EE143 – Fall 2016
Microfabrication Technologies

Lecture 8: Diffusion
Reading: Jaeger Chapter 4

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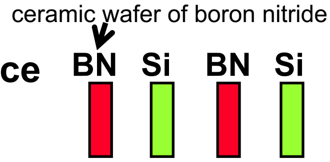
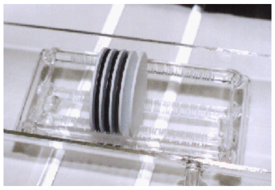
Surface Diffusion: Dopant Sources

(a) Gas Source: AsH_3, PH_3, B_2H_6

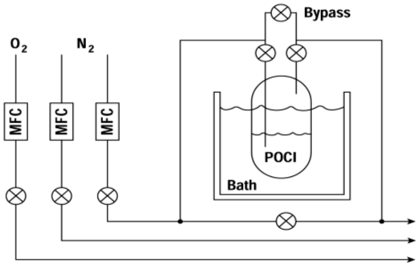
(b) Solid Source



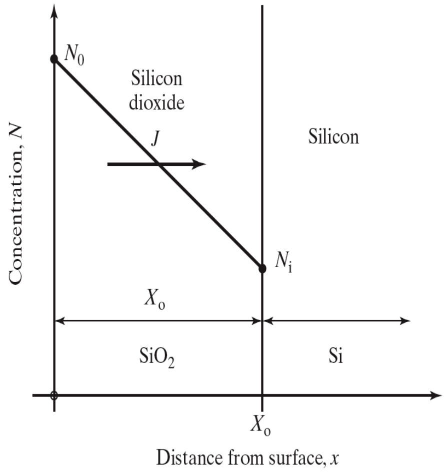


(c) Spin-on-glass **SiO_2+dopant oxide**

(d) Liquid Source.



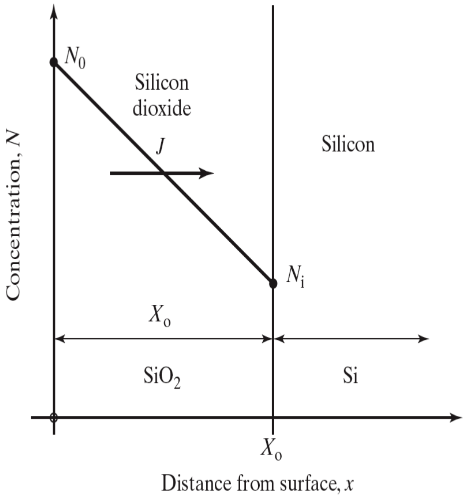
Fick’s First Law of Diffusion



$$J = -D\frac{\partial N}{\partial x}$$

D = diffusion coefficient

Fick’s Second Law of Diffusion



Continuity Equation for Particle Flux:
Rate of increase of concentration is equal to the negative of the divergence of the particle flux

$$\frac{\partial N}{\partial t} = -\frac{\partial J}{\partial x}$$

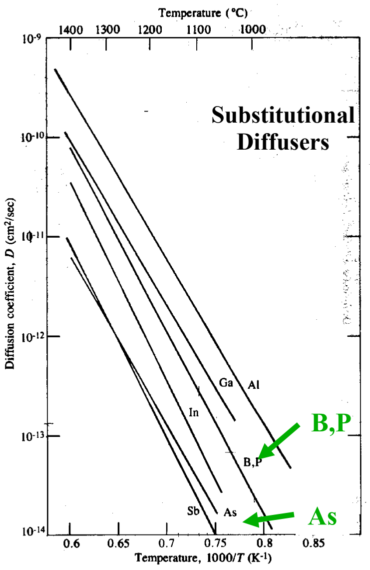
(in one dimension)

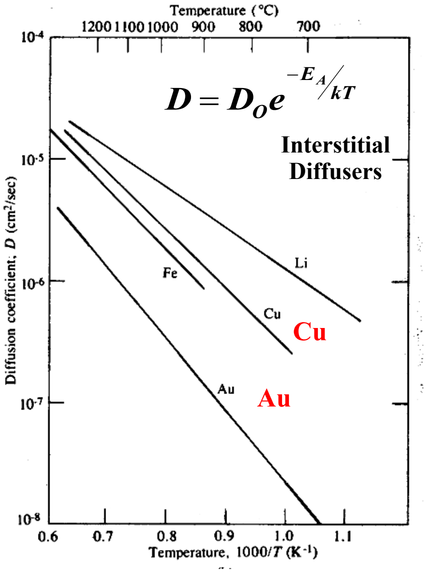
Fick's Second Law of Diffusion:
Combine First Law with Continuity Eqn.

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

Assumes D is concentration-independent, which isn't true in many situations in modern devices

Diffusion Coefficients of Impurities in Si





$$D = D_O e^{-E_A/kT}$$

Diffusion Coefficients

$$D = D_O \exp\left(-\frac{E_A}{kT}\right)$$ Arrhenius Relationship

E_A = activation energy

k = Boltzmann's constant = 1.38×10^{-23} J/K

T = absolute temperature

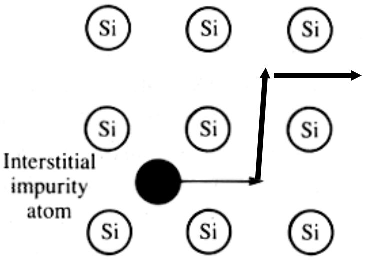
TABLE 4.1 Typical Diffusion Coefficient Values for a Number of Impurities.

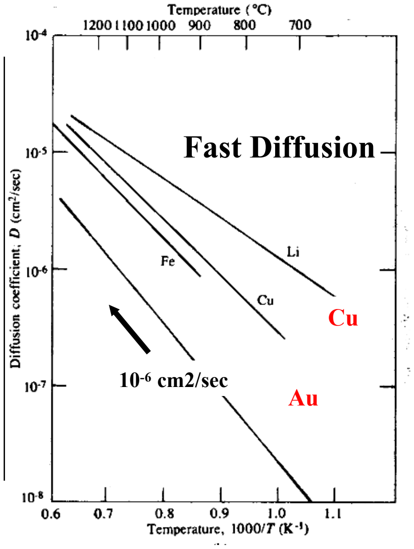
Element	D_0(cm²/sec)	E_A(eV)
B	10.5	3.69
Al	8.00	3.47
Ga	3.60	3.51
In	16.5	3.90
P	10.5	3.69
As	0.32	3.56
Sb	5.60	3.95

Diffusion Mechanisms in Si

(a) Interstitial Diffusion

Example: Cu, Fe, Li, H



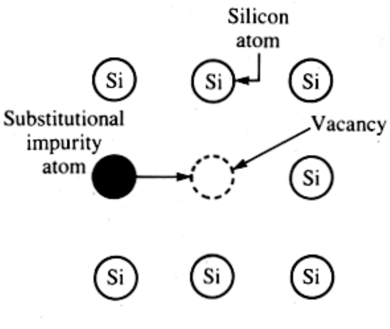


Diffusion Mechanisms in Si

(b) Substitutional Diffusion

(c) Interstitialcy Diffusion

Example: Dopants in Si (e.g. B, P,As,Sb)



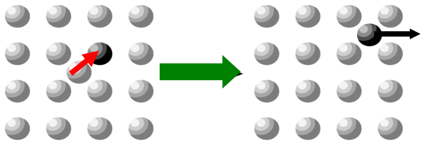
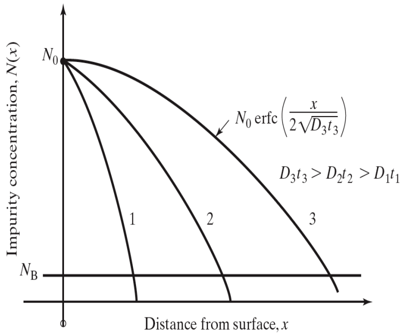


Figure 3.5 In interstitialcy diffusion an interstitial silicon atom displaces a substitutional impurity, driving it to an interstitial site where it diffuses some distance before it returns to a substitutional site.

Constant Source Diffusion
Complementary Error Function Profiles



Concentration : $N(x,t) = N_0 erfc\left(\frac{x}{2\sqrt{Dt}}\right)$

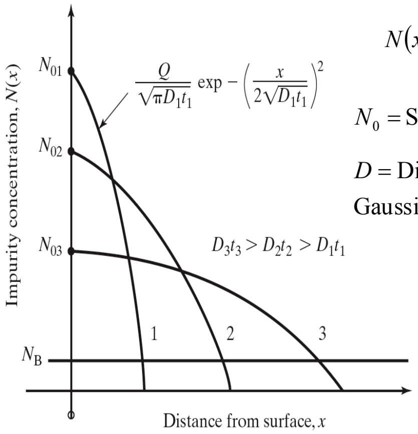
Total Dose : $Q = \int_0^\infty N(x,t)dx = 2N_0\sqrt{\frac{Dt}{\pi}}$

N_0 = Surface Concentration

D = Diffusion Coefficient

erfc = Complementary Error Function

Limited Source Diffusion
Gaussian Profiles



Concentration :

$$N(x,t) = N_0 \exp\left[-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right] = \frac{Q}{\sqrt{\pi Dt}}\exp\left[-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right]$$

N_0 = Surface Concentration $N_0 = \frac{Q}{\sqrt{\pi Dt}}$

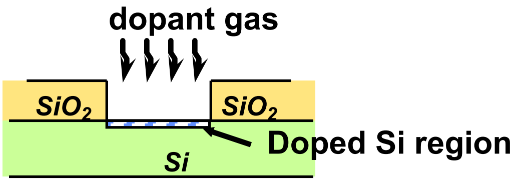
D = Diffusion Coefficient

Gaussian Profile

Two Step Dopant Diffusion

(1) Predeposition

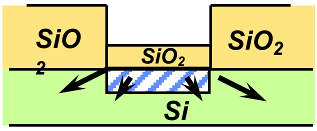
dose control



(2) Drive-in

profile control
(junction depth;
concentration)

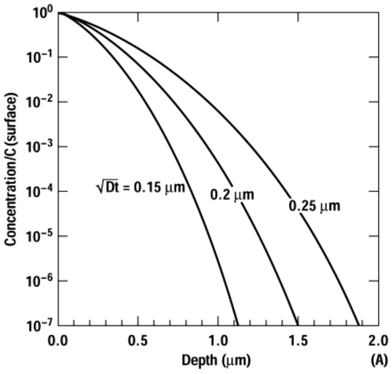
Turn off dopant gas
or seal surface with oxide



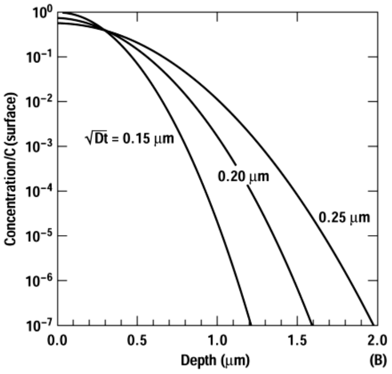
Note: Predeposition by diffusion can be replaced by a shallow implantation step.

Normalized Concentration versus Depth

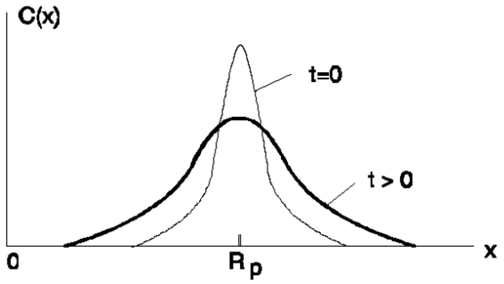
Predeposition



Drive-in

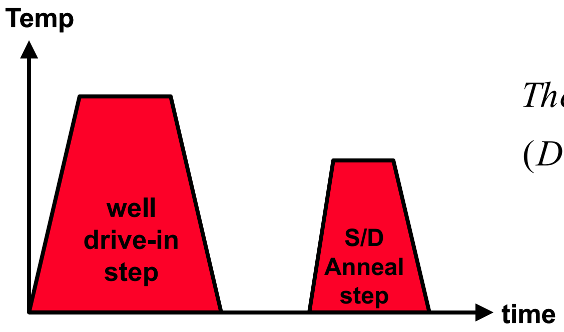


Diffusion of Gaussian Implantation Profile



Successive Diffusions: Thermal Budget

Example: Dt_{total} for Well drive-in and S/D annealing

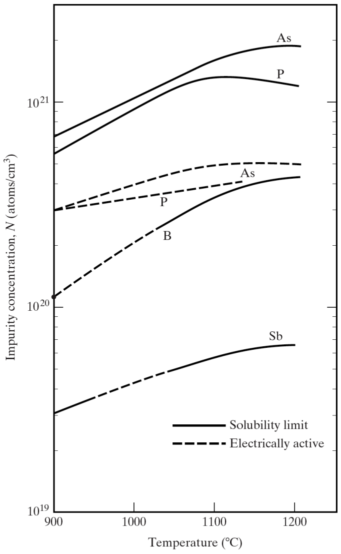


Thermal Budget

$$(Dt)_{effective} = \sum_{step\ i} (Dt)_i$$

For a complete process flow, only those steps with high Dt values are important

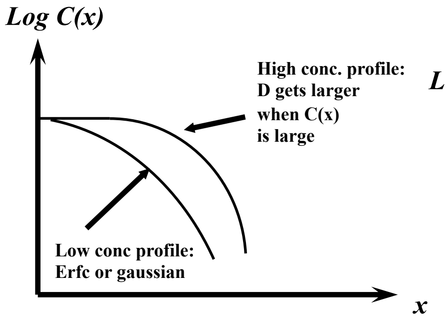
Solid Solubility Limits

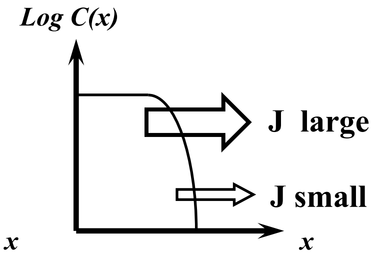


- There is a limit to the amount of a given impurity that can be “dissolved” in silicon (the Solid Solubility Limit)
- At high concentrations, all of the impurities introduced into silicon will not be electrically active

High Concentration Diffusion Effects

1) E-Field Enhanced Diffusion
2) Charged point defects enhanced diffusion

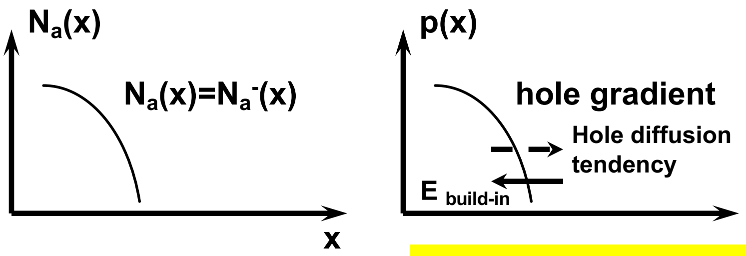




* C(x) looks “flatter” at high conc. regions

Electric-field Enhancement

Example: Acceptor Diffusion



Complete acceptor ionization at diffusion temperature

At thermal equilibrium, hole current =0
Hole gradient creates build-in electric field to counteract the hole diffusion tendency

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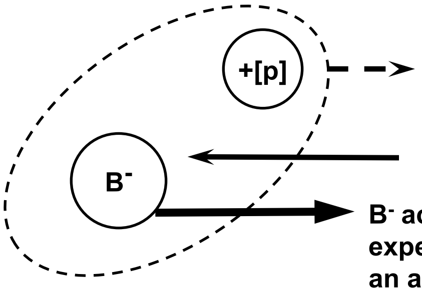
Electric Field Enhancement



holes tend to move away due to hole concentration gradient

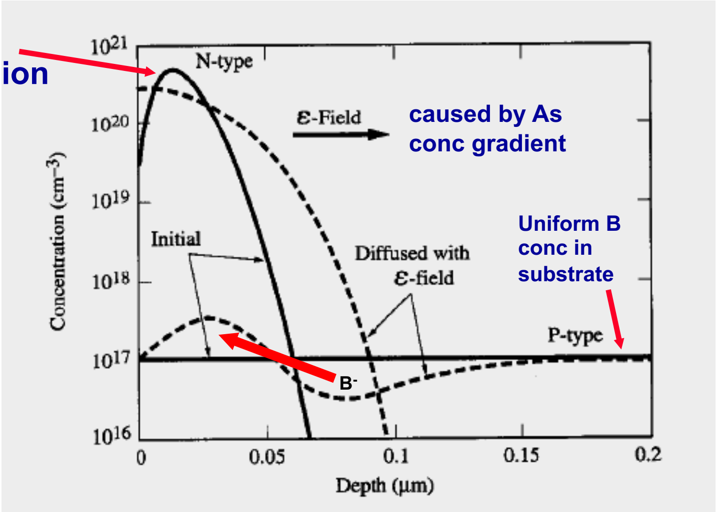
$E_{build\text{-}in}$

B^- acceptors experience an additional drift force

Enhanced
Diffusion for B^- acceptor atoms

Electric Field Enhancement – Substrate Perturbation

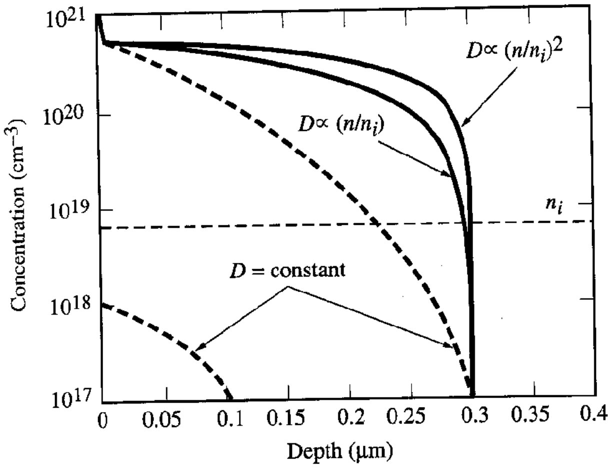
As diffusion



caused by As conc gradient

Uniform B conc in substrate

Example : High Concentration Arsenic diffusion profile becomes “box-like”



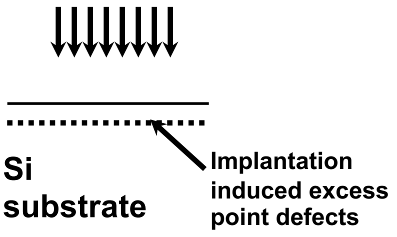
Summary of High-Concentration Diffusion

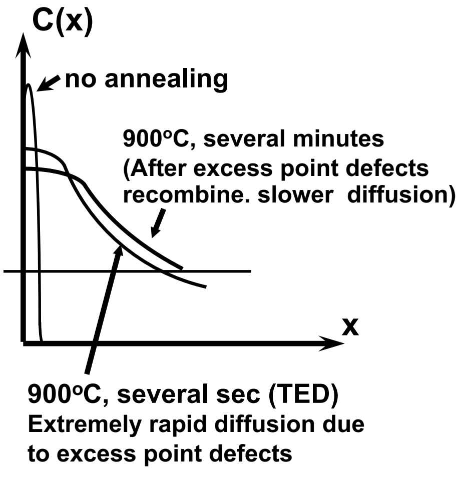
- If doping conc < n_i:
  - – Use constant diffusivity solutions
  - – (profile is erfc or half-gaussian)

- If doping conc > n_i:
  - – Solution requires numerical techniques

Transient Enhanced Diffusion (TED)

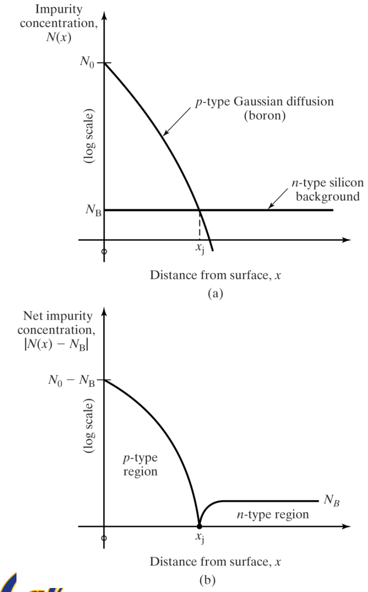
Dopant Implantation





Implantation creates large number of excess Si interstitials and vacancies. (1000X than thermal process). After several seconds of annealing, the excess point defects recombine.

Diffusion: p-n Junction Formation



x_j = Metallurgical Junction Depth

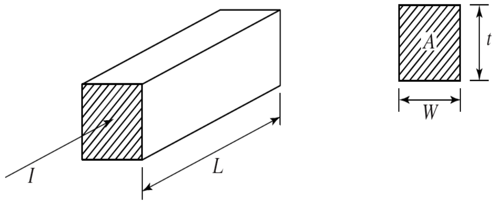
P-n junction occurs at the point x_j where the net impurity concentration is zero

(i.e. p-type doping cancels out n-type doping)

Gaussian Profile: $x_j = 2\sqrt{Dt \ln\left(\frac{N_0}{N_B}\right)}$

Error Function profile: $x_j = 2\sqrt{Dt}\,\mathrm{erfc}^{-1}\left(\frac{N_B}{N_0}\right)$

Sheet Resistance

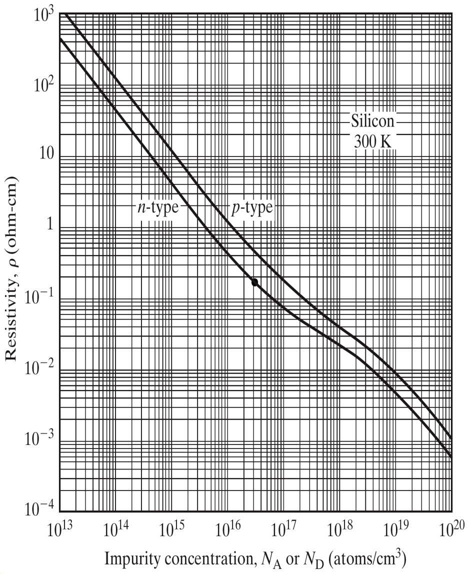


$$A = W \bullet t$$

$$R = \left(\frac{\rho}{t}\right)\left(\frac{L}{W}\right) = R_S\left(\frac{L}{W}\right)$$

$$R_S = \frac{\rho}{t} = \text{Sheet Resistance [Ohms per Square]}$$

Resistivity vs. Doping

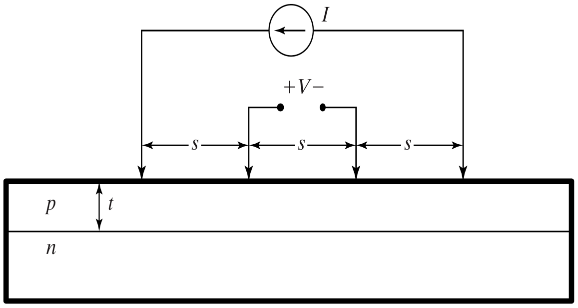


$$\rho = \sigma^{-1} = \left[q\left(\mu_n n + \mu_p p\right)\right]^{-1}$$

$$\text{n-type}: \ \rho \cong \left[q\mu_n\left(N_D - N_A\right)\right]^{-1}$$

$$\text{p-type}: \ \rho \cong \left[q\mu_p\left(N_A - N_D\right)\right]^{-1}$$

Resistivity Measurement: Four-Point Probe



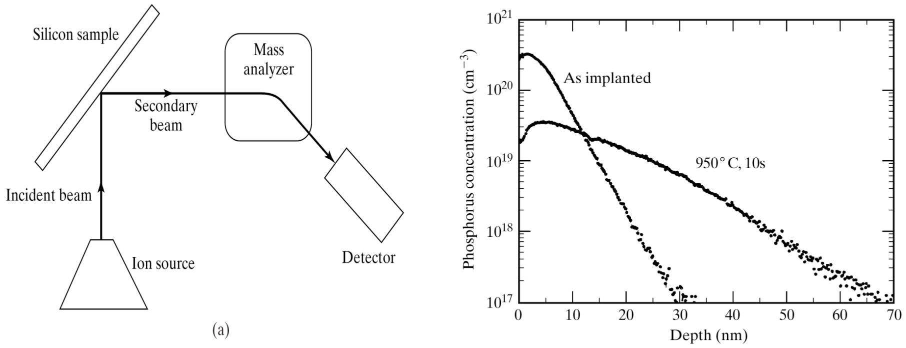
$$\rho = 2\pi s\frac{V}{I} \quad [\Omega\text{-m}]\ \text{for} \quad t >> s$$

$$\rho = \frac{\pi t}{\ln 2}\frac{V}{I} \quad [\Omega\text{-m}]\ \text{for} \quad s >> t$$

$$R_S = \frac{\rho}{t} = \frac{\pi}{\ln 2}\frac{V}{I} \cong 4.53\frac{V}{I} \quad [\Omega/\text{square}]$$

Four Terminal Resistance Measurement

Impurity Profiling with Secondary Ion Mass Spectroscopy (SIMS)



(a)

(b)