PHY 752 Solid State Physics
11-11:50 AM MWF Olin 103

Plan for Lecture 31:

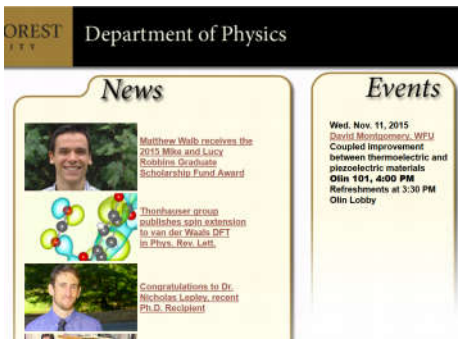
Chapter 14 in GGGPP:

Inhomogeneous semiconductors

1. **p-n junctions**
2. **Metal-semiconductor junctions**

Lecture notes prepared with materials from GGGPP textbook

21	Mon, 10/19/2015	Chap. 10	X-ray and neutron diffraction	#19
22	Wed, 10/21/2015	Chap. 10	Scattering of particles by crystals	#20
23	Fri, 10/23/2015	Chap. 11	Optical and transport properties of metals	#21
24	Mon, 10/26/2015	Chap. 11	Optical and transport properties of metals	#22
25	Wed, 10/28/2015	Chap. 11	Transport in metals	#23
26	Fri, 10/30/2015	Chap. 12	Optical properties of semiconductors and insulators	
27	Mon, 11/02/2015	Chap. 7 & 12	Excitons	#24
28	Wed, 11/04/2015	Chap. 9	Lattice vibrations	#25
29	Fri, 11/06/2015	Chap. 9	Lattice vibrations	#26
30	Mon, 11/09/2015	Chap. 13	Defects in semiconductors	#27
31	Wed, 11/11/2015	Chap. 14	Transport in semiconductors	#28
32	Fri, 11/13/2015	Chap. 14	Transport in semiconductors	
33	Mon, 11/16/2015	Chap. 15	Electron gas in Magnetic fields	
34	Wed, 11/18/2015	Chap. 17	Magnetic ordering in crystals	
35	Fri, 11/20/2015	Chap. 18	Superconductivity	
36	Mon, 11/23/2015	Chap. 18	Superconductivity	
	Wed, 11/25/2015		*Thanksgiving Holiday*	
	Fri, 11/27/2015		*Thanksgiving Holiday*	
37	Mon, 11/30/2015	Chap. 18	Superconductivity	
	Wed, 12/02/2015		Student presentations I	
	Fri, 12/04/2015		Student presentations II	
	Mon, 12/07/2015		Begin Take-home final	



FOREST UNIVERSITY Department of Physics

WFU Physics Colloquium

TITLE: Coupled improvement between thermoelectric and piezoelectric materials

SPEAKER: David Montgomery,

Department of Physics,
Wake Forest University

TIME: Wednesday November 11, 2015 at 4:00 PM

PLACE: Room 101 Olin Physical Laboratory

Refreshments will be served at 3:30 PM in the Olin Lounge. All interested persons are cordially invited to attend.

ABSTRACT

A new device architecture combining thermoelectric and piezoelectric materials is discussed. Thermo-piezoelectric generators (TPEGs) exhibit a synergistic effect that amplifies output voltage, and has been observed to increase initial piezoelectric values through a time dependent thermoelectric/pyroelectric effect. TPEGs are built by integrating insulating layers of polyvinylidene fluoride (PVDF) piezoelectric films between flexible thin

Impurity states in doped semiconductors at T=0 K

Donor impurities n-type

Acceptor impurities p-type

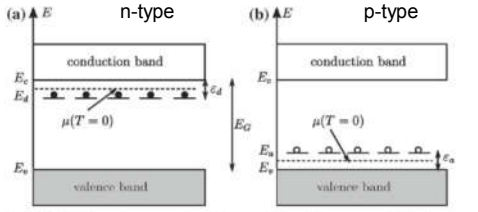


Figure 13.7 (a) Schematic representation of the energy levels of a homogeneously doped n-type semiconductor at $T = 0$ (in abscissa any arbitrary direction in the homogeneous material can be considered). Typical energy values are $E_G = E_c - E_v \approx 1$ eV and $\varepsilon_d = E_c - E_d \approx 10$ meV. The Fermi level at zero temperature lies at $(1/2)(E_d + E_c)$, which is the middle point between E_d and E_c. (b) Schematic representation of the energy levels of a homogeneously doped p-type semiconductor at $T = 0$; typical values of $\varepsilon_a = E_a - E_v$ are of the order of 10 meV. The Fermi level at zero temperature lies at $(1/2)(E_v + E_a)$, which is the middle point between E_v and E_a.

Composite p- and n- type semiconductor at T>0 K -- distribution of ionized impurity states

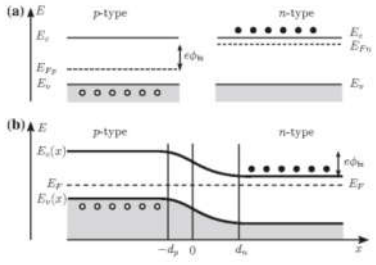


Figure 14.1 (a) Energy bands and *Fermi levels* in two physically separated p-type and n-type pieces of the same semiconductor. The majority carriers (electrons in n-type and holes in p-type regions) are indicated by full dots and empty dots, respectively, while minority carriers are not indicated for simplicity. (b) Energy band profile and *unique Fermi level* across the p-n junction at equilibrium.

Composite p- and n- type semiconductor -- electrostatic effects

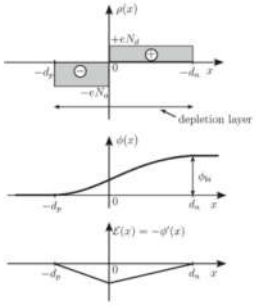
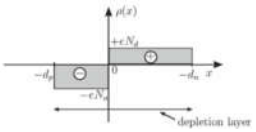


Figure 14.2 Charge density $\rho(x)$ at a p-n junction in the depletion layer approximation, electrostatic potential $\phi(x)$, and internal electric field $\mathcal{E}(x)$.

Model electrostatic configuration due to ionized impurities



$$\rho(x) = \begin{cases} -eN_a & -d_p < x < 0, \\ +eN_d & 0 < x < d_n, \\ 0 & \text{for } x < -d_p \text{ and } x > d_n. \end{cases}$$

Poisson's equation for resulting electrostatic potential

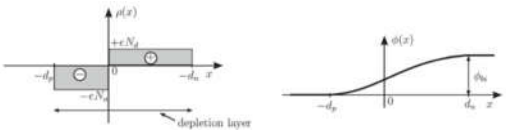
$$-\frac{d^2\phi}{dx^2} = \frac{\rho(x)}{\varepsilon}$$

$$\phi(x) = \begin{cases} \frac{eN_a}{2\varepsilon}(x + d_p)^2 & -d_p \le x \le 0, \\ \phi_{bi} - \frac{eN_d}{2\varepsilon}(x - d_n)^2 & 0 \le x \le d_n. \end{cases}$$

$$N_a d_p = N_d d_n,$$

$$\phi_{bi} = \frac{e}{2\varepsilon}[N_a d_p^2 + N_d d_n^2].$$

Model p-n junction -- continued



Relationship of depletion layer lengths to built-in potential

$$d_p = \left[\frac{N_d}{N_a}\frac{1}{N_a + N_d}\frac{2\varepsilon\phi_{bi}}{e}\right]^{1/2} \quad \text{and} \quad d_n = \left[\frac{N_a}{N_d}\frac{1}{N_a + N_d}\frac{2\varepsilon\phi_{bi}}{e}\right]^{1/2}$$

Total width of the depletion layer:

$$w = d_p + d_n = \left[\frac{N_a + N_d}{N_a N_d}\frac{2\varepsilon\phi_{bi}}{e}\right]^{1/2}.$$

Typical values:

$$w \approx 5000\,\text{Å}$$

$$\frac{\phi_{bi}}{w} \approx 2\times10^4\,V/m$$

p-n junction in the presence of external voltage V

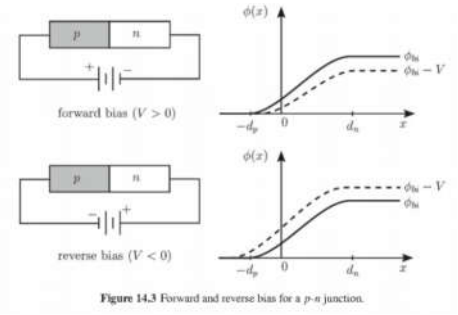


Figure 14.3 Forward and reverse bias for a p-n junction.

p-n junction in the presence of external voltage V

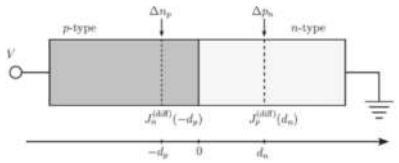


Figure 14.4 Schematic representation of a p-n homojunction with an applied potential V on the p-side (the n-side is grounded); Δn_p and Δp_n denote the change in the concentration of minority carriers at the boundaries between the space-charge region and the neutral regions. If V is positive, also Δn_p and Δp_n are positive (and vice versa). The electron diffusion current at $x = -d_p$, and the hole diffusion current at $x = d_n$ are indicated. The diode current is the sum $J_n^{(diff)}(-d_p) + J_p^{(diff)}(d_n)$ if recombination processes are negligible in the depletion region.

$$d_p = \left[\frac{N_d}{N_a}\frac{1}{N_a + N_d}\frac{2\varepsilon(\phi_{bi} - V)}{e}\right]^{1/2}, \quad d_n = \left[\frac{N_a}{N_d}\frac{1}{N_a + N_d}\frac{2\varepsilon(\phi_{bi} - V)}{e}\right]^{1/2},$$

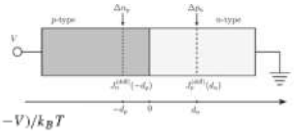
$$w = d_p + d_n = \left[\frac{N_a + N_d}{N_a N_d}\frac{2\varepsilon(\phi_{bi} - V)}{e}\right]^{1/2}.$$

Distribution of electrons and holes near p-n junction

$$n(x) = N_c(T)e^{-[E_c(x) - E_F]/k_B T} \quad \text{with} \quad E_c(x) = E_c - e\phi(x),$$

$$p(x) = N_v(T)e^{-[E_F - E_v(x)]/k_B T} \quad \text{with} \quad E_v(x) = E_v - e\phi(x).$$

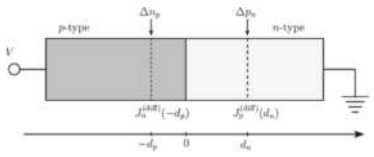
Comparison of of electron and concentrations at boundaries of depletion zone:



$$n_p(-d_p) = n_n(d_n)e^{-e(\phi_{bi} - V)/k_B T}$$

In terms of electron concentration well inside the n-type material (n_{n0}) and well inside the p-type material (n_{p0})

$$n_{p0} = n_{n0}e^{-e\phi_{bi}/kT}$$



$$n_p(-d_p) - n_{p0} \equiv \Delta n_p(-d_p) = n_{p0}(e^{eV/k_BT} - 1)$$
$$p_n(+d_n) - p_{n0} \equiv \Delta p_n(+d_n) = p_{n0}(e^{eV/k_BT} - 1)$$

Current-voltage characteristics of p-n junction

$$J = J_s\left(e^{eV/k_BT} - 1\right),$$

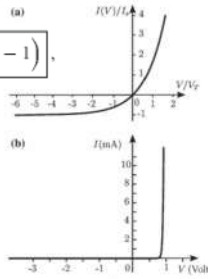


Figure 14.5 (a) Ideal characteristics $I(V) = I_s\,[\exp(V/V_T) - 1]$ of a p-n junction for values of V comparable with $V_T = 0.25$ mV. For diodes of small dimensions, typical values of I_s might be in the range around 10^{-15} A. (b) The $I(V)$ curve is plotted in an expanded scale, to make evident the rectifying characteristics of the diode.

Some details (covered in Chap. 13)

Electron and hole current densities in the presence of an electric field $\mathcal{E}$ within Drude model

$$\mathbf{J}_n = \frac{ne^2\tau_n}{m_c^*}\boldsymbol{\mathcal{E}} \equiv ne\mu_n\boldsymbol{\mathcal{E}}, \qquad \mathbf{J}_p = \frac{pe^2\tau_p}{m_v^*}\boldsymbol{\mathcal{E}} \equiv pe\mu_p\boldsymbol{\mathcal{E}}.$$

Electron and hole current densities due to both an electric field and a concentration gradient

$$\mathbf{J}_n = en\mu_n\boldsymbol{\mathcal{E}} + eD_n\nabla n, \qquad \mathbf{J}_p = ep\mu_p\boldsymbol{\mathcal{E}} - eD_p\nabla p,$$

diffusion constants

Electron and hole transport in p-n junction – continued

Boltzmann equation for electrons:

$$\frac{\partial n}{\partial t} = \frac{1}{e}\text{div } \mathbf{J}_n + \underbrace{G_n(\mathbf{r}, t) - R_n(\mathbf{r}, t)};$$

electron generation and recombination

Boltzmann equation for holes:

$$\frac{\partial p}{\partial t} = -\frac{1}{e}\text{div } \mathbf{J}_p + \underbrace{G_p(\mathbf{r}, t) - R_p(\mathbf{r}, t)}.$$

hole generation and recombination

Electron and hole transport in p-n junction – continued

Boltzmann equations in terms of applied field and density gradients

$$\boxed{\frac{\partial n}{\partial t} = D_n\frac{\partial^2 n}{\partial x^2} + \mu_n\frac{\partial(n\mathcal{E})}{\partial x} + G_n - R_n}.$$

$$\boxed{\frac{\partial p}{\partial t} = D_p\frac{\partial^2 p}{\partial x^2} - \mu_p\frac{\partial(p\mathcal{E})}{\partial x} + G_p - R_p}.$$

Model generation-recombination processes

$$G_n - R_n \approx \frac{n_0 - n}{t_n} \qquad G_p - R_p \approx \frac{p_0 - p}{t_p}$$

Electron and hole transport in p-n junction – continued

$$\boxed{\frac{\partial p}{\partial t} = D_p\frac{\partial^2 p}{\partial x^2} - \mu_p\mathcal{E}\frac{\partial p}{\partial x} - \mu_p p\frac{\partial \mathcal{E}}{\partial x} + \frac{p_0 - p}{t_p}}$$

n-semiconductor.

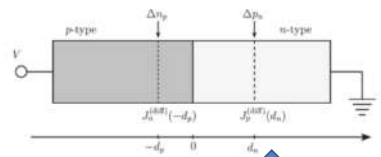
$n_0 >> p_0$

$$\boxed{\frac{\partial n}{\partial t} = D_n\frac{\partial^2 n}{\partial x^2} + \mu_n\mathcal{E}\frac{\partial n}{\partial x} + \mu_n n\frac{\partial \mathcal{E}}{\partial x} + \frac{n_0 - n}{t_n}}$$

p-semiconductor.

$p_0 >> n_0$

Electron and hole transport in p-n junction – continued



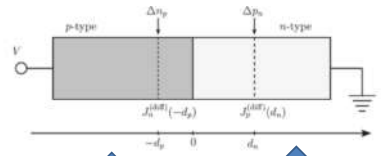
$$D_p \frac{d^2p}{dx^2} - \frac{p - p_0}{t_p} = 0 \quad n\text{-semiconductor}$$

$$p(x) - p_0 = \Delta p(0) e^{-x/L_p} \quad \text{with} \quad L_p^2 = D_p t_p.$$

$$J_p^{(\text{diff})}(x) = -eD_p \frac{\partial p}{\partial x} = eD_p \frac{\Delta p(0)}{L_p} e^{-x/L_p};$$

$$L_p \approx 0.01 \text{ cm}.$$

Electron and hole transport in p-n junction – continued



$$J_n^{(\text{diff})}(-d_p) = eD_n \frac{\Delta n_p(-d_p)}{L_n} \qquad J_p(d_n) \approx J_p^{(\text{diff})}(d_n) = eD_p \frac{p_{n0}}{L_p} \left(e^{eV/k_BT} - 1\right)$$

$$= eD_n \frac{n_{p0}}{L_n} \left(e^{eV/k_BT} - 1\right)$$

$$\boxed{J = J_s \left(e^{eV/k_BT} - 1\right)}, \qquad J_s = eD_p \frac{p_{n0}}{L_p} + eD_n \frac{n_{p0}}{L_n} = eL_p \frac{p_{n0}}{t_p} + eL_n \frac{n_{p0}}{t_n};$$