Semiconductors
Reference: Chapter 4 Jaeger or Chapter 3 Ruska

- Recall what determines conductor, insulator and semiconductor
- Plot the electron energy states of a material
- In some materials get the creation of a "band gap: E_g
- The lower band level is called the "Valance Band"
- The upper band level is called the "Conduction Band"
- At T = 0 K here are some types of structures
- Good conductors: Copper, Sodium: many empty states below E_g
- Modest conductors: No bandgap (Conductance & valence overlap)
- Insulators: Full Valance band: large E_g
- Semiconductors: Valance filled but E_g small
- Small band gap: relatively easy to move electrons
- Move from the valance to the conduction band.
- Get conduction when empty states at adjacent energy levels
- Conduction create by adding carriers: electrons in conduction
- Holes in valence band

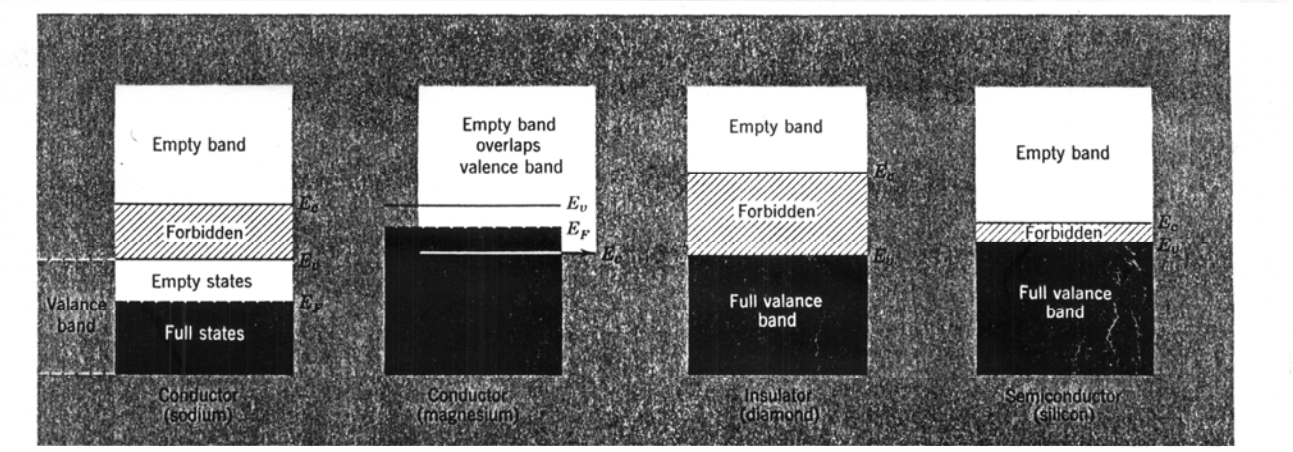


Figure 4.3 Simplified energy band diagrams for conductors, insulators, and semiconductors.

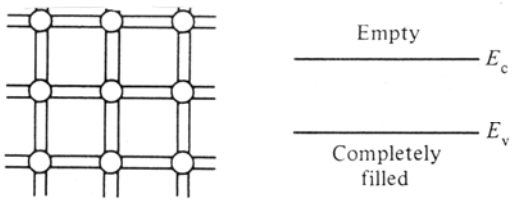
Conductor copper Conductor (Magnesium) Insulator Semiconductor

Creating Carriers in Semiconductors

- Width of the Band Gap in terms of electron volts,
- Energy electron gains accelerated through a one volt E field.
- 1 eV = 1.609×10^{-19} Joules
- Measure energies in eV because most useful for calculations.
- Typical Semiconductor band gaps

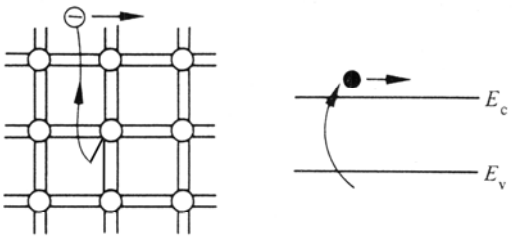
Germanium	0.67 eV
Silicon	1.11 eV
GaAs	1.40 eV
Diamond	5.60 eV

- Usually use relative position in band diagrams, setting:
- The Valance Band Edge $E_v = 0$
- The Conduction Band Edge $E_c = E_g$
- At room T semiconductors -few electrons in conduction band
- But can add a donor dopand (another material) that adds electrons
- Or an acceptor that creates holes in the valence band



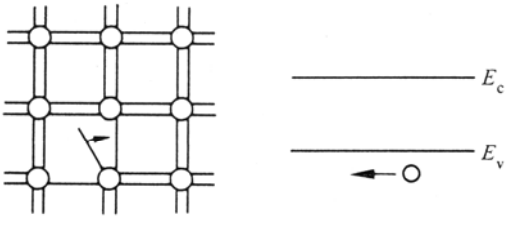
(a) No carriers

Undoped



(b) The electron

Donor atoms
Adds e to conduction
(e = electrons)

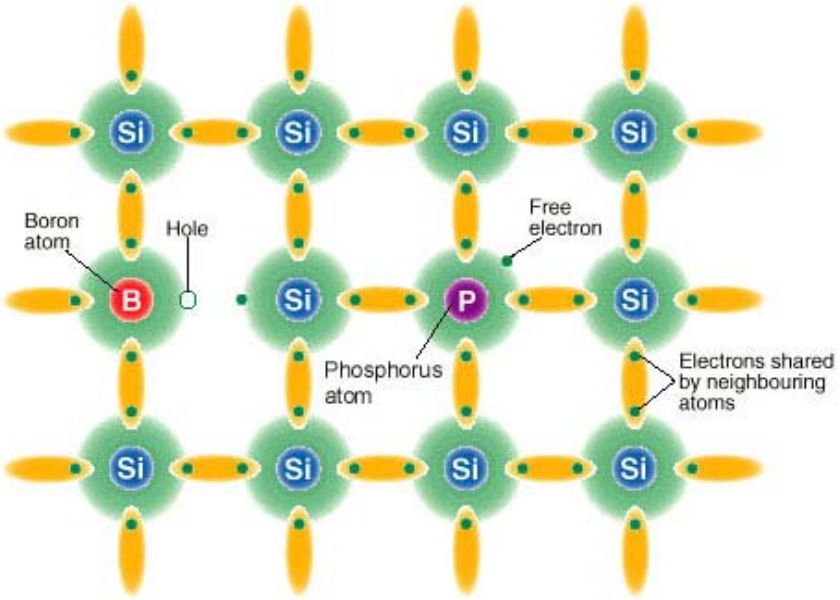


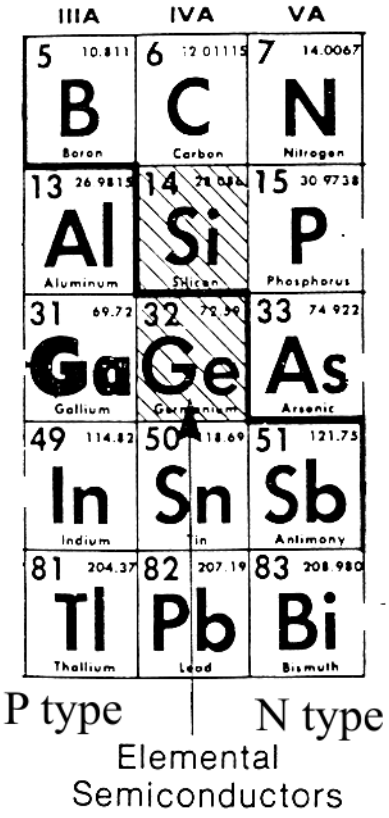
(c) The hole

Acceptor atoms
Add n to valence
(n= holes)

Doping and Silicon

- Dopants in silicon set from being a column IV element
- Column V extra electrons N type dopant N_D
- P Phospherus, As Arsenic & Sb Antimony most common
- Column III holes (missing e's) Acceptors P type dopant N_A
- B Boron, Al Aluminum most common
- For Diodes and transistors need to make P and N junctions
- Doping is inserting the impurities into the substrate





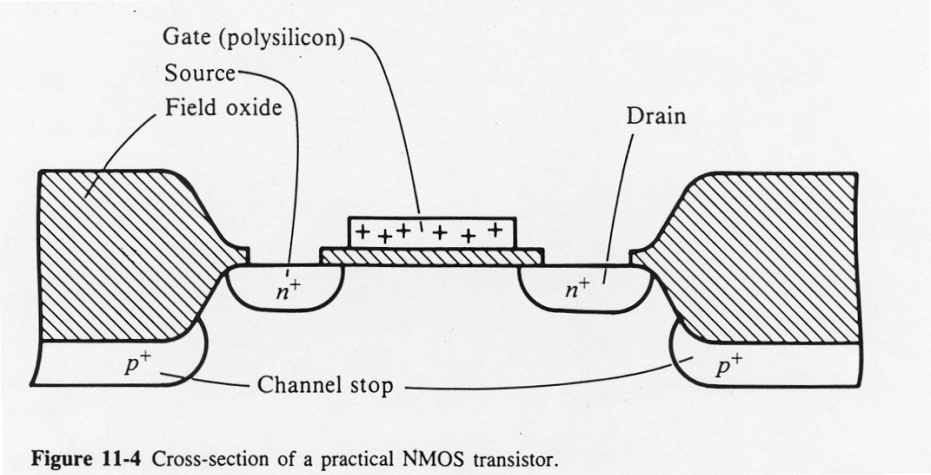


Figure 11-4 Cross-section of a practical NMOS transistor.

Diffusion and Ion implantation

- N & P Dopants determine the resistivity of material
- Very low levels for change 1 cm^3 Silicon has $5.5x10^{22}$ atoms
- Significant resistivity changes at even 10^{10} dopant atoms/cc
- Typical doping begins at 10^{13} atoms/cc N_A or N_D
- Note N lower resistivity than p: due to higher carrier mobility
- Near linear relationship below 0.2 ohm-cm (~10^{16} cm^{-3})
- Above that high doping effects
- At 10^{19} get significant degeneracy effects
- There quantum effects become important
- Typical Si wafer substrate is about 1-10 ohm-cm or 10^{15}-10^{16} cm^{-3}

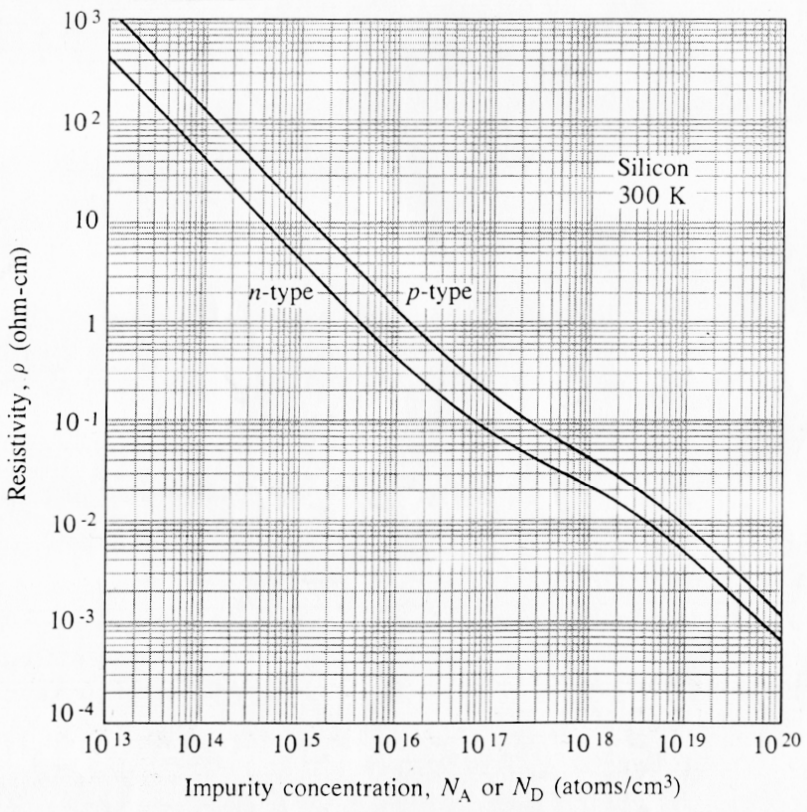


Fig. 4.8 Room-temperature resistivity in *n*- and *p*-type silicon as a function of impurity concentration. (Note that these curves are valid for either donor or acceptor impurities but not for compensated material containing both types of impurities.) Copyright 1987 Addison-Wesley Publishing Company. Reprinted with permission from ref. [3].

Diffusion and Dopant Location

- Dopping is adding impurities to Silicon
- Thermal diffusion process easiest
- Directly implanting (injecting) more expensive
- Dopant Atoms Substitutional – replaces Si:
- Called activated dopants – ie n and p carriers created
- Interstitial dopant: pushes out Si
- True Interstitial dopant atoms: not activated – no carriers
- Implanting produces mostly interstitial – needs to be activated

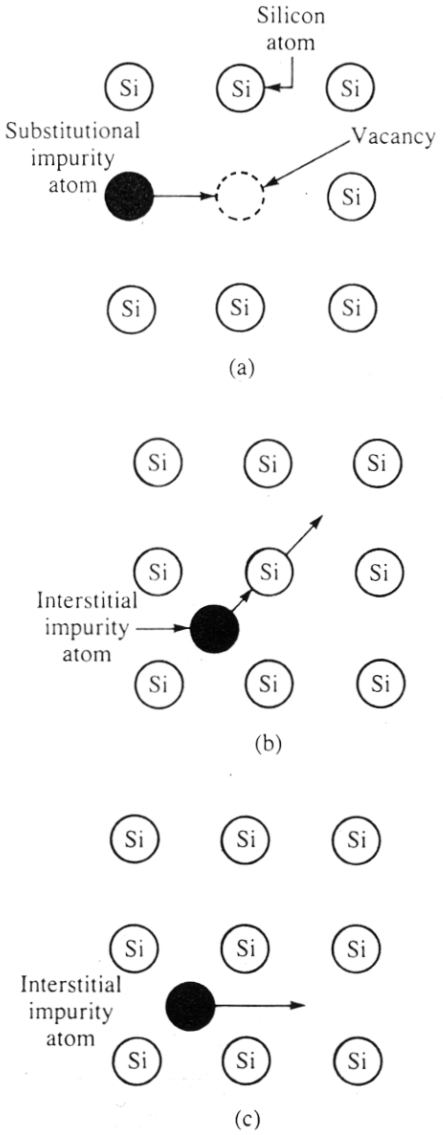


Fig. 4.1 Atomic diffusion in a two-dimensional lattice. (a) Substitutional diffusion, in which the impurity moves among vacancies in the lattice; (b) interstitialcy mechanism, in which the impurity atom replaces a silicon atom in the lattice, and the silicon atom is displaced to an interstitial site; (c) interstitial diffusion, in which impurity atoms do not replace atoms in the crystal lattice.

Diffusion under Concentration Gradient

- Dopant moves from heavy concentration area to lower concentration area
- Reason: simple statistics of motion: More dopant in heavy area
- Hence more heading in lower dopant direction
- Higher the temperature the faster dopants move
- Hence for doping done in a furnace

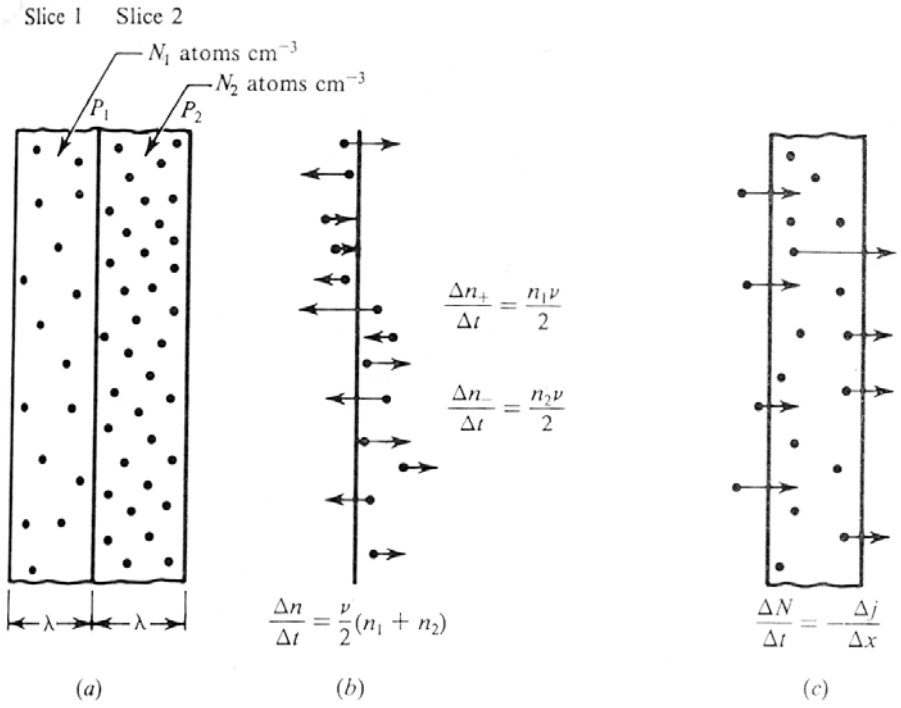
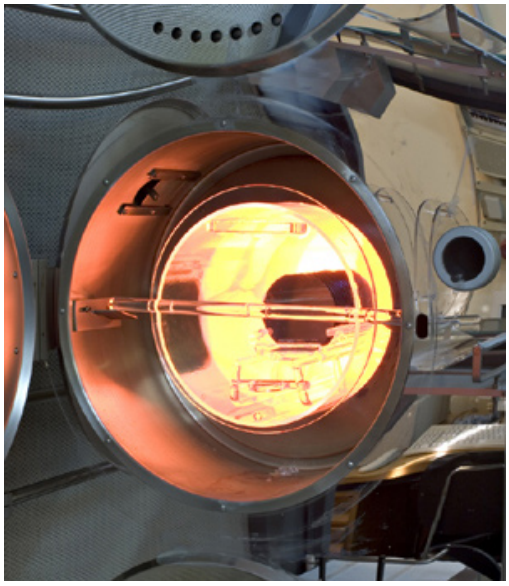


Figure 3-4 Diffusion under a concentration gradient: (*a*) two slices with different concentrations. (*b*) Focus on plane P_1 showing change in concentration. (*c*) Focus on slice 2 showing flux.



Diffusion Theory
Reference: Chapter 4 Jaeger or Chapter 3 Ruska

- Diffusion equations for the flux of dopants into the substrate
- Diffusion flow follows **Fick's First Law**

$$J = -D\frac{\partial N(x,t)}{\partial x} = -D\nabla N(x,t)$$

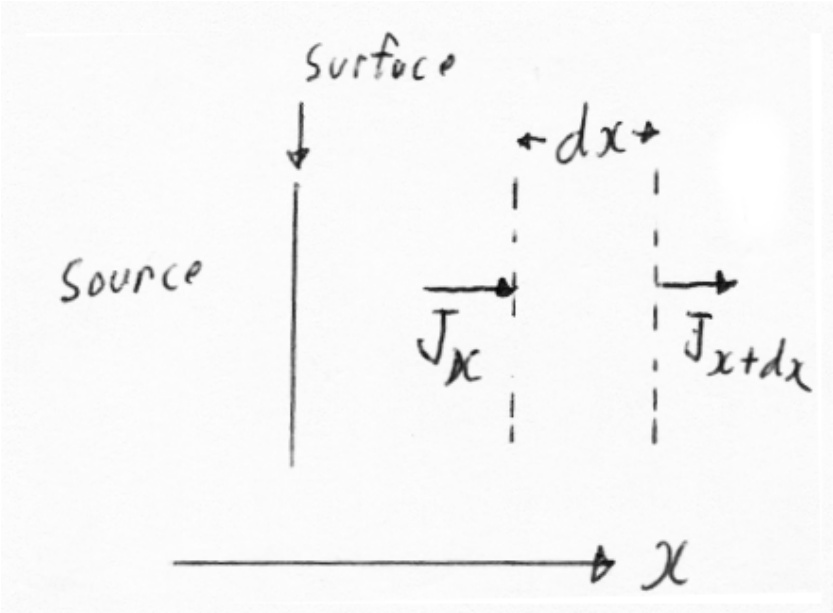
Where:
N = Impurity concentration: atoms/cc
J = particle flux (atoms/cc/sec)
D = diffusion coefficient (cm^2/sec)

- **Continuity Equation**
- Now relate the flux to the changes in time and position of dopant
- Continuity Equation: **Fick's Second Law**

$$\frac{\partial N}{\partial t} = -\frac{\partial J}{\partial x} = \frac{\partial}{\partial x}D\frac{\partial N(x,t)}{\partial x} = D\frac{\partial^2 N(x,t)}{\partial x^2} = D\nabla^2 N$$

Where: t = time

- This is the Diffusion differential equation in 1 dimension
- Assumption is that D is constant with x



Diffusion Solutions

- Solutions depend on Boundary Conditions
- Solutions in terms of Dt (Diffusion coef x time)
- Two typical cases depending on the source conditions

Constant Source Diffusion

- Constant source one common condition: ie unlimited dopant

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

- Total impurity concentration

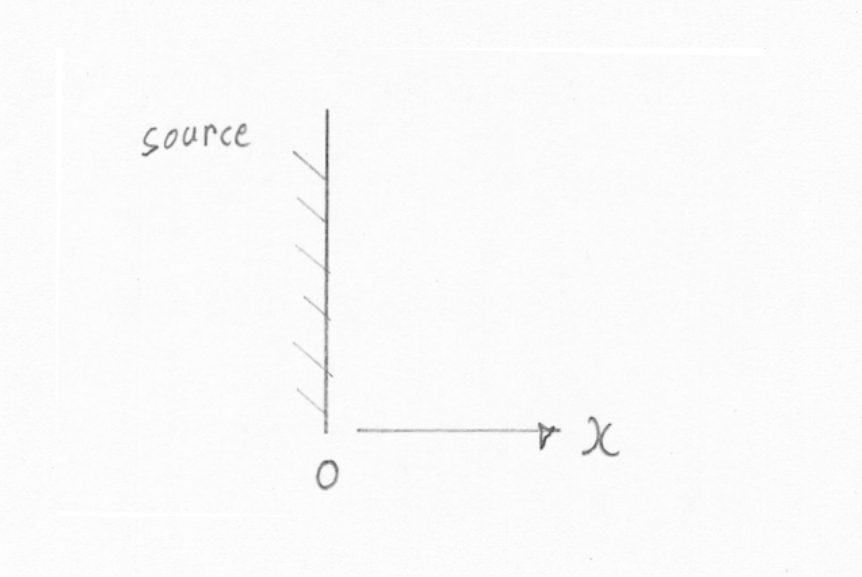
$$Q = \int_0^\infty N(x,t)\, dx = 2N_0\sqrt{\frac{Dt}{\pi}}$$

Limited Source Diffusion

- Total Dopant is fixed

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

- Thermal diffusion of starts with Constant source step
- Then uses dopant from that in a Limited Source drive in



Constant Source Diffusion Solutions

- Constant source one common condition: ie unlimited dopant
- Surface concentration is fixed for all diffusion time

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

- Note this involves the Complementary Error Function
- Total impurity concentration

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

- Constant source often puts initial dopant only on surface (in Lab)
- Called a predeposition
- Spin on dopants create constant source type doping

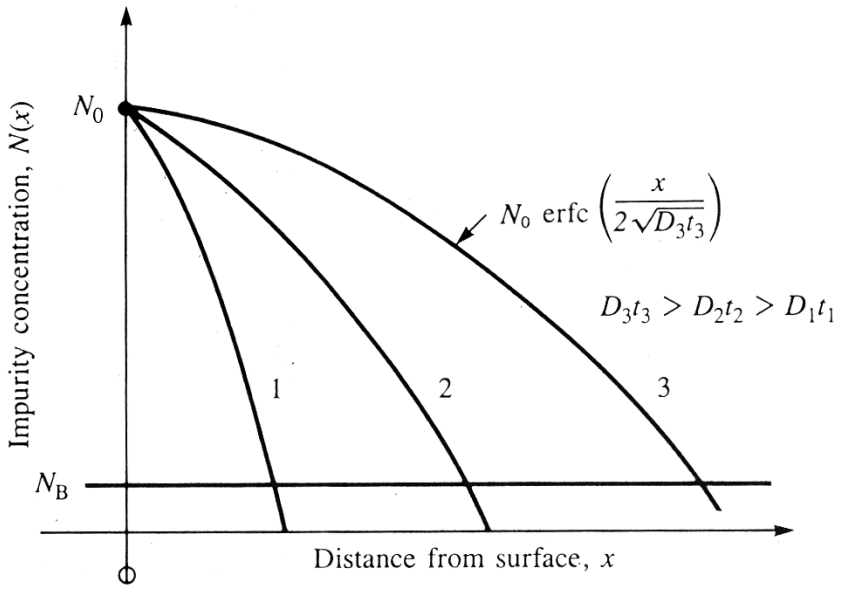


Fig. 4.2 A constant-source diffusion results in a complementary error function impurity distribution. The surface concentration N_0 remains constant and the diffusion moves deeper into the silicon wafer as the Dt product increases. Dt can change as a result of increasing diffusion time, increasing diffusion temperature, or a combination of both.

Useful Error Function erfc(x) Approximations

- Error function erf(x), Complementry Error Function erfc(x) are

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-s^2} ds$$

$$erfc(x) = 1 - erf(x) = \frac{2}{\sqrt{\pi}} \int_\infty^x e^{-s^2} ds$$

- erf(x) hard to find but easy to approximate with

$$erf(x) = 1 - \left(a_1 t + a_2 t^2 + a_3 t^3\right) e^{-x^2}$$

$$t = \frac{1}{1 + px} \quad where \quad p = 0.47047$$

$a_1 = 0.3480242$, $a_2 = -0.0958798$, $a_3 = 0.7478556$

- See Abramowitz & Segun (Handbook of Mathematical Functions)
- Error on this is $< 2.5 \times 10^{-5}$ for all x (<2% error for x << 5.5)
- We are using complementary error function

$$erfc(x) = 1 - erf(x) \qquad erfc(0) = 1 \qquad erfc(\infty) = 0$$

- Asymptotic approximation

$$erfc(x) \to \frac{e^{-x^2}}{x\sqrt{\pi}} \left[1 - \frac{1}{2x^2}\right] \quad as \quad x \to \infty$$

- For x>3.5 this has <1% error (use plot page following for x<3.5)
- Excel & Quatropro spreadsheet have erf and erfc built in.
  Must activate analysis toolpack & solver first
  but become inaccurate for x>5.4 – then use asymptotic
- Matlab & maple OK for higher x's

Limited Source Diffusion Solutions

- Where total dopant is fixed
- Surface dopant falls with time while dopant goes deeper

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

- Often do constant source first (high concentration very shallow)
- Then drive in deeper using limited source
- With an oxidation drive in

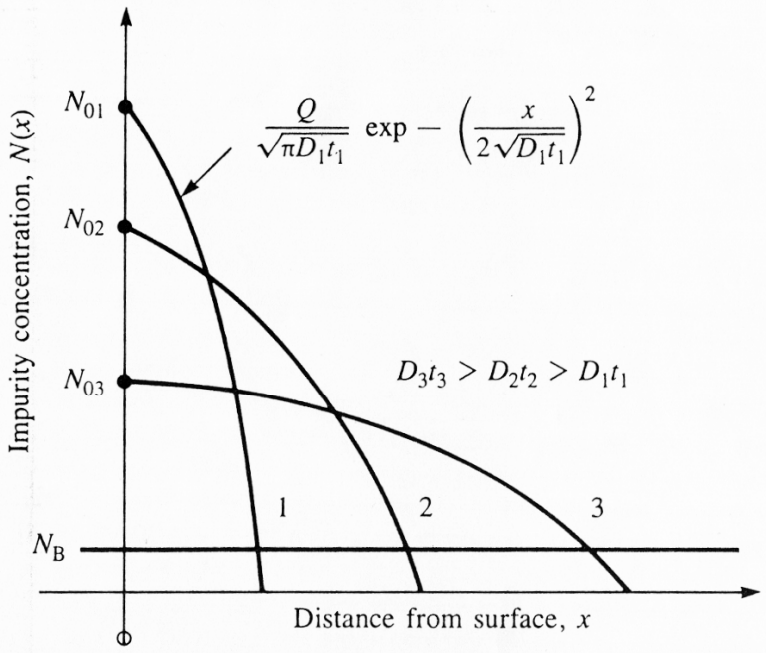


Fig. 4.3 A Gaussian distribution results from a limited-source diffusion. As the *Dt* product increases, the diffusion front moves more deeply into the wafer and the surface concentration decreases. The area under each of the three curves is the same.

Comparison of Normalized Gaussian & ERFC

- erfc(x) much steeper than Gaussian: thus sharper boundry
- For erfc use plot for x<3.5, asymptotic formula for > 3.5
- Use for getting inverse of erfc
- Use asymptotic eqn for inverse values of erfc(x)<10^{-6}

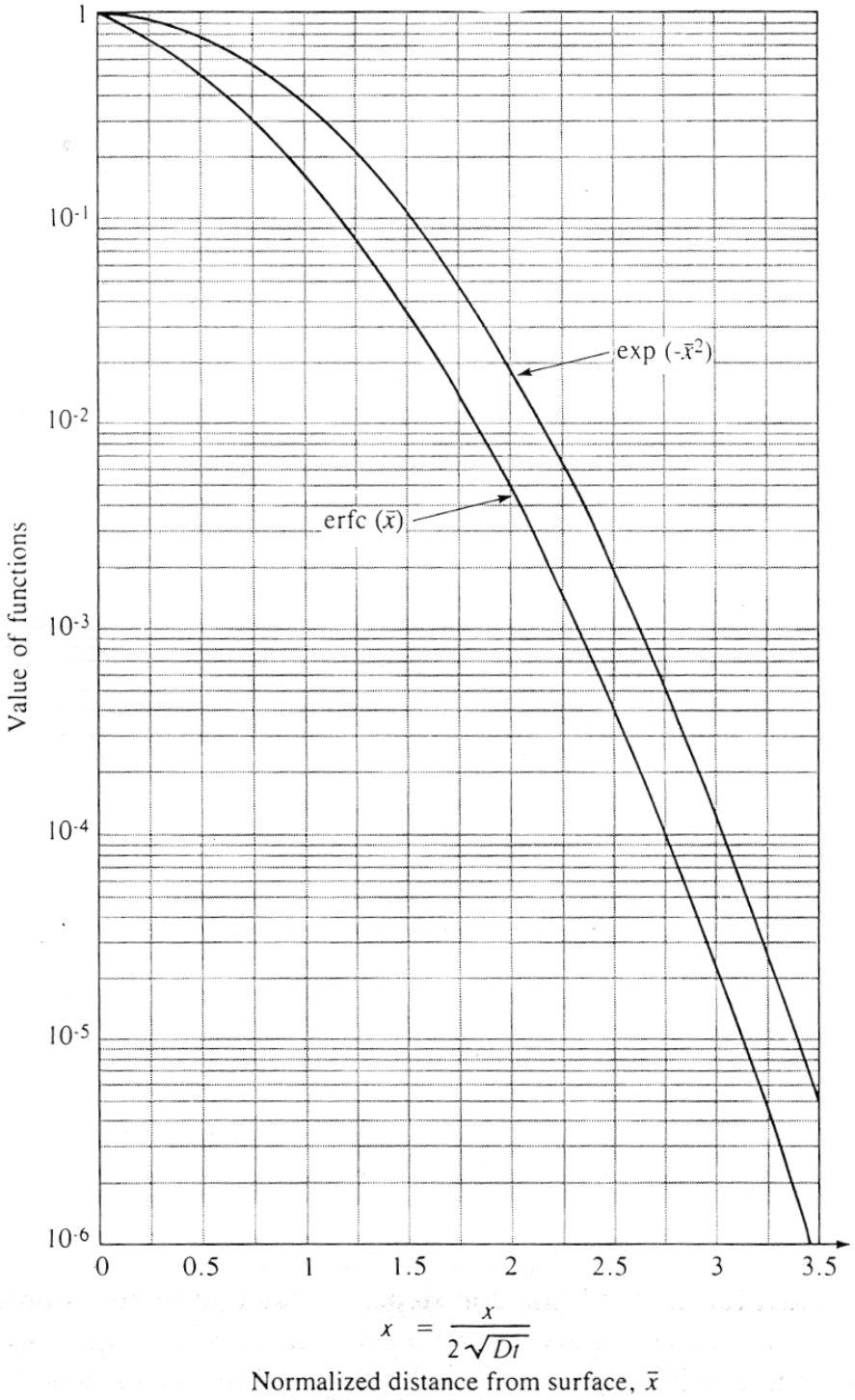


Fig. 4.4 A graph comparing the Gaussian and complementary error function (erfc) profiles. We will use this curve to evaluate the erfc and its inverse.

Diffusion Constants in Si

- For common dopants: Change with temperature
- Follows Arrhenius Formula (E_A = activation energy of diffusion)

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

E_A = activation energy of diffusion

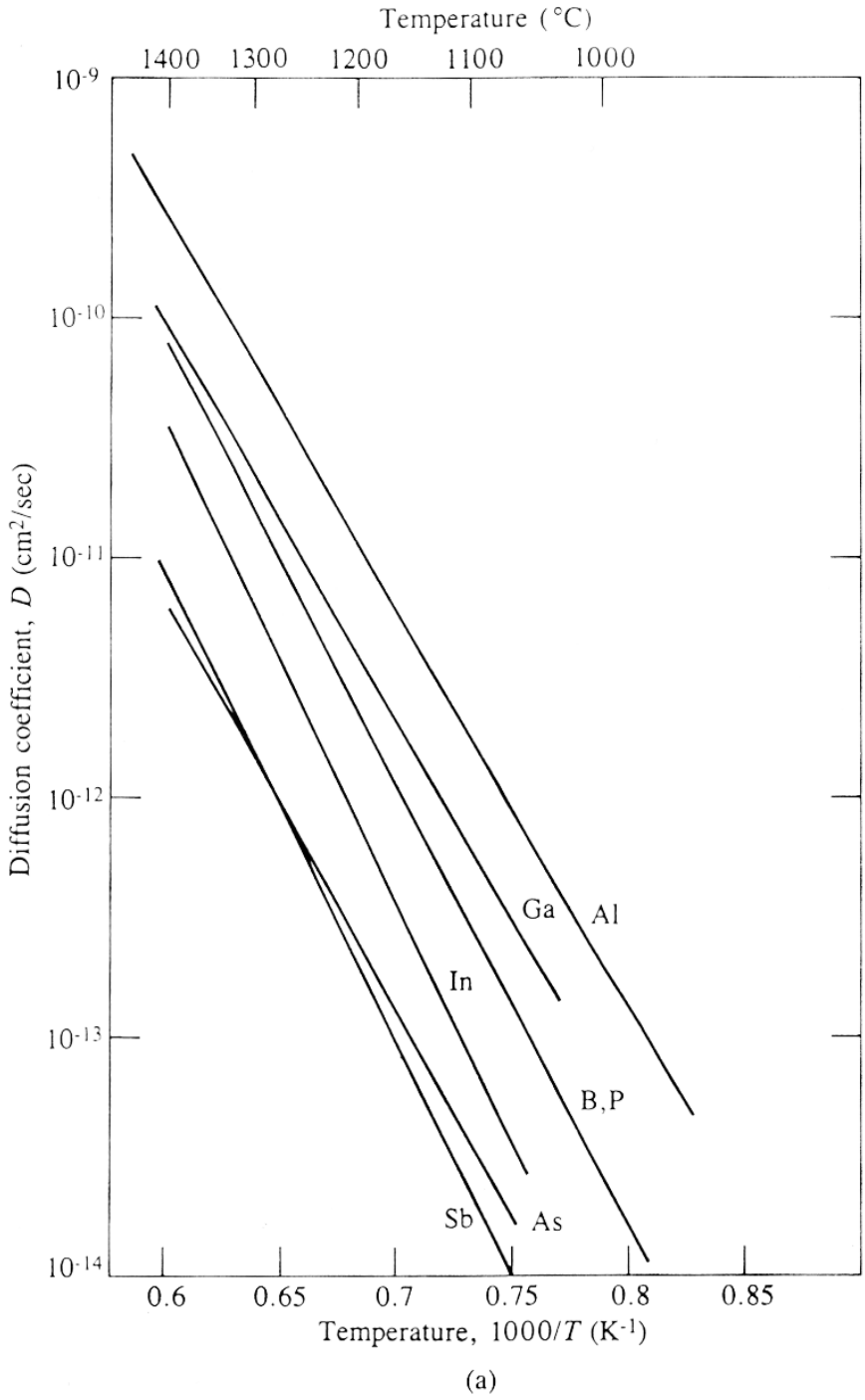


Fig. 4.5 Diffusion constants in silicon for (a) substitutional diffusers (above) and (b) interstitial diffusers (next page)

Diffusion Constants in Si

- High diffusion coef D for poisons: Cu, Au, Fe & Li

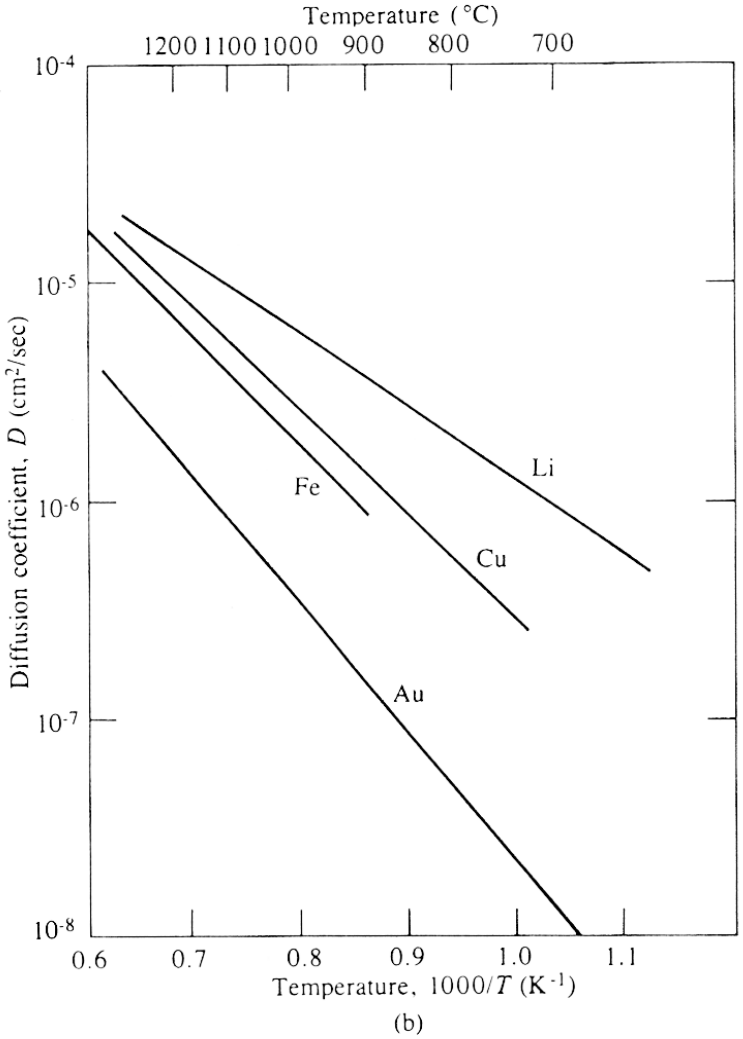


Fig. 4.5 (continued)

$$D = D_0 \exp \frac{-E_A}{KT}$$

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

Formation of PN Junction

- For diodes and transistors want to create a PN junction (interface)
- When diffusion falls below background dopant
- May be substrate level (diode) or previous diffusion
- Carrier level becomes

$$p\text{-}n = N_A\text{-}N_D$$

- This is diode junction depth x_j – note this is not an abrupt junction

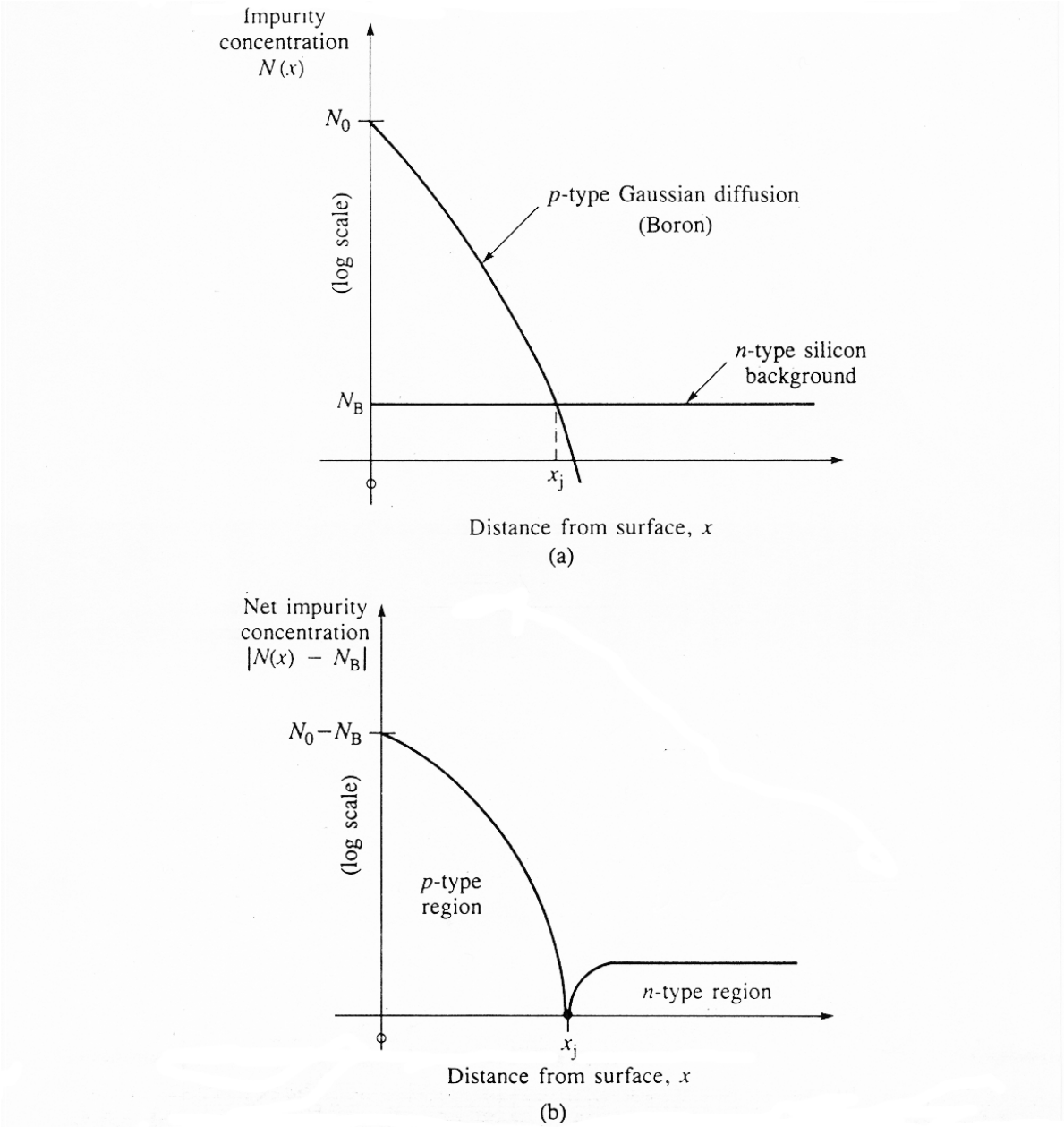


Fig. 4.7 Formation of a *pn* junction by diffusion. (a) An example of a *p*-type Gaussian diffusion into a uniformly doped *n*-type wafer; (b) net impurity concentration in the wafer. The metallurgical junction occurs at the point $x = x_j$, where the net concentration is zero. The material is converted to *p*-type to the left of x_j and remains *n*-type to the right of x_j.

Limits to Diffusion: Solid Solubility

- Sets upper limit to diffusion
- Silicon participates out the dopant at higher levels
- Limit is set the solid solubility of particular dopant in Si
- Complicated function of Temperature at diffusion

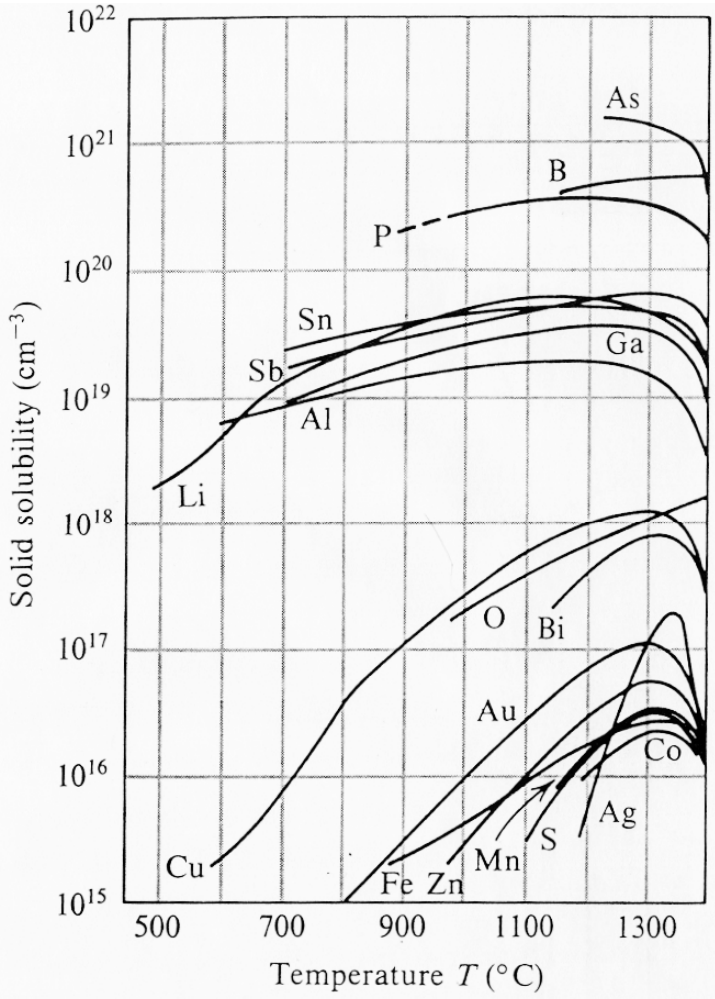


Figure 3-6 Solid solubilities of various impurities in silicon. (*Reference 7. Reprinted with permission from the* Bell System Technical Journal. *Copyright 1960, AT&T.*)

Common Process: Predeposition & Drive in

- Use diffusion to create thin layer of highly doped material
- Then drive in dopant from this layer as limited source at surface

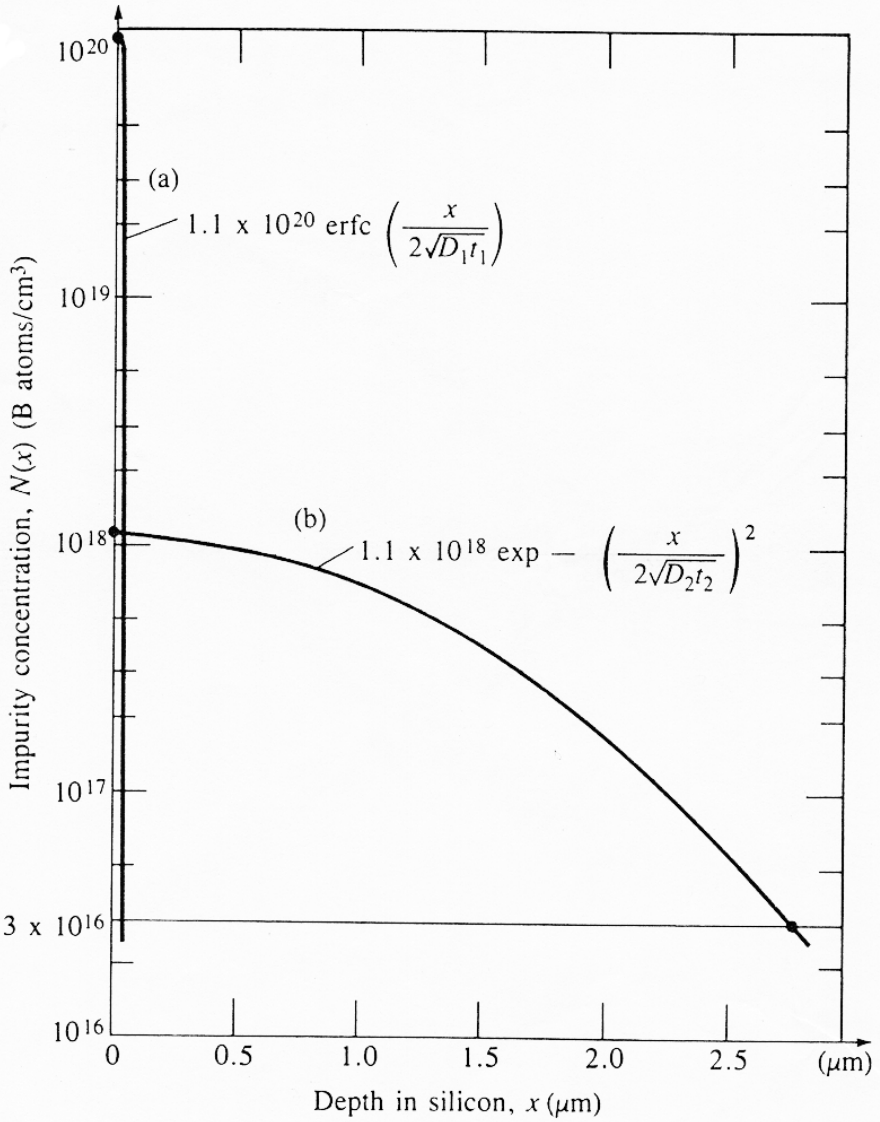


Fig. 4.9 Calculated boron impurity profiles for Example 4.2. (a) Following the predeposition step at 900 °C for 15 min; (b) following a subsequent 5-hr drive-in step at 1100 °C. The final junction depth is 2.77 μm with a surface concentration of $1.1 \times 10^{18}/\text{cm}^3$. The initial profile approximates an impulse.

Dopant And Masks

- Commonly use patterned layer (oxide mostly) as mask
- Hence grow oxide, pattern with resist, etch oxide, strip for mask
- Then diffuse dopant at high temp (too high for resist)
- Dopant diffuses under mask

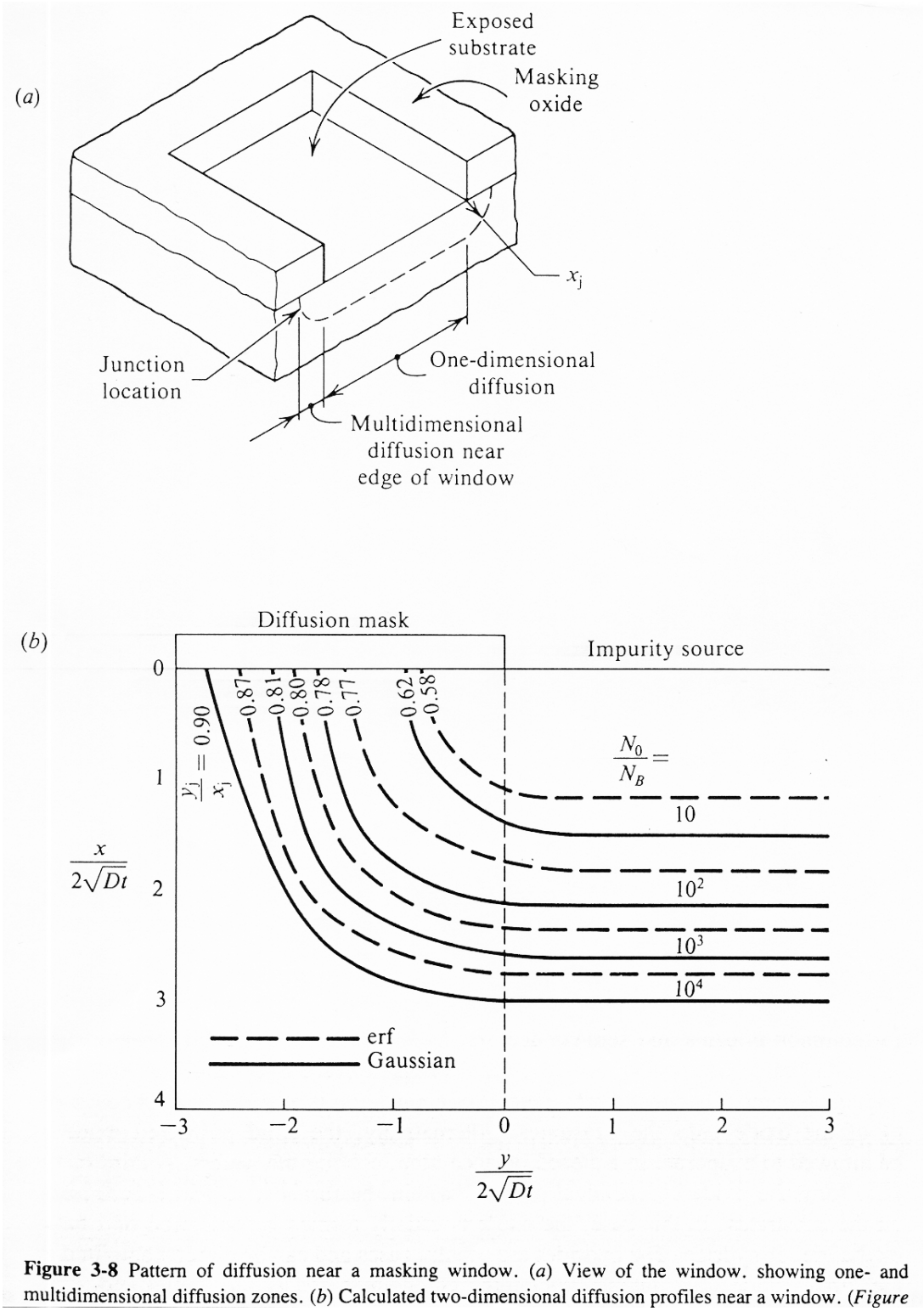


Figure 3-8 Pattern of diffusion near a masking window. (*a*) View of the window. showing one- and multidimensional diffusion zones. (*b*) Calculated two-dimensional diffusion profiles near a window. (*Figure*

Dopant Diffusion Under Mask

- Under mask diffusion depends on type: Constant or limited source

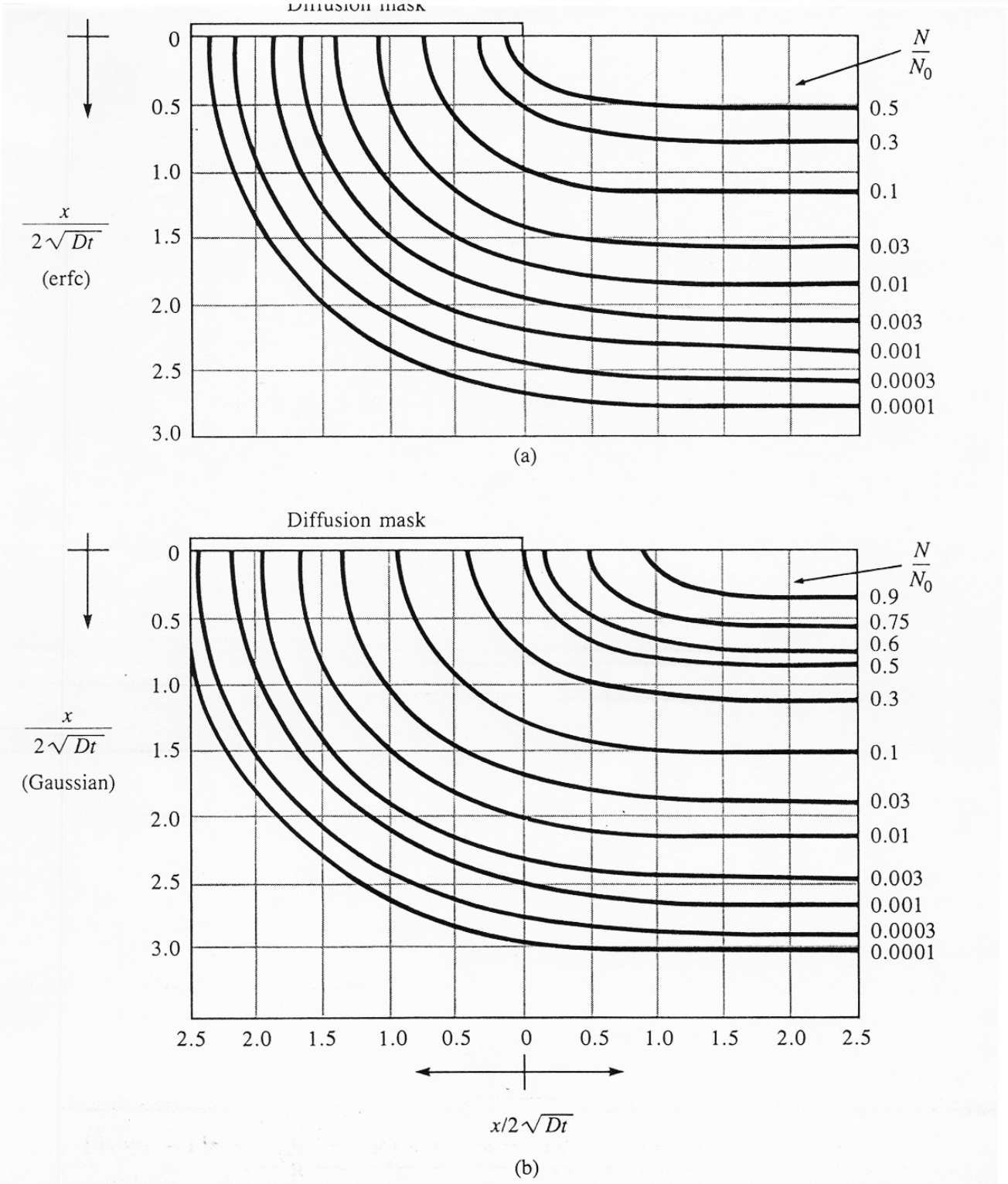


Fig. 4.10 Normalized two-dimensional Gaussian and complementary error function diffusions near the edge of a window in the barrier layer. Copyright 1965 by International Business Machines Corporation; reprinted with permission from ref. [4].

Common Dopant Sources

- Often have solid, liquid and gaseous sources
- Different materials for each source type

Type	Element	Compound Name	Formula	State	Diffusion Reactions*
N	Antimony	Antimony Trioxide	Sb_2O_3	Solid	
	Arsenic	Arsenic Trioxide	As_2O_3	Solid	$2AsH_3 + 3O_2 \longrightarrow As_2O_3 + 3H_2O$
		Arsine	AsH_3	Gas	
	Phosphorus	Phosphorus Oxychloride	$POCl_3$	Liquid	$4POCl_3 + 3O_2 \longrightarrow 2P_2O_5 + 6Cl_2$
		Phosphorus Pentoxide	P_2O_5	Solid	$2PH_3 + 4O_2 \longrightarrow P_2O_5 + 3H_2O$
		Phosphine	PH_3	Gas	
P	Boron	Boron Tribromide	BBr_3	Liquid	$4BBr_3 + 3O_2 \longrightarrow 2B_2O_3 + 6Br_2$
		Boron Trioxide	B_2O_3	Solid	$B_2H_6 + 3O_2 \longrightarrow B_2O_3 + 3H_2O$
		Diborane	B_2H_6	Gas	
		Boron Trichloride	BCl_3	Gas	$BCl_3 + 3H_2 \longrightarrow 2B + 6HCl$
		Boron Nitride	BN	Solid	
	Gold	Gold	Au	Solid (Evap.)	
	Iron		Fe	Undesirable impurities from contamination	
	Copper		Cu		
	Lithium		Li		
	Zinc		Zn		
	Manganese		Mn		
	Nickel		Ni		
	Sodium		Na		

*Note: Only selected diffusion reactions are listed

Figure 11.18 Deposition source table.

Furnace Susceptor Sources

- Boron Nitride wafer P solid sources susceptors, between wafers
- Grow layer of Boron oxide on surface (soft)
- In furnace oxide releases Boron to wafers
- Boron dopant on surface of wafers
- Note wafers front faces solid source
- Easy to do but disks change over time
- Phosphorous similar but is Phosphorous in Silicon Carbide matrix
- Note these sources must be kept at moderate temperature
- React with water if at room temp too long

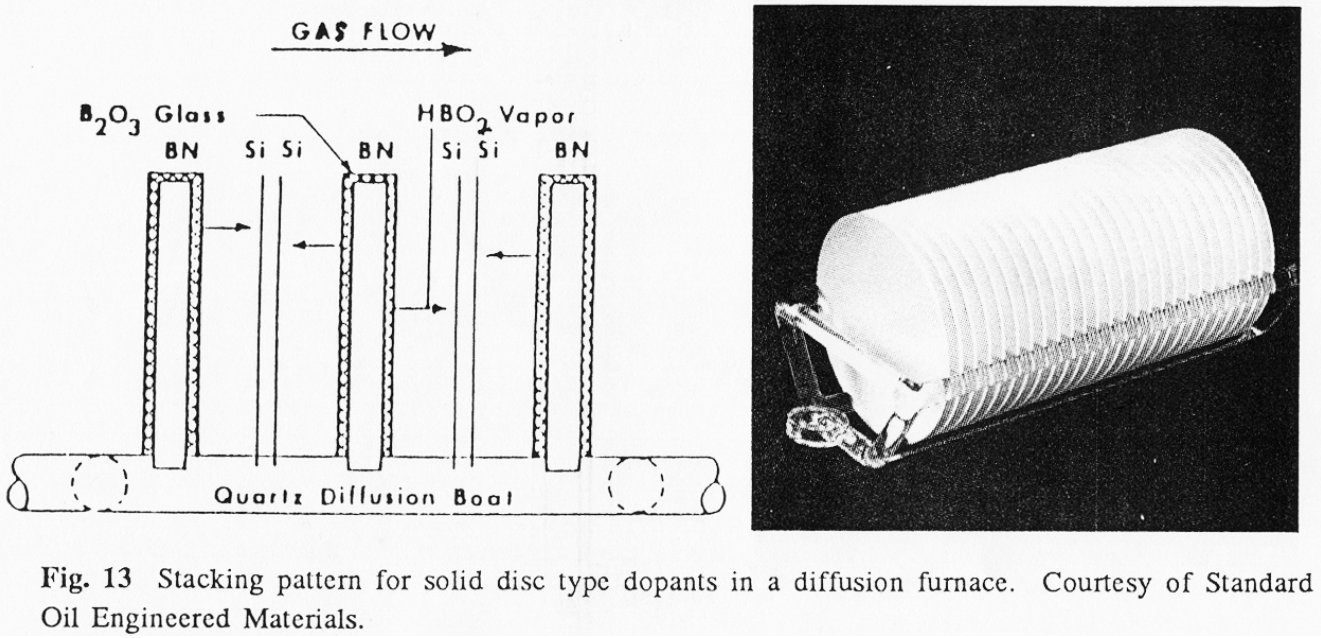


Fig. 13 Stacking pattern for solid disc type dopants in a diffusion furnace. Courtesy of Standard Oil Engineered Materials.

Gas Dopant Sources

- Dopant containing gas flows over wafer
- Usually has a carrier gas (nitrogen)
- Dangerous gas product output

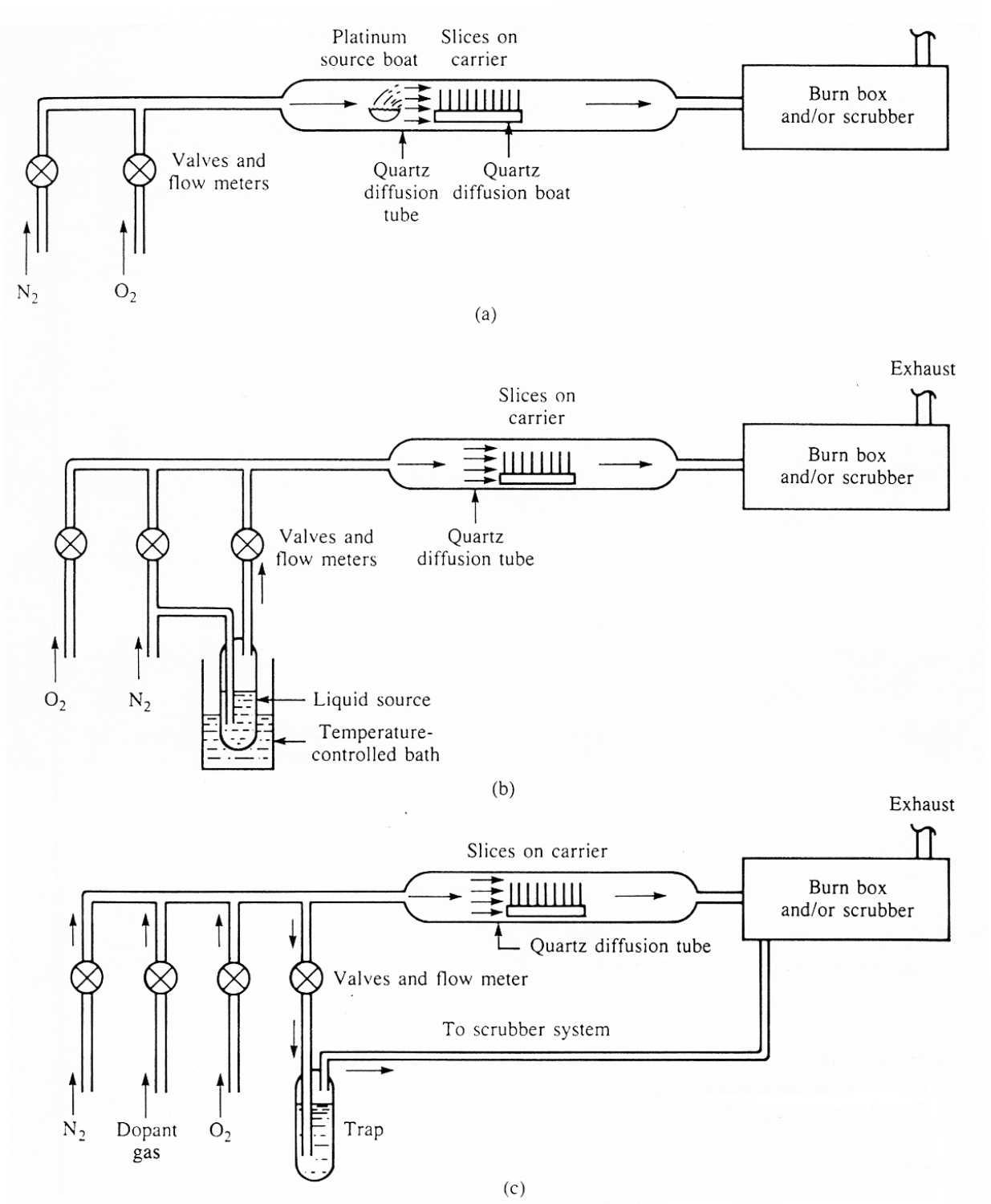


Fig. 4.22 Open-furnace-tube diffusion systems. (a) Solid source in a platinum source boat in the rear of diffusion tube; (b) liquid-source system with carrier gas passing through a bubbler; (c) diffusion system using gaseous impurity sources.

Bubbler Dopant Source

- Use gas or liquid dopant in bubbler to furnace

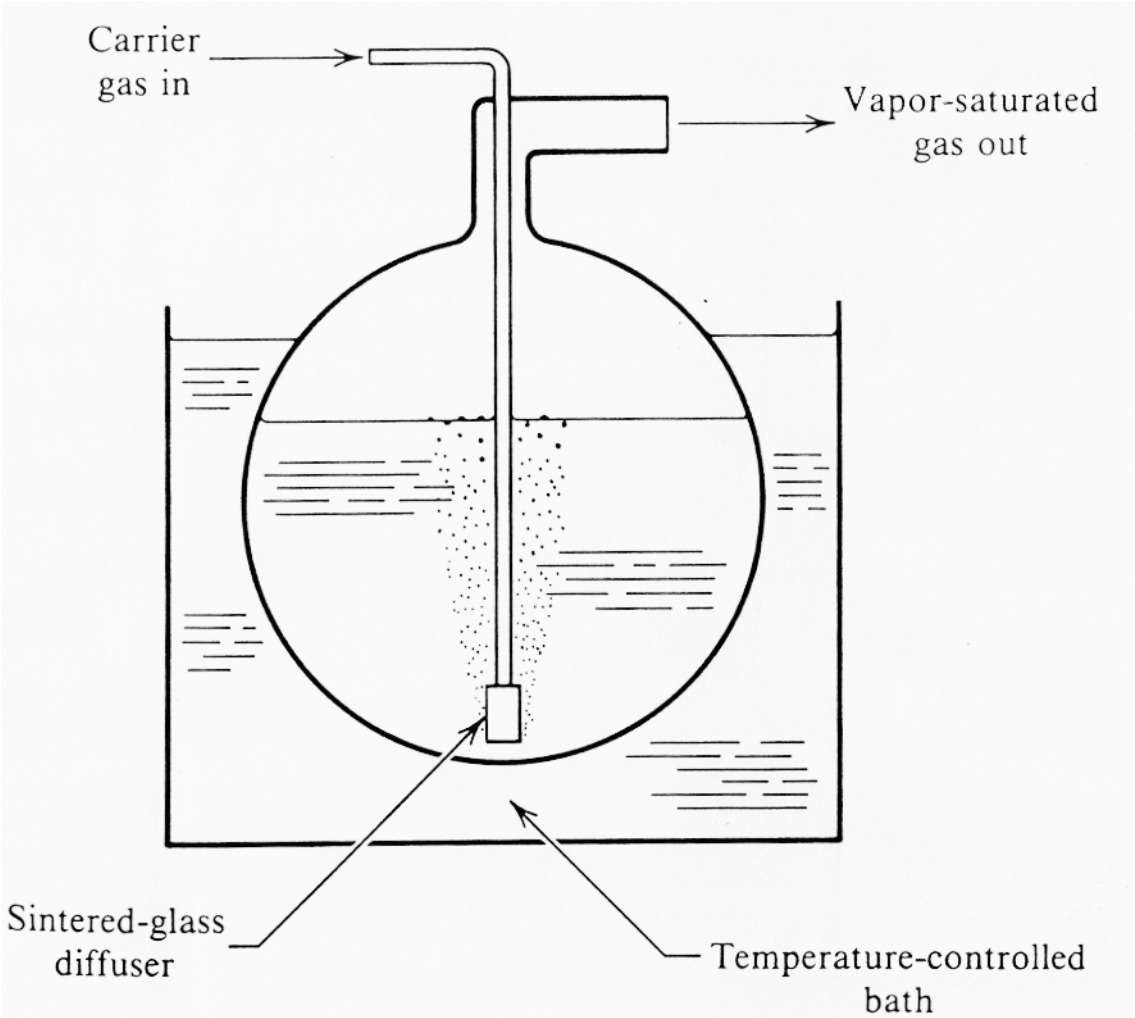


Figure 3-9 Vaporizer or "bubbler" for use with liquid sources.

Safety and Dopant Sources

- Common sources very deadly
- Measure exposure limit for 8 hours in parts per million (ppm)

Table 4.3 Threshold Limit Recommendations for Common Gaseous Sources.*[21]

Source	8-hour 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).

Uniformity of Dopant Distribution

- Variation with Vapour source Dopants
- Doping level varies with gas flow
- Note variation with flow direction

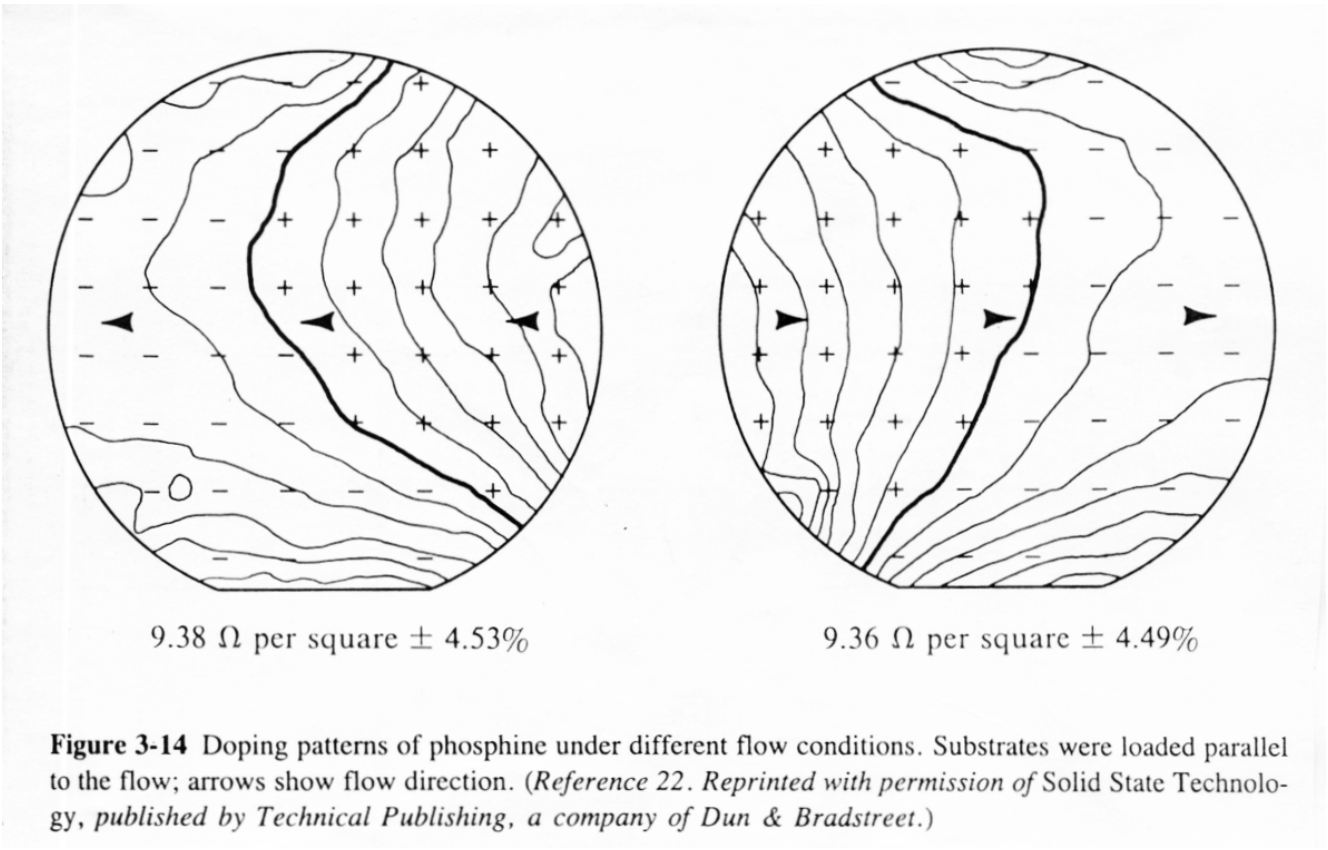


Figure 3-14 Doping patterns of phosphine under different flow conditions. Substrates were loaded parallel to the flow; arrows show flow direction. (*Reference 22. Reprinted with permission of* Solid State Technology, *published by Technical Publishing, a company of Dun & Bradstreet.*)

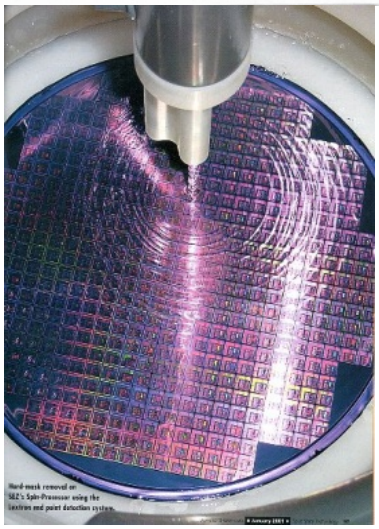
Spin-on Glass Dopants

- Glasses with dopant dissolved in solvent
- Called so-gel: typically Silicon-tetra-acetate $Si(CH_2COOH)_4$
- Spin on like photoresist
- Viscosity and spin speed control thickness
- Usually diluted with ethanol
- Types available:
  - As (arsenosilica)
  - B (Borosilica)
  - P (phosphorosilica)
  - Sb (antimoysilica)
- After spin on bake: 200-250^{o}C, 15 min.
- Baking densifies film, removes water
- Diffusion proceeds as with constant source diffusion
- Soft glass but does allow leveling in processes

Table 5. SELECTED SOURCES FOR CHEMICAL DIFFUSION IN SILICON

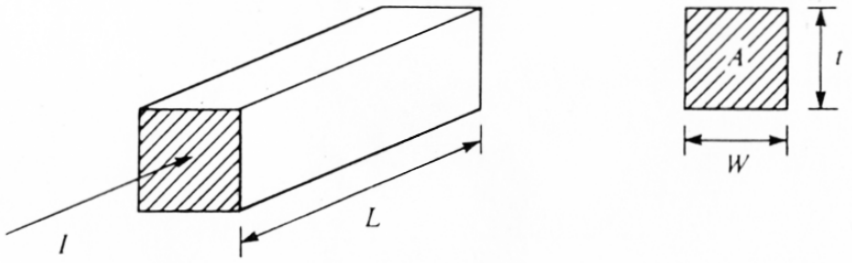
Dopant	Gaseous Source	Liquid Source	Solid Source
As	AsH_3, AsF_3	arsenosilica^s	$AlAsO_4{}^d$
P	PH_3, PF_3	$POCl_3$, phosphosilica^s	$NH_4H_2PO_4{}^d$, $(NH_4)_2H_2PO_4{}^d$
B	B_2H_6, BF_3, BCl_3	BBr_3, $(CH_3O)_3B$ borosilica^s	BN^d
Sb	$SbH_3{}^I$	Sb_3Cl_5, antimonysilica^s	Sb_2O_3, Sb_2O_4

d = disc source s = spin on source I = ion implantation source only



Sheet Resistance Definition

- First measure of doped region is the change in resistivity
- Sheet resistance used for thin films or layers
- Measure resistance in Ohms per square
- Typically put in a test (unprocessed) wafer at that doping process
- Use these monitor wafers for sheet resistance during processing



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

Fig. 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.

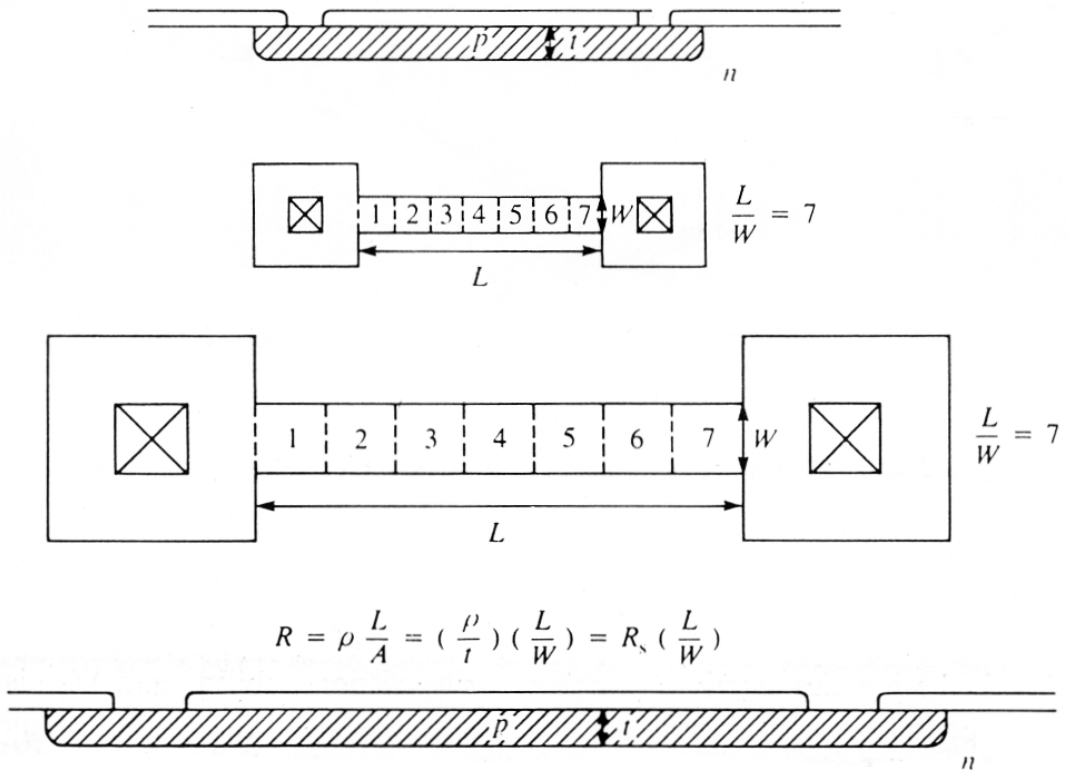
$$R = (\rho/t)\,(L/W) = R_s(L/W) \tag{4.14}$$

where $R_s = (\rho/t)$ is called the *sheet resistance* of the layer of material.

Test Structures for Sheet Resistance

- Always create test structures to monitor process
- Typically place at edge of chip
  or special patterns in wafer
- Measure resistance sheet resistance Ohms/sq.
- Linear test structures

$$R_s = \overline{\rho}/x_j = \left[\int_0^{x_j} \sigma(x)\,dx\right]^{-1}$$



$$R = \rho \frac{L}{A} = \left(\frac{\rho}{t}\right)\left(\frac{L}{W}\right) = R_\square \left(\frac{L}{W}\right)$$

Fig. 4.14 Top and side views of two diffused resistors of different physical size having equal values of resistance. Each resistor has a ratio L/W equal to 7 squares. Each end of the resistor contributes approximately 0.65 additional squares.

Estimating Resistance

- Often state size of structure in terms of squares
- Thus for metal contact to diffusion pads get

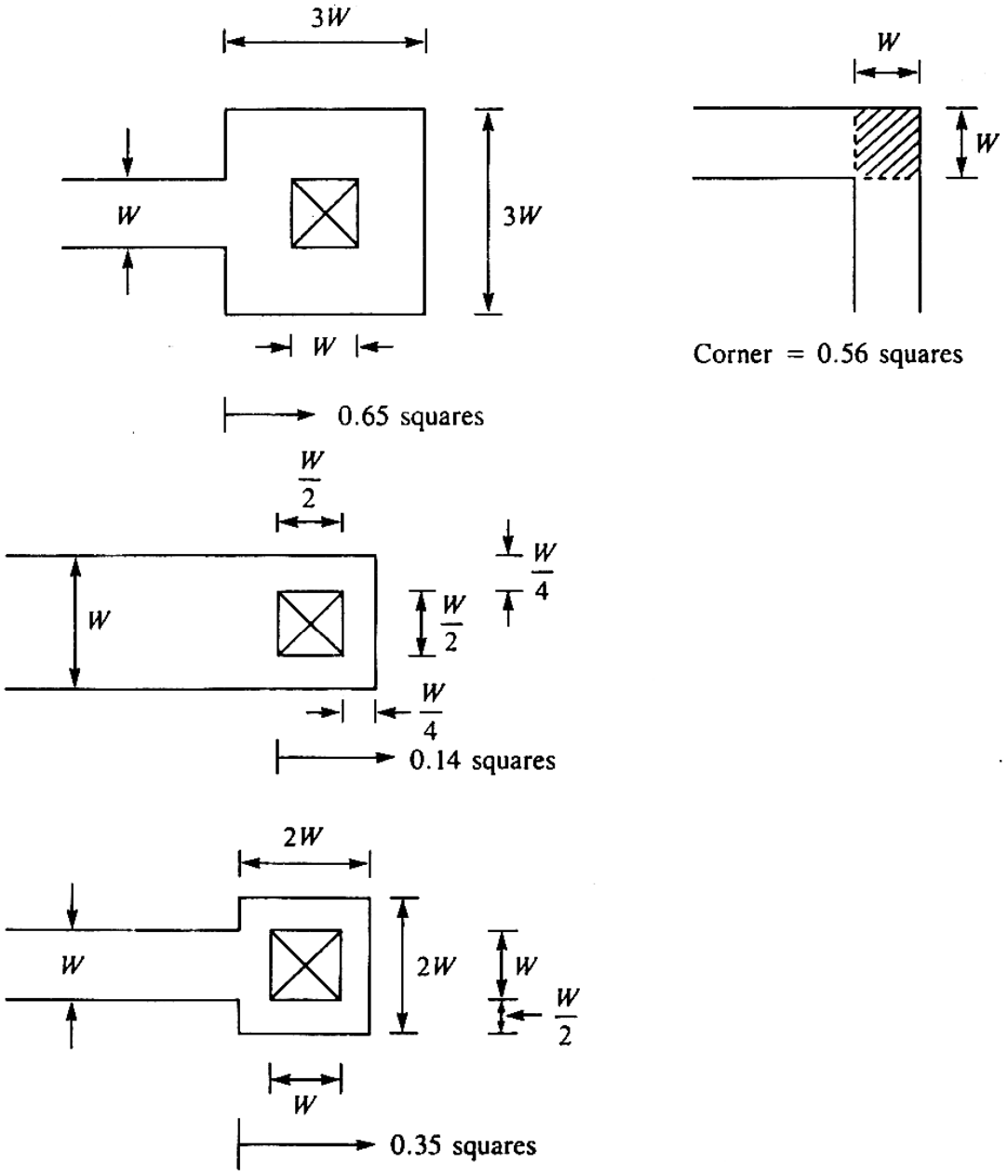
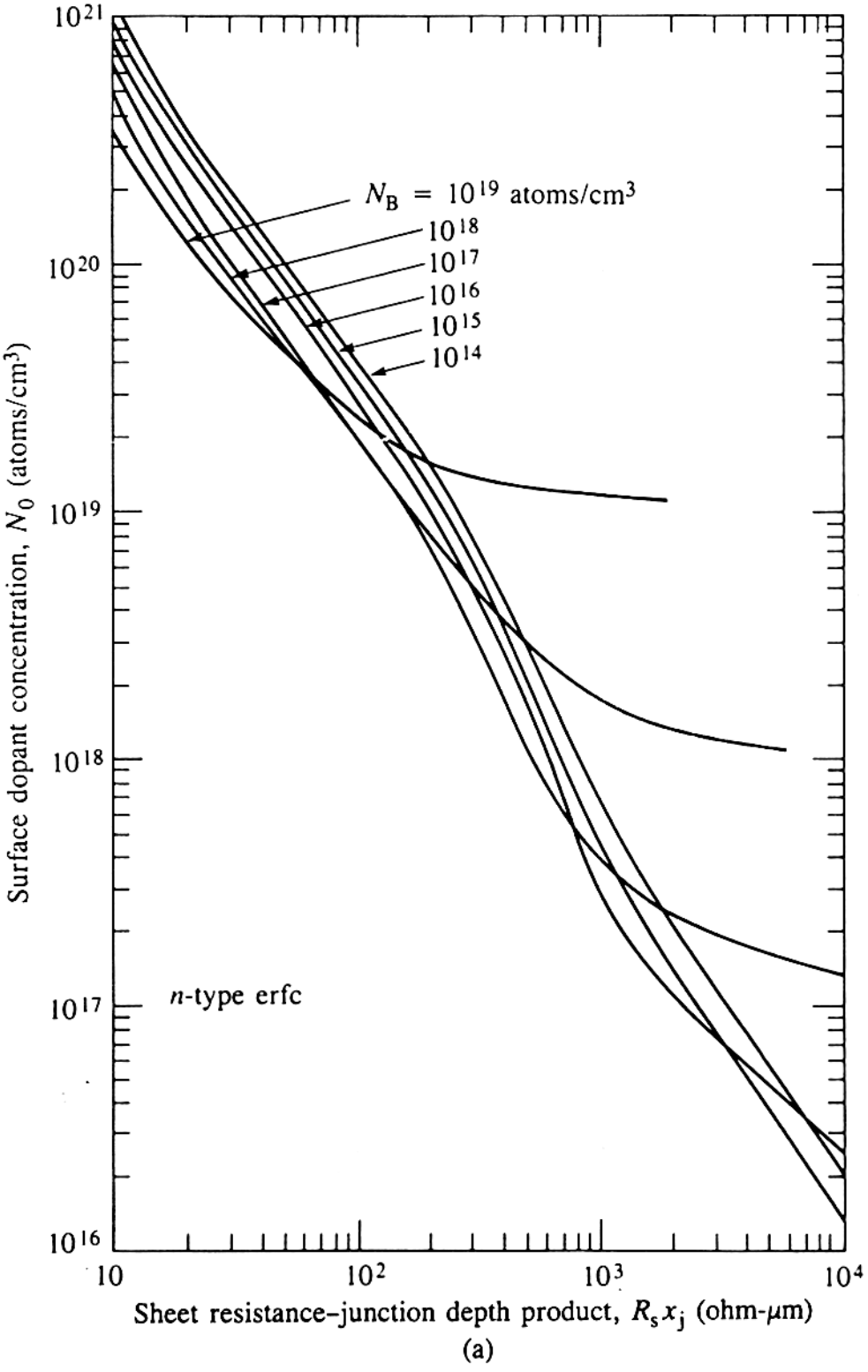


Fig. 4.15 Effective square contributions of various resistor end and corner configurations.

Surface Dopant Density vs Junction Depth

- Relationship between junction depth, Background N_B and surface dopant concentration N_0
- Different charts for Constant and Limited source, n & p type



4 Point Probe Sheet Resistance Measurement

- Test structures often not measureable during processing
- Instead use 4 point probe stations
- Use 2 current sources, separate from V measurement
- Thus do not get resistive loss in V measurement
- Use on test wafers
- Convert 4 point resistance R to sheet resistance R_s ($\Omega/\square$)

$$R_s = R\frac{\pi}{\ln(2)} = R * 4.53$$

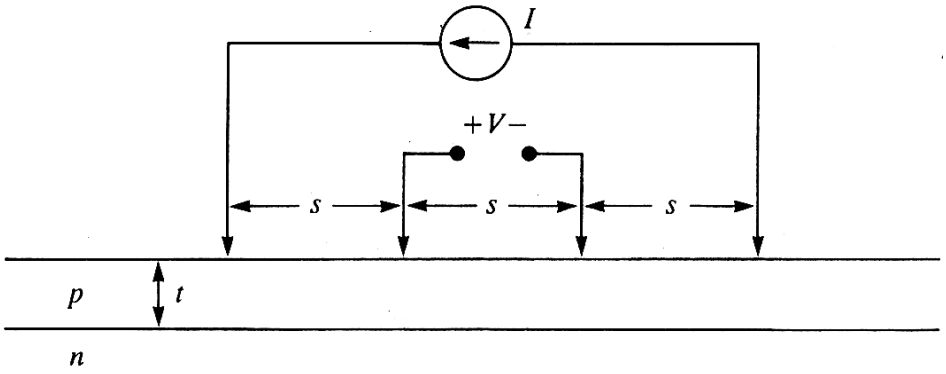
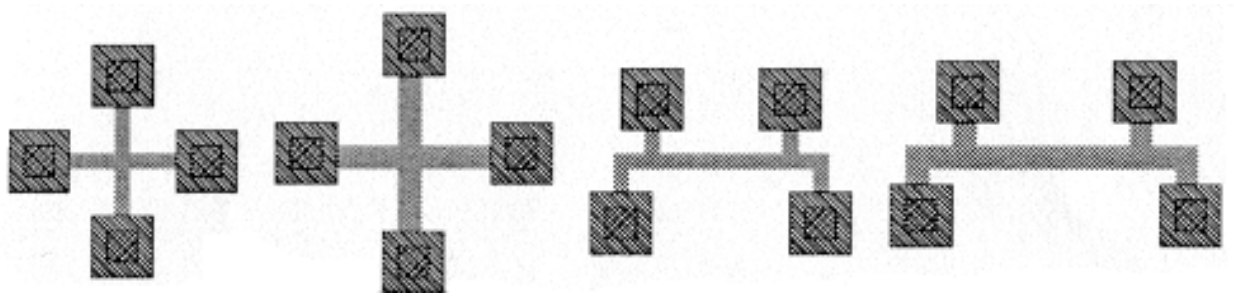


Fig. 4.17 Four-point probe with probe spacing *s* used for direct measurement of bulk wafer resistivity and the sheet resistance of thin diffused layers. A known current is forced through the outer probes, and the voltage developed is measured across the inner probes. (See eqs. (4.16) through (4.18).)

Common Resistance Test Structure: Van der Pauw

- 4 point probe type test structure for post fabrication tests
- Need to add metallization contacts first
- Measures sheet resistance



4 point structures on lab wafers – two for p and n dopants

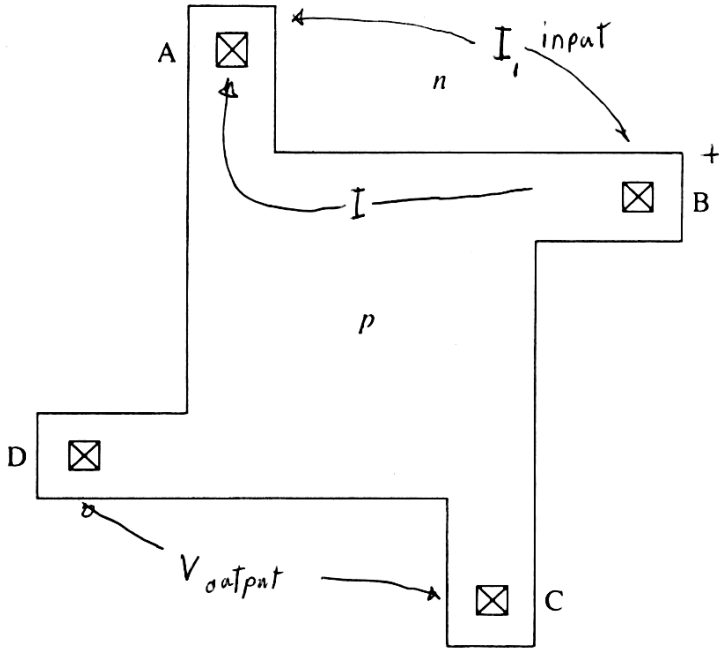


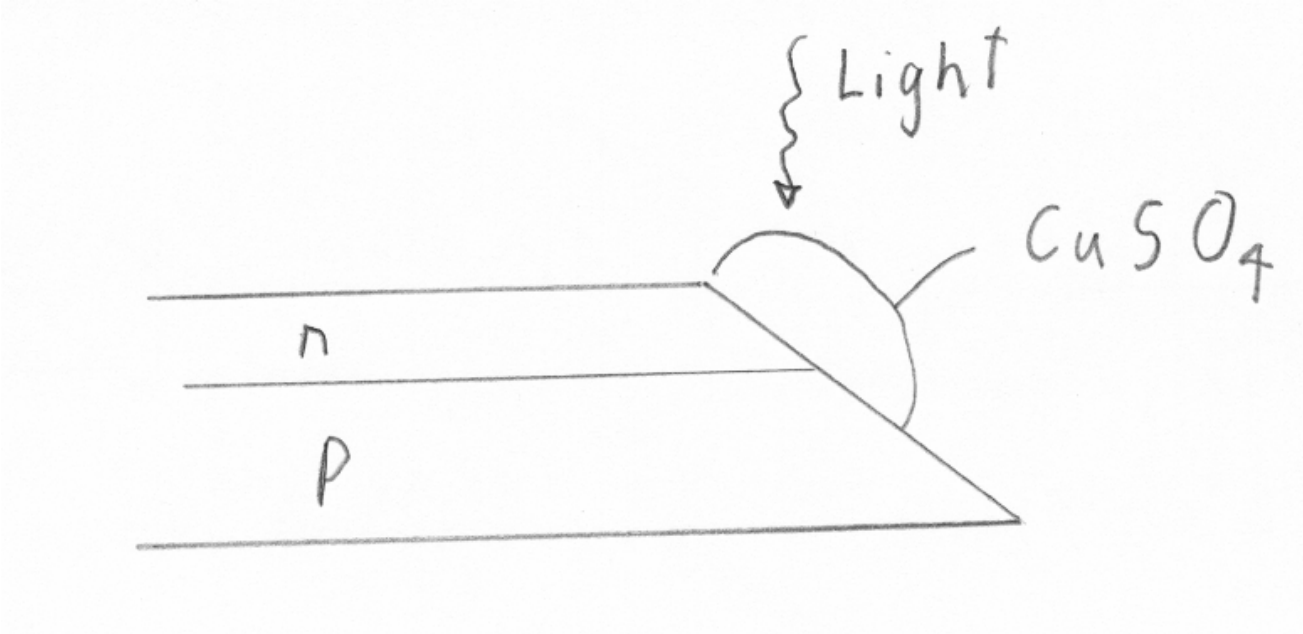
Fig. 4.19 A simple van der Pauw test structure used to measure the sheet resistance of a diffused layer. Sheet resistance is calculated using eq. (4.20).

Angle Lapping: Stain Measurement of Junction thickness

- For all doping need to determine dopant depth/profile
- For diodes/transistors junction depth important process
- Typically put in a test (unprocessed) wafer at that doping process
- Lap (grind away) test wafer at shallow angle (< 2^o)
- After lapping stain the wafer to identify dopant

Staining N type Junction

- Place drop of copper suphate ($CuSO_4$) junction
- Illuminate junction with intense light (UV best)
  causes junction to forward bias
- Voltage causes Cu^{++} to plate on n side



Interference Technique for Grove

- Angle lap & stain wafers
- Place Glass slide over wafer
- Illuminate with single wavelength light
  laser or sodium vapour light
- Get optical interference creating lines
  at half wavelength
- Junction depth by counting lines

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

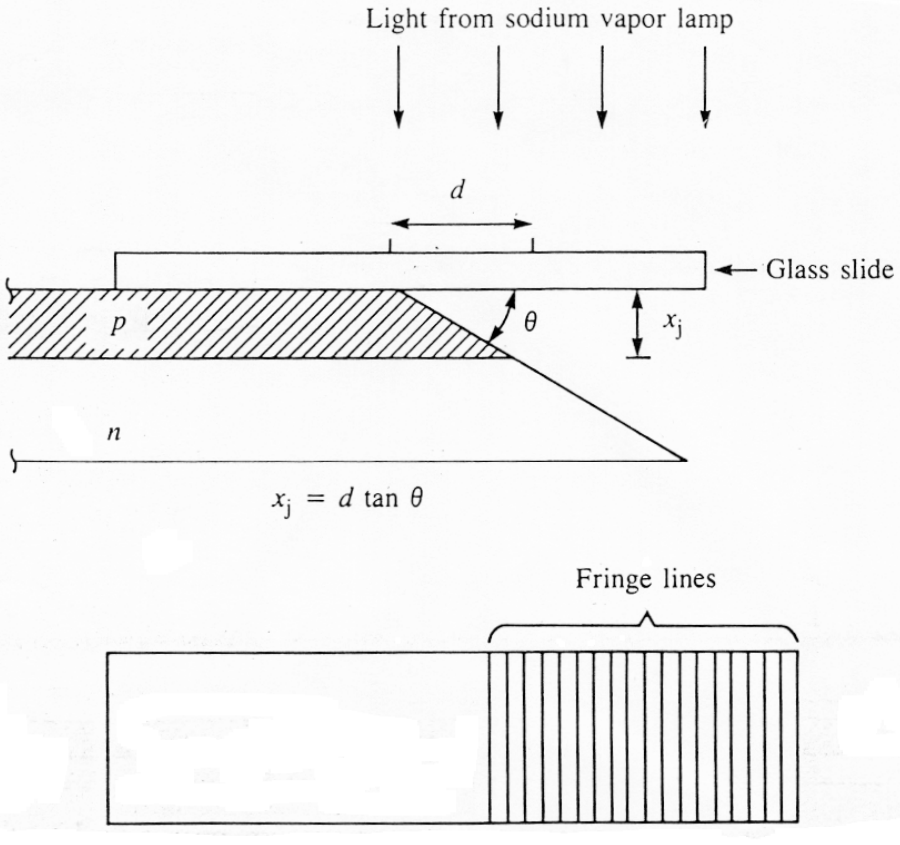
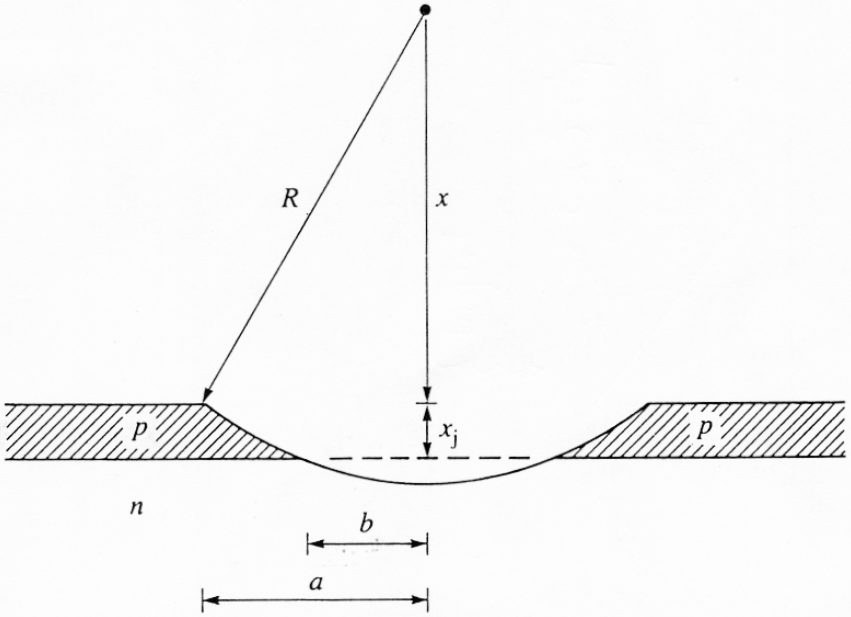


Fig. 4.12 Junction depth measurement by the angle-lap and stain method. Interference fringe lines are used to measure the distance d, which is related to the junction depth using eq. (4.12).

Cylinder Grove of Junctions

- To get shallow angle use a rotating cylinder
- Grove & stain, then measure linear distance
- Depth calculated as below

$$x_j = \sqrt{(R^2 - b^2)} - \sqrt{(R^2 - a^2)} \qquad (4.10)$$



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

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

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

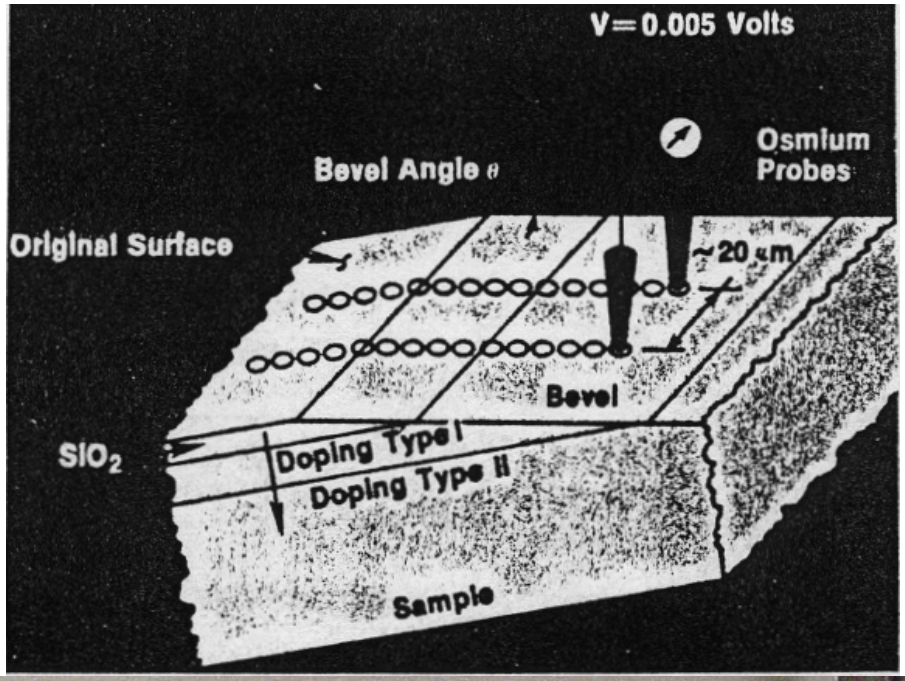
Fig. 4.11 Junction-depth measurement by the groove-and-stain technique. The distances a and b are measured through a microscope, and the junction depth is calculated using eq. (4.11).

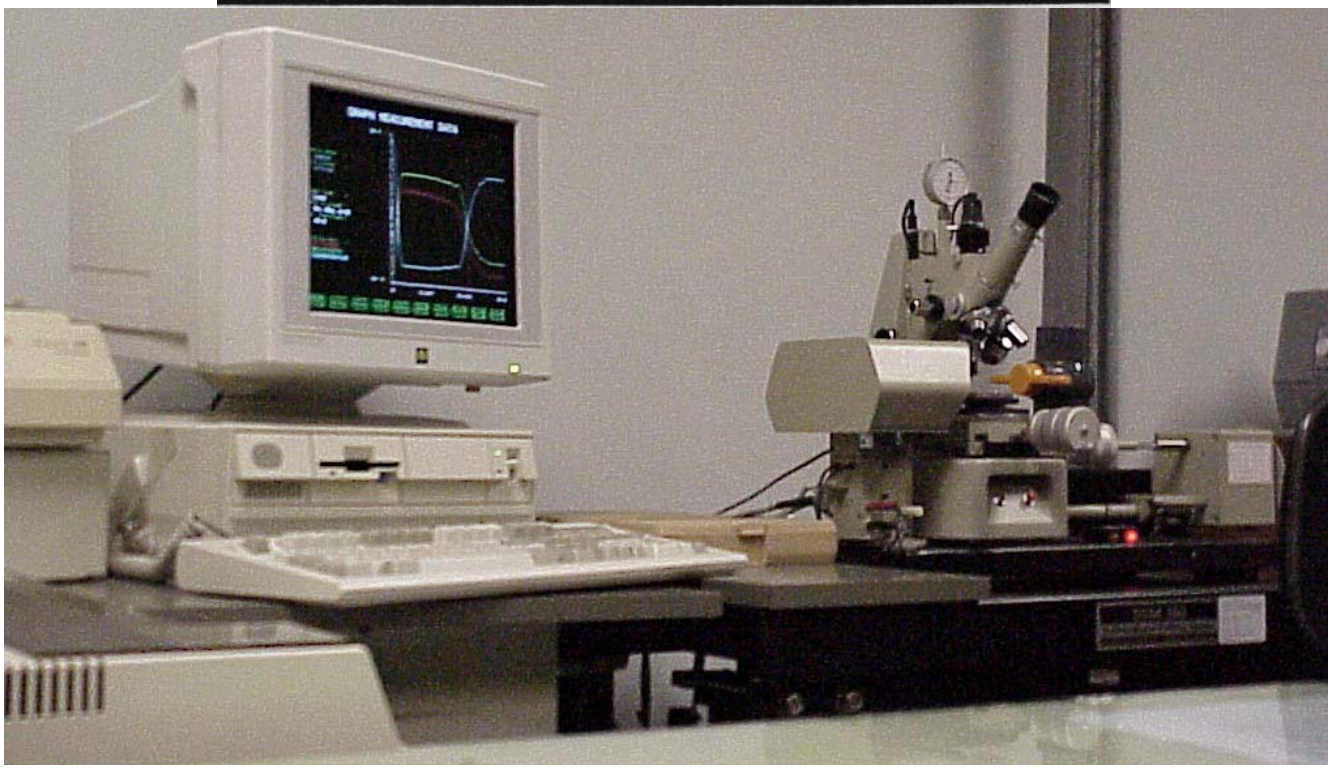
TABLE 4
Commonly used diffusion profile measurement techniques

Profile techniques	Characteristics	Ref.
Capacitance-Voltage	Carrier concentration at the edge of the depletion layer of a pn junction. Maximum total dopants 2×10^{12} atoms/cm^2.	33
Differential conductance	Resistivity and Hall effect mobility of net electrically active species. Requires thin-layer removal, concentration range from 10^{20} to 10^{18} atoms/cm^3.	34
Spreading resistance	Resistance on angle-beveled sample. Good for comparison with known profiles and quick semi quantative evaluation. $x_j \geq 1\mu$m.	35
SIMS	High sensitivity on many elements; for B and As detection limit is 5×10^{15}cm^{-3}. Capable of measuring total dopant profiles in 1000Å range. Needs standards.	36
Radioactive tracer analysis	Total concentration. Lower limit is 10^{15}cm^{-3}. Limited to radioactive elements with suitable half-life times: P, As, Sb, Na Cu, Au, etc.	37
Rutherford backscattering	Applicable only for elements heavier than Si.	38
Nuclear reaction	Measures total boron through ^{10}B(n,^{4}He)^{7}Li, or ^{11}B(p,α). Needs Van de Graaff generator.	39 40

Make shallow angle grove (few degrees)

- Allows a slow change across diffusion layers
- 1 deg angle causes 1 μm depth to become 57 μm wide layer
- Now use 4 point probe resistance method across width of grove
- Good for junctions greater than 1 microns
- Gives junction profiles





Secondary Ion Mass Spectrometry (SIMS)

- Bombard surface in vacuum with ions (1-20 KeV)
- Nocks atoms off surface (sputtering)
- Sputtered atoms collect in Mass Spectrometer
- Count the number of atoms with specific charge/mass ratio
  Si different than dopants
- Can sputter down depth of sample measuring ratios
- Get a depth versus dopant profile
- Can map the dopants vs position
- Expensive: about $500/$1000 per profile

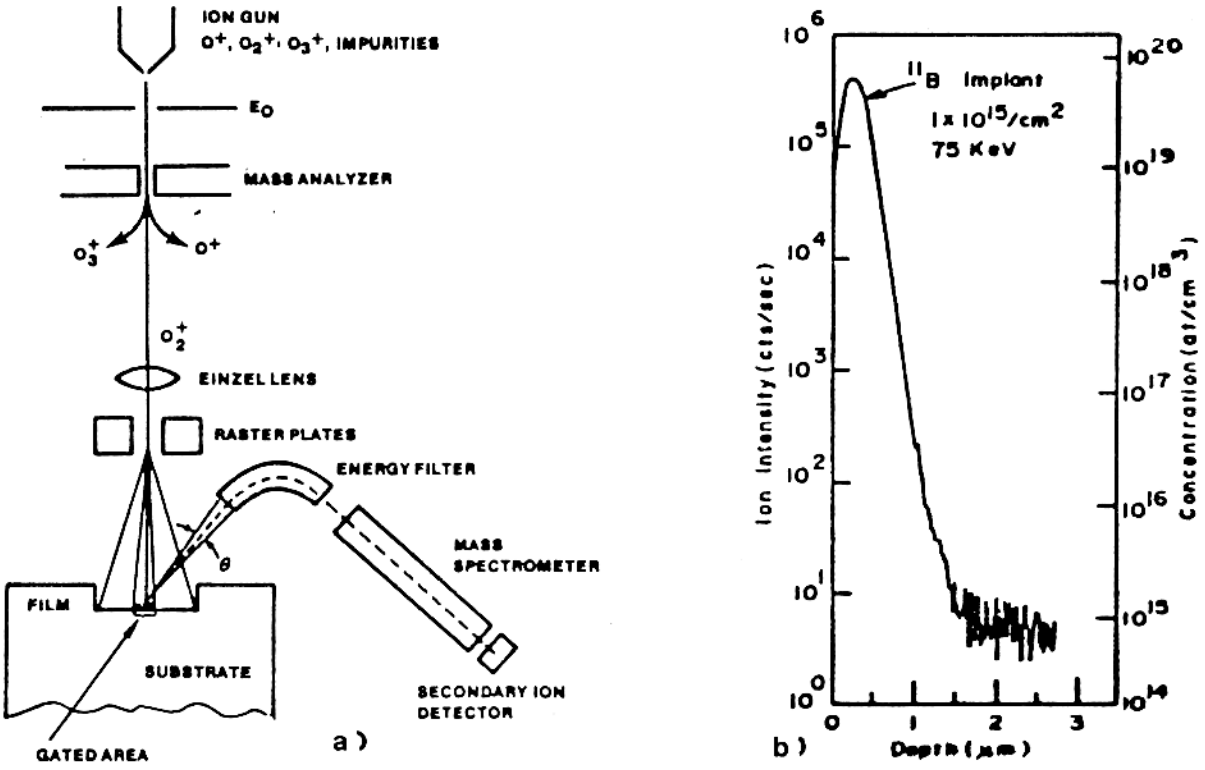


Fig. 18 (a) Schematic diagram of a secondary ion mass spectrometer. (b) Typical SIMS depth profile for boron into boron-doped silicon.

Scanning Ion Microscopy (SMIS)

- Get 2D map of dopant profile
- Expensive: about $1000 per profile
- Great for complex 2D structures