ECE321 Electronics I: Lecture 3

Chapter 2 Solid-State Electronics (Sections 2.7-2.11)

Microelectronic Circuit Design

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Announcements

- ECE 321: Textbook, Aris, & WebCT (lectures)
- ECE301: WebCT, experiments re-numbered, LTSpice (experiments 1 & 3), prelim assignments, surveys, etc
- Office hours & recitation
  - Morris office hours: Mon 9-10am Tues 12-1pm
    - (No office hours Mon 28th Jan)
  - Recitation (Omkar Joshi)
    Thur 3.15-4.15pm Room UTS 209
  - Joshi office hours: Mon 1-2pm Student lounge

Lecture Goals

- Explore semiconductors and discover how engineers control semiconductor properties to build electronic devices.
- Develop energy band models for semiconductors.
- Understand band gap energy and intrinsic carrier concentration.
- Understand drift and diffusion currents in semiconductors.
- Discuss the dependence of mobility on doping level.
- Understand integrated circuit processing (with a diode example)

Example 2.4

Find resistivity of Si doped with $N_D=2\text{x}10^{15}/\text{cm}^3$

Assume $N_A=0$, room temperature so $n_i=10^{10}/\text{cm}^3$

$N_D >> n_i$ so $n \approx N_D = 2 \text{ x } 10^{15}$ electrons/cm^3

$p = n_i^2/n = 10^{20}/2\text{x}10^{15} = 5 \text{ x } 10^4$ holes/cm^3

Note: Minority Carrier Suppression

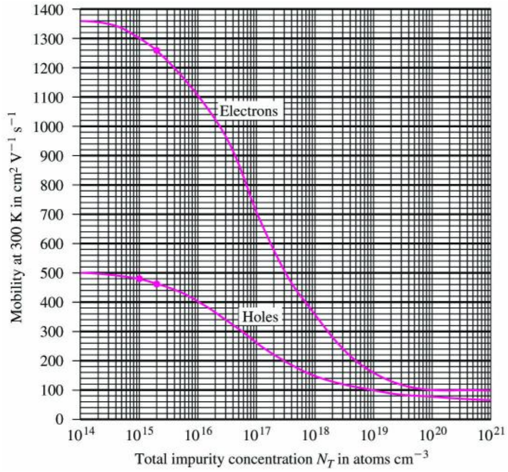
For $\mu_n=1320\text{cm}^2/\text{V.s}$ & $\mu_p=460\text{cm}^2/\text{V.s}$ (from Fig 2.8; ≤ intrins)

$\sigma = q[n\ \mu_n + p\ \mu_p]$

$= 1.6\text{x}10^{-19}[2\text{x}10^{15}\text{x}1320+5\text{x}10^4\text{x}460] = 0.422\ (\Omega.\text{cm})^{-1}$

$\rho = \sigma^{-1} = 2.37\ \Omega.\text{cm}$

Mobility and Resistivity in Doped Semiconductors



Impurities different size to Si atoms

Disrupt lattice periodicity

Decrease mobility

Note total doping density N_T

N_D incr, n incr, μ_n decr, σ incr

Mobility approximations

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

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

Example 2.5: N-type Si resistivity = 0.054 Ω.cm. Find N_D. (Assume N_A=0)

$\sigma \approx q\mu_n n \approx q\mu_n N_D = 1/0.054 = 18.52$ (Ω.cm)$^{-1}$

Need $\mu_n N_D = \sigma/q = 18.52/1.6\text{x}10^{-19} = 1.2 \text{ x } 10^{20}$ (V.s.cm)$^{-1}$ but μ_n and N_D are inter-dependent (Fig 2.8)

Iteration: Guess N_D, find μ_n from graph, find $\mu_n N_D$, check, repeat if necessary

	N_D (cm^{-3})	μ_n (cm^2/Vs)	$\mu_n N_D$ (Vs.cm)$^{-1}$
1	1 x 10^{16}	1250	1.3 x 10^{19}
2	1 x 10^{18}	260	2.5 x 10^{20}
3	1 x 10^{17}	80	8.0 x 10^{19}
4	5 x 10^{17}	380	3.8 x 10^{20}
5	4 x 10^{17}	430	1.7 x 10^{20}
6	2 x 10^{17}	600	1.2 x 10^{20}

Diffusion Current

- In practical semiconductors, it is quite useful to create carrier concentration gradients by varying the dopant concentration and/or the dopant 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.

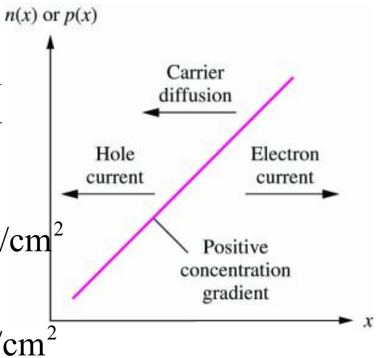
Diffusion Current (cont.)

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

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

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

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 Einstein'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 <u>thermal voltage</u>, $V_T = kT/q$, is approximately 25 mV at room temperature (0.0258V at 300K). We will encounter V_T throughout this book.

Total Current in a Semiconductor

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

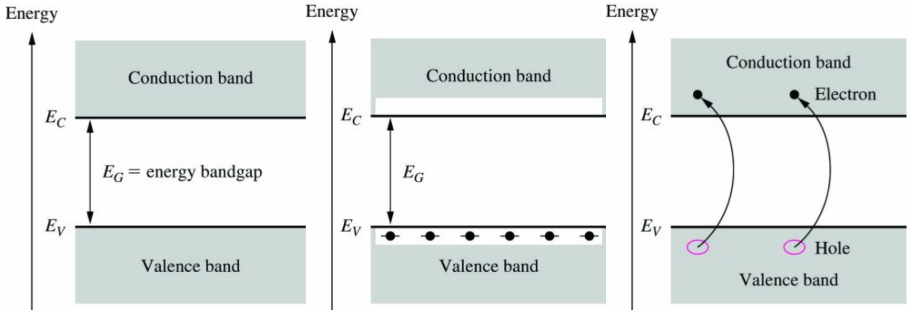
$$j_n^T = q\mu_n nE + qD_n \frac{\partial n}{\partial x}$$
$$j_p^T = q\mu_p pE - qD_p \frac{\partial p}{\partial x}$$

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.

Intrinsic Semiconductor Energy Band Model

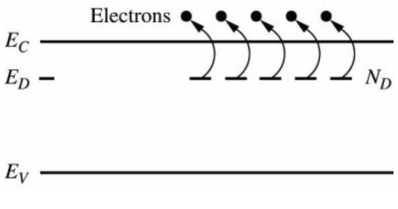


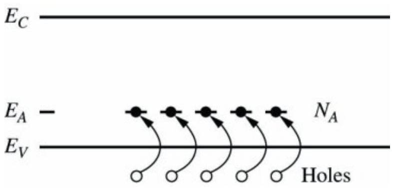
Semiconductor energy band model. E_C and E_V are energy levels at the edge of the conduction and valence bands.

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

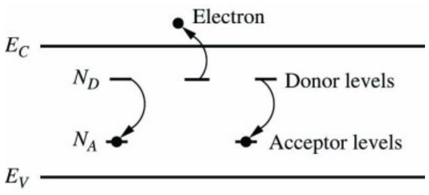




Semiconductor with donor or n-type dopants. The donor atoms have free electrons with energy E_D. Since E_D is close to E_C, (about 0.045 eV for phosphorous), it is easy for electrons in an n-type material to move up into the conduction band.

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.

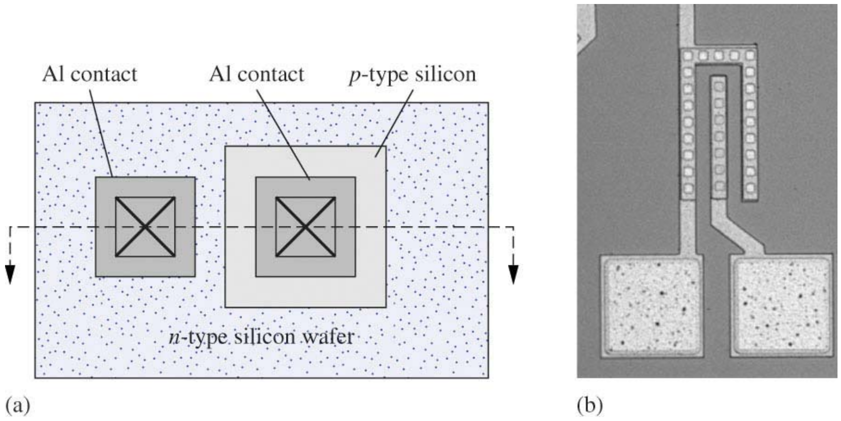
Energy Band Model for Compensated Semiconductor



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.

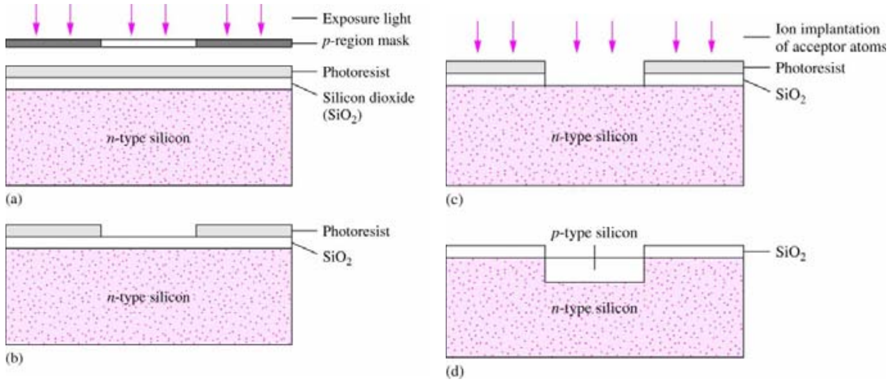
The combination of the covalent bond model and the energy band models are complementary and help us visualize the hole and electron conduction processes.

Integrated Circuit Fabrication Overview



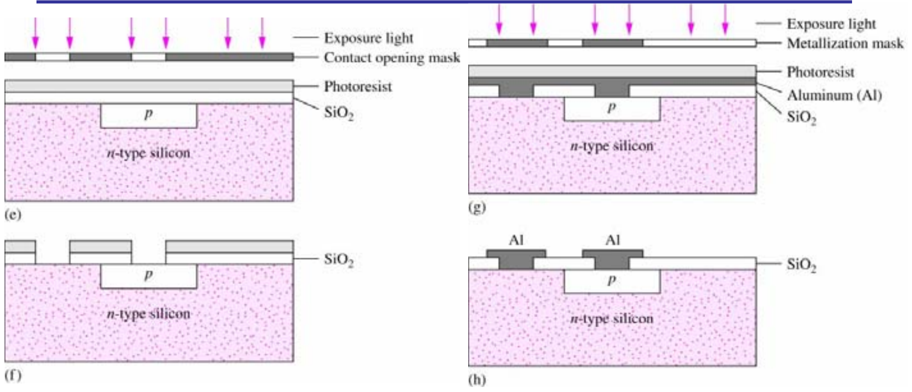
Top view of an integrated pn diode.

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.

Problem 2.14

Problem 2.38

End of Lecture 3

Assignment #1
(due at Lecture 5 Wed Jan 23rd)

Problems
2.5, 2.10, 2.15, 2.17, 2.30, 2.43, 2.46, 2.47