공정 6. Diffusion

↗ 관련 과목	
↗ 관련 시험/과제	
↗ 강의 일자	
☰ 상태	정리중
강의자료	Lecture6_Diffusion (Kwon).pdf

Purpose

Diffusion

- Diffusion has been **the primary method of introducing impurities** such as boron, phosphorus, and antimony into silicon. (doping해서 n-type, p-type 만들기)

Purpose

- Impurity control -> **resistivity** (MOSFET에서 drain, source 등)
- Majority carrier type
- Majority carrier concentration
- Diffusion depth

Process

high concentration으로 증착 후 높은 온도를 가해서 Si 안으로 확산되도록 함

1. Deposition(증착) of a high concentration of the desired impurity
2. At high temperature (900 to 1200 °C), the impurity atoms move from the surface into the silicon crystal

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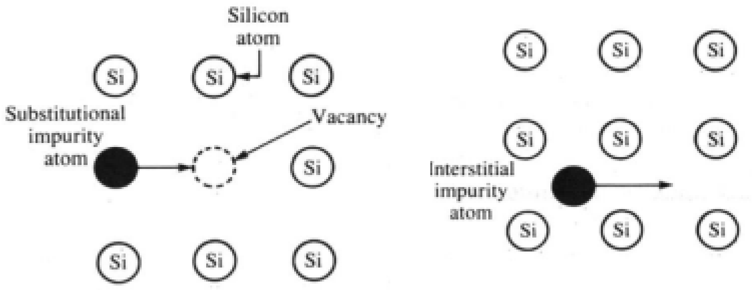
Mechanism

(1) **Substitutional or vacancy diffusion**

- vacancy : Si 간의 공유결합이 비어있는 공간, 그 자리로 impurity atom이 들어감
- Si lattice 안에는 vacancy가 존재할 수밖에 없으므로 가능
- 정해진 vacancy만큼 diffusion이 일어나므로 정확한 doping농도 계산하기 쉽다

(2) **Interstitial diffusion**

- Si 사이로 비집고 들어가는 것
- Interstitial diffusion은 substitutional diffusion보다 빠름
- impurity atom이 전류에 영향을 주려면 activation 공정 필요 (vacancy 안에 들어가도록)



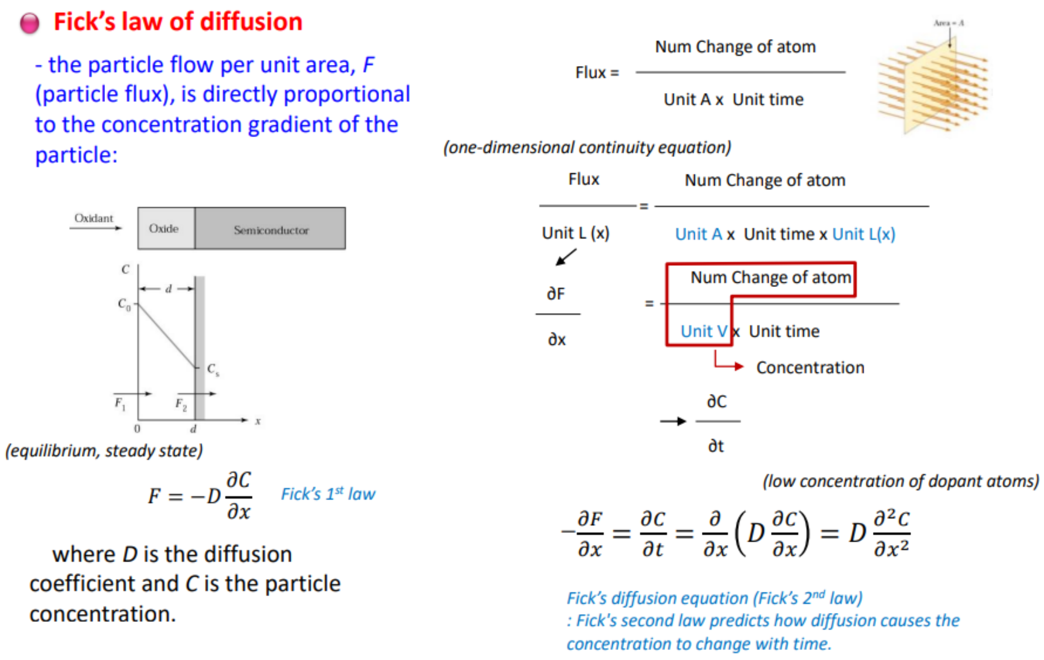
Substitutional diffusion	Interstitial diffusion
Need vacancy supply	Diffusion without vacancy
Slow diffusion	Rapid diffusion
Good process control	Need activation*

* Impurity atoms needs to occupy substitutional site in the lattice in order to be act as donors or acceptors

Modeling

유도 과정)

- oxidation은 시간에 따라 두께가 바뀌는 게 핵심이었는데 diffusion은 **시간에 따라 concentration이 바뀜**



Diffusion Coefficient

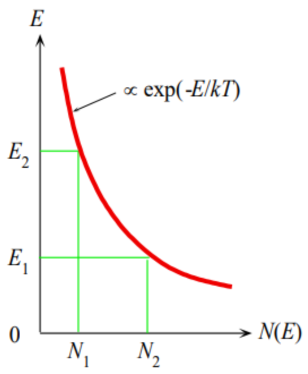
$$D = D_0 \exp(\frac{-E_a}{kT})$$

E_a : activation energy

k = (8.617)x10^{-5}eV/K (볼츠만 상수)

T는 절대온도이므로 K 단위로 꼭 환산!!!

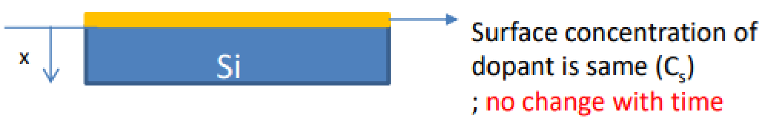
[Note] Boltzman Classical Statistics



Boltzman energy distribution : In statistical mechanics and mathematics, a Boltzmann distribution is a **probability distribution**, probability measure, or frequency distribution of particles in a system over various possible states.

Diffusion Profile: Constant Surface Concentration

erfc distribution



Boundary conditions:

i) C(0,t) = Cs , ii) C(∞, t) = 0

$$C(x,t) = C_s erfc\left(\frac{x}{\underline{2\sqrt{Dt}}}\right)$$

Diffusion length

Total number of dopant atoms per unit area (dose):

$$Q(t) = \int_0^\infty C(x,t)dx$$

Area under the diffusion profile

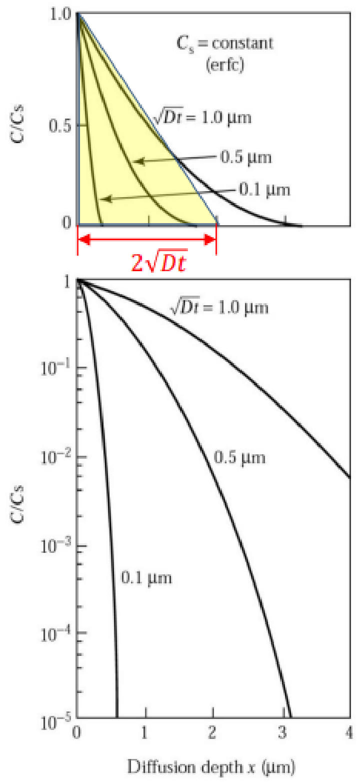
$$Q(t) = \frac{2}{\sqrt{\pi}} C_s\sqrt{Dt} \cong \underline{1.13}C_s\sqrt{Dt}$$

$A = \frac{1}{2} Cs \ X \ 2\sqrt{Dt} = Cs\sqrt{Dt}$

Correction constant

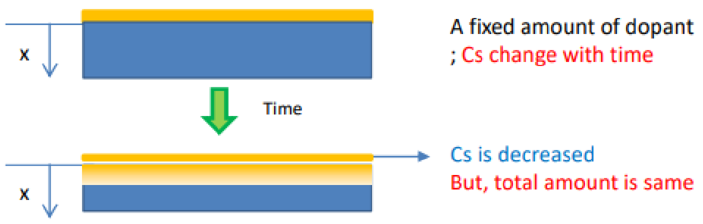
The gradient of diffusion profile (a related quantity):

$$\frac{\partial C}{\partial x}\Big|_{x,t} = \frac{C_s}{\sqrt{\pi Dt}} e^{-x^2/4Dt}$$



Diffusion Profile: Constant Total Dopant

Guassian distribution



$$\int_0^\infty C(x,t) = Q\ (constant), \qquad C(\infty, t) = 0$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

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

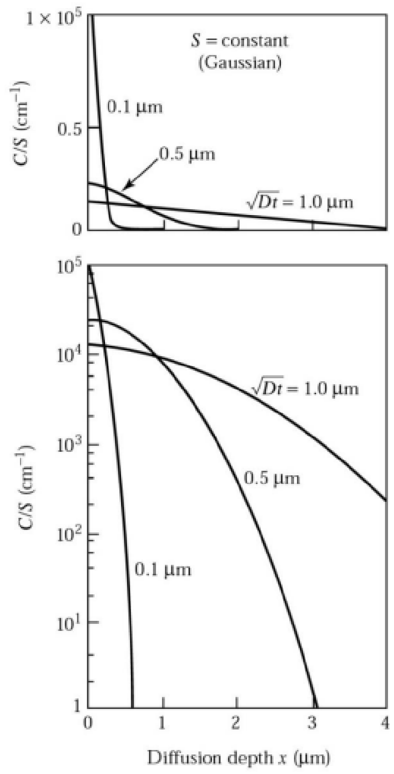
$C.F)\ C(x,t) = C_s erfc\left(\frac{x}{2\sqrt{Dt}}\right)$

$$C(0,t) = \frac{Q}{\sqrt{\pi Dt}}$$

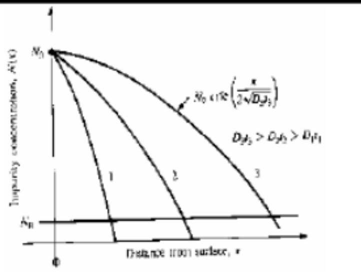
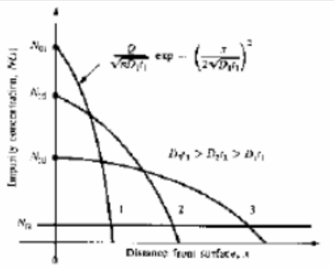
Surface concentration decrease with time

$$\frac{\partial C}{\partial x}\Big|_{x,t} = -\frac{xQ}{2\sqrt{\pi}(Dt)^{\frac{3}{2}}} = -\frac{x}{2Dt}C(0,t)$$

: The gradient of diffusion profile



📌 Summary: Diffusion Profile (중요!)

	Constant-source diffusion	Limited-source diffusion
Solution of equation (a)	$N(x,t) = N_0 erfc\left(\frac{x}{2\sqrt{Dt}}\right)$	$N(x,t) = \frac{Q_0}{\sqrt{\pi Dt}} \exp\left[-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right]$
Impurity distribution	 "complementary error function"	 "Gaussian distribution"
Dose (Q) =Total # of Impurity atoms per unit area [atom/cm^2]	$Q = \int_0^\infty N(x,t)dx = 2N_0\sqrt{\frac{Dt}{\pi}}$	Q_0

`3/29 → 3/31`

Two-Step Diffusion

Two-step diffusion (general process)

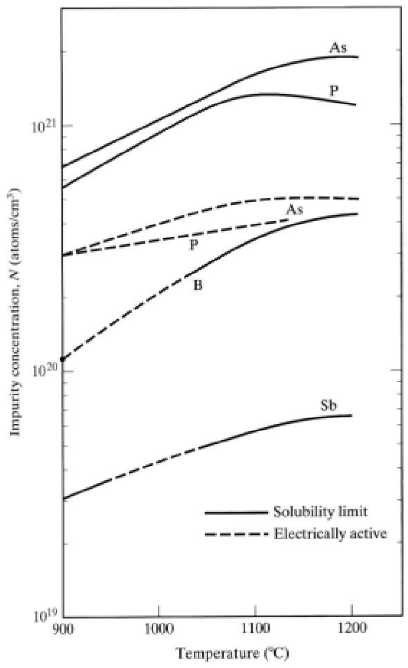
1. Pre-depostion : Constant surface concentration (D1t1) <— short-time
2. Drive-in (Redistribution) : Constant total dopant (D2t2) <— long-time

Successive diffusion

- We are interested in the **final impurity distribution** after all processing is complete.
- A wafer typically goes through many time-temperature cycles during predeposition, drive-in, oxide growth, CVD,etc.
- The effect of these steps is determined by calculating the total Dt for all ightemperature cycles affecting diffusion —> $(Dt)_{total} = \sum_i D_i t_i$

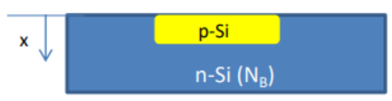
Solid Solubility Limits

- At a given temperature, there is an upper limit to the amount of an impurity which can be absorbed by silicon
- At high concentrations, only a fraction of the impurities actually contribute holes or electrons for conduction. The dotted line shows the “electrically active” portion of the impurity concentration.



Junction Formation

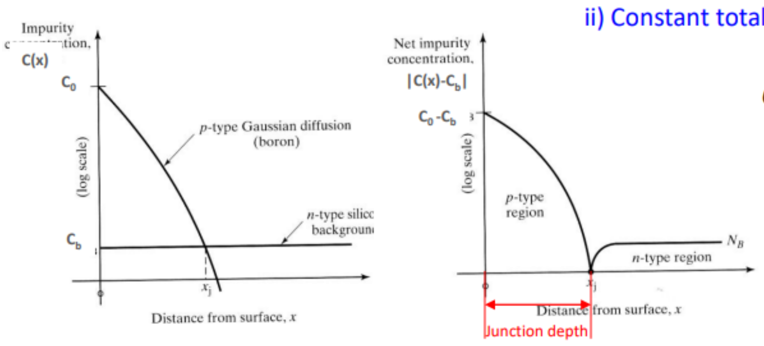
- Vertical diffusion and junction formation



i) Constant surface concentration (Erfc distribution)

$$C(x,t) = C_s erfc\left(\frac{x}{2\sqrt{Dt}}\right)$$

$$x_j = 2\sqrt{Dt}erfc^{-1}(\frac{C_b}{C_s})$$



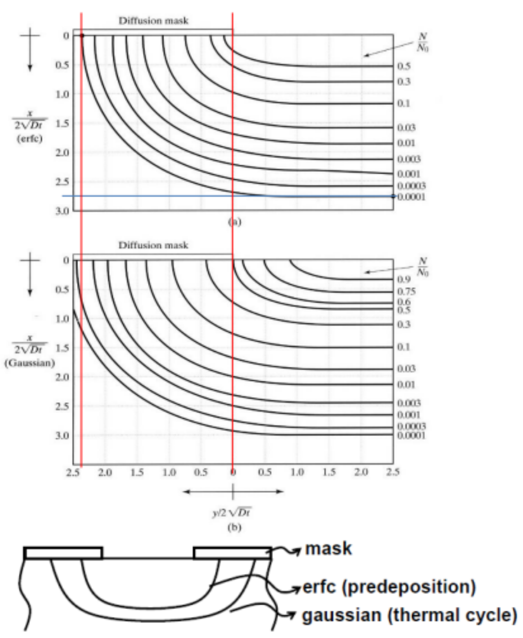
ii) Constant total dopant (Gaussian distribution)

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

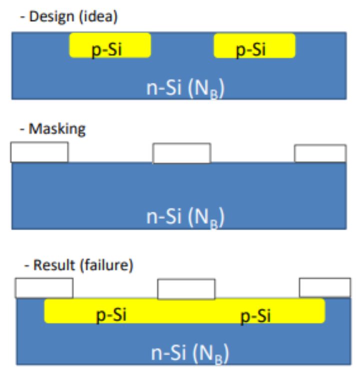
$$x_j = 2\sqrt{Dt \cdot ln(\frac{C_0}{C_b})}$$

Direction: Lateral

Lateral diffusion



- During diffusion, impurities not only diffuse vertically but also move laterally under the edge of any diffusion layer: important factor for design



Q) Constant surface diffusion, Junction depth is 2um, Cs=1x10^{20}/cm^3, C_b=1x10^{16}/cm^3.
the lateral diffusion underneath?

2.75 : 2.4 = 2 : X
X= 1.74 um

Mask for Diffusion : SiO_2

- Diffusion rate to SiO2 ≪ Diffusion rate to Si
  : Sb, As, B, P 에 좋은 diffusion mask
  : P보다 B에 더 효과적임
- SiO2는 Ga, Al 에는 좋은 diffusion mask가 아님
  → Si3N4 가 더 효과적

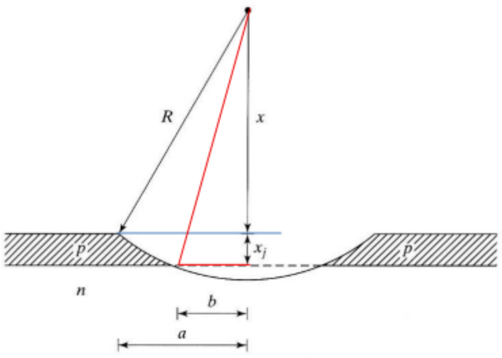
Evaluation of Diffusion Layers

How to know the a, b value ?
i) 0.1% HF + 0.5% HNO3 with high intensity light : pn Junction color change
ii) Measure the a, b length using microscope

Junction depth measurement

- **Groove and stain method (Old method)**

  : Cylindrical groove is mechanically ground into the surface of the wafer

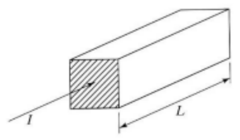


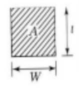
$$(x+x_j)-x=\sqrt{R^2-b^2}-\sqrt{R^2-a^2}=R\left(\sqrt{1-\left(\frac{b}{R}\right)^2}-\sqrt{1-\left(\frac{a}{R}\right)^2}\right)$$

$$\doteq R\left[\left(1-\frac{1}{2}\frac{b^2}{R^2}\right)-\left(1-\frac{1}{2}\frac{a^2}{R^2}\right)\right] \quad R>>a,\ R>>b$$

$$x_j \doteq \frac{a^2-b^2}{2R}=\frac{(a+b)(a-b)}{2R}$$

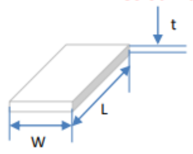
Sheet resistance





Resistance

$R=\rho L/A$ → Resistivity (material's own property)



$R=\rho L/wt=(\rho/t)(L/w)$ → Sheet resistance : R_s

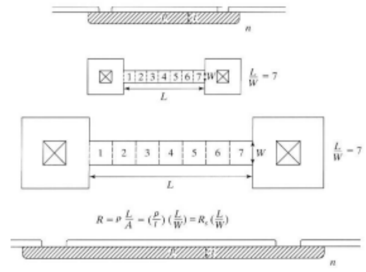
Unit - R:Ω Rs :Ω/□

(□ , there is no meaning – to avoid confusion)

- Why we use sheet resistance for micro fabrication?

: Easy for design

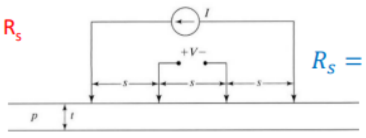
; a circuit designer need specify only the length and width of the resistance to define its value.



Measuring sheet resistance

Measuring sheet resistance: four point probe

I : out side two probes, V; Inside two probes



$R_s=\rho/t=\frac{\pi}{ln2}\cdot\frac{V}{I}$ for t ≪ s

Capacitance-voltage technique
Spreading-resistance profiling (SRP)
Secondary Ion Mass Spectroscopy (SIMS)