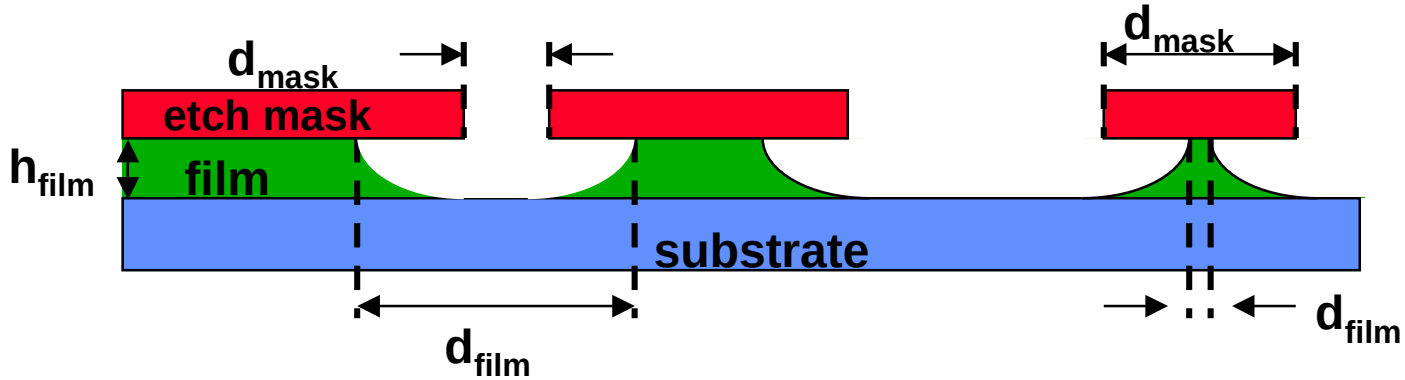
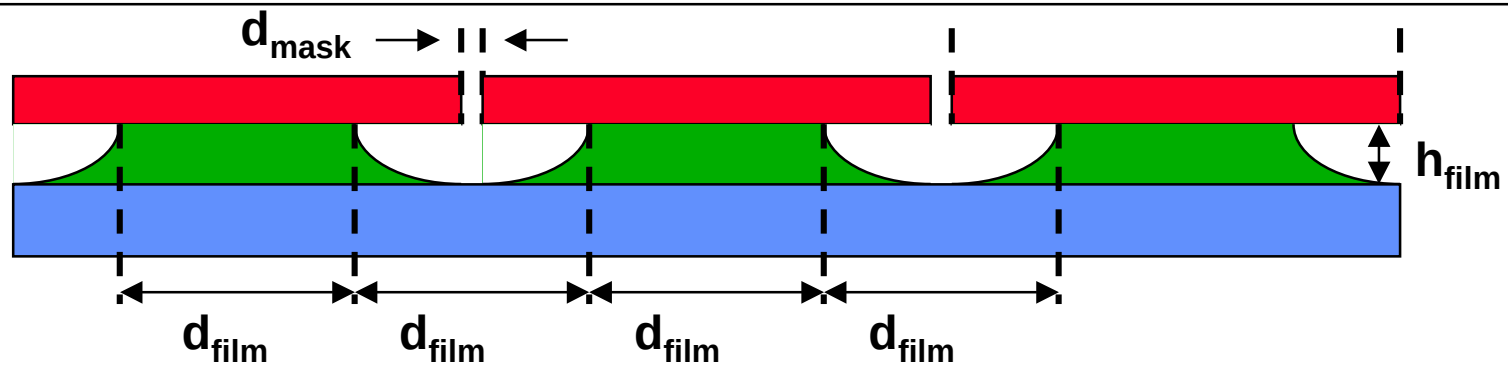
Etching terminology



- **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

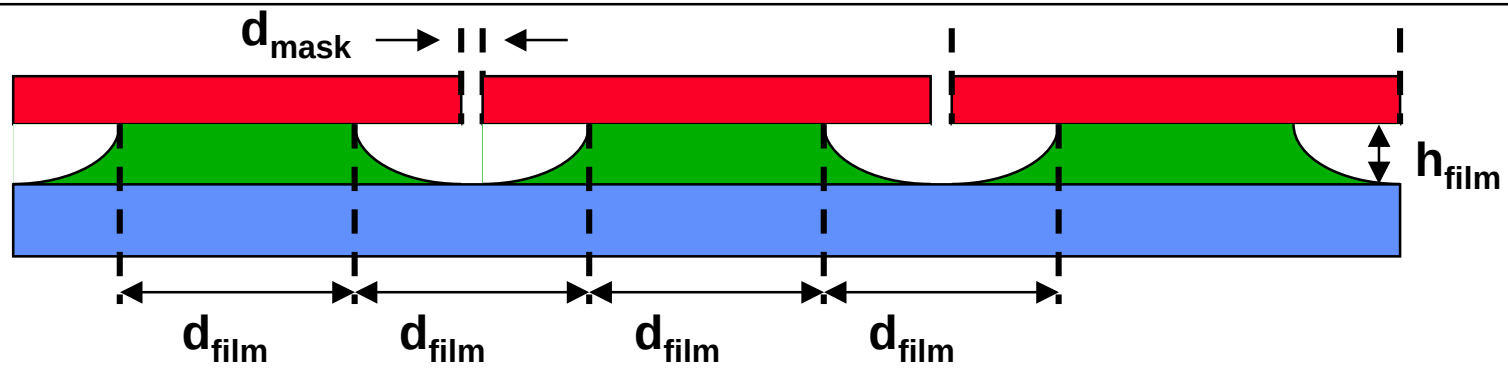
$$d_{mask} = d_f \cdot \left[1 - 2\frac{h_f}{d_f}\left(1 - A_f\right) \right]$$

    - h_f / d_f is the feature aspect ratio
    - since $d_m > 0$

$$\left[1 - 2\frac{h_f}{d_f}\left(1 - A_f\right) \right] > 0 \quad \Rightarrow \quad A_f \geq 1 - \frac{1}{2 \cdot \left(h_f / d_f\right)}$$

      - if aspect ratio is << 1 anisotropy is not needed
      - if aspect ratio is >> 1 need high anisotropy (i.e., $A_f \sim 1$)!

Example: undercut and feature aspect ratio



- example: want film to have "equal" lines and spaces after ISOTROPIC etch
  - for isotropic etch, etched just to completion, undercut = film thickness
- compensate for bias (undercut) by adjusting the mask features
  - here $d_f = d_m + 2h_f$ ➡ $d_m = d_f - 2h_f$ or $d_{mask} = d_f \cdot \left[1 - 2\frac{h_f}{d_f}\right]$
    - h_f / d_f is the feature aspect ratio
      - $h_f / d_f = 0.1$ ➔ $d_{mask} = 0.8 * d_{film}$
      - $h_f / d_f = 0.5$ ➔ $d_{mask} = 0$!!!!!!
      - if aspect ratio is ≥ 0.5 you canNOT make equal lines / spaces using an isotropic etch!!!!

Selectivity of etches

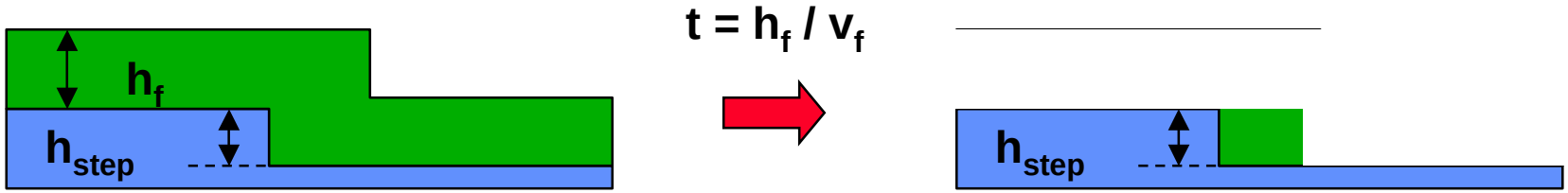
- need etch that removes film much faster than either the etch mask or “substrate”
- required selectivities depend on
  - uniformity of film thickness
  - uniformity of etch rates
  - anisotropy of etch rates
  - overetch required
  - acceptable loss of linewidth
  - acceptable “substrate” loss

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 $\Delta = h_{step} / h_{film}$

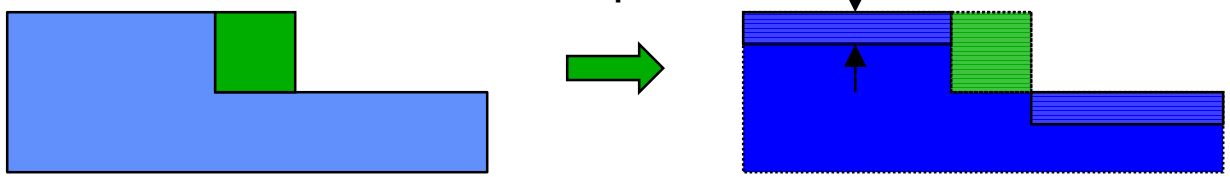
Film -to- substrate selectivity

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

over-etch etch time

$t = h_{step} / v_f$

$h_{sub} = t \cdot v_{sub}$



- substrate is "lost" during overetch
  - $h_{sub} = t_{over} \cdot v_{sub} = (h_{step} / v_f) \cdot v_{sub}$
    $= h_{step} \cdot (v_{sub} / v_f)$
  - 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
  - $S_{fs} = (h_{film} / h_{sub}) \cdot \Delta$

Effects of non-uniformities

- what if things aren't all uniform:
  - etch rate: $v_f \cdot (1 \pm \phi_f)$
  - thickness: $h_f \cdot (1 \pm \delta_f)$
  - 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

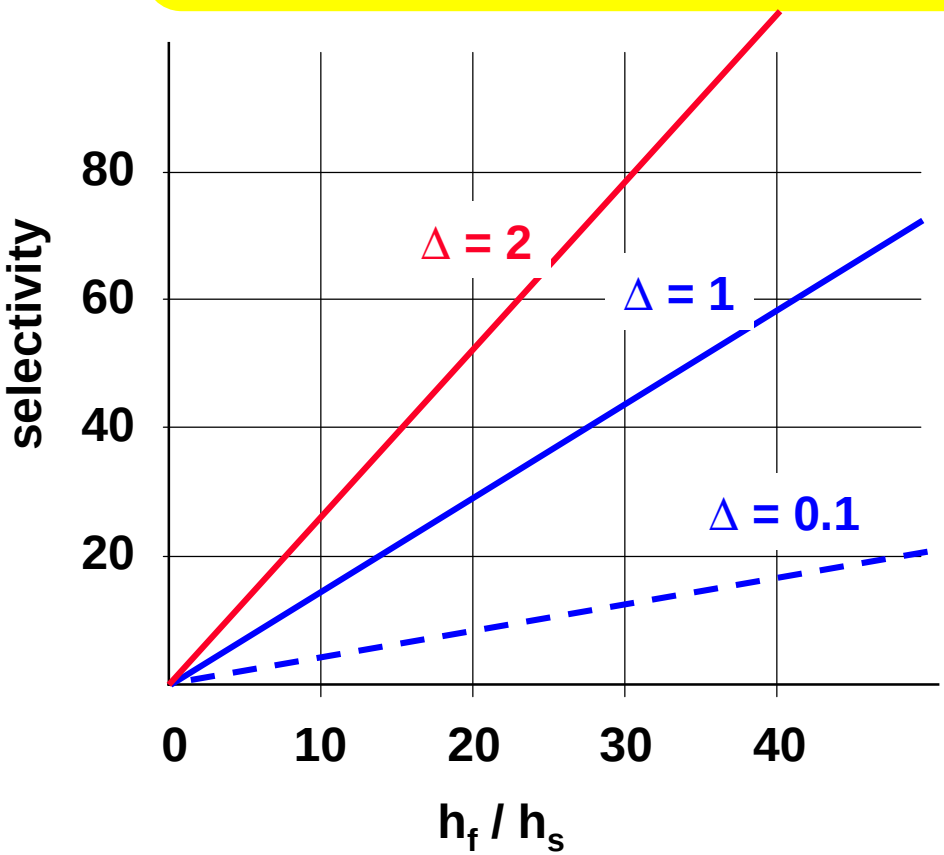
$$t_{exposed} = \underbrace{\frac{h_f \cdot (1+\delta_f)}{v_f \cdot (1-\phi_f)} \cdot (1+\Delta)}_{total\ \ etch\ \ time} - \underbrace{\frac{h_f \cdot (1-\delta_f)}{v_f \cdot (1+\phi_f)}}_{time\ \ sub.\ \ covered}$$

- 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

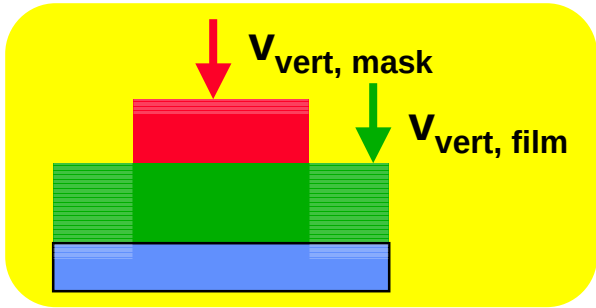
$$S_{fs} = \frac{v_f}{v_s} = \frac{h_f}{h_s} \cdot \left[\frac{\phi_f \cdot (2 + \Delta + \Delta \cdot \delta_f) + \delta_f \cdot (2 + \Delta) + \Delta}{1 - (\phi_f)^2} \right] \approx \frac{h_f}{h_s} \cdot \Delta$$



- etch rate uniformity ϕ_f = 0.1
- film thickness uniformity δ_f = 0.05
- note h_f / h_s tends to be BIG
  - you may not be willing to lose much substrate!

Film -to- mask selectivity

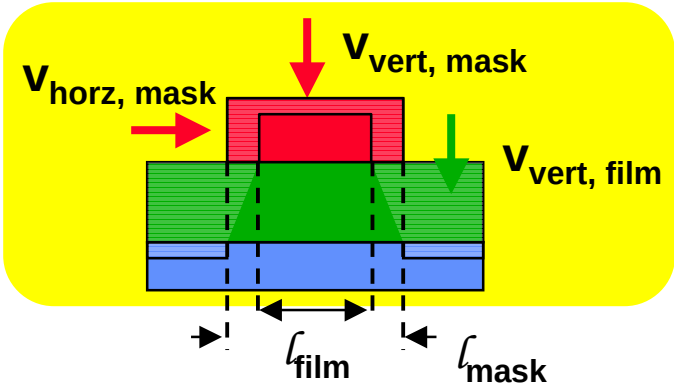
perfectly anisotropic vertical etch, both mask and film



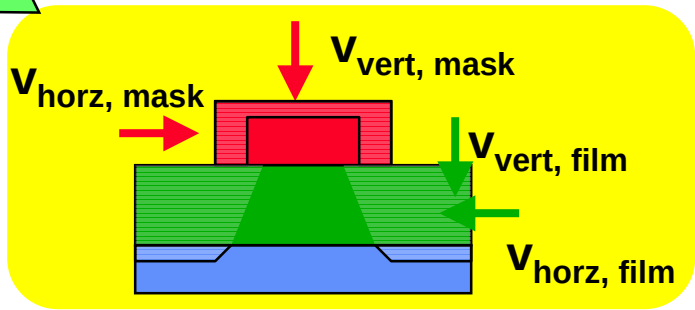
no linewidth loss

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

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



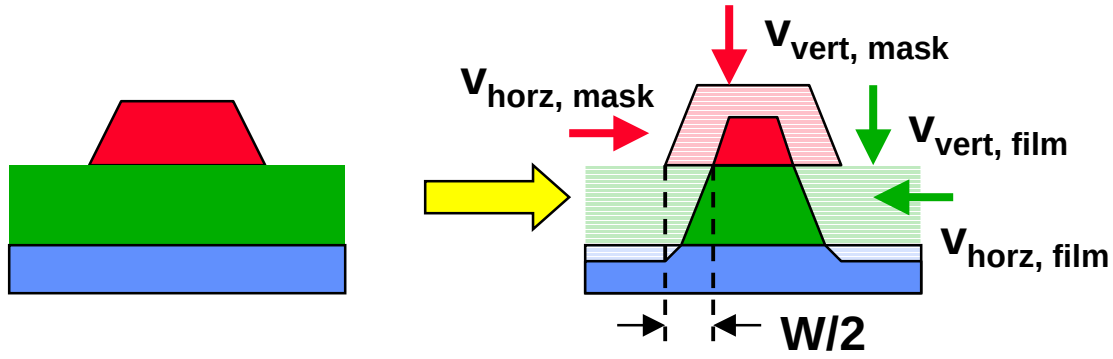
loss of linewidth $W = \ell_{mask} - \ell_{film}$



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

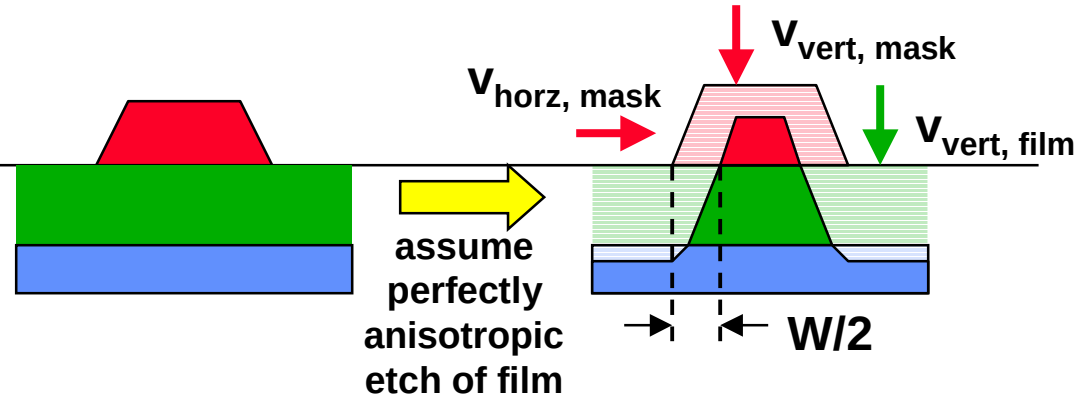
Film -to- mask selectivity

- 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: $v_f \cdot (1 \pm \phi_f)$

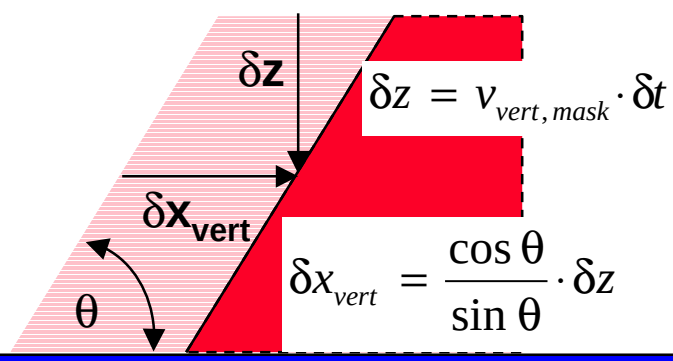
Film -to- mask selectivity



- non- uniformities:
  - etch rate: $v_f \cdot (1 \pm \phi_f)$
  - thickness: $h_f \cdot (1 \pm \delta_f)$
    - 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**

$$W = 2 \cdot v_{vert,mask} \left(\underbrace{\frac{v_{horz,mask}}{v_{vert,mask}}}_{1 - A_{mask}} + \cot\theta \right) \cdot \frac{h_f \cdot (1 + \delta_f)}{v_f \cdot (1 - \phi_f)} \cdot (1 + \Delta)$$

  - **let's use worst case mask etch so**

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

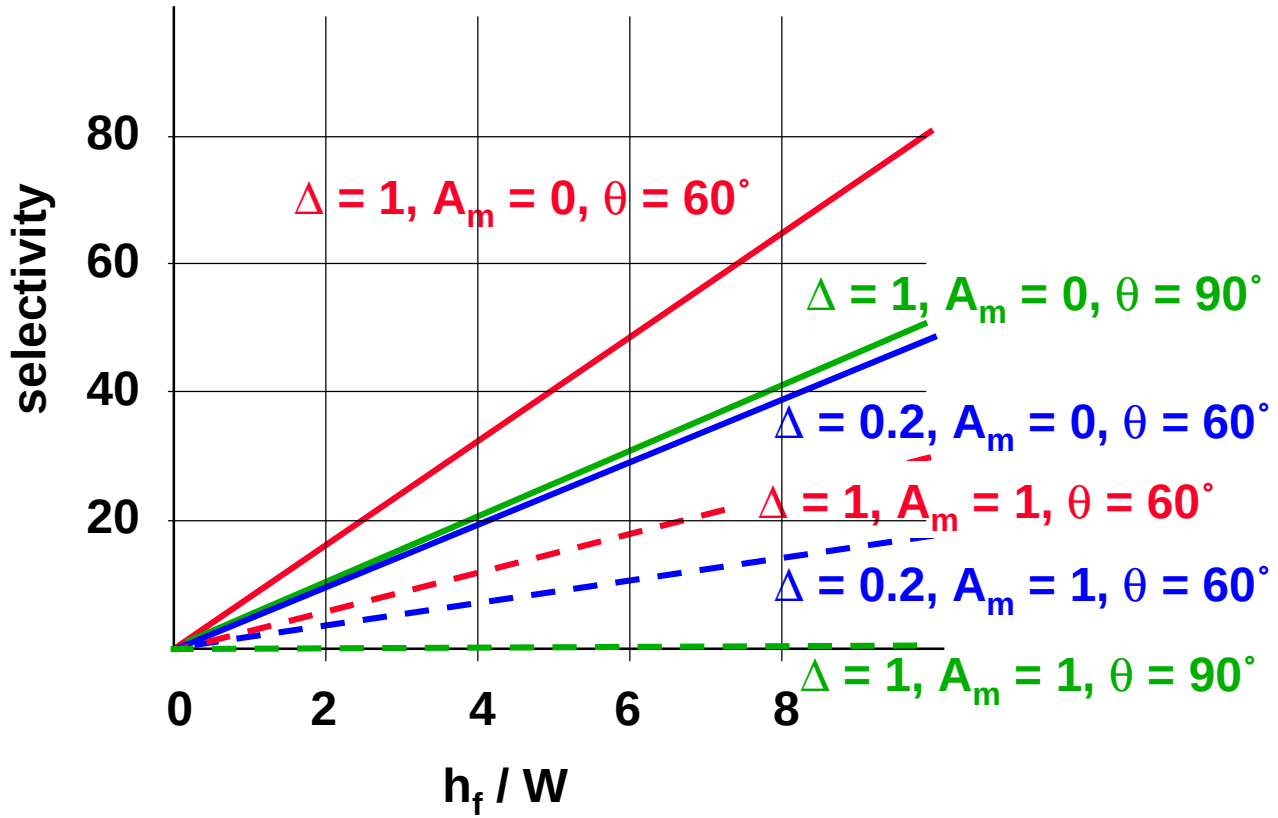
- **or**

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

- **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



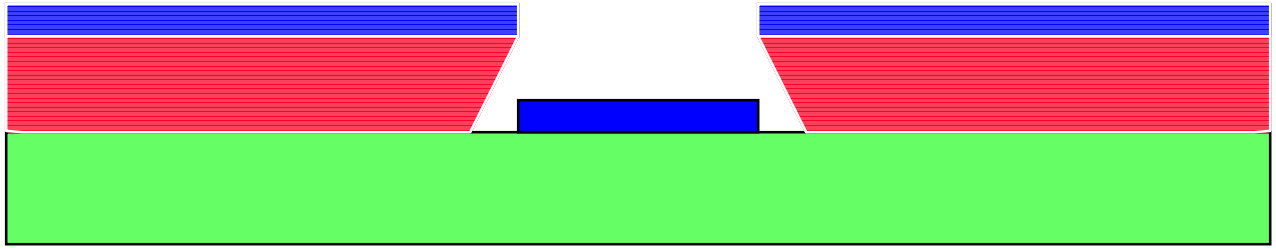
Lift-off patterning

- **“no-etch” thin film patterning process**
  - **do the lithography BEFORE film deposition**
- **extensively developed by IBM in the late 70’s for patterning of metals**
  - **Au and Pb for Josephson junction computers!**

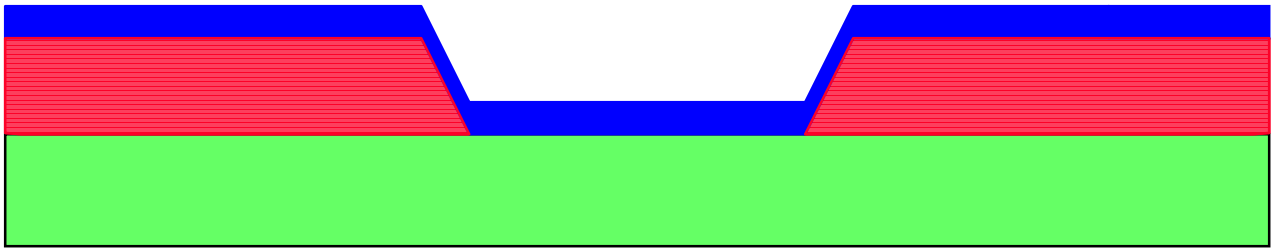
[1] C. Li and J. Richards, “A High Resolution Double Layer Photoresist Structure for Lift-Off Techno*logy*,” presented at IEDM, Washington, DC, 1980.
[2] M. Hatzakis, B. J. Canavello, and J. M. Shaw, “Single-Step Optical Lift-Off Process,” *IBM Journal of Research and Development*, vol. 24, pp. 452-460, 1980.
[3] R. M. Halverson, M. W. MacIntyre, and W. T. Motsiff, “The Mechanism of Single-Step Liftoff with Chlorobenzene in a Diazo-Type Resist,” *IBM Journal of Research and Development*, vol. 26, pp. 590-595, 1982.
[4] G. G. Collins and C. W. Halsted, “Process Control of the Chlorobenzene Single-Step Liftoff Process with a Diazo-Type Resist,” *IBM Journal of Research and Development*, vol. 26, pp. 596-604, 1982.
[5] P. L. Pai and W. G. Oldham, “A Liftoff Process Using Edge Detection (LOPED),” *IEEE Transactions on Semiconductor Manufacturing*, vol. 1, pp. 3-9, 1988.
[6] Y. Homma, A. Yajima, and S. Harada, “Feature Size Limit of Liftoff Metallization Technolog*y*,” *IEEE Transactions on Electron Devices*, vol. ED-29, pp. 512-517, 1982.
[7] S. Lyman, J. Jackel, and P. Liu, “Lift-off of thick metal layers using multilayer resist,” *Journal of Vacuum Science Technology B*, vol. 19, pp. 1325-1328, 1981.
[8] K. Grebe, I. Ames, and A. Ginzberg, “Masking of Deposited Thin Films by Means of an Aluminum-Photoresist Compos*ite*,” *Journal of Vacuum Science Technology B*, vol. 11, pp. 458, 1974.

Basic lift-off concept

- use resist with a “re-entrant” cross-sectional profile
- use deposition process with “poor” step coverage

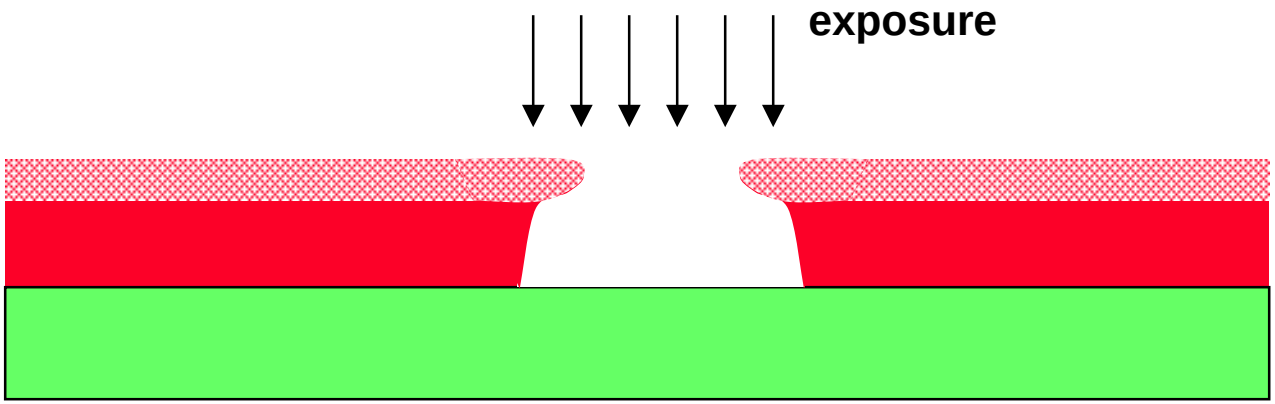


- now use solvent to dissolve resist, lifting off the material to be removed
- problem: resist edge profile frequently is not “re-entrant”



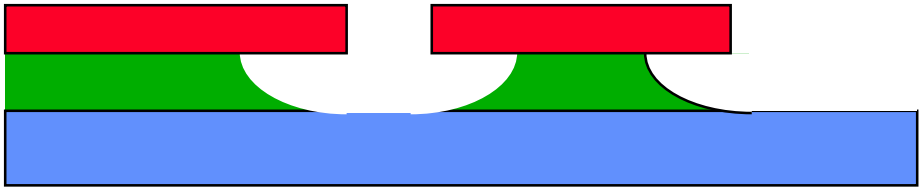
Chlorobenzene process

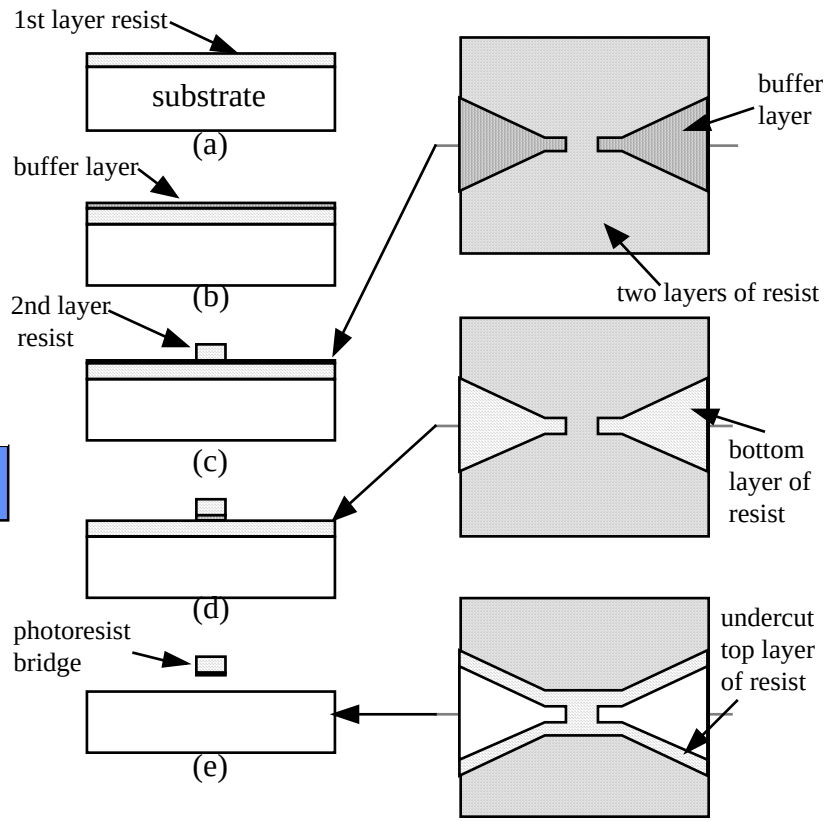
- objective: produce a “lip” on the surface of the photoresist
  - chlorobenzene soak process
    - soaking photoresist in solvent alters exposure or/and development characteristics
- process:
  - apply resist, expose
  - soak in chlorobenzene
  - develop



Bilayer lift-off

- use two separate layers
  - bottom layer: "sacrificial"
  - undercut top layer to form "lip"





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

Oxide wet etch

- basic oxide etch: hydrofluoric acid (HF)
  - $SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$
    - BHF: buffering agent (NH_4F) frequently added to keep [HF_2^-] constant
  - etch rate
    - thermally grown oxide: ~ few tenth's micron per minute
    - PECVD deposited oxide: few times faster than thermal
    - doped oxides (BSG, PSG): ~2-5X faster than thermal
  - selectivities
    - very high to photoresist
      - undercutting or resist adhesion failure biggest problem for long etches
    - very high to silicon

Silicon nitride wet etch

- HF, BHF etch
  - typically much slower than oxide etch rates
  - slowest for “high quality”, oxygen free nitride
    - rate in concentrated HF ranges from 0.01 – 0.1 micron / minute
    - about 10x slower in BHF
  - obviously no selectivity to oxide
- boiling H_3PO_4 (phosphoric acid)
  - nitride etch rate ~ 0.01 micron / minute
  - oxide etch rate ~ 0.001 micron / minute
  - silicon etch rate ~ 0.0003 micron / minute

Isotropic silicon wet etch: "HNA"

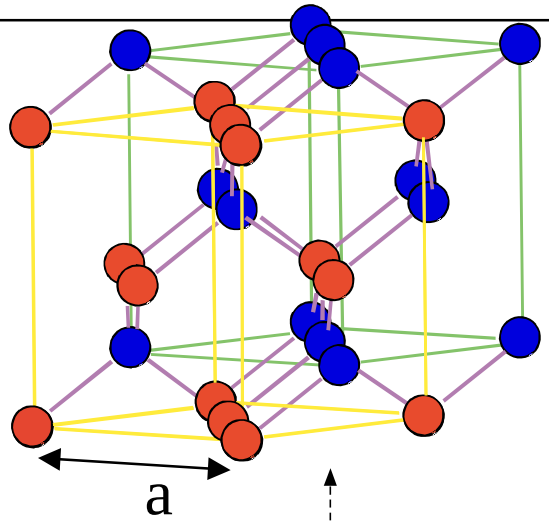
- mixture of HF (hydrofluoric acid), HNO_3 (nitric acid), and CH_3C00H (acetic acid)
- basic mechanism
  - injection of holes into Si to form Si_2^+ ("anodic" reaction)
  - attachment of OH^- to the Si^{2+} to form $Si(OH)_2^{2+}$ (oxidation step)
  - reaction of the "hydrated silica" to form soluble product
    - fluoride ions from HF form H_2SiF_6
  - dissolution of products into solution
- overall reaction for HNA:
  - $18HF + 4HNO_3 + 3Si \rightarrow 2H_2SiF_6 + 4NO^{(gas)} + 8H_2O$
  - recall mechanism required holes:
    - $HNO_2 + HNO_3 + H_2O \rightarrow 2HNO_2 + 2OH^- + 2h^+$
    - note this is an electrochemical reaction
      - is influenced by dopant type and concentration, as well as any external applied electrical bias

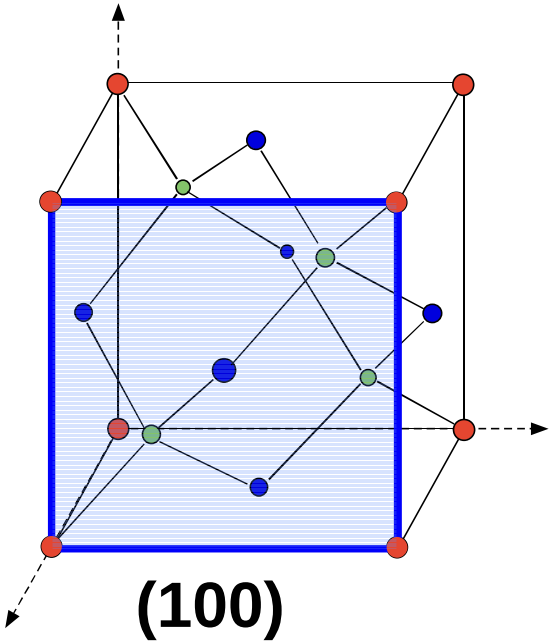
HNA formulations

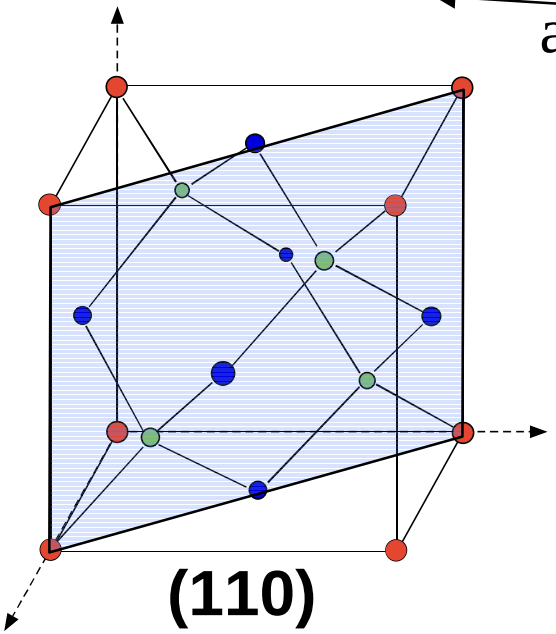
- HF : HNO_3 : water/CH_3COOH
  - 1 : 3 : 8
    - etch rate: 0.7 – 3 microns/minute
    - doping dependence: light doping < 10^{17} REDUCES rate ~ 150X
    - SiO_2 etch rate: 0.03 microns/minute
  - 1 : 2 : 1
    - etch rate: 4 microns/minute
    - doping dependence: none
    - SiO_2 etch rate: ?
  - 1 : 8.3 : 3.3
    - etch rate: 7 microns/minute
    - doping dependence: none
    - SiO_2 etch rate: 0.07 microns/minute

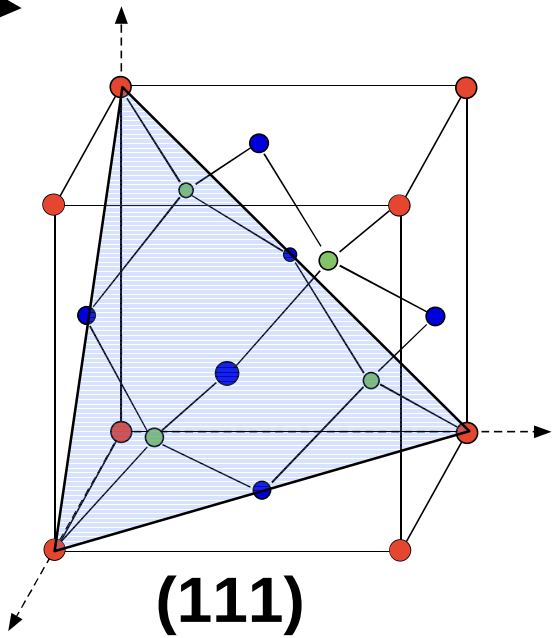
Crystallographic etching

- recall crystal lattice is face centered cubic (FCC), with two atom basis [at (0,0,0) and (1/4, 1/4, 1/4)]
  - two “interpenetrating” FCC lattices



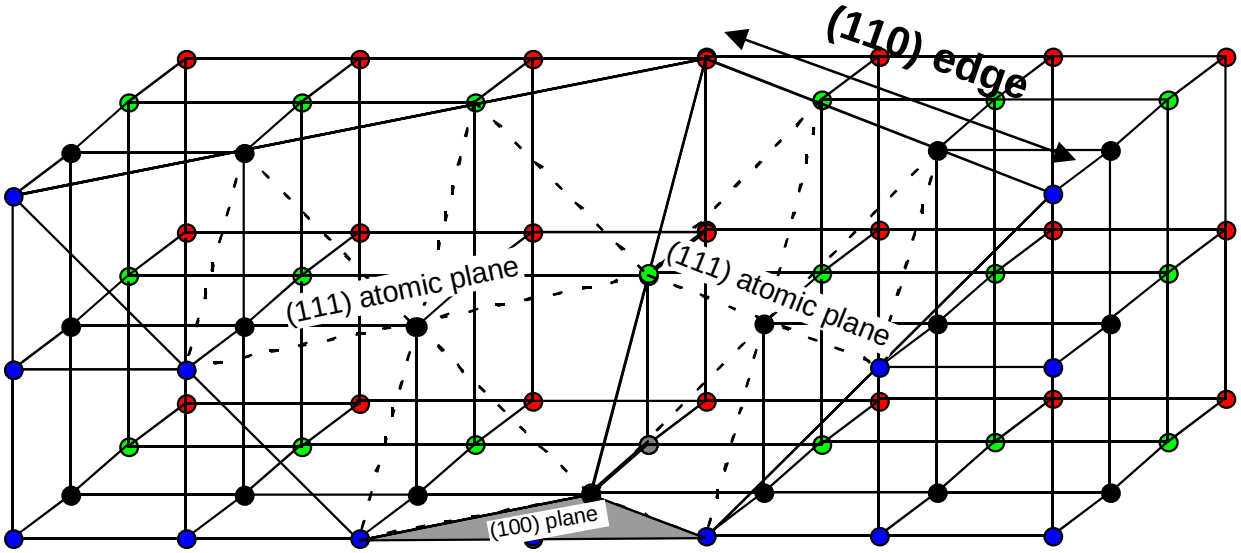


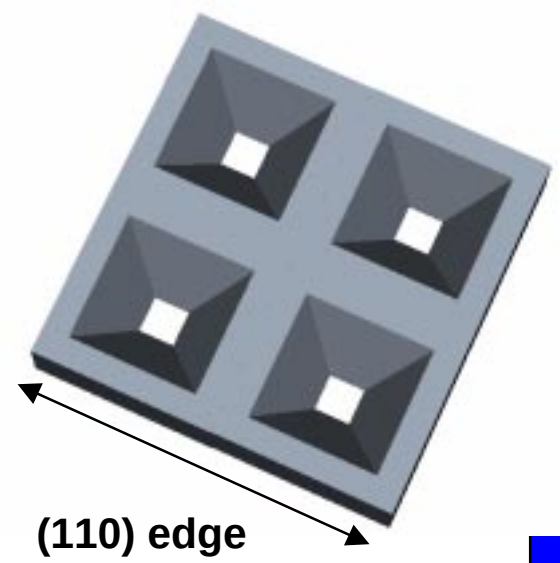




(111) planes

- **(111) planes etch the slowest, tend to be cleavage planes**
- **54.74° (111) wrt (100)**

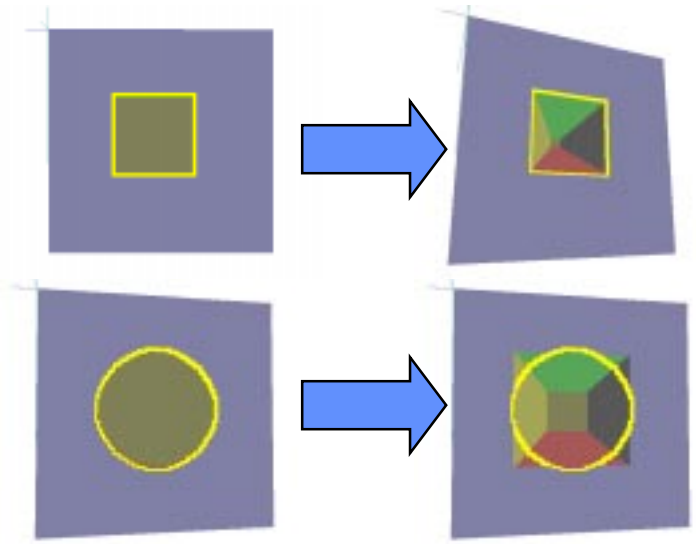




- **edge of "pit" lines up with (110)**

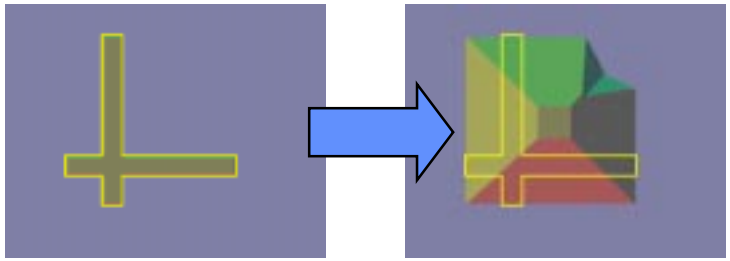
Masking

- assume bulk crystalline (100) silicon substrate combined with anisotropic etch
  - results in pyramidal shape
- bounding (111) planes can be reached using a variety of mask shapes
  - square mask opening, (100) wafer orientation, side of square is aligned to the (110) flat
  - what happens if you use a circular mask opening?
    - undercutting of the mask occurs until the (111) planes are reached
    - still forms a pyramidal pit!

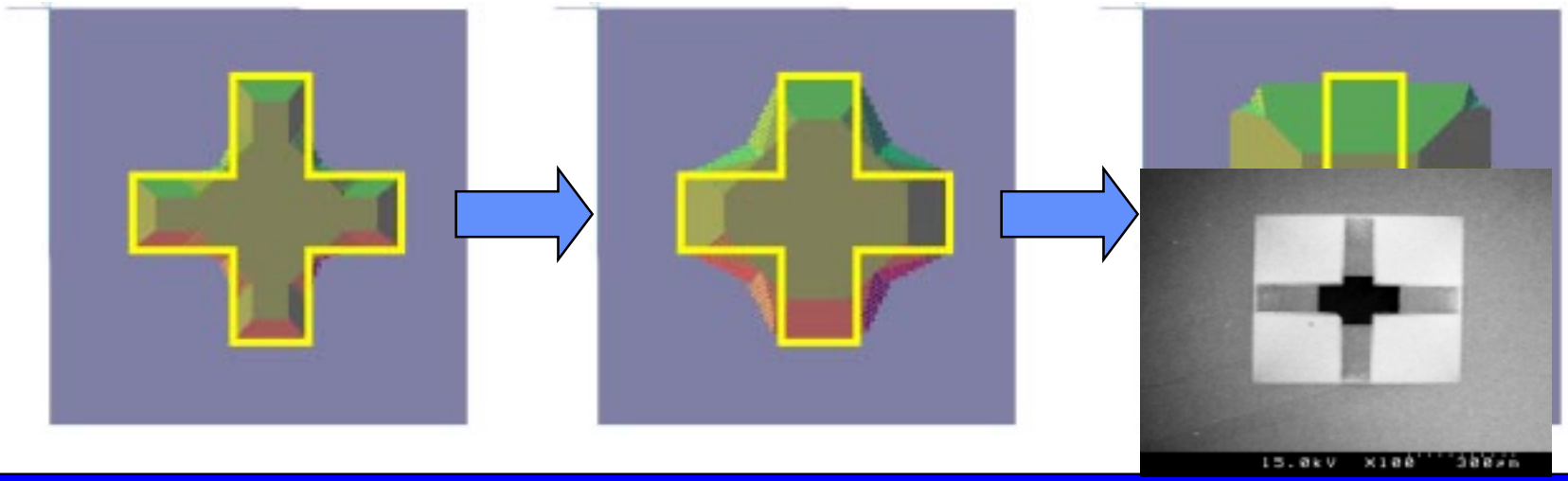


Other mask openings

- in general mask is undercut until (111) planes are reached
  - bars undercut until bounding planes are reached

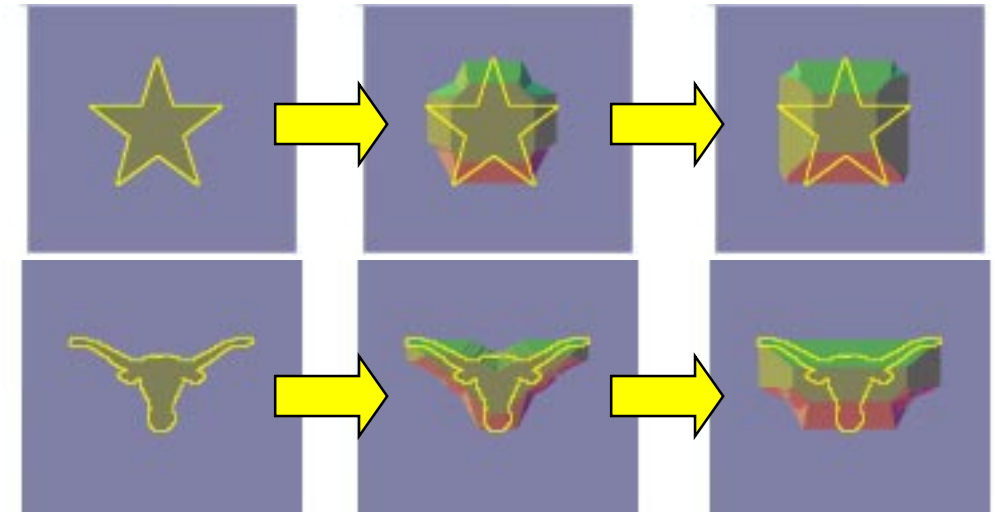


- "cross"-shaped mask opening will also undercut to form pyramidal pit

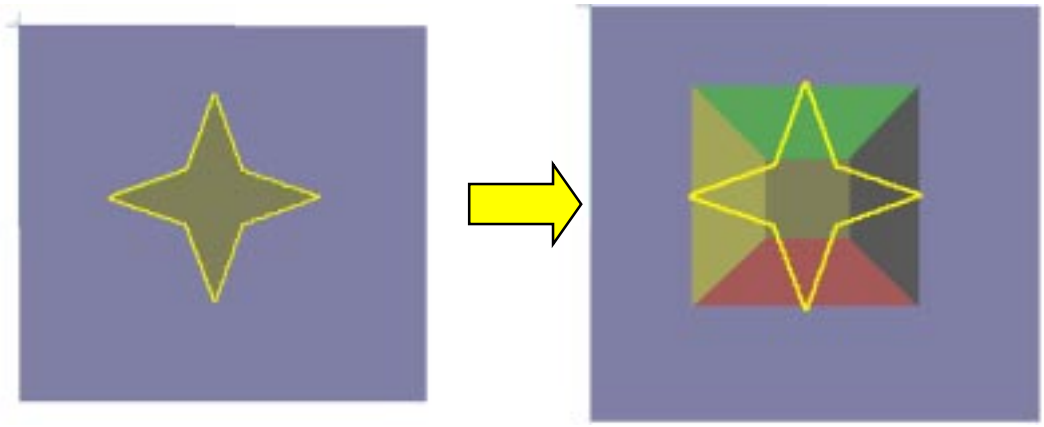


Other shapes?

- have to have a texana shape
  - "Texas" star
  - Longhorn

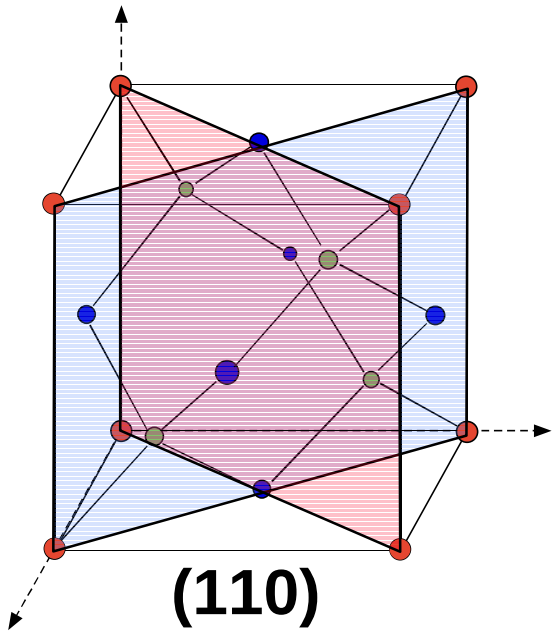


- "obtuse corner" cross
  - different bending stress / properties



Other orientations

- note (110) planes are perpendicular to one another



- anisotropic etch rates fastest to slowest
  - (110) : (100) : (111)
  - can etch “rectangular trenches” in (110) orientated substrates
  - sides of trenches are (110)

Anisotropic wet etch formulations

- alkali metal hydroxide etchants
  - examples: KOH, NaOH
  - typically 15 - 40w% concentration, dilutant water or isopropanol, ~70°C
  - proposed reactions:
    - $Si + 2OH^- \rightarrow Si(OH)_2^{2+} + 4e^-$
    - $4H_2O + 4e^- \rightarrow 4OH^- + 2H_2$ (gas)
    - $Si(OH)_2^{2+} + 4OH^- \rightarrow SiO_2(OH)_2^{2-} + 2H_2O$
    - overall: $Si + 2OH^- + 2H_2O \rightarrow SiO_2(OH)_2^{2-} + 2H_2$ (gas)
  - selectivities:
    - (100) : (111) about 400 : 1, (111) rate ~ 1 μm/min
    - p type doping > ~$2x10^{19}$: reduces etch rate
    - (oxide) : (111) about 1 : 1000
  - choice of concentration, etch temperature
    - affects etch rate, surface smoothness
    - generally, KOH tends to give very smooth (111) planes

Other formulations

- similar: ammonium hydroxide NH_4OH
  - 3.7wt% @ 75°C, (100) : (111) of 8,000 : 1 , but < 0.1 μm/min etch rate
  - hillock formation also a problem
- TMAH (tetramethyl ammonium hydroxide $(CH_3)_4NOH$)
  - 90°C, 10-40%, ~1 μm/min; surface roughness can be problem
  - (100) : (111) selectivity 10-35 : 1
  - boron doping stop
  - selectivity against oxide >1000
  - low aluminum etch rate
- EDP (ethylene diamine / pyrochatechol / water)
  - 115°C, ~1 μm/min, (100) : (111) selectivity 35 : 1
  - oxide selectivity >1000:1, etches aluminum
- hydrazine

Various issues

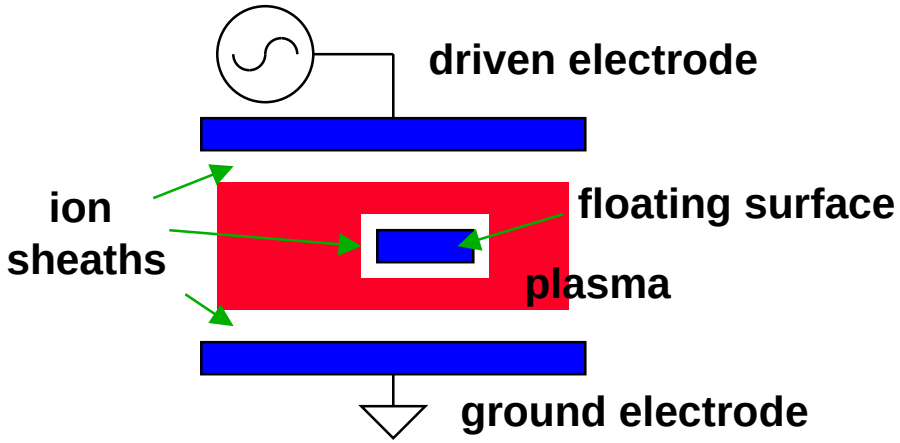
- safety hazards
  - EDP, hydrazine potentially quite hazardous
  - ammonia released from TMAH at elevated temperatures
- hydrogen bubbles
  - all the reactions tend to produce H_2
    - bubble formation can locally “mask” etch leading to rough surfaces
    - bubbles trapped inside sacrificial regions can stop etch or cause breakage

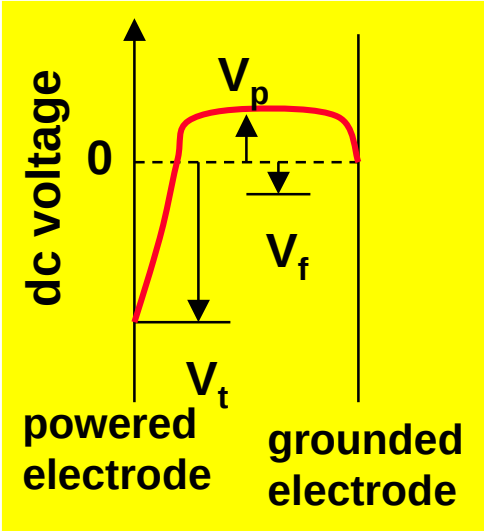
Plasma assistant pattern transfer

- 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^{-3}
  - typical ion densities ~10^{9} - 10^{12} cm^{-3}
    - 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

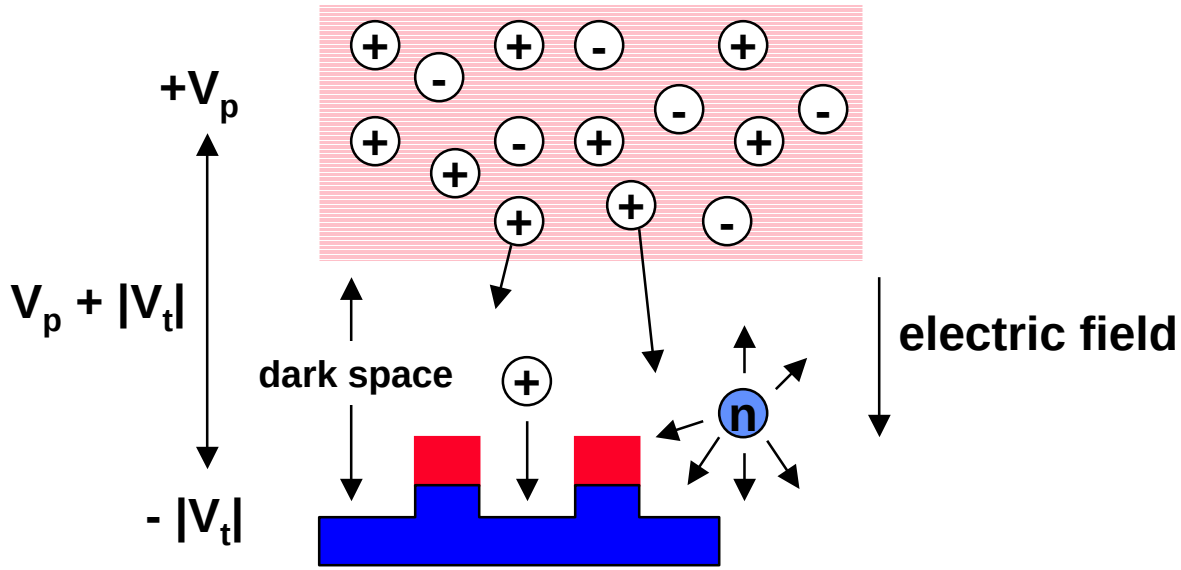




- typical parameters
  - ac frequency: 13.56 MHz, other industrially assigned
  - dc voltages depend on ratio of powered -to- grounded electrode areas
    - tens (~equal areas) to hundreds of volts possible (small powered area wrt grounded)

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



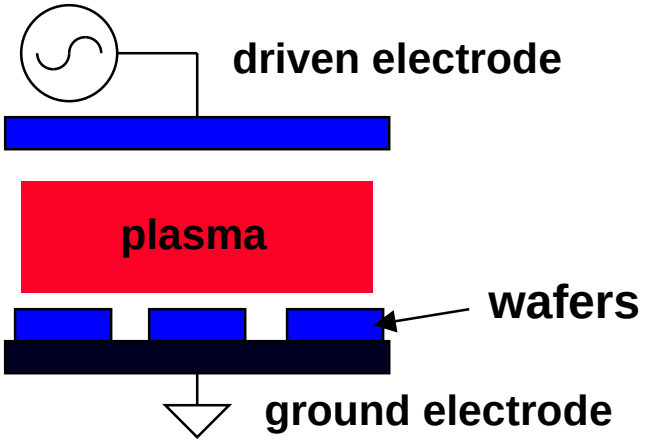
sample on powered electrode

Sputtering and ion milling

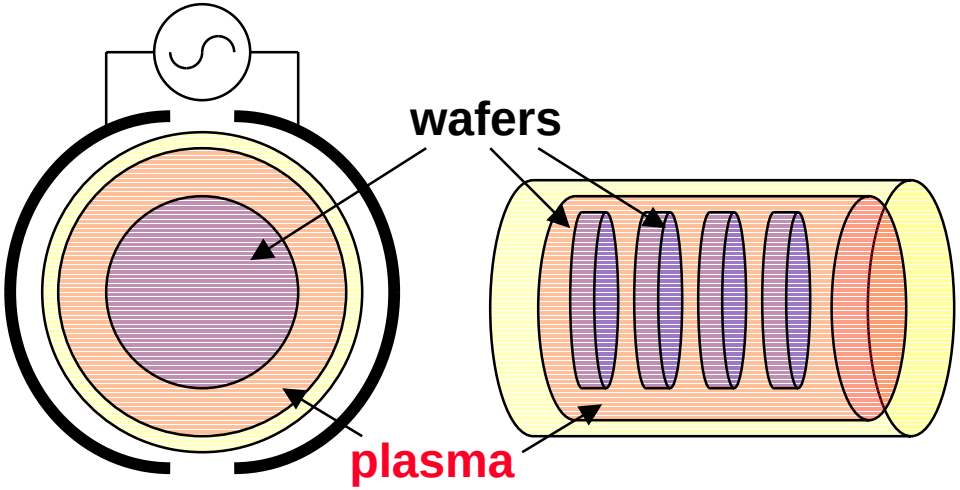
- if ion energy is ~500 eV substantial sputtering of “target” occurs
  - inert gas (Ar) typically used
- sputtering systems
  - accelerating potential from “self bias”
    - powered electrode area << ground area
    - sample placed on powered electrode
- ion mill
  - separate ion generation, acceleration, 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

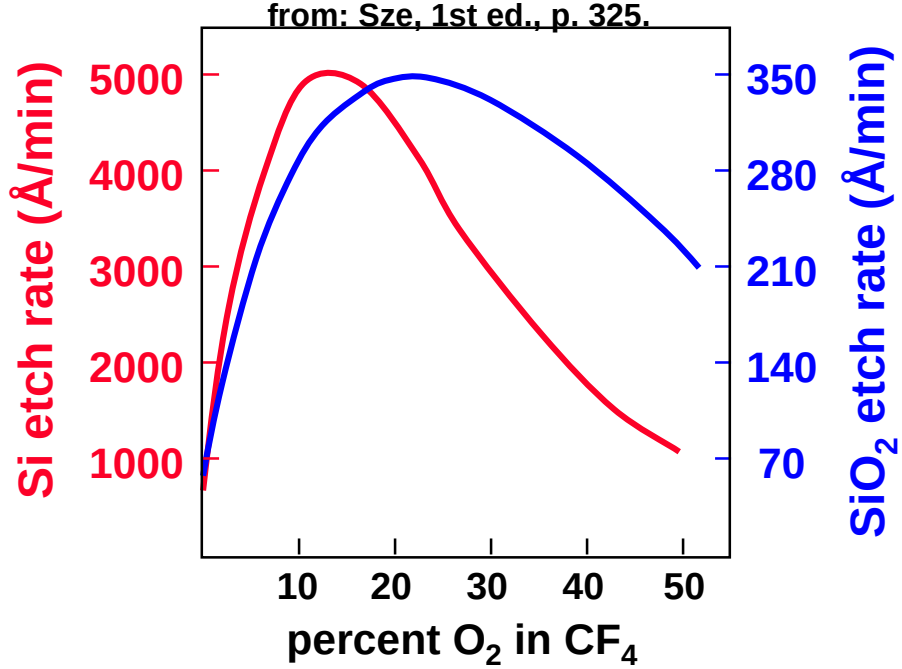
- ion-induced reactions
  - expose Si to Cl_2: no etching of the Si occurs
  - expose Si to Ar^+ ion mill beam: etch rate < 0.5 nm/min
  - expose to both: etch rate ~ 10 nm/min
    - note NO Cl_2 plasma was present in this example
- ion-enhanced reactions
  - XeF_2 will spontaneously etch Si: ~0.5 nm/min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

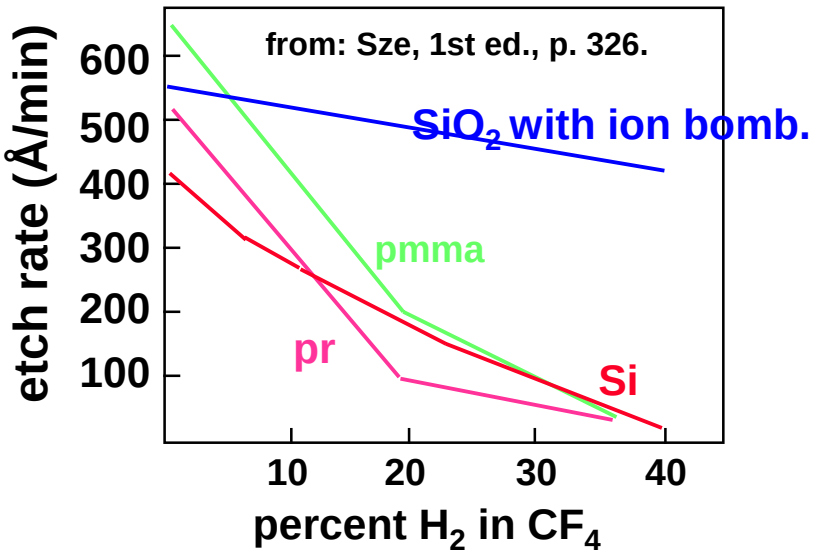
- add O_2 to gas mix
  - $CF_3^+ + O + e \rightarrow COF_2 + F^*$
    - competes with F for CF_3, drives [F] up
      - etch rates increase
  - peak selectivity ~15 ($Si:SiO_2$)

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

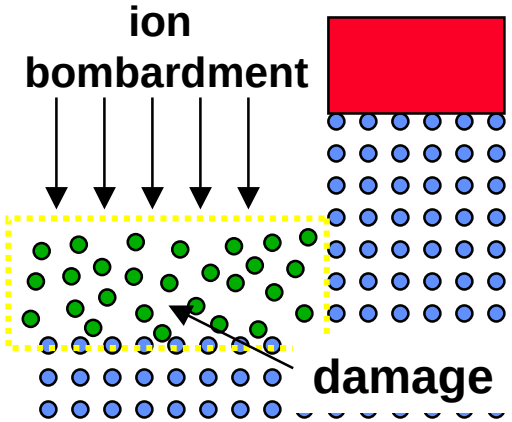


Ion assisted CF_x etching

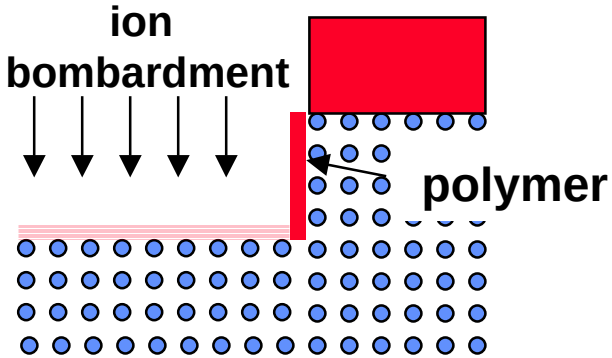
- add H_2 to CF_4 gas mix
  - $CF_4 + e \leftrightarrows CF_3^+ + F^* + 2e$
  - $H_2 + F^* \rightarrow HF$
  - so addition of H_2 drives [F] down
    - reduces Si etch rate
- BUT CF_3 will NOT etch SiO_2 UNLESS there is ion bombardment
  - $CF_x + SiO_2$ + "damage" $\rightarrow SiF_4$ (g) + (CO, CO_2, COF_2, etc.)
  - $CF_x + Si \rightarrow SiF_4$ (g) + C-F (polymer) $\rightarrow$ stops etch if no ion bombardment!
- 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
  - $Al + CCl_3^+ + (bmbrdmnt) \rightarrow AlCl_3\ (g) + C$
  - $Al + 3Cl^* \rightarrow AlCl_3\ (g)$
  - 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

Si Deep RIE

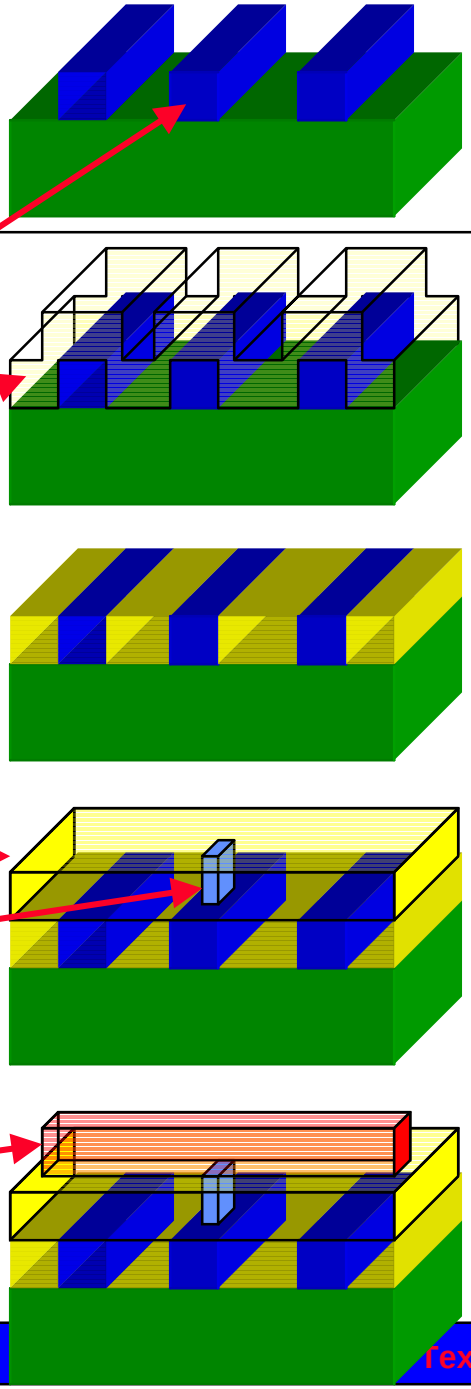
- desire: high etch rates, high aspect ratios
  - requires very high degrees of anisotropy
- Bosch process (German patent: Larmer and Schilp, 1994)
  - uses recombinant species and side-wall polymer formation
    - sequential etch / polymer deposition
      - high bias reactive ion etch: SF_6 / Ar typical
      - low bias polymerization: C_4F_8, CHF_3
      - repeat
- usually need high density plasma source
  - inductively coupled
- aspects ratios up to about 30:1
- etch rate: few microns per minute
- selectivities
  - to PR : 50-100
  - to oxide 100-200

Deep RIE

- pictures at http://www.ee.washington.edu/class/539/Lectures/lecture3/sld011.htm
- STS (http://www.stsystems.com/)
- BPS/Plasma Therm (model 790, ICP type)

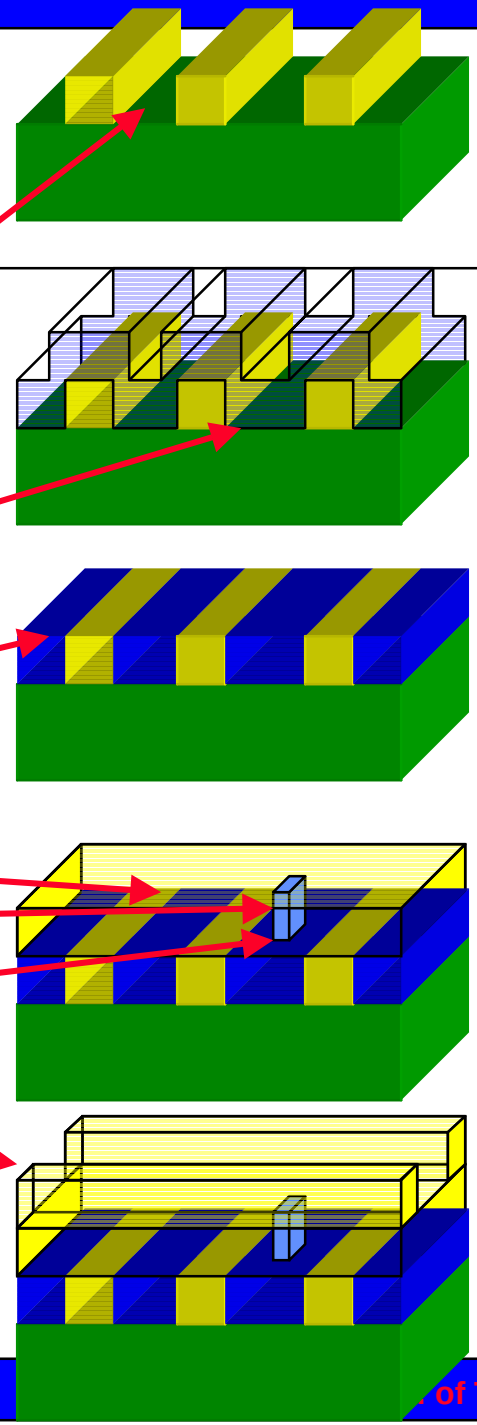
Chemical-mechanical polish (CMP)

- in multi- level interconnect planarization is limiting problem
- CMP
  - lithography/etch to pattern metals
  - deposit dielectric
  - polish to planarize dielectric surface
  - deposit dielectric
  - etch contact openings (vias) , deposit via “plug” material, etch/polish as needed
  - repeat starting with deposition/patterning of next metal lines

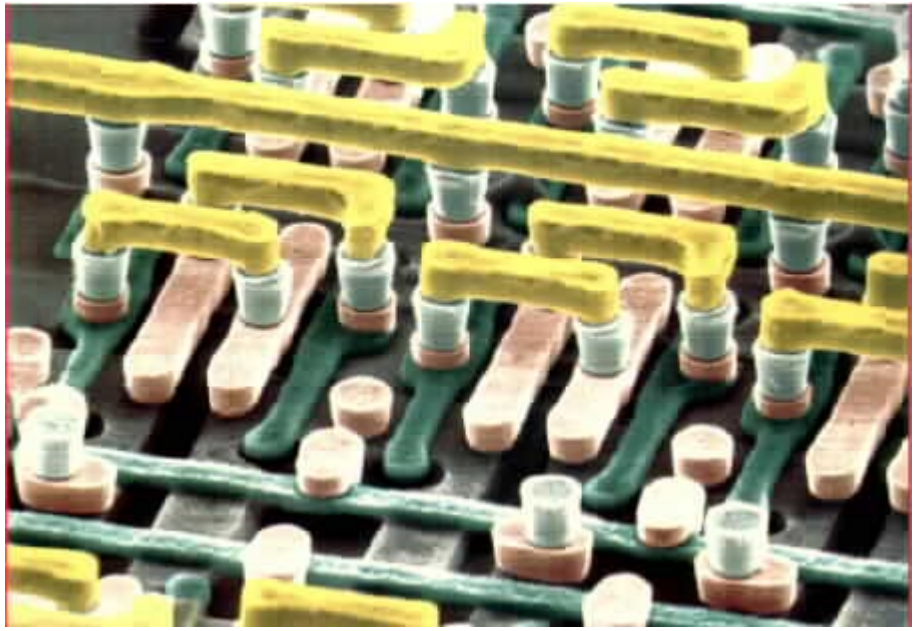


Damascene process

- deposit dielectric
- etch “trenches” that are where you want metal lines
- “line” trenches if necessary
- blanket deposit metal
- polish metal back to dielectric surface
- deposit dielectric
- open vias
- deposit via plug material
- repeat by depositing dielectric, etching trenches to be filled with metal



Damascene/CMP example



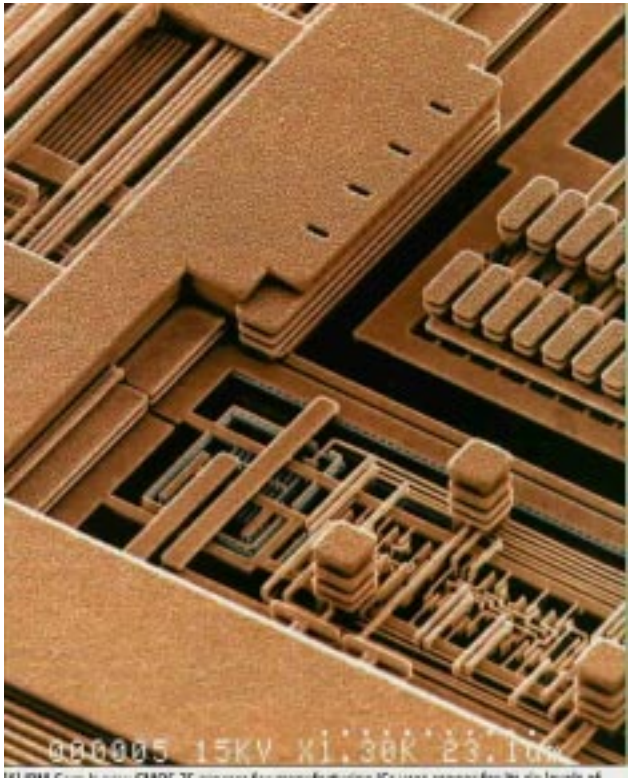
•ref: R. W. Mann, L. A. Clevenger, P. D. Agnello, and F. R. White, "Salicides and local interconnections for high-performance VLSI applications," IBM J. Res. Develop., vol. 39, pp. 403-417, 1995. Photo p. 414.

- dielectric layers have been etched away to reveal metal lines
- SRAM cell
  - green: word lines, salicided poly
  - yellow: 1st global, Ti/Al(Cu)/Ti/TiN
  - pink: local (intra-cell), tungsten
  - grey: contact studs, tungsten

Copper Interconnects: CMP example

- **multi-level copper interconnects**
  - **reduce electrical resistance, improve electromigration resistance**

C. Wu, “Computer Chips Take a Leap Forward,” in Science News, vol. 152, 1997, pp. 196.



L. Geppert, “Technology 1998, Analysis and Forcast: Solid State,” in *IEEE Spectrum*, vol. 35, 1998, pp. 23-28.

- **problems**
  - **dry etch of copper is challenging**
  - **corrosion**
    - **cover sidewalls with TiN, other refractory, before copper deposition**

Problems in CMP

- "dishing"
  - when making large area features the removal rate may not be uniform across the feature
  - copper: tends to get thinner near middle of large features
  - dielectrics: similar behavior
  - constrains ability to make "large" (i.e., width, length >> thinckness) structures