Chapter 2
Solid-State Electronics

Microelectronic Circuit Design

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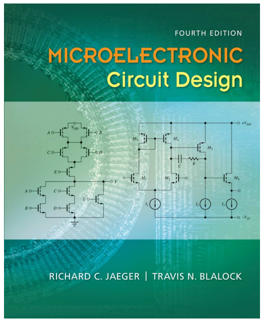
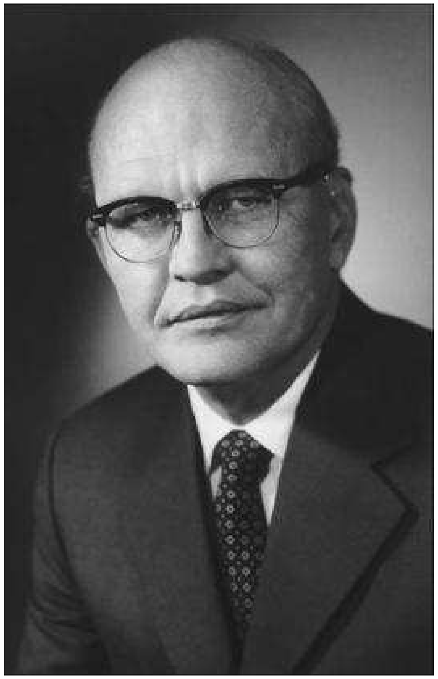


Chapter Goals

- Explore semiconductors and discover how engineers control semiconductor properties to build electronic devices.
- Characterize resistivity of insulators, semiconductors, and conductors.
- Develop covalent bond and energy band models for semiconductors.
- Understand bandgap energy and intrinsic carrier concentration.
- Explore the behavior of electrons and holes in semiconductors.
- Discuss acceptor and donor impurities in semiconductors.
- Learn to control the electron and hole populations using impurity doping.
- Understand drift and diffusion currents in semiconductors.
- Explore low-field mobility and velocity saturation.
- Discuss the dependence of mobility on doping level.

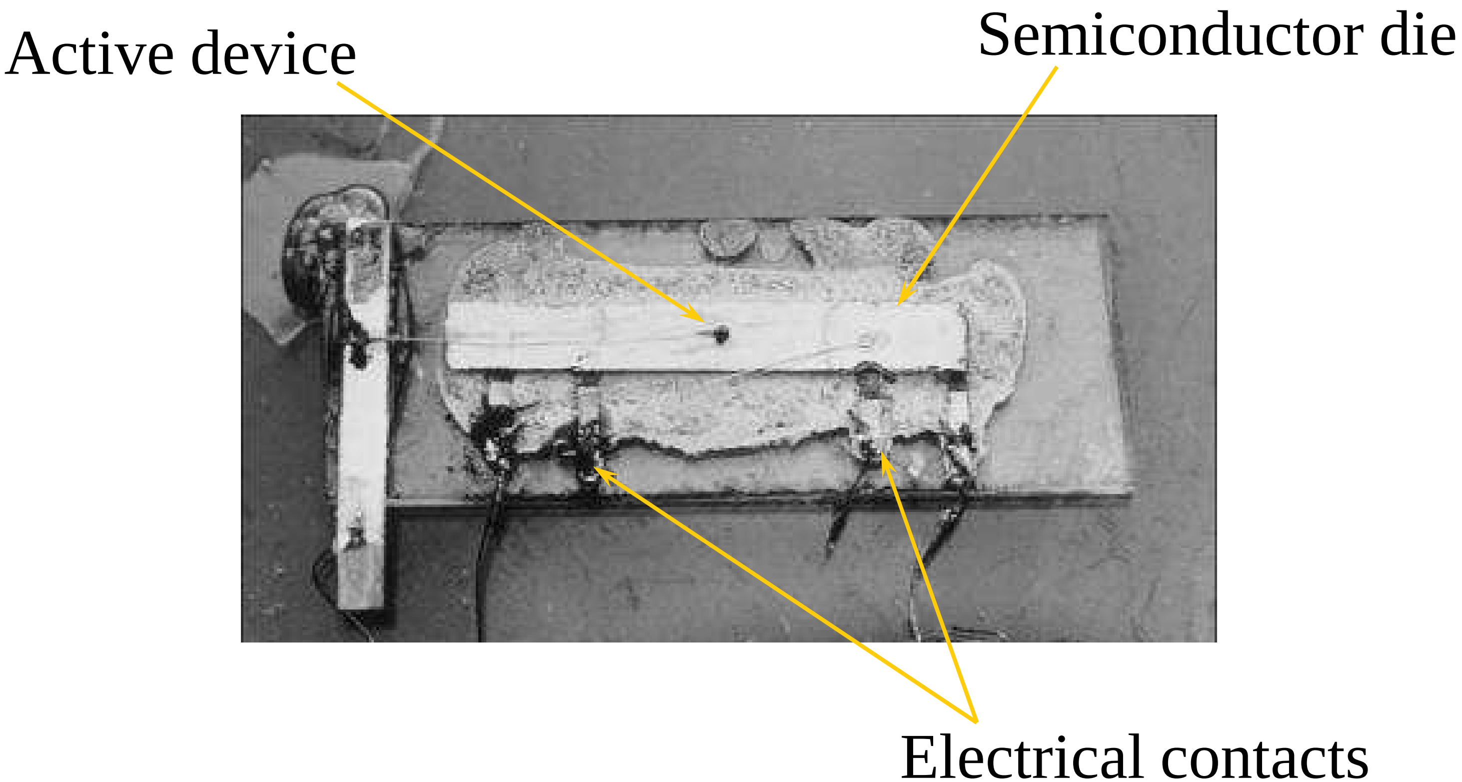
The Inventors of the Integrated Circuit



Jack Kilby

Andy Grove, Robert Noyce, and Gordon Moore with Intel 8080 layout.

The Kilby Integrated Circuit

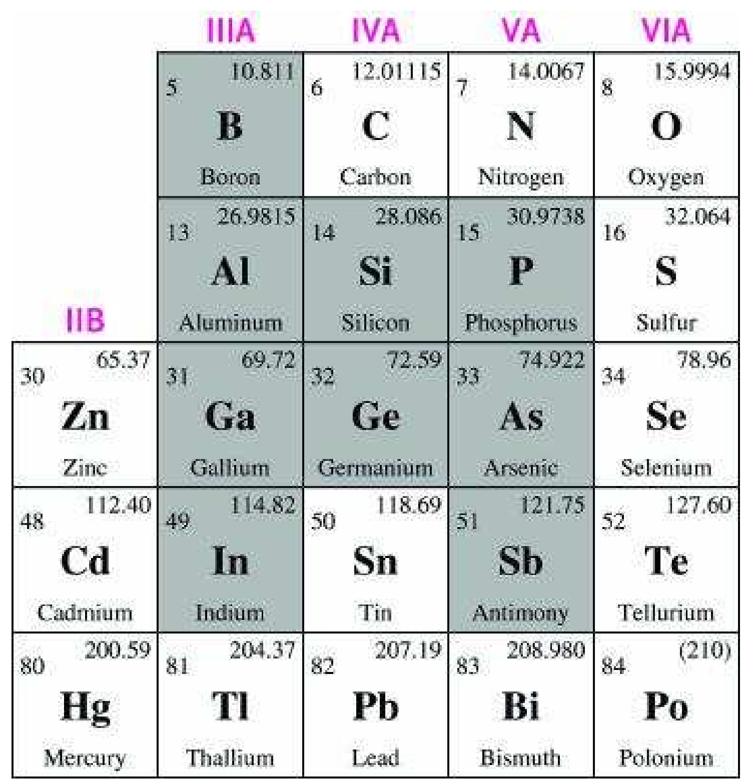


Solid-State Electronic Materials

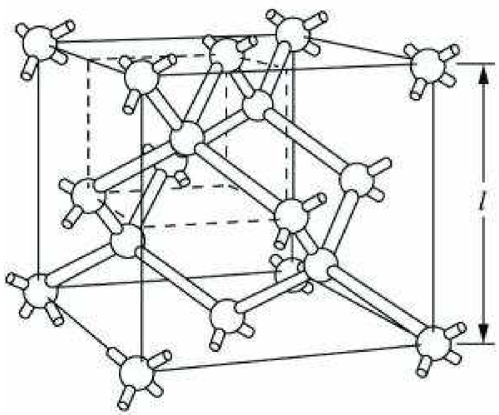
- Electronic materials fall into three categories:
  - Insulators Resistivity $\rho > 10^5\ \Omega$-cm
  - Semiconductors $10^{-3} < \rho < 10^5\ \Omega$-cm
  - Conductors $\rho < 10^{-3}\ \Omega$-cm
- Elemental semiconductors are formed from a single type of atom, typically Silicon.
- Compound semiconductors are formed from combinations of column III and V elements or columns II and VI.
- Germanium was used in many early devices.
- Silicon quickly replaced silicon due to its higher bandgap energy, lower cost, and is easily oxidized to form silicon dioxide insulating layers.

Semiconductor Materials (cont.)

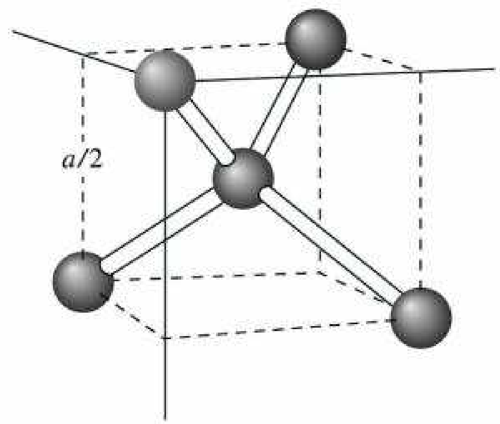
Semiconductor	**Bandgap Energy E_G (eV)**
Carbon (diamond)	5.47
Silicon	1.12
Germanium	0.66
Tin	0.082
Gallium arsenide	1.42
Gallium nitride	3.49
Indium phosphide	1.35
Boron nitride	7.50
Silicon carbide	3.26
Cadmium selenide	1.70



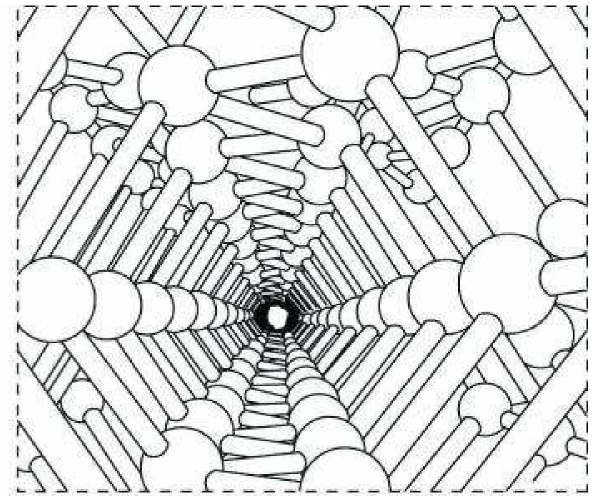
Covalent Bond Model



Silicon diamond lattice unit cell.

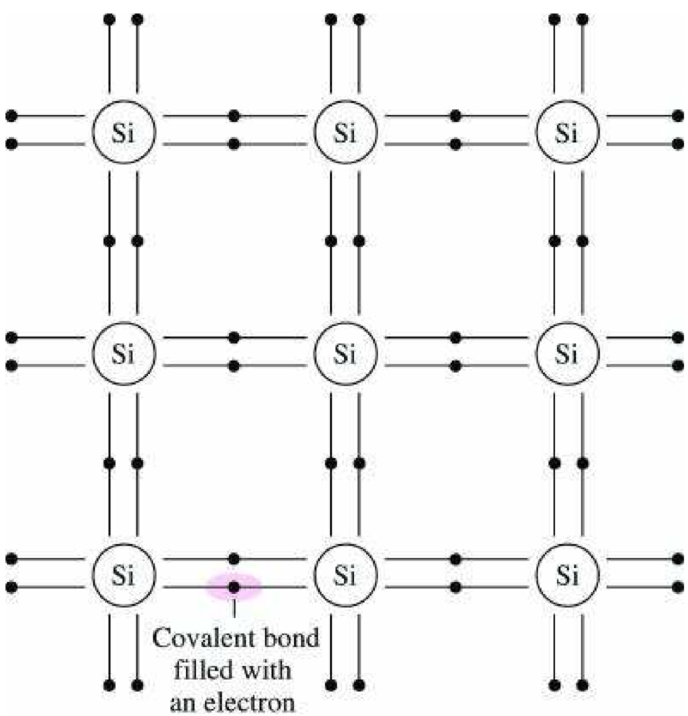


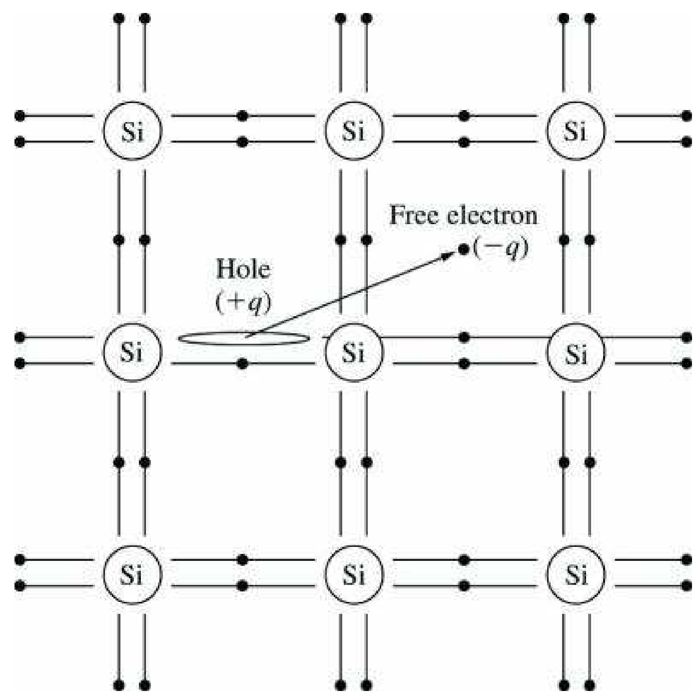
Corner of diamond lattice showing four nearest neighbor bonding.



View of crystal lattice along a crystallographic axis.

Silicon Covalent Bond Model (cont.)





Near absolute zero, all bonds are complete. Each Si atom contributes one electron to each of the four bond pairs.

Increasing temperature adds energy to the system and breaks bonds in the lattice, generating electron-hole pairs.

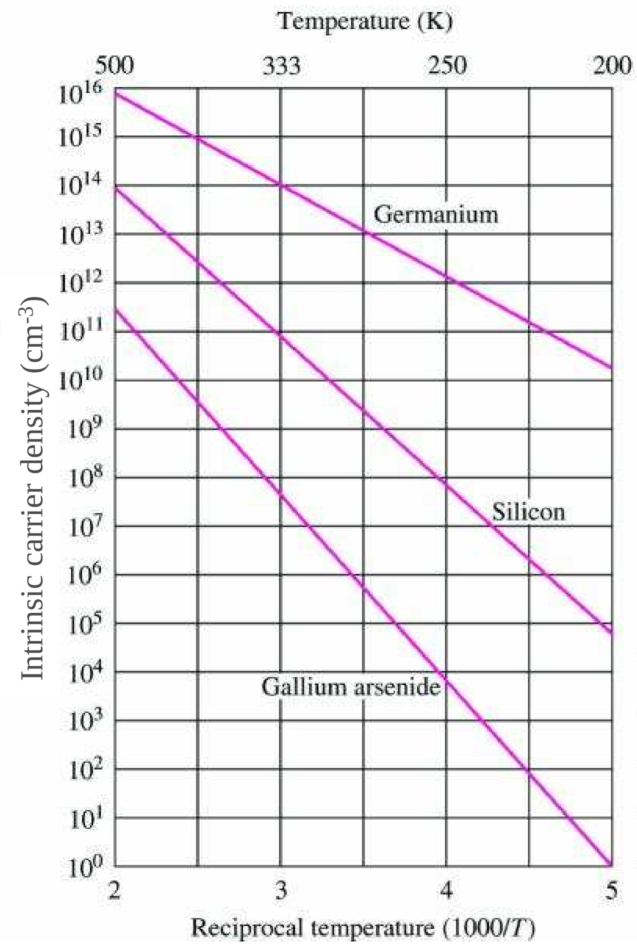
Intrinsic Carrier Concentration

- The density of carriers in a semiconductor as a function of temperature and material properties is:

$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) \quad \text{cm}^{-6}$$

- E_G = semiconductor bandgap energy in eV (electron volts)
- k = Boltzmann's constant, 8.62 x 10^{-5} eV/K
- T = absolute temperature, K
- B = material-dependent parameter, 1.08 x 10^{31} K^{-3} cm^{-6} for Si
- Bandgap energy is the minimum energy needed to free an electron by breaking a covalent bond in the semiconductor crystal.

Intrinsic Carrier Concentration (cont.)



	B ($K^{-3} \cdot cm^{-6}$)	E_G (eV)
Si	1.08×10^{31}	1.12
Ge	2.31×10^{30}	0.66
GaAs	1.27×10^{29}	1.42

- Electron density is n (electrons/cm^3) and n_i for intrinsic material $n = n_i$.
- Intrinsic refers to properties of pure materials.
- $n_i \approx 10^{10}$ cm^{-3} for Si

Electron and Hole Concentrations

- A vacancy is left when a covalent bond is broken.
- The vacancy is called a hole.
- A hole moves when the vacancy is filled by an electron from a nearby broken bond (hole current).
- Hole density is represented by *p*.
- For intrinsic silicon, $p = n_i$ and $n = n_i$.
- The product of the electron and hole concentrations is $pn = n_i^2$.
- The pn product above holds when a semiconductor is in thermal equilibrium (not with an external voltage or other stimulation applied).

Drift Current

- Electrical resistivity ρ and its reciprocal, *conductivity* σ, characterize current flow in a material when an electric field is applied.
- Charged particles move or *drift* under the influence of the applied field.
- The resulting current is called *drift current*.
- Drift current density is

$$j = Qv \quad (\mathrm{C/cm^3})(\mathrm{cm/s}) = \mathrm{A/cm^2}$$

j = current density (Coulomb charge moving through a unit area)

Q = charge density (Charge in a unit volume)

v = velocity of charge in an electric field.

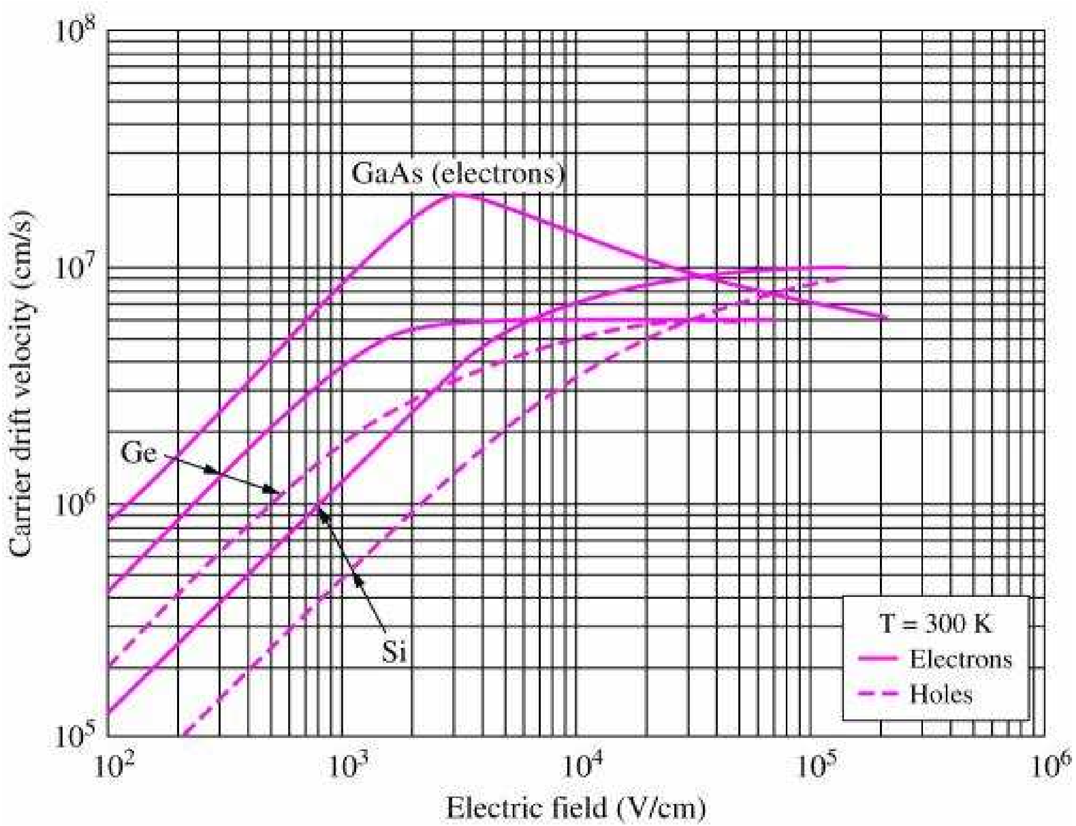
Note that "density" may mean area or volumetric density, depending on the context.

Mobility

- At low fields, carrier drift velocity v (cm/s) is proportional to electric field E (V/cm). The constant of proportionality is the mobility μ:
- $v_n = -\mu_n E$ and $v_p = +\mu_p E$, where
- v_n and v_p = electron and hole velocity (cm/s),
- μ_n and μ_p = electron and hole mobility ($cm^2/V{\cdot}s$)

- Hole mobility is less than electron since hole current is the result of multiple covalent bond hops, while electrons can move freely about the crystal.

Velocity Saturation



At high fields, carrier velocity saturates and this effect places upper limits on the speed of solid-state devices.

Intrinsic Silicon Resistivity

- Given drift current and mobility, we can calculate resistivity:

$$j_n^{drift} = Q_n v_n = (\text{-qn})(-\mu_n E) = qn\mu_n E \quad \text{A/cm}^2$$

$$j_p^{drift} = Q_p v_p = (\text{+qp})(+\mu_p E) = qp\mu_p E \quad \text{A/cm}^2$$

$$j_T^{drift} = j_n + j_p = q(n\,\mu_n + p\,\mu_p)E = \sigma E$$

This defines electrical conductivity:

$$\sigma = q(n\,\mu_n + p\,\mu_p) \qquad (\Omega\cdot\text{cm})^{-1}$$

Resistivity ρ is the reciprocal of conductivity:

$$\rho = 1/\sigma \qquad (\Omega\cdot\text{cm})$$

$$\left(\rho = \frac{E}{j_T^{drift}} = \frac{V/cm}{A/cm^2} = \Omega \cdot cm\right)$$

Example: Calculate the resistivity of intrinsic silicon

Problem: Find the resistivity of intrinsic silicon at room temperature and classify it as an insulator, semiconductor, or conductor.

Solution:

- **Known Information and Given Data:** The room temperature mobilities for intrinsic silicon were given following Eq. 2.4. For intrinsic silicon, the electron and hole densities are both equal to n_i.
- **Unknowns:** Resistivity ρ and classification.
- **Approach:** Use Eqs. 2.7 and 2.8. [$\sigma = q(n\,\mu_n + p\,\mu_p)$ $(\Omega\cdot\text{cm})^{-1}$]
- **Assumptions:** Temperature is unspecified; assume "room temperature" with $n_i = 10^{10}/\text{cm}^3$.
- **Analysis:** Next slide…

Example: Calculate the resistivity of intrinsic silicon (cont.)

- **Analysis:** Charge density of electrons is $Q_n = -qn_i$ and for holes is $Q_p = +qn_i$. Substituting into Eq. 2.7:

$$\sigma = (1.60 \text{ x } 10^{-10})[(10^{10})(1350) + (10^{10})(500)] \quad (\text{C})(\text{cm}^{-3})(\text{cm}^2/\text{V}\cdot\text{s})$$
$$= 2.96 \text{ x } 10^{-6} \, (\Omega\cdot\text{cm})^{-1} \quad \text{--->} \quad \rho = 1/\sigma = 3.38 \text{ x } 10^5 \, \Omega\cdot\text{cm}$$

From Table 2.1, intrinsic silicon is near the low end of the insulator resistivity range

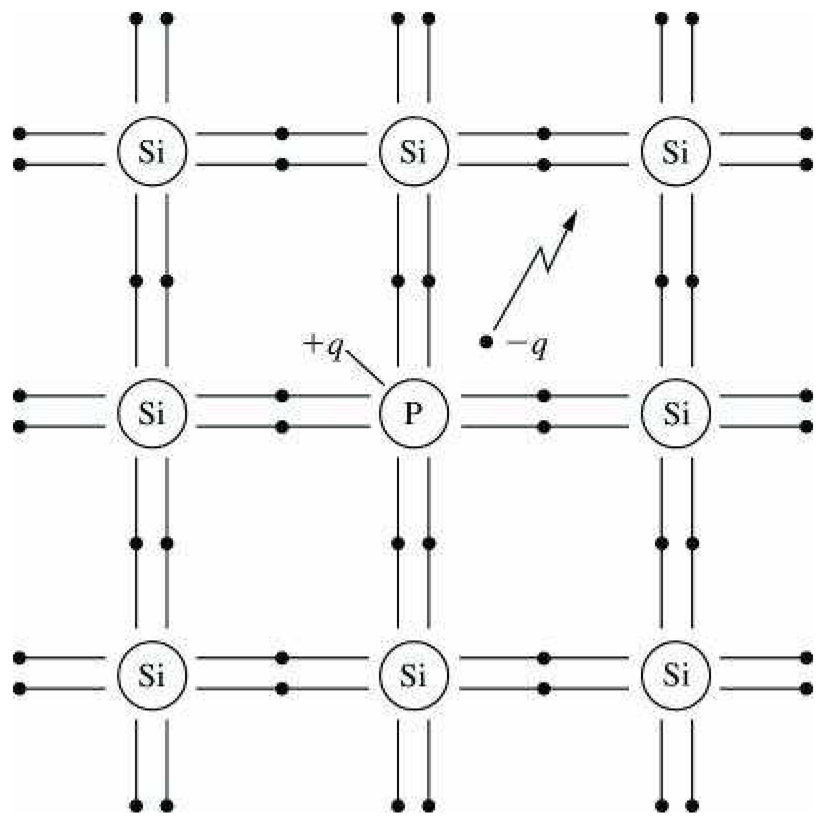
- **Check of Results:** Resistivity has been found, and intrinsic silicon is a poor insulator.

Semiconductor Doping

- Doping is the process of adding very small & well-controlled amounts of impurities into a semiconductor.
- Doping enables the control of the resistivity and other properties over a wide range of values.
- For silicon, impurities are from columns III and V of the periodic table.

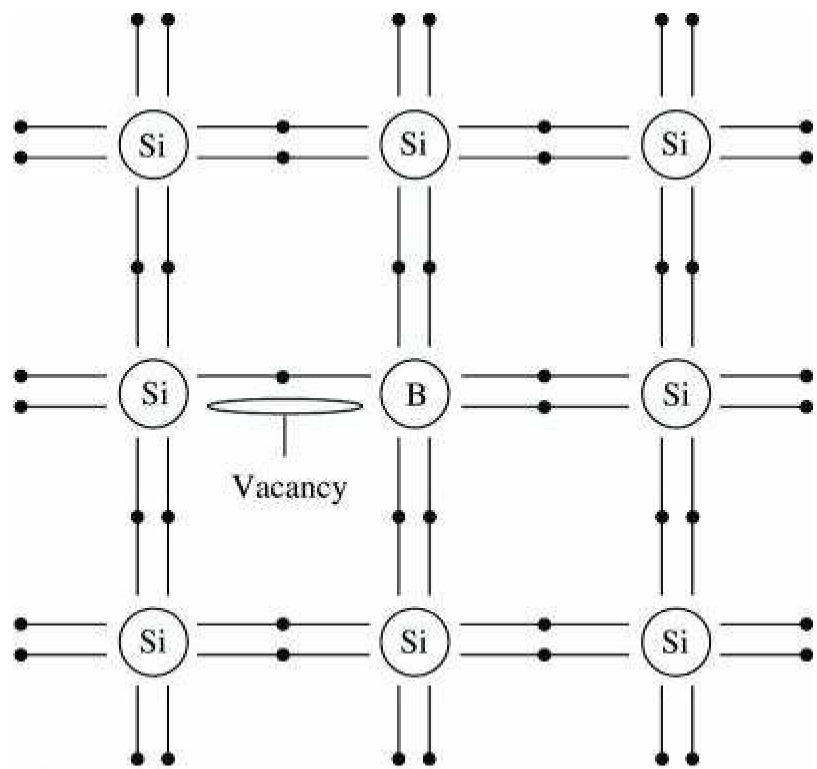
Donor Impurities in Silicon

- A phosphorous (or other column V element) atom replaces a silicon atom in the crystal lattice.
- Since phosphorous has five outer shell electrons, there is now an 'extra' electron in the structure.
- Material is still charge neutral, but very little energy is required to free the electron for conduction since it is not participating in a bond.



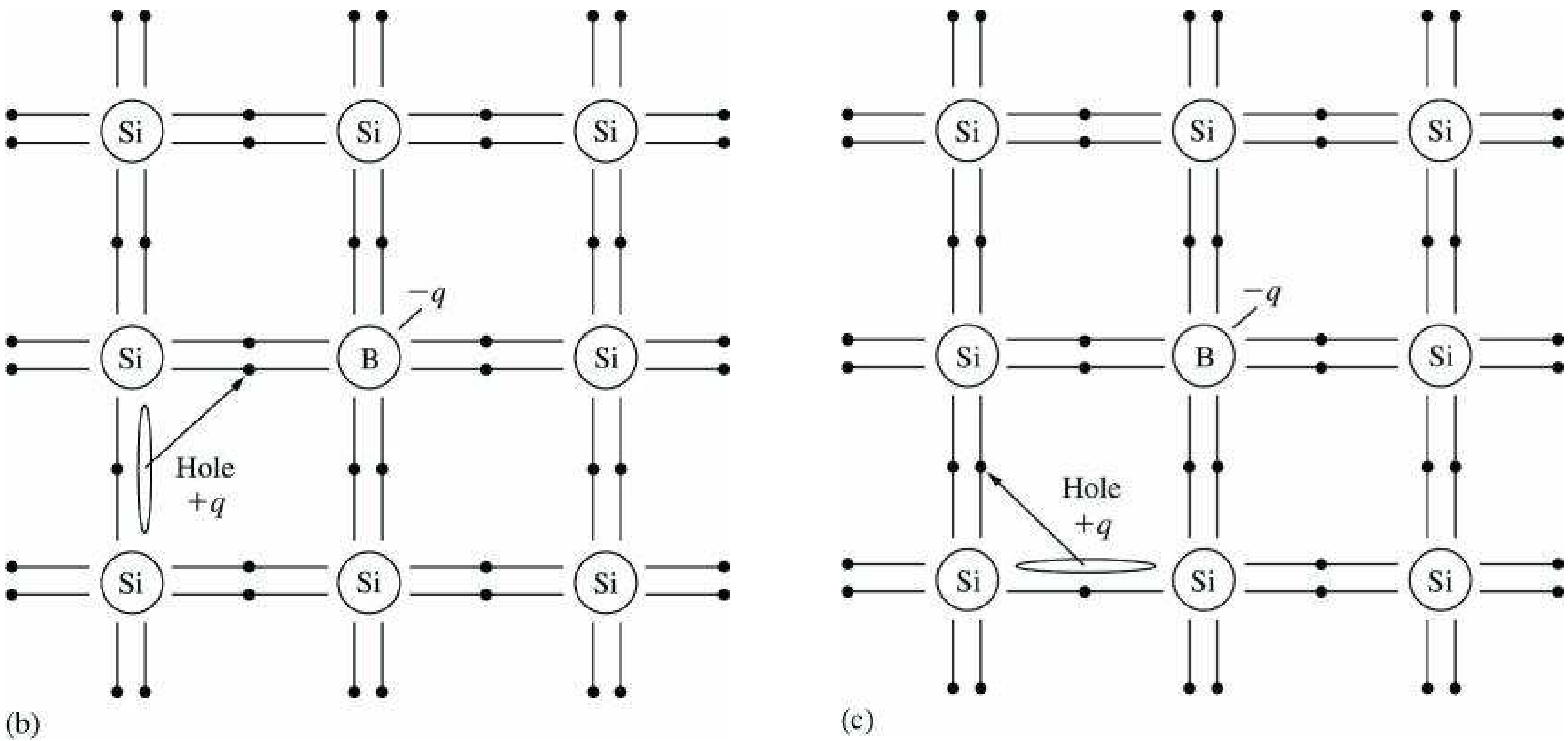
Acceptor Impurities in Silicon

- A boron (column III element) atom can replace a silicon atom.
- There is now an incomplete bond pair, creating a vacancy for an electron.
- Little energy is required to move a nearby electron into the vacancy.
- As the 'hole' propagates, charge is moved across the silicon.



(a)

Acceptor Impurities in Silicon (cont.)



A Hole is propagating through the silicon.

Doped Silicon Carrier Concentrations

- If $n > p$, the material is **n-type**.
  If $p > n$, the material is **p-type**.
- The carrier with the largest concentration is the majority carrier, the smaller is the minority carrier.
- $\mathbf{N_D}$ = donor impurity concentration (atoms/cm^3)
  $\mathbf{N_A}$ = acceptor impurity concentration (atoms/cm^3)
- Charge neutrality requires $q(N_D + p - N_A - n) = 0$
- It can also be shown that $pn = n_i^2$, even for doped semiconductors in thermal equilibrium.

n-type Material

- Substituting $p = n_i^2/n$ into $q(N_D + p - N_A - n) = 0$ yields $n^2 - (N_D - N_A)n - n_i^2 = 0$.
- Solving for n

$$n = \frac{(N_D - N_A) \pm \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2} \quad \text{and} \quad p = \frac{n_i^2}{n}$$

- For $(N_D - N_A) >> 2n_i$, $\quad n \cong (N_D - N_A)$.

p-type Material

- Similar to the approach used with n-type material we find the following equations:

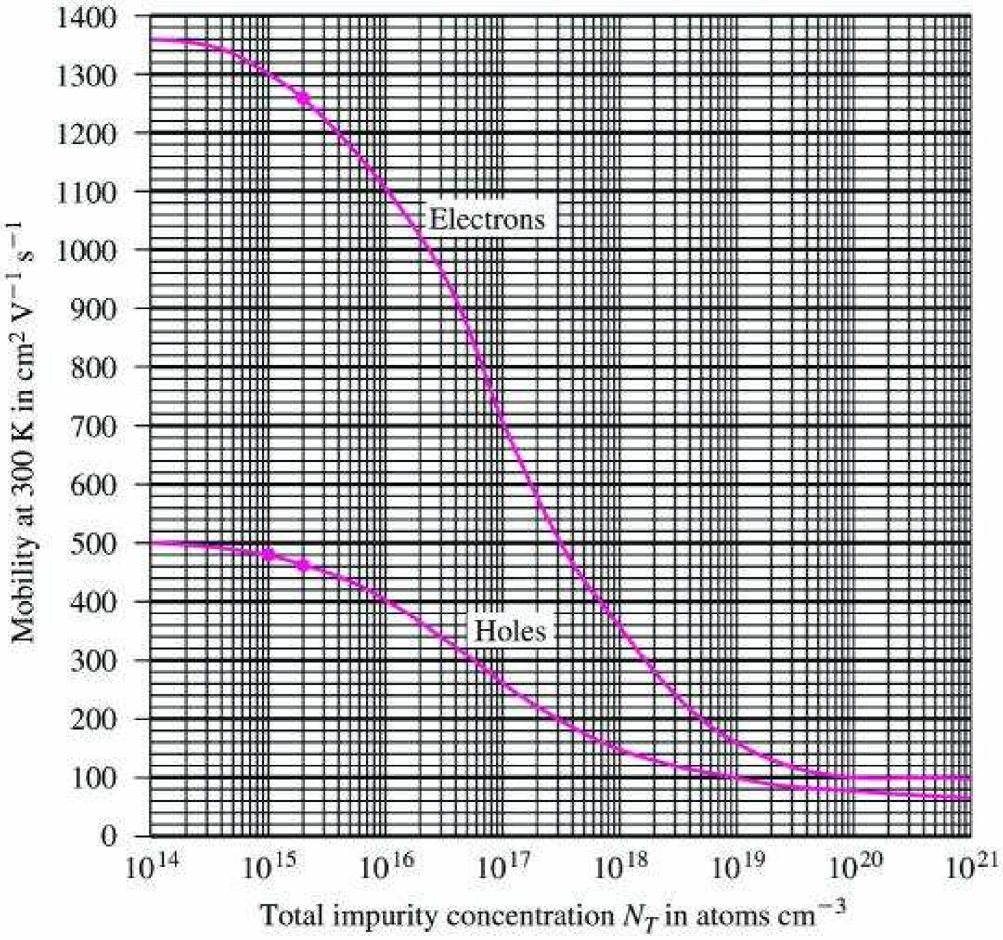
$$p = \frac{(N_A - N_D) \pm \sqrt{(N_A - N_D)^2 + 4n_i^2}}{2} \quad \text{and} \quad n = \frac{n_i^2}{p}$$

- We find the majority carrier concentration from charge neutrality (Eq. 2.10) and find the minority carrier conc. from the thermal equilibrium relationship (Eq. 2.2).
- For $(N_A - N_D) >> 2n_i$, $p \cong (N_A - N_D)$.

Practical Doping Levels

- Majority carrier concentrations are established at manufacturing time and are independent of temperature (over practical temp. ranges).
- However, minority carrier concentrations are proportional to n_i^2, a highly temperature dependent term.
- For practical doping levels, $n \cong (N_D - N_A)$ for n-type and $p \cong (N_A - N_D)$ for p-type material.
- Typical doping ranges are $10^{14}/cm^3$ to $10^{21}/cm^3$.

Mobility and Resistivity in Doped Semiconductors



Mobility approximations

$$\mu_n = 92 + \frac{1270}{1 + \left(\dfrac{N_T}{1.3 \times 10^{17}}\right)^{0.91}}$$

$$\mu_p = 48 + \frac{447}{1 + \left(\dfrac{N_T}{6.3 \times 10^{16}}\right)^{0.76}}$$

Diffusion Current

- In practical semiconductors, it is quite useful to create carrier concentration gradients by varying the doping concentration and/or the doping type across a region of semiconductor.
- This gives rise to a diffusion current resulting from the natural tendency of carriers to move from high concentration regions to low concentration regions.
- Diffusion current is analogous to a gas moving across a room to evenly distribute itself across the volume.

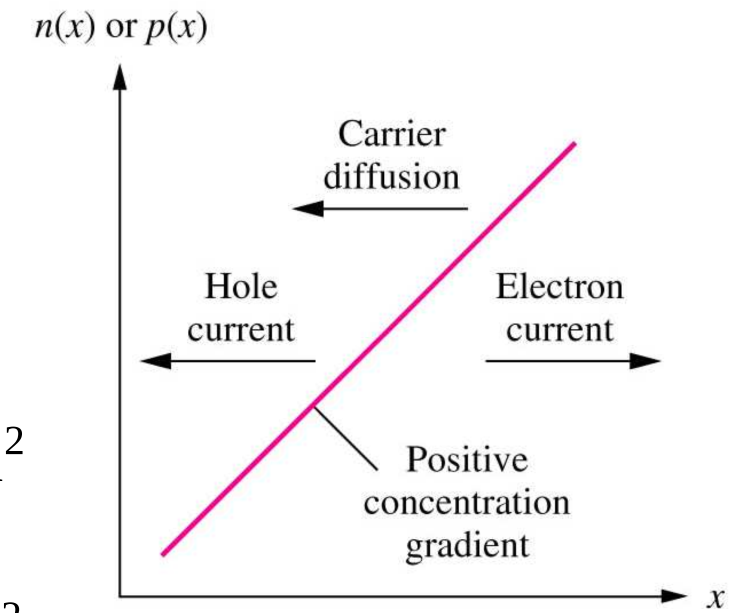
Diffusion Current (cont.)

- Carriers move toward regions of lower concentration, so diffusion current densities are proportional to the negative of the carrier gradient.

$$j_p^{diff} = (+q)D_p\left(-\frac{\partial p}{\partial x}\right) = -qD_p\frac{\partial p}{\partial x} \quad \text{A/cm}^2$$

$$j_n^{diff} = (-q)D_n\left(-\frac{\partial p}{\partial x}\right) = +qD_n\frac{\partial n}{\partial x} \quad \text{A/cm}^2$$

Diffusion current density equations



Diffusion currents in the presence of a concentration gradient.

Diffusion Current (cont.)

- D_p and D_n are the hole and electron diffusivities with units cm^2/s. Diffusivity and mobility are related by Einsteins's relationship:

$$\frac{D_n}{\mu_n} = \frac{kT}{q} = \frac{D_p}{\mu_p} = V_T = \text{Thermal voltage}$$

$$D_n = \mu_n V_T \ , \ \ D_p = \mu_p V_T$$

- The thermal voltage, $V_T = kT/q$, is approximately 25 mV at room temperature. We will encounter V_T throughout this book.

Total Current in a Semiconductor

- Total current is the sum of drift and diffusion current:

$$j_n^T = q\mu_n nE + qD_n \frac{\partial n}{\partial x}$$

$$j_p^T = q\mu_p pE - qD_p \frac{\partial p}{\partial x}$$

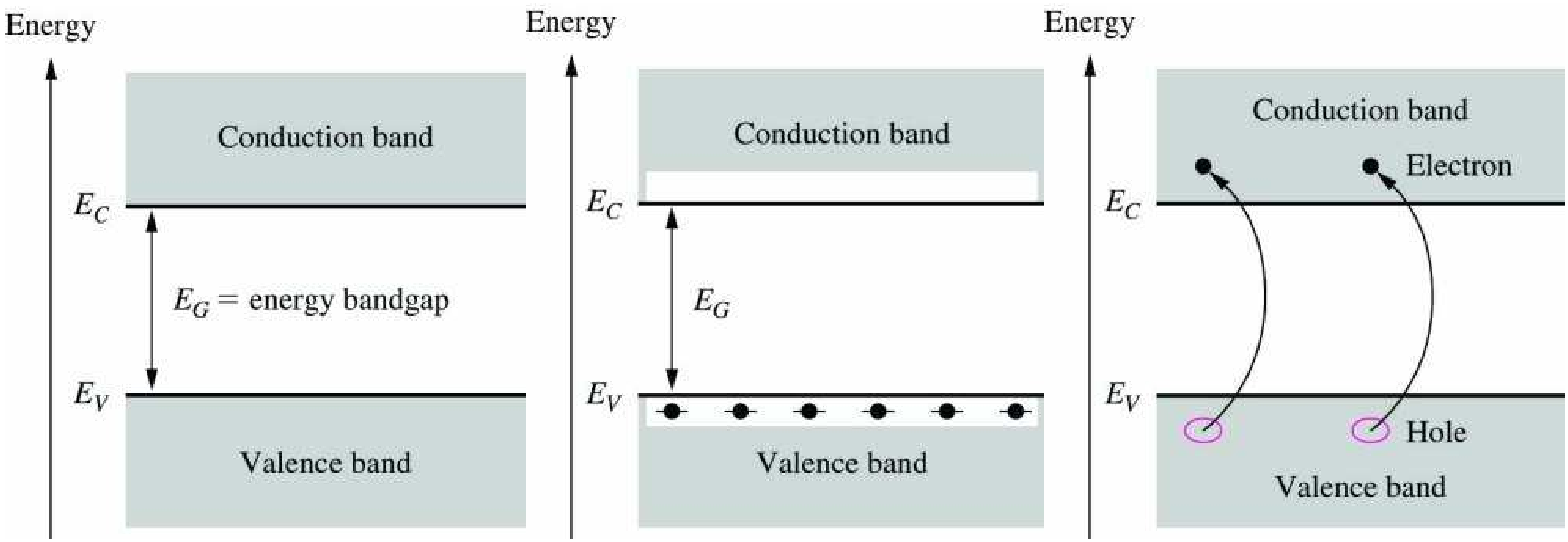
Rewriting using Einstein's relationship ($D_p = \mu_n V_T$),

$$j_n^T = q\mu_n n\left(E + V_T \frac{1}{n}\frac{\partial n}{\partial x}\right)$$

$$j_p^T = q\mu_p p\left(E - V_T \frac{1}{p}\frac{\partial p}{\partial x}\right)$$

In the following chapters, we will use these equations, combined with Gauss' law, $\nabla\cdot(\varepsilon E)=Q$, to calculate currents in a variety of semiconductor devices.

Semiconductor Energy Band Model

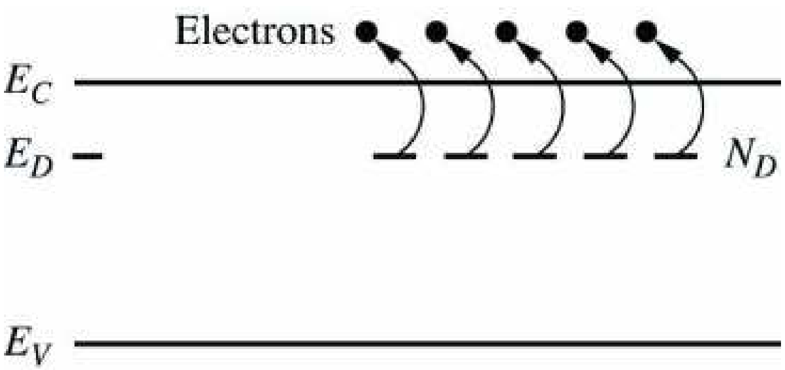


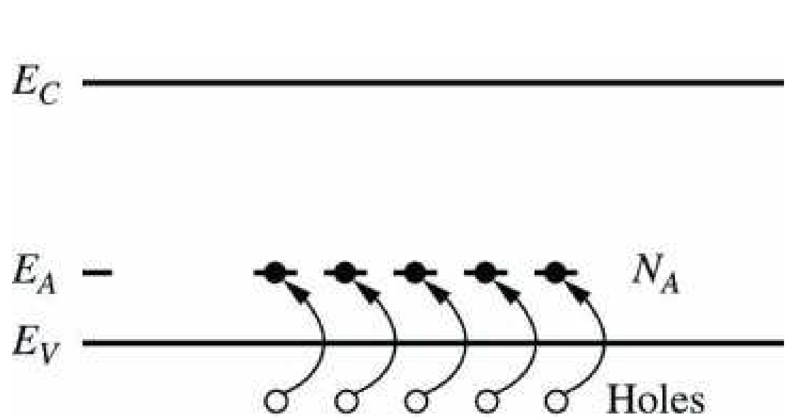
Semiconductor energy band model. E_C and E_V are energy levels at the edge of the conduction and valence bands.

Electron participating in a covalent bond is in a lower energy state in the valence band. This diagram represents 0 K.

Thermal energy breaks covalent bonds and moves the electrons up into the conduction band.

Energy Band Model for a Doped Semiconductor

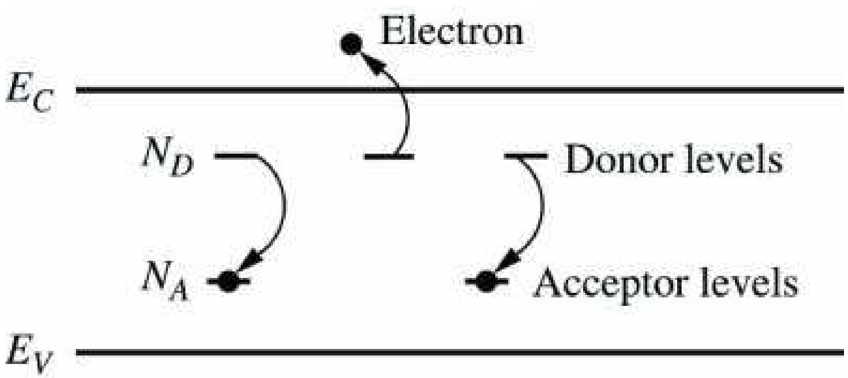




Semiconductor with donor or n-type dopants. The donor atoms have extra electrons with energy E_D. Since E_D is close to E_C, (about 0.045 eV for phosphorous), it is easy for electrons in an n-type material to move up into the conduction band.

Semiconductor with acceptor or p-type dopants. The donor atoms have unfilled covalent bonds with energy state E_A. Since E_A is close to E_V, (about 0.044 eV for boron), it is easy for electrons in the valence band to move up into the acceptor sites and complete covalent bond pairs.

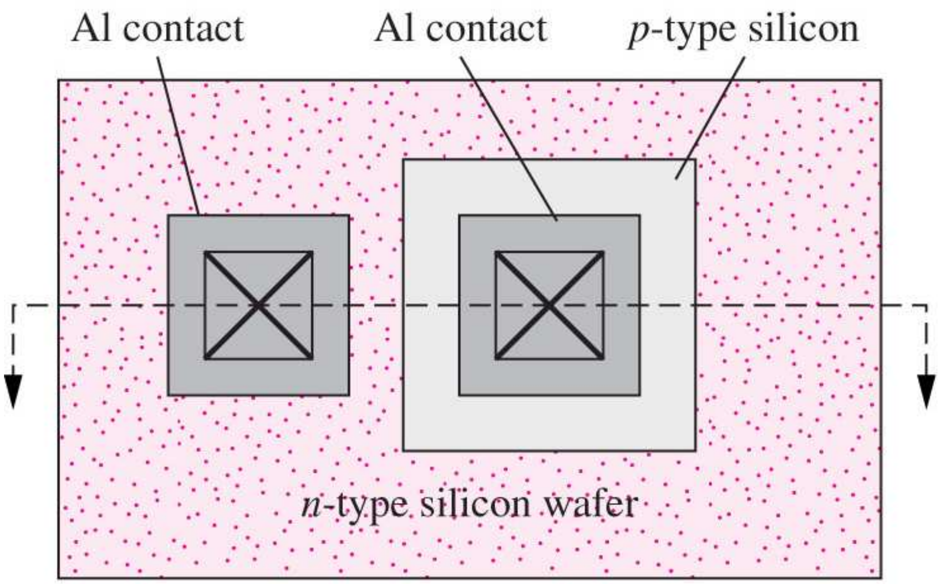
Energy Band Model for Compensated Semiconductor

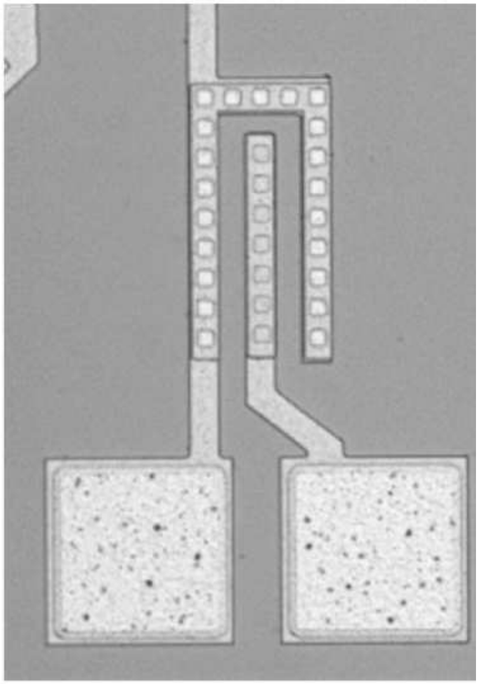


A compensated semiconductor has both n-type and p-type dopants. If $N_D > N_A$, there are more N_D donor levels. The donor electrons fill the acceptor sites. The remaining N_D-N_A electrons are available for promotion to the conduction band.

The combination of the covalent bond model and the energy band models are complementary and help us visualize the hole and electron conduction processes.

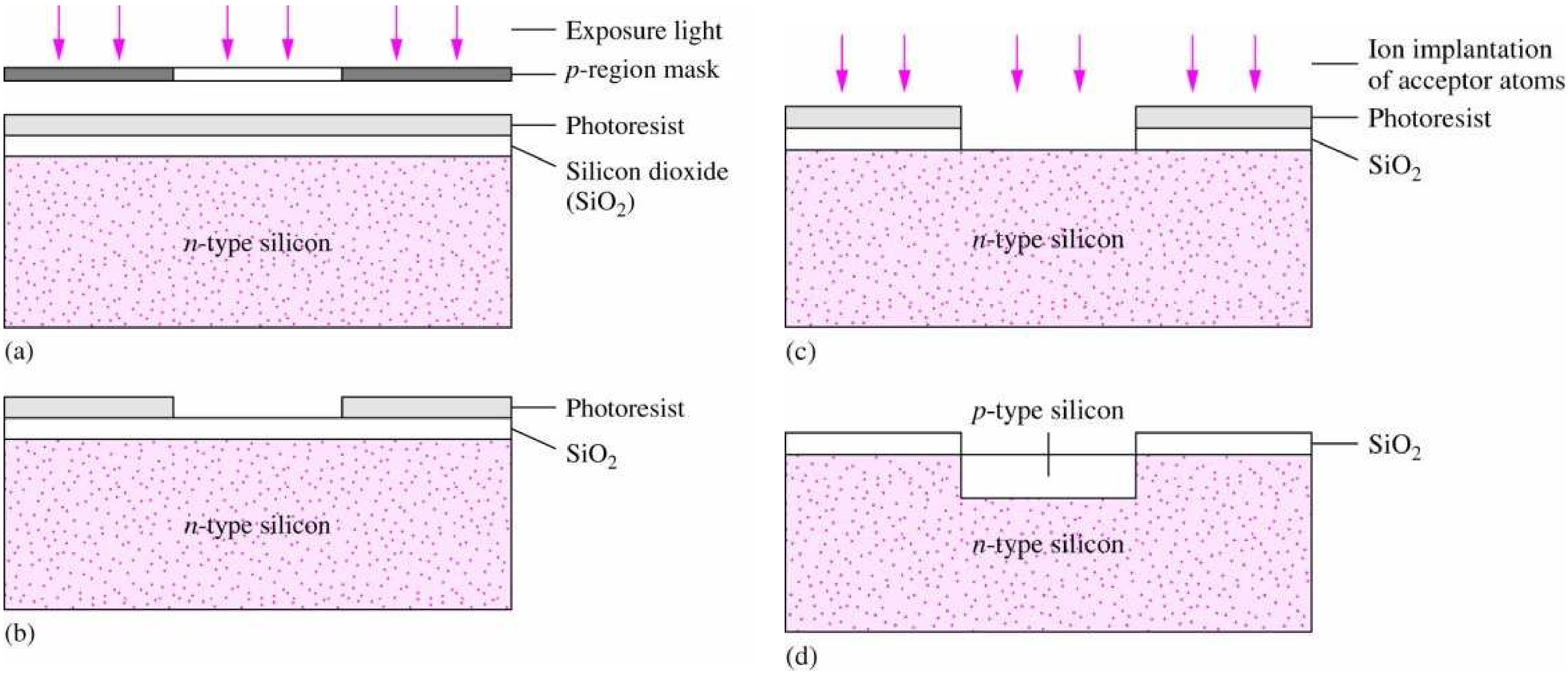
Integrated Circuit Fabrication Overview





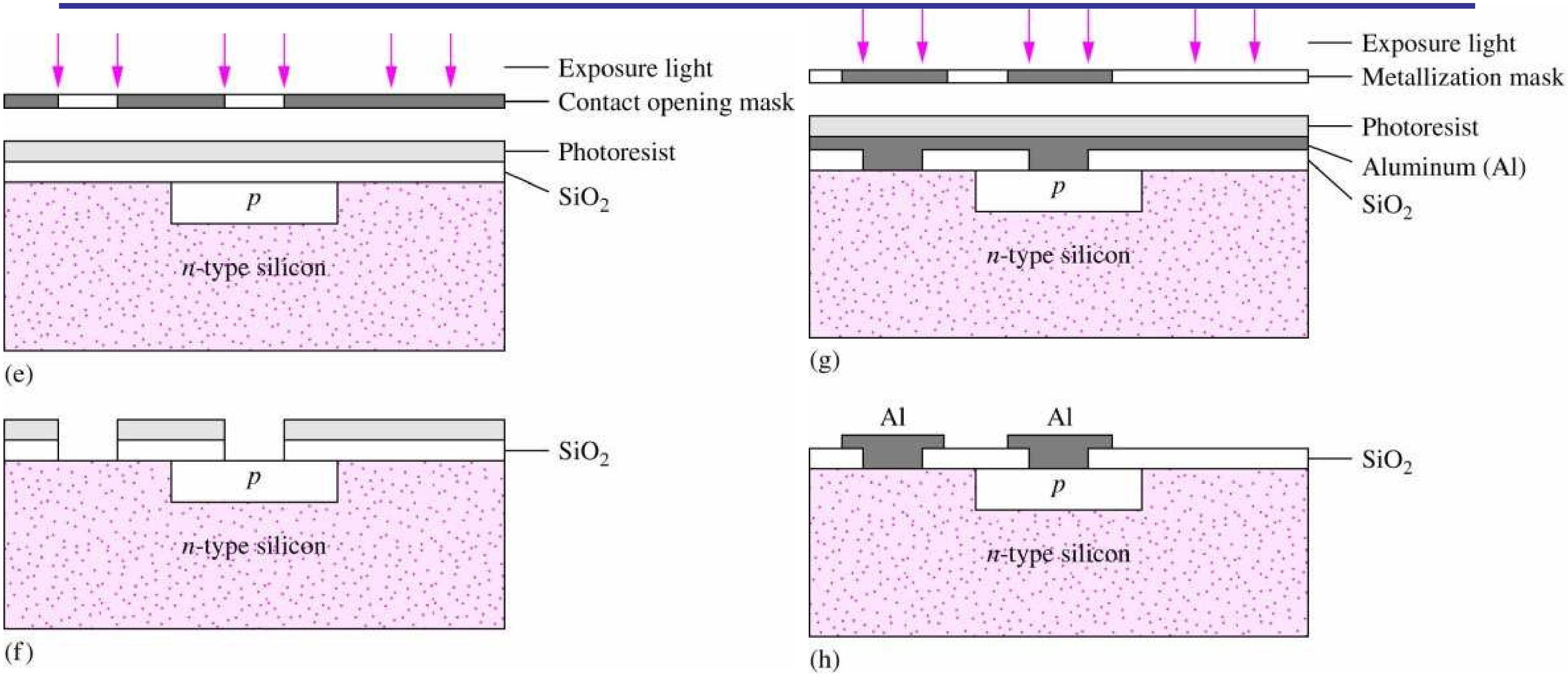
Top view of an integrated pn diode.

Integrated Circuit Fabrication (cont.)



(a) First mask exposure, (b) post-exposure and development of photoresist, (c) after SiO_2 etch, and (d) after implantation/diffusion of acceptor dopant.

Integrated Circuit Fabrication (cont.)



(e) Exposure of contact opening mask, (f) after resist development and etching of contact openings, (g) exposure of metal mask, and (h) After etching of aluminum and resist removal.

End of Chapter 2