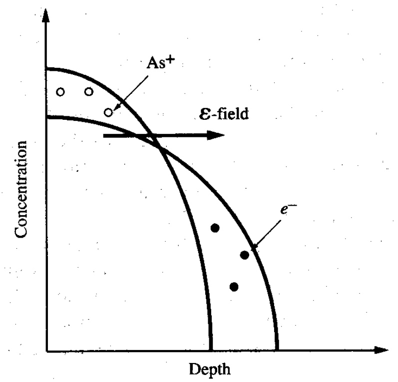
Effect of Electric field on diffusion



$$F = -hD\frac{\partial C}{\partial x}$$

$$h = 1 + \frac{C}{\sqrt{C^2 + 4n_i^2}}$$

J. D. Plummer, M. D. Deal, P. G. Griffin, Silicon VLSI Technology, Pearson Education, 2001

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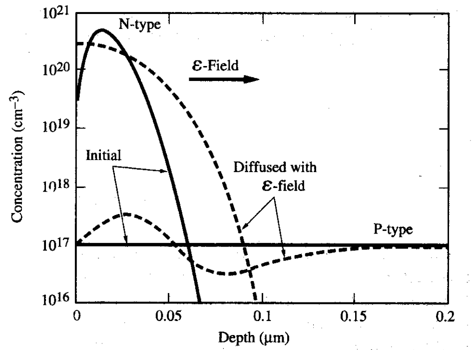
Effect of Electric field on diffusion (2)



J. D. Plummer, M. D. Deal, P. G. Griffin, Silicon VLSI Technology, Pearson Education, 2001

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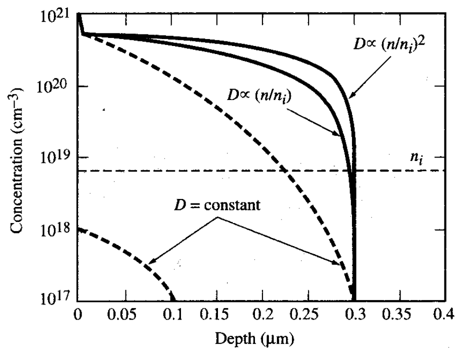
Concentration dependent diffusivity



J. D. Plummer, M. D. Deal, P. G. Griffin, Silicon VLSI Technology, Pearson Education, 2001

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Concentration dependent diffusivity (2)

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

$$D^{eff} = D^o + D^- \frac{n}{n_i} + D^{--}\left(\frac{n}{n_i}\right)^2$$; for n-type dopants

$$D^{eff} = D^o + D^+ \frac{p}{n_i} + D^{++}\left(\frac{p}{n_i}\right)^2$$; for p-type dopants

$$D^{eff} = D^o + D^- + D^{--}$$; for intrinsic case

Each diffusivity: $D = D_0 \exp\left(-\frac{E_D}{kT}\right)$

For values of concentration dependent diffusivities, see supplementary

J. D. Plummer, M. D. Deal, P. G. Griffin, Silicon VLSI Technology, Pearson Education, 2001

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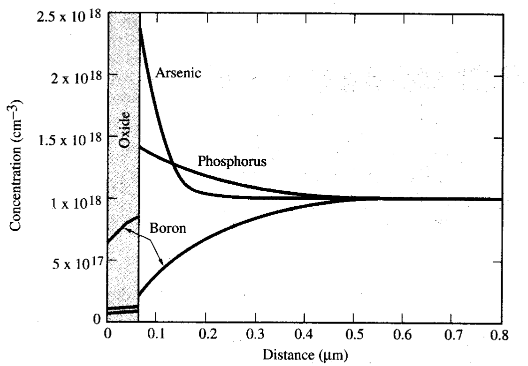
Segregation

- Due to the difference in solid solubility in the different materials on either sides of an interface, dopants can segregate
- Interface between thermal oxide and silicon is a frequently encountered example

$$K = \frac{C_{Si}}{C_{SiO_2}} \approx \begin{cases} 0.3 \text{ for B} \\ 10 \text{ for As} \\ 10 \text{ for Sb} \\ 10 \text{ for P} \end{cases}$$

J. D. Plummer, M. D. Deal, P. G. Griffin, Silicon VLSI Technology, Pearson Education, 2001

Segregation (2)

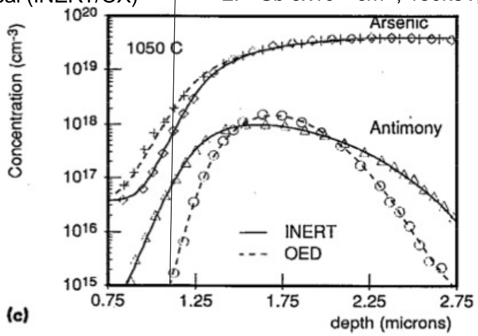


J. D. Plummer, M. D. Deal, P. G. Griffin, Silicon VLSI Technology, Pearson Education, 2001

Microscopic model of diffusion: Observations

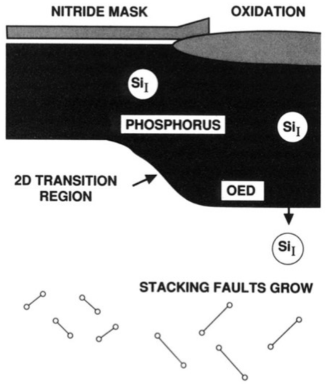
1μm Epitaxial silicon at low temp. + anneal (INERT/OX)

1. 10^{16} cm^{-2} As implanted at 50keV, annealed 1150C, 12 hrs
2. Sb 5x10^{13} cm^{-2}, 180keV, RTP



E. A. Perozziello, P. G. Griffin and J. D. Plummer, Applied Physics Letters, vol. 61, p. 303, 1992

Microscopic model of diffusion: Observations (3)



For more evidences on the role of vacancies and interstitials, see supplementary

Fahey, Griffin and Plummer, Reviews of Modern Physics, vol. 61, pp. 289, 1989

Microscopic model of diffusion: Observations (5)

TABLE II. Summary of interface processes on diffusion.

Stacking faults	Oxidation $I\uparrow V\downarrow$ Grow	Oxynitridation $I\uparrow V\downarrow$ Grow	Nitridation $I\downarrow V\uparrow$ Shrink
P,B diffusion			
intrinsic	Enhanced	Enhanced	Retarded
extrinsic	Enhanced	Enhanced	Retarded
Sb diffusion			
intrinsic	Enhancement precedes retardation	Enhancement precedes retardation	Enhanced
As diffusion			
intrinsic	Enhanced	Enhanced	Enhanced
extrinsic	Retarded or no effect	Enhanced	Enhanced
Ga diffusion			
intrinsic	Enhanced	Enhanced	Retarded

Fahey, Griffin and Plummer, Reviews of Modern Physics, vol. 61, pp. 289, 1989

Interstitial and vacancy assisted diffusion

- In general, a diffusion process can be thought to have a vacancy assisted component and an interstitial assisted component
- Suppose a fraction, f_v of the mobile dopants diffuse by vacancy mechanism and f_I by the interstitial mechanism

$$f_v + f_I = 1$$

- The effective diffusivity can be expressed as:

$$D_{A\_eff} = D_{A0}\left(f_I \frac{C_I}{C_{I0}} + f_V \frac{C_V}{C_{V0}}\right)$$

$D_{A\text{-}eff}$ is the effective diffusivity, C_{I0} and C_{V0} are the interstitial and vacancy concentration respectively at equilibrium and, C_I and C_V are the interstitial and vacancy concentration respectively under the processing condition.

J. D. Plummer, M. D. Deal, P. G. Griffin, Silicon VLSI Technology, Pearson Education, 2001

Interstitial and vacancy assisted diffusion (2)

	f_I	f_V
Silicon	0.6	0.4
Boron	1.0	0
Phosphorous	1.0	0
Arsenic	0.4	0.6
Antimony	0.02	0.98

J. D. Plummer, M. D. Deal, P. G. Griffin, Silicon VLSI Technology, Pearson Education, 2001

Dopant - defect interactions

$$A + I \leftrightarrow AI$$

$$I + V \leftrightarrow Si_S$$

$$Si_S + A_I \leftrightarrow A_S + I$$

$$C_{AI} = kC_A C_I$$

$$F_{AI} = -d_{AI}\frac{\partial C_{AI}}{\partial x} = -d_{AI}\left(kC_I\frac{\partial C_A}{\partial x} + kC_A\frac{\partial C_I}{\partial x}\right)$$

$$kC_I = \frac{C_{AI}}{C_A}; kC_A = \frac{C_{AI}}{C_I}$$

$$F_{AI} = -d_{AI}\left(\frac{C_{AI}}{C_A}\frac{\partial C_A}{\partial x} + \frac{C_{AI}}{C_I}\frac{\partial C_I}{\partial x}\right) = -d_{AI}C_{AI}\frac{\partial}{\partial x}\ln(C_A C_I)$$

J. D. Plummer, M. D. Deal, P. G. Griffin, Silicon VLSI Technology, Pearson Education, 2001

Field enhancement

$$F_{AI} = -d_{AI} C_{AI} \frac{\partial}{\partial x} \ln\left(C_A C_I \frac{n}{n_i}\right)$$

$$\frac{\partial C_A}{\partial t} = -\frac{\partial}{\partial x}(F_A + F_{AI}) \approx -\frac{\partial F_{AI}}{\partial x}$$

J. D. Plummer, M. D. Deal, P. G. Griffin, Silicon VLSI Technology, Pearson Education, 2001

More details in Fahey, Griffin and Plummer, Reviews of Modern Physics, vol. 61, pp. 289, 1989.

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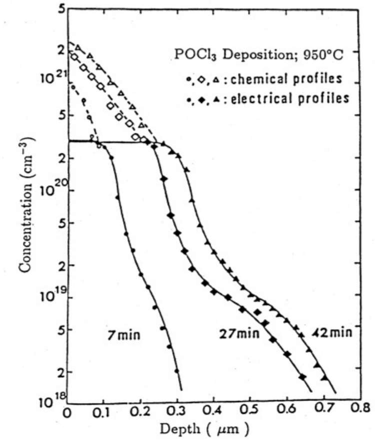
Phosphorous diffusion



Fahey, Griffin and Plummer, Reviews of Modern Physics, vol. 61, pp. 289, 1989

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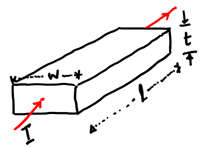
Sheet resistance: Definition & Calculation

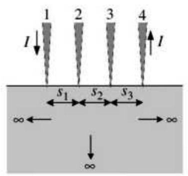


$$R = \frac{\rho l}{wt} = \left(\frac{\rho}{t}\right)\left(\frac{l}{w}\right) = R_{sheet}\left(\frac{l}{w}\right)$$

$$R_{sheet} = \frac{\rho}{t} = \frac{1}{\sigma t} = \frac{1}{q\int_0^t (n\mu_n + p\mu_p)dt}$$

Units of R_{sheet} is **ohms/square**

Measurement of sheet resistance



When $S_1 = S_2 = S_3 > t$

$$R_{sheet} = 4.532\frac{V}{I}$$

D. K. Schroeder, Semiconductor Material and Device Characterization (Wiley-IEEE)

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Summary of the chapter

- Solution of diffusion equations for one simple case, applicable in intrinsic diffusion
- Concept of thermal budget
- Deviations from simple theory
  - Field enhancement
  - Concentration dependent diffusion
  - Microscopic model of diffusion:
    - Role of interstitials and vacancies
  - Generalized model of diffusion in silicon
- Explaining anomalous diffusion of phosphorous

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