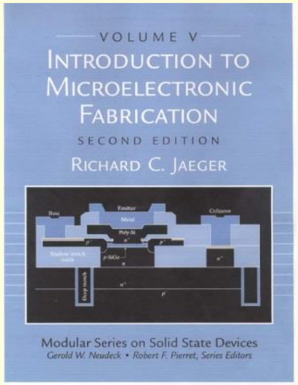
Introduction to Microelectronic Fabrication

Chapter 4
Diffusion



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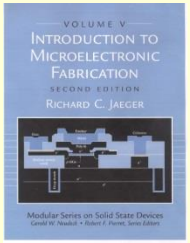
RICHARD C. JAEGER

Modular Series on Solid State Devices
Gerold W. Neudeck • Robert F. Pierret, Series Editors

Impurity Diffusion



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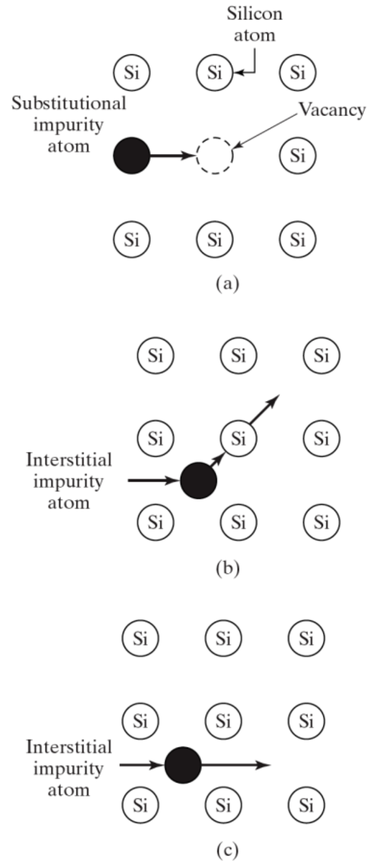
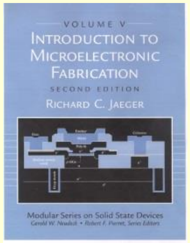


- Diffusion Mechanisms
  - Substitutional
  - Interstitial

FIGURE 4.1

Atomic diffusion in a two-dimensional lattice. (a) Substitutional diffusion, in which the impurity moves among vacancies in the lattice; (b) interstitialcy mechanism, in which the impurity atom replaces a silicon atom in the lattice, and the silicon atom is displaced to a interstitial site; (c) interstitial diffusion, in which impurity atoms do not replace atoms in the crystal lattice.

Diffusion
Fick's First Law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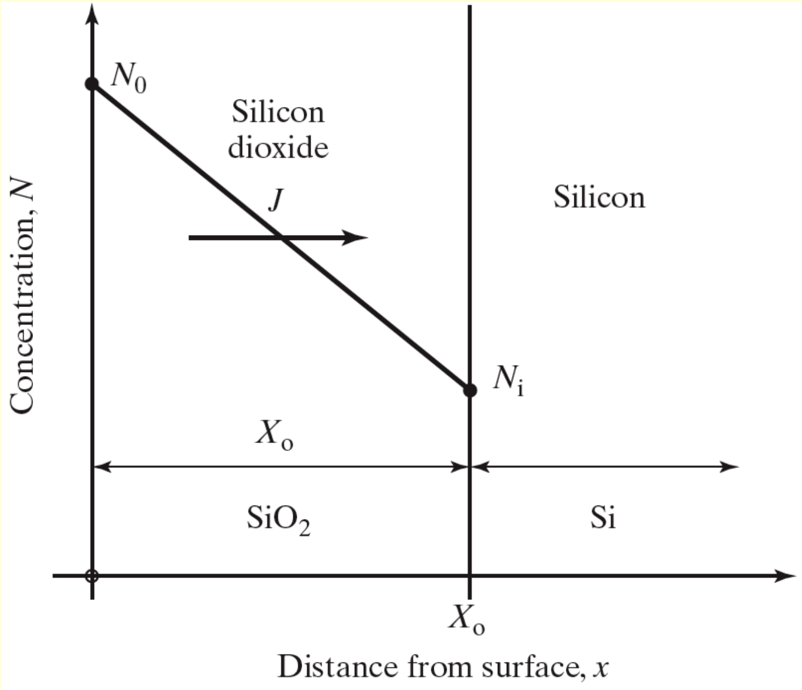
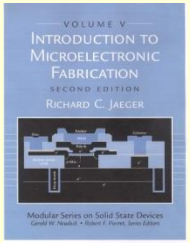


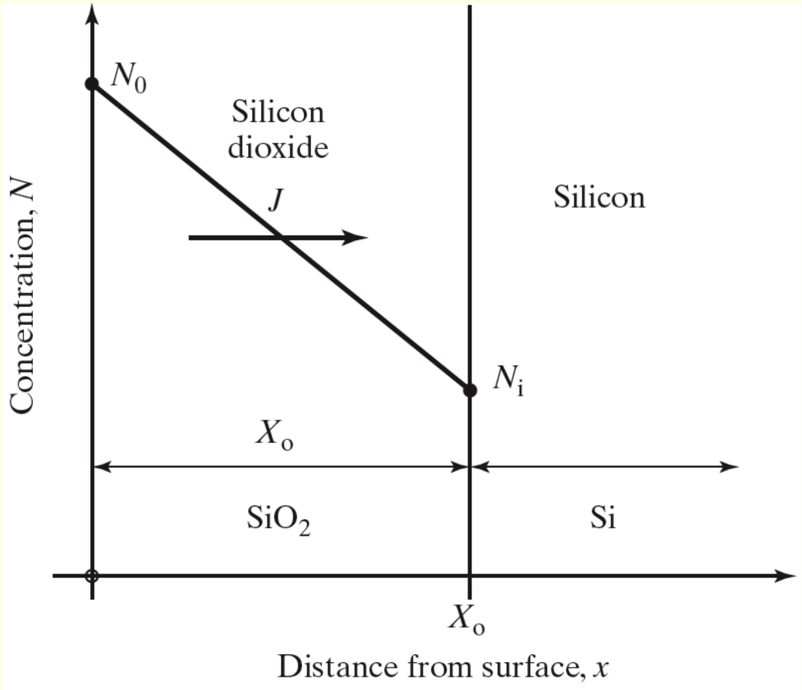
Particle flux J is proportional to the negative of the gradient of the particle concentration

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

D = diffusion coefficient

Diffusion
Fick's Second Law





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 :

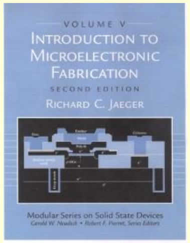
Combine First Law with Continuity Eqn.

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

D assumed to be independent of concentration!

Constant Source Diffusion

Complementary Error Function Profiles



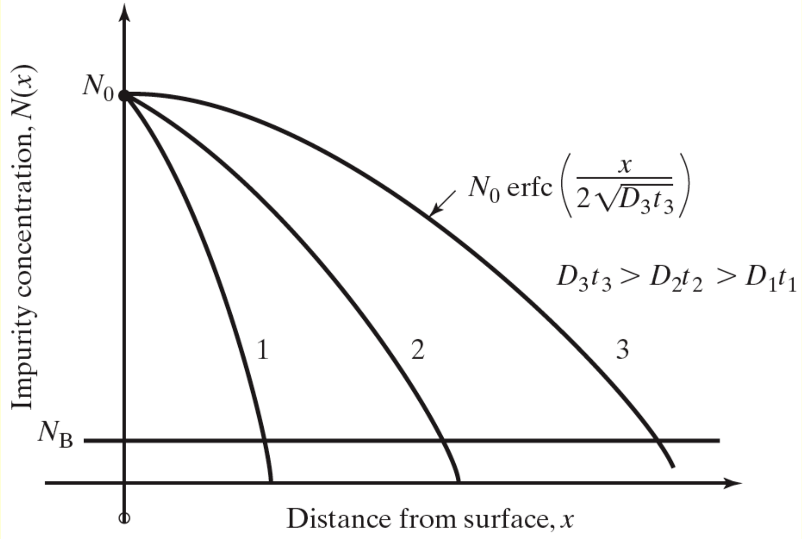


FIGURE 4.2

A constant-source diffusion results in a complementary error function impurity distribution. The surface concentration N_0 remains constant, and the diffusion moves deeper into the silicon wafer as the Dt product increases. Dt can change as a result of increasing diffusion time, increasing diffusion temperature, or a combination of both.

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

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

N_0 = Surface Concentration

D = Diffusion Coefficient

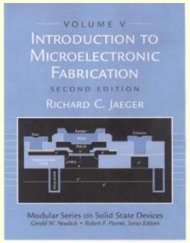
erfc = Complementary Error Function

$$erfc(z) = 1 - erf(z)$$

$$erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z \exp\left[-x^2\right]dx$$

Limited Source Diffusion

Gaussian Profiles



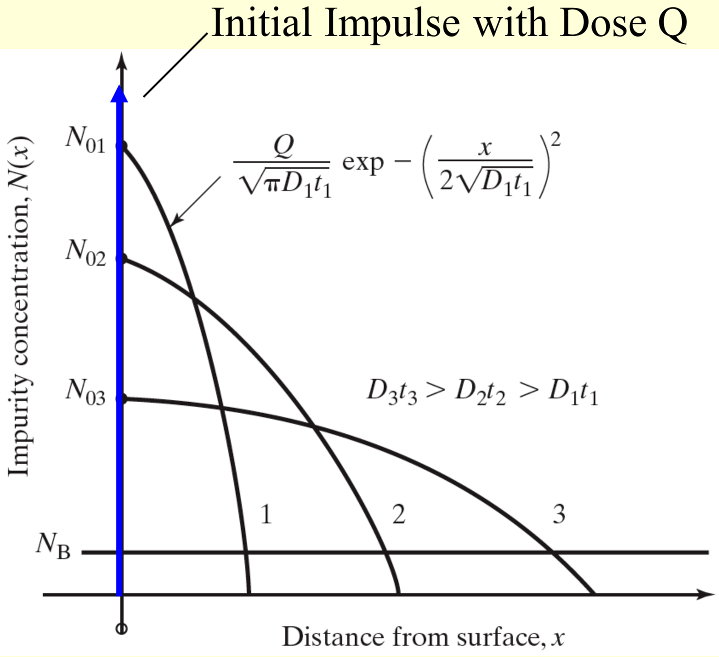

Initial Impulse with Dose Q

FIGURE 4.3

A Gaussian distribution results from a limited-source diffusion. As the Dt product increases, the diffusion front moves more deeply into the wafer, and the surface concentration decreases. The area (impurity dose) under each of the three curves is the same.

Concentration :

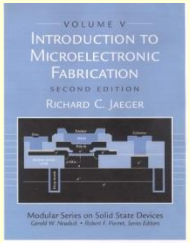
$$N(x,t) = N_0 \exp\left[-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right] = \frac{Q}{\sqrt{\pi Dt}} \exp\left[-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right]$$

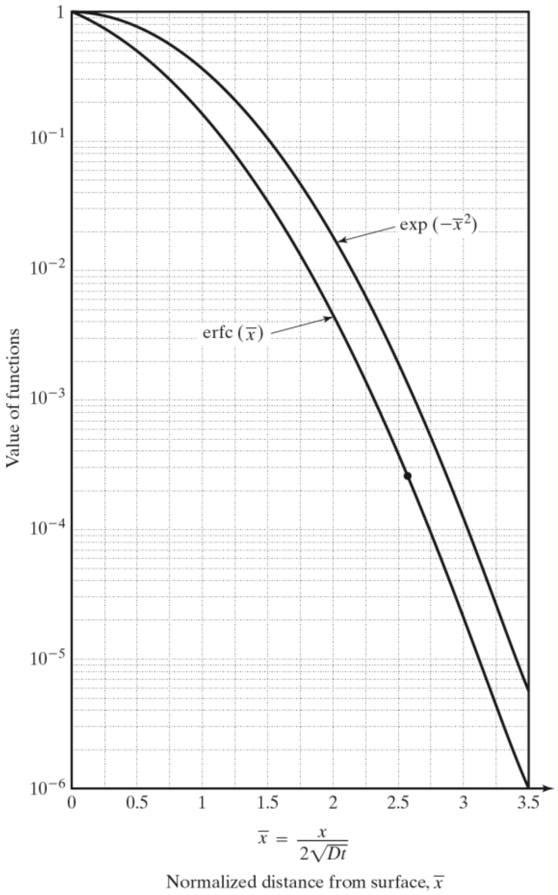
N_0 = Surface Concentration $N_0 = \frac{Q}{\sqrt{\pi Dt}}$

D = Diffusion Coefficient

Gaussian Profile

Diffusion
Profile Comparison





Complementary Error Function and Gaussian Profiles are Similar in Shape

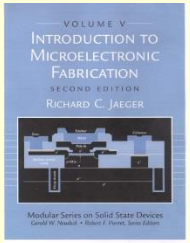
$$erfc(z) = 1 - erf(z)$$

$$erf(z) = \frac{2}{\sqrt{\pi}} \int_0^z \exp\left[-x^2\right] dx$$

FIGURE 4.4

A graph comparing the Gaussian and complementary error function (erfc) profiles. We use this curve to evaluate the erfc and its inverse.

Diffusion Coefficients



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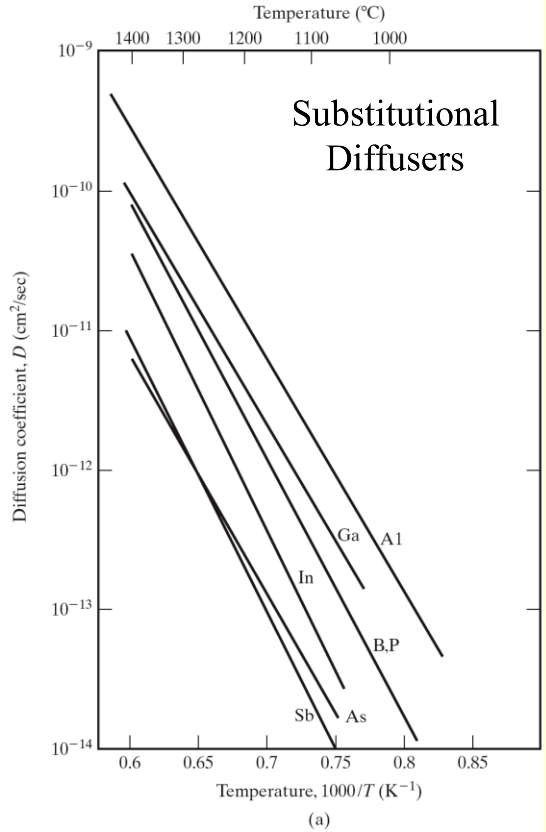
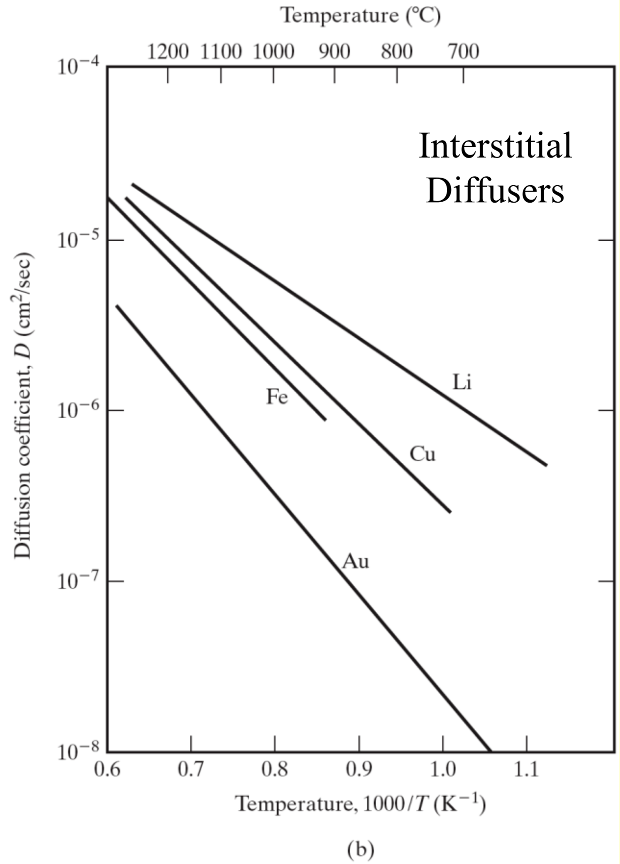


FIGURE 4.5

Diffusion constants in silicon for (a) substitutional diffusers (above) and (b) interstitial diffusers (next page). Copyright John Wiley & Sons, Inc.; reprinted with permission from Ref. [28].



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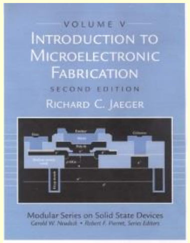


Diffusion Coefficients

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

E_A = activation energy

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

T = absolute temperature

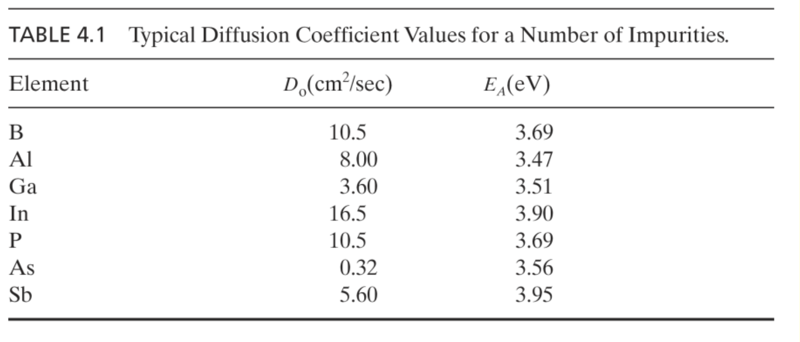
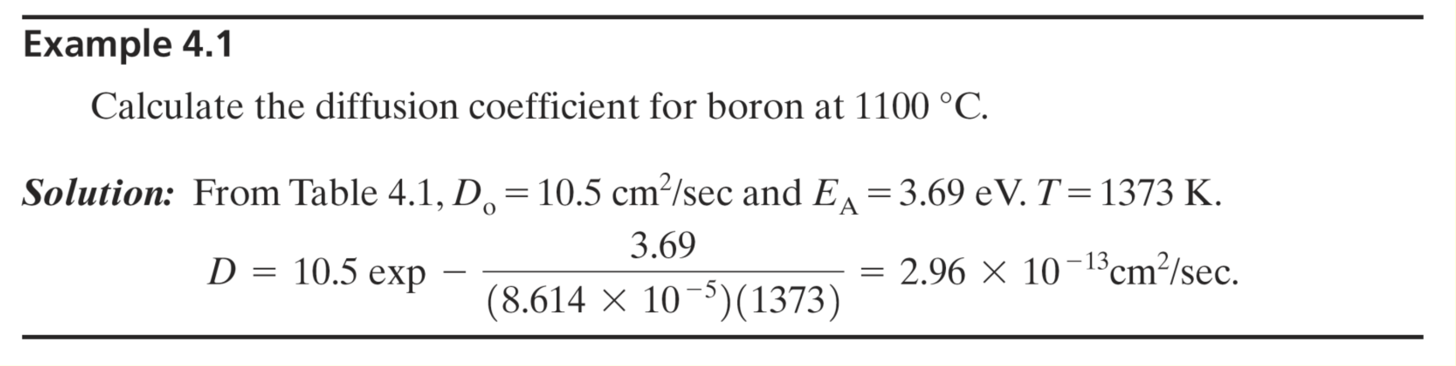


TABLE 4.1 Typical Diffusion Coefficient Values for a Number of Impurities.

Element	D_o(cm^2/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



Example 4.1

Calculate the diffusion coefficient for boron at 1100 °C.

Solution: From Table 4.1, $D_o = 10.5$ cm^2/sec and $E_A = 3.69$ eV. $T = 1373$ K.

$$D = 10.5 \exp - \frac{3.69}{(8.614 \times 10^{-5})(1373)} = 2.96 \times 10^{-13}\text{cm}^2/\text{sec}.$$

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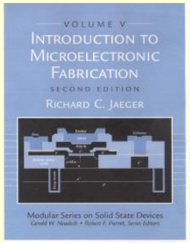

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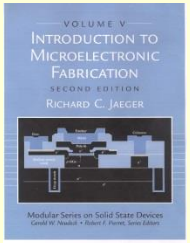
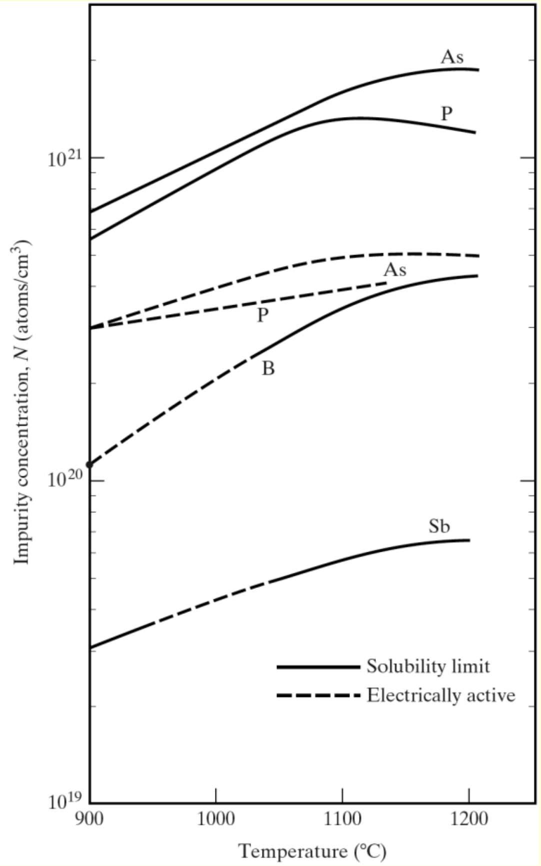
Successive Diffusions

- Successive Diffusions Using Different Times and Temperatures
- Final Result Depends Upon the Total Dt Product

$$(Dt)_{tot} = \sum_i D_i t_i$$

Diffusion
Solid Solubility Limits



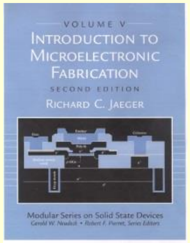


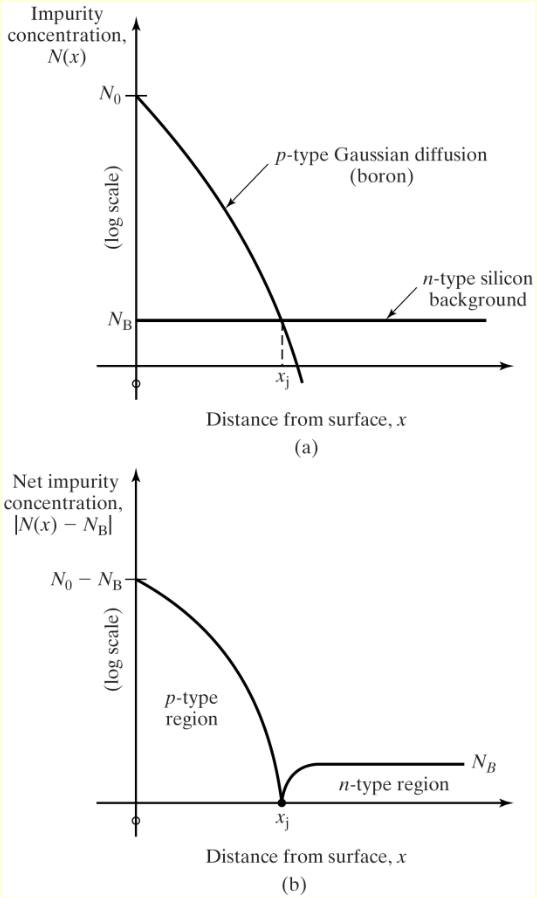
- There is a limit to the amount of a given impurity that can be “dissolved” in silicon (the Solid Solubility Limit)
- At high concentrations, all of the impurities introduced into silicon will not be electrically active

FIGURE 4.6

The solid-solubility and electrically active impurity-concentration limits in silicon for antimony, arsenic, boron, and phosphorus. Reprinted with permission from Ref. [29]. This paper was originally presented at the 1977 Spring Meeting of The Electrochemical Society, Inc., held in Philadelphia, Pennsylvania.

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

FIGURE 4.7

Formation of a *pn* junction by diffusion. (a) An example of a *p*-type Gaussian diffusion into a uniformly doped *n*-type wafer; (b) net impurity concentration in the wafer. The metallurgical junction occurs at the point $x = x_j$ where the net concentration is zero. The material is converted to *p*-type to the left of x_j and remains *n*-type to the right of x_j.

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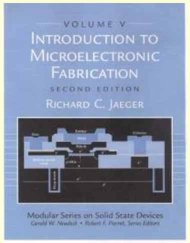
Diffusion
Resistivity vs. Doping



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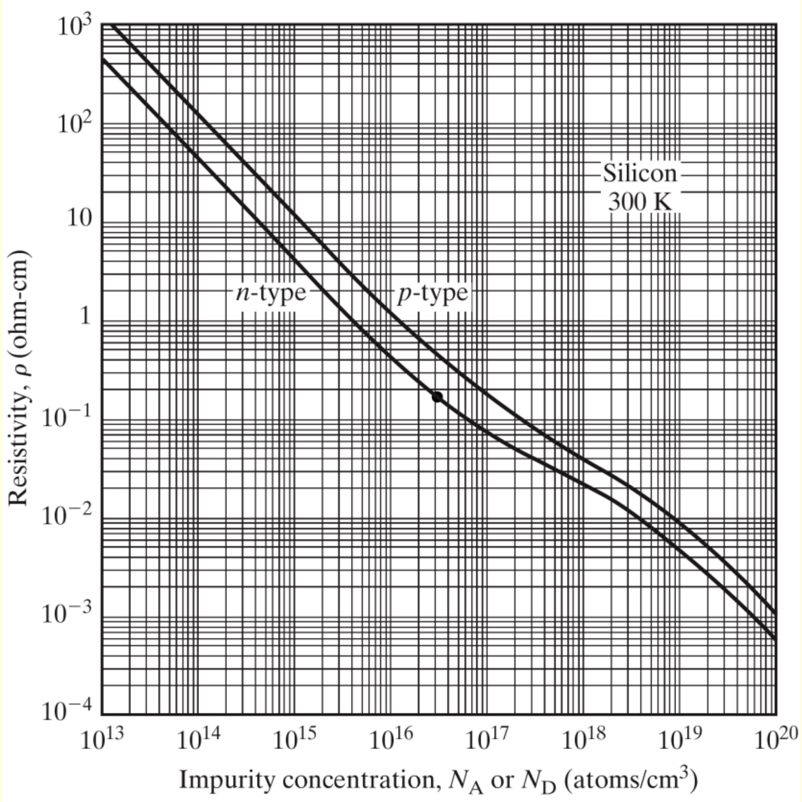


$$\rho = \sigma^{-1} = \left[q\left(\mu_n n + \mu_p p\right)\right]^{-1}$$

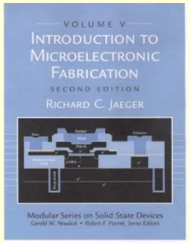
$$\text{n-type: } \rho \cong \left[q\mu_n\left(N_D - N_A\right)\right]^{-1}$$

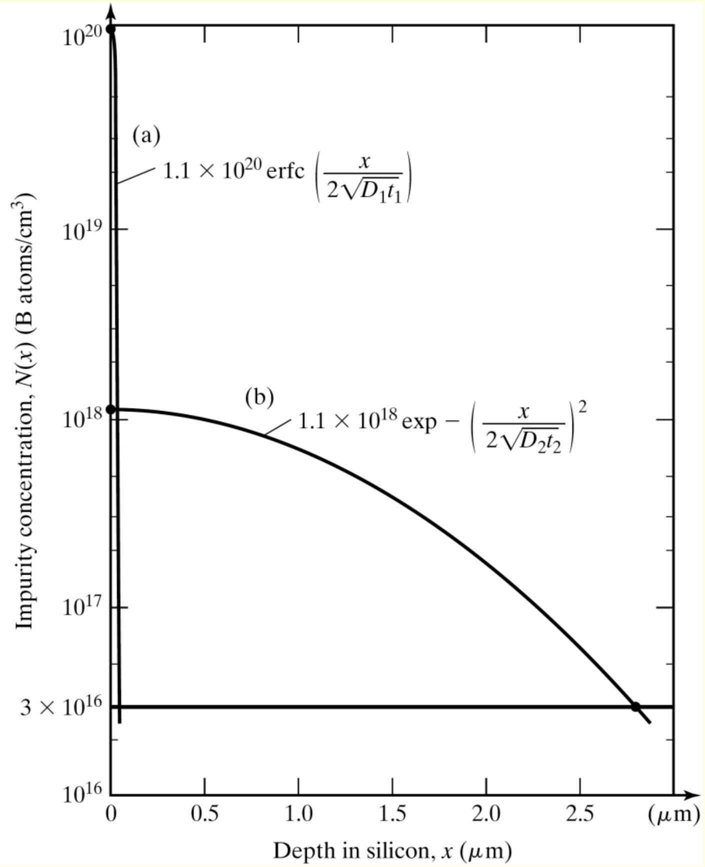
$$\text{p-type: } \rho \cong \left[q\mu_p\left(N_A - N_D\right)\right]^{-1}$$

FIGURE 4.8

Room-temperature resistivity in *n*- and *p*-type silicon as a function of impurity concentration. (Note that these curves are valid for either donor or acceptor impurities but not for compensated material containing both types of impurities.) Copyright 1987 Addison-Wesley Publishing Company. Reprinted with permission from Ref. [3].

Diffusion
Two Step Diffusion





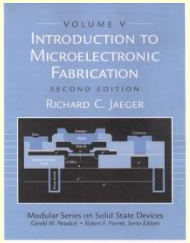
- Short constant source diffusion used to establish dose Q   (“Predep” step)
- Longer limited source diffusion drives profile in to desired depth (“drive in” step)
- Final profile is Gaussian

FIGURE 4.9

Calculated boron impurity profiles for Example 4.2. (a) Following the predeposition step at 900°C for 15 min; (b) following a subsequent 5-hr drive-in step at 1,100°C. The final junction depth is 2.77 μm with a surface concentration of 1.1×10^{18}/cm^3. The initial profile approximates an impulse.

Diffusion Calculation

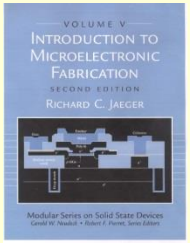
Example 4.3 - Boron Diffusion

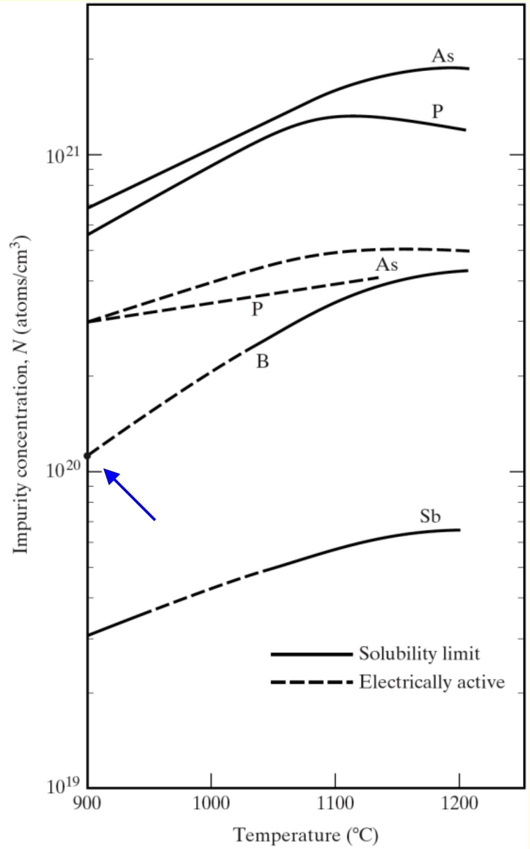


- A boron diffusion is used to form the base region of an npn transistor in a 0.18 Ω-cm n-type silicon wafer. A solid-solubility-limited boron predeposition is performed at 900^{o} C for 15 min followed by a 5-hr drive-in at 1100^{o}C. Find the surface concentration and junction depth (a) after the predep step and (b) after the drive-in step.

Diffusion Calculation

Example 4.3 - Boron Diffusion





Predeposition step is solid-solubility limited.

$$T_1 = 900^\circ C = 1173K \rightarrow N_O = 1.1x10^{20}/cm^3$$

$$D_1 = 10.5\exp\left[-\frac{3.69eV}{\left(8.614x10^{-5}eV/K\right)1173K}\right] = 1.45x10^{-15}cm^2/\sec$$

$$t_1 = 15\ \min = 900\ \sec \qquad D_1t_1 = 1.31x10^{-12}cm^2$$

$$N(x) = 1.1x10^{20}erfc\left(\frac{x}{2.28x10^{-6}cm}\right)/cm^3$$

$$\text{Dose:}\quad Q = 2N_O\sqrt{\frac{D_1t_1}{\pi}} = 1.42x10^{14}/cm^2$$

$$T_2 = 1100^\circ C = 1373K$$

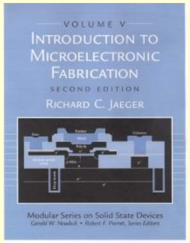
$$D_2 = 10.5\exp\left[-\frac{3.69eV}{\left(8.614x10^{-5}eV/K\right)1373K}\right] = 2.96x10^{-13}cm^2/\sec$$

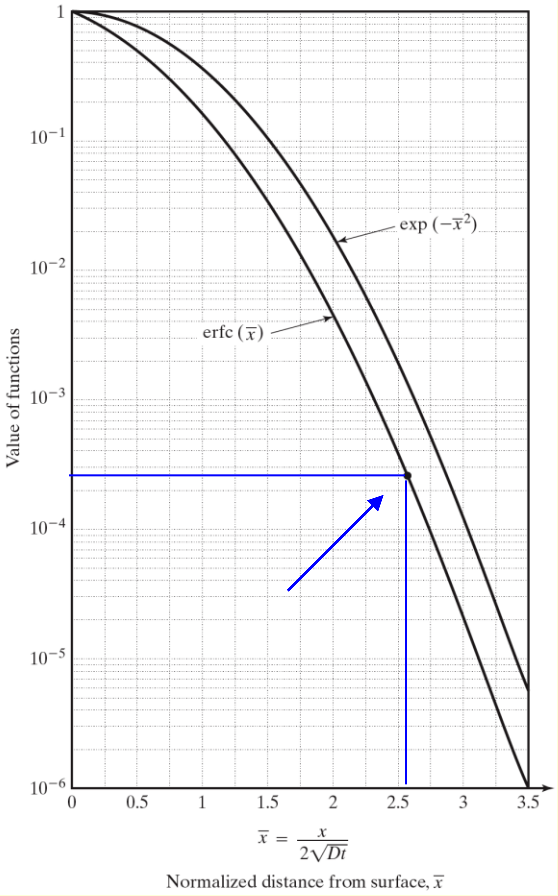
$$t_2 = 5\ hr = 18000\ \sec \qquad D_2t_2 = 5.33x10^{-9}cm^2$$

$$N_2(x) = \frac{1.42x10^{14}/cm^2}{\sqrt{\pi\left(5.33x10^{-9}cm^2\right)}}\exp\left(-\frac{x}{2\sqrt{D_2t_2}}\right)^2 = 1.1x10^{18}\exp\left(-\frac{x}{1.46x10^{-4}}\right)^2/cm^3$$

Diffusion Calculation

Example 4.3 (cont.)





$$N_1(x) = 1.1x10^{20} erfc\left(\frac{x}{2.28x10^{-6}cm}\right)/cm^3$$

$$x_{j1} = 2\sqrt{D_1 t_1}\, erfc^{-1}\left(\frac{N_o}{N_B}\right) = \left(2.28x10^{-6}cm\right) erfc^{-1}\left(\frac{3x10^{16}}{1.1x10^{20}}\right) = \left(2.28x10^{-6}cm\right) erfc^{-1}\left(2.73x10^{-4}\right)$$

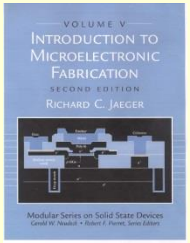
$$x_{j1} = \left(2.28x10^{-6}cm\right)\left(2.57\right) = 5.86x10^{-6}cm = 0.058$$

$$N_2(x) = 1.1x10^{18} \exp\left(-\frac{x}{1.46x10^{-4}}\right)^2 /cm^3$$

$$x_{j2} = 1.46x10^{-4}cm\sqrt{\ln\left(\frac{1.1x10^{18}}{3x10^{16}}\right)} = 2.77x10^{-4}cm = 2.77\mu m$$

Diffusion Calculation

Example 4.3 (cont.)



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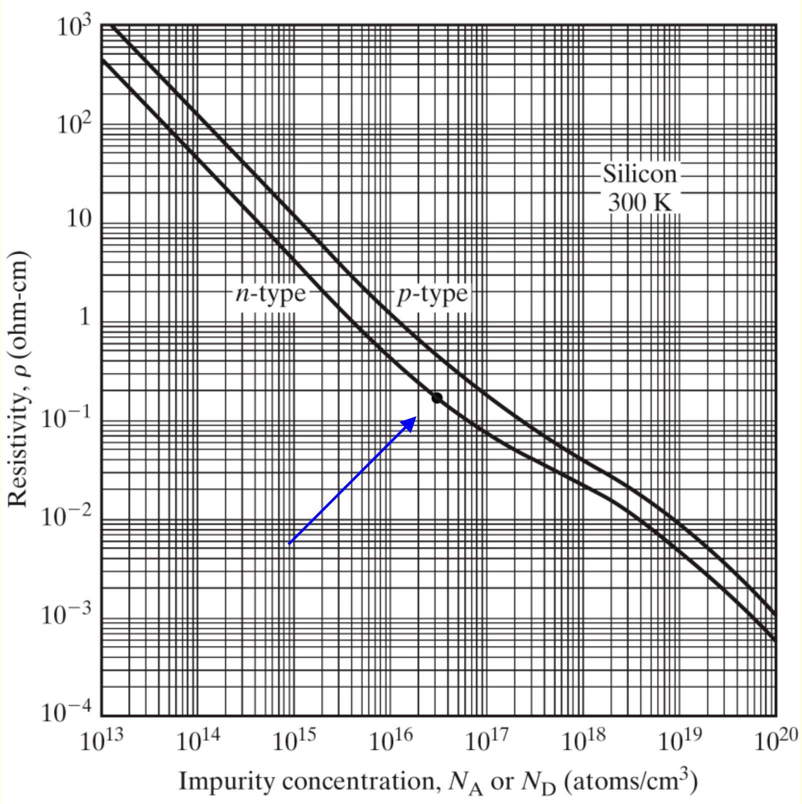
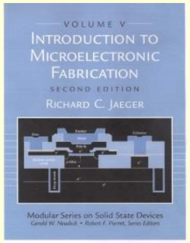


$$\text{Starting Wafer : n-type } 0.18\Omega - \text{cm}$$

$$\text{n-type } 0.18\Omega - \text{cm} \;\rightarrow N_D = 3 \text{ x } 10^{16}/\text{cm}^3$$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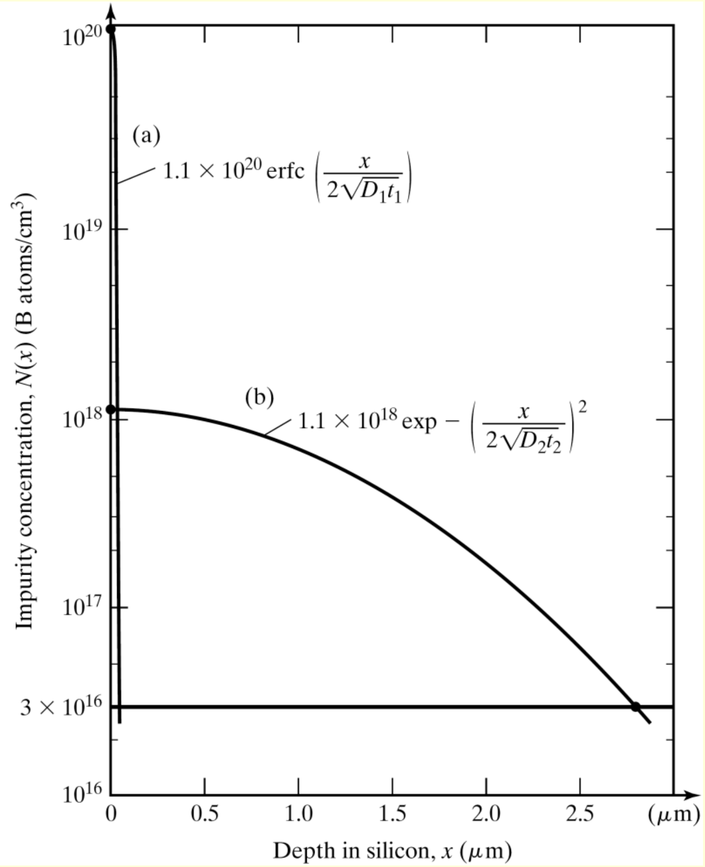
Two Step Diffusion



- Short constant source diffusion used to establish dose Q ("Predep" step)
- Longer limited source diffusion drives profile in to desired depth ("drive in" step)
- Final profile is Gaussian

FIGURE 4.9

Calculated boron impurity profiles for Example 4.2. (a) Following the predeposition step at 900°C for 15 min; (b) following a subsequent 5-hr drive-in step at 1,100°C. The final junction depth is 2.77 μm with a surface concentration of 1.1×10^{18}/cm^3. The initial profile approximates an impulse.

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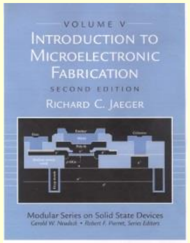
Lateral Diffusion Under Mask Edge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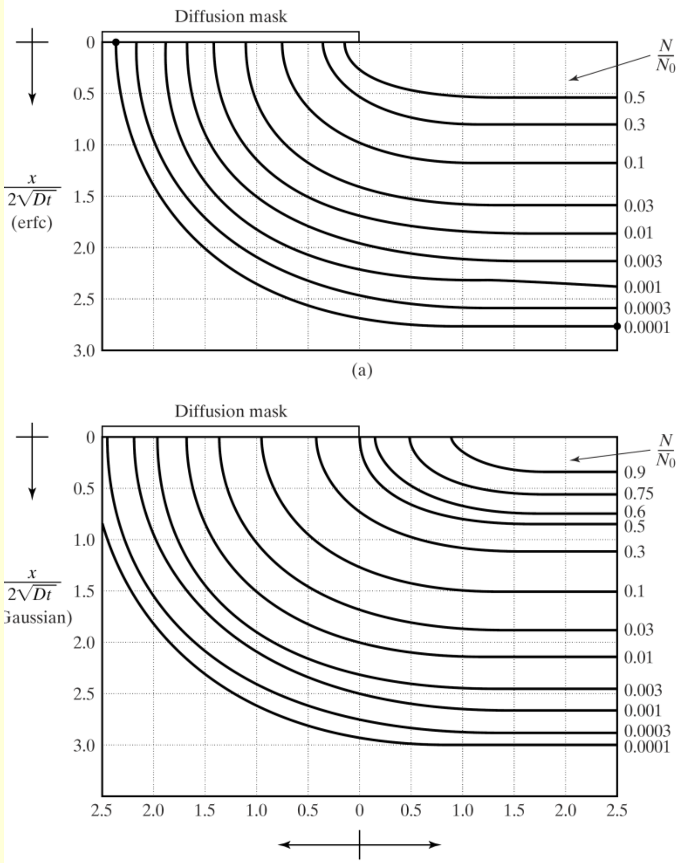
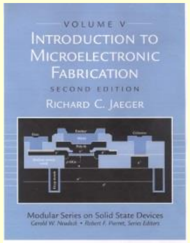


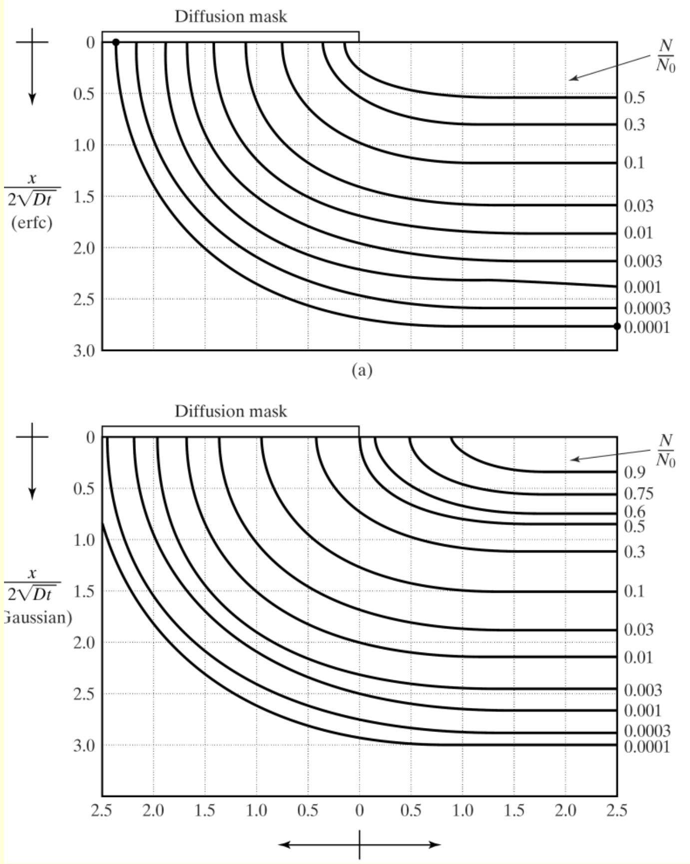
- Diffusion is really a 3-D process. As impurities diffuse vertically, they also diffuse horizontally in both directions.
- Diffusion proceeds laterally under the edge of the mask opening

FIGURE 4.10

Normalized two-dimensional complementary error function and Gaussian diffusions near the edge of a window in the barrier layer. Copyright 1965 by International Business Machines Corporation; reprinted with permission from Ref. [4].

Lateral Diffusion Under Mask Edge





Original Mask

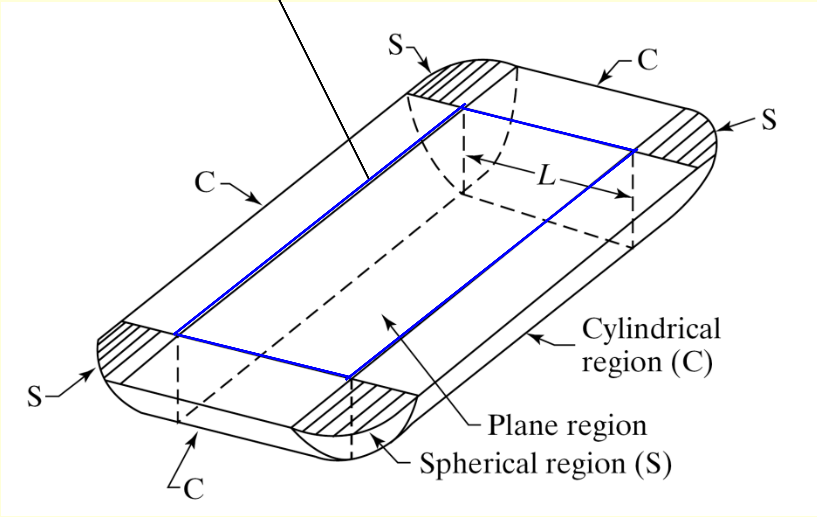
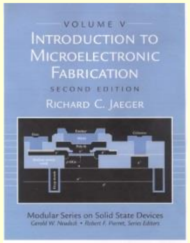
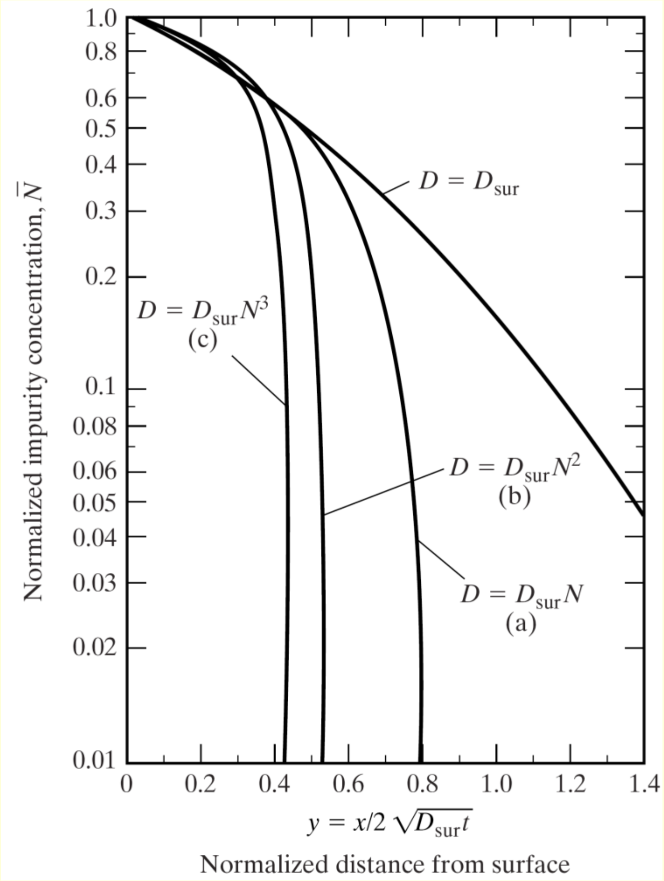


FIGURE 4.10

Normalized two-dimensional complementary error function and Gaussian diffusions near the edge of a window in the barrier layer. Copyright 1965 by International Business Machines Corporation; reprinted with permission from Ref. [4].

Concentration Dependent Diffusion





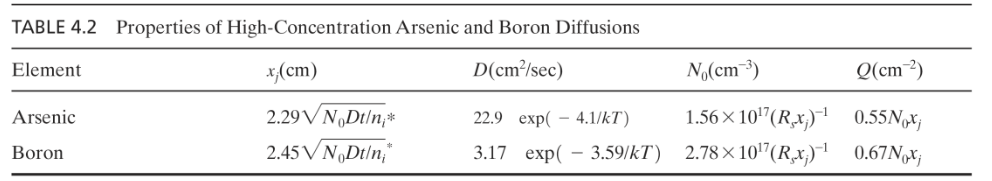


TABLE 4.2 Properties of High-Concentration Arsenic and Boron Diffusions

Element	x_j(cm)	D(cm^2/sec)	N_0(cm^{-3})	Q(cm^{-2})
Arsenic	$2.29\sqrt{N_0Dt/n_i}*$	22.9 exp(− 4.1/kT)	$1.56\times10^{17}(R_sx_j)^{-1}$	$0.55N_0x_j$
Boron	$2.45\sqrt{N_0Dt/n_i}^*$	3.17 exp(− 3.59/kT)	$2.78\times10^{17}(R_sx_j)^{-1}$	$0.67N_0x_j$

Second Law of Diffusion

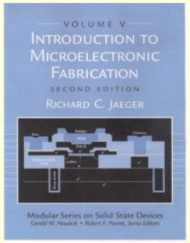
$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial x} D(x) \frac{\partial N}{\partial x}$$

Profiles More Abrupt at High Concentrations

FIGURE 4.11

Diffusion profiles for concentration-dependent diffusion. Copyright 1963 by the American Physical Society. Reprinted with permission from Ref. [6].

Concentration Dependent Diffusion



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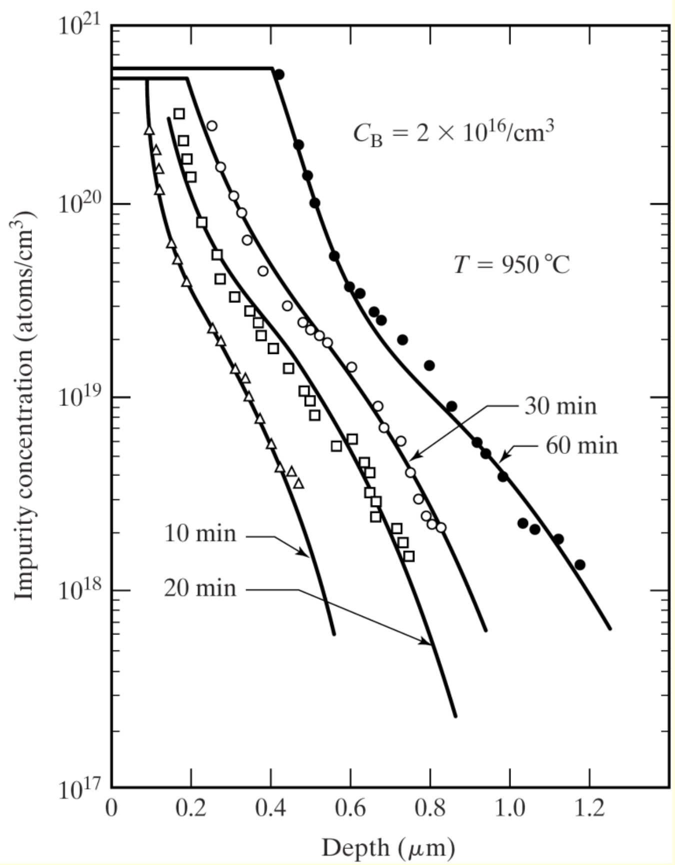
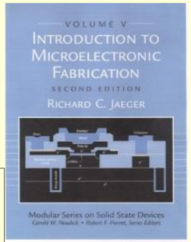
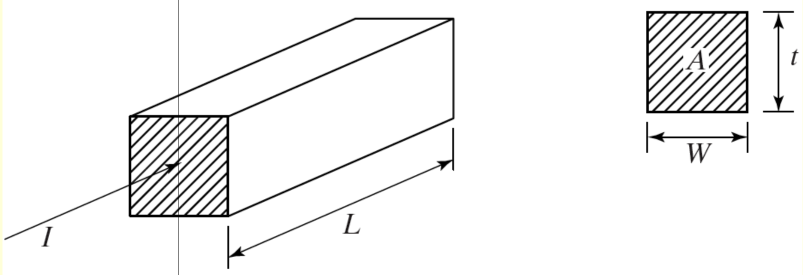


FIGURE 4.12

Shallow phosphorus diffusion profiles for constant-source diffusions at 950 $^{\text{O}}$C. Copyright 1969 IEEE. Reprinted with permission from Ref. [10].

Resistors
Sheet Resistance





$$R = \rho \frac{L}{A} \qquad \rho = \frac{1}{\sigma} \qquad \sigma = q\,(\mu_n n + \mu_p p)$$

FIGURE 4.13

Resistance of a block of material having uniform resistivity. A uniform current distribution is entering the material perpendicular to the end of the block. The ratio of resistivity to thickness is called the *sheet resistance* of the material.

$$A = W \bullet t$$

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

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

$$\left(\frac{L}{W}\right) = \text{Number of Squares of Material}$$

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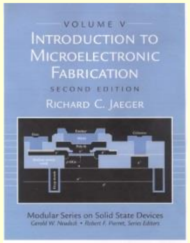
Resistors
Counting Squares



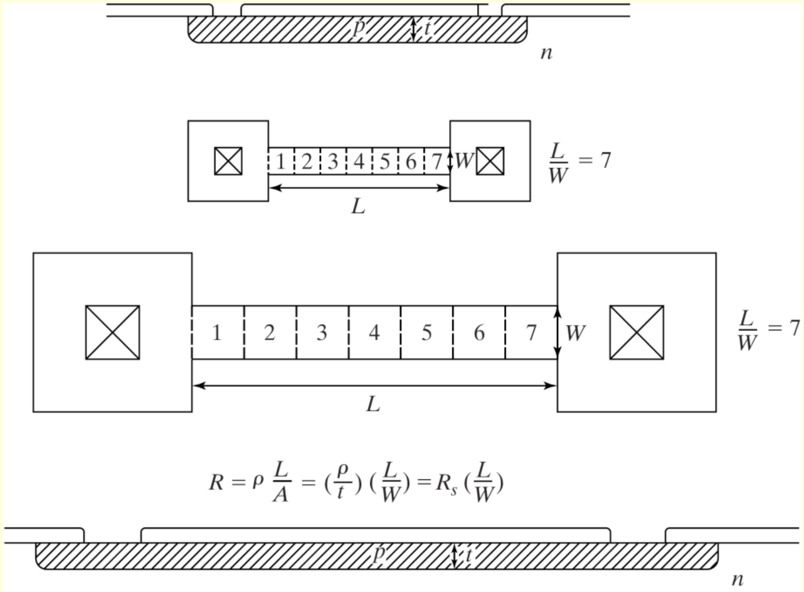


Figure 4.14

- Top and Side Views of Two Resistors of Different Size
- Resistors Have Same Value of Resistance
- Each Resistor is 7 □ in Length
- Each End Contributes Approximately 0.65 □
- Total for Each is 8.3 □

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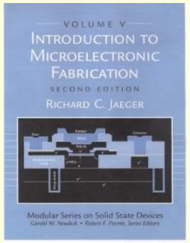
Resistors
Contact and Corner Contributions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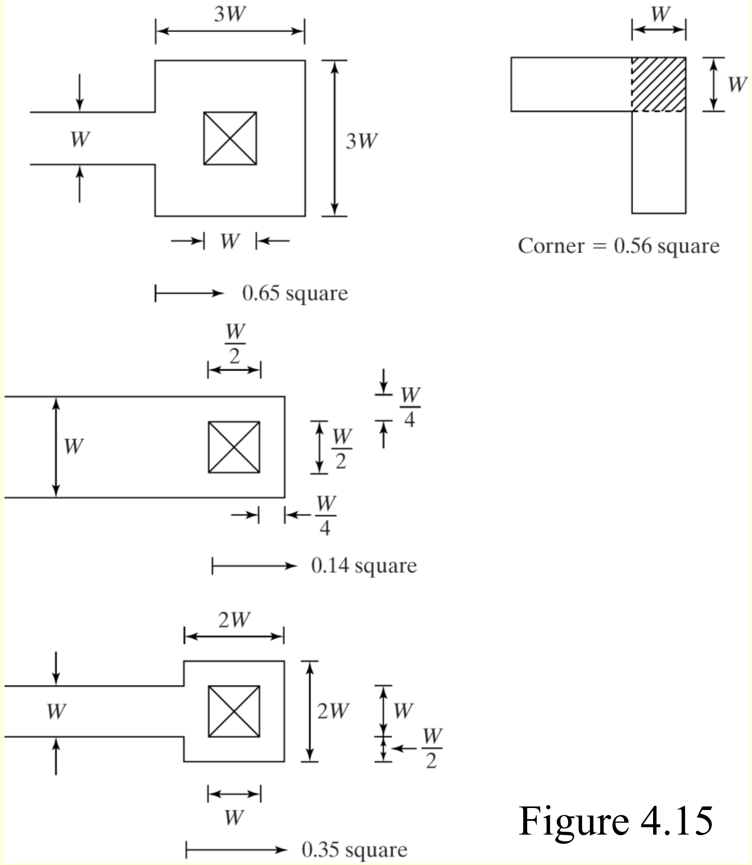

Figure 4.15

- Effective Square Contributions of Various Resistor End and Corner Configurations

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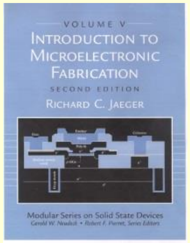
Sheet Resistance
Irvin's Curves



$$\bar{\rho} = \frac{1}{\bar{\sigma}} = \frac{1}{\dfrac{1}{x_j}\displaystyle\int_0^{x_j} \sigma(x)\,dx}$$

$$R_S = \frac{\bar{\rho}}{x_j} = \frac{1}{\displaystyle\int_0^{x_j} \sigma(x)\,dx}$$

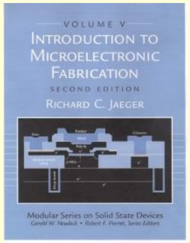
$$R_S \cong \left[\int_0^{x_j} q\mu N(x)\,dx\right]^{-1}$$

- Irvin Evaluated this Integral and Published a Set of Normalized Curves Plot Surface Concentration Versus Average Resistivity

$$\bar{\rho} = R_S x_j$$

- Four Sets of Curves
  - n-type and p-type
  - Gaussian and erfc

Sheet Resistance
Irvin’s Curves



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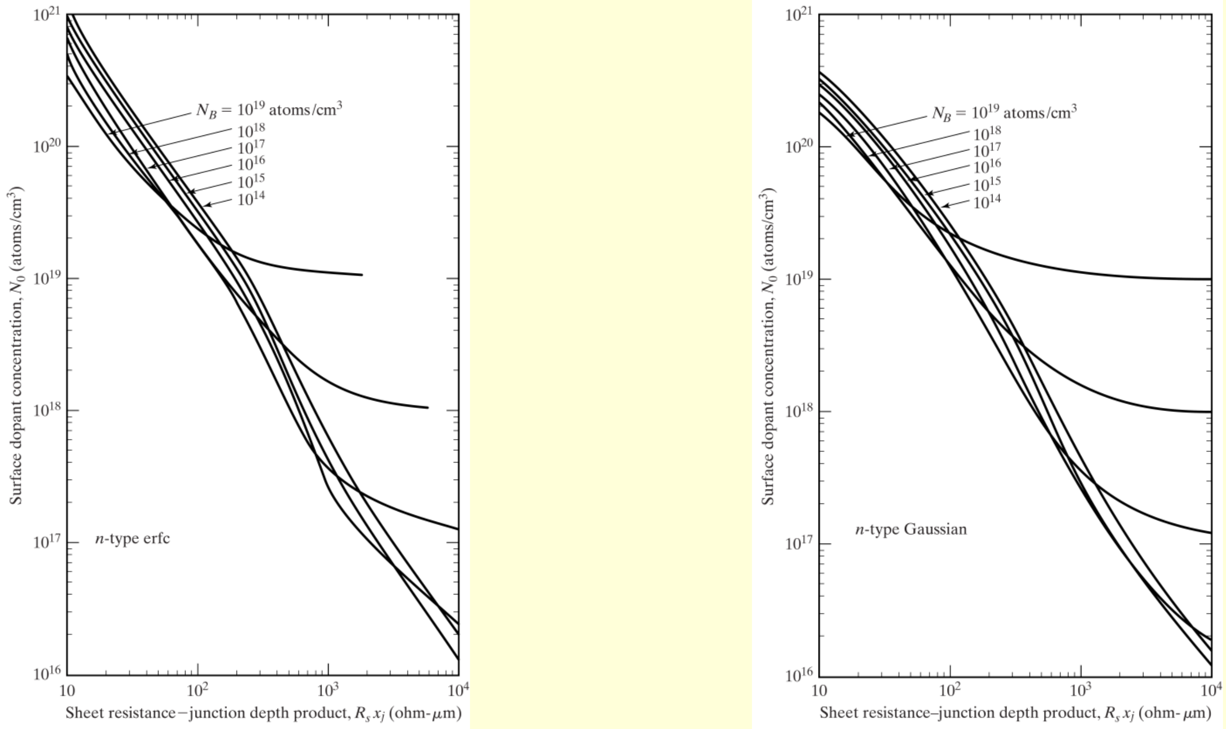

(a) (b)

FIGURE 4.16

Surface impurity concentration versus the sheet resistance–junction depth product for different silicon background concentrations at 300 K. (a) *n*-type erfc distribution; (b) *n*-type Gaussian distribution; (c) *p*-type erfc distribution; (d) *p*-type Gaussian distribution. After Ref. [2]. Reprinted from Ref. [5] with permission from the *AT&T Technical Journal*. Copyright 1962 AT&T.

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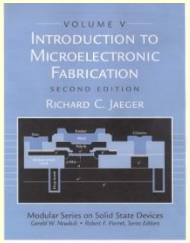
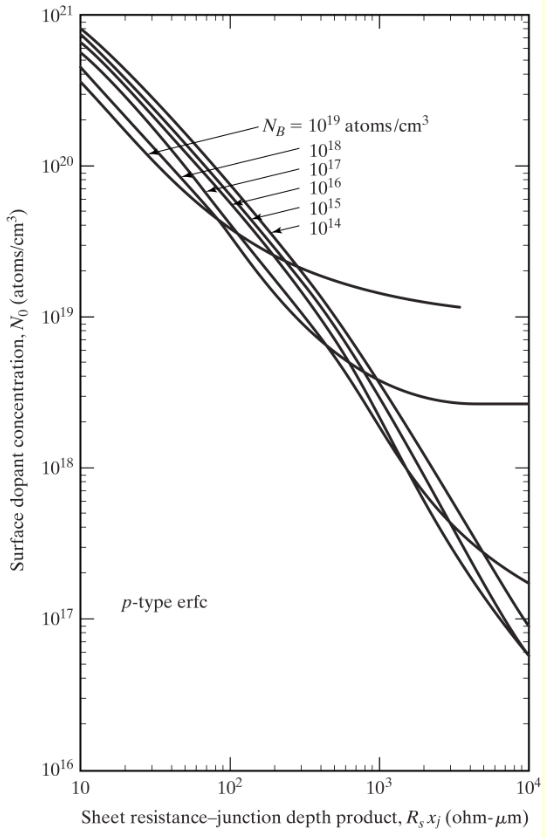
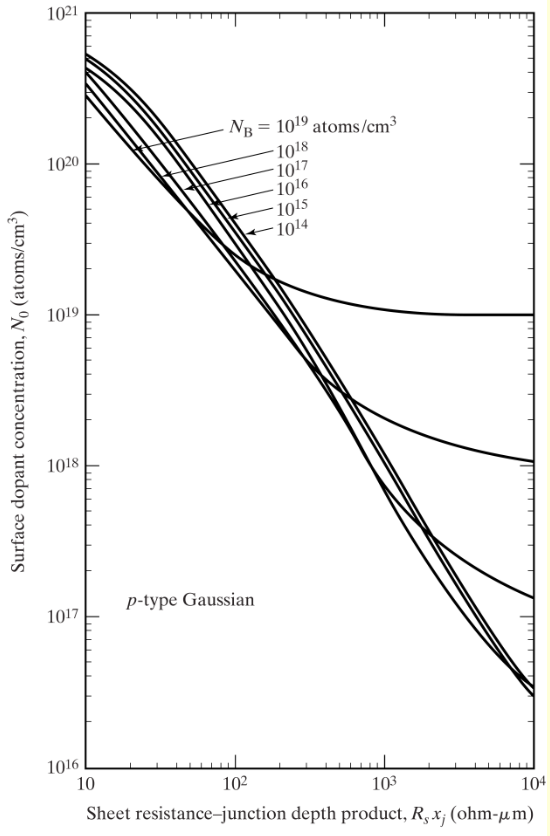
Sheet Resistance
Irvin's Curves (cont.)





(c)



(d)

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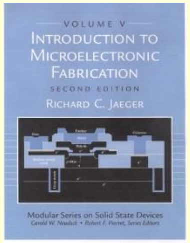
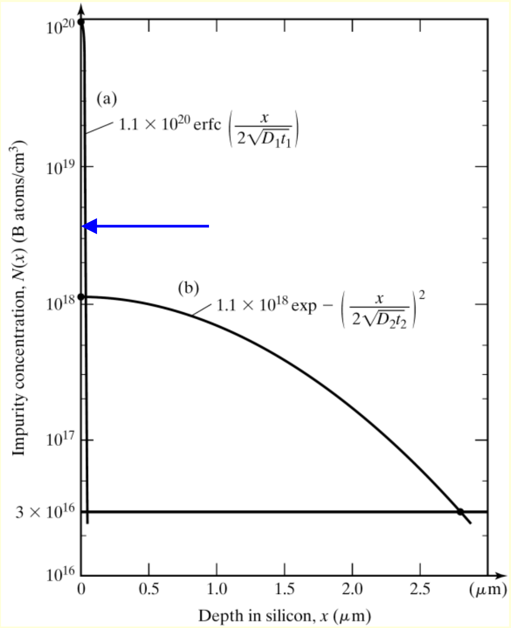
Two Step Diffusion

Sheet Resistance - Predep Step





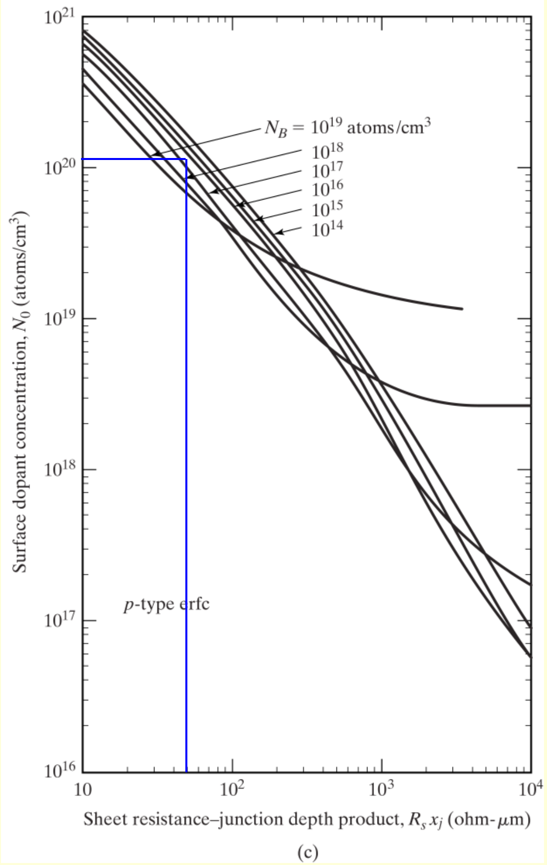
Initial Profile

$$N_o = 1.1x10^{20}/cm^3$$

$$N_B = 3x10^{16}/cm^3$$

$$x_j = 0.0587\ \mu m$$

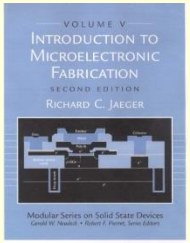
p – type erfc profile

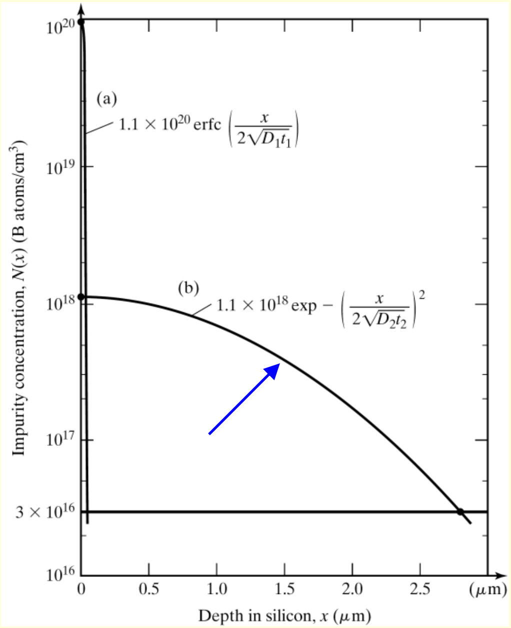


$$R_S x_j = 50\ \Omega\text{-}\mu m$$

$$R_S = \frac{32\ \Omega\text{-}\mu m}{0.0587\ \mu m} = 850\ \Omega/\text{Square}$$

Two Step Diffusion
Sheet Resistance - Drive-in Step





Final Profile

$$N_o = 1.1x10^{18}/cm^3$$

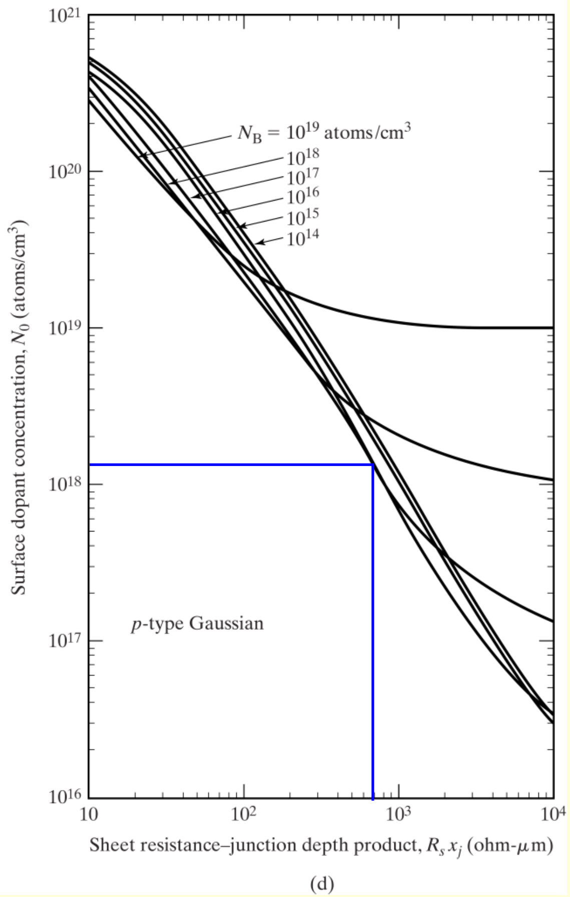
$$N_B = 3x10^{16}/cm^3$$

$$x_j = 2.73\ \mu m$$

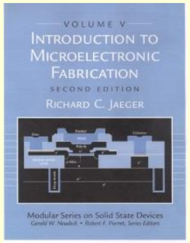
p – type Gaussian profile

$$R_S x_j = 700\ \Omega\text{-}\mu m$$

$$R_S = \frac{700\ \Omega\text{-}\mu m}{2.73\ \mu m} = 260\ \Omega/\text{Square}$$



Resistivity Measurement
Four-Point Probe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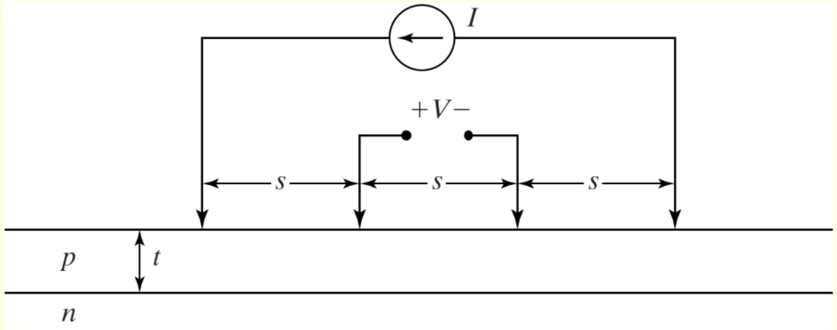

FIGURE 4.17

Four-point probe with probe spacing *s* used for direct measurement of bulk wafer resistivity and the sheet resistance of thin diffused layers. A known current is forced throught the outer probes, and the voltage developed is measured across the inner probes. (See Eqs. (4.16) through (4.18).)

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

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

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

Four Terminal Resistance Measurement

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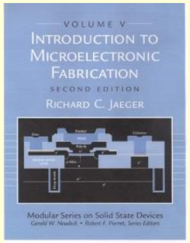
Four-Point Probe
Correction Factors



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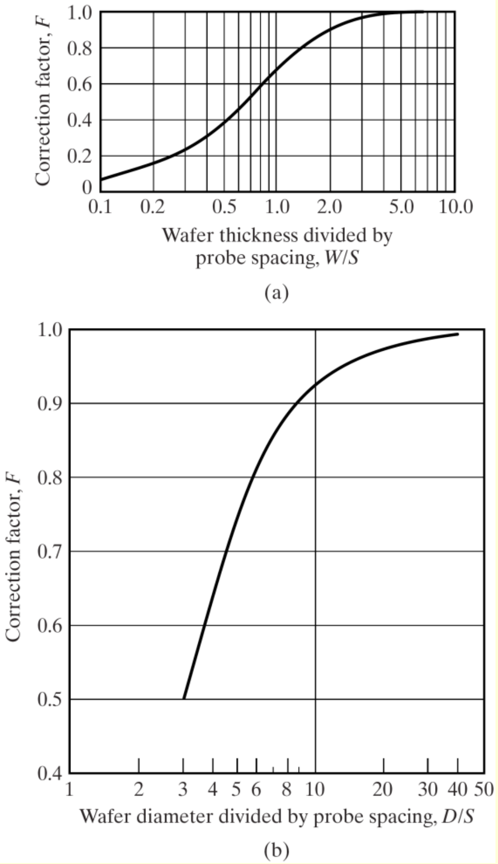


Correction Factors

(a) Wafers Thick Relative to the Probe Spacing

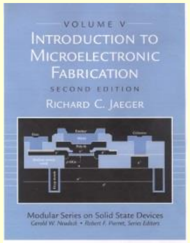
(b) Wafers of Finite Diameter

$$\rho = F\rho_{measured}$$

FIGURE 4.18

Four-point-probe correction factors, F, used to correct for (a) wafers which are relatively thick compared to the probe spacing s and (b) wafers of finite diameter. In each case __= $F_{\text{—measured}}$. (a) Copyright 1975 by McGraw-Hill Book Company. Reprinted with permission from Ref. [12]. (b) Reprinted from Ref. [30] with permission from the AT&T Technical Journal. Copyright 1958 AT&T.

Sheet Resistance
van der Pauw's Method



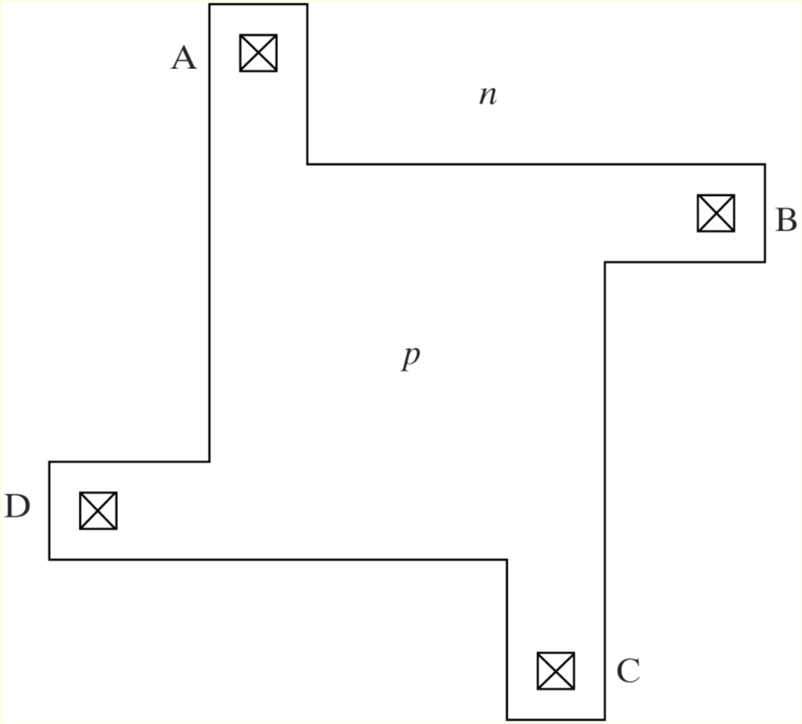


FIGURE 4.19

A simple van der Pauw test structure used to measure the sheet resistance of a diffused layer. Sheet resistance is calculated using Eq. (4.20).

Van der Pauw's Theory

Any Four-Terminal Region without Holes

$$\exp\left(-\pi t \frac{R_{AB,CD}}{\rho}\right) + \exp\left(-\pi t \frac{R_{BC,DA}}{\rho}\right) = 1$$

$$R_{AB,CD} = \frac{V_{CD}}{I_{AB}} \quad \text{and} \quad R_{BC,DA} = \frac{V_{DA}}{I_{BC}}$$

For symmetrical structure $R_{AB,CD} = R_{AB,CD}$

$$R_S = \frac{\rho}{t} = \left(\frac{\pi}{\ln 2}\right)\frac{V_{CD}}{I_{AB}}$$

Four Terminal Resistance Measurement

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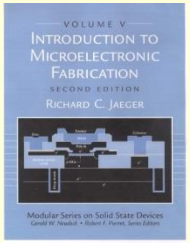
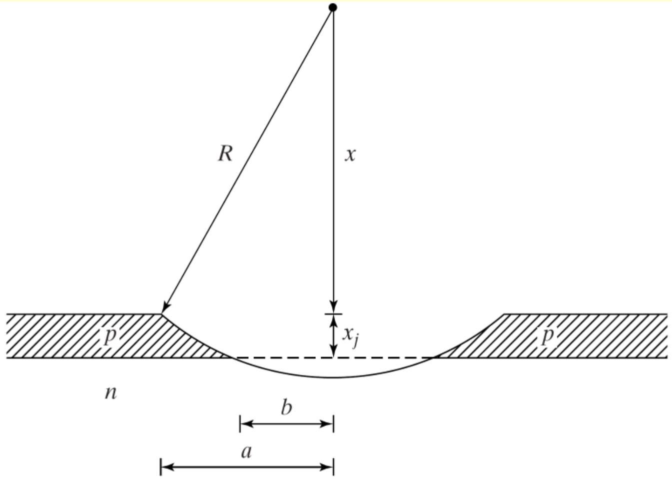
Junction Depth Measurement



- Groove and Stain Method

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



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

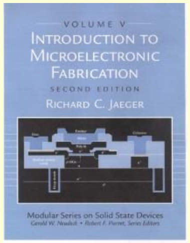
$$\doteq R\left\{\left(1 - \frac{1}{2}\frac{b^2}{R^2}\right) - \left(1 - \frac{1}{2}\frac{a^2}{R^2}\right)\right\} \quad \begin{matrix} R >> a \\ R >> b \end{matrix}$$

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

FIGURE 4.20

Junction-depth measurement by the groove-and-stain technique. The distances *a* and *b* are measured through a microscope, and the junction depth is calculated using Eq. (4.11).

Junction Depth Measurement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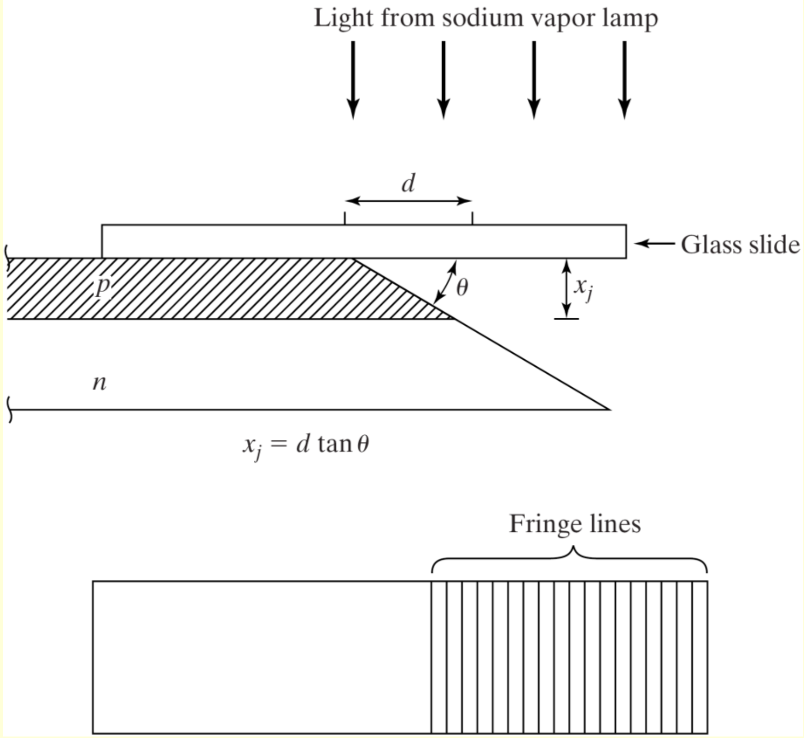


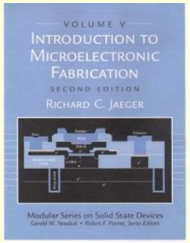
- Angle Lap Technique

$$x_j = d\tan\theta = N\frac{\lambda}{2}$$

FIGURE 4.21

Junction depth measurement by the angle-lap and stain method. Interference fringe lines are used to measure the distance *d*, which is related to the junction depth using Eq. (4.12).

Impurity Profiling
Spreading Resistance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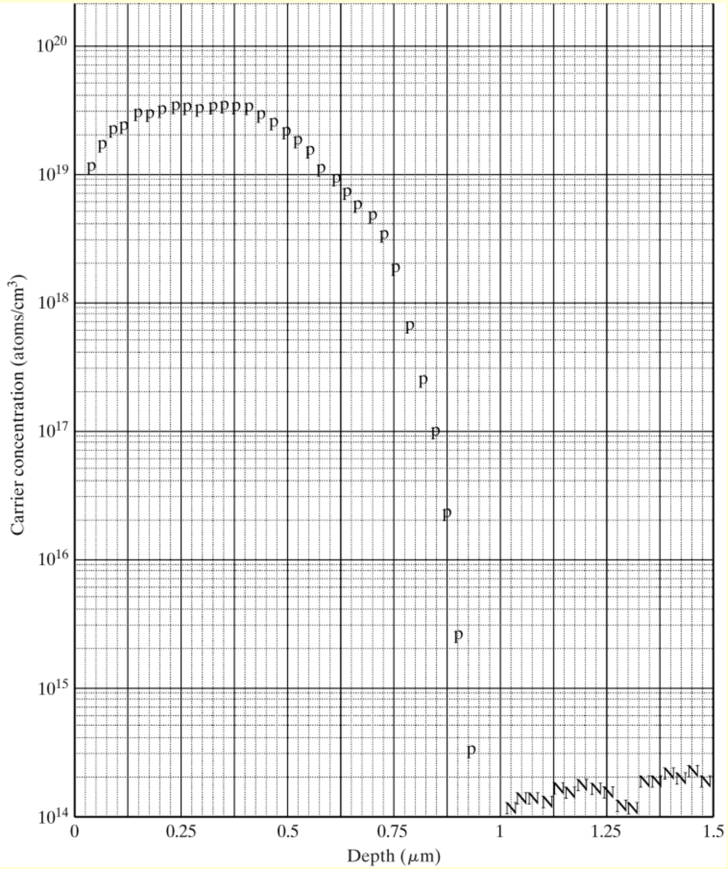
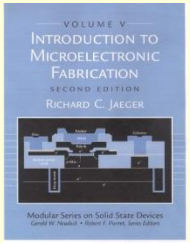
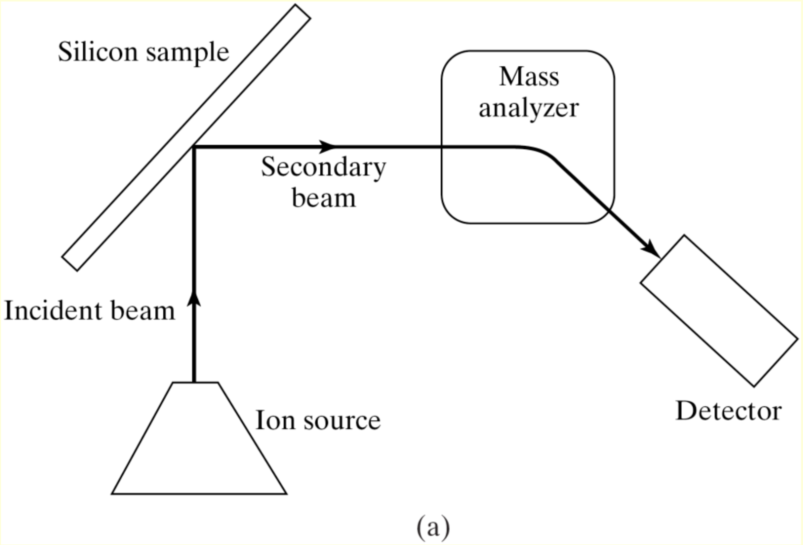


- Region of Interest is Angle-Lapped
- Two-Point Probe Resistance Measurements vs. Depth
- Profile Extracted

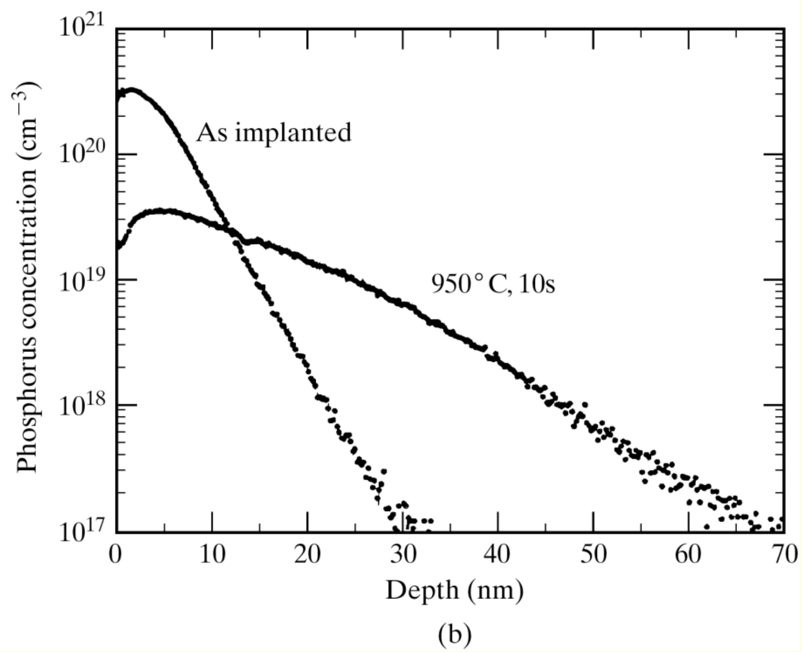
FIGURE 4.22
Example of an impurity profile measured using the spreading resistance method.

Impurity Profiling
Secondary Ion Mass Spectroscopy (SIMS)





(a)



(b)

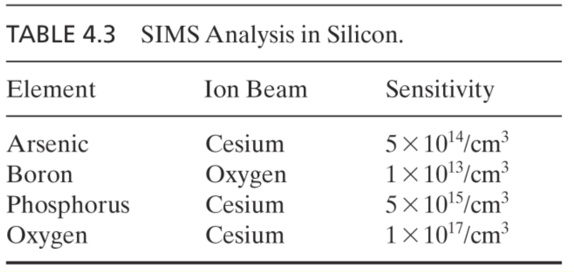


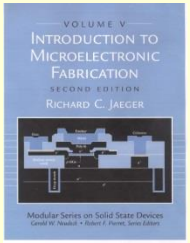
TABLE 4.3 SIMS Analysis in Silicon.

Element	Ion Beam	Sensitivity
Arsenic	Cesium	$5 \times 10^{14}/cm^3$
Boron	Oxygen	$1 \times 10^{13}/cm^3$
Phosphorus	Cesium	$5 \times 10^{15}/cm^3$
Oxygen	Cesium	$1 \times 10^{17}/cm^3$

FIGURE 4.23

(a) Concept of a SIMS analysis system. (b) Example of an impurity profile measured using the SIMS analysis. Copyright 1997 IEEE. Reprinted with permission from Ref. [17].

Diffusion Simulation



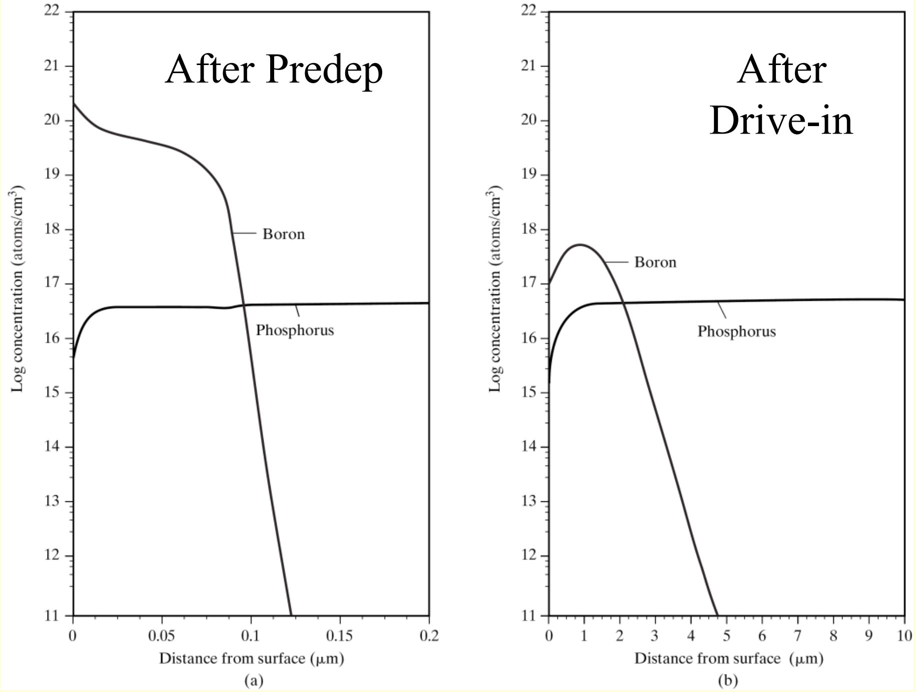
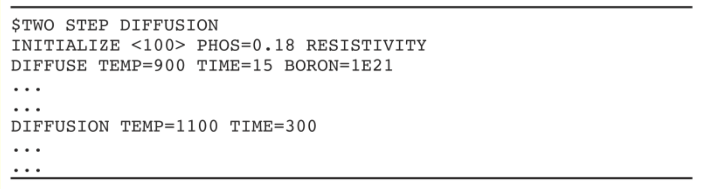
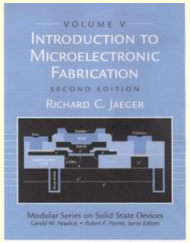


FIGURE 4.24
SUPREM simulation results for two-step boron diffusion into phosphorus doped wafer from Ex. 4.3.

SUPREM Simulation



```
$TWO STEP DIFFUSION
INITIALIZE <100> PHOS=0.18 RESISTIVITY
DIFFUSE TEMP=900 TIME=15 BORON=1E21
...
...
DIFFUSION TEMP=1100 TIME=300
...
...
```



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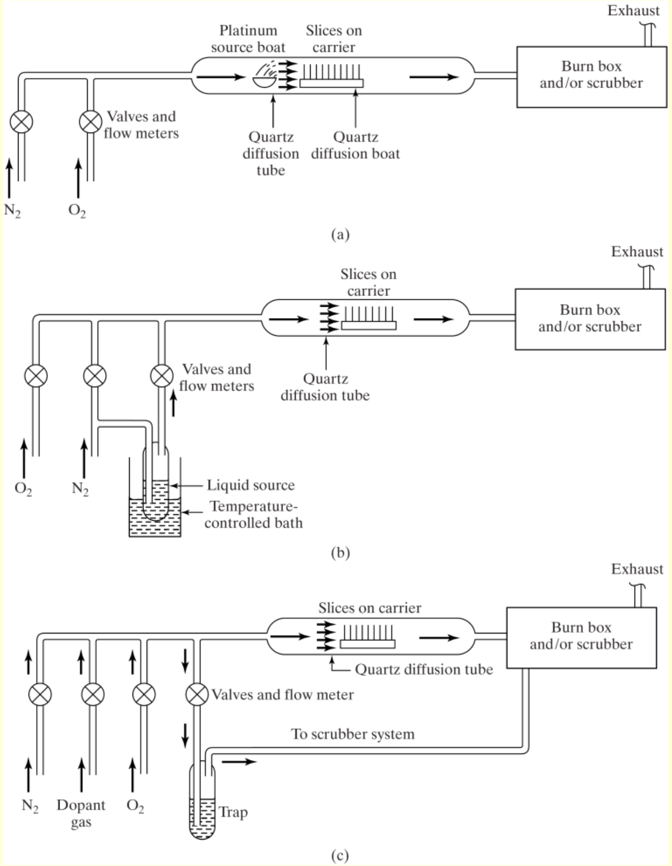
Diffusion Systems



Open Furnace Tube Systems

- (a) Solid source in platinum source boat
- (b) Liquid Source - carrier gas passing through bubbler
- (c) Gaseous impurity source

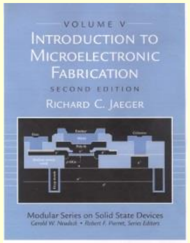
Wafers in Quartz Boat

Scrubber at Output

FIGURE 4.25

Open-furnace-tube diffusion systems. (a) Solid source in a platinum source boat in the rear of diffusion tube; (b) liquid-source system with carrier gas passing through a bubbler; (c) diffusion system using gaseous impurity sources. Copyright John Wiley and Sons. Reprinted with permission from Ref. [23].

Diffusion Systems
Boron Diffusion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Surface Reaction :

$$2B_2O_3 + 3Si \leftrightarrow 4B + 3SiO_2$$

Solid Sources : Boron Nitride & Trimethylborate (TMB

$$2(CH_3O)_3B + 9O_2 \xrightarrow{900^o C} B_2O_3 + 6CO_2 + 9H_2O$$

Class is using Boron Nitride Wafers

Liquid Sources : Boron Tribromide BBr_3

$$4BBr_3 + 3O_2 \rightarrow 3B_2O_3 + 6Br_2$$

Gaseous Source : Diborane B_2H_6 (Extremely Toxic)

$$B_2H_6 + 3O_2 \xrightarrow{300^o C} B_2O_3 + 3H_2O$$

$$B_2H_6 + 6CO_2 \xrightarrow{300^o C} B_2O_3 + 6CO + 3H_2O$$

All systems need careful scrubbing!

CO_2 BBr_3 CO TMB B_2H_6

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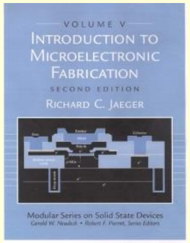
Diffusion Systems
Phosphorus Diffusion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Surface Reaction :

$$2P_2O_5 + 5Si \leftrightarrow 4P + 5SiO_2$$

Solid Sources :

Phosphorus Pentoxide
Ammonium monophosphate $\mathrm{NH_4H_2PO_4}$
Ammonium diphosphate $\mathrm{(NH_4)_2H_2PO_4}$

Liquid Source : Phosphorus Oxychloride $\mathrm{POCl_3}$

$$4POCl_3 + 3O_2 \rightarrow 3P_2O_5 + 6Cl_2$$

Gaseous Source : Phosphine $\mathrm{PH_3}$ (Extremely Toxic)

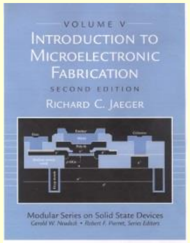
$$2\mathrm{P}H_3 + 4O_2 \rightarrow P_2O_5 + 3H_2O$$

All systems need careful scrubbing!

$\mathrm{P_2O_5}$ $\mathrm{POCl_3}$ $\mathrm{Cl_2}$

Diffusion Systems

Arsenic & Antimony Diffusion



Arsenic Surface Reaction

$$2As_2O_3 + 3Si \leftrightarrow 3SiO_2 + 4As$$

Solid Sources : Possible - Low Surface Concentations

Gaseous Source : Arsine AsH_3 (Extremely Toxic)

Ion – Implantation Is Normally Used for Deposition

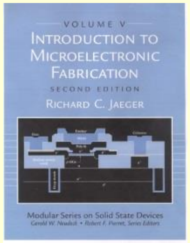
Antimony Surface Reaction

$$2Sb_2O_3 + 3Si \leftrightarrow 3SiO_2 + 4Sb$$

Liquid Source : Antimony Pentachloride Sb_3Cl_5

Ion – Implantation Is Normally Used for Depositior

Diffusion
Toxicity of Gaseous Sources



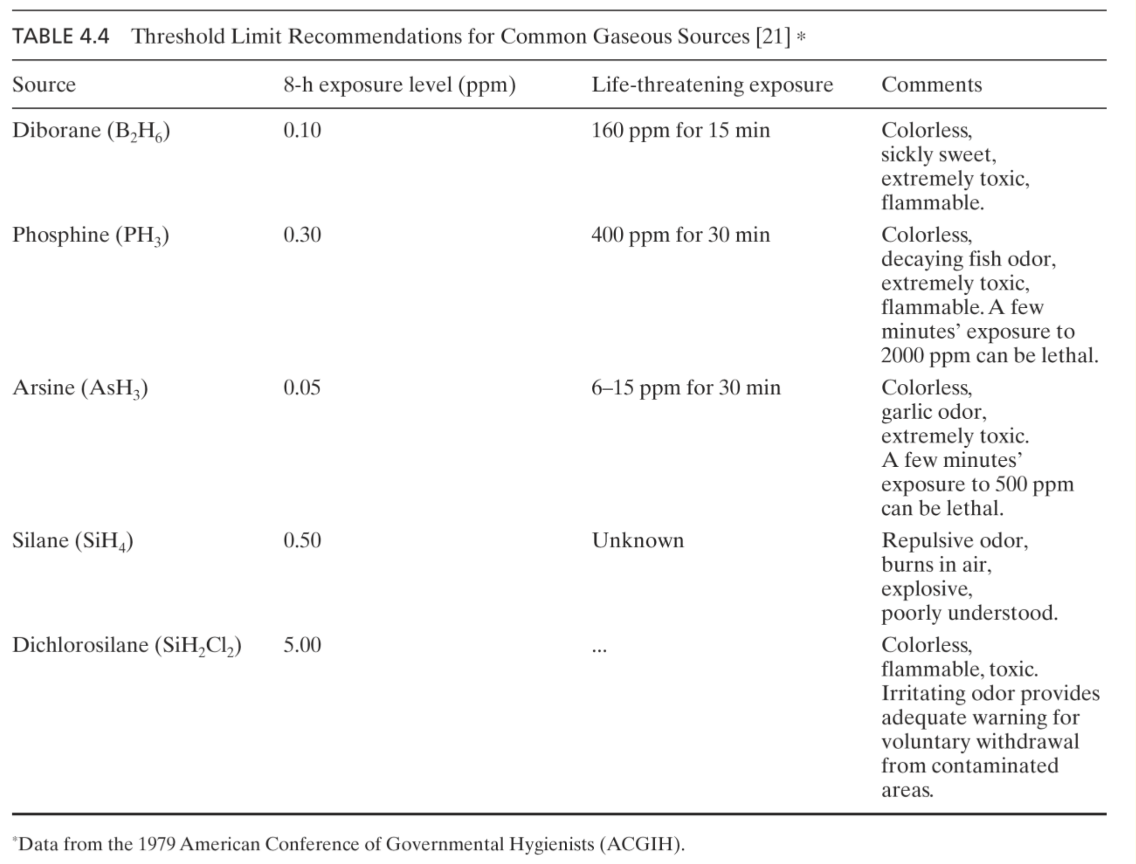


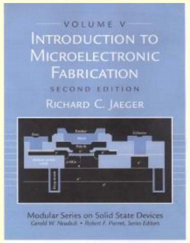
TABLE 4.4 Threshold Limit Recommendations for Common Gaseous Sources [21] *

Source	8-h exposure level (ppm)	Life-threatening exposure	Comments
Diborane (B_2H_6)	0.10	160 ppm for 15 min	Colorless, sickly sweet, extremely toxic, flammable.
Phosphine (PH_3)	0.30	400 ppm for 30 min	Colorless, decaying fish odor, extremely toxic, flammable. A few minutes' exposure to 2000 ppm can be lethal.
Arsine (AsH_3)	0.05	6–15 ppm for 30 min	Colorless, garlic odor, extremely toxic. A few minutes' exposure to 500 ppm can be lethal.
Silane (SiH_4)	0.50	Unknown	Repulsive odor, burns in air, explosive, poorly understood.
Dichlorosilane (SiH_2Cl_2)	5.00	...	Colorless, flammable, toxic. Irritating odor provides adequate warning for voluntary withdrawal from contaminated areas.

*Data from the 1979 American Conference of Governmental Hygienists (ACGIH).

Silane and Dichlorosilane Used for Polysilicon Deposition

Diffusion
Gettering



- Improves Quality of Wafers
  - Removes Metallic Impurities: Cu, Au, Fe, Ni (Rapid Diffusers)
  - Removes Crystal Defects: Dislocations
- Backside Treatment
  - Surface Damage e. g. Sandblasting
  - Phosphorus Diffusion
- Argon Implantation
- Internal Stress
- Crystal Defects
- Oxygen Incorporation
  - During Growth
  - Implantation

Diffusion
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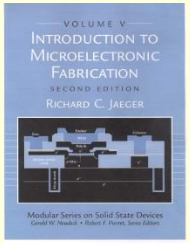

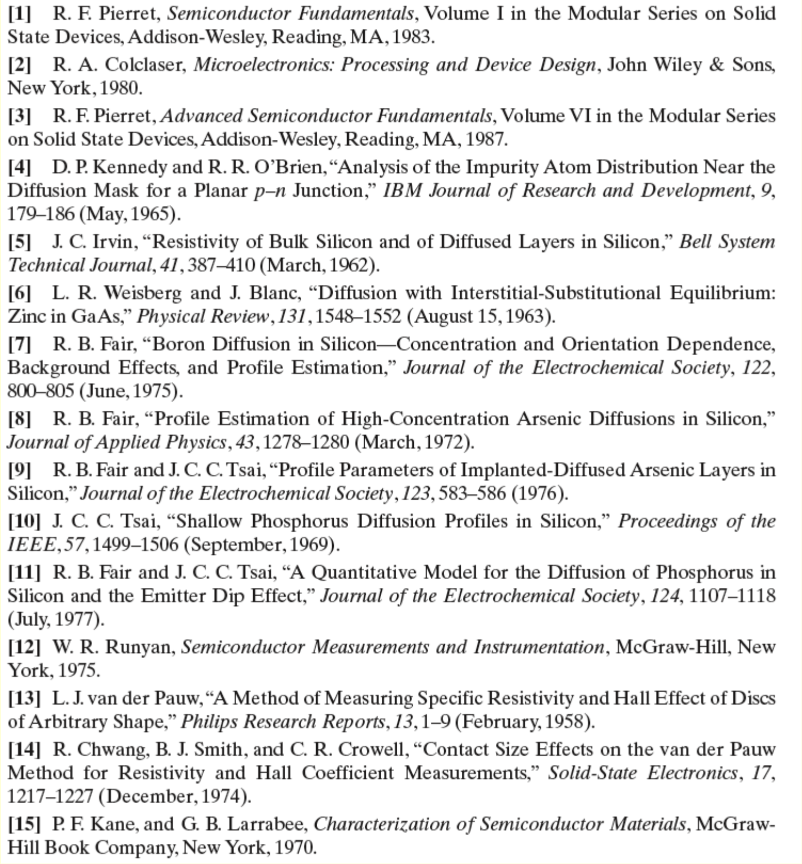

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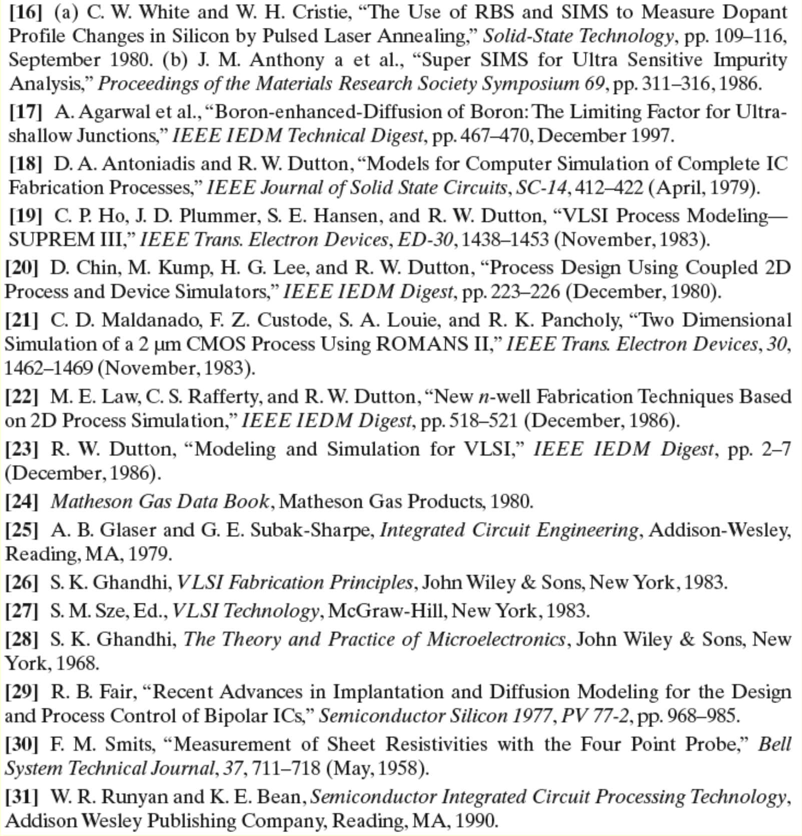

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End of Chapter 4