EE C245 – ME C218
Introduction to MEMS Design
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Lecture Module 4: Lithography, Etching, & Doping

Lecture Outline

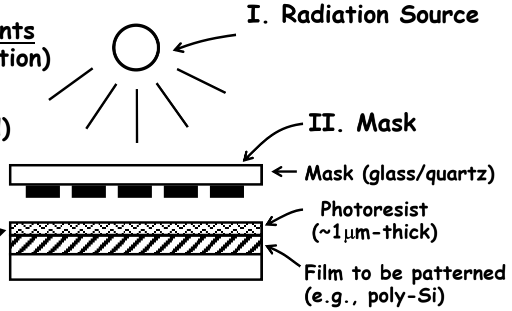
- Reading: Senturia, Chpt. 3; Jaeger, Chpt. 2, 4, 5
  - Lithography
  - Etching
    - Wet etching
    - Dry etching
  - Semiconductor Doping
    - Ion implantation
    - Diffusion

Lithography

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)



I. Radiation Source

Designated pattern
(clear or dark field)
emulsion chrome
- Generated from layout

II. Mask

Mask (glass/quartz)

Photoresist
(~1μm-thick)

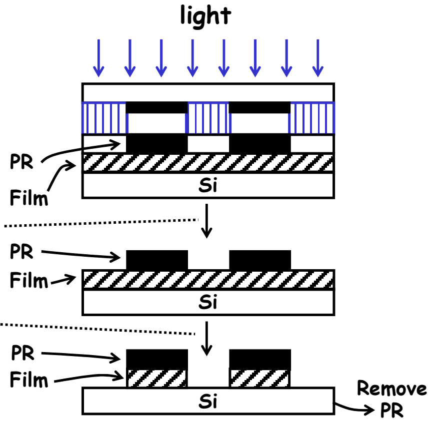
Film to be patterned
(e.g., poly-Si)

III. Photoresist

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 → 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

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

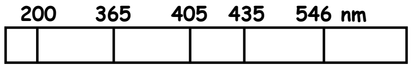
The shorter the wavelength → Better the resolution

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

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

II. Mask

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

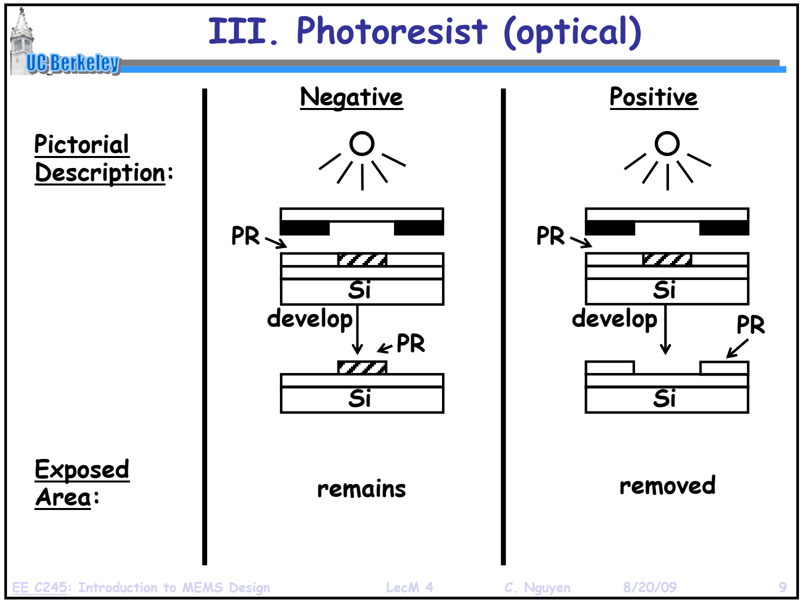
Electronic computer representation of layout (e.g., CIF, GDSII) ⇨ A single file contains all layers

↓ tape → mask generator

Masks for each layer

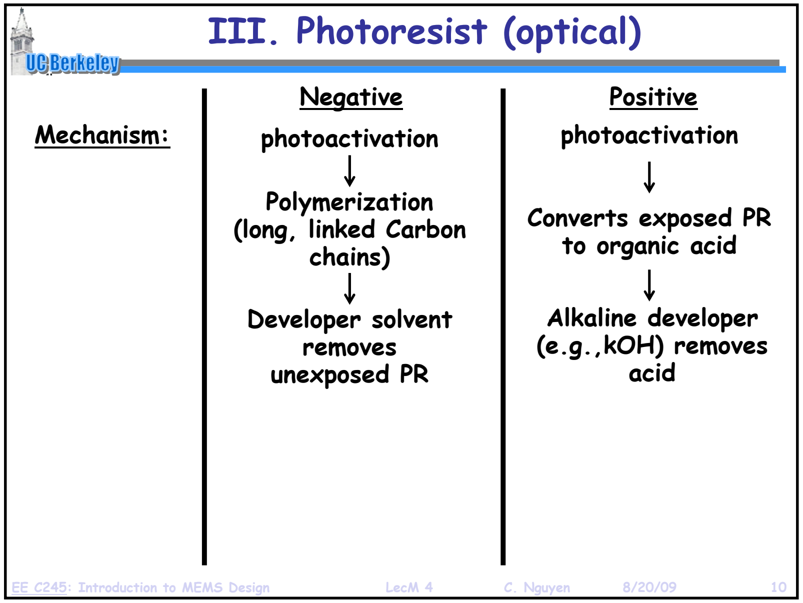
Mask Material:

- Fused silica (glass) → inexpensive, but larger thermal expansion coeff.
- Quartz → expensive, but smaller thermal expansion coeff.



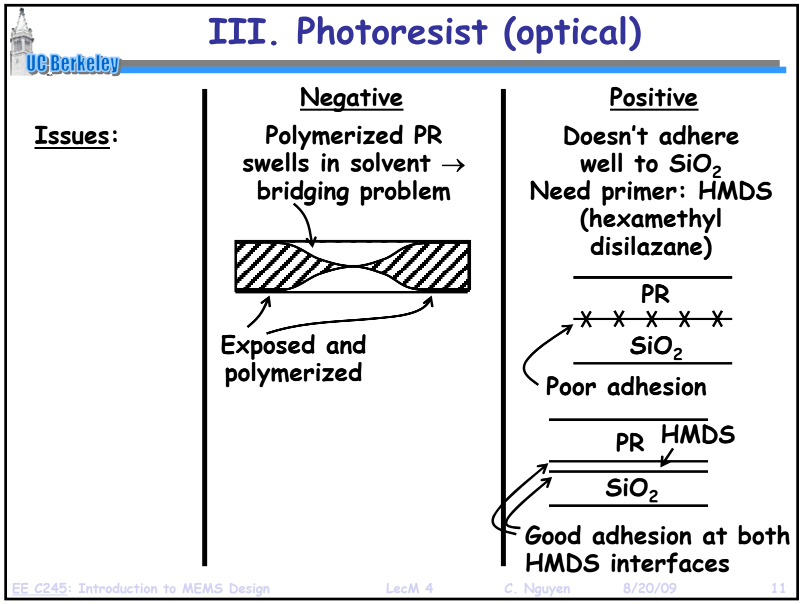
III. Photoresist (optical)

	Negative	Positive
Pictorial Description:		
Exposed Area:	remains	removed



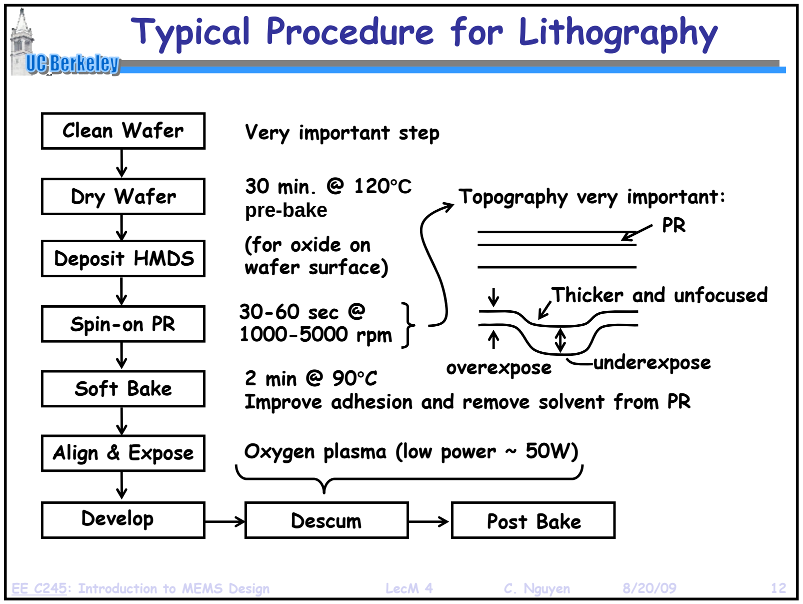
III. Photoresist (optical)

	Negative	Positive
Mechanism:	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



III. Photoresist (optical)

	Negative	Positive
Issues:	Polymerized PR swells in solvent → bridging problem	Doesn't adhere well to SiO_2 Need primer: HMDS (hexamethyl disilazane)



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

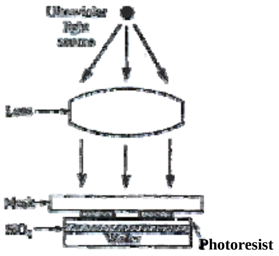
Develop → Descum → Post Bake

Oxygen plasma (low power ~ 50W)

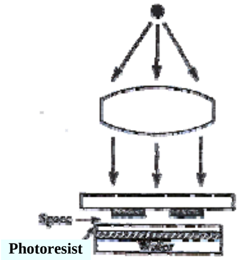
Topography very important:

IV. Exposure System/Optics

Contact Printing



Proximity Printing



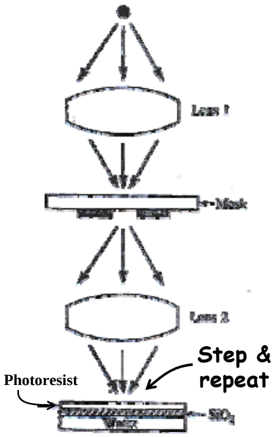
- Mask in contact with wafer
- *Problem*: mask pattern can become damaged with each exposure → must make a new mask after x number of exposures

- Mask in very close proximity but not touching

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

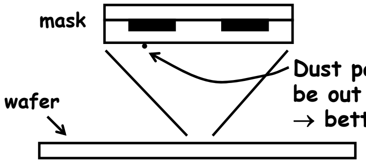
IV. Exposure System/Optics

Projection Printing



Step & repeat

- 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:



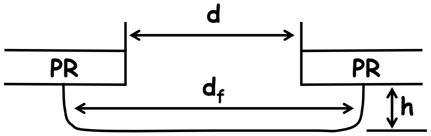
Dust particle will be out of focus → better yield!

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)



If 100% isotropic: $d_f = d + 2h$

Define: $B = d_f - d$

If $B = 2h \Rightarrow$ isotropic

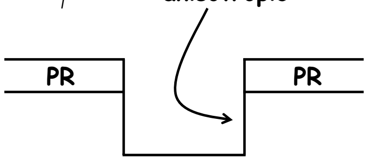
Etching Basics (cont.)

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

Degree of Anisotropy: (definition)

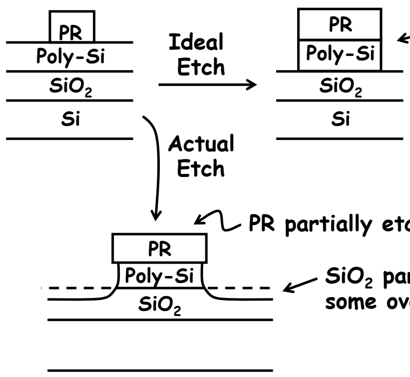
$$A_f = 1 - \frac{B}{2h} = 0 \quad \text{if 100\% isotropic}$$

$$0 < A_f \le 1 \leftarrow \text{anisotropic}$$



Etching Basics (cont.)

2. Selectivity -



Only poly-Si etched (no etching of PR or SiO$_2$)
⇓
Perfect selectivity

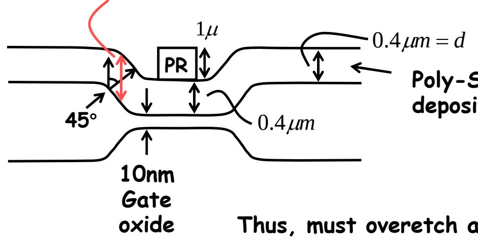
PR partially etched

SiO$_2$ partially etched after some overetch of the polysilicon

Etching Basics (cont.)

Why overetch?

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



Poly-Si → conformal if deposited by LPCVD

Thus, must overetch at least 40%:
40% overetch → (0.4)(0.4) = 0.16 μm poly
= ??? oxide

Depends on the selectivity of poly-Si over the oxide

Etching Basics (cont.)

Define selectivity of A over B:

$$S_{ab} = \frac{E.R._a}{E.R._b} \quad \begin{matrix} \longleftarrow \text{Etch rate of A} \\ \longleftarrow \text{Etch rate of B} \end{matrix}$$

Selectivity of A over B

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

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

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

e.g., polysilicon dry etch:

$$S_{poly/SiO_2} = \frac{5-7}{1}$$

Regular RIE
(but depends on type of etcher)

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

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

Etching Basics (cont.)

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

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

with better selectivity:

e.g., $S_{poly/SiO_2} = \frac{30}{1}$

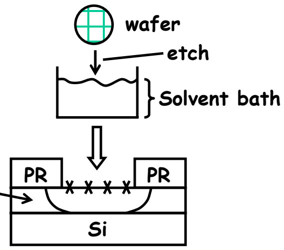
(Can attain with high density Cl plasma ECR etch!)

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

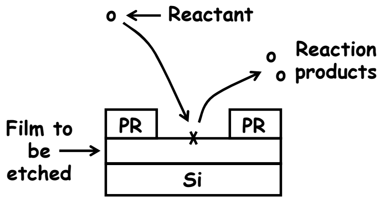
Wet Etching

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

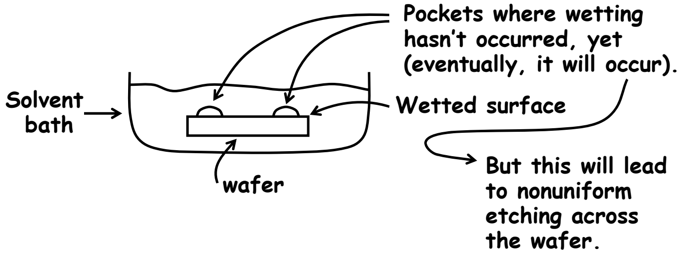
- **Advantages**:
  1. High throughput process → can etch many wafers in a single bath
  2. Usually fast etch rates (compared to many dry etch processes)
  3. Usually excellent selectivity to the film of interest

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.)

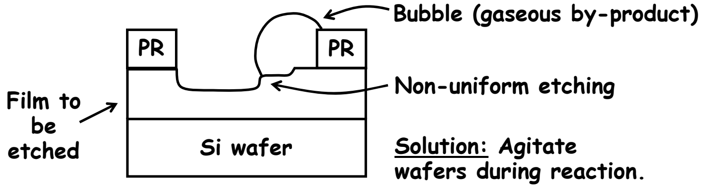
6. Incomplete wetting of the surface:



- 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.)

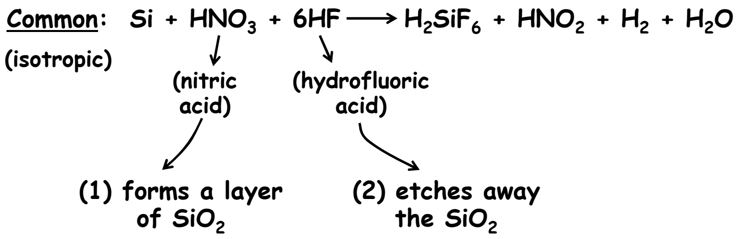
7. Bubble formation (as a reaction by-product)
   - If bubbles cling to the surface → get nonuniform etching



Solution: Agitate wafers during reaction.

Some Common Wet Etch Chemistries

Wet Etching Silicon:



Common: $Si + HNO_3 + 6HF \longrightarrow H_2SiF_6 + HNO_2 + H_2 + H_2O$

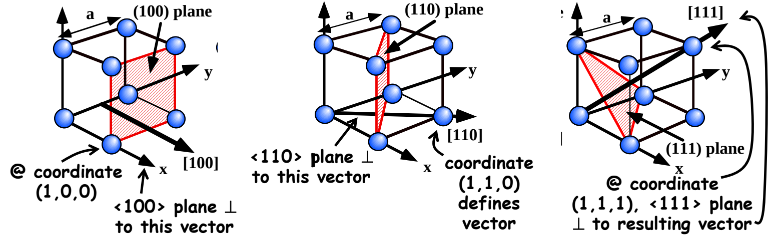
(isotropic)

HNO_3 (nitric acid) → (1) forms a layer of SiO_2

HF (hydrofluoric acid) → (2) etches away the SiO_2

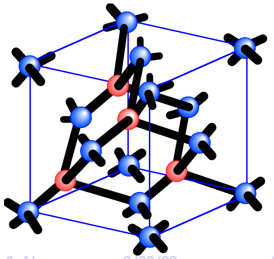
Different mixture combinations yield different etch rates.

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/cm^2 <111>
    - # available bonds/cm^2 <110>
    - # available bonds/cm^2 <100>

Increasing ↑



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. ↑ (<100>) ↖ Slower E.R. (<111>)

…in some solvents

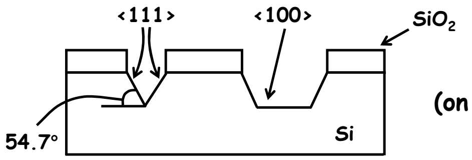
One such solvent: KOH + isopropyl alcohol

(e.g., 23.4 wt% KOH, 13.3 wt% isopropyl alcohol, 63 wt% H_2O)

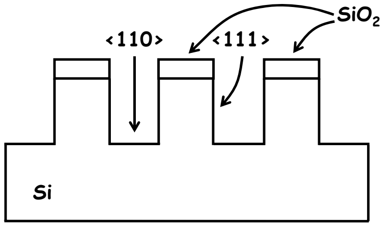
$$\Longrightarrow \text{E.R.}_{<100>} = 100 \times \text{E.R.}_{<111>}$$

Anisotropic Wet Etching (cont.)

Can get the following:



(on a <100> - wafer)



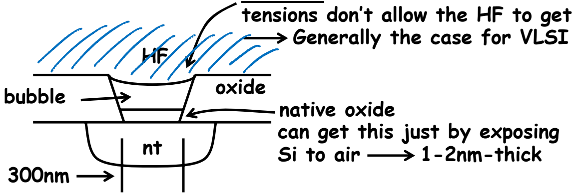
(on a <110> - wafer)

⟹ Quite anisotropic!

Wet Etching SiO_2

$$SiO_2 + 6HF \rightarrow H_2 + SiF_6 + 2H_2O$$

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

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

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_2 as an etch mask (E.R. ~2.5 nm/min)
    - A hassle → dry etch processes more common than wet
- Wet etchining aluminum
  - Typical etch solution composition:

80% phoshporic acid, 5% nitric acid, 5% acetic acid, 10% water

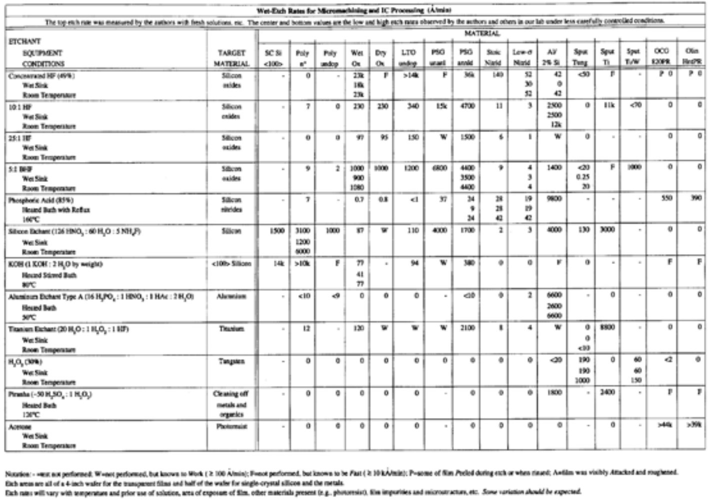
(H_2PO_4) (HNO_3) (CH_3COOH) (H_2O)

(1) Forms Al_2O_3 (aluminum oxide)

(2) Dissolves the Al_2O_3

  - **Problem**: H_2 gas bubbles adhere firmlly 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)



Wet-Etch Rates for Micromachining and IC Processing (Å/min)

The top etch rate was measured by the authors with fresh solutions, etc. The center and bottom values are the low and high etch rates observed by the authors and others in our lab under less carefully controlled conditions.

ETCHANT EQUIPMENT CONDITIONS	TARGET MATERIAL	MATERIAL															
		SC Si <100>	Poly n⁺	Poly undop	Wet Ox	Dry Ox	LTO undop	PSG unanl	PSG annld	Stoic Nitrid	Low-σ Nitrid	Al/2% Si	Sput Tung	Sput Ti	Sput Ti/W	OCG 820PR	Olin HntPR
Concentrated HF (49%) Wet Sink Room Temperature	Silicon oxides	-	0	-	23k 18k 23k	F	>14k	F	36k	140	52 30 52	42 0 42	<50	F	-	P 0	P 0
10:1 HF Wet Sink Room Temperature	Silicon oxides	-	7	0	230	230	340	15k	4700	11	3	2500 2500 12k	0	11k	<70	0	0
25:1 HF Wet Sink Room Temperature	Silicon oxides	-	0	0	97	95	150	W	1500	6	1	W	0	-	-	0	0
5:1 BHF Wet Sink Room Temperature	Silicon oxides	-	9	2	1000 900 1080	1000	1200	6800	4400 3500 4400	9	4 3 4	1400	<20 0.25 20	F	1000	0	0
Phosphoric Acid (85%) Heated Bath with Reflux 160°C	Silicon nitrides	-	7	-	0.7	0.8	<1	37	24 9 24	28 28 42	19 19 42	9800	-	-	-	550	390
Silicon Etchant (126 HNO_3 : 60 H_2O : 5 NH_4F) Wet Sink Room Temperature	Silicon	1500	3100 1200 6000	1000	87	W	110	4000	1700	2	3	4000	130	3000	-	0	0
KOH (1 KOH : 2 H_2O 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_3PO_4 : 1 HNO_3 : 1 HAc : 2 H_2O) Heated Bath 50°C	Aluminum	-	<10	<9	0	0	0	-	<10	0	2	6600 2600 6600	-	0	-	0	0
Titanium Etchant (20 H_2O : 1 H_2O_2 : 1 HF) Wet Sink Room Temperature	Titanium	-	12	-	120	W	W	W	2100	8	4	W	0 0 <10	8800	-	0	0
H_2O_2 (30%) Wet Sink Room Temperature	Tungsten	-	0	0	0	0	0	0	0	0	0	<20	190 190 1000	0	60 60 150	<2	0
Piranha (~50 H_2SO_4 : 1 H_2O_2) Heated Bath 120°C	Cleaning off metals and organics	-	0	0	0	0	0	-	0	0	0	1800	-	2400	-	F	F
Acetone Wet Sink Room Temperature	Photoresist	-	0	0	0	0	0	-	0	0	0	0	-	0	-	>44k	>39k

Notation: - =test not performed; W=not performed, but known to *Work* (≥ 100 Å/min); F=not performed, but known to be *Fast* (≥ 10 kÅ/min); P=some of film *Peeled* during etch or when rinsed; A=film was visibly *Attacked* and roughened.
Etch areas are all of a 4-inch wafer for the transparent 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.*

Film Etch Chemistries

- For some popular films:

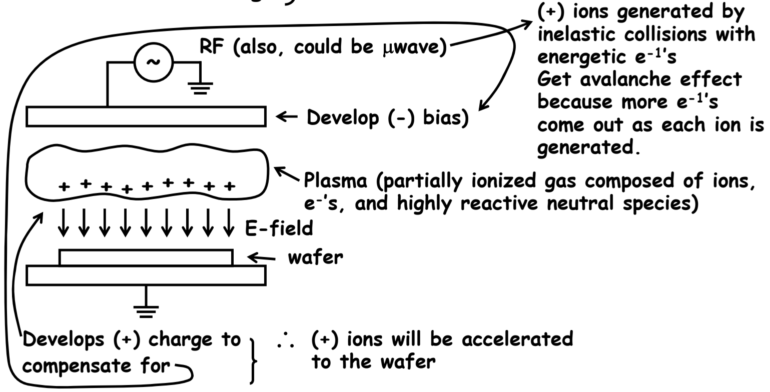
Material	Wet etchant	Etch rate [nm/min]	Dry etchant	Etch rate [nm/min]
Polysilicon	HNO_3:H_2O: NH_4F	120-600	SF_6 + He	170-920
Silicon nitride	H_3PO_4	5	SF_6	150-250
Silicon dioxide	HF	20-2000	CHF_3 + O_2	50-150
Aluminum	H_3PO_4:HNO_3: CH_3COOH	660	Cl_2 + $SiCl_4$	100-150
Photoresist	Acetone	>4000	O_2	35-3500
Gold	KI	40	n/a	n/a

Dry Etching

Dry Etching

- Physical sputtering
- Plasma etching
- Reactive ion etching

All based upon plasma processes.



RF (also, could be μwave)

← Develop (-) bias)

(+) ions generated by inelastic collisions with energetic e^{-1}'s
Get avalanche effect because more e^{-1}'s come out as each ion is generated.

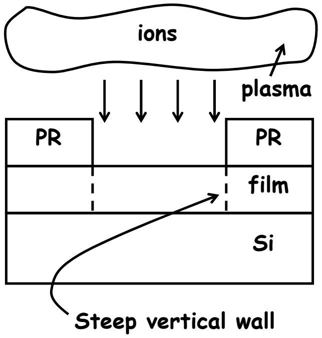
Plasma (partially ionized gas composed of ions, e^-'s, and highly reactive neutral species)

Develops (+) charge to compensate for

∴ (+) ions will be accelerated to the wafer

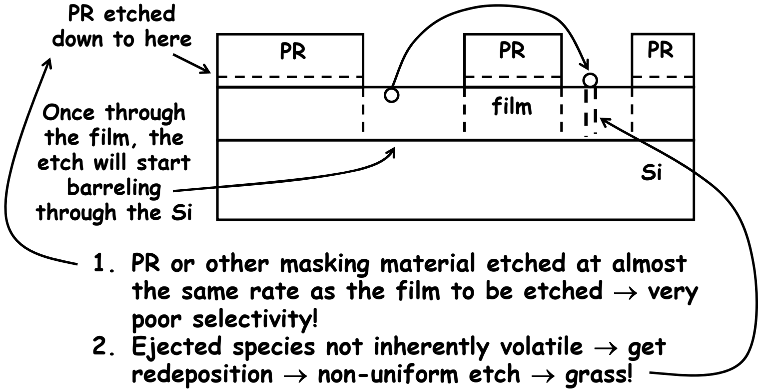
Physical Sputtering (Ion Milling)

- 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

Problems With Ion Milling



PR etched down to here

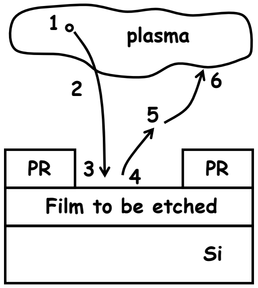
Once through the film, the etch will start barreling through the Si

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. ← MOST IMPORTANT STEP! (determines whether plasma etching is possible or not.)
6. Desorbed species diffuse into the bulk of the gas

Ex: Polysilicon Etching w/ CF_4 and O_2

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

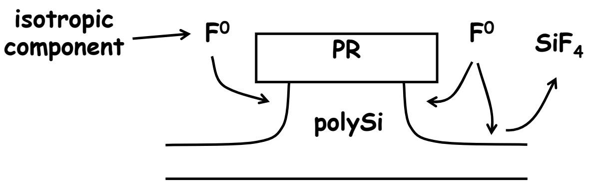
Neutral radical (highly reactive!)

Si

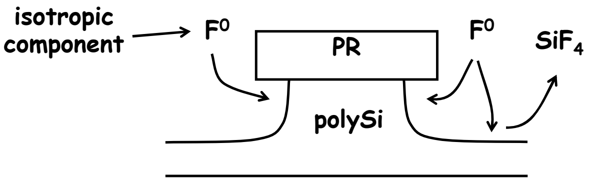
$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

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

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



Ex: Polysilicon Etching w/ CF_4 and O_2

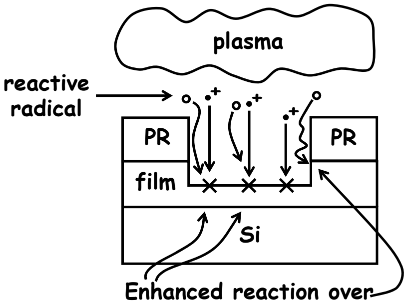


- **Problems**:
  1. Isotropic etching
  2. Formation of polymer because of C in CF_4
     - **Solution**: add O_2 to remove the polymer (but note that this reduces the selectivity, $S_{poly/PR}$)
- **Solution**:
  - Use Reactive Ion Etching (RIE)

Reactive Ion Etching (RIE)

- Use ion bombardment to aid and enhance reactive etching in a particular direction
  - **Result**: directional, anisotropic etching!
- RIE is somewhat of a misnomer
  - It's not ions that react … rather, it's still the neutral species that dominate reaction
  - Ions just enhance reaction of these neutral radicals in a specific direction
- Two principle postulated mechanisms behind RIE
  1. Surface damage mechanism
  2. Surface inhibitor mechanism

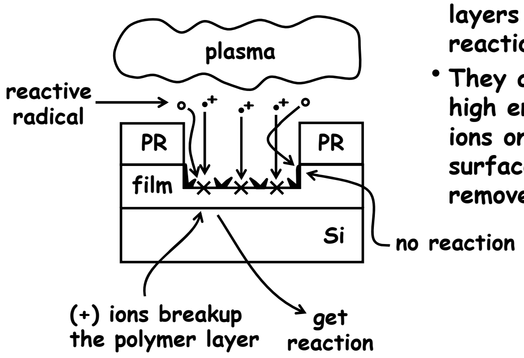
RIE: Surface Damage Mechanism



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

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

RIE: Surface Inhibitor Mechanism



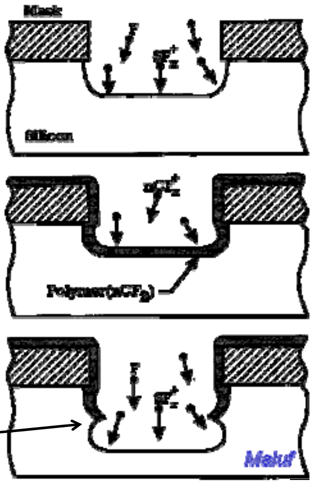
- Non-volatile polymer layers are a product of reaction
- They are removed by high energy directional ions on the horizontal surface, but not removed from sidewalls

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

Deep Reactive-Ion Etching (DRIE)

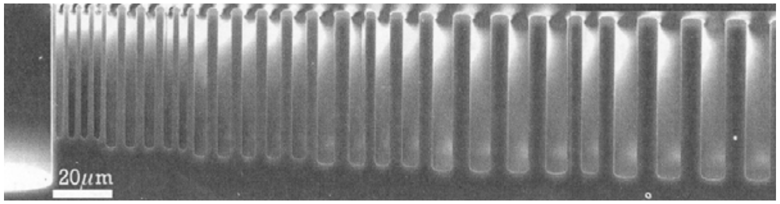
The Bosch process:

- Inductively-coupled plasma
- Etch Rate: 1.5-4 μm/min
- Two main cycles in the etch:
  - Etch cycle (5-15 s): SF_6 (SF_x^+) etches Si
  - Deposition cycle: (5-15 s): C_4F_8 deposits fluorocarbon protective polymer $(CF_2^-)_n$
- Etch mask selectivity:
  - SiO_2 ~ 200:1
  - Photoresist ~ 100:1
- Issue: finite sidewall roughness
  - scalloping < 50 nm
- Sidewall angle: 90° ± 2°

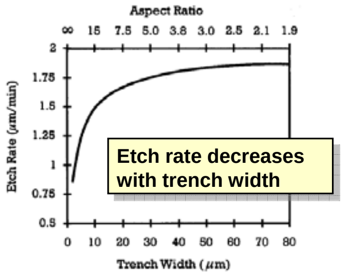


Maluf

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)

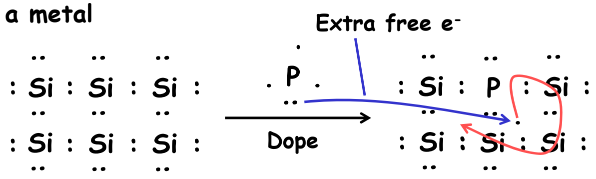


Etch rate decreases with trench width

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



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

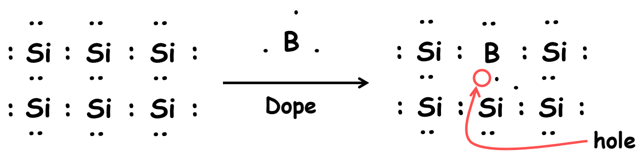
Doping of Semiconductors (cont.)

- **Conductivity Equation**:

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

conductivity; charge magnitude on an electron; electron mobility; electron density; hole mobility; hole density

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



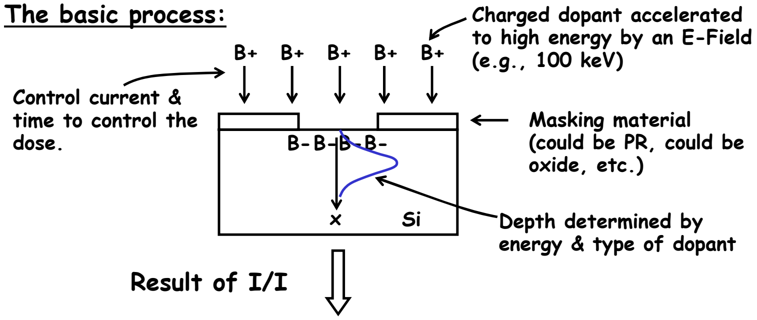
  - ↳ Lack of an e⁻ = hole = h⁺
  - ↳ When e⁻'s move into h⁺'s, the h⁺'s effectively move in the opposite direction → a h⁺ is a mobile (+) charge carrier

Ion Implantation

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)

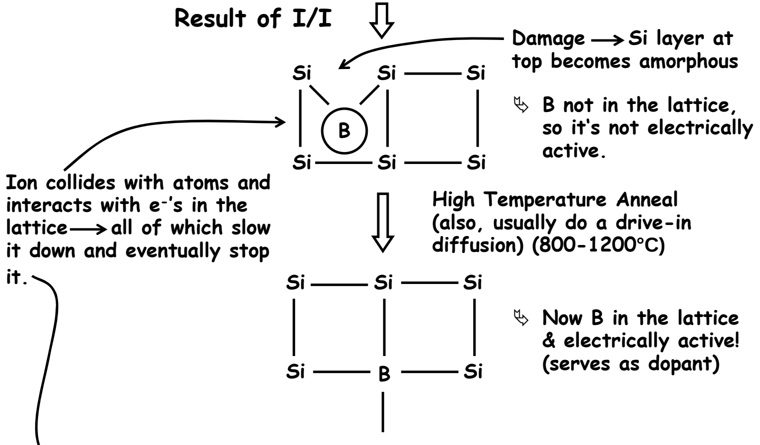
Control current & time to control the dose.

Masking material (could be PR, could be oxide, etc.)

Depth determined by energy & type of dopant

Result of I/I

Ion Implantation (cont.)



Damage → Si layer at top becomes amorphous

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

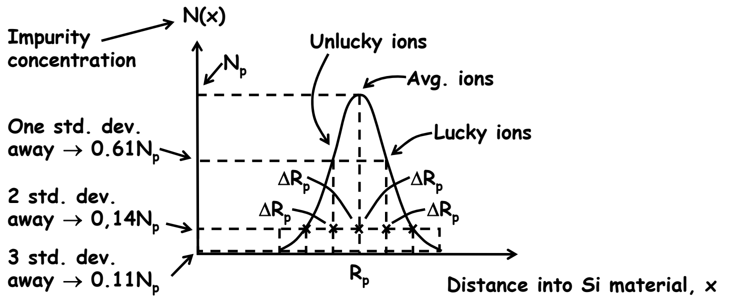
Ion collides with atoms and interacts with e⁻'s in the lattice → all of which slow it down and eventually stop it.

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



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

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

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 = $Q = \int_0^\infty N(x)dx \ [ions/cm^2]$

For an implant completely contained within the Si:

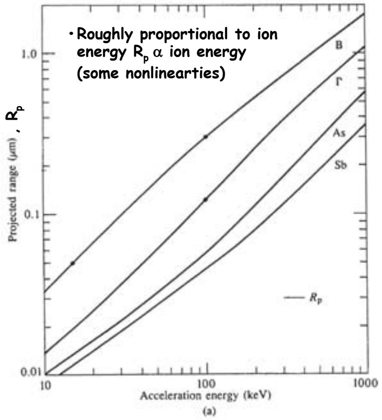
$$Q = \sqrt{2\pi} N_p \Delta R_p$$

Assuming the peak is in the silicon: (putting it in one-sided diffusion form) → So we can track the dopant front during a subsequent diffusion step.

$D_I = Q$

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

I/I Range Graphs



- Roughly proportional to ion energy $R_p \alpha$ ion energy (some nonlinearties)

Figure 6.1

- R_p is a function of the energy of the ion and atomic number of the ion and target material
- Lindhand, 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

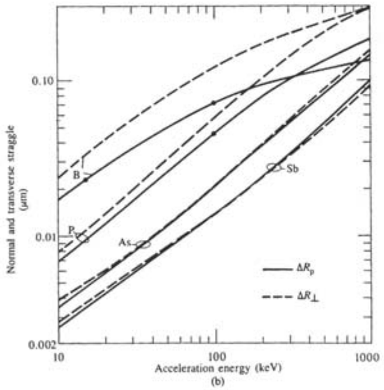


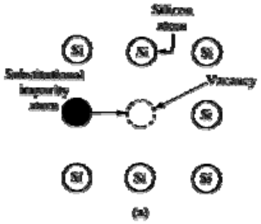
Figure 6.2

- Results for Si and SiO_2 surfaces are virtually identical → so we can use these curves for both

Diffusion

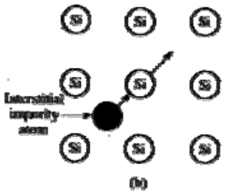
Diffusion in Silicon

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



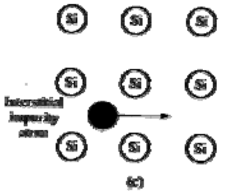
Substitutional Diffusion

- 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

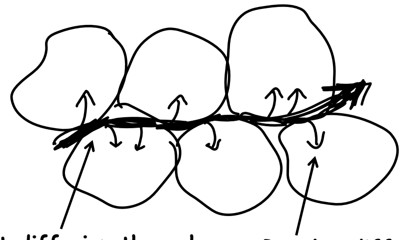


Interstitial Diffusion

- 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



Fast diffusion through grain boundaries

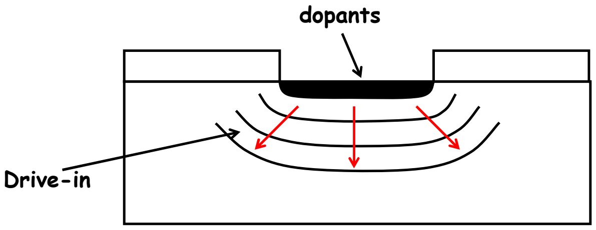
Regular diffusion into crystals

- In effect, larger surface area allows much faster volumetric diffusion

Basic Process for Selective Doping

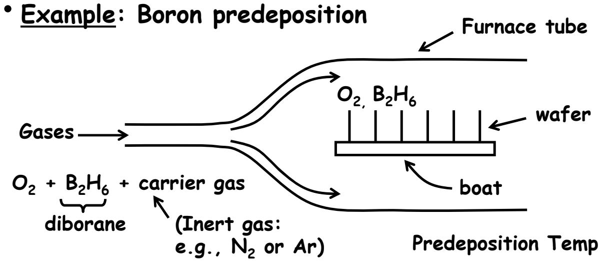
1. Introduce dopants (introduce a fixed dose Q of dopants)
   - (i) Ion implantation
   - (ii) Predeposition
2. Drive in dopants to the desired depth
   - High temperature > 900°C in N_2 or N_2/O_2

- **Result**:



Predeposition

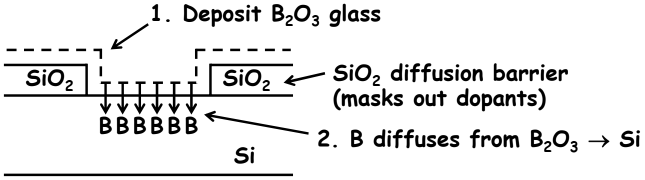
- Furnace-tube system using solid, liquid, or gaseous dopant sources
- Used to introduced a controlled amount of dopants
  - Unfortunately, not very well controlled
  - Dose (Q) range: 10^{13} – 10^{16} ± 20%
  - For ref: w/ ion implantation: 10^{11} – 10^{16} ± 1% (larger range & more accurate)
- **Example**: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



Predeposition Temp: 800-1100°C

Ex: Boron Predeposition

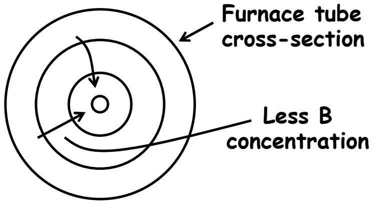
- Basic Procedure:


1. Deposit B_2O_3 glass

SiO_2 diffusion barrier (masks out dopants)

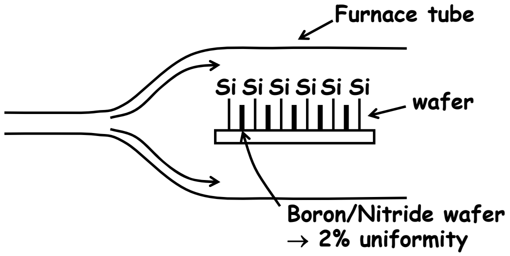
2. B diffuses from B_2O_3 → Si

- 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



Ex: Boron Predeposition (cont.)

For better uniformity, use solid source:



Boron/Nitride wafer → 2% uniformity

Reactions:

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

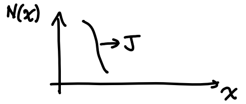
$Si + O_2 \rightarrow SiO_2$

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

Modeling



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

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

Fick's Law of Diffusion – (1^{st} law)

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

flux [#/cm²·s] — D: Diffusion Coefficient

Continuity Equation for Particle Flux –

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

$\frac{\partial N(x,t)}{\partial t}$: rate of increase of conc. w/ time

$-\vec{\nabla}\cdot\vec{J}$: negative of the divergence of particle flux

Diffusion Modeling (cont.)

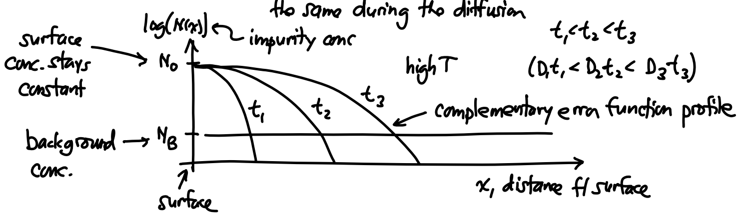
⇒ we're interested for now in the one-dimensional form:

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

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



Diffusion Modeling (Predeposition)

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

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

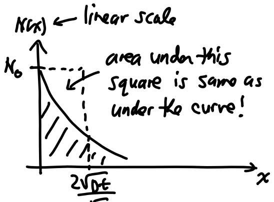
$$N(x,t) = N_0\left[1 - \frac{1}{\pi}\int_0^{\frac{x}{2\sqrt{Dt}}} e^{-y^2}dy\right]$$

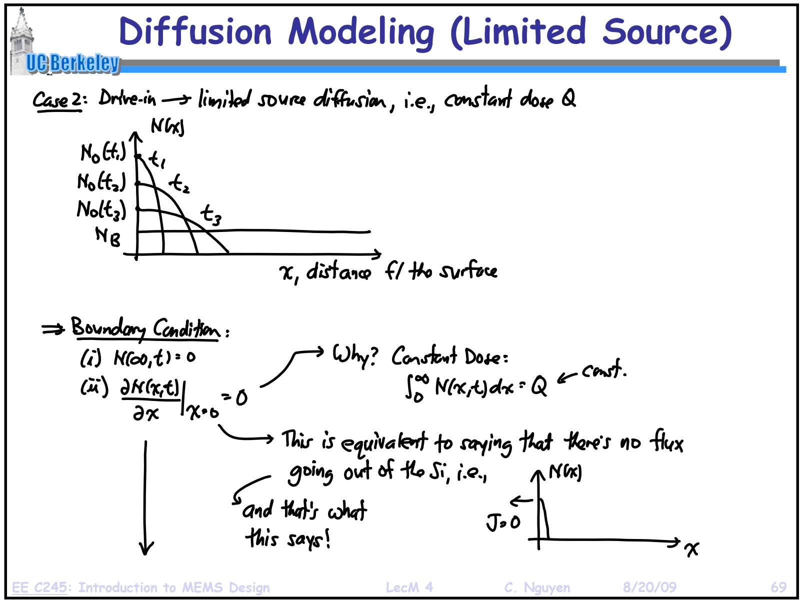
$$\boxed{N(x,t) = N_0\,\mathrm{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)}$$ ⇒ again, complementary error function (read tables or graph)

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

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

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





Diffusion Modeling (Limited Source)

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

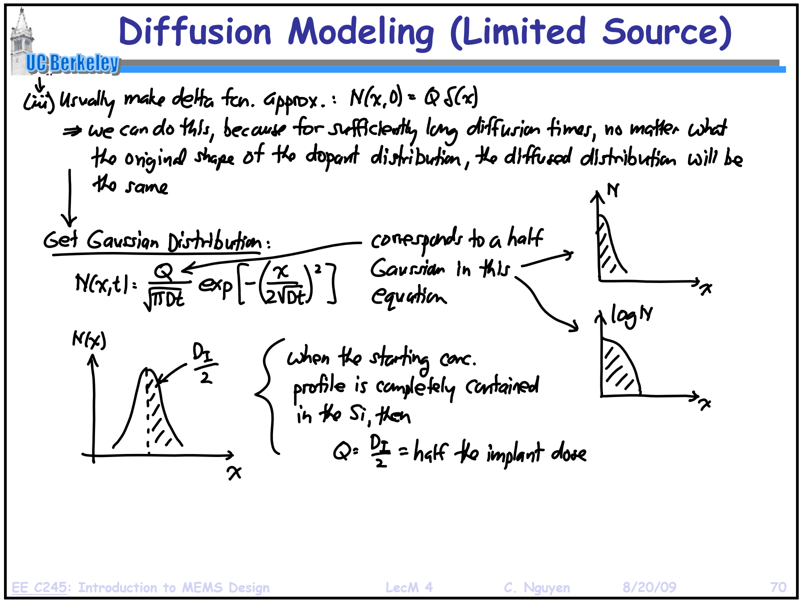
⇒ Boundary Condition:

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

(ii) $\left.\frac{\partial N(x,t)}{\partial x}\right|_{x=0}=0$ → Why? Constant Dose: $\int_0^\infty N(x,t)dx = Q$ ← const.

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

and that's what this says!



Diffusion Modeling (Limited Source)

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

⇒ 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

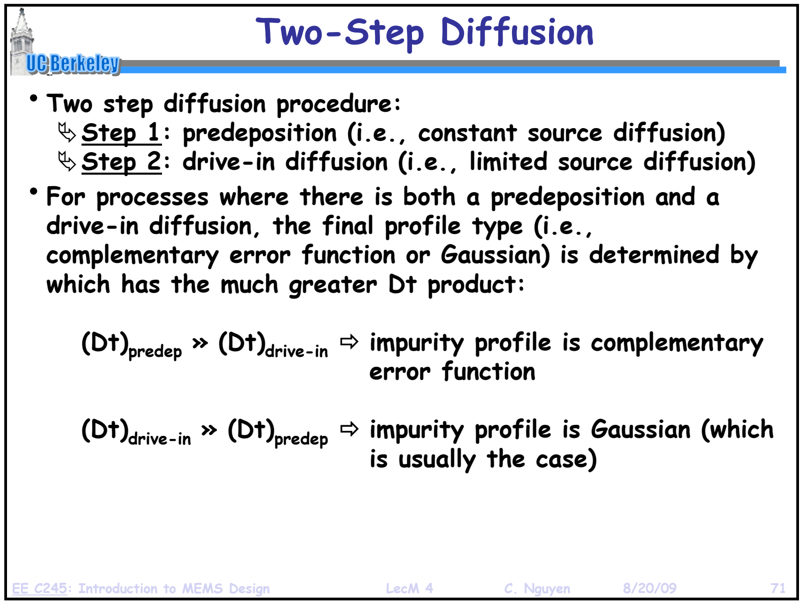
Get Gaussian Distribution:

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

corresponds to a half Gaussian in this equation

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

$Q = \frac{D_I}{2}$ = half the implant dose

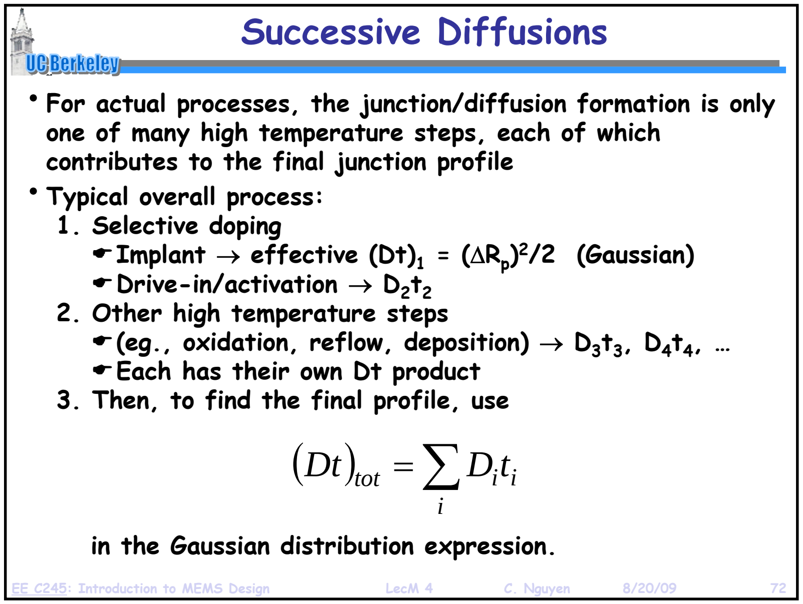


Two-Step Diffusion

- 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:

$(Dt)_{predep} \gg (Dt)_{drive\text{-}in}$ ⇨ impurity profile is complementary error function

$(Dt)_{drive\text{-}in} \gg (Dt)_{predep}$ ⇨ 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 → effective $(Dt)_1 = (\Delta R_p)^2/2$ (Gaussian)
     - Drive-in/activation → D_2t_2
  2. Other high temperature steps
     - (eg., oxidation, reflow, deposition) → D_3t_3, D_4t_4, …
     - Each has their own Dt product
  3. Then, to find the final profile, use

$$(Dt)_{tot} = \sum_i D_i t_i$$

in the Gaussian distribution expression.

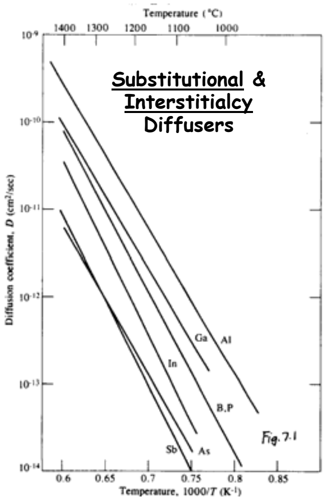
The Diffusion Coefficient

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

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

Element	D_o(cm²/sec)	E_A(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

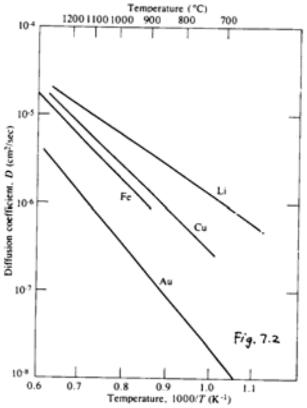
Diffusion Coefficient Graphs



Substitutional & **Interstitialcy** Diffusers

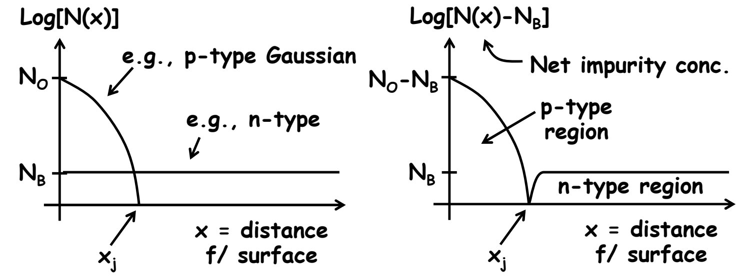
Interstitial Diffusers

↳ 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



Expressions for x_j

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

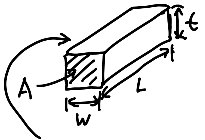
$$N(x_j,t) = N_o \exp\left[-\left(\frac{x_j}{2\sqrt{Dt}}\right)^2\right] = N_B \quad \rightarrow \quad x_j = 2\sqrt{Dt\ln\left(\frac{N_o}{N_B}\right)}$$

- For a complementary error function profile:

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

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**:



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

ohms per square

Ω/□

[A=tW]

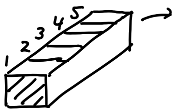
sheet resistance

unit squares of material in the resistor

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

σ = conductivity = $q(\mu_n n + \mu_p p)$

e.g.,

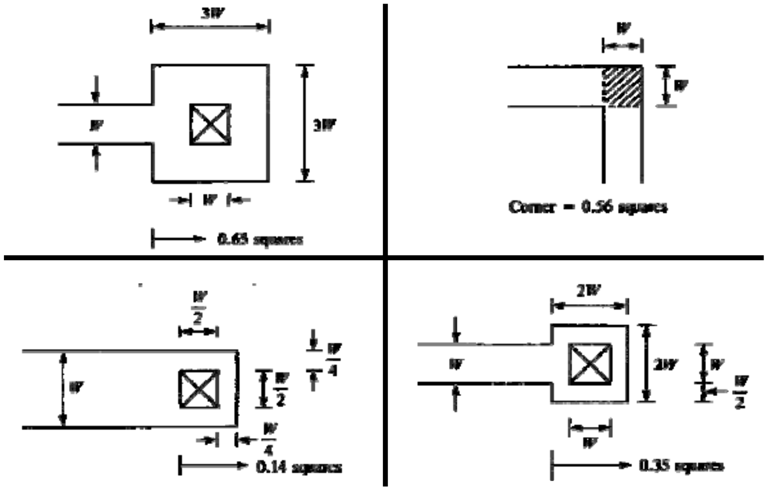


→ 5 □'s of material

$\therefore R = R_s \times 5$

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

Squares From Non-Uniform Traces



Sheet Resistance of a Diffused Junction

- For diffused layers:

Sheet resistance

Effective resistivity

Majority carrier mobility

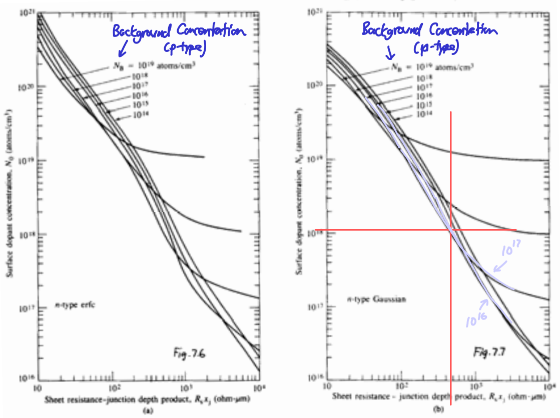
Net impurity concentration

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

[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)



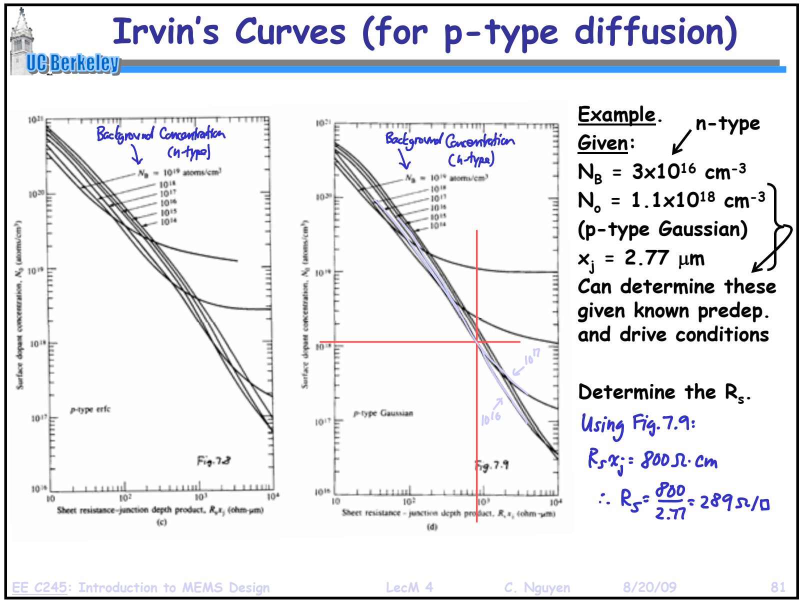
Example.
Given: p-type
N_B = 3x10^{16} cm^{-3}
N_o = 1.1x10^{18} cm^{-3}
(n-type Gaussian)
x_j = 2.77 μm
Can determine these given known predep. and drive conditions

Determine the R_s.

Using Fig. 7.7:

$R_s x_j = 470\ \Omega\cdot\mu m$

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



Irvin's Curves (for p-type diffusion)

Example.

Given:

n-type

N_B = 3x10^{16} cm^{-3}

N_o = 1.1x10^{18} cm^{-3}

(p-type Gaussian)

x_j = 2.77 μm

Can determine these given known predep. and drive conditions

Determine the R_s.

Using Fig. 7.9:

$R_s x_j = 800 \Omega \cdot cm$

$\therefore R_s = \frac{800}{2.77} = 289 \Omega/\square$