



Radiation Detection and Measurement

Lecture 25

Chapter 11: Semiconductor Diode Detectors

General properties

- Have excellent energy resolution, compact size, relatively fast timing characteristics, and a tunable effective thickness
- Tend to have small size limitations and performance can be degraded by radiation damage
- Many material may be used but silicon is often employed for charged particle detection, while germanium is more common for gamma ray spectroscopy

Semiconductor properties

Band structure in solids:

- Similar to inorganic scintillator, semiconductor detectors derive their energy bands from the lattice structure for electrons
- Gaps may again be formed with forbidden energy levels
- Valence band: (lowest energy levels) the levels that the outer shell electron are bound to lattice sites

Semiconductor properties

- Conduction band: (higher energy levels) the levels where electrons with enough energy occupy and can migrate freely through the lattice
- Bandgap: region (forbidden) with no intrinsic levels between the valence and conduction bands. The gap energy (E_g) is usually 5eV or more for an insulator and less for semiconductors

Semiconductor properties

- Generally there are equal numbers of electrons and lattice sites so there are just enough electrons to fill all the lattice sites and energy levels in the valence band
- Fig 11.1 shows the band structure for insulators and semiconductors

Semiconductor properties

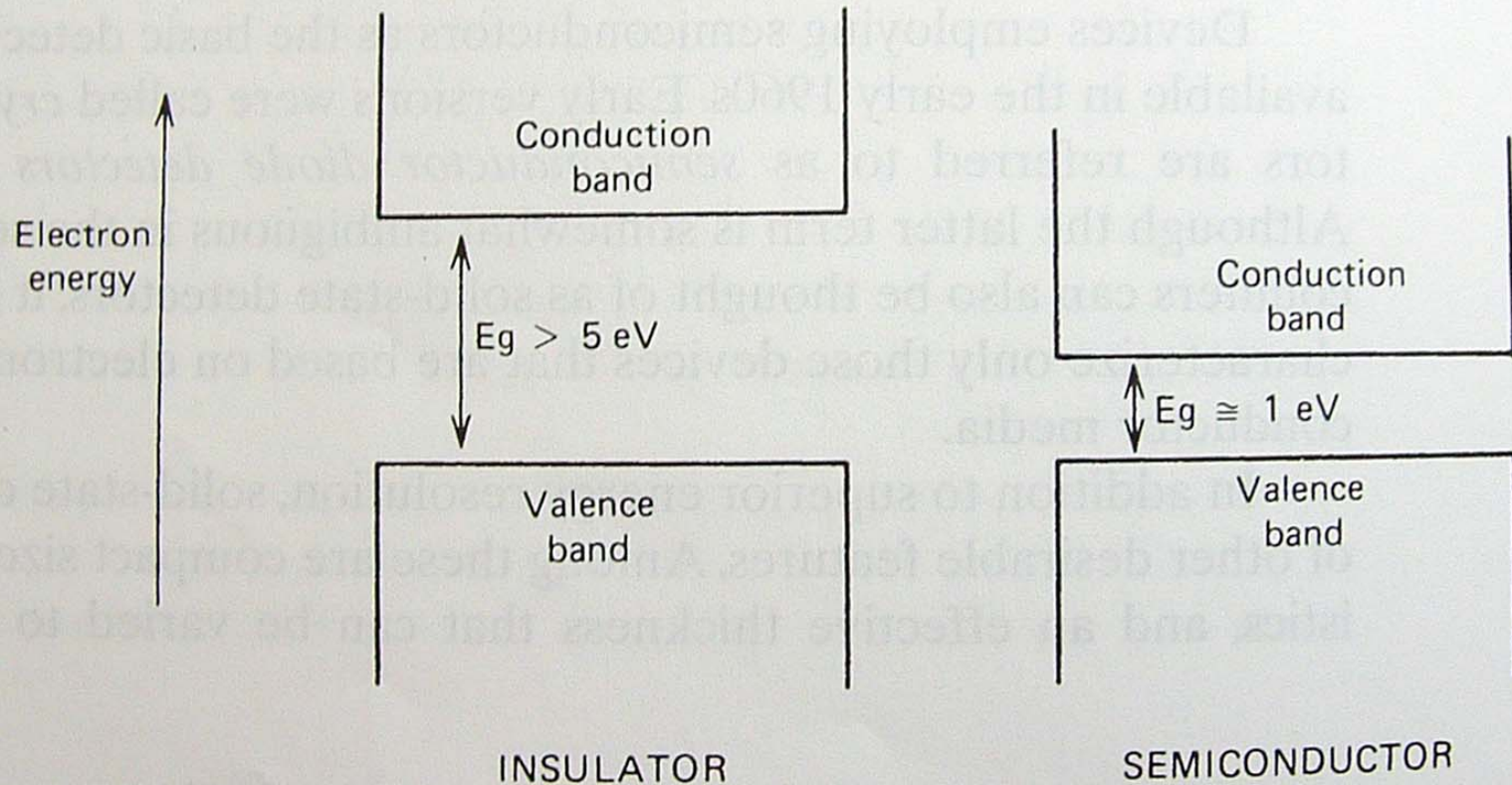


Figure 11.1 Band structure for electron energies in insulators and semiconductors.

Semiconductor properties

Charge Carriers:

- It is possible and even likely that at temperatures above absolute zero that some electrons will be elevated to the conduction band
- The statistical probability of the event of electrons excitation is provided by the Boltzman distribution.

Semiconductor properties

- The probability that an electron will have an energy greater than that of E_g is given by:

$$p(T) = CT^{3/2} \exp\left(-\frac{E_g}{2k_B T}\right)$$

- where T is in Kelvins, E_g is the band gap energy, k_B is the Boltzman constant, and C is a constant of proportionality characteristics of the material

Semiconductor properties

- Note a decrease in E_g and increase T will both increase the likelihood of electron excitation
- When an electron is excited it forms an electron hole pair. The electron excitation leaves a hole in the valence band. While the electron in the conduction band moves opposite the direction of an applied field the positive hole moves with the electric field

Semiconductor properties

- The electron hole pair is analogous to an ion pair formed in a gas
- Once an electron pair is excited, in the absence of an applied field the electron will fall back into an equilibrium consistent with the thermal state (number of excited electron is dependent on $p(T)$), where the rate of recombination is equal to the rate of formation

Semiconductor properties

- Due to the thermal excitations the electrons and holes will tend to diffuse through the lattice
- The cross section of this thermal diffusion (broadening spatial distribution) can be approximated by a Gaussian function with a standard deviation σ :

Semiconductor properties

$$\sigma = \sqrt{2Dt}$$

– Where $D = \mu \frac{k_B T}{e}$, the diffusion coefficient,

μ the mobility of the charge carrier and

$$\frac{k_B T}{e} = 0.0253 \text{ V}$$

for $T = 293$ degrees Kelvin (20 degree Celsius)

Semiconductor properties

- If we now apply an electric field $\mathcal{E}(x)$ we provide a potential for the charge carriers at low to moderate electric field values the drift velocities of the charge carriers are proportional to the electric field with their respective mobilities as the proportionality constants:

$$v_n = \mu_n \mathcal{E}$$

$$v_e = \mu_e \mathcal{E}$$

Semiconductor properties

- At higher electric fields the drift velocity rises more slowly and then saturates, seen in Fig 11.2
- If we now introduce our drift velocities into our Gaussian distribution:

$$\sigma = \sqrt{\frac{2vk_B Tt}{\epsilon e}} = \sqrt{\frac{2k_B Tx}{\epsilon e}}$$

– where x is now the drift distance.

Semiconductor properties

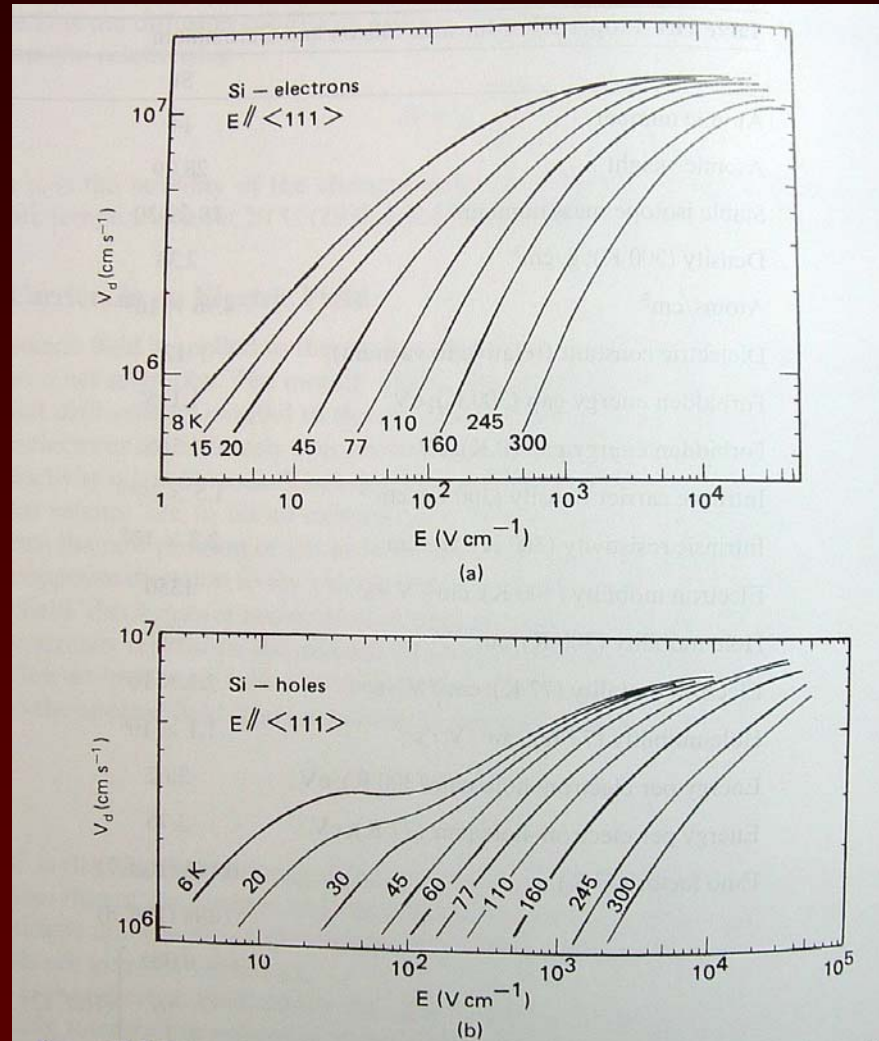


Figure 11.2 Drift velocity as a function of electric field applied parallel to the $\langle 111 \rangle$ crystallographic direction. Absolute temperature is the parameter for the different curves. (a) Electrons in silicon; (b) holes in silicon; (c) electrons in germanium; (d) holes in germanium. (From Ottaviani et al.¹⁵)

Semiconductor properties

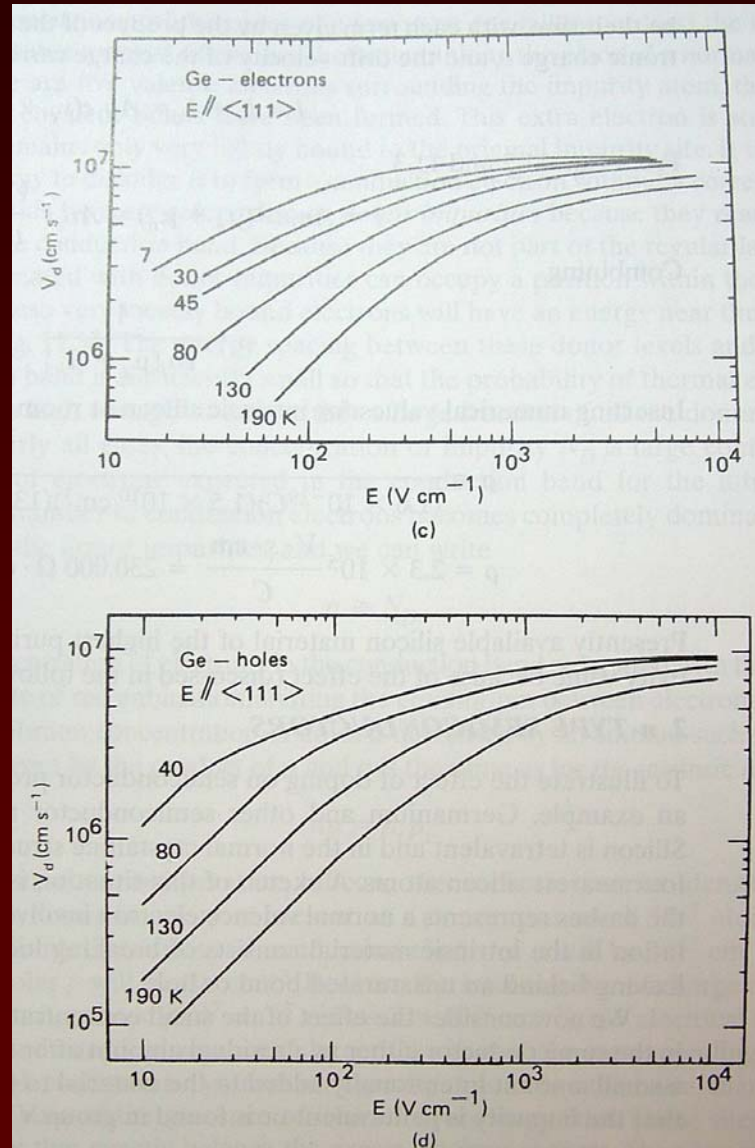


Figure 11.2 (Continued)

Semiconductor properties

- For small volume detectors $\sigma \sim 100 \mu\text{m}$
- The diffusion limits the precision for spatially resolved measurements as well as the collection time.
- Although the collection time will in general not be noticeable, it may become apparent in large- volume detectors or when precision timing or position are involved.
- Table 11.1 lists the intrinsic properties of Si and Ge

Semiconductor properties

Table 11.1 Properties of Intrinsic Silicon and Germanium

	Si	Ge
Atomic number	14	32
Atomic weight	28.09	72.60
Stable isotope mass numbers	28-29-30	70-72-73-74-76
Density (300 K); g/cm ³	2.33	5.32
Atoms/cm ³	4.96×10^{22}	4.41×10^{22}
Dielectric constant (relative to vacuum)	12	16
Forbidden energy gap (300 K); eV	1.115	0.665
Forbidden energy gap (0 K); eV	1.165	0.746
Intrinsic carrier density (300 K); cm ⁻³	1.5×10^{10}	2.4×10^{13}
Intrinsic resistivity (300 K); $\Omega \cdot \text{cm}$	2.3×10^5	47
Electron mobility (300 K); cm ² /V · s	1350	3900
Hole mobility (300 K); cm ² /V · s	480	1900
Electron mobility (77 K); cm ² /V · s	2.1×10^4	3.6×10^4
Hole mobility (77 K); cm ² /V · s	1.1×10^4	4.2×10^4
Energy per electron-hole pair (300 K); eV	3.62	
Energy per electron-hole pair (77 K); eV	3.76	2.96
Fano factor (77 K)	0.143 (Ref. 7)	0.129 (Ref. 9)
	0.084 (Ref. 8)	0.08 (Ref. 10)
	0.085	< 0.11 (Ref. 11)
	to	0.057
	0.137	0.064
	0.16 (Ref. 13)	0.058 (Ref. 14)

Source: G. Bertolini and A. Coche (eds.), *Semiconductor Detectors*, Elsevier-North Holland, Amsterdam, 1968, except where noted.

Effects of impurities and dopants

- Intrinsic semiconductors
- n-type semiconductors
- p-type semiconductors

Intrinsic semiconductors

- Pure semiconductors
- At equilibrium the number of electrons (or concentrations of “n”) in the conduction band is equal to the number of holes (or concentration of “p”) in the valence band ;
i.e. $n_i = p_i$
- These are known as the intrinsic carrier densities

Intrinsic semiconductors

- We define the resistivity $\rho = 1/\sigma$ (σ is the conductivity)
- For a slab of semiconductor with thickness (t), area (A) and applied voltage (V), the current (I) for each charge carrier is:

$$I = AV / \rho t \Rightarrow \rho = AV / It$$

Intrinsic semiconductors

- Both the electrons and holes contribute to the current

$$I = I_n + I_e = A n_i e (\nu_e + \nu_n)$$

- where each current is the product of their area, carrier density ($n_i = p_i$) and charge.

Intrinsic semiconductors

- Note the drift velocities are in opposite directions but the charge is opposite, so they are additive currents. We can replace with the mobilities

$$I = An_i e \mathcal{E} (\mu_e + \mu_n) = An_i e \frac{V}{t} (\mu_e + \mu_n)$$

Intrinsic semiconductors

- Solving for resistivity (ρ):

$$\rho = \frac{AV}{It} = \frac{1}{n_i e (\mu_e + \mu_n)}$$

- For Si at room temperature we get $\rho = 230,000 \text{ } \Omega\cdot\text{cm}$ (this is intrinsic Si)

n-type semiconductors

- Seen in Fig 11.3 a Si atom is replaced with a donor atom, P (phosphorous) in this case with an extra electron, occupying a substitution site in the silicon crystal. Note the added energy level (b) created in the band gap it is from the donor's free electron)

n-type semiconductors

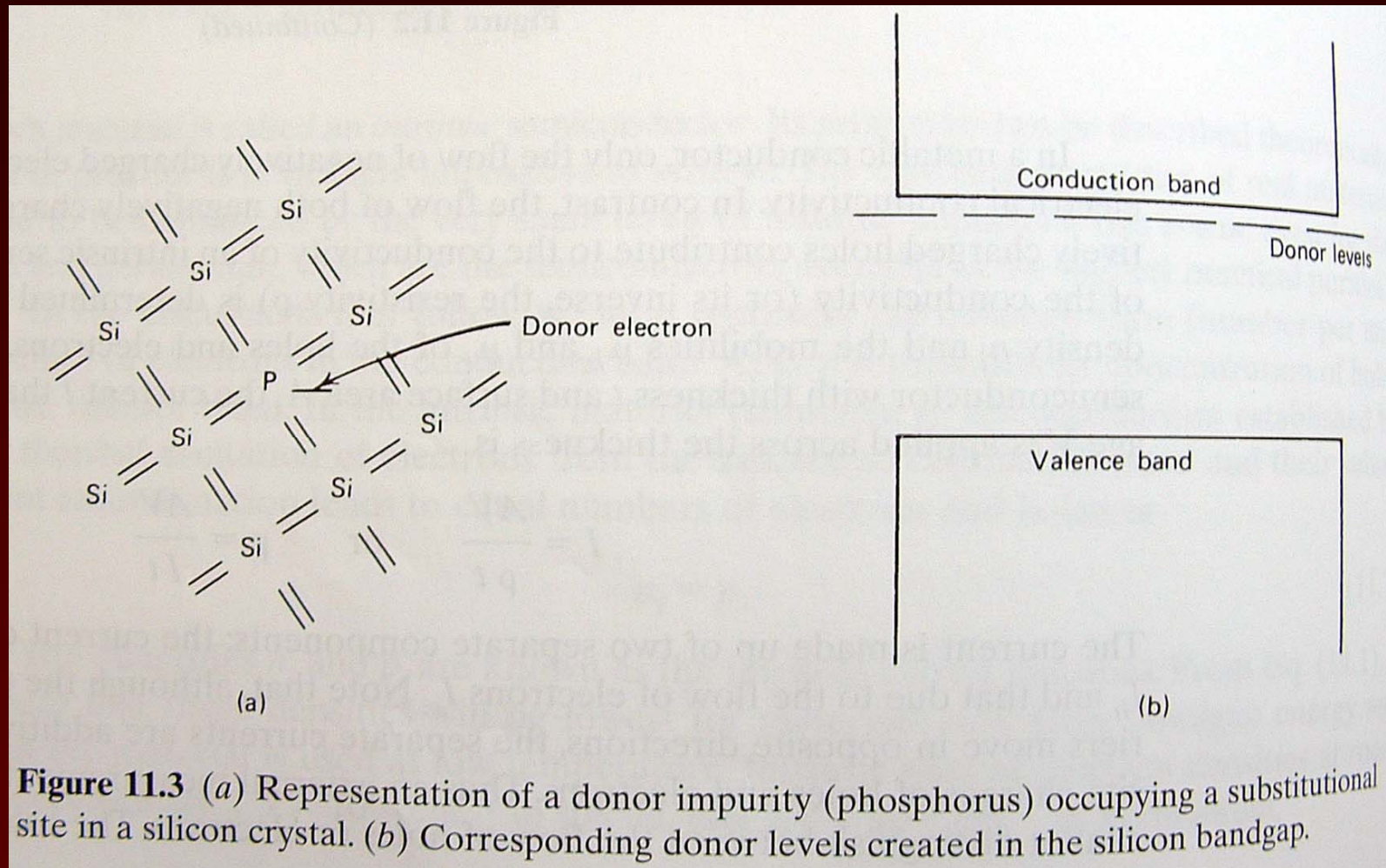


Figure 11.3 (a) Representation of a donor impurity (phosphorus) occupying a substitutional site in a silicon crystal. (b) Corresponding donor levels created in the silicon bandgap.

n-type semiconductors

- The extra electron is formed from the atomic structure of phosphorous which has 5 valence electrons while silicon only has 4. 4 of the 5 electrons form the covalent bonds as a substitution in the lattice leaving a free electron only weakly bound to the site.

n-type semiconductors

- The energy level formed is close to the conduction band since the electron only requires a little energy to become free from the lattice site
- The statistical thermal fluctuations can now easily excite the electron to the conduction band

n-type semiconductors

- The donor impurities readily contributes electrons to the conduction band, and thus the number of electrons contributed to the conduction band from impurities (N_D) is much greater than the expected number from thermal excitation of the intrinsic electrons. $N_D \gg n_i$

n-type semiconductors

- So the large contribution of electrons from impurities become the charge carriers n
 N_D
- The increase of available electrons also increases the equilibrium value and rate of recombination of electron hole pairs
- The new equilibrium is now $n_p = n_i p_i$, thus the number of equilibrium holes decreases while the electron increases, $n \gg p$.

n-type semiconductors

- The electrical conductivity is almost exclusively determined by the flow of electrons (the majority carriers) and the holes (minority carriers) play a very small role.
- The total current now becomes:

$$I = I_n + I_e = An_i e (n v_e + p v_n)$$

n-type semiconductors

$$I = An_i e \mathcal{E} (n \mu_e + p \mu_n) = An_i e \frac{V}{t} (n \mu_e + p \mu_n)$$

- and with $n \gg p$ and $n \cong N_D$:

$$I = \frac{AeV}{t} N_D \mu_e$$

- for a slab of thickness t , area A and applied voltage V

n-type semiconductors

- We can again solve for ρ :

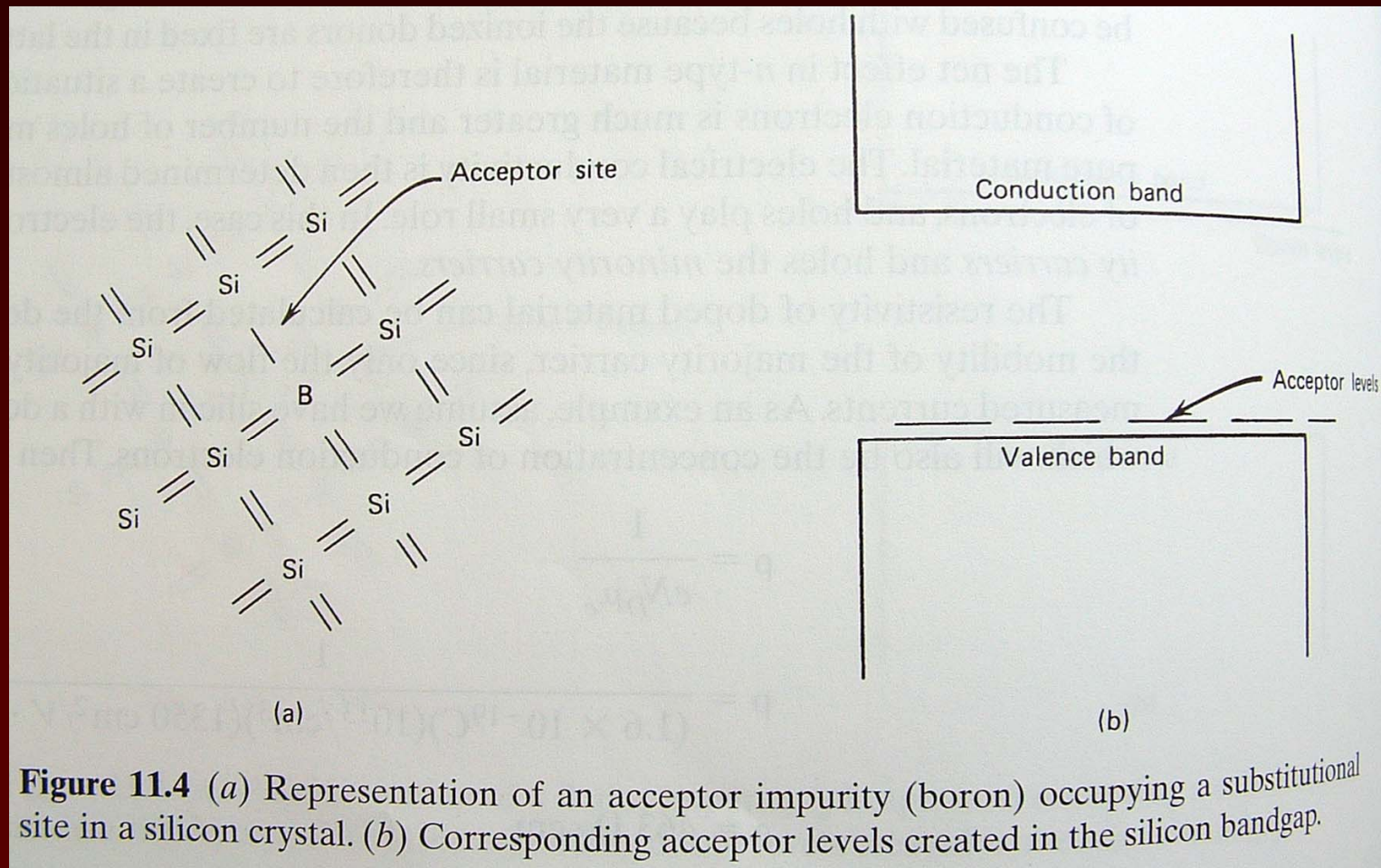
$$\rho = \frac{AV}{It} = \frac{1}{eN_D\mu_e}$$

- for Si with a donor density of $10^{13}/\text{cm}^3$;
 $\rho = 463 \, \Omega.\text{cm}$

p-type semiconductors

- Illustrated in Fig 11.4 an acceptor of one less electron filling a lattice site creates a covalent band deficit, in this case boron substitution into silicon. Note that the energy formed is close to the valence band in the band gap, now an acceptor site (as opposed to a donor site) it will now accept an electron.

p-type semiconductors



p-type semiconductors

- The acceptor site will attract an electron which will be less bound than the covalent bond electrons, thus the energy level is higher (slightly) than the valence band.
- Thermal excitation will excite a covalent electron into the acceptor site leaving a hole in the donating valence site.

p-type semiconductors

- The concentration of acceptor impurities (N_A) will now be much larger than p_i or $N_A \gg p_i$ (the number of intrinsic holes, so $p \approx N_A$)
- The equilibrium constant is again $np = n_i p_i$

Compensated material

- One can add appropriate numbers of ions to either a p or n material to provide equal concentrations.
- This material is called compensated and in theory will have properties similar to an intrinsic semiconductor

Compensated material

- In practice this is difficult (can be done using lithium ion drifting) but for such a compensated material it is assigned subscripts of i (n_i, p_i) since its behavior mimics that of the intrinsic materials

Heavily doped materials

- Thin layers of semiconductor material with heavy doping (n-type or p-type) are designed with n^+ and p^+ and are suitable for use as electrical contact materials

Trapping and recombination:

- Shallow impurities: donor or acceptor energy levels introduced near the edges of the forbidden band (“shallow” refers to the closeness to the band gap edge energies)
- Deep impurities ; some impurities (i.e. gold, cadmium, zinc or other metallic atoms) occupying the lattice sites introduce energy levels towards the middle of the band gap cause the following:

Trapping and recombination:

1. act as traps for charge carriers and release them after a long delay
2. may act as recombination centers, capturing both majority and minority carriers and causing them to annihilate
3. both effects reduce the life time of charge carriers and cause collection losses of the charge carriers

Trapping and recombination:

- Trapping length is the mean distance traveled by a charge carrier before trapping or recombination (equal to the mean life time times the average drift velocity).