COE 360 Principles of VLSI Design
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Lecture#2

Basic Properties of Semiconductor Devices

1. N-type & P-type semiconductors
2. PN Junction
3. Built-In Potential
4. Forward-Biased PN Junction
5. Reverse-Biased PN Junction
6. Transition Capacitance
7. Junction Breakdown

COE 360 : Lec #2

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- The Fermi level for an n-type semiconductor is above E_{Fi}. However, the Fermi level for a p-type semiconductor is below E_{Fi}. This is illustrated in the figure below.

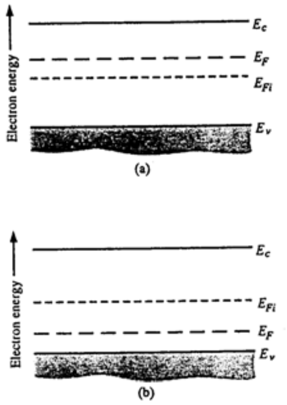


Figure Position of Fermi level for an (a) n-type ($N_d > N_a$) and (b) p-type ($N_a > N_d$) semiconductor.

- As the doping levels increase, the Fermi energy level moves closer to the valence band for the p-type material and closer to the conduction band for the n-type material, as shown below.

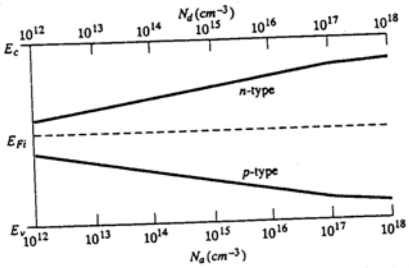


Figure Position of Fermi level as a function of donor concentration (n-type) and acceptor concentration (p-type).

- In addition to a conduction current, the transport of charges in a semiconductor maybe accounted for by diffusion, which is charge movement due to a nonuniform concentration of particles in a semiconductor.

- PN junction:

- The PN junction is the basic building block on which the operation of all semiconductor devices depends.
- The PN junction is formed from a single-crystal material in which one region is doped with acceptor impurity atoms to form the p-region, and the adjacent region is doped with donor atoms to form the n-region. The interface separating the n- and p-regions is called the metallurgical junction.

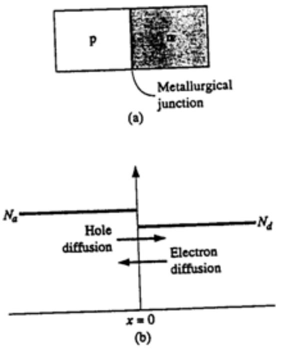


Figure (a) Simplified geometry of a pn junction. (b) The doping profile of an ideal uniformly doped pn junction.

- Initially, at the metallurgical contact, there is a very large density gradient in both the electron and hole concentrations. Majority carrier electrons in the n-region will begin diffusing into the p-region and majority carrier holes in the p-region will begin diffusing into the n-region.

- As electrons diffuse from the n-region, positively charged donor atoms are left behind. Similarly, as holes diffuse from the p-region, they uncover negatively charged acceptor atoms.

- The net positive and negative charges in the n- and p-regions induce an electric field in the region near the metallurgical junction, in the direction from the positive to the negative charge, or from the n- to the p-region.

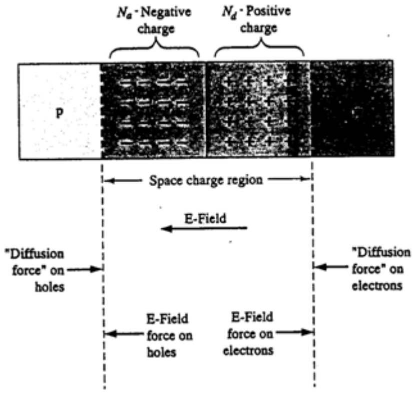


Figure The space charge region, the electric field, and the forces acting on the charged carriers.

- The net positively and negatively charged regions are referred to as the space charge region. Essentially all electrons and holes are swept out of the space charge region by the electric field. Since the space charge region is depleted of any mobile charge, this region is also referred to as the depletion region.

- Density gradients still exist in the majority carrier concentrations at each edge of the depletion region. The density gradient can be thought of as producing a "diffusion force" that acts on the majority carriers. The electric field in the depletion region produces another force on the electrons and holes which is in the opposite direction to the "diffusion force" for each type of particle.

- Under thermal equilibrium, the "diffusion force" and the E-field force exactly balance each other. Thus, further diffusion of majority carriers across the junction is stopped by the electric field.

- <u>Zero Applied Bias</u>

- If we assume no voltage is applied across the pn junction, then the junction is in thermal equilibrium — the Fermi energy level is constant throughout the entire system. The energy band diagram for the pn junction in thermal equilibrium is shown below.

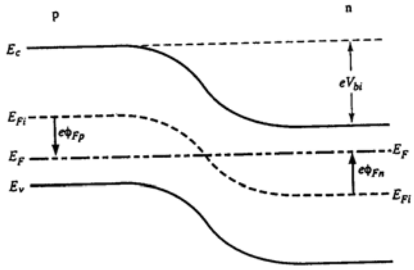


Figure Energy-band diagram of a pn junction in thermal equilibrium.

- The conduction and valence band energies must bend as we go through the depletion region, since the relative position of the conduction and valence bands with respect to the Fermi energy changes between the p- and n-regions.

- Electrons in the conduction band of the n-region see a potential barrier in trying to move into the conduction band of the p-region. This potential barrier is referred to as the <u>built-in potential barrier</u> and is denoted as V_{bi}.

- $V_{bi} = \frac{KT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$
  where $V_t = \frac{KT}{e}$ is defined as the thermal voltage
  and N_a is the concentration of acceptors in the p material
  and N_d is the concentration of donors in the n material.

- Due to the separation of positive and negative space charge densities in the depletion region, an electric field is created. The electric field direction is from the n- to the p-region. The maximum (magnitude) electric field occurs at the metallurgical junct.

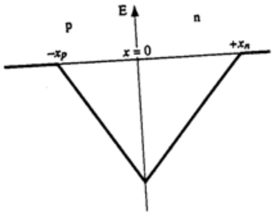


Figure Electric field in the space charge region of a uniformly doped pn junction.

- The width of the depletion region $w = w_n + w_p$, where w_n (w_p) is the width of the depletion region into the n (p) side.

- If the p-side is heavily doped while the n-side is lightly doped (i.e. $N_a >> N_d$, resulting in n^+p junction), then the width of the depletion region into the lightly doped side (w_n) will be greater than that into the heavily doped side (w_p), i.e $w_n >> w_p$ and $W \simeq W_{lightly\text{-}doped}$.

- In general, higher doping concentrations result in the narrower depletion region width.

- Reverse-Biased PN junction:

- If a positive voltage is applied to the n-region with respect to the p-region, the pn junction is called reverse-biased. Under this condition, we will no longer be in an equilibrium condition – the Fermi energy level will no longer be constant through the system.

- The figure below shows the energy band diagram for the reverse-biased pn junction. The total potential barrier, indicated by V_{total}, has increased by V_R, the magnitude of the applied reverse-bias voltage.

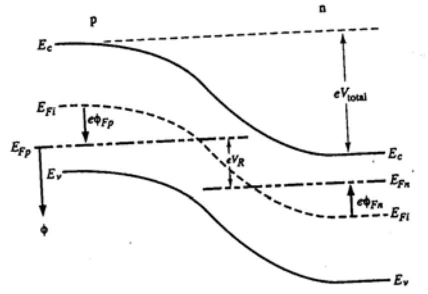


Figure Energy-band diagram of a pn junction under reverse bias.

- The applied reverse-bias voltage induces an electric field, Eapp, in the same direction of the built-in electric field and hence increases the junction potential as it pushes majority free carriers away from the junction causing the depletion region to get wider, i.e. $W_r > W_o$, where W_r is the depletion region under reverse bias, and W_o is width of the depletion region under zero bias.

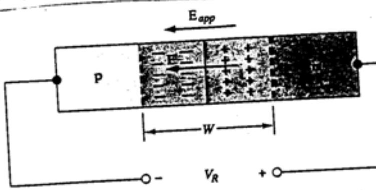


Figure A pn junction with an applied reverse-bias voltage showing the directions of the electric field induced by V_R and the space charge electric field.

- Forward - Biased pn junction

- If a positive voltage is applied to the p-region with respect to the n-region, the pn junction is called forward biased.

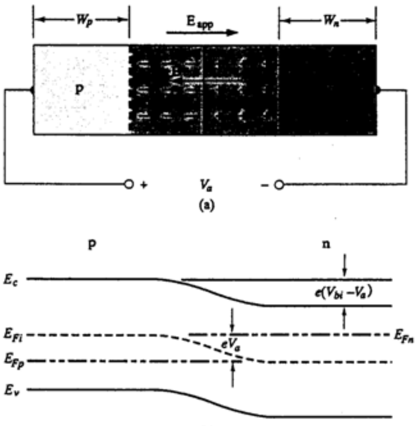


Figure (a) A pn junction with an applied forward-bias voltage showing the directions of the electric field induced by V_a and the space charge electric field. (b) Energy-band diagram of the forward-biased pn junction.

- The electric field, E_{app}, induced by the applied voltage is in the opposite direction to the thermal equilibrium space charge electric field, so the net electric field in the space charge region is reduced below the equilibrium value.

- The forward-bias voltage lowers the potential barrier so that majority carrier electrons from the n-region are injected across the junction into the p-region, thereby increasing the minority carrier electron concentration. The minority carrier electron concentration in the p-region can deviate from its thermal equilibrium value by orders of magnitude.

- The same process occurs for majority carrier holes in the p-region which are injected across the space charge region into the n-region. Thus, by applying a forward-bias voltage, we create excess minority carriers in each region of the pn junction.
- The forward-bias voltage causes the depletion region width to get narrower, i.e. $W_f < W_0$, where W_f is the depletion region widths under forward bias.

- Transition Capacitance:

Because positive ions exist on one side of the junction and negative ions on the other side, this causes the pn junction to have a capacitive effect. The transition capacitance, C_T, is given by

$$C_T = A * \varepsilon_0 \varepsilon_r / W$$

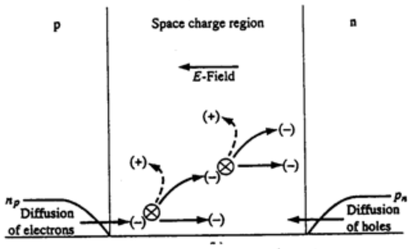
A = cross sectional area
ε_0 = permitivity of free space
ε_r = relative permitivity of the semiconductor material
W = transition region width

- Accordingly, the higher the doping concentrations of the pn junction are, the narrower the transition region width and the higher the junction transition capacitance will be.

Junction Breakdown

- In the ideal pn junction, a reverse-bias voltage will result in a small reverse-bias current through the device. However, the reverse-bias voltage may not increase without limit; at some particular voltage, the reverse-bias current will increase rapidly. The applied voltage at this point is called the breakdown voltage.

- The breakdown process occurs when electrons and/or holes moving across the depletion region, acquire sufficient energy from the electric field to create electron-hole pairs by colliding with atomic electrons within the depletion region. The newly created electrons and holes move in opposite directions due to the electric field and thereby add to the existing reverse-bias current. In addition, the newly generated electrons and holes may acquire sufficient energy to ionize other atoms, leading to the breakdown. This process is called the avalanche breakdown process.



- The higher the doping concentrations of the PN junction are the higher the magnitude of the built-in electric field will be. Thus, pn junctions with higher doping concentrations have lower breakdown voltages.