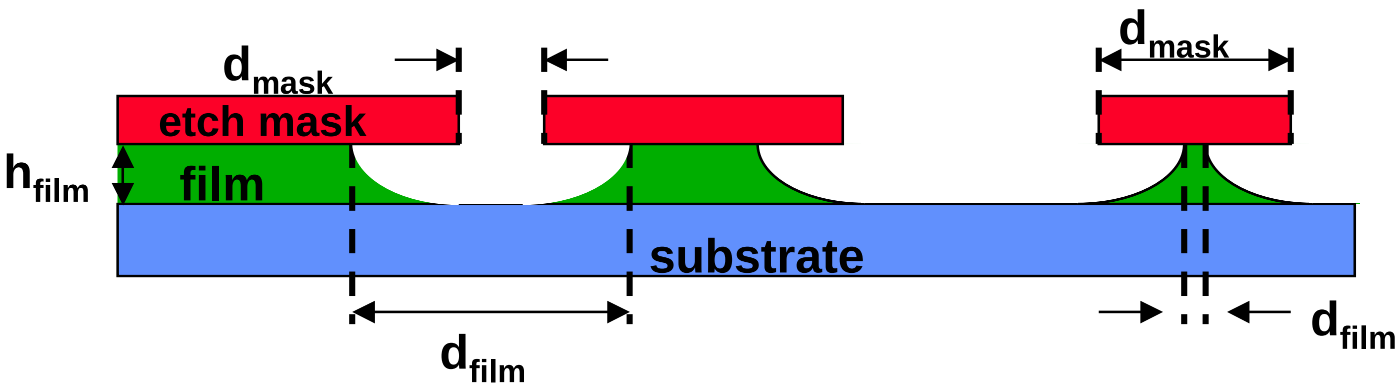
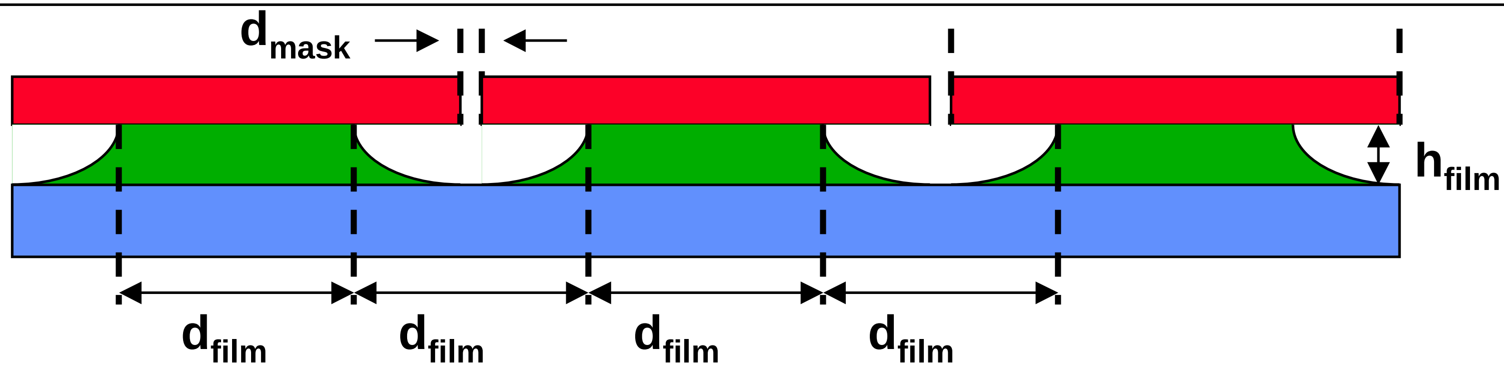
Etching terminology



- bias B
  - $B \equiv d_f - d_m$ (i.e., twice the "undercut)
- anisotropy A
  - $A_{film} \equiv 1 - v_l / v_v$
    - $v_l \equiv$ lateral etch rate
    - $v_v \equiv$ vertical etch rate
  - for films etched <u>just to completion</u>
    - $A_f = 1 - |B| / 2h_f$
      - $h_f \equiv$ film thickness
  - $A_f = 0$ isotropic
  - $A_f = 1$ perfectly anisotropic

Impact undercut and feature aspect ratio



- example: want film to have "equal" lines and spaces after etch
- can we compensate for bias (undercut) by adjusting the mask?
  - recall $|B| = d_f - d_m$ ➡ $d_m = d_f - |B|$
  - but for films etched just to completion $|B| = 2 h_f (1 - A_f)$
  - so

$$d_{mask} = d_f \cdot \left[1 - 2\frac{h_f}{d_f}\left(1 - A_f\right)\right]$$

    - h_f / d_f is the feature aspect ratio
    - since $d_m > 0$ $\left[1 - 2\frac{h_f}{d_f}\left(1 - A_f\right)\right] > 0 \Rightarrow A_f > 1 - \frac{1}{2 \cdot \left(h_f / d_f\right)}$
      - if aspect ratio is << 1 anisotropy is not needed
      - if aspect ratio is >> 1 need high anisotropy (i.e., $A_f \sim 1$)!

Selectivity of etches

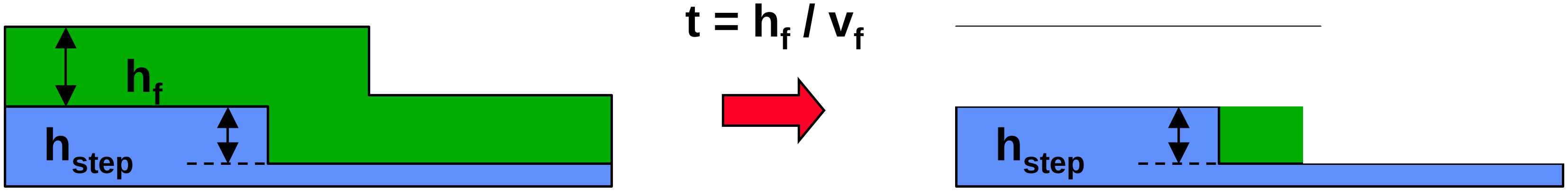
- **need etch that removes film much faster than either the etch mask or “substrate”**
- **required selectivities depend on**
  - **uniformity of film thickness**
  - **uniformity of etch rates**
  - **anisotropy of etch rates**
  - **overetch required**
  - **acceptable loss of linewidth**
  - **acceptable “substrate” loss**

Selectivity and Over-etch time

- how long must you etch?
  - etch time = film thickness / film etch rate
- BUT
  - what if film thickness is not uniform?
    - etch time = largest film thickness / film etch rate
  - example: conformal film over a step, perfectly anisotropic etch

nominal etch time

$t = h_f / v_f$



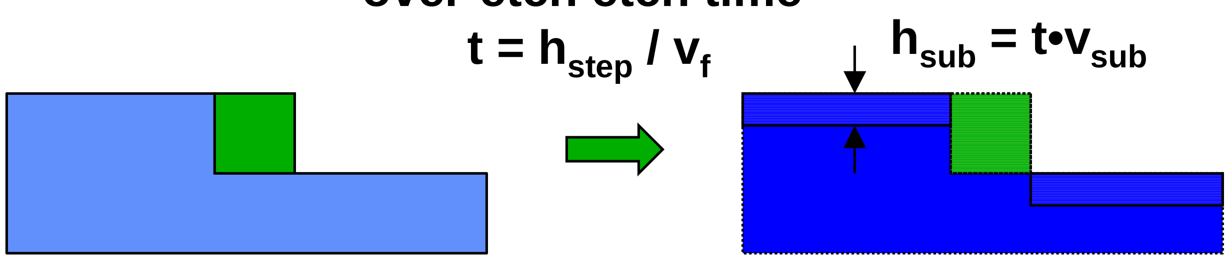
  - must continue etch for time = h_{step} / v_{film} to clear "residue"
    - total etch time is then
      $T = h_f/v_f + h_{step}/v_f = h_f/v_f \cdot (1 + \Delta)$
      - Δ is the fractional over-etch time,
        - here $\Delta = h_{step} / h_{film}$

Film -to- substrate selectivity

- does over-etch matter?
  - what about "substrate" exposed during over-etch period?

over-etch etch time

$t = h_{step} / v_f$



- substrate is "lost" during overetch
  - $h_{sub} = t_{over} \bullet v_{sub} = (h_{step} / v_f) \bullet v_{sub}$
    $= h_{step} \bullet (v_{sub} / v_f)$
  - but v_f / v_{sub} is the film-to-substrate selectivity S_{fs}, so
    - $S_{fs} = h_{step} / h_{sub}$
- recalling $\Delta = h_{step} / h_{film}$ we get
  - $S_{fs} = (h_{film} / h_{sub}) \bullet \Delta$

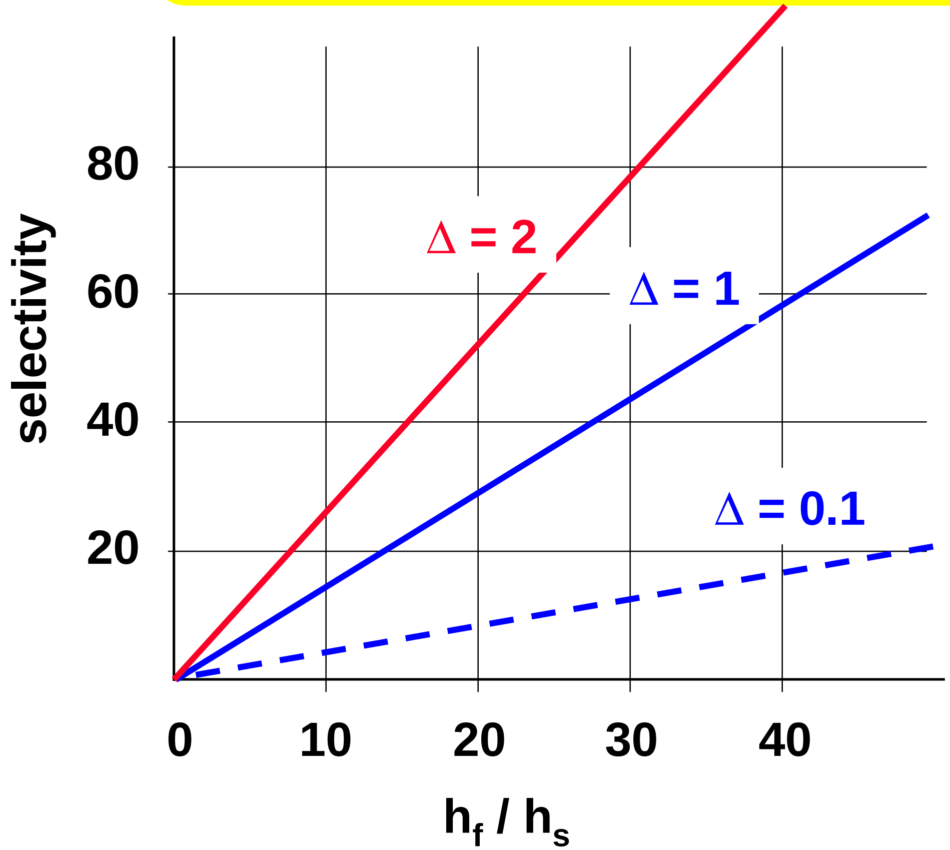
Effects of non-uniformities

- what if things aren't all uniform:
  - etch rate: $v_f \bullet (1 \pm \phi_f)$
  - thickness: $h_f \bullet (1 \pm \delta_f)$
  - so now etch time is $$t = \frac{h_f \cdot (1 \pm \delta_f)}{v_f \cdot (1 \pm \phi_f)} \cdot (1+\Delta)$$
  - to ensure complete etch you must use the longest time: $$t = \frac{h_f \cdot (1+\delta_f)}{v_f \cdot (1-\phi_f)} \cdot (1+\Delta)$$
- how long is the "substrate" exposed?
  - shortest time substrate could be coverd by film: consider thinnest film removed at fastest film etch rate! $$t_{covered} = \frac{h_f \cdot (1-\delta_f)}{v_f \cdot (1+\phi_f)}$$
- so the substrate is exposed to the etch for a time $$t_{exposed} = \underbrace{\frac{h_f \cdot (1+\delta_f)}{v_f \cdot (1-\phi_f)} \cdot (1+\Delta)}_{total\ \ etch\ \ time} - \underbrace{\frac{h_f \cdot (1-\delta_f)}{v_f \cdot (1+\phi_f)}}_{time\ \ sub.\ covered}$$
- so the amount of substrate lost is

$$h_s = v_s \cdot t_{exposed} = v_s \cdot \frac{h_f}{v_f} \cdot \left[\frac{(1+\delta_f) \cdot (1+\Delta)}{(1-\phi_f)} - \frac{(1-\delta_f)}{(1+\phi_f)} \right] = \underbrace{\left(\frac{v_s}{v_f} \right)}_{(S_{fs})^{-1}} \cdot h_f \cdot \left[\frac{(1+\delta_f) \cdot (1+\Delta)}{(1-\phi_f)} - \frac{(1-\delta_f)}{(1+\phi_f)} \right]$$

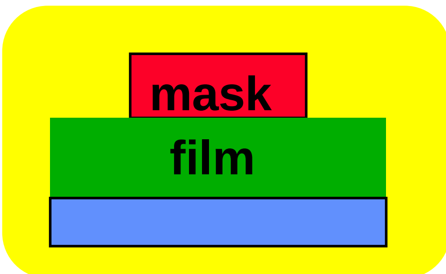
Example results for film - substrate selectivity

$$S_{fs} = \frac{v_f}{v_s} = \frac{h_f}{h_s}\cdot\left[\frac{\phi_f\cdot\left(2+\Delta+\Delta\cdot\delta_f\right)+\delta_f\cdot(2+\Delta)+\Delta}{1-\left(\phi_f\right)^2}\right]\approx\frac{h_f}{h_s}\cdot\Delta$$

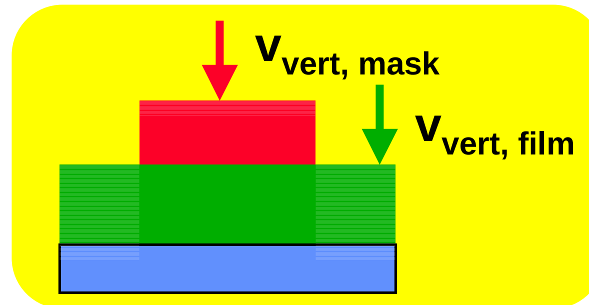


- etch rate uniformity ϕ_f = 0.1
- film thickness uniformity δ_f = 0.05

Film -to- mask selectivity



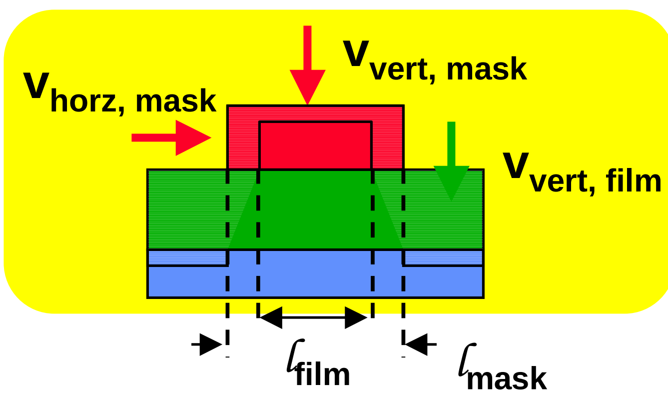
perfectly anisotropic vertical etch, btoh mask and film



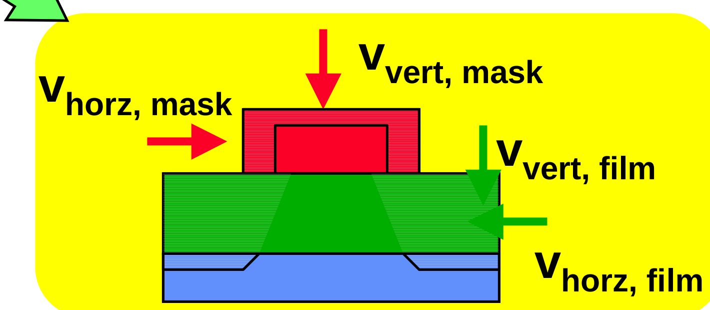
no linewidth loss

$A_{film} = 1$, but $A_{mask} < 1$

$A_{film} < 1$, $A_{mask} < 1$



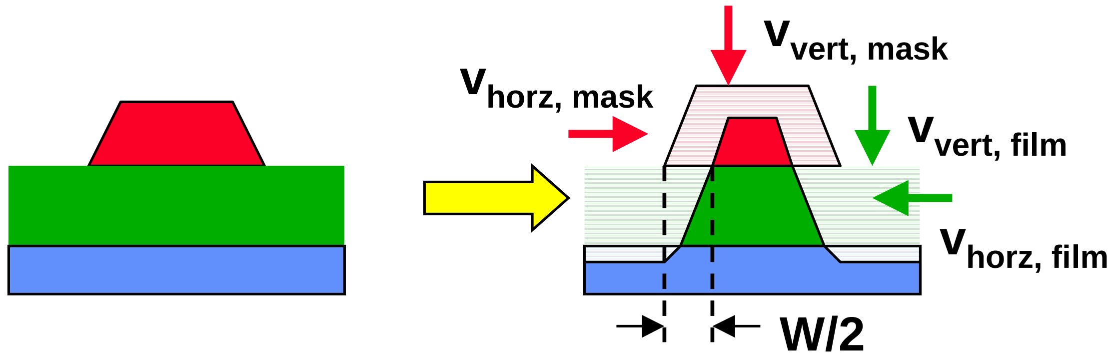
loss of linewidth $W = \ell_{mask} - \ell_{film}$



- need to consider "loss of linewidth" due to mask erosion
  - function of mask edge profile and anisotropy of etch (both mask and film!)

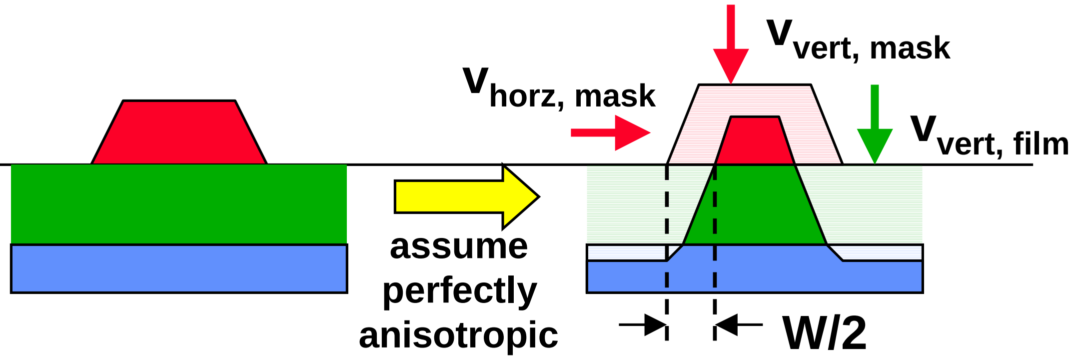
Film -to- mask selectivity

- need to consider "loss of linewidth" due to mask erosion
  - function of:
    - anisotropy of etch (both mask and film!)
    - also a function of <u>the mask edge profile</u>



- should also include impact of various non-uniformites
  - film thickness: $h_f \cdot (1 \pm \delta_f)$
  - etch rates:
    - mask: $v_m \cdot (1 \pm \phi_m)$
    - film: $v_f \cdot (1 \pm \phi_f)$

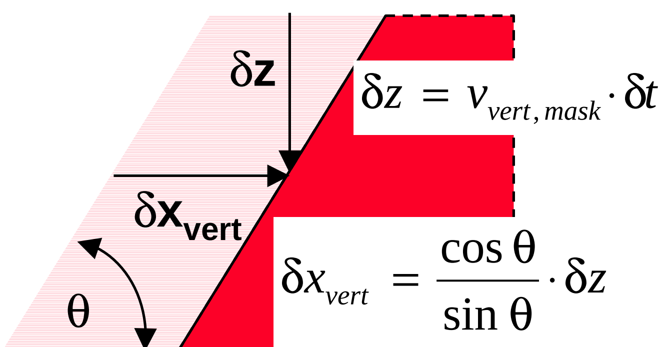
Film -to- mask selectivity



- non- uniformities:
  - etch rate: $v_f \bullet (1 \pm \phi_f)$
  - thickness: $h_f \bullet (1 \pm \delta_f)$
    - to ensure complete etch you must use the longest time:

$$t_{etch} = \frac{\overbrace{h_f \cdot (1 + \delta_f)}^{thickest\ film}}{\underbrace{v_f \cdot (1 - \phi_f)}_{slowest\ etch\ rate}} \cdot \underbrace{(1 + \Delta)}_{fractional\ over-etch}$$

- during this time two terms contribute to lateral mask erosion:
  - vertical etch of mask combined with slope



$$\delta z = v_{vert,mask} \cdot \delta t$$

$$\delta x_{vert} = \frac{\cos\theta}{\sin\theta} \cdot \delta z$$

- plus simple horizontal etch
- total mask erosion is just sum of terms:

$$\delta x_{tot} = v_{horz,mask} \cdot \delta t + \frac{\cos\theta}{\sin\theta} \cdot v_{vert,mask} \cdot \delta t$$

Film -to- mask selectivity

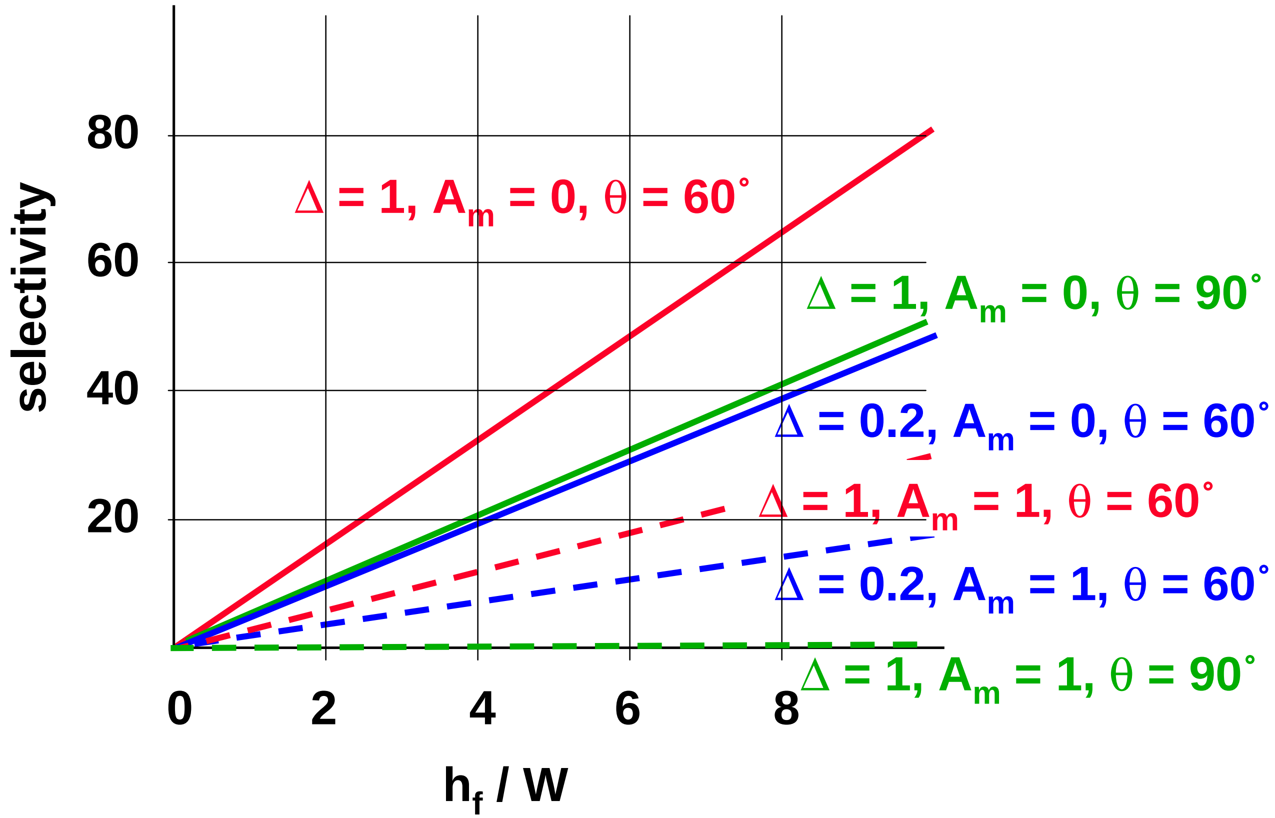
- so total mask edge movement is $\frac{W}{2} = \left(v_{horz,\,mask} + v_{vert,\,mask} \cdot \cot\theta\right) \cdot t_{etch}$
  - or
$$W = 2 \cdot v_{vert,mask} \left(\underbrace{\frac{v_{horz,mask}}{v_{vert,mask}}}_{1-A_{mask}} + \cot\theta \right) \cdot \frac{h_f \cdot \left(1+\delta_f\right)}{v_f \cdot \left(1-\phi_f\right)} \cdot (1+\Delta)$$
  - let's use worst case mask etch so
$$W = 2 \cdot \underbrace{\frac{v_{mask} \cdot \left(1+\phi_m\right)}{v_f}}_{1/S_{fm}} \cdot \left(\left[1-A_{mask}\right] + \cot\theta\right) \cdot \frac{h_f \cdot \left(1+\delta_f\right)}{\left(1-\phi_f\right)} \cdot (1+\Delta)$$

- or
$$S_{fm} = 2 \cdot \frac{h_f}{W} \cdot \frac{(1+\phi_m) \cdot \left(1+\delta_f\right) \cdot (1+\Delta)}{\left(1-\phi_f\right)} \cdot \left(\left[1-A_{mask}\right] + \cot\theta\right)$$

– NOTE THIS ASSUMED PERFECTLY ANISOTROPIC ETCH OF FILM!!!

Sample results for film - mask selectivity

- etch rate uniformity ϕ_f & ϕ_m = 0.1
- film thickness uniformity δ_f = 0.05



Wet chemical etching

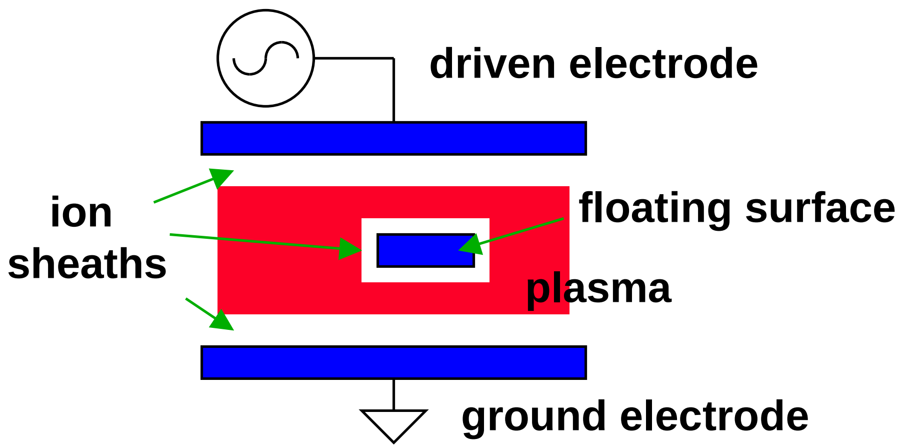
- dominant etch process through late 1970's
- tends to be isotropic
  - A ~ 0
  - exception: anisotropic crystal etches
    - for silicon etch rates along various crystal directions can vary widely
      - (111) tends to be slowest
- tends to produce high selectivities

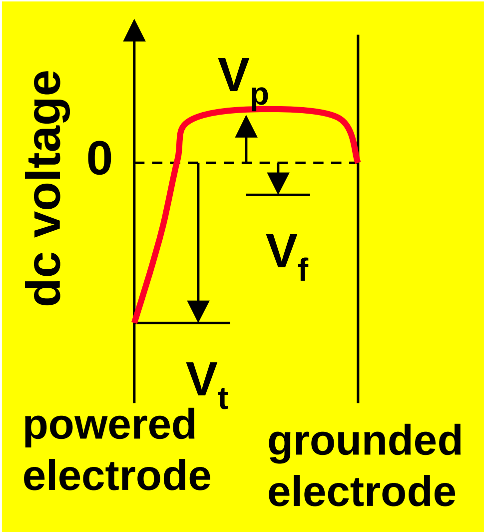
Plasma assistant pattern transfer

- includes
  - ion milling, sputtering
  - plasma etching
  - reactive ion etching (RIE)
- all use plasmas
  - typical pressures 10^{-3} - 10 Torr
    - mean free paths 10 mm - 5 μm
    - number density 10^{13} - 10^{17} cm^{-2}
  - typical ion densities ~10^{9} - 10^{12} cm^{-2}
    - most gas molecules are NOT ionized
  - temperature
    - electron: ~10^{4} K
    - gas: ~ambient

RF discharges and potentials

- electron and ion mobilities are very different
  - leads to separation of charge in rf discharge
    - electrons can "follow" field reversals, ions cannot
- plasma can act like a diode
  - dc potentials can be developed even for pure ac drive

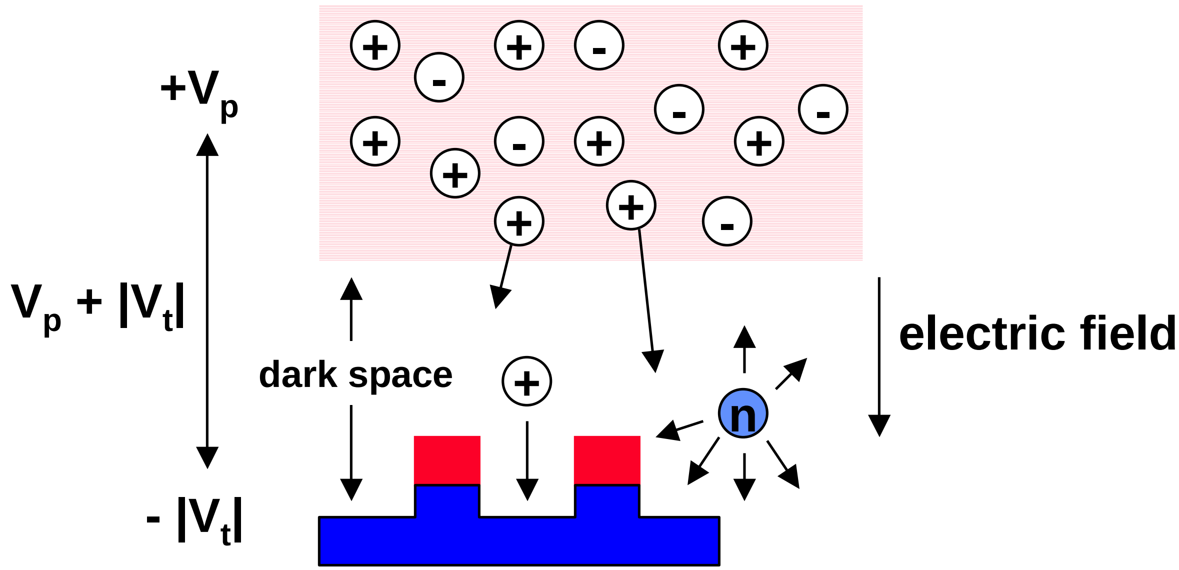




- typical parameters
  - ac frequency: 13.56 MHz, other industrially assigned
  - dc voltages depend on ratio of powered -to- grounded electrode areas
    - tens (~equal areas) to hundreds of volts possible (small powered area wrt grounded)

Ion bombardment in plasma discharge

- dc bias voltage / field between plasma and electrode accelerates ions towards surface
  - positive ions strike surface anisotropically
  - recall most gas molecules are neutral
    - still strike surface isotropically



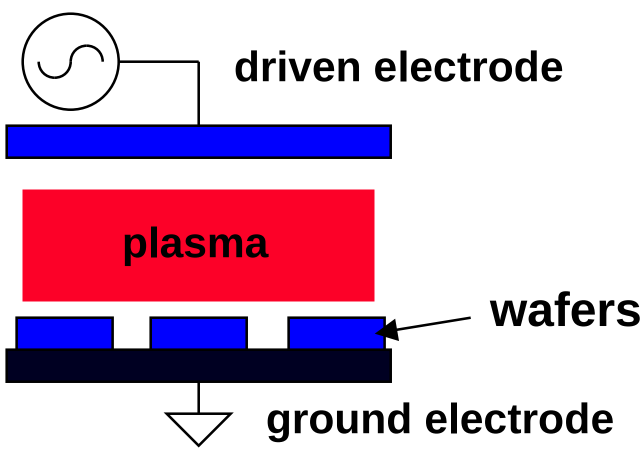
sample on powered electrode

Sputtering and ion milling

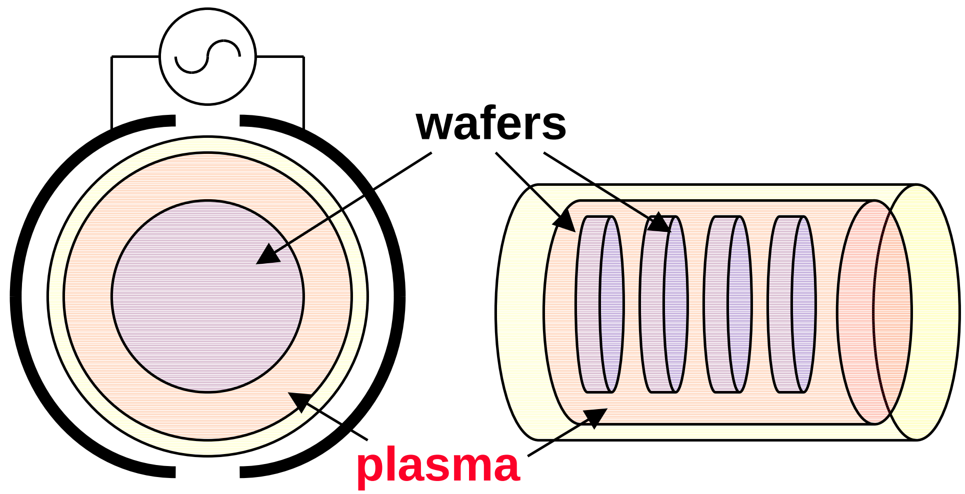
- if ion energy is ~500 eV substantial sputtering of "target" occurs
  - inert gas (Ar) typically used
- sputtering systems
  - accelerating potential from "self bias"
    - powered electrode area << ground area
    - sample placed on powered electrode
- ion mill
  - separate ion generation, acceleration, and sample chamber
- process is purely physical
  - "everything" sputters
  - <u>very low selectivity</u>

Plasma etching

- use reactive species produced in a plasma discharge to drive chemistry
  - need to produce volatile reaction products
- usually try to avoid ion bombardment
  - keep accelerating voltages small
  - process is mainly chemical
    - high selectivity
    - low anisotropy



planar system



barrel system

Reactive Ion Etching (RIE)

- similar to sputter etcher but replace noble gas with reactive gases like to those used in plasma etching
  - want high energy ions at surface
    - high accelerating voltages
      - substrates on powered electrode
      - asymmetric electrodes
        - area of powered electrode < grounded electrode
    - low pressures 10^{-3} - 10^{-1} Torr
- in both plasma etching and RIE feed- gas composition produces the reactive species necessary for etching
  - chemistry tends to be isotropic
  - ion bombardment of surfaces generates the anisotropy in plasma assisted pattern transfer

Ion- induced and ion- enhanced gas phase etching

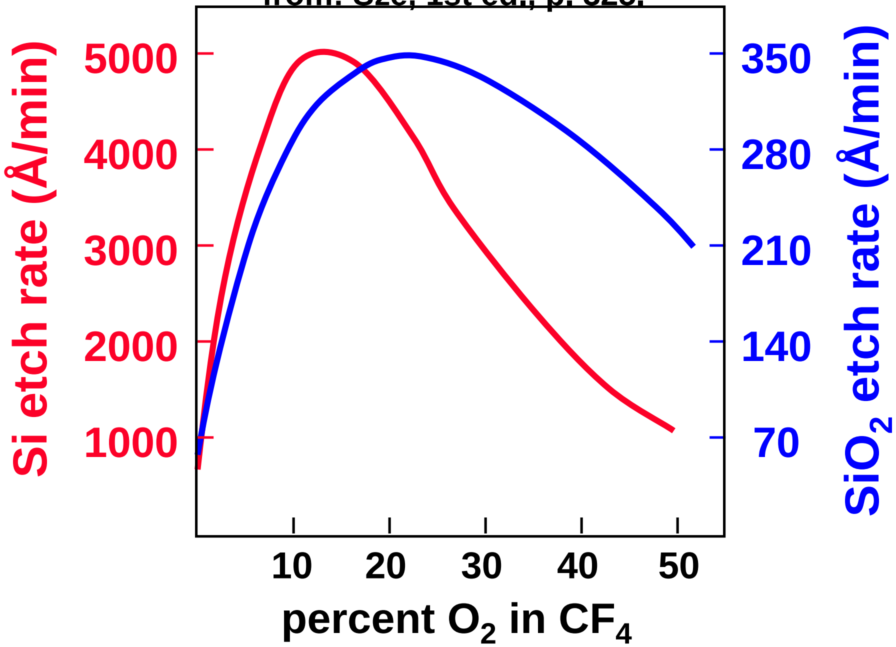
- ion-induced reactions
  - expose Si to Cl_2: no etching of the Si occurs
  - expose Si to Ar^+ ion mill beam: etch rate < 0.5 nm/min
  - expose to both: etch rate ~ 10 nm/min
    - note NO Cl_2 plasma was present in this example
- ion-enhanced reactions
  - XeF_2 will spontaneously etch Si: ~0.5 nm/min
  - but if expose to both XeF_2 and Ar^+ ion beam etch rate increases dramatically (~6 nm/min)

CF_4 plasma etching

- electron impact in plasma produces reactive radicals
  - $CF_4 + e \leftrightarrows CF_3^+ + F^* + 2e$
  - competing reactions between free F and CF_3 tends to keep F concentration low
  - free fluorine etches both Si and SiO_2, but etches Si faster
    - $Si + 4F \rightarrow SiF_4$ (g)
    - $SiO_2 + 4F \rightarrow SiF_4$ (g) $+ O_2$
  - these are isotropic!

- add O_2 to gas mix
  - $CF_3^+ + O + e \rightarrow COF_2 + F^*$
    - competes with F for CF_3, drives [F] up
      - etch rates increase
  - peak selectivity ~15 (Si:SiO_2)

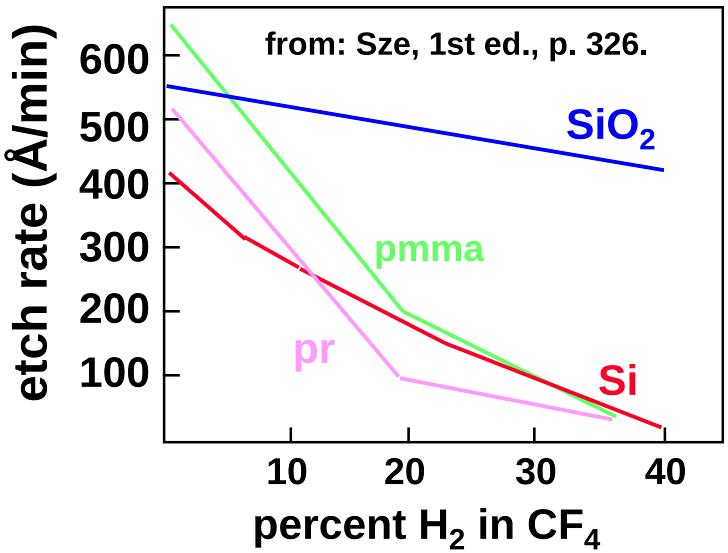
from: Sze, 1st ed., p. 325.



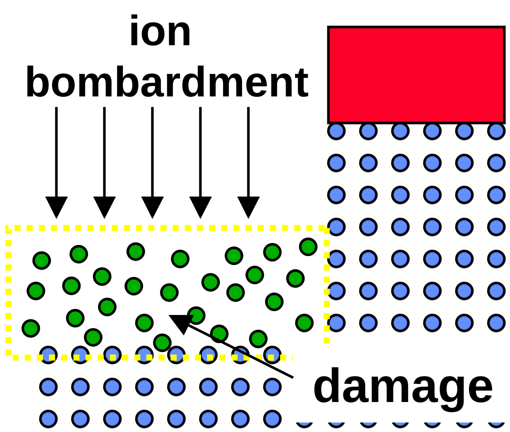
Ion assisted CF_x etching

- add H_2 to CF_4 gas mix
  - $CF_4 + e \leftrightarrows CF_3^+ + F^* + 2e$
  - $H_2 + F^* \rightarrow HF$
  - so addition of H_2 drives [F] down
    - reduces Si etch rate
- BUT CF_3 will NOT etch SiO_2 UNLESS there is ion bombardment
  - $CF_x + SiO_2$ + "damage" $\rightarrow SiF_4$ (g) + (CO, CO_2, COF_2, etc.)
  - CF_x + Si $\rightarrow SiF_4$ (g) + C-F (polymer) $\rightarrow$ stops etch!

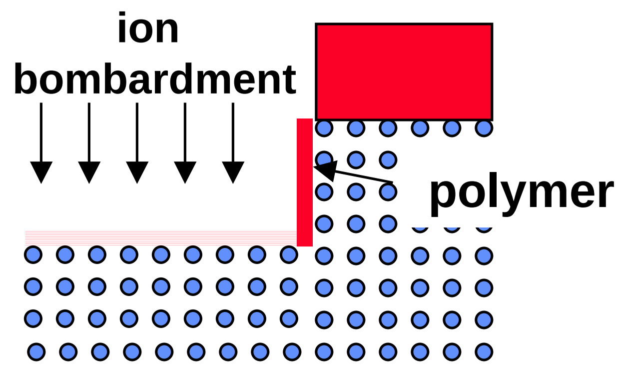
- summary:
  - $CF_4 + H_2$ (40%) : SiO_2 / Si selectivity ~ 10:1
    - can improve oxide-to-silicon selectivity by decreasing F:C ratio: use CHF_3
  - $CF_4 + O_2$ (10%) : Si / SiO_2 selectivity ~ 15:1



Mechanisms for ion-enhancement and induced anisotropy



surface damage induced anisotropy



surface inhibitor mechanism anisotropy

- **example of polymer formation:**
  - Si etched in Cl_2 plasma (~isotropic)
    - $e + Cl_2 \rightarrow e + 2Cl$
    - $Si + xCl \rightarrow SiCl_x \uparrow$
  - "recombinant" species C_2F_6
    - $e + C_2F_6 \rightarrow 2CF_3 + e$
    - $[CF_3 + Cl]_x \rightarrow [CF_3Cl]_3$ *(polymer)*
    - at ~85% C_2F_6 no undercutting occurs

Aluminum plasma etch

- **use volatile aluminum chloride**
  - **Al + CCl_3^+ + (bmbrdmnt) → $AlCl_3$ (g) + C**
  - **Al + $3Cl^*$ → $AlCl_3$ (g)**
  - **problems**
    - **initial Al_2O_3 on surface harder to etch (mostly by CCl_3^+)**
    - **selectivity wrt SiO_2 < ~20**
    - **selectivity wrt photoresist < ~15**
  - **can also use BCl_3, may include some O_2**

Etch summary

material etched	etch gas(es)	volatile product	selectivities
Si	$CF_4 + O_2$, etc.	SiF_4	15:1 ($Si:SiO_2$)
SiO_2	$CF_4 + H_2$, etc.	SiF_4	20:1 ($SiO_2:Si$)
organics	O_2	CO_2, H_2O	high
Al	CCl_4, BCl_3, etc.	$AlCl_3$	15:1 ($Al:SiO_2$); few:1 (Al:Si)
Mo	CF_4	MoF_6	
W	CF_4	WF_6	

- **things that are hard to dry etch**
  - **copper: no volatile reaction products**
  - **use CMP instead**