3.23 Electrical, Optical, and Magnetic Properties of Materials
Fall 2007

3.23 Fall 2007 – Lecture 14

INHOMOGENEOUS SEMICONDUCTORS

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Russell Ohl **Shockley, Bardeen, and Brattain**

William Shockley

Electronic Bands in Sodium Chloride

(advisor John C. Slater, MIT, 1936)

http://dspace.mit.edu/handle/1721.1/10879

ELECTRONIC BANDS IN SODIUM CHLORIDE

BY

WILLIAM SHOCKLEY

B.Sc., California Institute of Technology
1932

Submitted in Partial Fulfillment of the

Requirements for the Degree of

DOCTOR OF PHILOSOPHY

from the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
1936

Signature of Author....................................

Department of Physics, May 14, 1936.

Signature of Professor
in Charge of Research....................................

Signature of Chairman of Department
Committee on Graduate Students....................

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Last time

1. Band structure of direct- and indirect-gap semiconductors, in excruciating detail
2. Carriers in thermal equilibrium, density of available states
3. Law of mass action
4. Consequences for intrinsic semiconductors, extrinsic semiconductors
5. Impurity levels, hydrogen model of donors, acceptor states
6. Temperature dependence of majority carriers: intrinsic range, extrinsic/saturation range, freeze out.

Study

- Early part of Chap 29 (Inhomogeneous semiconductors) ,Ashcroft-Mermin (to be posted, together with Chap 28, really to be posted, s'il vous plaît)

Density of available states

$$g_c(\varepsilon) = \sqrt{2(\varepsilon - \varepsilon_c)}\,\frac{m_c^{3/2}}{\pi^2\hbar^3}$$

$$\Uparrow$$

$$\underbrace{\int_{\varepsilon_c}^{\infty} d\varepsilon\, g_c(\varepsilon)\, e^{-(\varepsilon-\varepsilon_c)/k_B T}}$$

$$N_c(T) = \frac{1}{4}\left(\frac{2m_c k_B T}{\pi\hbar^2}\right)^{3/2} = 2.5\left(\frac{m_c}{m}\right)^{3/2}\left(\frac{T}{300K}\right)^{3/2} 10^{19}/cm^3$$

Law of Mass Action

$$n_c p_v = N_c P_v e^{-E_g/k_B T}$$

Intrinsic case

$$n_i = \sqrt{n_c p_v} = \sqrt{N_c P_v} e^{-E_g / 2k_B T}$$

$$n_c(T) = N_c(T) e^{-(\varepsilon_c - \mu)/k_B T}$$

$$p_v(T) = P_v(T) e^{-(\mu - \varepsilon_v)/k_B T}$$

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Please see: Fig. 11 in Sze, S. M. "Physics of Semiconductor Devices." Chapter 1 in *Physics and Properties of Semiconductors - A Resume.* New York, NY: John Wiley & Sons, 1981.

$$\mu_i = \varepsilon_v + \frac{1}{2} E_g + \frac{3}{4} k_B T \ln\left(\frac{m_v}{m_c}\right)$$

Extrinsic case

$$n_c(T) - p_v(T) = \Delta n$$

Extrinsic case

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Please see Fig. 13.3 in Kittel, Charles, and Herbert Kroemer. *Thermal Physics*. San Francisco, CA: W. H. Freeman, 1980.

Temperature dependence of majority carriers

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Please see Fig. 2.22 in Pierret, Robert F. *Semiconductor Device Fundamentals*. Reading, MA: Addison-Wesley, 1996.

Impurity types, levels

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Please see: Fig. 13 in Sze, S. M. "Physics of Semiconductor Devices." Chapter 1 in *Physics and Properties of Semiconductors - A Resume.* New York, NY: John Wiley & Sons, 1981.

Population of impurity levels (donor)

Population of impurity levels (acceptor)

Conductivity in semiconductors

$$\sigma = n_e e \frac{e\tau_e}{m_e} + n_h e \frac{e\tau_h}{m_h}$$

$$\mu_e = \frac{e\tau_e}{m_e}$$

$$\mu_h = \frac{e\tau_h}{m_e}$$

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Please see: Table 3 in Kittel, Charles. "Introduction to Solid State Physics." Chapter 8 in *Semiconductor Crystals.* New York, NY: John Wiley & Sons, 2004.

Impurity band conduction

Equilibrium carrier densities of impure semiconductors

Equilibrium carrier densities of impure semiconductors

Semiconductor carrier engineering

- Adding impurities to determine carrier type
  n_i^2 for Si: ~10^{20}cm^{-3}
  - Add 10^{16}cm^{-3} (~1ppm) phosphorous (donors) to Si: $n_{\mathbf{c}}$~N_d
  - $n_{\mathbf{c}}$~10^{16}cm^{-3}, $p_{\mathbf{v}}$~10^4 (n_i^2/N_d)
- Adding impurities to change carrier density
  - 1 part in 10^6 impurity in a crystal (~10^{22}cm^{-3} atom density)
  - 10^{22}/ 10^6 =10^{16} dopant atoms per cm^{-3}
  - conductivity is proportional to the # of carriers leading to 6 orders of magnitude change in conductivity!

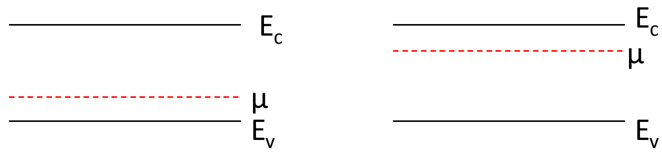
Impurities at the ppm level drastically change the conductivity (5-6 orders of magnitude)

Simplified expressions

Abrupt junction

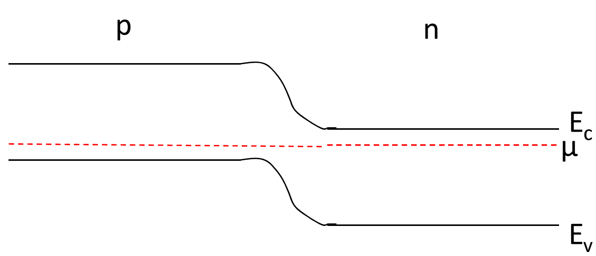
The p-n junction (diode)

p-type material at equilibrium	n-type material at equilibrium
$p \sim N_A$	$n \sim N_D$
$n \sim n_i^2/N$	$p \sim n_i^2/N$
$\mu_p = \mu_i^{A} - k_b T \ln\left(\frac{N_A}{n_i}\right)$	$\mu_n = \mu_i^{D} + k_b T \ln\left(\frac{N_D}{n_i}\right)$

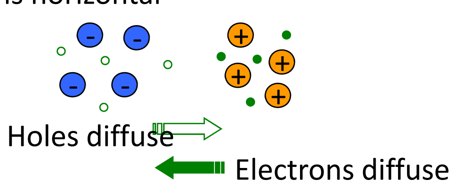


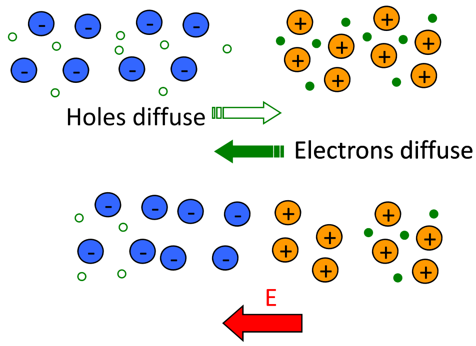
What happens when you join these together?

Joining p and n



Carriers flow under driving force of diffusion until μ is horizontal





An electric field forms due to the deviation from charge neutrality

Therefore, a steady-state balance is achieved where diffusive flux of the carriers is balanced by the drift flux

Chemical potential

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Please see: Fig. 29.2 in Ashcroft, Neil W., and Mermin, N. David. *Solid State Physics.* Belmont, CA: Brooks/Cole, 1976.

Carrier concentration in a p-n junction

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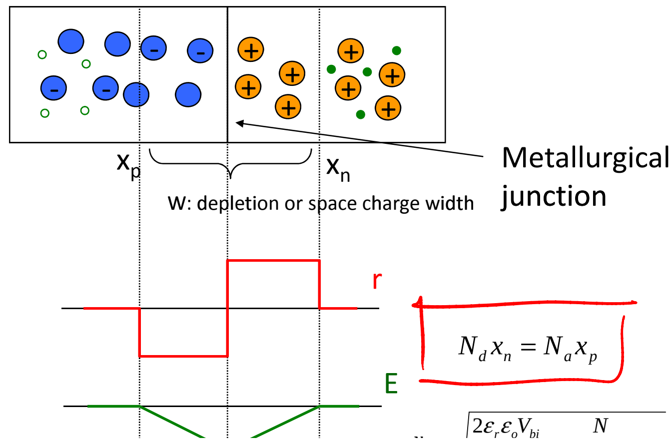
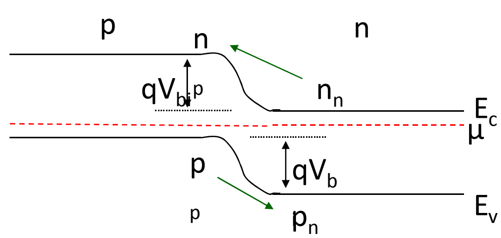


$$E = \int \frac{\rho(x)}{\varepsilon} dx$$

What is the built-in voltage V_{bi}?



$qV_{bi} = \mu_n - \mu_p$

$$\mu_p = \mu_i - k_b T \ln\left(\frac{N_a}{n_i}\right) \qquad \mu_n = \mu_i + k_b T \ln\left(\frac{N_D}{n_i}\right)$$

$$\therefore V_{bi} = \frac{k_b T}{q} \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

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Please see: Fig. 29.4 in Ashcroft, Neil W., and Mermin, N. David.
Solid State Physics. Belmont, CA: Brooks/Cole, 1976.

Operation under bias

Rectification

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Please see: Fig. 29.5 in Ashcroft, Neil W., and Mermin, N. David.
Solid State Physics. Belmont, CA: Brooks/Cole, 1976.