**Etching Basics (cont.)**

2. **Selectivity**

- **Ideal Etch**
  - PR
  - Poly-Si
  - SiO$_2$
  - Si
  - Only poly-Si etched (no etching of PR or SiO$_2$)
- **Actual Etch**
  - PR partially etched
  - Poly-Si
  - SiO$_2$
  - Si
  - SiO$_2$ partially etched after some overetch of the polysilicon

**Why overetch?**

- **Ideal Etch**
  - $\frac{\sqrt{d^2 - 1.4d}}{d} = 0.56\mu m$
- **Actual Etch**
  - Poly-Si \rightarrow conformal if deposited by LPCVD
  - Thickness spots due to topography!

**Depends on the selectivity of poly-Si over the oxide**

**Define selectivity of A over B:**

- $S_{ab} = \frac{E.R._a}{E.R._b}$
  - Etch rate of A
  - Etch rate of B
- **Selectivity of A over B**
  - e.g., wet poly etch (HNO$_3$ + NH$_4$ + H$_2$O)
    - $S_{poly/SiO_2} = \frac{15}{1}$ (very good selectivity)
  - e.g., polysilicon dry etch:
    - $S_{poly/SiO_2} = \frac{5}{7}$ (but depends on type of etcher)
    - ECR: 30:1
    - Bosch: 100:1 (or better)

**If $S_{poly/SiO_2} = \frac{8}{1}$**

- 40% overetch removes
  - $\frac{0.16}{8} = 20\text{nm of oxide!}$
- This will etch all poly over the thin oxide, etch thru the 10nm of oxide, then start etching into the silicon substrate \nobreakdash-- needless to say, this is bad!

- **With better selectivity:**
  - e.g., $S_{poly/SiO_2} = \frac{30}{1}$
  - (Can attain with high density Cl plasma ECR etch!)
  - 40% overetch removes $\frac{0.16}{30} = 5.3\text{nm}$ (better)
**Dry Etching**

Dry etching is a process used in the fabrication of microelectromechanical systems (MEMS) and semiconductor devices. It involves the removal of material from a substrate without the use of liquid or wet chemicals. This process is crucial in the fabrication of microstructures, enabling precise control over the dimensions and shapes of the devices.

**Physical Sputtering (Ion Milling)**

- **Bombard substrate with energetic ions** → etching via physical momentum transfer
- **Give ions energy and directionality using E-fields**
- **Highly directional → very anisotropic**

- **Steep vertical wall**

**Problems With Ion Milling**

1. PR or other masking material etched at almost the same rate as the film to be etched → very poor selectivity!
2. Ejected species not inherently volatile → get redeposition → non-uniform etch → grass!

*Because of these problems, ion milling is not used often (very rare)*

**Physical Etching**

- **Physical sputtering**
- **Plasma etching**
- **Reactive ion etching**

All based upon plasma processes. (+) ions generated by inelastic collisions with energetic $e^-$s. Get avalanche effect because more $e^-$s come out as each ion is generated.

Develop (+) charge to compensate for (+) ions will be accelerated to the wafer.

**Dry Etching**

- **Develop (-) bias**
- **RF (also, could be microwave)**
- **(+/-) ions generated by inelastic collisions with energetic $e^-$s.**
- **Get avalanche effect because more $e^-$s come out as each ion is generated.**

Develops (+) charge to compensate for. (+) ions will be accelerated to the wafer.
Plasma Etching

* Plasma (gas glow discharge) creates reactive species that chemically react with the film in question
* Result: much better selectivity, but get an isotropic etch

Plasma Etching Mechanism:
1. Reactive species generated in a plasma.
2. Reactive species diffuse to the surface of material to be etched.
3. Species adsorbed on the surface.
4. Chemical reaction.
5. By-product desorbed from surface.
6. Desorbed species diffuse into the bulk of the gas

MOST IMPORTANT STEP! (determines whether plasma etching is possible or not.)

Ex: Polysilicon Etching w/ CF₄ and O₂

CF₄ → CF₄⁺ + CF₃⁺ + CF₂⁺ + CF⁺ + F⁺ + F₀ + CF₂⁺ + ...

result: (highly reactive)

Si⁺ + CF₄ → CF₃ + F + e⁻

SiF₆, SiF₄ both volatile: dry etching is possible.

• F₀ is the dominant reactant → but it can’t be given a direction → thus, get isotropic etch!

Ex: Polysilicon Etching w/ CF₄ and O₂

• Problems:
  1. Isotropic etching
  2. Formation of polymer because of C in CF₄

  Solution: add O₂ to remove the polymer (but note that this reduces the selectivity, S_{poly/PR})

• Solution:
  Use Reactive Ion Etching (RIE)

Reactive Ion Etching (RIE)

• Use ion bombardment to aid and enhance reactive etching in a particular direction
  Result: directional, anisotropic etching!

• RIE is somewhat of a misnomer
  It’s not ions that react … rather, it’s still the neutral species that dominate reaction
  Ions just enhance reaction of these neutral radicals in a specific direction

• Two principle postulated mechanisms behind RIE
  1. Surface damage mechanism
  2. Surface inhibitor mechanism
RIE: Surface Damage Mechanism

- Relatively high energy impinging ions (>50 eV) produce lattice damage at surface
- Reaction at these damaged sites is enhanced compared to reactions at undamaged areas

Enhanced reaction over plasma

Result: E.R. at surface >> E.R. on sidewalls

RIE: Surface Inhibitor Mechanism

- Non-volatile polymer layers are a product of reaction
- They are removed by high energy directional ions on the horizontal surface, but not removed from sidewalls

Enhanced reaction over plasma

Result: E.R. at surface >> E.R. on sidewalls

Deep Reactive-Ion Etching (DRIE)

The Bosch process:
- Inductively-coupled plasma
- Etch Rate: 1.5 - 4 μm/min
- Two main cycles in the etch:
  - Etch cycle (5-15 s): SF₆ (SF₆⁻) etches Si
  - Deposition cycle (5-15 s): C₄F₈ deposits fluorocarbon protective polymer (CF₂)n
- Etch mask selectivity:
  - SiO₂ ~ 200:1
  - Photoresist ~ 100:1
- Issue: finite sidewall roughness
  - scalloping < 50 nm
- Sidewall angle: 90° ± 2°

DRIE Issues: Etch Rate Variance

- Etch rate is diffusion-limited and drops for narrow trenches
  - Adjust mask layout to eliminate large disparities
  - Adjust process parameters (slow down the etch rate to that governed by the slowest feature)
Semiconductor Doping

Doping of Semiconductors

- Semiconductors are not intrinsically conductive
- To make them conductive, replace silicon atoms in the lattice with dopant atoms that have valence bands with fewer or more e−'s than the 4 of Si
- If more e−'s, then the dopant is a donor: P, As
  - Extra e− is effectively released from the bonded atoms to join a cloud of free e−'s, free to move like e−'s in a metal
- If fewer e−'s, then the dopant is an acceptor: B
  - Lack of an e− = hole = h+

Doping of Semiconductors (cont.)

- Conductivity Equation:
  \[ \sigma = q \mu_n n + q \mu_p p \]
  - Conductivity
  - \( q \) = charge magnitude on an electron
  - \( \mu_n \) = electron mobility
  - \( n \) = electron density
  - \( \mu_p \) = hole mobility
  - \( p \) = hole density

- If fewer e−'s, then the dopant is an acceptor: B
  - \( \vdots \) ... \( \vdots \) ... \( \vdots \) : Si : Si : Si : B : Si : B : Si : Si :
  - Dope: Si : Si : Si
  - New hole moved

General Comments on Predeposition

- Higher doses only: \( Q = 10^{13} - 10^{16} \text{ cm}^{-2} \) (I/I is \( 10^{11} - 10^{16} \))
- Dose not well controlled: ± 20% (I/I can get ± 1%)
- Uniformity is not good
  - ± 10% w/ gas source
  - ± 2% w/ solid source
- Max. conc. possible limited by solid solubility
  - Limited to \( \approx 10^{20} \text{ cm}^{-3} \)
  - No limit for I/I → you force it in here!
- For these reasons, I/I is usually the preferred method for introduction of dopants in transistor devices
- But I/I is not necessarily the best choice for MEMS
  - I/I cannot dope the underside of a suspended beam
  - I/I yields one-sided doping → introduces unbalanced stress → warping of structures
  - I/I can do physical damage → problem if annealing is not permitted
- Thus, predeposition is often preferred when doping MEMS
Diffusion Modeling

Dependence:

\[ N(x,t) \rightarrow J \]

Fick's Law of Diffusion (1st law):

\[ J(x,t) = -D \frac{\partial N(x,t)}{\partial x} \]

Continuity Equation for Particle Flux:

\[ \frac{\partial N(x,t)}{\partial t} = -\nabla \cdot J \]

\[ = \text{rate of increase of conc. on time} \]

\[ = \text{negative of divergence of particle flux} \]

Diffusion Coefficient

\[ D \]

Diffusion Modeling (cont.)

We're interested in now in the one-dimensional form:

\[ \frac{\partial N(x,t)}{\partial t} = D \frac{\partial^2 N(x,t)}{\partial x^2} \]

\[ \text{Fick's 2nd law of diffusion in 1-D} \]

Solutions:

- depended upon boundary condition
- use variable separation, or laplace transform techniques

Case 1: Predeposition → constant source diffusion → surface concentration stays the same during the diffusion

\[ t_s < t < t_e \]

\[ (t_s < t < t_e) \]

Complementary error function profile:

- background = \( N_b \)
- surface concentration = \( N_s \)
- \( t_s \)
- \( t_e \)
- \( x_i \), distance from surface

Diffusion Modeling (Predeposition)

If plotted on a linear scale, would look like this:

\[ N(x) \]

Boundary Conditions:

\[ N(0,t) = N_s \]

\[ N(\infty,t) = N_b \]

\[ N(x,0) = N_i \]

\[ N(x,t) = N_0 \text{erfc} \left( \frac{x}{2 \sqrt{Dt}} \right) \]

\[ \text{erfc} \]

\[ \text{complementary error function, real numbers only} \]

\[ Q = \int_0^x N_i(x,t) dx \]

\[ Q(t) = \frac{2 D N_i}{x_i} \text{erfc} \left( \frac{x_i}{2 \sqrt{D t}} \right) \]

\[ x \]

- area under the curve

\[ x \]

- characteristic diffusion length

\[ 2 \sqrt{Dt} \]

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