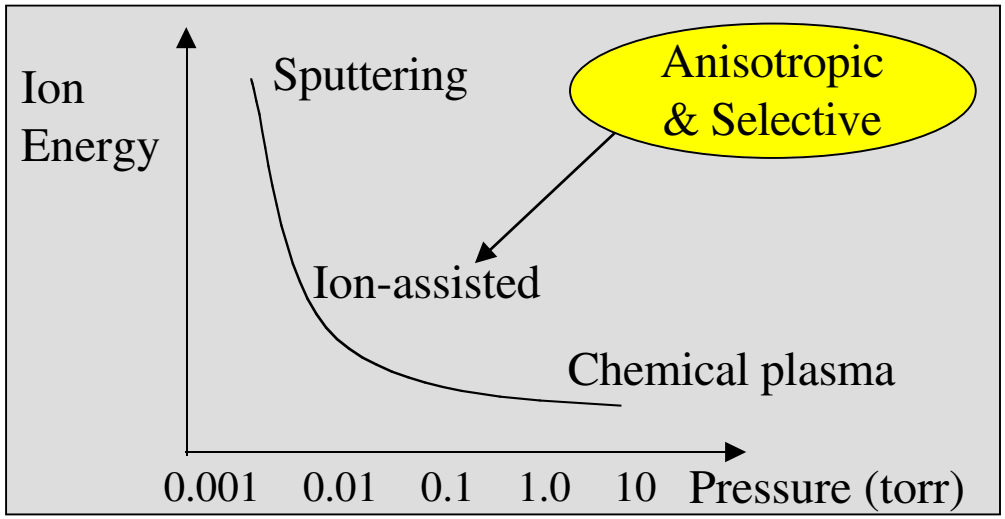
Note: Angular dependence ➢ faceting

Ion Energy (eV)	Reaction
< 3	Physical absorption
4 - 10	Surface sputtering
10 - 5000	Sputtering
10,000 - 20,000	Implantation

- Sputtering reduces the need for product volatility
- Provides directional anisotropy
- Inert gases provide good yields & avoid contamination/reaction
- Redeposition is an issue
- Limited aspect ratio

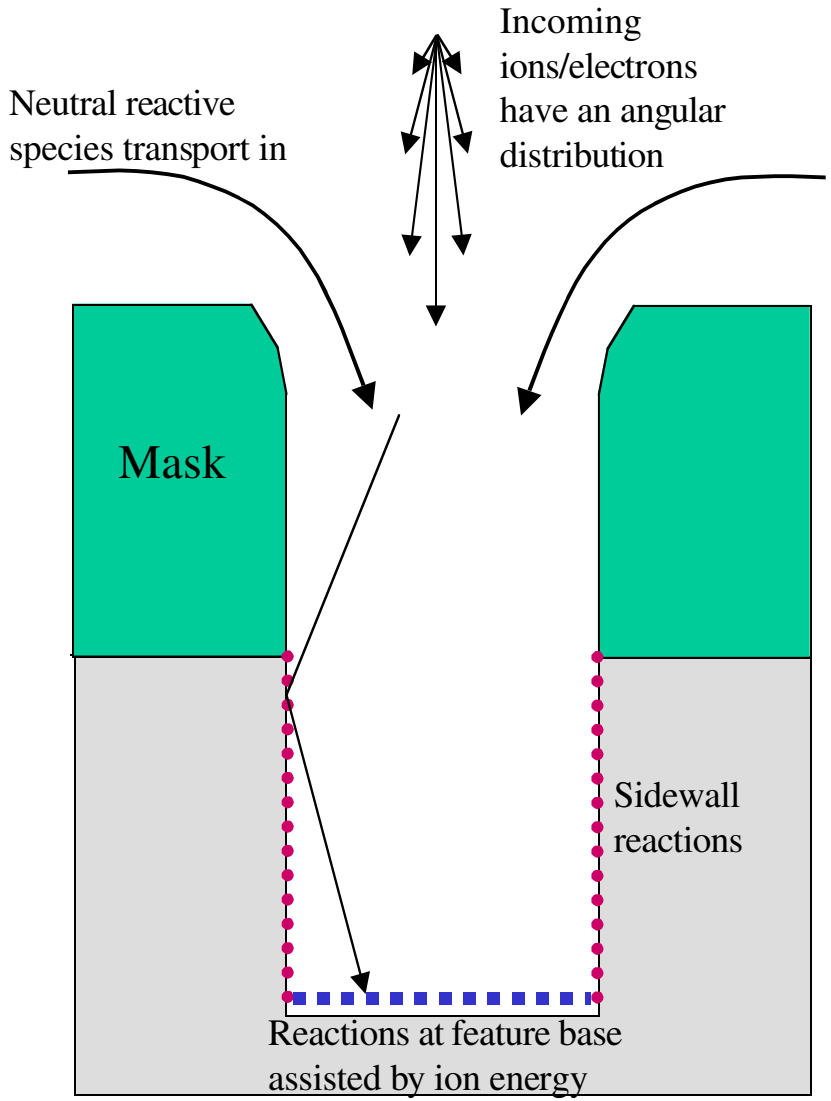
Dry Chemical Etching





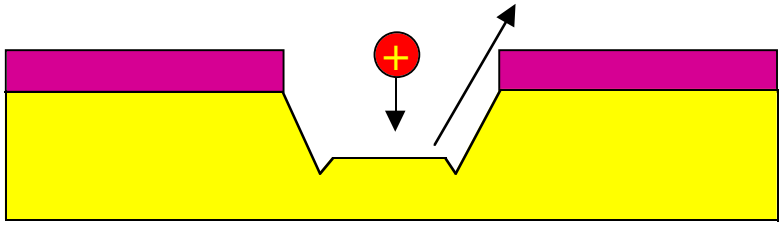
- Substrate removal is accomplished primarily by reactive species generated in the plasma
- Reaction rate can be strongly influenced by ions
  - — Surface damage
  - — Surface cleaning
  - — Energy for reaction
  - ➢ anisotropy
- Low pressure yields normal ion incidence, but typically low ion densities ➢ low etch rates
  - — Use magnetic confinement to increase ion density at low pressures

Etching of Structures

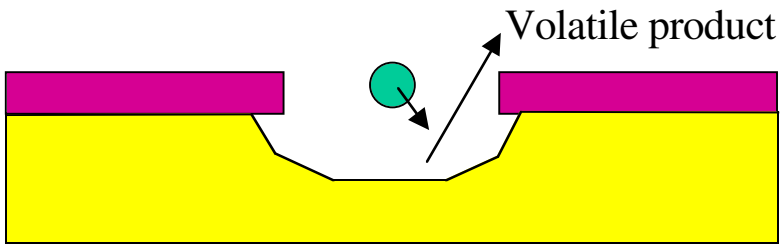


- Sidewall reactions can lead to an isotropic etch component, or to the build up of a passivating layer that protects the sidewall
  - In this case, there is a competition between the passivating and etching reactions at the feature base
- Substrate temperature can play an important role in determining reaction rates on sidewalls. Rates tend to be temperature independent on base because of ion energy input.
- Passivating effect of sidewall species depends on their volatility - controlled by temperature
  - E.g. HSQ-bilayer: CO etch products freeze on sidewalls providing passivation

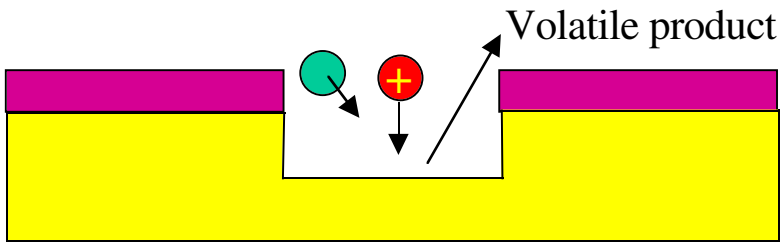
Etch Profiles



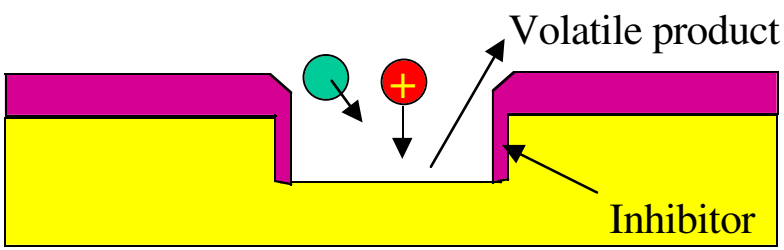
Sputtering: erosion of mask occurs most rapidly at mask corners. Ion reflection from sidewalls can lead to trenching



Chemical: isotropic etching

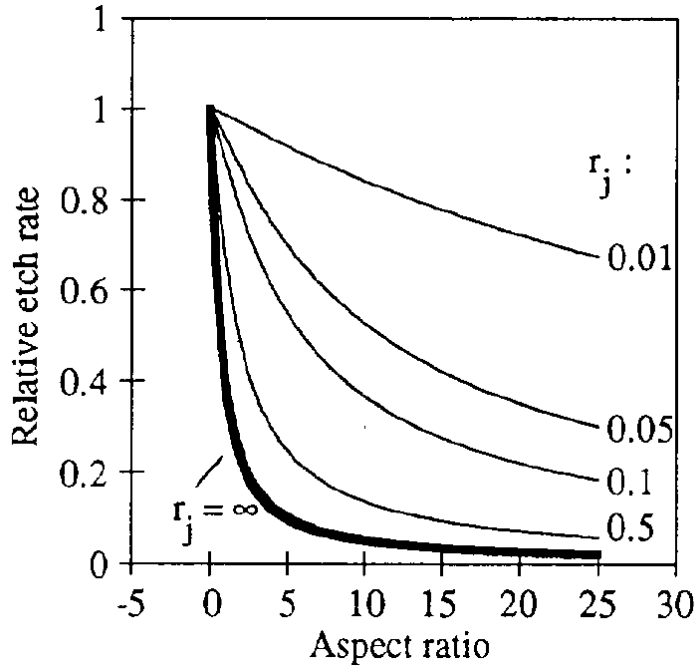


Ion-enhanced: good anisotropy provided by directionality of ion flux



Ion-ehanced inhibitor: species formed on sidewalls prevent etching. Ion impacts on horizontal surfaces cause etching of protective species and substrate

RIE-lag Model



$$\text{Neutral Flux}: \quad \frac{F_c}{F_0} = \frac{1}{\sqrt{1+4A^2}}, \quad \frac{F_{av}}{F_0} = \sqrt{1+A^2} - A$$

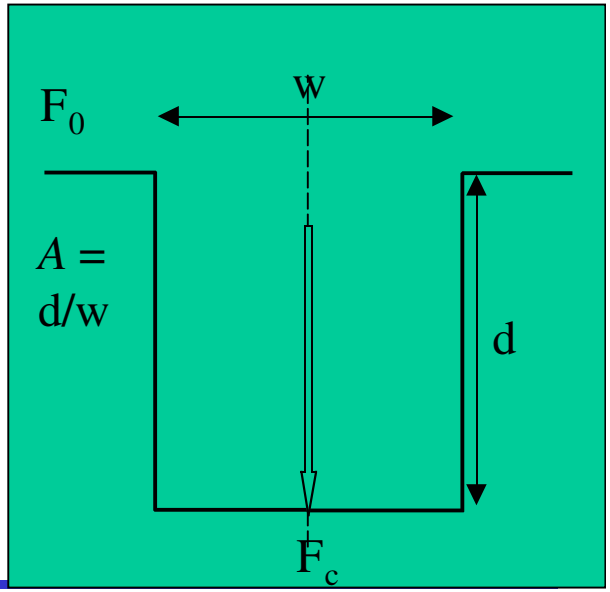
F_c = flux at center, F_{av} = average flux

$$\text{Etch Rate}: \quad E_0 \propto \frac{cI}{1+r},$$

$$\text{Effective Ion / Neutral flux}: r = \frac{cI}{sF_0}$$

I = ion flux, F_0 = neutral flux, c = reaction coefficient, s = sticking coefficient

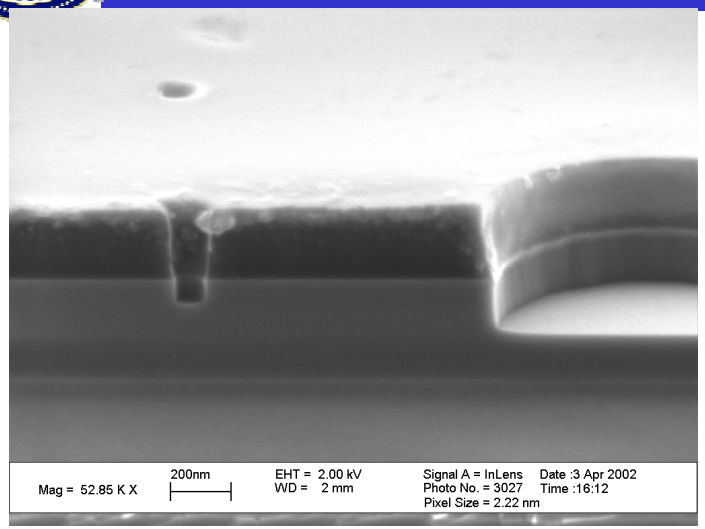
$$\frac{E_{av}}{E_0} = \frac{1+r}{1+r\left(\sqrt{1+A^2} - A\right)^{-1}}$$



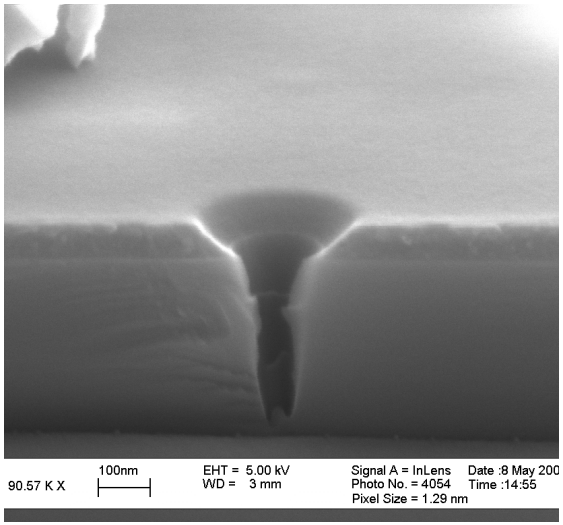
- When r is <<1, etch rate is independent of neutral flux
  - Reagent molecules supplied to excess
- Typically $0.01 < r < 0.5$

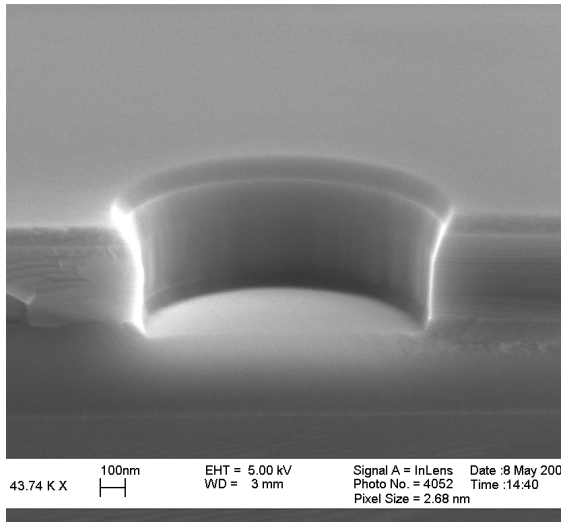
The Dependen ce of Nanostructure Etch Rates on Feature Size , J.M.F. Zachariasse and A.N. Broers, *Microelectronic Engineering*, **30** p349 (1996)

RIE-lag



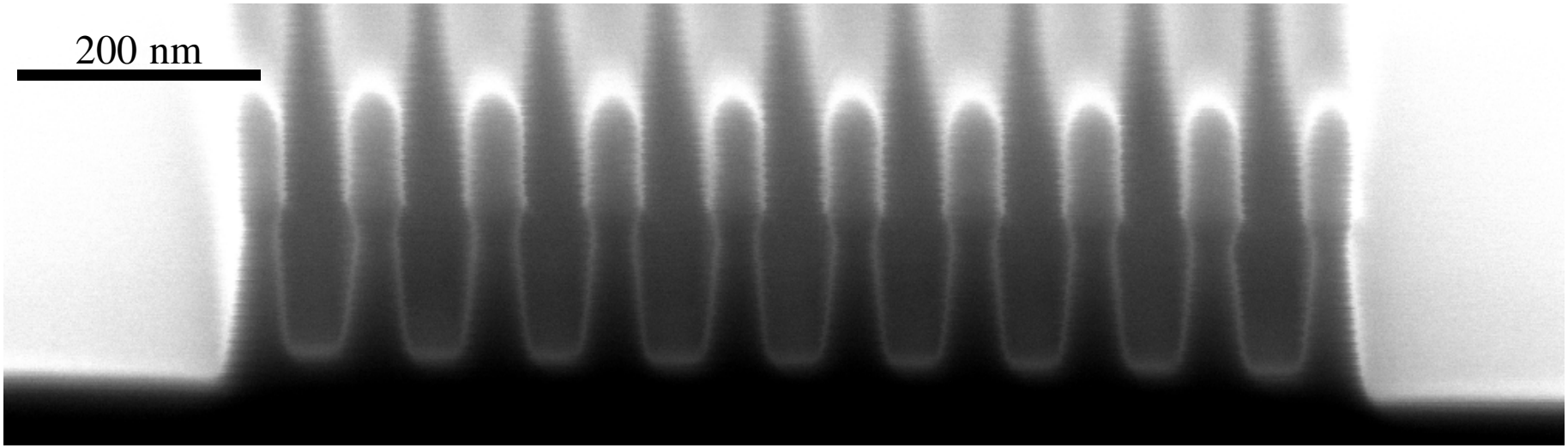
- HBr etching — 20 sccm, 2 mTorr, FP 60 W, ICP 700 W: 2 mins (left) & 4 mins (right) etching: very noticeable etch rate differences between 1 µm and 100 nm holes
- Reduction in HBr pressure to 0.5 mTorr results in minimal improvement





- HBr/Cl_2 etching — 20 sccm for both gases, 3.8 mTorr, FP 60 W, ICP 700 W: 4 mins etching: less noticeable etch rate differences between 1 µm and 100 nm hole

Microloading & Bowing



- Microloading and sidewall bowing in Si etched with HSQ/AZPN114 bilayer mask in Cl_2/HBr plasma

Aspect Ratio Effects

- Microloading: etch rate depends on local pattern density
- Aspect-ratio dependent etching (ARDE), RIE-lag: smaller features etch more slowly - controlled by geometry of individual features
- Faceting: etch rate is dependent on angle between incident ions and surface - mask corners etch faster
- Electron shading - charging: electrons charge all surfaces, but ions neutralize bottom of features, as etching proceeds electrons cannot reach bottom and resulting charge distribution causes ion flux to sidewalls to increase
  - Retrograde profiles
  - Notching
  - Gate oxide degradation
- Microtrenching: ions scattered from sidewalls and arriving off-normal have higher sputter yield
- Bowing: caused by ion scattering within feature, from collisions with neutrals or from deflection due to charge build-up

Microscopic Un iformity in Plasma Etching , R.A. Gottsch o, C.W. Jurgensen and D.J. Viktavage, *J. Vac. Sci. Technol.*, **B10** p2133 (1992)

Etching Chemistries

- F/C ratio: etching and polymerization occur simultaneously. Fluorine scavengers such as H lower the F/C ratio, decrease etch rates and increase polymerization. O_2 removes C in the form of CO or CO_2 and increases etch rate. NF_3 and ClF_3 eliminate polymer, but are also less aggressive to resist.
- Selectivity: closer the process is to point of polymer formation, the higher the selectivities that can be reached. Low temperature, high pressures, high H content all lead to increased polymer formation.
- Substrate bias: increased substrate bias allows for greater selectivity by eroding polymer on the base of an etched feature.
- III-V s: III-fluorides involatile, III-chlorides volatile at high temperatures
- Metals: halo- and fluoro-carbons can reduce metal oxides. Sputtering is essential to act on surface oxides.
- Resist: resist degradation can be mitigated by using etching conditions that allow some polymerization to occur, compensating for the loss of resist through etching.
- C: carbon degrades selectivity in some cases because of the ability of C to reduce SiO_2 and other oxides