Lecture Outline

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

Lithography

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

I. Radiation Source

II. Mask

III. Photoresist

IV. Exposure System

Four Main Components (that affect resolution)

Designated pattern (clear or dark field)

Emulsion chrome

% Generated from layout

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

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

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

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

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

The shorter the wavelength → Better the resolution

Today's prime choice due to cost and throughput.

Optical Sources:
- Mercury arc lamp (mercury vapor discharge)
- For deep UV, need Excimer laser (very expensive)

Can expose billions of devices at once!

II. Mask

II. Mask → has become one of today's biggest bottlenecks!

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

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

**Pictorial Description:**

**Exposed Area:**

**Negative**

- PR
- Si
- develop
- PR
- Si remains

**Positive**

- PR
- Si
- develop
- PR
- Si removed

**Mechanism:**

**Negative**

- photoactivation
- Polymerization (long, linked Carbon chains)
- Developer solvent removes unexposed PR

**Positive**

- photoactivation
- Converts exposed PR to organic acid
- Alkaline developer (e.g., KOH) removes acid
### III. Photoresist (optical)

#### Issues:
- **Negative**
  - Polymerized PR swells in solvent → bridging problem
  - Exposed and polymerized

- **Positive**
  - Doesn’t adhere well to SiO₂
  - Need primer: HMDS (hexamethyldisilazane)

![Diagram showing PR and SiO₂ interfaces with and without HMDS](image)

- Poor adhesion
- Good adhesion at both HMDS interfaces

#### Typical Procedure for Lithography

1. **Clean Wafer**
2. **Dry Wafer**
3. **Deposit HMDS**
4. **Spin-on PR**
5. **Soft Bake**
6. **Align & Expose**
7. **Develop**
8. **Descum**
9. **Post Bake**

**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

**Topography very important:**
- Thicker and unfocused
- Overexpose, Underexpose

**Oxygen plasma (low power ~ 50W)**
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
  - 1X printing very useful for MEMS → can expose surfaces with large topography (where reduction printers cannot)

- **Proximity Printing**
  - Mask in very close proximity but not touching

**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

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)

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

\[
0 < A_f \leq 1 \quad \text{anisotropic}
\]

Etching Basics (cont.)

2. Selectivity -

<table>
<thead>
<tr>
<th>PR</th>
<th>Poly-Si</th>
<th>SiO₂</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tr>
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Ideal Etch

<table>
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<td></td>
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<tr>
<td>Poly-Si</td>
<td>SiO₂</td>
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Actual Etch

<table>
<thead>
<tr>
<th>PR</th>
<th>Poly-Si</th>
<th>SiO₂</th>
<th>Si</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
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<tr>
<td>Poly-Si</td>
<td>SiO₂</td>
<td>Si</td>
<td></td>
</tr>
</tbody>
</table>

Only poly-Si etched (no etching of PR or SiO₂)

SiO₂ partially etched after some overetch of the polysilicon

Perfect selectivity
Etching Basics (cont.)

Why overetch?

\[ \sqrt{A} = 1.4d = 0.56 \mu m \rightarrow \text{Thicker spots due to topography!} \]

Poly-Si \rightarrow \text{conformal if deposited by LPCVD}

10nm Gate oxide

Thus, must overetch at least 40%:

40% overetch \rightarrow (0.4)(0.4) = 0.16 \mu m poly = ??? oxide

Depends on the selectivity of poly-Si over the oxide

Etching Basics (cont.)

Define selectivity of A over B:

\[ S_{ab} = \frac{E.R._{A}}{E.R._{B}} \]

Etch rate of A

Etch rate of B

Selectivity of A over B

e.g., wet poly etch (HNO\textsubscript{3} + NH\textsubscript{4} + H\textsubscript{2}O)

\[ S_{\text{poly/SiO}_2} = \frac{15}{1} \] (very good selectivity)

\[ S_{\text{poly/PR}} = \text{Very high (but PR can still peel off after soaking for > 30 min., so beware)} \]

\[ S_{\text{poly/SiO}_2} = \frac{5 - 7}{1} \] (but depends on type of etcher)

\[ S_{\text{poly/PR}} = \frac{4}{1} \] (ECR: 30:1 Bosch: 100:1 (or better)}
Etching Basics (cont.)

If \( S_{\text{poly}/\text{SiO}_2} = \frac{8}{1} \) \( \implies 40\% \) 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:
\[ e.g., S_{\text{poly}/\text{SiO}_2} = \frac{30}{1} \]

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

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

Wet Etching
Wet Etching

* Wet etching: dip wafer into liquid solution to etch the desired film
  - Generally isotropic, thus, inadequate for defining features < 3 \( \mu m \)-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 \( \rightarrow \) 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:
   - 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]

Film to be etched

Si wafer

Solution: Agitate wafers during reaction.

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.ₘₐₓ = 100 × E.R.ₜₜₜₜ
Anisotropic Wet Etching (cont.)

Can get the following:

(on a <100> - wafer)

(on a <110> - wafer)

Very anisotropic!

Wet Etching SiO$_2$

SiO$_2$ + 6HF $\rightarrow$ H$_2$ + SiF$_6$ + 2H$_2$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
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
    \( (\text{H}_2\text{PO}_4) \)  \( (\text{HNO}_3) \)  \( (\text{CH}_3\text{COOH}) \)  \( (\text{H}_2\text{O}) \)
    
    \(\text{(1) Forms Al}_2\text{O}_3 \) (aluminum oxide)
    \(\text{(2) Dissolves the Al}_2\text{O}_3\)

   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)

| ETCHING | CHEMICALS | TaSiN | Poly | Novobel | Novatis | Lepus | Hestor | Alumina | Alumina | Pits | Tantalum | Tantalum | Alumina | Alumina | Alumina | Alumina | Alumina | Alumina | Alumina | Alumina | Alumina | Alumina |
|---------|------------|-------|------|---------|---------|-------|--------|---------|---------|------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|          |            |       |      |         |         |       |        |         |         |      |          |          |         |         |         |         |         |         |         |         |         |         |         |         |         |

Notes: * Tests not performed; N/A not measured, not necessary to have a test (K. Williams). Preliminary tests were done using the material provided by the research team. The material used was supplied in a powder form and was not in a liquid state.

* Tests were performed to determine the etch rate and to establish the optimal etch conditions for each material. The etch rates were measured using a profilometer and were repeated multiple times to ensure accuracy.

* Tests were performed in a controlled environment to maintain consistent conditions. The temperature and humidity were monitored and controlled to ensure the accuracy of the test results.

* Tests were performed on a small scale to determine the etch rate and to establish the optimal etch conditions for each material.
**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>H₂PO₄·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

\[ \text{All based upon plasma processes.} \]

\[ \text{(+)} \text{ ions generated by inelastic collisions with energetic e}^+\text{s} \]
\[ \text{Get avalanche effect because more e}^-\text{s come out as each ion is generated.} \]

\[ \text{Plasma (partially ionized gas composed of ions, e}^+\text{s, and highly reactive neutral species)} \]

\[ \text{Develop (-) bias} \]

\[ \text{RF (also, could be microwave)} \]

\[ \text{E- field} \]

\[ \text{wafer} \]

\[ \text{Develops (+) charge to compensate for} \]
\[ \text{(+)} \text{ ions will be accelerated to the wafer} \]

Physical Sputtering (Ion Milling)

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

\[ \text{ions} \]
\[ \text{plasma} \]

\[ \text{PR} \]
\[ \text{film} \]
\[ \text{Si} \]

Steep vertical wall
Problems With Ion Milling

PR etched down to here

Once through the film, the etch will start barreling through the Si

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 with CF$_4$ and O$_2$**

\[ \text{CF}_4 \xrightarrow{\text{plasma}} \text{CF}_4^+ + \text{CF}_3^+ + \text{CF}_2^+ + \text{CF}^+ + \text{F}^+ + \text{F}_0 + \text{CF}_2^+ + \ldots \]

*F$_0$ is the dominant reactant → but it can’t be given a direction → thus, get isotropic etch!*

SiCF$_6$, SiF$_4$ ← both volatile . dry etching is possible.

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, $S_{\text{poly/PR}}$)

- **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

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)

*Etch rate decreases with trench width*
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⁻
    
    \[
    \text{Si : Si : Si :} \quad \text{Dope} \quad \text{Si : Si : Si :}
    \]

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

Doping of Semiconductors (cont.)

- Conductivity Equation:
  
  \[
  \sigma = q \mu_n n + q \mu_p p
  \]

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

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

  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
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:

- 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

Control current & time to control the dose.

Result of I/I
Ion Implantation (cont.)

Result of I/I

Damage → Si layer at top becomes amorphous

B not in the lattice, so it’s not electrically active.

Ion collides with atoms and interacts with e−'s in the lattice → all of which slow it down and eventually stop it.

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

Now B in the lattice & electrically active! (serves as dopant)

This is a statistical process → implanted impurity profile can be approximated by a Gaussian distribution.

Statistical Modeling of I/I

Impurity concentration

N(x)

One std. dev. away → 0.61N_p

2 std. dev. away → 0.14N_p

3 std. dev. away → 0.11N_p

Distance into Si material, x

N_p

Unlucky ions

Avg. ions

Lucky ions

ΔR_p

ΔR_p

ΔR_p

R_p

Projected range = avg. distance on ion trends before stopping

ΔR_p

Straggle = 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 \( \Rightarrow \) Implanted Dose \( Q = \int_0^\infty N(x)dx \text{ [ions/cm}^2\text{]} \)

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)

\[ D_I = \frac{Q}{\sqrt{\pi(Dt)_{eff}}} \exp \left[ -\frac{(x-R_p)^2}{2(\Delta R_p)^2} \right], \text{ where } (Dt)_{eff} = \frac{(\Delta R_p)^2}{2} \]

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**

![Image of I/I Straggle Graphs]

- Results for Si and SiO<sub>2</sub> surfaces are virtually identical → so we can use these curves for both

**Figure 6.2**

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

- 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:

Predeposition

* Furnace-tube system using solid, liquid, or gaseous dopant sources
* Used to introduced 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

Furnace tube

Gases

$O_2 + B_2H_6 +$ carrier gas

diborane (Inert gas: e.g., $N_2$ or $Ar$)

Predeposition Temp: 800-1100°C
Ex: Boron Predeposition

* Basic Procedure:
1. Deposit B$_2$O$_3$ glass
2. B diffuses from B$_2$O$_3$ \( \rightarrow \) Si

* Difficult to control dose Q, because it's heavily dependent on partial pressure of B$_2$H$_6$ gas flow, this is difficult to control itself, get only 10% uniformity

Ex: Boron Predeposition (cont.)

For better uniformity, use solid source:

Reactions:
- B$_2$H$_6$ $+$ 3O$_2$ $\rightarrow$ 3H$_2$O $+$ B$_2$O$_3$
- Si $+$ O$_2$ $\rightarrow$ SiO$_2$
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: \( \pm 20\% \) (I/I can get \( \pm 1\% \))
- Uniformity is not good
  - \( \pm 10\% \) w/ gas source
  - \( \pm 2\% \) w/ solid source
- Max. conc. possible limited by solid solubility
  - Limited to \( \sim 10^{20} \text{ cm}^{-3} \)
  - No limit for I/I \( \rightarrow \) 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 \( \rightarrow \) introduces unbalanced stress \( \rightarrow \) warping of structures
  - I/I can do physical damage \( \rightarrow \) problem if annealing is not permitted
- Thus, predeposition is often preferred when doping MEMS

Diffusion Modeling

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

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

Flux \([\text{#/cm}^2\cdot\text{s}]\) \( \sim \) Diffusion Coefficient

Continuity Equation for Particle Flux -

General form:

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

Rate of increase negative of the divergence of conc. \( \wedge \) time of particle flux
Diffusion Modeling (cont.)

∂²N(x,t) / ∂x² = - ∂J / ∂x (2)

[Fick’s 2nd Law of Diffusion in 1-D]

Solutions: dependent upon boundary conditions
- use variable separation or Laplace transform techniques

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

surface conc. stays constant

N₀

t₁

t₂

t₃

high T

(diffusion coefficient)

complementary error function profile

surface concentration

N₈
t₁ distance from surface

Diffusion Modeling (Predeposition)

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

Boundary Conditions:
(i) N(0,t) = N₀
(ii) N(∞,t) = 0

N(x,t) = N₀ [1 - erf(x / 2√Dt)]

(N(x,t) = N₀ erf(x / 2√Dt))

= again, complementary error function

Dose, Q = total # of impurity atoms per unit area in the Si

= area under the curve

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

= Q(e) = N₀ / 2√Dt cm²

2√Dt = characteristic diffusion length
Diffusion Modeling (Limited Source)

\[ \text{Case 2: Drive-in} \rightarrow \text{limited source diffusion, i.e., constant dose } Q \]

\[ N(x, t) = \text{constant} \]

\[ \frac{\partial N(x, t)}{\partial x} \bigg|_{x=0} = 0 \]

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

\[ J = 0 \]

\[ \text{This says!} \]

\[ \frac{D_x}{2} = \text{half the implant dose} \]

\[ \text{Get Gaussian distribution:} \]

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

\[ \text{corresponds to a half Gaussian in this equation} \]

\[ \text{when the starting profile is completely contained in the Si, then} \]

\[ Q \cdot \frac{D_x}{2} = \text{half the implant dose} \]
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 $(Dt)_1 = (\Delta R_p)^2/2$ (Gaussian)
     - Drive-in/activation $\rightarrow D_2t_2$
  2. Other high temperature steps
     - (e.g., oxidation, reflow, deposition) $\rightarrow D_3t_3, D_4t_4, \ldots$
     - Each has their own $Dt$ product
  3. Then, to find the final profile, use

  $$\left(Dt\right)_{\text{tot}} = \sum_i D_iti$$

  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 & Interstitial Diffusers

Interstitial Diffusers

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

$x_j$ = point at which diffused impurity profile intersects the background concentration, $N_B$

\[ \log[N(x)] \]

\[ N_o \]

\[ N_B \]

\[ x_j \]

$x = \text{distance from surface}$

\[ \text{e.g., p-type Gaussian} \]

\[ \text{e.g., n-type} \]

\[ \log[N(x) - N_B] \]

\[ N_o - N_B \]

\[ N_B \]

\[ x_j \]

$x = \text{distance from surface}$

Net impurity conc.

$p$-type region

$n$-type region

Expressions for $x_j$

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

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

• For a complementary error function profile:

\[
N(x_j, t) = N_o \text{erfc} \left( \frac{x_j}{2\sqrt{Dt}} \right) = N_B \rightarrow x_j = 2\sqrt{Dt} \text{erfc}^{-1} \left( \frac{N_B}{N_o} \right)
\]
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:

\[ R = \frac{L}{A} = \frac{P}{t} \frac{L}{w} = R_s \frac{L}{w} \]

\[ \text{number of squares} \]

\[ \text{Uniformly doped material with resistivity } \rho = \frac{1}{\sigma} \]

\[ \sigma = \text{conductivity} = q(\mu_n + \mu_p) \]

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

# Squares From Non-Uniform Traces

- Corner = 0.56 squares

- 0.36 squares

- 0.34 squares

- 0.35 squares
Sheet Resistance of a Diffused Junction

- For diffused layers:
  
  \[ R_s = \frac{\rho}{x_j} = \left[ \int_{x_o}^{x_j} \sigma(x)dx \right]^{-1} = \left[ \int_{x_o}^{x_j} q\mu N(x)dx \right]^{-1} \]

  - This expression neglects depletion of carriers near the junction, \( x_j \rightarrow \) 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.
    
    \( \triangleright \) 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)

\( x_j = 2.77 \mu\text{m} \)

Can determine these given known predep. and drive conditions.

Determine the \( R_s \).

Using Fig. 7C:

\[ R_s x_j = 4.7 \Omega \mu\text{m} \]

\( \therefore R_s = \frac{4.7}{2.77} = 1.7 \Omega/\mu\text{m} \)
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)
\(x_j = 2.77 \mu\text{m}\)
Can determine these
given known predep.
and drive conditions

Determine the \(R_s\).

Using Fig. 7.9:
\(R_s x_j = 800 \Omega \cdot \text{cm}\)
\[R_s = \frac{800}{2.77} = 289 \Omega \text{/cm}\]