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Dry Etching

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Dry Etching

- Physical sputtering
- Plasma etching
- Reactive ion etching

} All based upon plasma processes.

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Physical Sputtering (Ion Milling)

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

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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)

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Plasma Etching

- Plasma (gas glow discharge) creates reactive species that chemically react w/ 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. ← MOST IMPORTANT STEP! (determines whether plasma etching is possible or not.)
6. Desorbed species diffuse into the bulk of the gas

Ex: Polysilicon Etching w/ CF_4 and O_2

$CF_4 \xrightarrow{\text{plasma}} CF_4^+ + CF_3^+ + CF_2^+ + CF^+ + F^+ + F^0 + CF_2^+ + \ldots$

F^0: Neutral radical (highly reactive!)

Si

$e^- + CF_4 \rightarrow CF_3 + F + e^-$

$SiCF_6$, SiF_4 ← both volatile ∴ dry etching is possible.

- F° is the dominant reactant → but it can't be given a direction → thus, get isotropic etch!

Ex: Polysilicon Etching w/ CF_4 and O_2

- Problems:
  1. Isotropic etching
  2. Formation of polymer because of C in CF_4
     - Solution: add O_2 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

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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

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

Result: E.R. @ 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): SF_6 (SF_x^+) etches Si
  - Deposition cycle: (5-15 s): C_4F_8 deposits fluorocarbon protective polymer $(CF_2^-)_n$
- Etch mask selectivity:
  - SiO_2 ~ 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)

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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
  - The 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

Extra free e⁻

: Si : Si : Si : → Dope (P) → : Si : P : Si :
: Si : Si : Si : → : Si : Si : Si :

  - The larger the # of donor atoms, the larger the # of free e⁻'s → the higher the conductivity

Doping of Semiconductors (cont.)

- Conductivity Equation:

$$\sigma = q\mu_n n + q\mu_p p$$

conductivity (σ); charge magnitude on an electron (q); electron mobility (μ_n); electron density (n); hole mobility (μ_p); hole density (p)

- If fewer e⁻'s, then the dopant is an acceptor: B

: Si : Si : Si : → Dope (B) → : Si : B : Si :
: Si : Si : Si : → : Si : Si : Si :

hole (+), new hole

  - Lack of an e⁻ = hole = h⁺
  - When e⁻'s move into h⁺'s, the h⁺'s effectively move in the opposite direction → a h⁺ is a mobile (+) charge carrier

General Comments on Predeposition

- Higher doses only: Q = 10^{13} – 10^{16} 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 ~10^{20} 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

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Diffusion Modeling

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Modeling $N(x)$ → J (plot of $N(x)$ vs. x)

⇒ Dopants from points of high conc. move to points of low conc. w/ flux J

⇒ Question: What's $N(x,t)$? ← fcn of time

Fick's Law of Diffusion – (1st law)

$$J(x,t) = -D\frac{\partial N(x,t)}{\partial x} \quad (1)$$

flux [#/cm²·s] ; D = Diffusion Coefficient

Continuity Equation for Particle Flux –

General Form:
$$\frac{\partial N(x,t)}{\partial t} = -\vec{\nabla}\cdot\vec{J}$$

$\frac{\partial N}{\partial t}$: rate of increase of conc. w/ time ; $-\vec{\nabla}\cdot\vec{J}$: negative of the divergence of particle flux

Diffusion Modeling (cont.)

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⇒ we're interested for now in the one-dimensional form:

$$\frac{\partial N(x,t)}{\partial t} = -\frac{\partial J}{\partial x} \quad (2)$$

$\left[\frac{\partial}{\partial x}(1)\text{ and substitute (2) in (1)}\right] \Rightarrow \frac{\partial N(x,t)}{\partial t} = D\frac{\partial^2 N(x,t)}{\partial x^2}$ [Fick's 2nd Law of Diffusion in 1-D]

Solutions: → dependent upon boundary conditions
↳ use variable separation or Laplace Xform techniques

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

Plot labels: $\log(N(x))$ ← impurity conc; surface conc. stays constant → N_0; background conc. → N_B; high T; $t_1 < t_2 < t_3$; $(Dt_1 < D_2t_2 < D_3t_3)$; curves t_1, t_2, t_3 ← complementary error function profile; x, distance f/ surface; surface

Diffusion Modeling (Predeposition)

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⇒ if plotted on a linear scale, would look like this: (plot with N_0, x)

⇒ Boundary Condition:
(i) $N(0,t) = N_0$
(ii) $N(\infty,t) = 0$

$$N(x,t) = N_0\left[1 - \frac{2}{\sqrt{\pi}}\int_0^{\frac{x}{2\sqrt{Dt}}} e^{-y^2}dy\right]$$

$$\boxed{N(x,t) = N_0\,\mathrm{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)}$$

⇒ again, complementary error function (read tables or graph)

Dose, $Q \triangleq$ total # of impurity atoms per unit area in the Si = area under the curve

$$Q = \int_0^\infty N(x,t)dx \Rightarrow \boxed{Q(t) = N_0\frac{2\sqrt{Dt}}{\sqrt{\pi}}\ \mathrm{cm^{-2}}}$$

$\boxed{2\sqrt{Dt} \triangleq \text{characteristic diffusion length}}$

Plot labels: $N(x)$ ← linear scale; N_0; area under this square is same as under the curve!; $\frac{2\sqrt{Dt}}{\sqrt{\pi}}$; x

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