EE669: VLSI Technology

Dopant Diffusion in Silicon

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Diffusion examples

- Deposition of a glass containing high concentration of the dopant on the Si surface and subsequent high temperature “drive-in”
  - Phosphosilicate glass deposition on Si wafers from solid sources, by reaction with $POCl_3$ + O_2, or by reaction with H_3PO_4 + O_2
  - The glass has to be etched away subsequent to the drive-in process
- Implantation (deposition) of dopants into the semiconductor and subsequent high temperature annealing to remove implant damage, dopant activation, and some times intentional diffusion
- Deposition of doped silicon and diffusion during the deposition (epitaxial silicon) or during a subsequent anneal step (poly-Si emitter process for Bipolar Junction Transistor fabrication)
- Diffusion of dopants already present in silicon during any high temperature process (e.g.: oxide growth, epitaxial growth of low doped Si on heavily doped Si)

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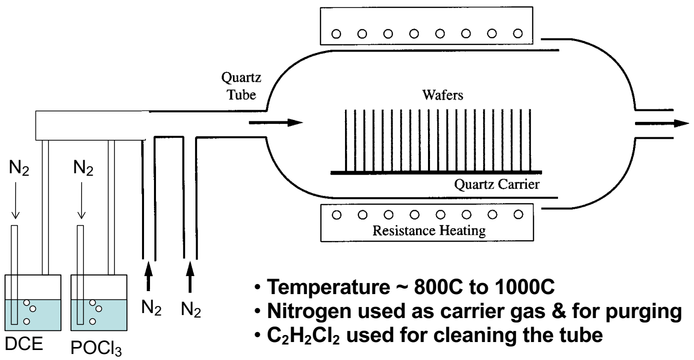
Furnace diffusion of phosphorous using $POCl_3$



- Temperature ~ 800C to 1000C
- Nitrogen used as carrier gas & for purging
- $C_2H_2Cl_2$ used for cleaning the tube

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

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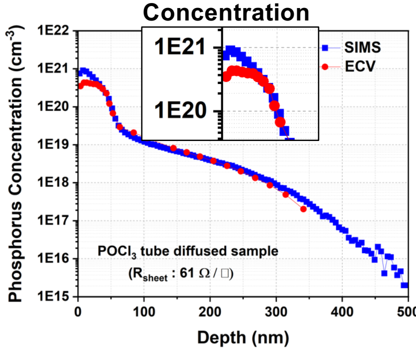
Chemical Concentration and Electrically Active Concentration



SIMS: Secondary Ion Mass Spectroscopy;
ECV: Electrochemical Capacitance Voltage

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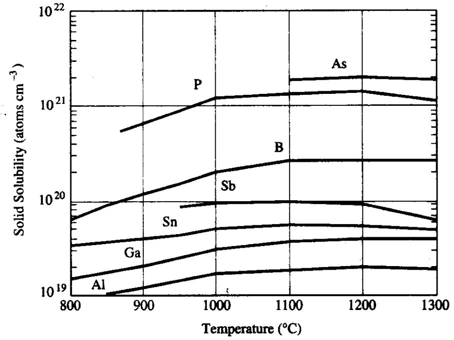
Solid solubility

The maximum concentration of a dopant that can be dissolved in a semiconductor under equilibrium conditions without formation of separate phases.



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

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Diffusion theory: quick review

- Fick's first law of diffusion: $F = -D\dfrac{\partial C}{\partial x}$
- Diffusion coefficient: $D = D_0 e^{-E_a/k_B T}$
- Fick's second law of diffusion: $\dfrac{\partial C}{\partial t} = \dfrac{\partial}{\partial x}\left(D\dfrac{\partial C}{\partial x}\right)$

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Solution for fixed dose condition

Q

0 x

At t = 0

C ➔ 0 for x > 0 & x < 0
C ➔ infinity at x = 0

$\int_{-\infty}^{\infty} C(x,t)dx = Q$; at all times

$$C(x,t) = \frac{Q}{2\sqrt{\pi D t}}\exp\left(-\frac{x^2}{4Dt}\right) = C(0,t)\exp\left(-\frac{x^2}{4Dt}\right)$$

Exercise: Prove that the equation given is a solution to the Fick's second law of diffusion.

$$C(x,t) = C(0,t)\exp\left(-\frac{x^2}{L_D^2}\right); \qquad L_D = 2\sqrt{Dt}$$

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

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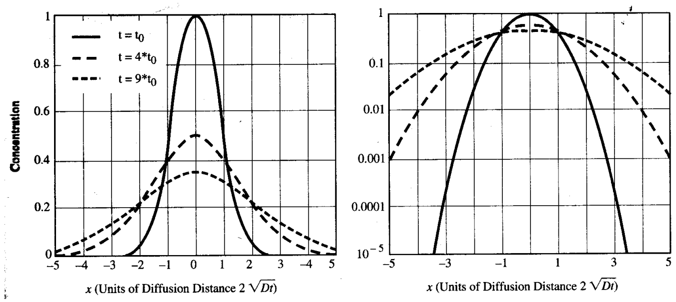
Solution for fixed dose condition (2)



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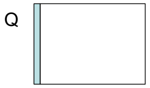
Solution for fixed dose at the surface of the semiconductor (3)



$$C(x,t) = \frac{Q}{\sqrt{\pi D t}} \exp\left(-\frac{x^2}{4Dt}\right) = C(0,t) \exp\left(-\frac{x^2}{4Dt}\right)$$

For example, phosphorous diffusion using $POCl_3$.

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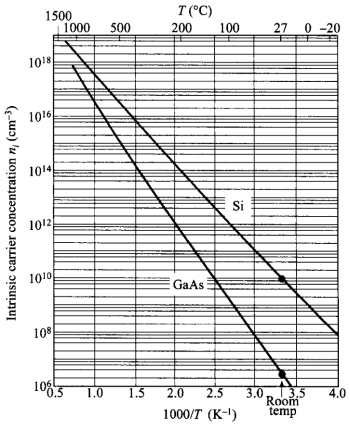
Exercise

Derive the solution for the diffusion equation for diffusion from an infinite source.

Intrinsic silicon



S. M. Sze, Physics of Semiconductor Devices

Exercise: Determine the temperature at which the intrinsic carrier concentration is equal to the doping concentration, for a silicon wafer doped with 10^{17} cm^{-3} of boron.

Intrinsic diffusivities in Si

The dopant concentrations are low such that at the process temperature, the semiconductor can be considered intrinsic.

$$D = D_0 \exp\left(-\frac{E_A}{kT}\right)$$

	Si	B	In	As	Sb	P	Units
D_0	560	1.0	1.2	9.17	4.58	4.7	cm^2 s^{-1}
E_A	4.76	3.5	3.5	3.99	3.88	3.68	eV

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

The concept of thermal budget

- The factor "Dt" is seen to appear together in the solutions we have worked out for diffusion.
- Suppose that the "Dt" is the same for two different diffusion processes conducted at two different temperatures, the two processes have same "thermal budget".
- The thermal budget of various processes (also other than diffusion) are important as any dopants already present in the semiconductor can diffuse during other high temperature processes.

Exercise:
(1) For a fixed dose diffusion of Boron from a delta profile positioned at the center (along the thickness) of a silicon wafer, the following parameters are given: $Q = 10^{15}\ cm^{-2}$, T = 1000℃, t = 30 min. Plot the diffusion profile at the end of the diffusion. You may assume intrinsic diffusion.
(2) In the above problem, supposing that the diffusion was carried out at 900℃ with the same thermal budget, what was the duration of diffusion.

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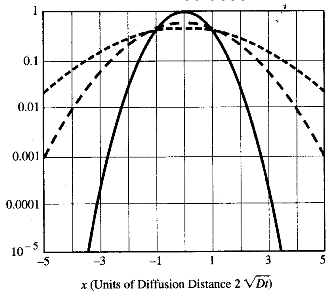
Deviation from the simple theory

Fixed dose



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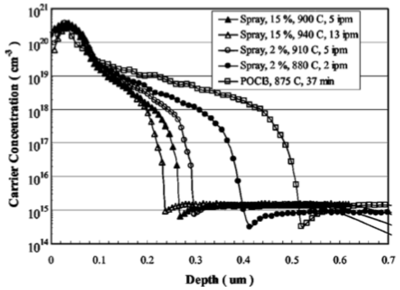

Kim et al., Development of a phophorous spray diffusion system for low-cost silicon solar cells, J. Electrochem. Soc., 153 (7), 2006, pp. A13891-A1396.

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