Lecture Outline

* Reading: Senturia, Chpt. 3; Jaeger, Chpt. 2, 4, 5
  - Lithography
  - Etching
    - Wet etching
    - Dry etching
  - Semiconductor Doping
    - Ion implantation
    - Diffusion
Lithography

Method for massive patterning of features on a wafer → pattern billions of devices in just a few steps

I. Radiation Source

Four Main Components (that affect resolution)

Designated pattern (clear or dark field)

- emulsion
- chrome

- Generated from layout

II. Mask

- Mask (glass/quartz)

III. Photoresist

- Photoresist (~1μm-thick)

- Film to be patterned (e.g., poly-Si)

IV. Exposure System → contact, step and repeat optics → this is where the real art is!
Lithography (cont.)

The basic Process - (Positive Resist Example)

Exposed PR $\rightarrow$ converts to another form after reaction with light (e.g., (+)-resist: polymer $\rightarrow$ organic acid)

Dip or spray wafer with developer $\rightarrow$ if (+) resist, developer is often a base

Etch $\rightarrow$ PR protects film; open areas of film get etched

Lithography (cont.)

With each masking step usually comes a film deposition, implantation and/or etch. Thus, the complexity of a process is often measured by # masks required.

- NMOS: 4-6 masks
- Bipolar: 8-15 masks
- BICMOS: ~20 masks
- CMOS: 8-28 masks

Multi-level metallization

Comb-Drive Resonator: 3 masks
GHz Disk: 4 masks

Now, take a closer look at the 4 components:
I. Radiation Source

I. Radiation Source
Several types: optical (visible, UV, deep UV light), e-beam, X-ray, ion beam

The shorter the wavelength \(\rightarrow\) Better the resolution
Today's prime choice due to cost and throughput.

Optical Sources:
- Mercury arc lamp (mercury vapor discharge)

we have all of these in our \(\mu\)lab
- I-line
- G-line (we have both in our \(\mu\)lab)

For deep UV, need Excimer laser (very expensive)

Glass opaque, so must use quartz mask and lens

II. Mask

II. Mask \(\rightarrow\) has become one of today's biggest bottlenecks!

Electronic computer representation of layout (e.g., CIF, GDSII) \(\Rightarrow\) A single file contains all layers

tape \(\rightarrow\) mask generator

Masks for each layer

Mask Material:
- Fused silica (glass) \(\rightarrow\) inexpensive, but larger thermal expansion coeff.
- Quartz \(\rightarrow\) expensive, but smaller thermal expansion coeff.
### III. Photoresist (optical)

#### Pictorial Description:

- **Negative**
  - Exposed Area: PR remains
  - Mechanism:
    - Photoactivation → Polymerization (long, linked Carbon chains) → Developer solvent removes unexposed PR

- **Positive**
  - Exposed Area: PR removed
  - Mechanism:
    - Photoactivation → Converts exposed PR to organic acid → Alkaline developer (e.g., KOH) removes acid
III. Photoresist (optical)

Negative
Polymerized PR swells in solvent → bridging problem
Exposed and polymerized

Positive
Doesn’t adhere well to SiO₂
Need primer: HMDS (hexamethyl disilazane)
PR × × × × SiO₂
Poor adhesion
PR HMDS
SiO₂
Good adhesion at both HMDS interfaces

Typical Procedure for Lithography

Clean Wafer
Dry Wafer
Deposit HMDS
Spin-on PR
Soft Bake
Align & Expose
Develop

Very important step
30 min. @ 120°C pre-bake
(for oxide on wafer surface)
30-60 sec @ 1000-5000 rpm
2 min @ 90°C
Improve adhesion and remove solvent from PR

Oxygen plasma (low power ~ 50W)

Topography very important:
Thicker and unfocused
overexpose
underexpose
IV. Exposure System/Optics

Contact Printing

- Mask in contact with wafer
- **Problem:** mask pattern can become damaged with each exposure → must make a new mask after x number of exposures

Proximity Printing

- Mask in very close proximity but not touching

* 1X printing very useful for MEMS → can expose surfaces with large topography (where reduction printers cannot)

IV. Exposure System/Optics

Projection Printing

- Dominates in IC transistor fabrication
- 5X or 10X reduction typical
- Mask minimum features can be larger than the actual printed features by the focused reduction factor → less expensive mask costs
- Less susceptible to thermal variation (in the mask) than 1X printing
- Can use focusing tricks to improve yield:

  - Dust particle will be out of focus → better yield!
Etching Basics

- Removal of material over designated areas of the wafer
- Two important metrics:
  1. Anisotropy
  2. Selectivity

1. Anisotropy -
   a) Isotopic Etching (most wet etches)

   ![Diagram](image)

   If 100% isotropic: \(d_f = d + 2h\)
   Define: \(B = d_f - d\)
   If \(B = 2h\) ⇒ isotropic
**Etching Basics (cont.)**

b) Partially Isotropic: \( B < 2h \)
   (most dry etches, e.g., plasma etching)

Degree of Anisotropy: (definition)

\[
A_f = 1 - \frac{B}{2h} = 0 \quad \text{if 100% isotropic}
\]

\( 0 < A_f \leq 1 \) \( \Rightarrow \) anisotropic

---

**Etching Basics (cont.)**

2. Selectivity -

- **Ideal Etch**: Only poly-Si etched (no etching of PR or SiO\(_2\))
  - Perfect selectivity

- **Actual Etch**: PR partially etched
  - SiO\(_2\) partially etched after some overetch of the polysilicon
Etching Basics (cont.)

Why overetch?

\[ \sqrt{d} = 1.4d = 0.56 \mu m \]

Thicker spots due to topography!

\[ 1 \mu m - 0.4 \mu m = d \]

Poly-Si \to conformal if deposited by LPCVD

Thus, must overetch at least 40%:

40\% overetch \to (0.4)(0.4) = 0.16 \mu m \text{ poly}

Depends on the selectivity of poly-Si over the oxide

Etching Basics (cont.)

Define selectivity of A over B:

\[ S_{ab} = \frac{E.R._A}{E.R._B} \]

Selectivity of A over B

e.g., wet poly etch (HNO\(_3\) + NH\(_4\) + H\(_2\)O)

\[ S_{\text{poly/SiO}_2} = \frac{15}{1} \]

(very good selectivity)

\[ S_{\text{poly/PR}} = \]

Very high (but PR can still peel off after soaking for \(> 30\) min., so beware)

e.g., polysilicon dry etch:

\[ S_{\text{poly/SiO}_2} = \frac{5 - 7}{1} \]

(but depends on type of etcher)

\[ S_{\text{poly/PR}} = \frac{4}{1} \]

\(\text{ECR: 30:1, Bosch: 100:1 (or better)}\)
Etching Basics (cont.)

If \( S_{poly/\text{SiO}_2} = \frac{8}{1} \), \( 40\% \) 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 \( \rightarrow \) needless to say, this is bad!

with better selectivity:

\( e.g., \quad S_{poly/\text{SiO}_2} = \frac{30}{1} \)

(Can attain with high density Cl plasma ECR etch!)

\[
40\% \text{ overetch removes } \frac{0.16}{30} = 5.3\text{nm} \quad \text{(better)}
\]

Wet Etching
Wet Etching

* Wet etching: dip wafer into liquid solution to etch the desired film
  - Generally isotropic, thus, inadequate for defining features < 3μm-wide

* General Mechanism -
  1. Diffusion of the reactant to the film surface
  2. Reaction: adsorption, reaction, desorption
  3. Diffusion of reaction products from the surface

Wet Etching (cont.)

* There are many processes by which wet etching can occur
  - Could be as simple as dissolution of the film into the solvent solution
  - Usually, it involves one or more chemical reactions
    - Oxidation-reduction (redox) is very common:
      (a) Form layer of oxide
      (b) Dissolve/react away the oxide

* Advantages:
  1. High throughput process → can etch many wafers in a single bath
  2. Usually fast etch rates (compared to many dry etch processes)
  3. Usually excellent selectivity to the film of interest
### Wet Etching Limitations

1. **Isotropic**
   - Limited to <3μm features
   - But this is also an advantage of wet etching, e.g., if used for undercutting for MEMS
2. Higher cost of etchants & DI water compared w/ dry etch gas expenses (in general, but not true vs. deep etchers)
3. **Safety**
   - Chemical handling is a hazard
4. Exhaust fumes and potential for explosion
   - Need to perform wet etches under hood
5. Resist adhesion problems
   - Need HMDS (but this isn’t so bad)

### Wet Etch Limitations (cont.)

6. Incomplete wetting of the surface:
   - Pockets where wetting hasn’t occurred, yet (eventually, it will occur).
   - But this will lead to nonuniform etching across the wafer.

For some etches (e.g., oxide etch using HF), the solution is to dip in DI water first, then into HF solution → the DI water wets the surface better.
**Wet Etch Limitations (cont.)**

7. Bubble formation (as a reaction by-product)
   - If bubbles cling to the surface → get nonuniform etching

![Diagram showing bubble formation during wet etching]

**Non-uniform etching**

Solution: Agitate wafers during reaction.

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**Some Common Wet Etch Chemistries**

**Wet Etching Silicon:**

**Common:** \( \text{Si} + \text{HNO}_3 + 6\text{HF} \rightarrow \text{H}_2\text{SiF}_6 + \text{HNO}_2 + \text{H}_2 + \text{H}_2\text{O} \)

(isotropic) (nitric acid) (hydrofluoric acid)

(1) forms a layer of \( \text{SiO}_2 \) (2) etches away the \( \text{SiO}_2 \)

Different mixture combinations yield different etch rates.
**Silicon Crystal Orientation**

- Silicon has the basic diamond structure
  - Two merged FCC cells offset by (a/4) in x, y, and z axes
  - From right:
    - # available bonds/cm² <111>
    - # available bonds/cm² <110>
    - # available bonds/cm² <100>

**Anisotropic Wet Etching**

**Anisotropic etches also available for single crystal Si:**

- Orientation-dependent etching: <111>-plane more densely packed than <100>-plane
  - Faster E.R.
  - Slower E.R.

- ...in some solvents
  - One such solvent: KOH + isopropyl alcohol
  - (e.g., 23.4 wt% KOH, 13.3 wt% isopropyl alcohol, 63 wt% H₂O)

- E.R. <100> = 100 × E.R. <111>
Anisotropic Wet Etching (cont.)

Can get the following:

(on a <100> - wafer)

(54.7°)

(on a <110> - wafer)

Quite anisotropic!

Wet Etching SiO₂

\[
\text{SiO}_2 + 6\text{HF} \rightarrow \text{H}_2 + \text{SiF}_6 + 2\text{H}_2\text{O}
\]

Generally used to clear out residual oxides from contacts

Problem: Contact hole is so thin that surface tensions don't allow the HF to get into the contact

Generally the case for VLSI circuits

Solution: add a surfactant (e.g., Triton X) to the BHF before the contact clear etch

1. Improves the ability of HF to wet the surface (hence, get into the contact)

2. Suppresses the formation of etch by-products, which otherwise can block further reaction if by-products get caught in the contact

Native oxide can get this just by exposing Si to air → 1-2nm-thick
More Wet Etch Chemistries

- Wet etching silicon nitride
  - Use hot phosphoric acid: 85% phosphoric acid @ 180°C
  - Etch rate ~ 10 nm/min (quite slow)
  - Problem: PR lifted during such etching
  - Solution: use SiO₂ as an etch mask (E.R. ~2.5 nm/min)
    - A hassle → dry etch processes more common than wet
- Wet etching aluminum
  - Typical etch solution composition:
    80% phosphoric acid, 5% nitric acid, 5% acetic acid, 10% water
    \[
    \text{(H}_2\text{PO}_4) \quad \text{(HNO}_3) \quad \text{(CH}_3\text{COOH}) \quad \text{(H}_2\text{O})
    \]
    - (1) Forms Al₂O₃ (aluminum oxide)
    - (2) Dissolves the Al₂O₃
  - Problem: H₂ gas bubbles adhere firmly to the surface → delay the etch → need a 10–50% overetch time
  - Solution: mechanical agitation, periodic removal of wafers from etching solution

Wet Etch Rates (f/K. Williams)

<table>
<thead>
<tr>
<th>Material</th>
<th>SC/mmin</th>
<th>Poly</th>
<th>MOV</th>
<th>Low K</th>
<th>Other</th>
<th>Etching Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>100</td>
<td>10</td>
<td>100</td>
<td>10</td>
<td>100</td>
<td>Buffered Oxide</td>
</tr>
<tr>
<td>Aluminum</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>Membrane Etch</td>
</tr>
<tr>
<td>Titanium</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>Wet Etch</td>
</tr>
<tr>
<td>Copper</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>Wet Etch</td>
</tr>
<tr>
<td>Glass</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>Wet Etch</td>
</tr>
<tr>
<td>Diamond</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>Wet Etch</td>
</tr>
</tbody>
</table>

Notes:
- f = film thickness (microns)
- K = etch rate (microns per minute)
- Ox = oxide
- B = buffered oxide
- Membrane = membrane etch
- Wet Etch = wet etch
- Buffered Oxide = buffered oxide
- Membrane Etch = membrane etch
- Wet Etch = wet etch
## Film Etch Chemistries

* For some popular films:

<table>
<thead>
<tr>
<th>Material</th>
<th>Wet etchant</th>
<th>Etch rate [nm/min]</th>
<th>Dry etchant</th>
<th>Etch rate [nm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polysilicon</td>
<td>HNO₃:H₂O:NH₄F</td>
<td>120-600</td>
<td>SF₆ + He</td>
<td>170-920</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>H₃PO₄</td>
<td>5</td>
<td>SF₆</td>
<td>150-250</td>
</tr>
<tr>
<td>Silicon dioxide</td>
<td>HF</td>
<td>20-2000</td>
<td>CHF₃ + O₂</td>
<td>50-150</td>
</tr>
<tr>
<td>Aluminum</td>
<td>H₃PO₄:HNO₃:CH₃COOH</td>
<td>660</td>
<td>Cl₂ + SiCl₄</td>
<td>100-150</td>
</tr>
<tr>
<td>Photoresist</td>
<td>Acetone</td>
<td>&gt;4000</td>
<td>O₂</td>
<td>35-3500</td>
</tr>
<tr>
<td>Gold</td>
<td>KI</td>
<td>40</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

### Dry Etching
Dry 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 (-) bias

Plasma (partially ionized gas composed of ions, e−'s, and highly reactive neutral species)

E-field

(+), ions will be accelerated to the wafer

Develops (+) charge to compensate for

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
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)

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.
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/ CF\textsubscript{4} and O\textsubscript{2}

\[ \text{CF}_4 \rightarrow \text{CF}_4^* + \text{CF}_3^* + \text{CF}_2^* + \text{CF}^* + \text{F}^* + \text{F}_0^* + \text{CF}_2^* + \ldots \]  

plasma

\[ \text{Si} \quad \text{Neutral radical (highly reactive!)} \]

\[ \text{e}^- + \text{CF}_4 \rightarrow \text{CF}_3 + \text{F} + \text{e}^- \]

\[ \text{SiCF}_6, \text{SiF}_4 \leftarrow \text{both volatile} \quad \therefore \text{dry etching is possible.} \]

* F\textsuperscript{0} is the dominant reactant \rightarrow but it can't be given a direction \rightarrow thus, get isotropic etch!

---

Ex: Polysilicon Etching w/ CF\textsubscript{4} and O\textsubscript{2}

\[ \text{isotropic component} \rightarrow \text{F}_0^* \quad \text{PR} \quad \text{SiF}_4 \]

\[ \text{polySi} \]

---

**Problems:**

1. Isotropic etching
2. Formation of polymer because of C in CF\textsubscript{4}
   \[ \text{Solution: add O}_2 \text{ to remove the polymer (but note that this reduces the selectivity, } S_{\text{poly/PR}}) \]

**Solution:**

\[ \text{Use Reactive Ion Etching (RIE)} \]
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

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$_4$F$_8$ 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)

---

**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.

\[ \text{Extra free e}^- \]

\[ \text{Si : Si : Si :} \quad \text{P : Si : Si :} \]

- The larger the # of donor atoms, the larger the # of free e$^-$s $\rightarrow$ the higher the conductivity.

Doping of Semiconductors (cont.)

- Conductivity Equation:

\[ \sigma = q\mu_n n + q\mu_p p \]

- If fewer e$^-$s, then the dopant is an acceptor: B

\[ \text{Si : Si : Si :} \quad \text{B : Si : Si :} \]

- Lack of an e$^-$ = hole = h$^+$
- When e$^-$s move into h$^+$s, the h$^+$s effectively move in the opposite direction $\rightarrow$ a h$^+$ is a mobile (+) charge carrier.
Ion Implantation

- Method by which dopants can be introduced in silicon to make the silicon conductive, and for transistor devices, to form, e.g., pn-junctions, source/drain junctions, ...

The basic process:

- Control current & time to control the dose.
- Charged dopant accelerated to high energy by an E-Field (e.g., 100 keV)
- Masking material (could be PR, could be oxide, etc.)
- Depth determined by energy & type of dopant

Result of I/I
Ion Implantation (cont.)

Result of I/I

\[ \text{Damage} \rightarrow \text{Si layer at top becomes amorphous} \]

\[ \text{B not in the lattice, so it's not electrically active.} \]

High Temperature Anneal (also, usually do a drive-in diffusion) (800-1200°C)

\[ \text{Now B in the lattice & electrically active!} \]

\[ \text{(serves as dopant)} \]

This is a statistical process \( \rightarrow \) implanted impurity profile can be approximated by a Gaussian distribution.

Statistical Modeling of I/I

\[ N(x) \]

\[ \Delta R_p \]

\[ \Delta R_p \]

\[ \Delta R_p \]

\[ R_p \]

\[ \text{Distance into Si material, } x \]

\[ R_p \triangleq \text{Projected range} = \text{avg. distance on ion trends before stopping} \]

\[ \Delta R_p \triangleq \text{Straggle} = \text{std. deviation characterizing the spread of the distribution.} \]
Analytical Modeling for I/I

Mathematically:

\[ N(x) = N_p \exp \left[ - \frac{(x - R_p)^2}{2(\Delta R_p)^2} \right] \]

Area under the impurity distribution curve \( \int_0^\infty N(x)dx \) [ions/cm²]

Implied Dose \( Q = \int_0^\infty N(x)dx \) [ions/cm²]

For an implant completely contained within the Si:

\[ Q = \sqrt{2\pi} N_p \Delta R_p \]

Assuming the peak is in the silicon: (putting it in one-sided diffusion form)

\[ D_I = \frac{Q}{D_t/}= \frac{D_I}{2} \exp \left[ - \frac{(x - R_p)^2}{2(\Delta R_p)^2} \right] \]

where \( (D_t)_\text{eff} = \frac{(\Delta R_p)^2}{2} \)

I/I Range Graphs

- \( R_p \) is a function of the energy of the ion and atomic number of the ion and target material
- Lindhard, Scharff and Schiott (LSS) Theory:
  - Assumes implantation into amorphous material, i.e., atoms of the target material are randomly positioned
  - Yields the curves of Fig. 6.1 and 6.2
- For a given energy, lighter elements strike Si with higher velocity and penetrate more deeply
I/I Straggle Graphs

*Results for Si and SiO₂ surfaces are virtually identical → so we can use these curves for both

**Figure 6.2**

Diffusion
Diffusion in Silicon

- Movement of dopants within the silicon at high temperatures
- Three mechanisms: (in Si)

**Substitutional Diffusion**
- Impurity moves along vacancies in the lattice
- Substitutes for a Si atom in the lattice

**Interstitial Diffusion**
- Impurity atom replaces a Si atom in the lattice
- Si atom displaced to an interstitial site

**Interstitialcy Diffusion**
- Impurity atoms jump from one interstitial site to another
- Get rapid diffusion
- Hard to control
- Impurity not in lattice so not electrically active

Diffusion in Polysilicon

- In polysilicon, still get diffusion into the crystals, but get more and faster diffusion through grain boundaries
- Result: overall faster diffusion than in silicon

- Fast diffusion through grain boundaries
- Regular diffusion into crystals

- In effect, larger surface area allows much faster volumetric diffusion
Basic Process for Selective Doping

1. Introduce dopants (introduce a fixed dose $Q$ of dopants)
   (i) Ion implantation
   (ii) Predeposition

2. Drive in dopants to the desired depth
   - High temperature $> 900^\circ C$ in $N_2$ or $N_2/O_2$
   - Result:

   ![Diagram showing dopant drive-in process]

Predeposition

- Furnace-tube system using solid, liquid, or gaseous dopant sources
- Used to introduce a controlled amount of dopants
  - Unfortunately, not very well controlled
  - Dose ($Q$) range: $10^{13} - 10^{16} \pm 20\%$
  - For ref: w/ ion implantation: $10^{11} - 10^{16} \pm 1\%$ (larger range & more accurate)
- Example: Boron predeposition

![Diagram showing predeposition process with furnace tube]
**Ex: Boron Predeposition**

* Basic Procedure:

1. Deposit $\text{B}_2\text{O}_3$ glass

   ![Diagram of SiO$_2$ diffusion barrier (masks out dopants)]

2. B diffuses from $\text{B}_2\text{O}_3 \rightarrow \text{Si}$

* Difficult to control dose $Q$, because it’s heavily dependent on partial pressure of $\text{B}_2\text{H}_6$ gas flow

\( \therefore \) this is difficult to control itself

\( \therefore \) get only 10% uniformity

---

**Ex: Boron Predeposition (cont.)**

For better uniformity, use solid source:

![Diagram of furnace tube cross-section with less B concentration]

Reactions:

$$
\text{B}_2\text{H}_6 + 3\text{O}_2 \rightarrow 3\text{H}_2\text{O} + \text{B}_2\text{O}_3
$$

$$
\text{Si} + \text{O}_2 \rightarrow \text{SiO}_2
$$
**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

**Diffusion Modeling**

Fick's Law of Diffusion:

$$j(x, t) = -D \frac{\partial N(x, t)}{\partial x}$$  \hspace{1cm} (1)

- $j(x, t)$: Flux [#/cm$^2$.s]
- $D$: Diffusion Coefficient

Continuity Equation for Particle Flux:

$$\frac{\partial N(x, t)}{\partial t} - \nabla \cdot j = 0$$

- Rate of increase of conc. w/ time of particle flux
- Negative of the divergence of particle flux
Diffusion Modeling (cont.)

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

\[ \frac{\partial N(x, t)}{\partial t} = - \frac{\partial J}{\partial x} \tag{2} \]

\[ \left( \frac{\partial}{\partial x} \right) \text{ and substitute } (\Omega) \text{ in (1)} \rightarrow \frac{\partial N(x, t)}{\partial t} = D \frac{\partial^2 N(x, t)}{\partial x^2} \]

[Pick's 2nd Law of Diffusion in 1-D]

Solutions: dependent upon boundary conditions
- Use variable separation or replace Xform techniques

Case 1: Predeposition - constant source diffusion. Surface concentration stays the same during the diffusion, \( t < t_s < t_3 \)

Surface conc. stays constant

\[ t_1, t_2, t_3 \]

Background conc.

Complementary error function profile

**Diffusion Modeling (Predeposition)**

⇒ if plotted on a linear scale, would look like this:

⇒ Boundary Conditions:

(i) \( N(0, t) = N_0 \)

(ii) \( N(\infty, t) = 0 \)

\[ N(x, t) = N_0 \left[ 1 - \frac{x}{\sqrt{4D \pi t}} \right] \]

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

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

Dose, \( Q \equiv \) total \# of impurity atoms per unit area in the Si:

\[ Q = \int_0^L N(x, t) \, dx \Rightarrow Q(\Omega) = N_0 \frac{2 \sqrt{Dt}}{\pi} \text{ cm}^{-2} \]

\[ 2 \sqrt{Dt} \equiv \text{characteristic diffusion length} \]

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Diffusion Modeling (Limited Source)

**Case 2:** Drive-in \( \rightarrow \) limited source diffusion, i.e., constant dose \( Q \)

\[ N(x,t) = \begin{cases} N_0(t) & t \leq t_1, \\
N_0(t_1) & t_1 < t < t_2, \\
N_0(t_2) & t \geq t_2 \end{cases} \]

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

\[
N(x,t) = N_0(t) \exp \left[ -\frac{(x - x_0)^2}{2D_0t} \right]
\]

**Boundary Conditions:**

1. \( N(x,t) = 0 \) at \( x = 0 \)
2. \( \frac{\partial N(x,t)}{\partial x} \bigg|_{x=0} = 0 \)

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

This is equivalent to saying that there's no flux going out of the Si, i.e.,

\[ J(x) = 0 \]

And that's what this says!

**Remarks:**

- Usually make delta fun. approx.: \( N(x,0) = \delta(x) \)

\[ \Rightarrow \text{we can do this, because for sufficiently long diffusion times, no matter what the original shape of the dopant distribution, the diffused distribution will be the same} \]

To get Gaussian distribution:

\[ N(x,t) = \frac{Q}{\sqrt{4\pi D_0 t}} \exp \left[ -\frac{(x - x_0)^2}{4D_0 t} \right] \]

**Corresponds to a half Gaussian in this Equation**

**Notes:**

- When the starting conc. profile is completely contained in the Si, then

\[ Q \cdot \frac{D_0 t}{2} = \text{half the implant dose} \]
Two-Step Diffusion

- Two step diffusion procedure:
  - **Step 1**: predeposition (i.e., constant source diffusion)
  - **Step 2**: drive-in diffusion (i.e., limited source diffusion)

- For processes where there is both a predeposition and a drive-in diffusion, the final profile type (i.e., complementary error function or Gaussian) is determined by which has the much greater $Dt$ product:

  \[(Dt)_{\text{predep}} \gg (Dt)_{\text{drive-in}} \Rightarrow \text{impurity profile is complementary error function}\]

  \[(Dt)_{\text{drive-in}} \gg (Dt)_{\text{predep}} \Rightarrow \text{impurity profile is Gaussian (which is usually the case)}\]

Successive Diffusions

- For actual processes, the junction/diffusion formation is only one of many high temperature steps, each of which contributes to the final junction profile

- Typical overall process:
  1. Selective doping
     - Implant $\rightarrow$ effective $\langle Dt \rangle_1 = (\Delta R_p)^2/2$ (Gaussian)
     - Drive-in/activation $\rightarrow D_2t_2$
  2. Other high temperature steps
     - (eg., oxidation, reflow, deposition) $\rightarrow D_3t_3, D_4t_4, ...$
     - Each has their own $Dt$ product
  3. Then, to find the final profile, use

     \[
     (Dt)_{\text{tot}} = \sum_i D_it_i
     \]

     in the Gaussian distribution expression.
The Diffusion Coefficient

\[ D = D_0 \exp \left( -\frac{E_A}{kT} \right) \]  
(as usual, an Arrhenius relationship)

<table>
<thead>
<tr>
<th>Element</th>
<th>( D_0 ) (cm(^2)/sec)</th>
<th>( E_A ) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>10.5</td>
<td>3.69</td>
</tr>
<tr>
<td>Al</td>
<td>8.00</td>
<td>3.47</td>
</tr>
<tr>
<td>Ga</td>
<td>3.60</td>
<td>3.51</td>
</tr>
<tr>
<td>In</td>
<td>16.5</td>
<td>3.90</td>
</tr>
<tr>
<td>P</td>
<td>10.5</td>
<td>3.69</td>
</tr>
<tr>
<td>As</td>
<td>0.32</td>
<td>3.56</td>
</tr>
<tr>
<td>Sb</td>
<td>5.60</td>
<td>3.95</td>
</tr>
</tbody>
</table>

Diffusion Coefficient Graphs

Substitutional & Interstitialcy Diffusers

Interstitial Diffusers

Note the much higher diffusion coeffs. than for substitutional
Metallurgical Junction Depth, $x_j$

$x_j = \text{point at which diffused impurity profile intersects the background concentration, } N_B$

- Log[$N(x)$]
  - e.g., p-type Gaussian
  - e.g., n-type

- Log[$N(x) - N_B$]
  - Net impurity conc.
  - p-type region
  - n-type region

$x = \text{distance f/ surface}$

Expressions for $x_j$

* Assuming a Gaussian dopant profile: (the most common case)

$$N(x,t) = N_o \exp \left[ - \left( \frac{x_j}{2\sqrt{Dt}} \right)^2 \right] = N_B \rightarrow x_j = 2\sqrt{Dt \ln \left( \frac{N_o}{N_B} \right)}$$

* For a complementary error function profile:

$$N(x,t) = N_o \text{erfc} \left( \frac{x_j}{2\sqrt{Dt}} \right) = N_B \rightarrow x_j = 2\sqrt{Dt} \text{erfc}^{-1} \left( \frac{N_B}{N_o} \right)$$
Sheet Resistance

- Sheet resistance provides a simple way to determine the resistance of a given conductive trace by merely counting the number of effective squares.

**Definition:**

\[ R = \frac{\rho L}{A} = \frac{\rho L}{LW} = R_s \left( \frac{L}{W} \right) \]

- Uniformly doped material with resistivity \( \rho \).
- Conductivity \( \sigma = \frac{1}{\rho} \).
- Unit square of material in the resistor:

\[ \sigma = \text{conductivity} = \rho (\mu_e n + \mu_h p) \]

- What if the trace is non-uniform? (e.g., a corner, contains a contact, etc.)

**# Squares From Non-Uniform Traces**

- 3W x W:
  - 0.65 squares

- W x W:
  - 0.14 squares

- W x 2W:
  - 0.35 squares

- W x W/4:
  - Corner = 0.56 squares
Sheet Resistance of a Diffused Junction

* For diffused layers:

\[
R_s = \frac{P}{x_j} = \left[ \int_{x_0}^{x_j} \sigma(x) dx \right]^{-1} = \left[ \int_{x_0}^{x_j} q \mu N(x) dx \right]^{-1}
\]

[extrinsic material]

* This expression neglects depletion of carriers near the junction, \( x_j \) → thus, this gives a slightly lower value of resistance than actual

* Above expression was evaluated by Irvin and is plotted in “Irvin’s curves” on next few slides
  * Illuminates the dependence of \( R_s \) on \( x_j \), \( N_o \) (the surface concentration), and \( N_B \) (the substrate background conc.)

Irvin’s Curves (for n-type diffusion)

Example. p-type

Given:

\( N_B = 3 \times 10^{16} \text{ cm}^{-3} \)
\( N_o = 1.1 \times 10^{18} \text{ cm}^{-3} \)
(n-type Gaussian)
\( x_j = 2.77 \mu m \)

Can determine these given known predep. and drive conditions

Determine the \( R_s \).

Using Fig. 7.7:

\( R_s x_j = 4.70 \Omega \mu m \)
\( R_s = \frac{4.70}{2.77} = 1.70 \Omega/\mu m \)
Irvin's Curves (for p-type diffusion)

Example.  n-type
Given:  
\[ N_b = 3 \times 10^{16} \text{ cm}^{-3} \]
\[ N_o = 1.1 \times 10^{18} \text{ cm}^{-3} \]
(p-type Gaussian)  
\[ x_j = 2.77 \text{ \mu m} \]
Can determine these given known predep.  and drive conditions

Determine the \( R_s \).

Using Fig. 7.9:
\[ R_s x_j = 800.5 \text{ \mu m} \]
\[ \Rightarrow R_s = \frac{800.5}{2.77} \approx 289 \text{ \Omega} \]