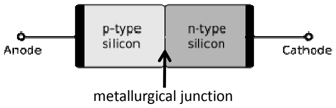
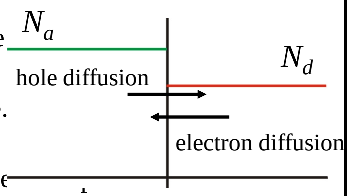
pn-junctions



- In thermal equilibrium, the Fermi level is constant throughout a system. If 2 systems with different Fermi levels are brought into contact, electrons will diffuse from the higher Fermi level system, to the lower one, to fill empty states
- *e.g.* pn-junction – provides characteristics needed for rectifiers, amplifiers, switching circuits etc. Formed from single crystal, in which the two halves are differently doped.
- Consider a step junction between the two regions that are uniformly doped – initially very large change in density gradient of both electron and hole concentrations.
- Majority carrier electrons (from n-region) will diffuse into p-region and recombine with holes, and majority carrier holes will diffuse into n-region and recombine.



- Positively-charged donor atoms and negatively-charge behind → this net charge induces an electric field around the metallurgical junction.

http://en.wikipedia.org/wiki/P-n_junction http://britneyspears.ac/physics/pn/pnjunct.htm
http://en.wikipedia.org/wiki/Diode http://hyperphysics.phy-astr.gsu.edu/hbase/solids/pnjun.html

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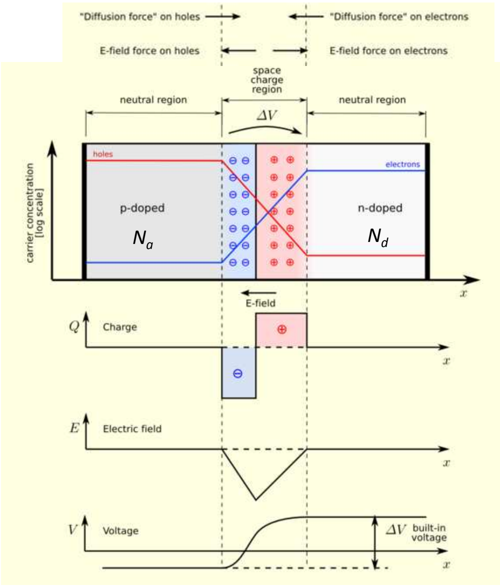
pn junctions

- The region around the junction becomes charged and depleted of free charge carriers: “space charge” or “depletion” region – the region acts as an insulator.
- Density gradients still exist in the majority carrier concentrations at edge of space charge region → produces a "diffusion force” that acts on the majority carriers
- The junction is in thermal equilibrium when, with no voltage applied, the “diffusion force” and E-field force balance each other
- → the Fermi level is constant throughout

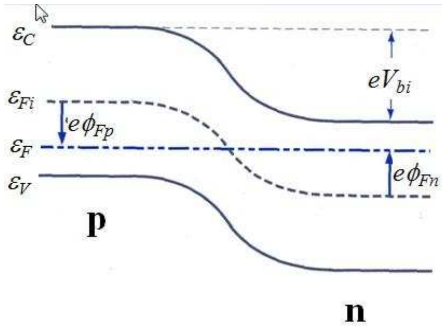


Energy bands of pn junctions:
zero applied bias

- The n region is left positively charged and the p region negatively charged. This results in the lowering of electron energy levels on the n side and the raising on the p side, which causes the ε_F to be position-independent as required *i.e.* CB and VB "bend"

- Electrons in conduction band of n-region see a *built-in potential barrier* (V_{bi}) in trying to move into p-region. It maintains equilibrium between the majority carriers in one region, and the minority carriers in the other (*i.e.* electrons in n-region and the electrons in the p-region, and holes in the n-region and holes in the p-region.)

- Since ε_{Fi} is equidistant from conduction band edge throughout, then $V_{bi} = |\phi_{Fn}| + |\phi_{Fn}|$



(ϕ's are potentials)

We define the potentials

$$e\phi_{Fn} = \varepsilon_{Fi} - \varepsilon_F \text{ in the n - region}$$

$$e\phi_{Fp} = \varepsilon_{Fi} - \varepsilon_F \text{ in the p - region}$$

Note: diagram above is of *electron* energy levels, sp that a region of low energy, is a region of high electrostatic potential.

http://www.acsu.buffalo.edu/~wie/applet/pnformation/pnformation.html

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Energy bands of pn junctions:
zero applied bias

In the n-type region

$$n_0 = N_d = n_i \,\mathbf{exp}\left[\frac{\varepsilon_F - \varepsilon_{Fi}}{k_B T}\right] = n_i \,\mathbf{exp}\left[\frac{-(e\phi_{Fn})}{k_B T}\right]$$

i.e. assume complete ionisation, and $N_d >> n_i$

$$\phi_{Fn} = -\frac{k_B T}{e}\,\mathbf{ln}\left(\frac{N_d}{n_i}\right)$$

Similarly in the p - type region,

$$\phi_{Fp} = +\frac{k_B T}{e}\,\mathbf{ln}\left(\frac{N_a}{n_i}\right)$$

$$\therefore V_{bi} = \frac{k_B T}{e}\,\mathbf{ln}\left(\frac{N_a N_d}{n_i^2}\right) = V_t \,\mathbf{ln}\left(\frac{N_a N_d}{n_i^2}\right)$$

$(V_{bi} = |\phi_{Fn}| + |\phi_{Fn}|\ )$

$$\boxed{e\phi_{Fn} = \varepsilon_{Fi} - \varepsilon_F}$$

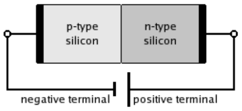
$$n_0 = n_i \exp\left[\frac{\varepsilon_F - \varepsilon_{Fi}}{k_B T}\right]$$

$$p_0 = n_i \exp\left[\frac{\varepsilon_{Fi} - \varepsilon_F}{k_B T}\right]$$

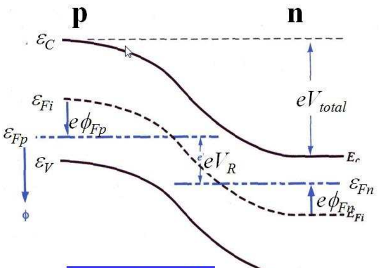
(slide 107)

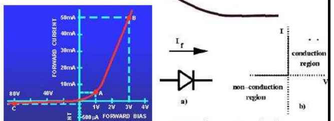
where V_t is ***thermal voltage***
Note: change of notation…
N_d is now the **net** donor concentration **in the n-region** and N_a is the **net** acceptor concentration **in the p-region**

Energy bands of pn junctions: **reverse bias**



- Diagram shows the energy-band diagram when a voltage is applied to n-region with respect to p-region
  - we are no longer be in an equilibrium condition and the Fermi Energy level will no longer be constant.
  - as the positive potential is downwards, then Fermi-level on n-side is below than on p-side.
- The holes in the p-region are pulled away from the junction, causing the width of the depletion zone to increase. Similarly, because the electrons will also be pulled away from the junction. Therefore the space charge region widens, and does so increasingly with increasing reverse-bias voltage. This increases the voltage barrier causing a high resistance to the flow of charge carriers thus allowing minimal electric current to cross the p–n junction.
- $V_{total} = V_R + V_{bi}$ where V_R is the applied reverse bias voltage and V_{bi} is the thermal equilibrium built-in potential.





IV characteristics of a pn-junction diode

Elementary **Optical** Properties of Semiconductors (see also **PHY3129 Device Physics)**

- Possible photon-semiconductor interactions: with *lattice, impurities, defects* and *valence electrons*
- If enough energy is imparted to elevate electron from valence band into conduction band → Optical **absorption** to generate electron-hole pairs "excess carrier concentrations".
- **Recombination →** emission of a photon **LUMINESCENCE**

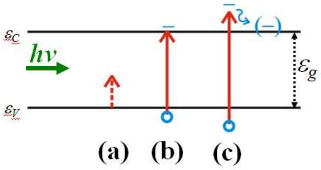
- Optical energy (*hv*) absorbed in a semiconductor generates excess electron-hole pairs producing "photocurrents". The output terminals of a solar cell are connected to a resistive load → electrical power.
- Photodetectors also convert optical signals into electrical signals – photo-generated excess electron-hole pairs change the semiconductors conductivity (measured as a change in current). A photodiode is a pn junction with reverse bias voltage applied: excess electron-hole pairs created in the space-charge region are separated very quickly by electric field → photocurrent (proportional to photon flux)
- Inverse of photodetector is *electroluminescence*: this is the process of generating photon emission when the excitation of excess el-hole pairs is a result of an electric current caused by an applied E-field. If a "forward bias" voltage is applied across a pn junction then electrons and holes injected across space charge region where they become excess minority carriers → they diffuse into neutral semiconductor and recombine with majority carriers → if direct bandgap material, then a photon is emitted (Light Emitting Diode)

Fundamental (optical) absorption, and absorption coefficient

Illuminate semiconductor with light –photons either propagate through semiconductor or are absorbed – depending on photon energy and magnitude of band gap.

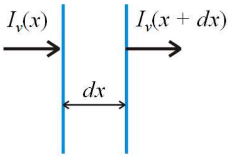
(a) If photon energy $h\nu < \varepsilon_g$ then photons not readily absorbed – light transmitted.

(b) and (c) If $h\nu$ = or > ε_g : photon can interact with electron and may elevate it into conduction band. Electron created in CB and hole in VB - an **electron-hole pair** (photon absorbed)



Any excess energy will give electron/hole additional kinetic energy which will be dissipated as heat (c).

- I_ν : intensity of photon flux (ν is frequency) (units of energy cm^{-2} s^{-1})
- Energy absorbed per unit time in distance dx is $\alpha I_\nu(x)dx$ where the α is the absorption coefficient: the relative number of photons absorbed per unit distance (cm^{-1}).



$$I_\nu(x+dx) - I_\nu(x) = \frac{dI_\nu(x)}{dx}dx = -\alpha I_\nu(x)dx$$

$$\frac{dI_\nu(x)}{dx} = -\alpha I_\nu(x)$$

And hence, If $I_\nu(0) = I_{\nu 0}$ then

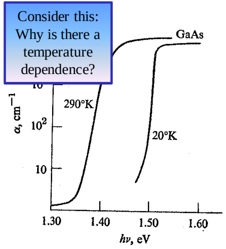
$$\boxed{I_\nu(x) = I_{\nu 0}\exp(-\alpha x)}$$

Electron-hole pair generation rate

- The rate at which energy is absorbed per unit volume is $\alpha I_\nu(x)$. If we assume one absorbed photon at an energy $h\nu$ creates one electron-hole pair, then the generation rate of electron-hole pairs is:

$$G = \frac{\alpha I_\nu(x)}{h\nu} \quad \text{units: number per cm}^{-3}\text{ per s}$$

- If on average, one absorbed photon produces less than one electron-hole pair, then this equation must also be multiplied by an efficiency factor, η
- Absorption coeff. (α) is very strong function of photon energy and band gap energy
- Probe band structure by measuring absorption spectrum. *i.e.* use beam of photons and study changes in transmitted radiation.
- **Fundamental Absorption:** *i.e.* excitation of an electron from valence to conduction band, manifested as a rapid rise in absorption: estimation of **energy gap** can be made using **absorption edge**.



Consider this: Why is there a temperature dependence?