ECE321 Electronics I: Lecture 2

Chapter 2 Solid-State Electronics (Sections 2.1-2.6)

Microelectronic Circuit Design

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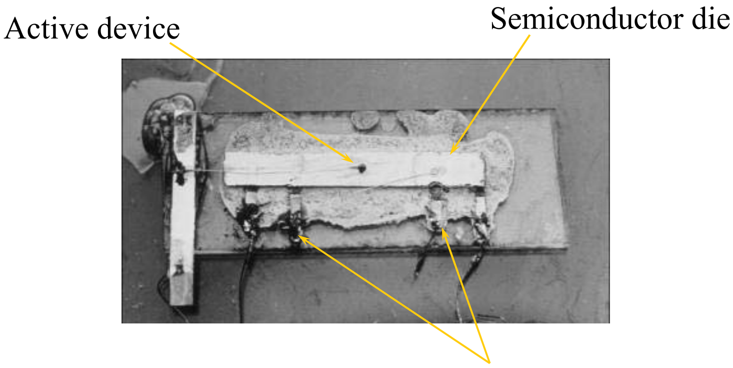
Chapter Goals (Lectures 2 & 3)

- 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 band gap 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 Kilby Integrated Circuit (1950s)

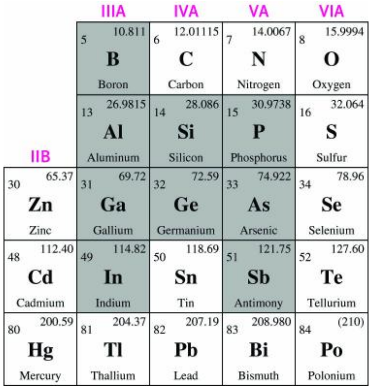


Solid-State Electronic Materials

- Electronic materials fall into three categories:
  - Insulators Resistivity (ρ) > 10^5 Ω-cm
  - Semiconductors $10^{-3} < \rho < 10^5$ Ω-cm
  - Conductors $\rho < 10^{-3}$ Ω-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 germanium due to its higher band-gap energy, lower cost, and is easily oxidized to form silicon-dioxide insulating layers.

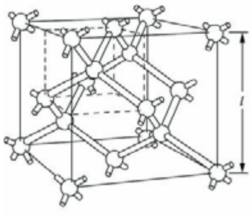
Semiconductor Materials (cont.)

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

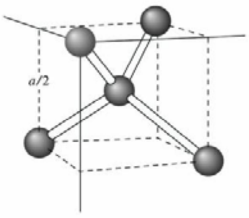


IIB	IIIA	IVA	VA	VIA
	5 **B** Boron 10.811	6 **C** Carbon 12.01115	7 **N** Nitrogen 14.0067	8 **O** Oxygen 15.9994
	13 **Al** Aluminum 26.9815	14 **Si** Silicon 28.086	15 **P** Phosphorus 30.9738	16 **S** Sulfur 32.064
30 **Zn** Zinc 65.37	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.59	33 **As** Arsenic 74.922	34 **Se** Selenium 78.96
48 **Cd** Cadmium 112.40	49 **In** Indium 114.82	50 **Sn** Tin 118.69	51 **Sb** Antimony 121.75	52 **Te** Tellurium 127.60
80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.37	82 **Pb** Lead 207.19	83 **Bi** Bismuth 208.980	84 **Po** Polonium (210)

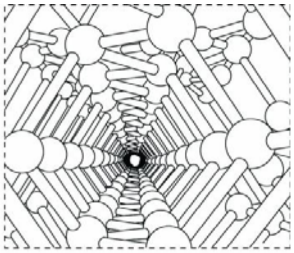
Covalent Bond Model (shared electrons) Valence = 4; “stable-8” configuration



Silicon diamond lattice unit cell.

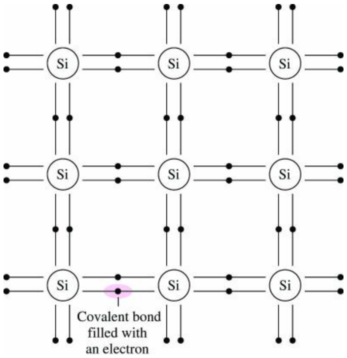


Corner of diamond lattice showing four nearest neighbor bonding.

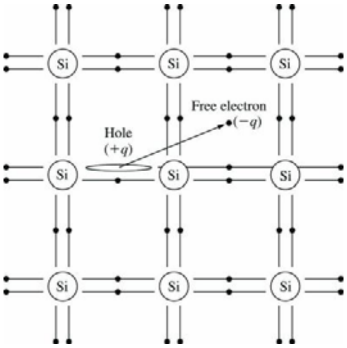


View of crystal lattice along a crystallographic axis.

Intrinsic (pure) 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.

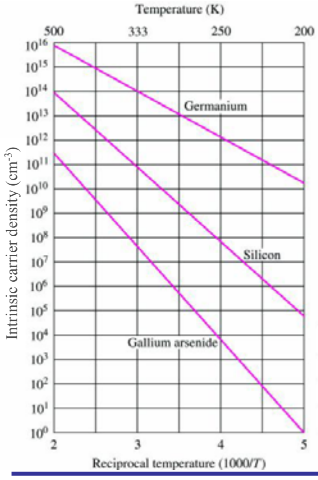
Intrinsic Carrier Concentration
n_i = electron density = p_i = hole density

- 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, 8.62×10^{-5} eV/K
- T = absolute termperature, K
- B = material-dependent parameter, 1.08×10^{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.
- Example 2.1:
  n_i (300K) = 6.73×10^9 cm^{-3}
  ≈ 10^{10} cm^{-3} for Si
- Approx 5×10^{22} atoms/cm^3 means approx 1 in 10^{13} bonds broken at room temperature (300K)

Electron-hole concentrations

- A <u>vacancy</u> is left when a covalent bond is broken.
- The vacancy is called a <u>hole</u>.
- 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, $n = n_i = p = p_i$.
- The product of electron and hole concentrations is $pn = n_i^2$ (Law of Mass Action).
- The pn product above holds when a semiconductor is in thermal equilibrium (not with an external voltage 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

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

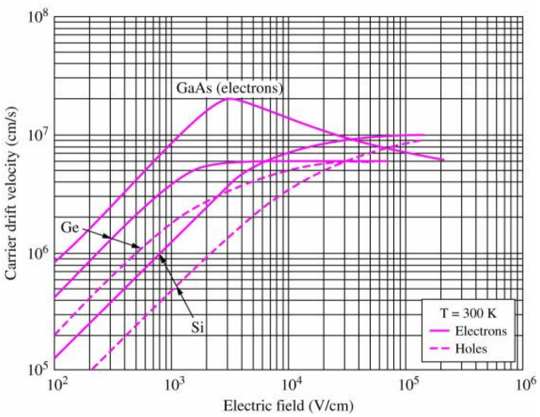
j = current density, (Coulomb charge moving through a unit area)
Q = charge density, (Charge in a unit volume)
v = velocity of charge in an electric field.

Note that "density" may mean area or volumetric density, depending on the context: current density/unit area; charge density/unit volume.

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 ($\mathrm{cm^2/V \cdot s}$)
- $\mu_n = 1350\ \mathrm{cm^2/V \cdot s}$, $\mu_p = 500\ \mathrm{cm^2/V \cdot s}$ (intrinsic Si at 300K)
- Hole mobility is less than electron mobility, since hole current is the result of multiple covalent bond disruptions, while electrons can move freely about the crystal.

Velocity Saturation



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

Intrinsic Silicon Resistivity

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

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

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

where q = electronic charge = 1.6 x 10^{-19}C

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

This defines electrical conductivity:

$\sigma = q(n\ \mu_n + p\ \mu_p)$ (Ω·cm)$^{-1}$

Resistivity ρ is the reciprocal of conductivity:

$\rho = 1/\sigma$ (Ω·cm)

Units: [ρ] = [E]/[j] = [V/cm]/[A/cm^2] = Ω.cm

Example 2.2: 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 right after Eq. 2.5. For intrinsic silicon, the electron and hole densities are both equal to n_i.
- **Unknowns:** Resistivity ρ and classification.
- **Approach:** Use Eqs. 2.8 and 2.9. [$\sigma = q(n\,\mu_n + p\,\mu_p)$ $(\Omega\cdot\text{cm})^{-1}$]
- **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. 2.8:

  $$\sigma = (1.60 \times 10^{-19})[(10^{10})(1350) + (10^{10})(500)] \quad (\text{C})(\text{cm}^{-3})(\text{cm}^2/\text{V}\cdot\text{s})$$
  $$= 2.96 \times 10^{-6}\ (\Omega\cdot\text{cm})^{-1} \dashrightarrow \rho = 1/\sigma = 3.38 \times 10^{5}\ \Omega\cdot\text{cm}$$

  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.

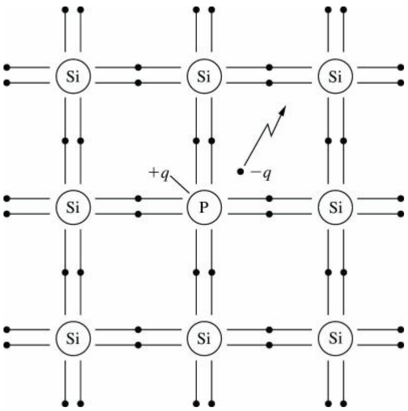
Extrinsic (doped) Silicon: Semiconductor Doping

- 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:

Group III: B, Al, Ga, In
Group V: P, As, Sb

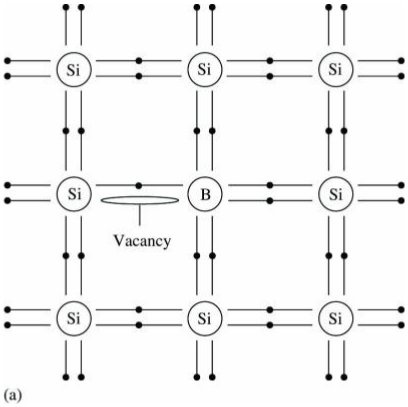
Donor Impurities in Silicon

- Phosphorous (or other column V element) atom replaces silicon atom in 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.
- Electron is free to drift in applied electric field

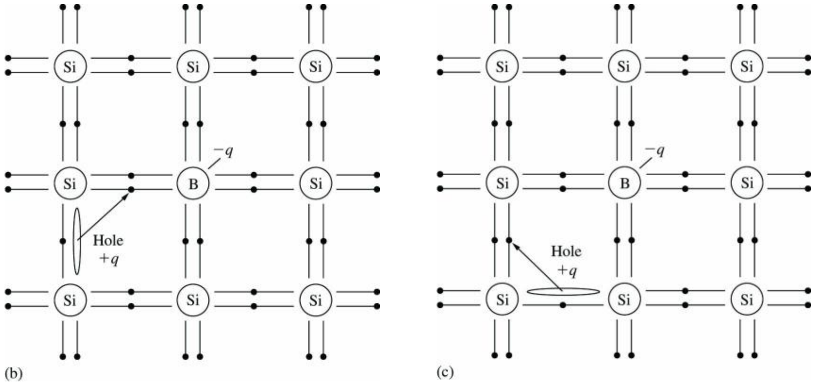


Acceptor Impurities in Silicon

- Boron (column III element) has been added to silicon.
- 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.



Acceptor Impurities in Silicon (cont.)



Hole is propagating through the silicon, indirectly by electron movements.

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.
- N_D = donor impurity concentration atoms/cm3
  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.

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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 $(N_D - N_A) >> 2n_i$, $n \cong (N_D - N_A)$
  $\approx N_D$ if $N_A = 0$.

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. 2.3).
- For $(N_A - N_D) >> 2n_i$, $p \cong (N_A - N_D) \approx N_A$ if $N_D = 0$.

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, (highly temperature dependent).
- For practical doping levels, $n \cong (N_D - N_A)$ for n-type and $p \cong (N_A - N_D)$ for p-type material.
- Doping compensation.
- Typical doping ranges are $10^{14}/\text{cm}^3$ to $10^{21}/\text{cm}^3$.
- Compare 5×10^{22} atoms/cm^3.

End of Lecture 2