

MIT OpenCourseWare
<http://ocw.mit.edu>

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

For information about citing these materials or our Terms of Use, visit: <http://ocw.mit.edu/terms>.

3.23 Fall 2007 – Lecture 14

INHOMOGENEOUS SEMICONDUCTORS

Images removed due to copyright restrictions.

Russell Ohl

Shockley, Bardeen, and Brattain

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

William Shockley

Electronic Bands in Sodium Chloride

(advisor John C. Slater, MIT, 1936)

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

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

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.....

TABLE OF CONTENTS

	page
I. INTRODUCTION	1
II. THE FOCK EQUATIONS AND THE HARTREE APPROXIMATION	2
III. GENERAL REMARKS ABOUT THE POTENTIALS	23
IV. CALCULATION OF THE POTENTIAL AND THE RADIAL FUNCTIONS FOR THE FILLED BANDS	29
V. SOME THEOREMS INVOLVING CENTERS OF SYMMETRY	33
VI. FORMULATION OF THE BOUNDARY CONDITIONS	40
VII. Cl-Cl CASE	48
VIII. THE METHOD OF $k \rightarrow 0$	74
IX. METHODS OF CONSTRUCTING CONTOURS FOR THE FACE-CENTERED LATTICE	88
X. Na-Cl CUBE-CUBE JOINING	94
XI. Cl-Cl-Na JOINING	105
XII. SUMMARY OF THE WORK ON THE Cl ⁻ 3p BAND REMARKS ABOUT TOTAL ENERGY	116
XIII. CONCERNING EXCITATION	120
XIV. TEST OF THE SLATER CONDITIONS FOR FACE-CENTERED AND BODY-CENTERED LATTICES	131

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.

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

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)

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Density of available states

$$g_c(\varepsilon) = \sqrt{2(\varepsilon - \varepsilon_c)} \frac{m_c^{3/2}}{\pi^2 \hbar^3}$$
$$\int_{\varepsilon_c}^{\infty} d\varepsilon g_c(\varepsilon) e^{-(\varepsilon - \varepsilon_c)/k_B T}$$
$$N_c(T) = \frac{1}{4} \left(\frac{2m_c k_B T}{\pi \hbar^2} \right)^{3/2} = 2.5 \left(\frac{m_c}{m} \right)^{3/2} \left(\frac{T}{300K} \right)^{3/2} 10^{19} / \text{cm}^3$$

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Law of Mass Action

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

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Intrinsic case

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

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

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

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

Image removed due to copyright restrictions.
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.

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Extrinsic case

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

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Extrinsic case

Image removed due to copyright restrictions.

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

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Temperature dependence of majority carriers

Image removed due to copyright restrictions.

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

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Impurity types, levels

Image removed due to copyright restrictions.

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.

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Population of impurity levels (donor)

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Population of impurity levels (acceptor)

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Conductivity in semiconductors

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

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

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

Text removed due to copyright restrictions.

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

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Impurity band conduction

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Equilibrium carrier densities of impure semiconductors

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Equilibrium carrier densities of impure semiconductors

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Semiconductor carrier engineering

- Adding impurities to determine carrier type
 - n_i^2 for Si: $\sim 10^{20} \text{cm}^{-3}$
 - Add 10^{16}cm^{-3} ($\sim 1 \text{ppm}$) phosphorous (donors) to Si: $n_c \sim N_d$
 - $n_c \sim 10^{16} \text{cm}^{-3}$, $p_v \sim 10^4$ (n_i^2/N_d)
- Adding impurities to change carrier density
 - 1 part in 10^6 impurity in a crystal ($\sim 10^{22} \text{cm}^{-3}$ 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)

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Simplified expressions

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Abrupt junction

Image removed due to copyright restrictions.

Please see: Fig. 29.1 in Ashcroft, Neil W., and Mermin, N. David.
Solid State Physics. Belmont, CA: Brooks/Cole, 1976.

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

The p-n junction (diode)

p-type material at equilibrium n-type material at equilibrium

$$p \sim N_A$$

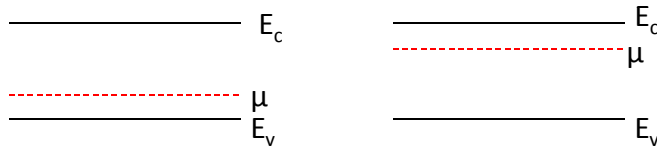
$$n \sim n_i^2 / N$$

$$\mu_p = \mu_i^A - k_b T \ln \left(\frac{N_A}{n_i} \right)$$

$$n \sim N_D$$

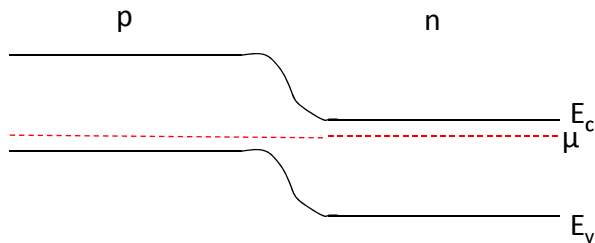
$$p \sim n_i^2 / N$$

$$\mu_n = \mu_i^D + k_b T \ln \left(\frac{N_D}{n_i} \right)$$

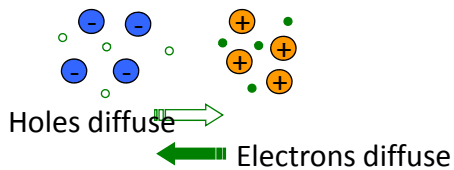


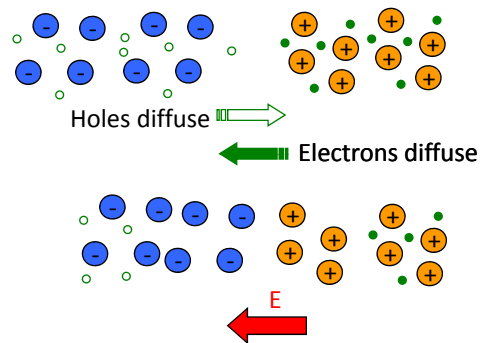
What happens when you join these together?

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

Image removed due to copyright restrictions.

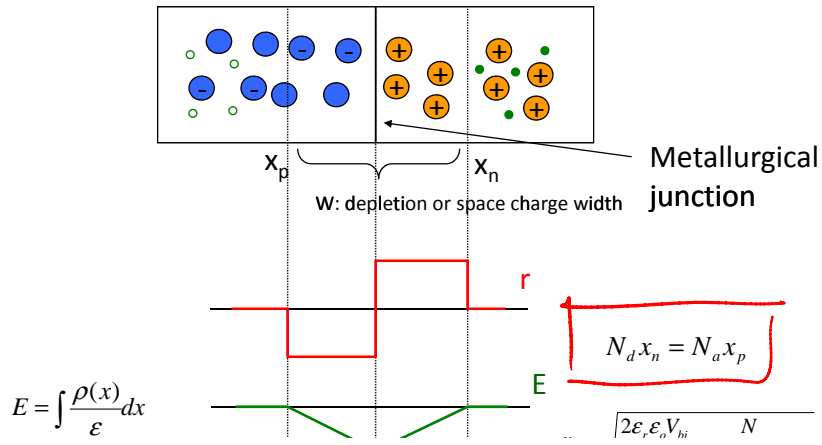
Please see: Fig. 29.2 in Ashcroft, Neil W., and Mermin, N. David.
Solid State Physics. Belmont, CA: Brooks/Cole, 1976.

Carrier concentration in a p-n junction

Images removed due to copyright restrictions. Please see

<http://commons.wikimedia.org/wiki/Image:Pn-junction-equilibrium.svg>

<http://commons.wikimedia.org/wiki/Image:Pn-junction-equilibrium-graphs.png>



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

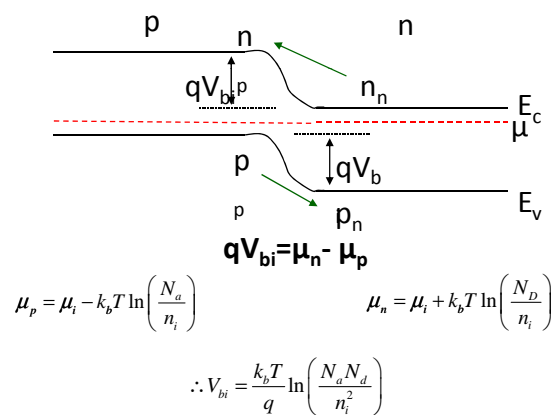


Image removed due to copyright restrictions.
Please see: Fig. 29.4 in Ashcroft, Neil W., and Mermin, N. David.
Solid State Physics. Belmont, CA: Brooks/Cole, 1976.

Operation under bias

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)

Rectification

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

3.23 Electronic, Optical and Magnetic Properties of Materials - Nicola Marzari (MIT, Fall 2007)