Diffusion Modeling

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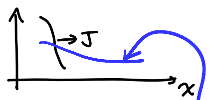
Modeling



⇒ 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 – (1st law)

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

flux [#/cm²·s]   Diffusion Coefficient

Continuity Equation for Particle Flux –

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

rate of increase of conc. w/ time

negative of the divergence of particle flux

Diffusion Modeling (cont.)

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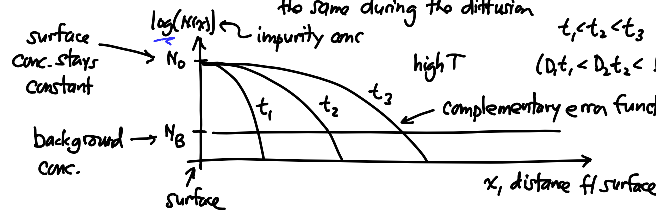
⇒ we're interested for now in the one-dimensional form:

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

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

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

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



Diffusion Modeling (Predeposition)

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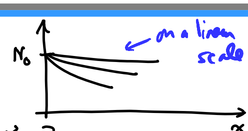
⇒ if plotted on a linear scale, would look like this:



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

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

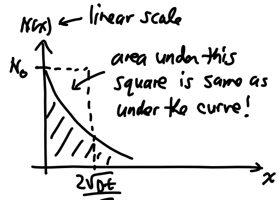
$$\boxed{N(x,t) = N_o\,\mathrm{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)}$$

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

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

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

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



Diffusion Modeling (Limited Source)

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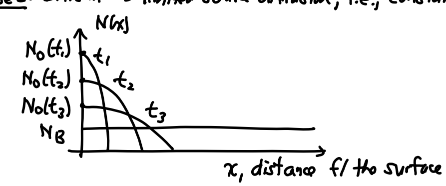
Case 2: Drive-in → limited source diffusion, i.e., constant dose Q



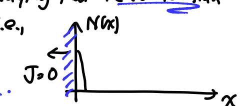
⇒ Boundary Condition:
(i) $N(\infty,t) = 0$
(ii) $\left.\frac{\partial N(x,t)}{\partial x}\right|_{x=0} = 0$

→ 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!

Assumption.



Diffusion Modeling (Limited Source)

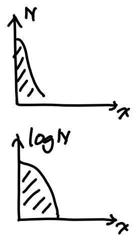
(iii) Usually make delta fcn. approx.: $N(x,0) = Q\,\delta(x)$

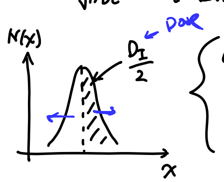
⇒ we can do this, because for sufficiently long diffusion times, no matter what the original shape of the dopant distribution, the diffused distribution will be the same

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:

  $T_{f(T)}$

  $(Dt)_{predep} \gg (Dt)_{drive\text{-}in}$ ⇨ 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 → $D_2 t_2$
  2. Other high temperature steps
     - (eg., oxidation, reflow, deposition) → $D_3 t_3$, $D_4 t_4$, …
     - 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)

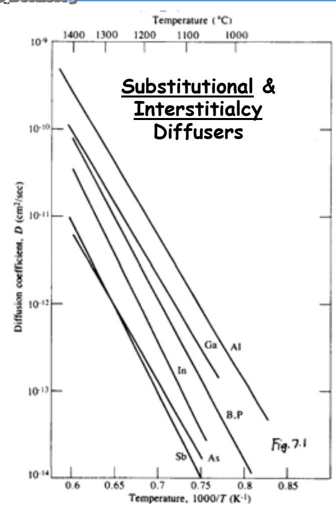
Table 4.1 Typical Diffusion Coefficient Values for a Number of Impurities.

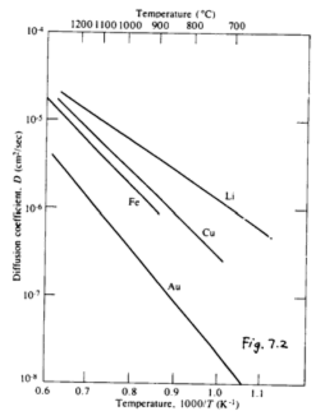
Element	$D_0(cm^2/sec)$	$E_A(eV)$
B	10.5	3.69
Al	8.00	3.47
Ga	3.60	3.51
In	16.5	3.90
P	10.5	3.69
As	0.32	3.56
Sb	5.60	3.95

Diffusion Coefficient Graphs

Interstitial Diffusers

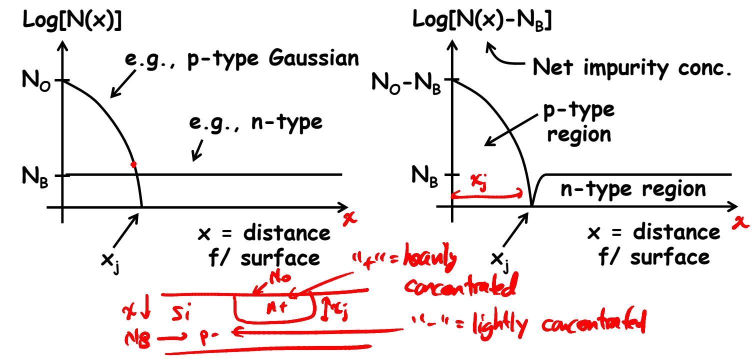
↳ Note the much higher diffusion coeffs. than for substitutional





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)

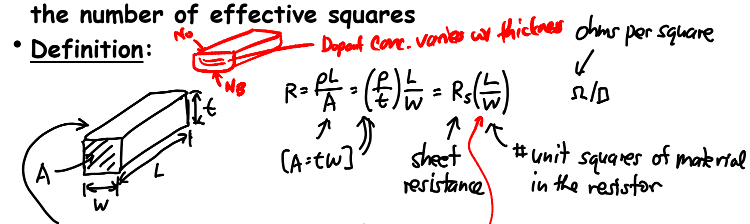
$$N(x_j,t) = N_o \exp\left[-\left(\frac{x_j}{2\sqrt{Dt}}\right)^2\right] = N_B \quad \rightarrow \quad x_j = 2\sqrt{Dt\ln\left(\frac{N_o}{N_B}\right)}$$

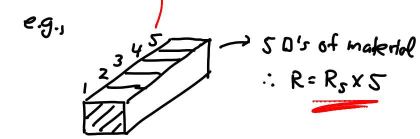
- For a complementary error function profile:

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

Sheet Resistance

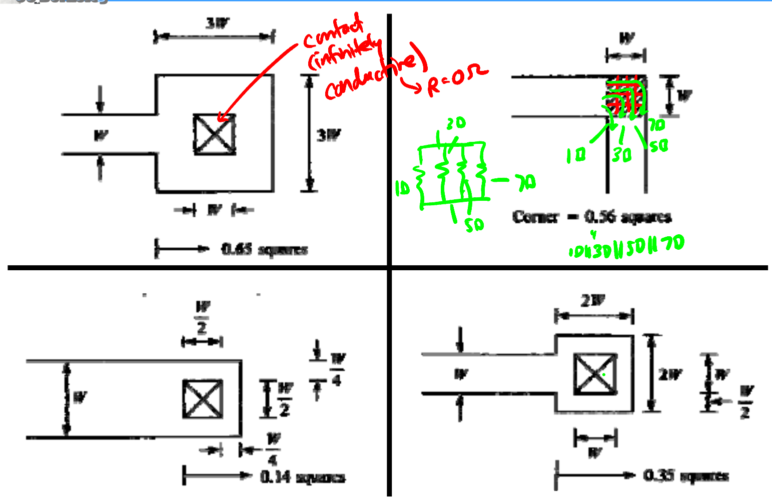
- Sheet resistance provides a simple way to determine the resistance of a given conductive trace by merely counting the number of effective squares
- **Definition:**





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

Squares From Non-Uniform Traces



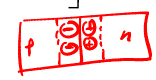
Sheet Resistance of a Diffused Junction

- For diffused layers:

Sheet resistance; Effective resistivity; Majority carrier mobility; Net impurity concentration

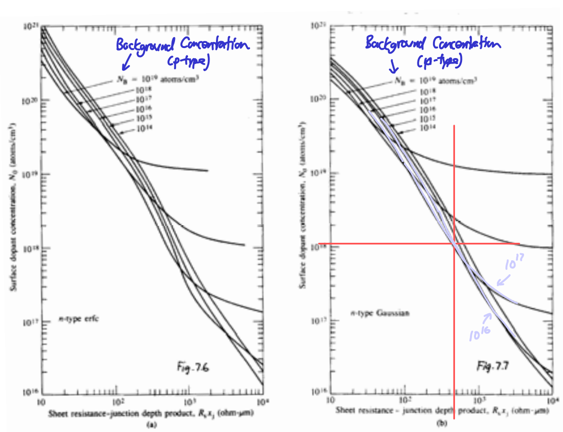
$$R_s = \frac{\bar{\rho}}{x_j} = \left[\int_o^{x_j} \sigma(x)dx\right]^{-1} = \left[\int_o^{x_j} q\mu N(x)dx\right]^{-1}$$

[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)

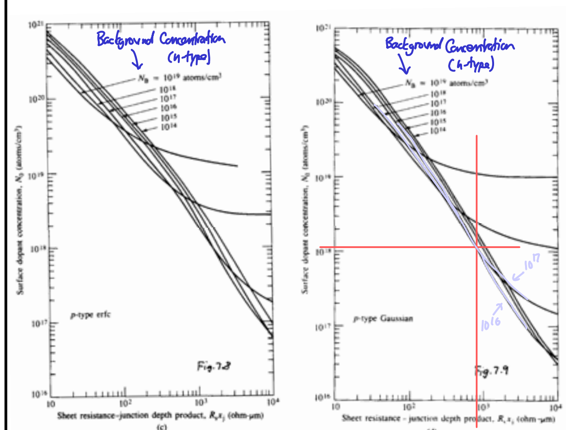


Example. Given: p-type
N_B = 3x10^{16} cm^{-3}
N_o = 1.1x10^{18} cm^{-3}
(n-type Gaussian)
x_j = 2.77 μm
Can determine these given known predep. and drive conditions

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
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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:
$R_s x_j = 800\,\Omega\cdot cm$
$\therefore R_s = \frac{800}{2.77} = 289\,\Omega/\square$

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EE C245 – ME C218
Introduction to MEMS Design
Fall 2008

Prof. Clark T.-C. Nguyen

Dept. of Electrical Engineering & Computer Sciences
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Lecture Module 5: Surface Micromachining

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Lecture Outline

- Reading: Senturia Chpt. 3, Jaeger Chpt. 11, Handout: "Surface Micromachining for Microelectromechanical Systems"
- Lecture Topics:
  - Polysilicon surface micromachining
  - Stiction
  - Residual stress
  - Topography issues
  - Nickel metal surface micromachining
  - 3D "pop-up" MEMS
  - Foundry MEMS: the "MUMPS" process
  - The Sandia SUMMIT process

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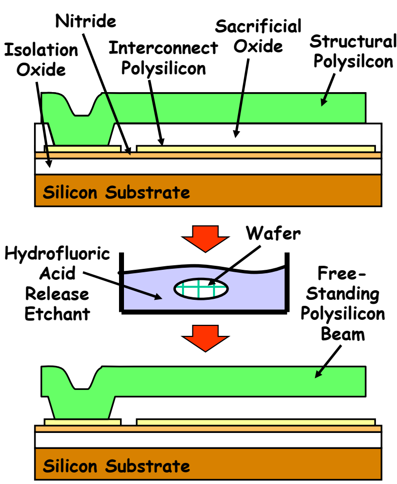
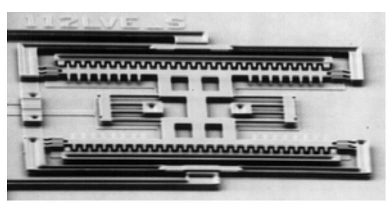
Polysilicon Surface-Micromachining



- Uses IC fabrication instrumentation exclusively
- *Variations*: sacrificial layer thickness, fine- vs. large-grained polysilicon, *in situ* vs. $POCL_3$-doping



300 kHz Folded-Beam Micromechanical Resonator

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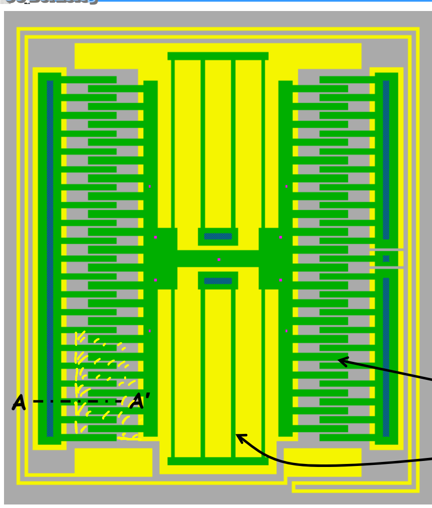
Polysilicon

Why Polysilicon?

- Compatible with IC fabrication processes
  - Process parameters for gate polysilicon well known
  - Only slight alterations needed to control stress for MEMS applications
- Stronger than stainless steel: fracture strength of polySi ~ 2-3 GPa, steel ~ 0.2GPa-1GPa
- Young's Modulus ~ 140-190 GPa
- Extremely flexible: maximum strain before fracture ~ 0.5%
- Does not fatigue readily
- Several variations of polysilicon used for MEMS
  - LPCVD polysilicon deposited undoped, then doped via ion implantation, PSG source, $POCl_3$, or B-source doping
  - In situ-doped LPCVD polysilicon
  - Attempts made to use PECVD silicon, but quality not very good (yet) → etches too fast in HF, so release is difficult

Polysilicon Surface-Micromachining Process Flow

Layout and Masking Layers



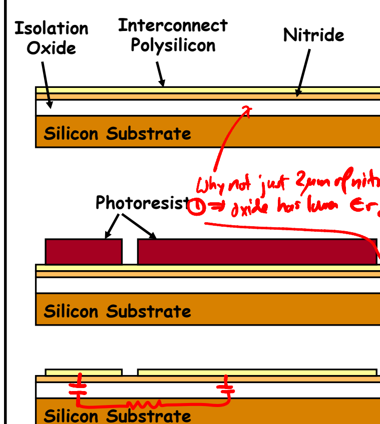
- At Left: Layout for a folded-beam capacitive comb-driven micromechanical resonator
- Masking Layers: clear field
  - 1st Polysilicon: POLY1(cf)
  - Anchor Opening: ANCHOR(df) dark field
  - 2nd Polysilicon: POLY2(cf)

Capacitive comb-drive for linear actuation

Folded-beam support structure for stress relief

Surface-Micromachining Process Flow

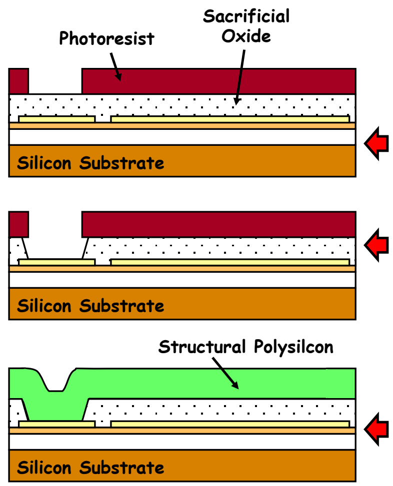
Cross-sections through A-A'



Why not just 2μm of nitride?
① ⇒ oxide has lower ϵ_r ← permittivity
② Can't put down Si_3N_4 thicker than 200nm w/o peeling

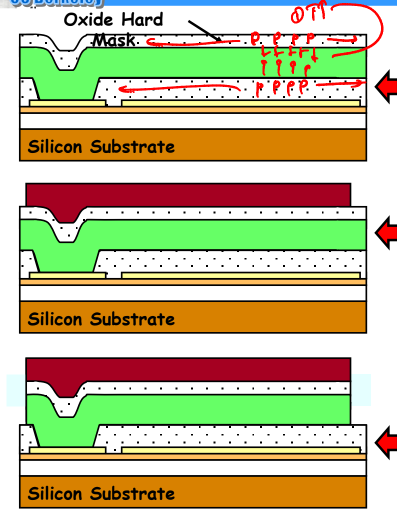
- Deposit isolation LTO (or PSG):
  - Target = 2μm
  - 1 hr. 40 min. LPCVD @450°C
- Densify the LTO (or PSG)
  - Anneal @950°C for 30 min.
- Deposit nitride:
  - Target = 100nm
  - 22 min. LPCVD @800°C
- Deposit interconnect polySi:
  - Target = 300nm
  - In-situ Phosphorous-doped
  - 1 hr. 30 min. LPCVD @650°C
- Lithography to define poly1 interconnects using the POLY1(cf) mask
- RIE polysilicon interconnects:
  - $CCl_4/He/O_2$ @300W,280mTorr
- Remove photoresist in PRS2000

Surface-Micromachining Process Flow



- Deposit sacrificial PSG:
  - Target = 2μm
  - 1 hr. 40 min. LPCVD @450°C
- Densify the PSG
  - Anneal @950°C for 30 min.
- Lithography to define anchors using the ANCHOR(df) mask
  - Align to the poly1 layer
- Etch anchors
  - RIE using CHF_3/CF_4/He @350W,2.8Torr
  - Remove PR in PRS2000
  - Quick wet dip in 10:1 HF to remove native oxide
- Deposit structural polySi
  - Target = 2μm
  - In-situ Phosphorous-doped
  - 11 hrs. LPCVD @650°C

Surface-Micromachining Process Flow



- Deposit oxide hard mask
  - Target = 500nm
  - 25 min. LPCVD @450°C PSG
- Stress Anneal
  - 1 hr. @ 1050°C
  - Or RTA for 1 min. @ 1100°C in 50 sccm N_2
- Lithography to define poly2 structure (e.g., shuttle, springs, drive & sense electrodes) using the POLY2(cf) mask
  - Align to the anchor layer
  - Hard bake the PR longer to make it stronger
- Etch oxide mask first
  - RIE using CHF_3/CF_4/He @350W,2.8Torr
- Etch structural polysilicon
  - RIE using $CCl_4/He/O_2$ @300W,280mTorr
  - Use 1 min. etch/1 min. rest increments to prevent excessive temperature