CHE323/CHE384
Chemical Processes for Micro- and Nanofabrication

Formulas
Lectures 1-19

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 1

Doping, Conductivity, Resistance

- Doping charge balance: $N_D^+ + p = N_A^- + n$
- Mass action equation: $np = n_i^2$

$N_A = acceptor\ concentration$ | $N_D^+ = ionized\ donor\ concentration$
$N_D = donor\ concentration$ | $n = mobile\ electron\ concentration$
$N_A^- = ionized\ acceptor\ conc.$ | $p = mobile\ hole\ concentration$

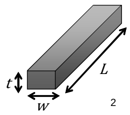
- Resistivity and conductivity:

$$\frac{1}{\rho} = \sigma = q\left(n\mu_n + p\mu_p\right)$$

$Resistance\ R = \rho\frac{L}{A},\ A = wt$

$Sheet\ Resistance\ R_s = \rho/t$

q = charge on electron = 1.6 X 10^{-19} C
μ_n = electron mobility = 1500 cm^2/Vs for Si at 300K
μ_p = hole mobility = 450 cm^2/Vs for Si at 300K
n_i = 1.5 X 10^{10} cm^{-3} for Si at 300K



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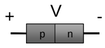
P-N Junction

- Built-in voltage (V_0) and the depletion width (W)

$$V_0 = \frac{kT}{q} ln\left(\frac{N_A N_D}{n_i^2}\right) \qquad W = \sqrt{\frac{2\varepsilon_{Si}\left(V_0 - V\right)}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}$$



$$\varepsilon_{Si} = 11.7\varepsilon_0, \quad \varepsilon_0 = 8.8542\times10^{-12}\ C/V\,m \qquad \text{At } T = 300\text{ K}, \ \frac{kT}{q} = 25\,mV$$

- Diode Equation: current $I_{diode} = I_0\left(e^{qV/kT} - 1\right)$
- Capacitance: $C_{p-n\,junction} = \frac{\varepsilon A}{W} = A\sqrt{\frac{q\varepsilon_{Si}}{2\left(V_0 - V\right)}\left(\frac{N_D N_A}{N_D + N_A}\right)}$

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Deal-Grove Oxidation Model

$$t_{ox}^2 + At_{ox} = B(t + \tau) \qquad \tau = \frac{t_o^2 + At_o}{B}$$

TABLE 4.1 / OXIDATION COEFFICIENTS FOR SILICON (111) Wafers

	Dry			Wet (640 torr)	
Temperature (°C)	A (μm)	B (μm²/hr)	τ (hr)	A (μm)	B (μm²/hr)
800	0.370	0.0011	9	—	—
920	0.235	0.0049	1.4	0.50	0.203
1000	0.165	0.0117	0.37	0.226	0.287
1100	0.090	0.027	0.076	0.11	0.510
1200	0.040	0.045	0.027	0.05	0.720

The τ parameter is used to compensate for the rapid growth regime for thin oxides *(after Deal and Grove).*

For (100) wafers, multiply A by 1.68.

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Deal-Grove Temperature Dependence

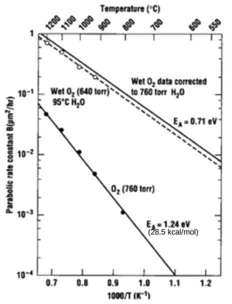

Figure 4.2 Arrhenius plot of the B oxidation coefficient. The wet parameters depend on the H_2O concentration and therefore on the gas flows and pyrolysis conditions *(after Deal and Grove).* (111) Wafers

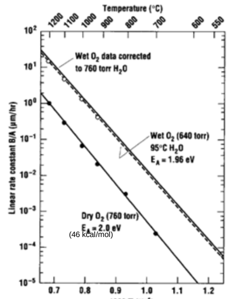

Figure 4.3 Arrhenius plot of the ratio (B/A) of the oxidation parameters *(after Deal and Grove).* (111) wafers

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Diffusion Review

- Fick's 2nd law of Diffusion (in 1-D):

$$\frac{\partial C(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial C(x,t)}{\partial x}\right)$$

- In 3-D: $\frac{\partial C}{\partial t} = \nabla(D\nabla C), \qquad \nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$
- Analytical solutions are for D = constant and certain special boundary conditions
- Electric field enhancement: $\eta \approx \frac{C(z)}{\sqrt{C^2(z) + 4n_i^2}}$

$$D_{enhanced} = D(1 + \eta)$$

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Diffusion Case 1: Constant Source

- Initial and boundary conditions
  - $C(0,t) = C_s$ (concentration at top is constant)
  - $C(z,0) = 0$ for $z > 0$ (initial condition)
  - $C(\infty,t) = 0$
- Solution: $C(z,t) = C_s erfc\left(\frac{z}{2\sqrt{Dt}}\right), \quad t > 0$

$\sqrt{Dt}$ = diffusion length (average distance a dopant moves)

$$Q_T(t) = \int_0^\infty C(z,t)dz = \frac{2}{\sqrt{\pi}} C_s \sqrt{Dt}$$

Diffusion Case 2: Limited Source

(drive-in diffusion)

- Initial and boundary conditions
  - $C(z,0) = 0, z > 0$
  - $dC(0,t)/dt = 0$ (no flux at top)
  - $C(\infty,t) = 0$
  - Constant dose: $\int_0^\infty C(z,t)dz = Q_T = constant$
- Solution:

$$C(z,t) = \frac{Q_T}{\sqrt{\pi Dt}} e^{-z^2/4Dt}, \quad t > 0$$

Case 3: Buried Gaussian Source

- Initial and boundary conditions
  - Gaussian: $C(z,0) = \frac{Q_T}{\sqrt{2\pi\sigma_o^2}} e^{-(z-\mu)^2/2\sigma_o^2}, \quad z \geq 0, \mu \gg \sigma_o$
  - $dC(0,t)/dt = 0$ (no flux at top)
  - $C(\infty,t) = 0$
- Solution: $\sigma^2 = \sigma_o^2 + 2Dt$ ($\sqrt{2Dt}$ = diffusion length)

$$C(z,t) = \frac{Q_T}{\sqrt{2\pi\sigma^2}} e^{-(z-\mu)^2/2\sigma^2}, \quad z \geq 0, t \geq 0$$

Gaussian Ion Implantation Model

- Gaussian model for the distribution of dopants
  - Mean = R_p = projected range
  - Standard deviation = ΔR_p = straggle
  - Dose = ϕ (# dopants/cm^2)

$$N(x) = \frac{\phi}{\sqrt{2\pi}\Delta R_p} e^{-\left(x-R_p\right)^2/2\Delta R_p^2}$$

- Lateral scattering
  - For As, Sb: $\Delta R_\perp \approx \Delta R_p$
  - For P: $\Delta R_\perp \approx 1.2\Delta R_p$
  - For B: $\Delta R_\perp \approx 2\Delta R_p$

Ion Implantation Model Parameters

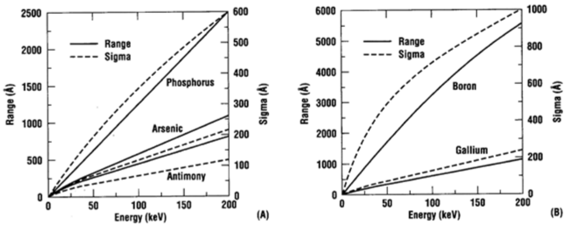

Figure 5.9 Projected range (solid lines and left axis) and standard deviation (dashed lines and right axis) for (A) n-type, (B) p-type, and (C) other species into a silicon substrate; (D) n-type and (E) p-type dopants into a GaAs substrate; and several implants into (F) SiO_2 and (G) AZ111 photoresist *(data from Gibbons* et al.).

$$\Delta R_p \approx \frac{2}{3} R_p \left(\frac{\sqrt{M_i M_t}}{M_i + M_t}\right) \qquad i = ion,\ t = target \quad M = atomic\ mass$$

Thermal Transfer Mechanisms

- Radiative: Stefan-Boltzmann equation

$$Heat\ Flow = \dot{q} = \varepsilon\sigma T^4$$

ε = emissivity of emitting body (ε = 1 for black body)
σ = Stefan-Boltzmann Constant = 5.6697 x 10^{-8} W/m^2-K^4

- Conduction: $\dot{q} = k\nabla T$
- Convection: $\dot{q} = h(T - T_\infty)$

$$\varepsilon(\lambda) = 1 - R(\lambda) - T(\lambda)$$

$$\varepsilon_{Si} \approx 0.7, \qquad T_{Si} \approx 0$$