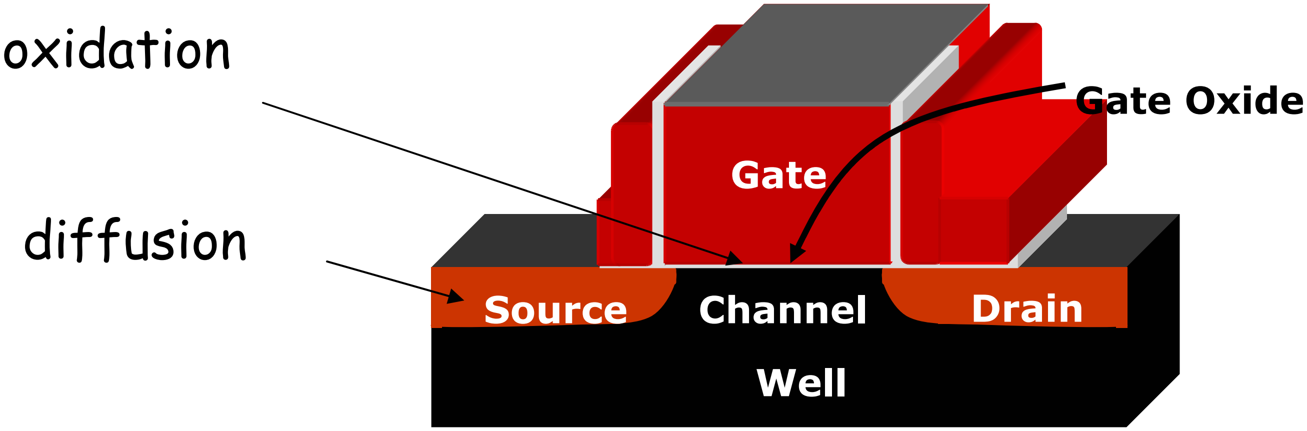
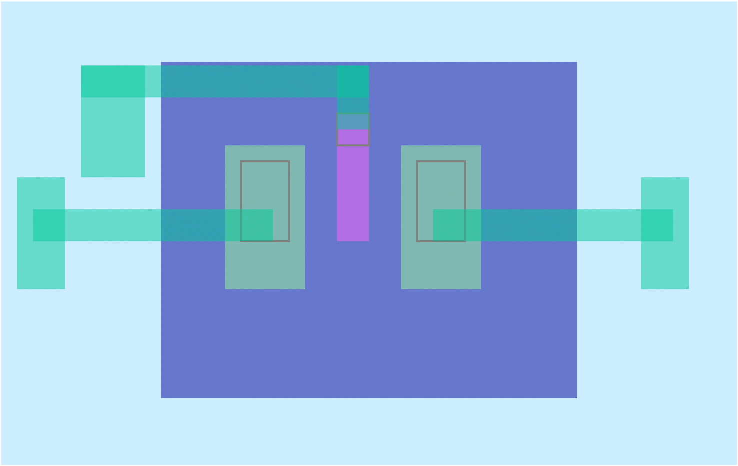
Building a 3D Structure, layer by layer



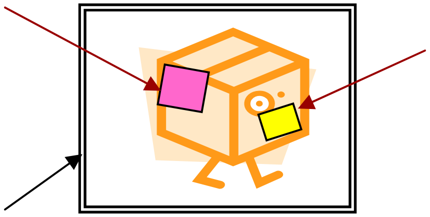


Well
Source and drain
Gate
Windows
Metal interconnects

What are the key elements of this 'new' fabrication technology?

- Making a pattern (template)
- Transferring that template into your material

1. Lithography
2. Metalization and making contact to the outside world
3. Defining local electronic behavior: doping
4. Isolating electronic regions: oxidation
5. Carving out different regions of the material: etching



n-doped

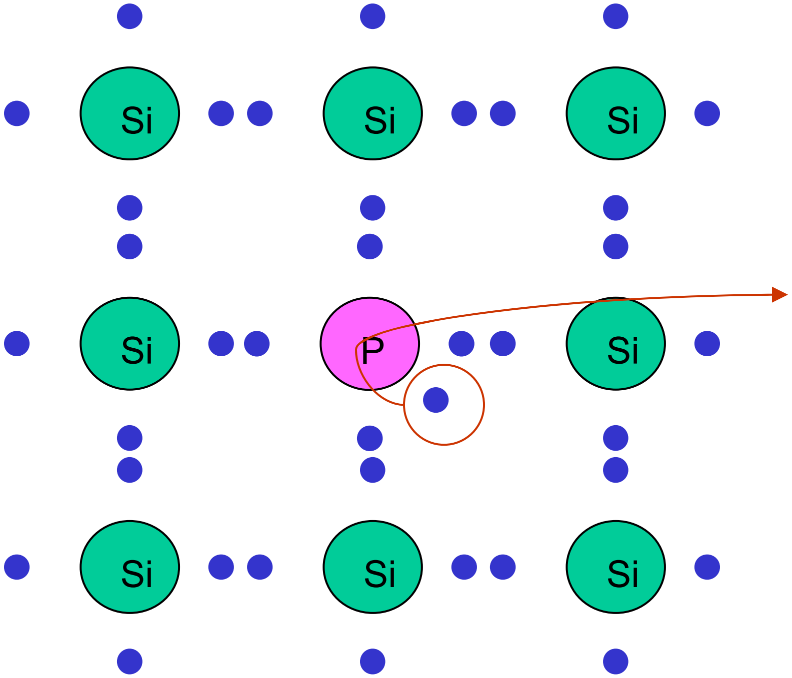
p-doped

Oxide isolation
Gate oxides

The critical physical phenomenon for diffusion and oxidation

N-type Silicon

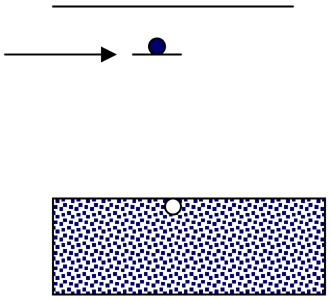
Add Phosphorus with 5 bonding electrons



Extra electron negatively charged

Conduction band

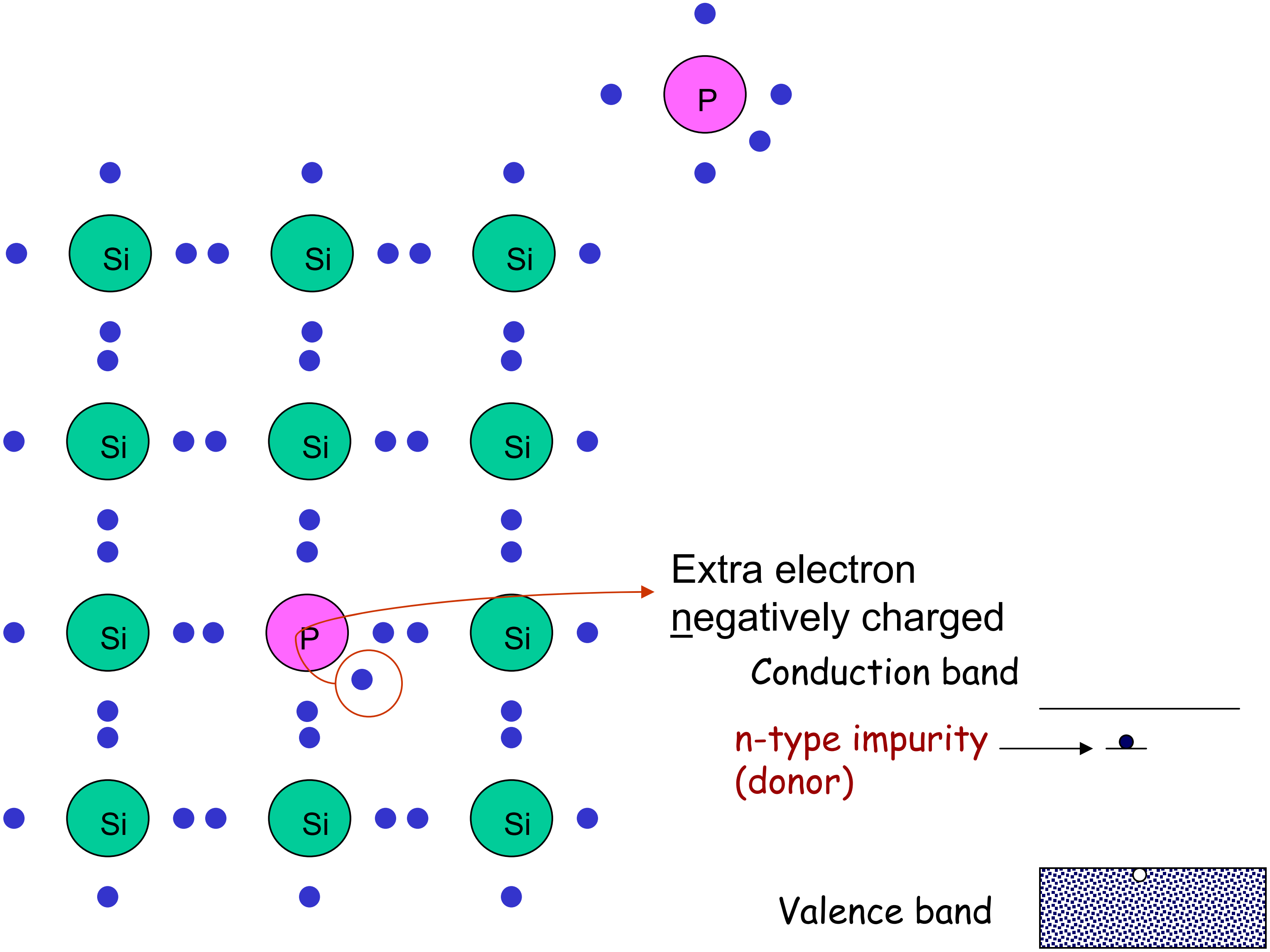
n-type impurity (donor)



Valence band

Dopants provide mobile carriers, but leave ionized cores

How to place dopants into the material?



Extra electron
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Conduction band

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Valence band

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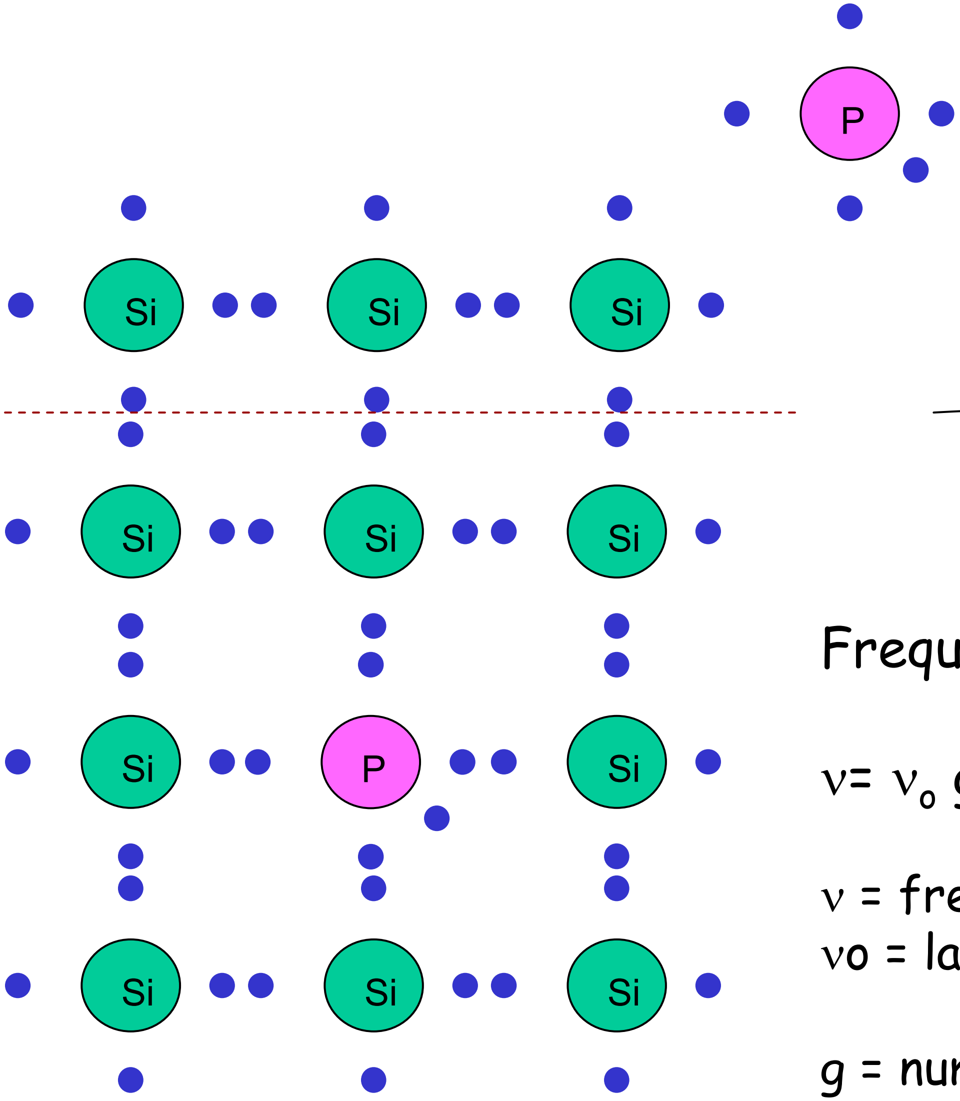
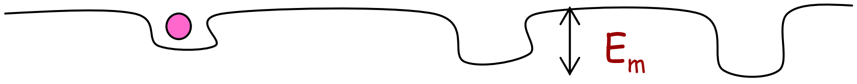


Interstitial

Potential landscape

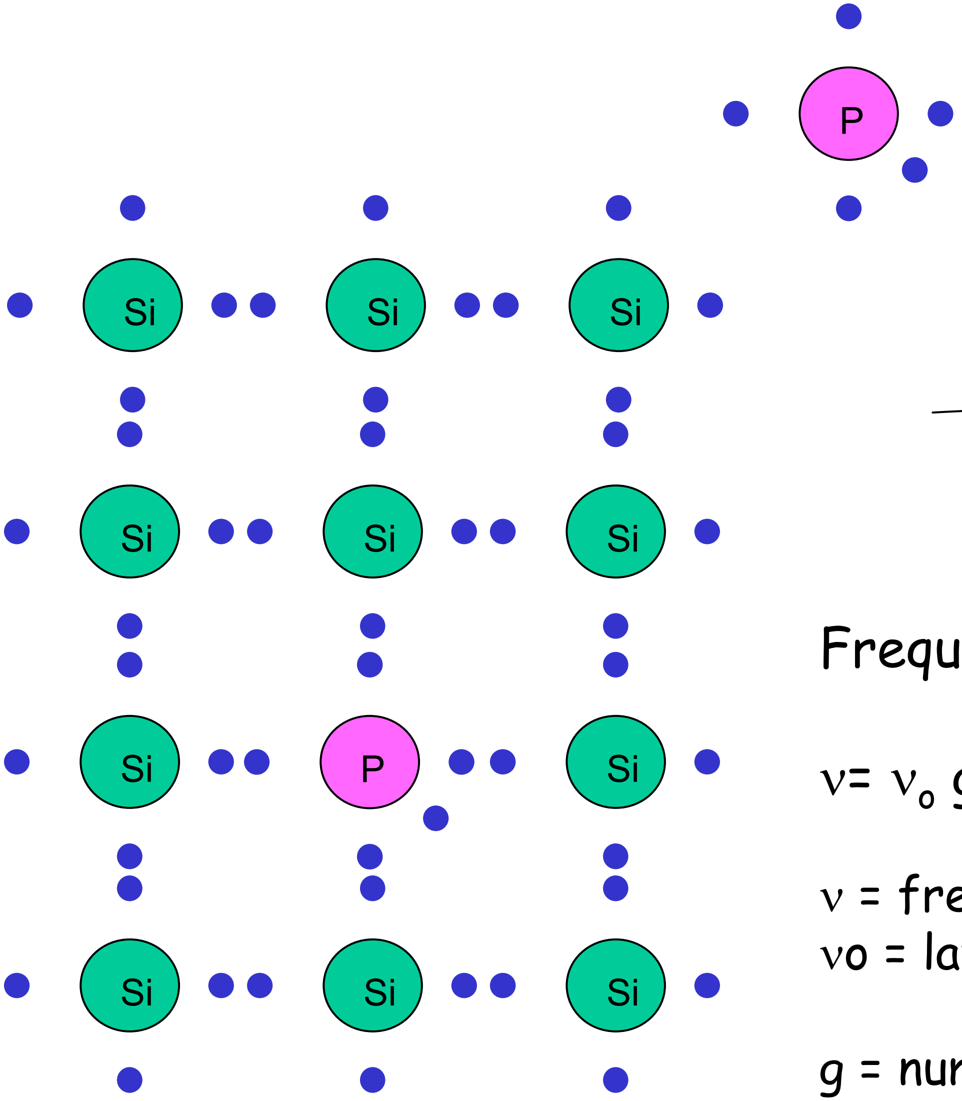


Frequency of hopping

$$\nu = \nu_o\ g \exp\{-E_m/kT\}$$

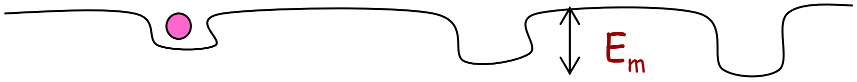
ν = frequency of jumps
νo = lattice vibration frequency
= 10^{13}-10^{14} sec $^{-1}$
g = number of sites available to jump to
E_m = an activation energy

How to place dopants into the material?



Substitutional

Potential landscape



Frequency of hopping

$$\nu = \nu_o\, g \exp\{-E_n/kT\} \exp\{-E_s/kT\}$$

ν = frequency of jumps
νo = lattice vibration frequency
= 10^{13}-10^{14} sec $^{-1}$
g = number of sites available to jump to
E_n = an activation energy
E_s = energy of formation of a vacancy

Interstitial versus Substitutional Diffusion

Interstitial

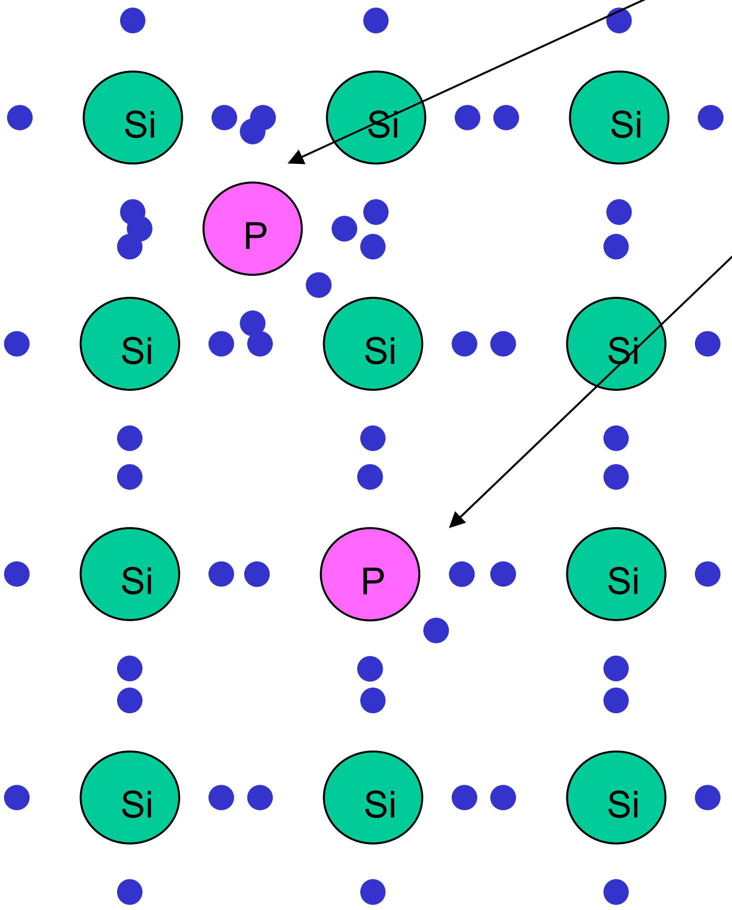
$E_m \sim 0.6 - 1.2$ eV

~ 1 jump /minute

Substitutional

$E_n + E_s \sim 3\text{-}4$ eV

~ 1 jump/10 ^{45} years



Frequency of hopping

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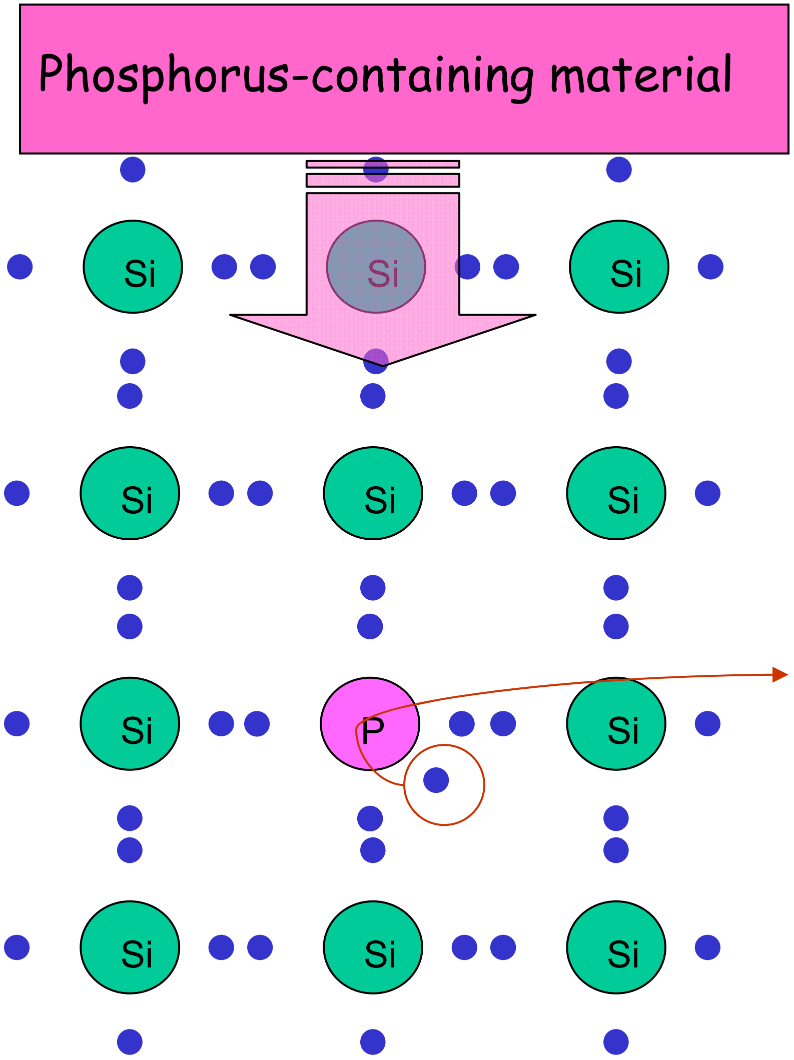
How to place dopants into the material?



FORMERLY

$$\text{Flux} = P_{eq}/\{2\pi kTM\}^{1/2}$$

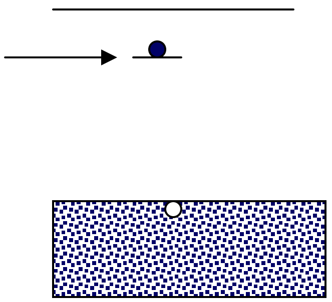
Use a mechanism with a FLUX that depends on a CONCENTRATION GRADIENT

Extra electron
negatively charged

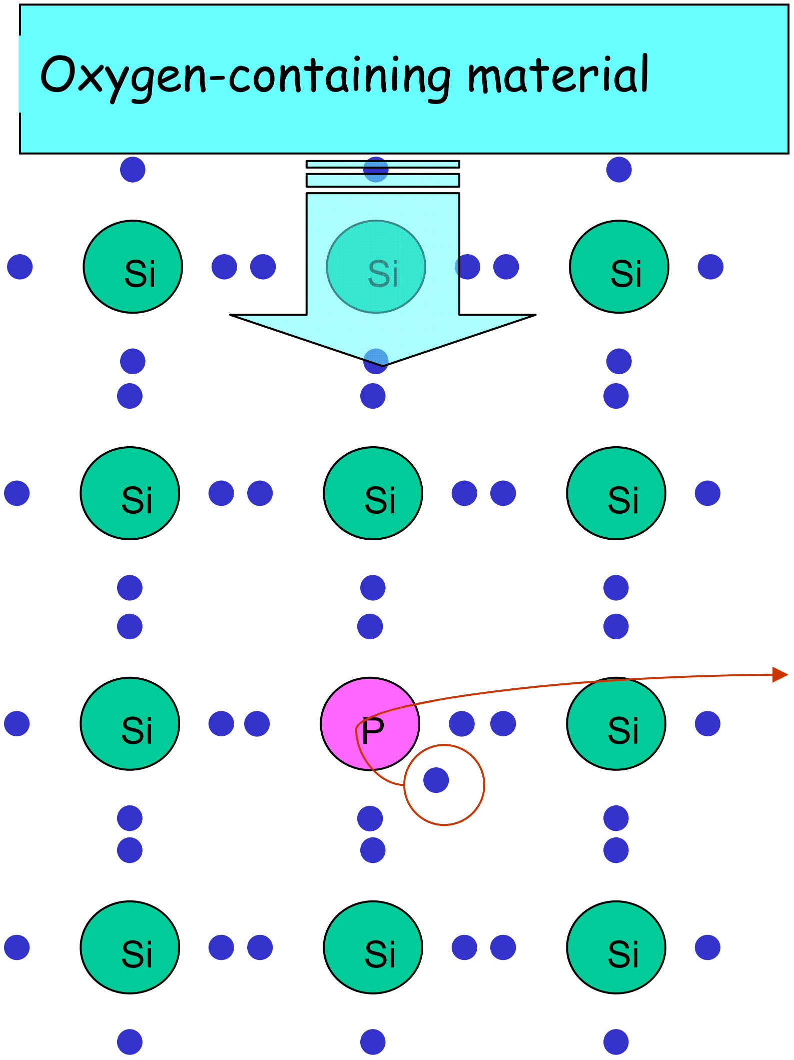
Conduction band

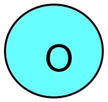
n-type impurity
(donor)

Valence band



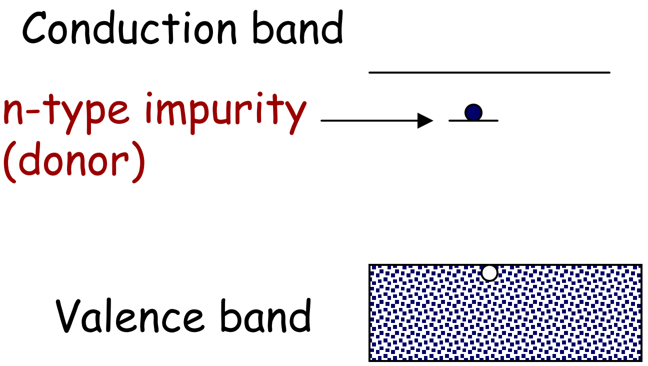
How to form an oxide in the material?


Oxygen-containing material



Use a mechanism with a FLUX that depends on a CONCENTRATION GRADIENT

Extra electron
negatively charged


Conduction band

n-type impurity
(donor)

Valence band

Diffusion at the Atomic Level

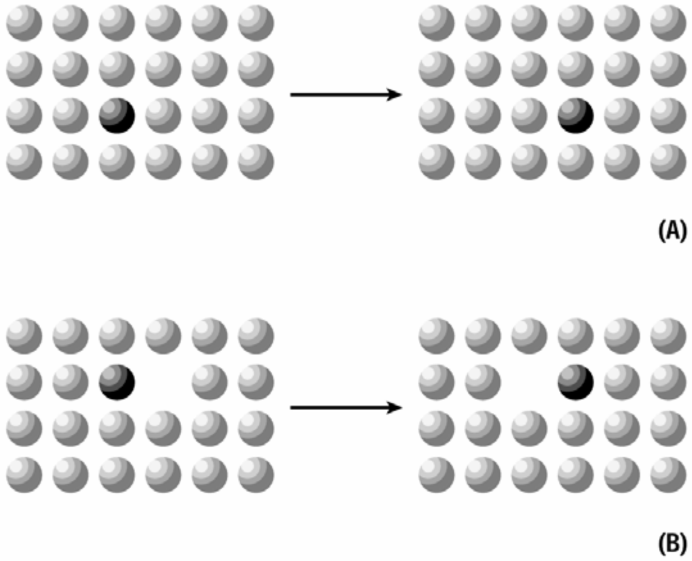


Figure 3.3 Diffusion of an impurity atom by direct exchange (A) and by vacancy exchange (B). The latter is much more likely due to the lower energy required.

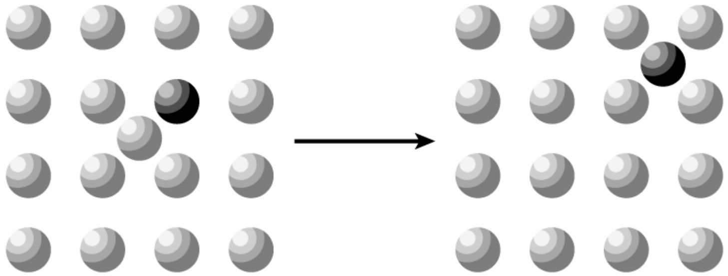


Figure 3.5 In interstitialcy diffusion an interstitial silicon atom displaces a substitutional impurity, driving it to an interstitial site where it diffuses some distance before it returns to a substitutional site.

Fick's First Law: $j = -D\, dC/dx$

j = flux, D = diffusion constant
C = concentration of impurities

Fick's Second Law

$$dC/dt = D\, d^2C/dx^2$$

Pre-deposition and Drive-in Diffusion Profiles: Solutions to Fick's 2nd Law

Erfc (complementary error function)
'infinite' source

Gaussian: finite source

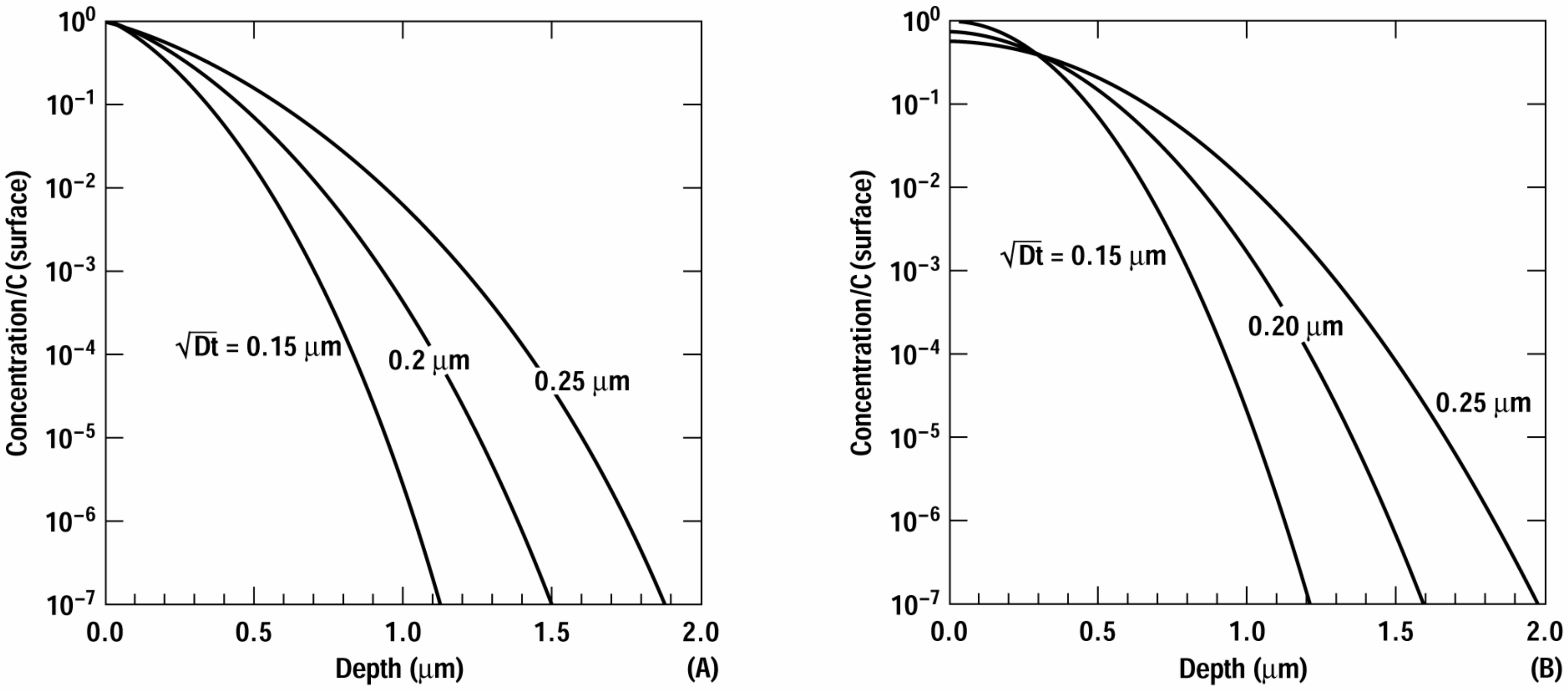
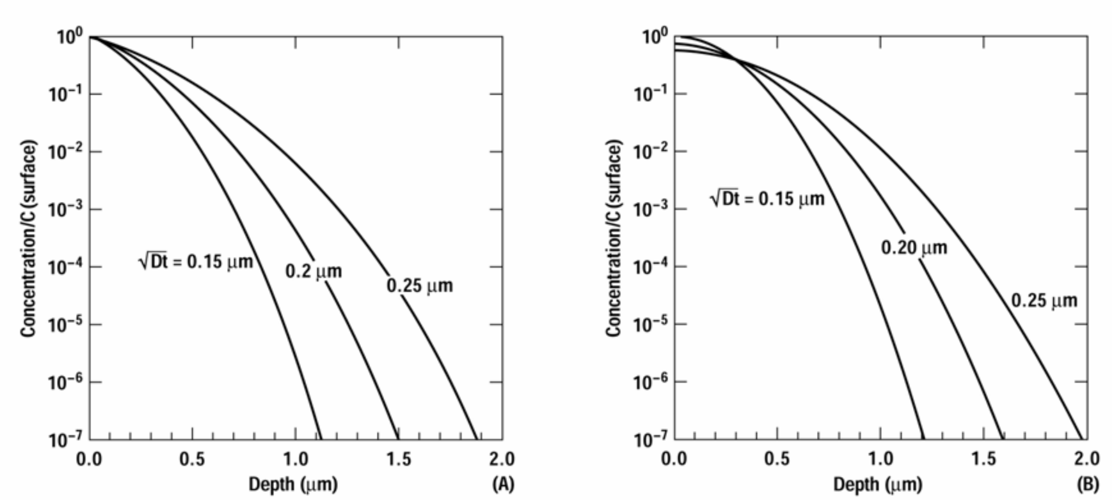


Figure 3.7 Concentration as a function of depth for (A) predeposition and (B) drive in diffusions for several values of the characteristic diffusion length.

Pre-deposition and Drive-in Diffusion Profiles



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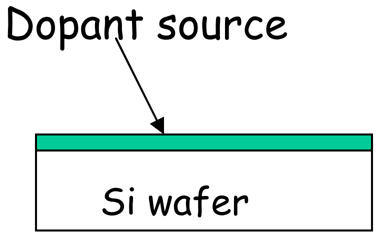


Step 1: carry out 'predeposition' for short time, low T to introduce a 'finite' amount of impurity to serve as source

$$Q_0 = 2/\pi^{\frac{1}{2}}\, C(0,t_1)\,(D_1t_1)^{\frac{1}{2}}$$

Step 2: Remove excess source from material surface. Drive-in the amount Q_0 into the material for a (longer) time t_2, and at a higher T.

$$C(x,t_1,t_2) = Q_0/(\pi D_2t_2)^{1/2} \exp\{-x^2/(4D_2t_2)\}$$

$$= 2/\pi\, [(D_1t_1)/(D_2t_2)]^{1/2} \exp\{-x^2/(4D_2t_2)\}$$

Forming an electronic junction in a semiconductor

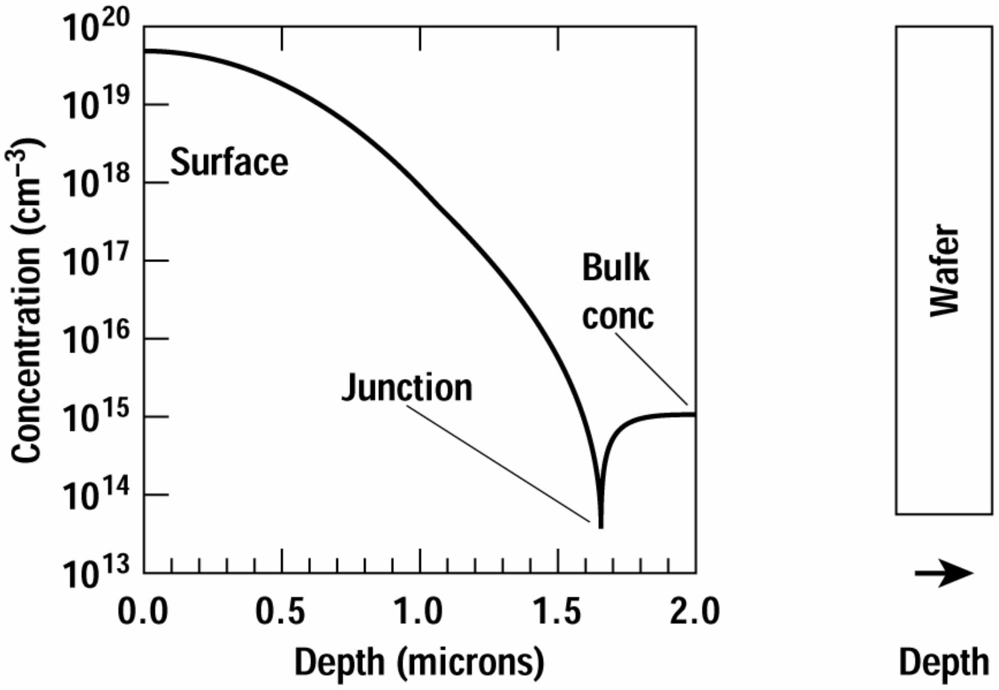
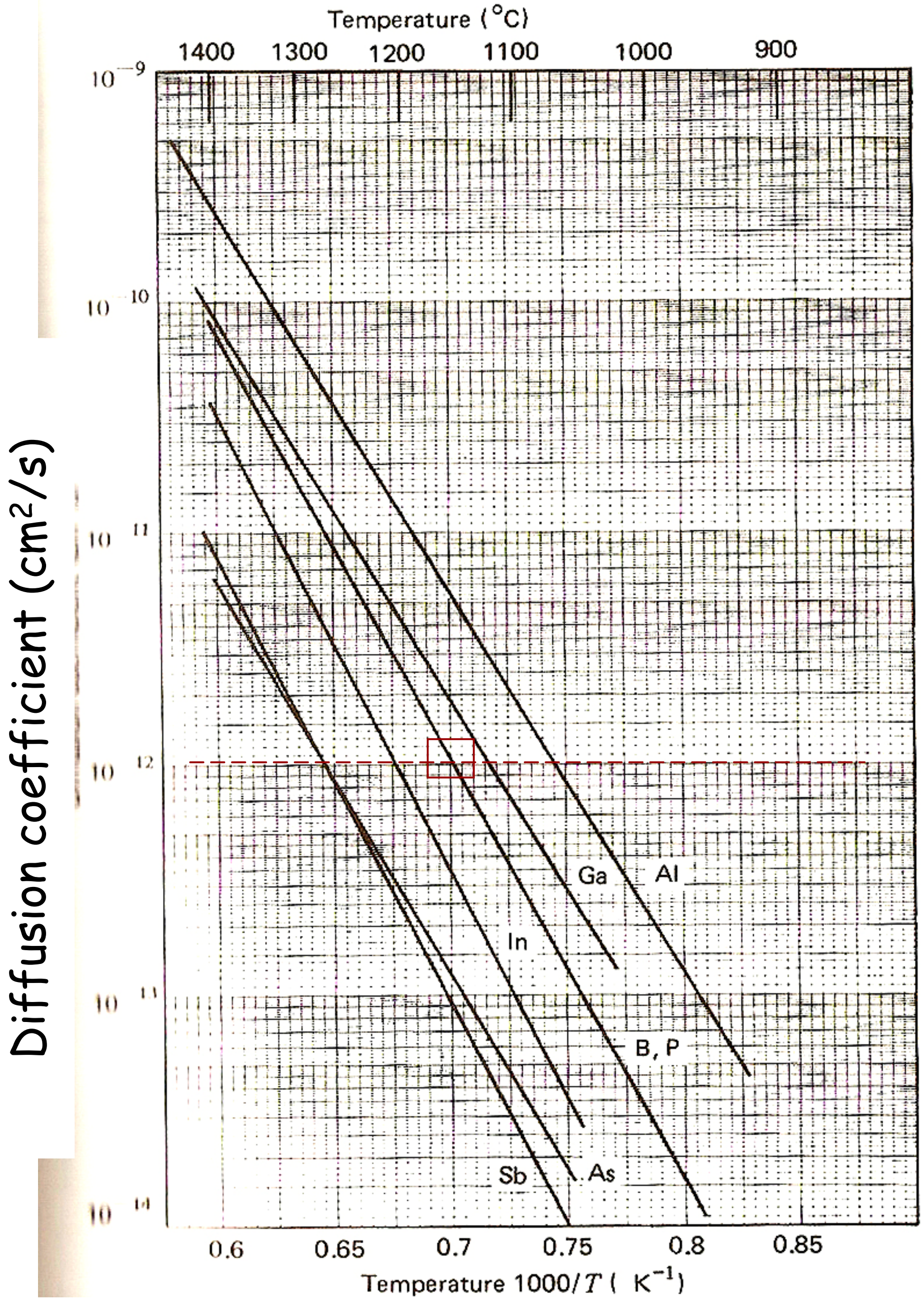


Figure 3.1 Typical concentration plot of impurities or carriers as a function of depth into the wafer. Note that these profiles are typically much less than 1% of the total wafer thickness.

Diffusion Constants in Silicon vs. Temperature

$L_d = [Dt]^{1/2}$

For L_d = 0.2 microns,
D = 10^{-12} cm^2/sec,
t = ?



From Ghandhi
VLSI Fabrication Principles

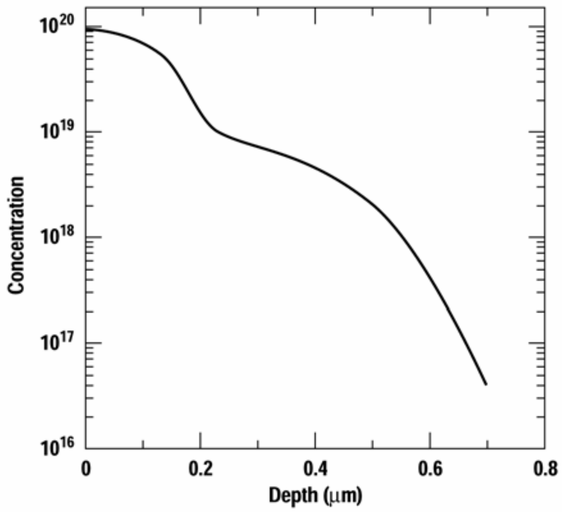


Figure 3.10 Typical profile for a high concentration phosphorus diffusion.

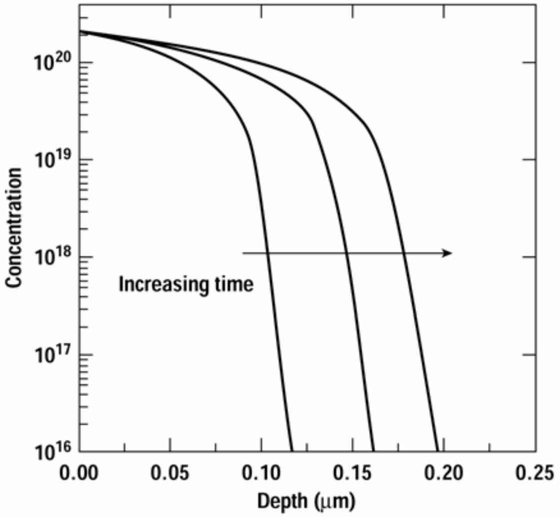


Figure 3.9 Typical profile for a high concentration arsenic diffusion.

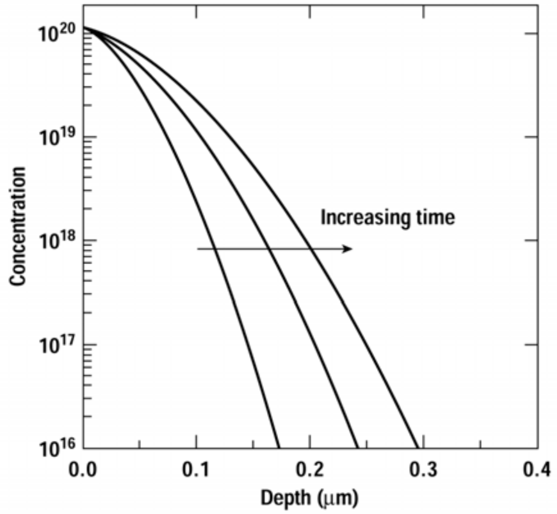
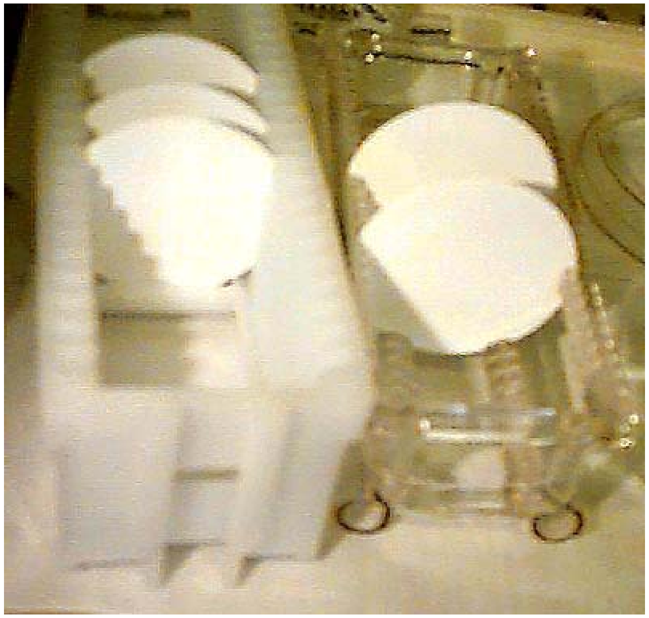


Figure 3.8 Typical profile for a high concentration boron diffusion.

High dopant concentrations, local electric fields, clustering, may lead to different diffused profiles

Diffusion Furnaces



Source wafers