Etching terminology

- **bias B**
  - $B = d_f - d_m$ (i.e., twice the "undercut")

- **anisotropy A**
  - $A_{film} = 1 - \frac{v_l}{v_v}$
    - $v_l \equiv$ lateral etch rate
    - $v_v \equiv$ vertical etch rate
  - for films etched just to completion
    - $A_f = 1 - \frac{|B|}{2h_f}$
      - $h_f \equiv$ 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 \Rightarrow d_m = d_f - |B|
  - but for films etched just to completion $|B| = 2 h_f (1 - A_f)$
  - so
    $$ d_{mask} = d_f \left[ 1 - 2 \frac{h_f}{d_f} \left( 1 - A_f \right) \right] $$
- $h_f / d_f$ is the feature aspect ratio
- since $d_m > 0$
  $$ \left[ 1 - 2 \frac{h_f}{d_f} \left( 1 - A_f \right) \right] > 0 \Rightarrow A_f \geq 1 - \frac{1}{2 \cdot (h_f / d_f)} $$
  - 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 \( d_f = d_m + 2h_f \) \( \Rightarrow \ d_m = d_f - 2h_f \) or \( d_{mask} = d_f \cdot \left[ 1 - 2 \frac{h_f}{d_f} \right] \)

- \( h_f / d_f \) is the feature aspect ratio
  - \( h_f / d_f = 0.1 \) \( \Rightarrow \ d_{mask} = 0.8 \cdot d_{film} \)
  - \( h_f / d_f = 0.5 \) \( \Rightarrow \ d_{mask} = 0 \) !!!!!
  - If aspect ratio is \( \geq 0.5 \) 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

\[ t = \frac{h_f}{v_f} \]

- must continue etch for time = \( \frac{h_{\text{step}}}{v_{\text{film}}} \) to clear “residue”
  - total etch time is then
    \[ T = \frac{h_f}{v_f} + \frac{h_{\text{step}}}{v_f} = \frac{h_f}{v_f} \cdot (1 + \Delta) \]
    - \( \Delta \) is the fractional over-etch time,
      - here \( \Delta = \frac{h_{\text{step}}}{h_{\text{film}}} \)
Film -to- substrate selectivity

• does over-etch matter?
  – what about “substrate” exposed during over-etch period?
    over-etch etch time
    \[
    t = \frac{h_{\text{step}}}{v_f}
    \]
    
    \[
    h_{\text{sub}} = t \cdot v_{\text{sub}}
    \]

• substrate is “lost” during overetch
  – \( h_{\text{sub}} = t_{\text{over}} \cdot v_{\text{sub}} = \left( \frac{h_{\text{step}}}{v_f} \right) \cdot v_{\text{sub}} \)
    \[
    = h_{\text{step}} \cdot \left( \frac{v_{\text{sub}}}{v_f} \right)
    \]
  – but \( v_f / v_{\text{sub}} \) is the film-to-substrate selectivity \( S_{fs} \), so
    \[
    S_{fs} = \frac{h_{\text{step}}}{h_{\text{sub}}}
    \]
  • recalling \( \Delta = \frac{h_{\text{step}}}{h_{\text{film}}} \) we get
    \[
    S_{fs} = \left( \frac{h_{\text{film}}}{h_{\text{sub}}} \right) \cdot \Delta
    \]
Effects of non-uniformities

- what if things aren’t all uniform:
  - etch rate: $v_f (1 \pm \phi_f)$
  - thickness: $h_f (1 \pm \delta_f)$
  - so now etch time is $t = \frac{h_f (1 \pm \delta_f)}{v_f (1 \pm \phi_f)} (1+\Delta)$

- to ensure complete etch you must use the longest time: $t = \frac{h_f (1+\delta_f)}{v_f (1-\phi_f)} (1+\Delta)$

- how long is the “substrate” exposed?
  - shortest time substrate could be covered by film: consider thinnest film removed at fastest film etch rate!
  
  $t_{covered} = \frac{h_f (1-\delta_f)}{v_f (1+\phi_f)}$

- so the substrate is exposed to the etch for a time
  
  $t_{exposed} = \frac{h_f (1+\delta_f)}{v_f (1-\phi_f)} (1+\Delta) - \frac{h_f (1-\delta_f)}{v_f (1+\phi_f)}$

- so the amount of substrate lost is
  
  $h_s = v_s \cdot t_{exposed} = v_s \frac{h_f}{v_f} \left[ \frac{(1+\delta_f)(1+\Delta)}{(1-\phi_f)} - \frac{(1-\delta_f)}{(1+\phi_f)} \right] = \left( \frac{v_s}{v_f} \right) h_f \left[ \frac{(1+\delta_f)(1+\Delta)}{(1-\phi_f)} - \frac{(1-\delta_f)}{(1+\phi_f)} \right]$

  $\left( S_{fs} \right)^{-1}$
Example results for film - substrate selectivity

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

- etch rate uniformity \( \phi_f = 0.1 \)
- film thickness uniformity \( \delta_f = 0.05 \)
- note \( h_f / h_s \) tends to be BIG
  - you may not be willing to lose much substrate!

Graph showing selectivity vs. \( h_f / h_s \) with lines for \( \Delta = 0.1, 1, 2 \), indicating the trend of selectivity increases with increasing \( h_f / h_s \).
Film-to-mask selectivity

- perfectly anisotropic vertical etch, both mask and film
- A_{film} = 1, but 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 the mask edge profile

- 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: \( v_f (1 \pm \phi_f) \)
  - thickness: \( h_f (1 \pm \delta_f) \)

- to ensure complete etch you must use the longest time:

\[
t_{\text{etch}} = \frac{h_f \cdot (1 + \delta_f)}{v_f \cdot (1 - \phi_f)} \cdot \frac{1 + \Delta}{\text{fractional over-etch}}
\]

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

- total mask erosion is just sum of terms:

\[
\delta x_{\text{tot}} = v_{\text{horz,mask}} \cdot \delta t + \frac{\cos \theta}{\sin \theta} \cdot v_{\text{vert,mask}} \cdot \delta t
\]
Film -to- mask selectivity

• so total mask edge movement is

\[
\frac{W}{2} = \left( v_{\text{horz, mask}} + v_{\text{vert, mask}} \cdot \cot \theta \right) t_{\text{etch}}
\]

- or

\[
W = 2 \cdot v_{\text{vert, mask}} \left( \frac{v_{\text{horz, mask}}}{v_{\text{vert, mask}}} \right) + \cot \theta \cdot \frac{h_f \cdot (1 + \delta_f)}{v_f \cdot (1 - \phi_f)} \cdot (1 + \Delta)
\]

- let’s use worst case mask etch so

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

- or

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

• NOTE THIS ASSUMED PERFECTLY ANISOTROPIC ETCH OF FILM!!!
Sample results for film - mask selectivity

- etch rate uniformity $\phi_f & \phi_m = 0.1$
- film thickness uniformity $\delta_f = 0.05$
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!

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
  - $A \sim 0$
  - 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)
  - $\text{SiO}_2 + 6\text{HF} \rightarrow \text{H}_2\text{SiF}_6 + 2\text{H}_2\text{O}$
    - BHF: buffering agent ($\text{NH}_4\text{F}$) frequently added to keep $[\text{HF}_2^-]$ 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 \( \text{H}_3\text{PO}_4 \) (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), HNO₃ (nitric acid), and CH₃C00H (acetic acid)
• basic mechanism
  – injection of holes into Si to form Si₂⁺ (“anodic” reaction)
  – attachment of OH⁻ to the Si²⁺ to form Si(OH)_2²⁺ (oxidation step)
  – reaction of the “hydrated silica” to form soluble product
    • fluoride ions from HF form H₂SiF₆
  – dissolution of products into solution
• overall reaction for HNA:
  – 18HF + 4HNO₃ + 3Si → 2H₂SiF₆ + 4NO(gas) + 8H₂O
  – recall mechanism required holes:
    • HNO₂ + HNO₃ + H₂O → 2HNO₂ + 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$_3$COOH
  - 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$_2$O + 4e⁻ $\rightarrow$ 4OH⁻ + 2H$_2$ (gas)
    • Si(OH)$_2^{2+}$ + 4OH⁻ $\rightarrow$ SiO$_2$(OH)$_2^{2-}$ + 2H$_2$O
    • overall: Si + 2OH⁻ + 2H$_2$O $\rightarrow$ 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 $\text{NH}_4\text{OH}$
  - $3.7\text{wt}\%$ @ $75^\circ\text{C}$, ($100$) : ($111$) of $8,000 : 1$, but $< 0.1 \mu\text{m/min etch rate}$
  - hillock formation also a problem
- TMAH (tetramethyl ammonium hydroxide ($\text{CH}_3)_4\text{NOH}$)
  - $90^\circ\text{C}$, $10$-$40\%$, $\sim 1 \mu\text{m/min}$; 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)
  - $115^\circ\text{C}$, $\sim 1 \mu\text{m/min}$, ($100$) : ($111$) 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 $\text{H}_2$
    • 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 $\sim 10^9 - 10^{12}$ cm$^{-3}$
    - most gas molecules are NOT ionized
  - temperature
    - electron: $\sim 10^4$ K
    - gas: $\sim$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

V_p + |V_t|

sample on powered electrode

evapor deposition
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
  - very low selectivity
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
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
  - $\text{CF}_4 + e \rightleftharpoons \text{CF}_3^+ + \text{F}^- + 2e$
  - 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
  - $\text{CF}_3^+ + \text{O} + e \rightarrow \text{COF}_2 + \text{F}^-$
    - competes with F for CF$_3$, drives [F] up
    - etch rates increase
  - peak selectivity $\sim$15 (Si:SiO$_2$)

---

from: Sze, 1st ed., p. 325.
Ion assisted CF$_x$ etching

- add H$_2$ to CF$_4$ gas mix
  - CF$_4$ + e $\rightleftharpoons$ CF$_3^+$ + F$^- + 2$e
  - 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 $\sim$ 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 $\sim$ 15:1
Mechanisms for ion-enhancement and induced anisotropy

- Example of polymer formation:
  - Si etched in Cl$_2$ plasma (~isotropic)
    - e + Cl$_2$ → e + 2Cl
    - Si + xCl → SiCl$_x$ ↑
  - “recombinant” species C$_2$F$_6$
    - e + C$_2$F$_6$ → 2CF$_3$ + e
    - [CF$_3$ + Cl]$_x$ → [CF$_3$Cl]$_3$ (polymer)
    - at ~85% C$_2$F$_6$ no undercutting occurs
Aluminum plasma etch

- use volatile aluminum chloride
  - $\text{Al} + \text{CCl}_3^+ + (\text{bmbrdmnt}) \rightarrow \text{AlCl}_3 (g) + C$
  - $\text{Al} + 3\text{Cl}^- \rightarrow \text{AlCl}_3 (g)$
- problems
  - initial $\text{Al}_2\text{O}_3$ on surface harder to etch (mostly by $\text{CCl}_3^+$)
  - selectivity wrt $\text{SiO}_2 < \sim 20$
  - selectivity wrt photoresist $< \sim 15$
- can also use $\text{BCl}_3$, may include some $\text{O}_2$
Etch summary

<table>
<thead>
<tr>
<th>material etched</th>
<th>etch gas(es)</th>
<th>volatile product</th>
<th>selectivities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>CF$_4$ + O$_2$, etc.</td>
<td>SiF$_4$</td>
<td>15:1 (Si:SiO$_2$)</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>CF$_4$ + H$_2$, etc.</td>
<td>SiF$_4$</td>
<td>20:1 (SiO$_2$:Si)</td>
</tr>
<tr>
<td>organics</td>
<td>O$_2$, etc.</td>
<td>CO$_2$, H$_2$O</td>
<td>high</td>
</tr>
<tr>
<td>Al</td>
<td>CCl$_4$, BCl$_3$, etc.</td>
<td>AlCl$_3$</td>
<td>15:1 (Al:SiO$_2$); few:1 (Al:Si)</td>
</tr>
<tr>
<td>Mo</td>
<td>CF$_4$</td>
<td>MoF$_6$</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>CF$_4$</td>
<td>WF$_6$</td>
<td></td>
</tr>
</tbody>
</table>

- 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$_4$F$_8$, 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

- 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

• 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


- 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 >> thickness) structures