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# EE C247B - ME C218

## Introduction to MEMS Design


### Spring 2015

Prof. Clark T.-C. Nguyen

Dept. of Electrical Engineering & Computer Sciences  
University of California at Berkeley  
Berkeley, CA 94720

Lecture Module 4: Lithography, Etching, & Doping

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## Lecture Outline

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

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# Lithography

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# Lithography

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

**Four Main Components (that affect resolution)**

The diagram illustrates the lithography process. At the top, a radiation source (I) emits light through a mask (II) which has a designated pattern (clear or dark field). The mask is made of glass or quartz. Below the mask is a layer of photoresist (~1 μm-thick) which is generated from layout (emulsion or chrome). Underneath the photoresist is a film to be patterned (e.g., poly-Si). The process is part of an exposure system (IV) which involves contact, step, and repeat. The text notes that the exposure system is where the real art is.

I. Radiation Source

II. Mask  
Mask (glass/quartz)

III. Photoresist  
Photoresist (~1 μm-thick)

IV. Exposure System ⇔ contact, step and repeat  
↳ optics → this is where the real art is!

Designated pattern (clear or dark field)

emulsion    chrome

Generated from layout

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

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**Lithography (cont.)**

**The basic Process - (Positive Resist Example)**

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

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

Etch → PR protects film; open areas of film get etched

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**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:

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**I. Radiation Source**

**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.

Can expose billions of devices at once!

**Optical Sources:**

↪ Mercury arc lamp (mercury vapor discharge)

we have all of these in our μlab

200	365	405	435	546	nm

↪ I-line      ↪ G-line (we have both in our μlab)

↪ For deep UV, need Excimer laser (very expensive)

↪ Glass opaque, so must use quartz mask and lens

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**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

↓ tape → mask generator

Masks for each layer


**Mask Material:**

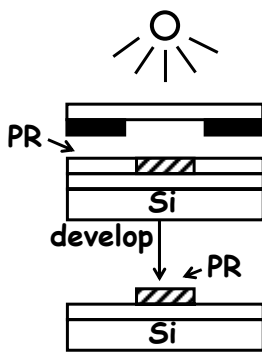
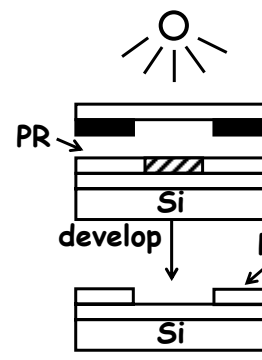
↪ Fused silica (glass) → inexpensive, but larger thermal expansion coeff.

↪ Quartz → expensive, but smaller thermal expansion coeff.

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**III. Photoresist (optical)**



	<u>Negative</u>	<u>Positive</u>
<u>Pictorial Description:</u>		
<u>Exposed Area:</u>	remains	removed

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**III. Photoresist (optical)**



	<u>Negative</u>	<u>Positive</u>
<u>Mechanism:</u>	photoactivation ↓ Polymerization (long, linked Carbon chains) ↓ Developer solvent removes unexposed PR	photoactivation ↓ Converts exposed PR to organic acid ↓ Alkaline developer (e.g., KOH) removes acid

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**III. Photoresist (optical)**

**Issues:**

Negative

Polymerized PR swells in solvent → bridging problem

Exposed and polymerized

Positive

Doesn't adhere well to SiO<sub>2</sub>  
 Need primer: HMDS (hexamethyl disilazane)

Poor adhesion

Good adhesion at both HMDS interfaces

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**Typical Procedure for Lithography**

**Clean Wafer**    Very important step

**Dry Wafer**    30 min. @ 120°C pre-bake

**Deposit HMDS**    (for oxide on wafer surface)

**Spin-on PR**    30-60 sec @ 1000-5000 rpm

**Soft Bake**    2 min @ 90°C  
 Improve adhesion and remove solvent from PR

**Align & Expose**    Oxygen plasma (low power ~ 50W)

**Develop** → **Descum** → **Post Bake**

Topography very important:

Thicker and unfocused

overexpose    underexpose

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**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

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**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:

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## Etching

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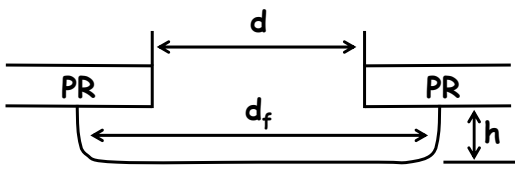
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## Etching Basics

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

1. Anisotropy -

a) Isotropic Etching (most wet etches)



If 100% isotropic:  $d_f = d + 2h$   
Define:  $B = d_f - d$   
If  $B = 2h \Rightarrow$  isotropic

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**Etching Basics (cont.)**

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

**Degree of Anisotropy: (definition)**

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

$$0 < A_f \leq 1 \quad \leftarrow \text{anisotropic}$$

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**Etching Basics (cont.)**

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2. **Selectivity** -

PR  
Poly-Si  
SiO<sub>2</sub>  
Si

Ideal Etch →

PR  
Poly-Si  
SiO<sub>2</sub>  
Si

Only poly-Si etched (no etching of PR or SiO<sub>2</sub>)

Perfect selectivity

Actual Etch

PR partially etched

SiO<sub>2</sub> partially etched after some overetch of the polysilicon

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**Etching Basics (cont.)**

**Why overetch?**

$\sqrt{2}d = 1.4d = 0.56\mu m \rightarrow$  Thicker spots due to topography!

1 $\mu m$  PR

45°

10nm Gate oxide

0.4 $\mu m$

0.4 $\mu m = d$

Poly-Si  $\rightarrow$  conformal if deposited by LPCVD

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

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**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 ( $HNO_3 + NH_4 + H_2O$ )

$$S_{poly/SiO_2} = \frac{15}{1} \text{ (very good selectivity)}$$

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

e.g., polysilicon dry etch:


Regular RIE

$$S_{poly/SiO_2} = \frac{5-7}{1} \text{ (but depends on type of etcher)}$$

$S_{poly/PR} = \frac{4}{1}$

ECR: 30:1  
 Bosch: 100:1 (or better)

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 **Etching Basics (cont.)**

If  $S_{poly/SiO_2} = \frac{8}{1} \Rightarrow$  40% overetch removes

$\frac{0.16}{8} = 20 \text{ nm of oxide!} \Rightarrow$  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.,  $S_{poly/SiO_2} = \frac{30}{1}$

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


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

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 **Wet Etching**

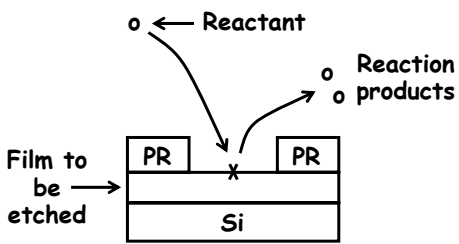
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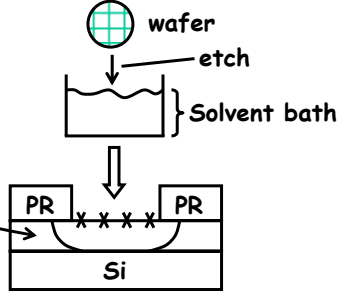
## Wet Etching



- **Wet etching:** dip wafer into liquid solution to etch the desired film
  - ↳ Generally isotropic, thus, inadequate for defining features  $< 3\mu\text{m}$ -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

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## 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

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### Wet Etching Limitations

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1. Isotropic
  - ↖ Limited to  $<3\mu\text{m}$  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)

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### Wet Etch Limitations (cont.)

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6. Incomplete wetting of the surface:

Solvent bath →

wafer

Wetted 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

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**Wet Etch Limitations (cont.)**

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

**Solution:** Agitate wafers during reaction.

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**Some Common Wet Etch Chemistries**

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**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.

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### 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/cm<sup>2</sup>  $\langle 111 \rangle$
    - # available bonds/cm<sup>2</sup>  $\langle 110 \rangle$
    - # available bonds/cm<sup>2</sup>  $\langle 100 \rangle$

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### Anisotropic Wet Etching

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

- ↳ Orientation-dependent etching:  $\langle 111 \rangle$ -plane more densely packed than  $\langle 100 \rangle$ -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% H<sub>2</sub>O)

⇒ E.R. <sub>$\langle 100 \rangle$</sub>  = 100 × E.R. <sub>$\langle 111 \rangle$</sub>

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**Anisotropic Wet Etching (cont.)**

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Can get the following:

(on a <100> - wafer)

(on a <110> - wafer)

⇒ Quite anisotropic!

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**Wet Etching SiO<sub>2</sub>**

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

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

bubble → native oxide can get this just by exposing Si to air → 1-2nm-thick

**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

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## 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 SiO<sub>2</sub> 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:
 

(H<sub>2</sub>PO<sub>4</sub>)
(HNO<sub>3</sub>)
(CH<sub>3</sub>COOH)
(H<sub>2</sub>O)

    - (1) Forms Al<sub>2</sub>O<sub>3</sub> (aluminum oxide)
    - (2) Dissolves the Al<sub>2</sub>O<sub>3</sub>
  - ↪ **Problem:** H<sub>2</sub> 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

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## Wet Etch Rates (f/ K. Williams)

ETCHANT EQUIPMENT CONDITIONS	TARGET MATERIAL	MATERIAL															
		SC Si <100>	Poly Si*	Poly Ox	Wet Ox	Dry Ox	LTO undop	PSG unrat	PSG undd	SiO <sub>2</sub> nitrid	Low-n Nitrid	AU 2% Si	Sput Tung	Sput Ti	Sput Ti/W	OCG 820PR	Olin HPRP
Concentrated HF (49%) Wet Slak Room Temperature	Silicon oxides	-	0	-	23k 18k 23k	F	>14k	F	36k 140	52 30 52	42 0 42	-50	F	-	P	0	P
10:1 HF Wet Slak Room Temperature	Silicon oxides	-	7	0	230 230	230	340	15k	4700 11	3 2500 2500 12k	0	11k	<70	0	0	0	0
25:1 HF Wet Slak Room Temperature	Silicon oxides	-	0	0	97 95	95	150	W	1500 6	1 W	0	-	-	0	0	0	0
5:1 BHF Wet Slak Room Temperature	Silicon oxides	-	9	2	1000 900 1080	1000	1200	6800	4400 3500 4400	9 3 4	1400 6.25 20	<20	F	1000	0	0	0
Phosphoric Acid (85%) Heated Bath with Reflux 160°C	Silicon nitrides	-	7	-	0.7 0.8	0.8	<1	37	34 9 28 24	28 19 42	9800	-	-	-	550	300	
Silicon Etchant (126 HNO <sub>3</sub> : 60 H <sub>2</sub> O : 5 NH <sub>4</sub> F) Wet Slak Room Temperature	Silicon	1500	3100 1200 6000	1000	87	W	110	4000	1700	2	3	4000	150	3000	-	0	0
KOH (1 KOH : 2 H <sub>2</sub> O by weight) Heated Stirred Bath 80°C	<100> Silicon	14k	>10k	F	77 41 77	-	94	W	380	0	0	F	0	-	-	F	F
Aluminum Etchant Type A (16 H <sub>2</sub> PO <sub>4</sub> : 1 HNO <sub>3</sub> : 2 H <sub>2</sub> O) Heated Bath 50°C	Aluminum	-	<10	<9	0	0	0	-	<10	0	2	6600 2600 6600	-	0	-	0	0
Titanium Etchant (20 H <sub>2</sub> O : 1 H <sub>2</sub> O <sub>2</sub> : 1 HF) Wet Slak Room Temperature	Titanium	-	12	-	120	W	W	W	2100	8	4	W	0 0 110	8100	-	0	0
H <sub>2</sub> O <sub>2</sub> (30%) Wet Slak Room Temperature	Tungsten	-	0	0	0	0	0	0	0	0	0	<20	190 190 1000	0 60 150	60	<2	0
Piranha (-50 H <sub>2</sub> SO <sub>4</sub> : 1 H <sub>2</sub> O <sub>2</sub> ) Heated Bath 120°C	Cleaning off metals and organics	-	0	0	0	0	0	-	0	0	0	1800	-	2400	-	F	F
Acetone Wet Slak Room Temperature	Photoresist	-	0	0	0	0	0	-	0	0	0	-	0	-	>4k	>30k	

Notation: -=not performed. W=not performed, but known to work (> 100 Å/min); F=not performed, but known to be flat (> 10 Å/min); P=some of film pitted during etch or when rinsed; A=film was visibly attacked and roughened.  
 Each area was etched for 4-6 inch wafer for the measurement films and half of the wafer for single-crystal silicon and the metals.  
 Etch rates will vary with temperature and prior use of solution, area of exposure of film, other materials present (e.g., photoresist), film impurities and microstructure, etc. Some variation should be expected.

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**Film Etch Chemistries**

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- For some popular films:

Material	Wet etchant	Etch rate [nm/min]	Dry etchant	Etch rate [nm/min]
Polysilicon	HNO <sub>3</sub> :H <sub>2</sub> O: NH <sub>4</sub> F	120-600	SF <sub>6</sub> + He	170-920
Silicon nitride	H <sub>3</sub> PO <sub>4</sub>	5	SF <sub>6</sub>	150-250
Silicon dioxide	HF	20-2000	CHF <sub>3</sub> + O <sub>2</sub>	50-150
Aluminum	H <sub>3</sub> PO <sub>4</sub> :HNO <sub>3</sub> : CH <sub>3</sub> COOH	660	Cl <sub>2</sub> + SiCl <sub>4</sub>	100-150
Photoresist	Acetone	>4000	O <sub>2</sub>	35-3500
Gold	KI	40	n/a	n/a


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**Dry Etching**

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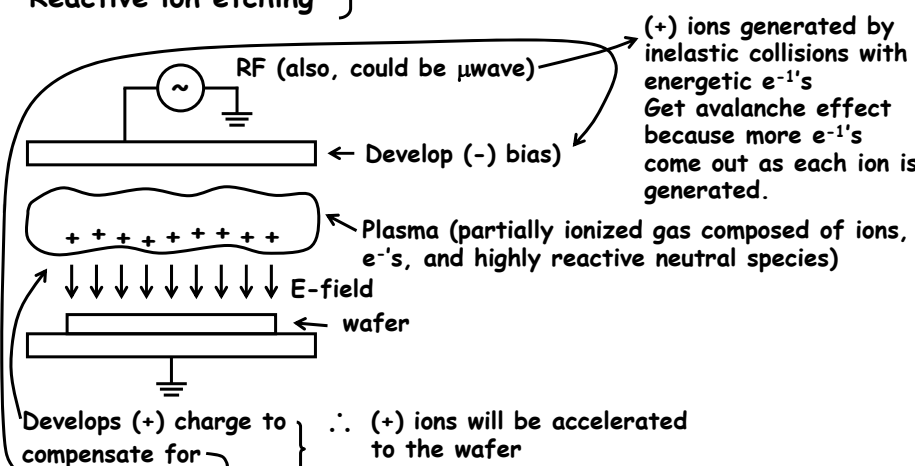
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### Dry Etching



- Physical sputtering
- Plasma etching
- Reactive ion etching

} All based upon plasma processes.




Develops (+) charge to compensate for

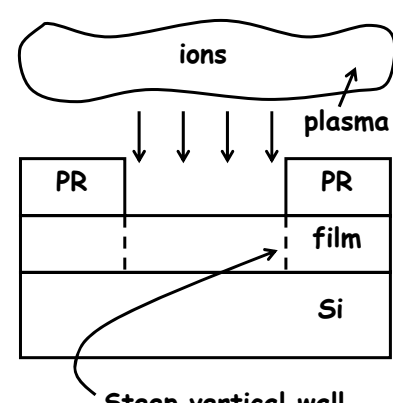
∴ (+) ions will be accelerated to the wafer

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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



Steep vertical wall

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### 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)

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### Plasma Etching

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

**Plasma Etching Mechanism:**

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

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**Ex: Polysilicon Etching w/  $CF_4$  and  $O_2$**

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

Si

Neutral radical (highly reactive!)  
 $e^- + CF_4 \rightarrow CF_3 + F + e^-$

$SiCF_6, SiF_4 \leftarrow$  both volatile  $\therefore$  dry etching is possible.

- $F^0$  is the dominant reactant  $\rightarrow$  but it can't be given a direction  $\rightarrow$  thus, get isotropic etch!


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**Ex: Polysilicon Etching w/  $CF_4$  and  $O_2$**

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- Problems:**
  - Isotropic etching
  - Formation of polymer because of C in  $CF_4$   
 $\rightarrow$  **Solution:** add  $O_2$  to remove the polymer (but note that this reduces the selectivity,  $S_{\text{poly/PR}}$ )
- Solution:**  
 $\rightarrow$  Use Reactive Ion Etching (RIE)

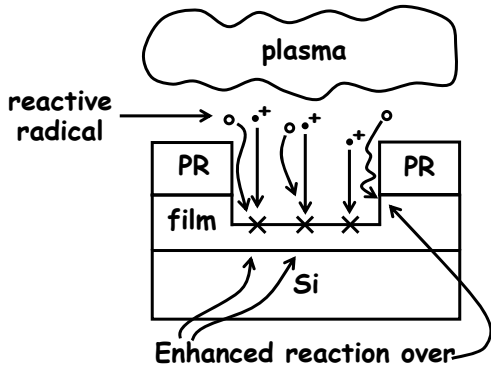
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 **Reactive Ion Etching (RIE)**

- 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

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**RIE: Surface Inhibitor Mechanism**

The diagram shows a cross-section of a substrate with a photoresist (PR) film. A plasma is applied above the film. Reactive radicals (represented by circles with a dot) are shown reacting with the PR film. Positive ions (represented by circles with a plus sign) are shown being directed towards the horizontal surface of the film, where they cause the polymer to break up. On the sidewalls, the ions do not cause a reaction, leading to the formation of a non-volatile polymer layer. The silicon (Si) substrate is shown below the film, with a note indicating 'no reaction' occurs there.

- 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

(+) ions breakup the polymer layer get reaction

**Result: E.R. @ surface >> E.R. on sidewalls**

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**Deep Reactive-Ion Etching (DRIE)**

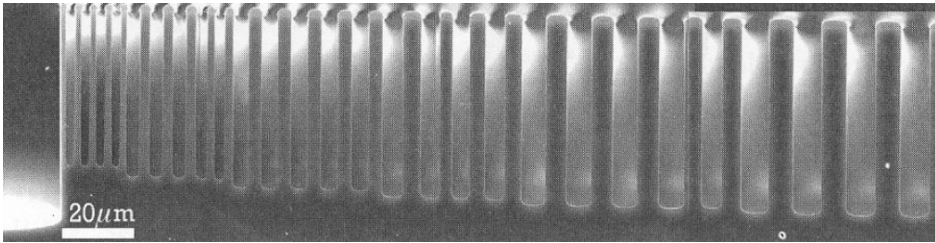
**The Bosch process:**

- Inductively-coupled plasma
- Etch Rate: 1.5-4  $\mu\text{m}/\text{min}$
- Two main cycles in the etch:
  - ↳ **Etch cycle** (5-15 s):  $\text{SF}_6$  ( $\text{SF}_x^+$ ) etches Si
  - ↳ **Deposition cycle** (5-15 s):  $\text{C}_4\text{F}_8$  deposits fluorocarbon protective polymer  $(\text{CF}_2)_n$
- Etch mask selectivity:
  - ↳  $\text{SiO}_2 \sim 200:1$
  - ↳ Photoresist  $\sim 100:1$
- **Issue:** finite sidewall roughness
  - ↳ scalloping < 50 nm
- Sidewall angle:  $90^\circ \pm 2^\circ$

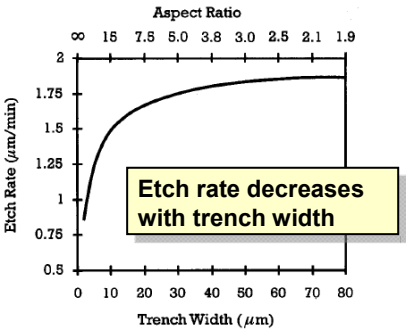
The diagram illustrates the Bosch process in three stages. In the first stage, a mask is applied to a silicon substrate. In the second stage,  $\text{SF}_6$  ions etch the silicon, while  $\text{C}_4\text{F}_8$  ions deposit a protective polymer layer on the sidewalls. In the third stage, the process repeats, showing the formation of a scalloped sidewall profile. The name 'Maluf' is written at the bottom right of the diagram.

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**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)



Trench Width ( $\mu\text{m}$ )	Etch Rate ( $\mu\text{m}/\text{min}$ )
0	0.5
10	1.25
20	1.5
30	1.65
40	1.7
50	1.75
60	1.78
70	1.8
80	1.8

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**Semiconductor Doping**

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### Doping of Semiconductors

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- 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<sup>-</sup>'s than the 4 of Si
- If more e<sup>-</sup>'s, then the dopant is a donor: P, As
  - The extra e<sup>-</sup> is effectively released from the bonded atoms to join a cloud of free e<sup>-</sup>'s, free to move like e<sup>-</sup>'s in a metal

- The larger the # of donor atoms, the larger the # of free e<sup>-</sup>'s → the higher the conductivity

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### Doping of Semiconductors (cont.)

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- Conductivity Equation:

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

conductivity →  $\sigma$     ← charge magnitude on an electron  
 electron mobility    electron density    hole mobility    hole density
- If fewer e<sup>-</sup>'s, then the dopant is an acceptor: B
  - 
  - Lack of an e<sup>-</sup> = hole = h<sup>+</sup>
  - When e<sup>-</sup>'s move into h<sup>+</sup>'s, the h<sup>+</sup>'s effectively move in the opposite direction → a h<sup>+</sup> is a mobile (+) charge carrier

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## Ion Implantation

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## 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

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### 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<sup>-</sup>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.

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### Statistical Modeling of I/I

Impurity concentration →  $N(x)$

Unlucky ions

Avg. ions

Lucky ions

One std. dev. away →  $0.61N_p$

2 std. dev. away →  $0.14N_p$

3 std. dev. away →  $0.11N_p$

$R_p$

Distance into Si material,  $x$

$R_p \triangleq$  Projected range = avg. distance on ion trends before stopping

$\Delta R_p \triangleq$  Straggle = std. deviation characterizing the spread of the distribution.

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**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 } **Implanted Dose =  $Q = \int_0^{\infty} N(x) dx$  [ions / cm<sup>2</sup>]**

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)

$D_I = Q$  → So we can track the dopant front during a subsequent diffusion step.

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

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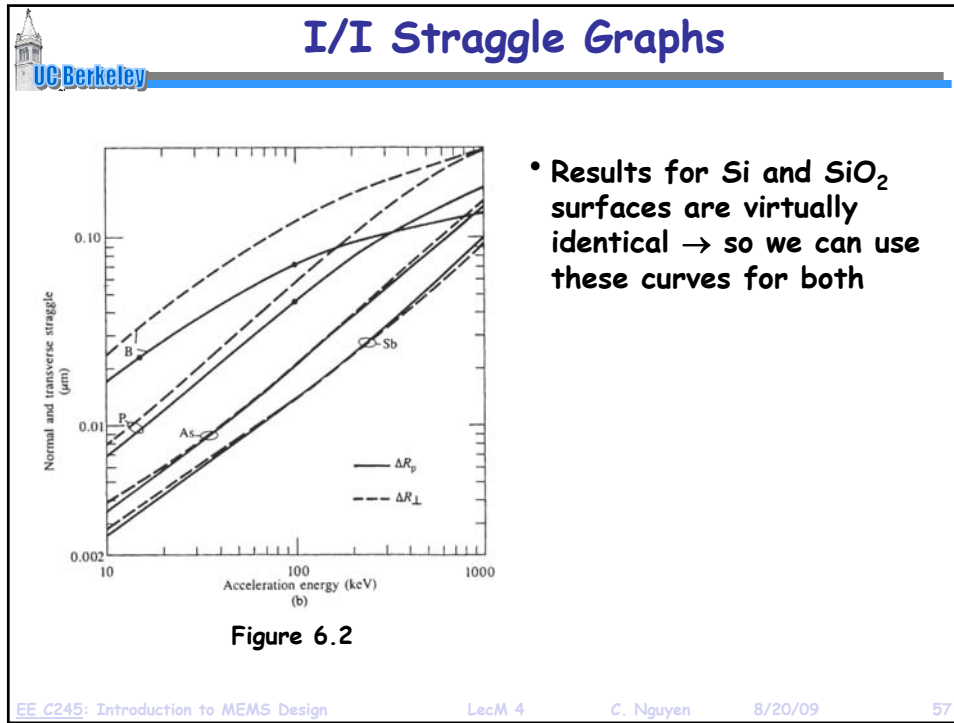
**I/I Range Graphs**

• Roughly proportional to ion energy  $R_p \propto$  ion energy (some nonlinearities)

- $R_p$  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

Figure 6.1

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## Diffusion

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### Diffusion in Silicon

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

(a)

(b)

(c)

**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

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### Diffusion in Polysilicon

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- 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

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### Basic Process for Selective Doping

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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  $> 900^{\circ}\text{C}$  in  $\text{N}_2$  or  $\text{N}_2/\text{O}_2$

• Result:

The diagram shows a cross-section of a semiconductor well. A black layer labeled 'dopants' is on top of the well. Red arrows labeled 'Drive-in' point downwards from the dopant layer into the well and then into the substrate, indicating the diffusion process.

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### Predeposition

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- 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

The diagram shows a furnace tube system. Gases ( $\text{O}_2$ ,  $\text{B}_2\text{H}_6$ , and carrier gas) enter from the left. The carrier gas is identified as an inert gas like  $\text{N}_2$  or  $\text{Ar}$ . The gases flow through a boat containing a wafer. The predeposition temperature is  $800-1100^{\circ}\text{C}$ .

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**Ex: Boron Predeposition**

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- Basic Procedure:
  1. Deposit  $B_2O_3$  glass
  2. B diffuses from  $B_2O_3 \rightarrow Si$

- Difficult to control dose  $Q$ , because it's heavily dependent on partial pressure of  $B_2H_6$  gas flow
  - ↳ this is difficult to control itself
  - ↳ get only 10% uniformity

Furnace tube cross-section  
Less B concentration

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

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For better uniformity, use solid source:

Furnace tube  
wafer  
Boron/Nitride wafer  
→ 2% uniformity

**Reactions:**

$$B_2H_6 + 3O_2 \rightarrow 3H_2O + B_2O_3$$

$$Si + O_2 \rightarrow SiO_2$$

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**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

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**Diffusion Modeling**

**Modeling**  $N(x)$

$\Rightarrow$  Dopants from points of high conc. move to points of low conc. w/ flux  $J$

$\Rightarrow$  Question: What's  $N(x,t)$ ?  
 ↷ fun of time

**Fick's Law of Diffusion - (1<sup>st</sup> law)**

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

↑ flux [ $\#/\text{cm}^2 \cdot \text{s}$ ]      ↑ Diffusion Coefficient

**Continuity Equation for Particle Flux -**

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

↑ rate of increase of conc. w/ time      ↑ negative of the divergence of particle flux

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### Diffusion Modeling (cont.)

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

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

[ $\frac{\partial}{\partial x}$  (1) and substitute (2) in (1)] ⇒  $\frac{\partial N(x,t)}{\partial t} = D \frac{\partial^2 N(x,t)}{\partial x^2}$  [Fick's 2<sup>nd</sup> 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

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### Diffusion Modeling (Predeposition)

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

⇒ Boundary Conditions:

(i)  $N(0,t) = N_0$   
 (ii)  $N(\infty,t) = 0$

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

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

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

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

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

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

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### Diffusion Modeling (Limited Source)

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

$N(x)$   
 $N_0(t_1)$   
 $N_0(t_2)$   
 $N_0(t_3)$   
 $N_B$   
 $x$ , distance  $x$  from the surface

$\Rightarrow$  Boundary Condition:

(i)  $N(\infty, t) = 0$   
 (ii)  $\frac{\partial N(x, t)}{\partial x} \Big|_{x=0} = 0$

Why? Constant Dose:  $\int_0^\infty N(x, t) dx = Q \leftarrow \text{const.}$

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

$N(x)$   
 $J=0$   
 $x$

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### Diffusion Modeling (Limited Source)

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(iii) Usually make delta fcn. approx.:  $N(x, 0) = Q \delta(x)$

$\Rightarrow$  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

Get Gaussian Distribution:  $N(x, t) = \frac{Q}{\sqrt{\pi Dt}} \exp\left[-\left(\frac{x}{\sqrt{2Dt}}\right)^2\right]$


corresponds to a half Gaussian in this equation

$N(x)$   
 $\frac{D_I}{2}$   
 $x$

When the starting conc. profile is completely contained in the Si, then  
 $Q = \frac{D_I}{2} = \text{half the implant dose}$

$\log N$   
 $x$

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## Two-Step Diffusion

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- 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:
  - $(Dt)_{\text{predep}} \gg (Dt)_{\text{drive-in}} \Rightarrow$  impurity profile is complementary error function
  - $(Dt)_{\text{drive-in}} \gg (Dt)_{\text{predep}} \Rightarrow$  impurity profile is Gaussian (which is usually the case)

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## Successive Diffusions

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- 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  $\rightarrow D_2 t_2$
  2. Other high temperature steps
    - ↳ (eg., oxidation, reflow, deposition)  $\rightarrow D_3 t_3, D_4 t_4, \dots$
    - ↳ Each has their own  $Dt$  product
  3. Then, to find the final profile, use
 
$$(Dt)_{\text{tot}} = \sum_i D_i t_i$$

in the Gaussian distribution expression.

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**The Diffusion Coefficient**

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

**Table 4.1** Typical Diffusion Coefficient Values for a Number of Impurities.

Element	$D_0(\text{cm}^2/\text{sec})$	$E_A(\text{eV})$
B	10.5	3.69
Al	8.00	3.47
Ga	3.60	3.51
In	16.5	3.90
P	10.5	3.69
As	0.32	3.56
Sb	5.60	3.95

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**Diffusion Coefficient Graphs**

**Substitutional & Interstitial Diffusers**

Fig. 7.1

**Interstitial Diffusers**

↳ Note the much higher diffusion coeffs. than for substitutional

Fig. 7.2

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**Metallurgical Junction Depth,  $x_j$**

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

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**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:

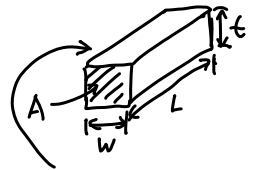
$$N(x_j, t) = N_o \operatorname{erfc}\left(\frac{x_j}{2\sqrt{Dt}}\right) = N_B \rightarrow x_j = 2\sqrt{Dt} \operatorname{erfc}^{-1}\left(\frac{N_B}{N_o}\right)$$

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## Sheet Resistance

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



Uniformly doped material  
 w/ resistivity  $\rho = \frac{1}{\sigma}$

$\sigma = \text{conductivity} = q(\mu_n n + \mu_p p)$

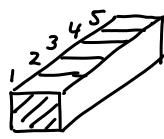
$$R = \frac{\rho L}{A} = \left(\frac{\rho}{t}\right) \frac{L}{W} = R_s \left(\frac{L}{W}\right)$$

$\Omega/D$

ohms per square  
 $\downarrow$   
 $\Omega/D$

sheet resistance      # unit squares of material in the resistor


e.g.,

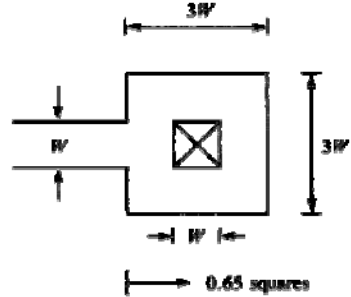
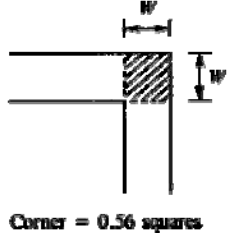
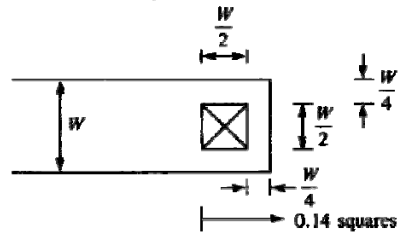
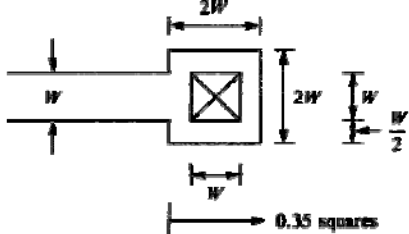


5 D's of material  
 $\therefore R = R_s \times 5$
- What if the trace is non-uniform? (e.g., a corner, contains a contact, etc.)

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## # Squares From Non-Uniform Traces

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 <p>0.65 squares</p>	 <p>Corner = 0.56 squares</p>
 <p>0.14 squares</p>	 <p>0.35 squares</p>

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### Sheet Resistance of a Diffused Junction

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- For diffused layers:

Majority carrier mobility

Net impurity concentration

Effective resistivity

Sheet resistance

$$R_s = \frac{\rho}{x_j} = \left[ \int_0^{x_j} \sigma(x) dx \right]^{-1} = \left[ \int_0^{x_j} q\mu N(x) dx \right]^{-1}$$

[extrinsic material]

- 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
  - ☞ Illuminates the dependence of  $R_s$  on  $x_j$ ,  $N_0$  (the surface concentration), and  $N_B$  (the substrate background conc.)

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### Irvin's Curves (for n-type diffusion)

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Figure 7.6: n-type erf curves. Y-axis: Surface dopant concentration,  $N_s$  (atoms/cm<sup>3</sup>). X-axis: Sheet resistance-junction depth product,  $R_s x_j$  (ohm- $\mu$ m). Curves for  $N_B = 10^{14}, 10^{15}, 10^{16}, 10^{17}, 10^{18}$  atoms/cm<sup>3</sup>.

Figure 7.7: n-type Gaussian curves. Y-axis: Surface dopant concentration,  $N_s$  (atoms/cm<sup>3</sup>). X-axis: Sheet resistance-junction depth product,  $R_s x_j$  (ohm- $\mu$ m). Curves for  $N_B = 10^{14}, 10^{15}, 10^{16}, 10^{17}, 10^{18}$  atoms/cm<sup>3</sup>. A red vertical line is drawn at  $R_s x_j = 470$  and a red horizontal line at  $N_s = 1.1 \times 10^{18}$ .

**Example.** p-type

**Given:**

- $N_B = 3 \times 10^{16} \text{ cm}^{-3}$
- $N_0 = 1.1 \times 10^{18} \text{ cm}^{-3}$  (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. 7.7:

$R_s x_j = 470 \Omega \cdot \mu\text{m}$

$\therefore R_s = \frac{470}{2.77} = 170 \Omega/\square$

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