EE/CE 3310 (Electronic Devices)

Review Notes

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*Some errors may be present

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Chapter 1

Semiconductor Structure

Semiconductors are elements that have a conductivity between that of a metal and an insulator. The band gap (energy between conduction and valence bands) is low in semiconductors, which leads to this property. This conductive property can be changed by various methods, making semiconductors important in circuit technology. Either single elements or combinations of elements have semiconducting properties.

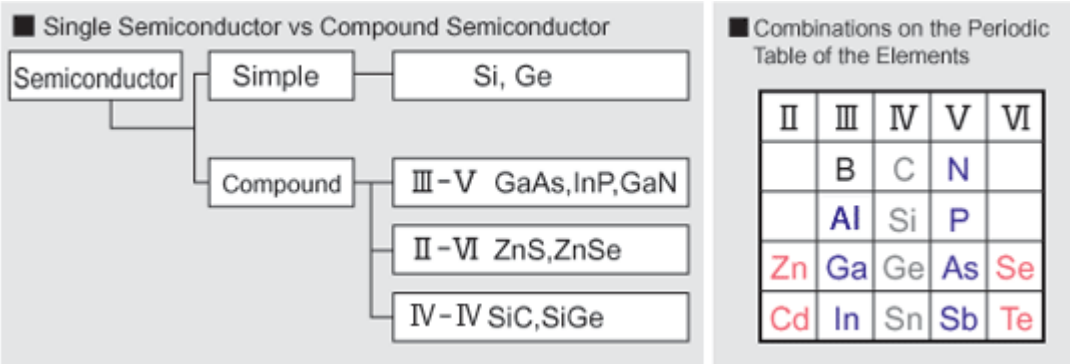

Figure 1.1: Semiconducting Materials

Semiconductors have an energy structure that consists of a conduction and valance band separated by a bandgap. Electrons in the conduction band are "free" (conducting), while valence electrons are trapped in the crystalline bonds. Bandgap size is determined by covalent bond strength, which mainly depends on atom size.

With some excitation equal to or greater than bandgap size E_g, electrons can move from the valence to conduction bands which creates a "hole" in the valence band. After some time they fall back down (filing the hole), either releasing a photon (direct bandgap) or phonon (indirect bandgap).

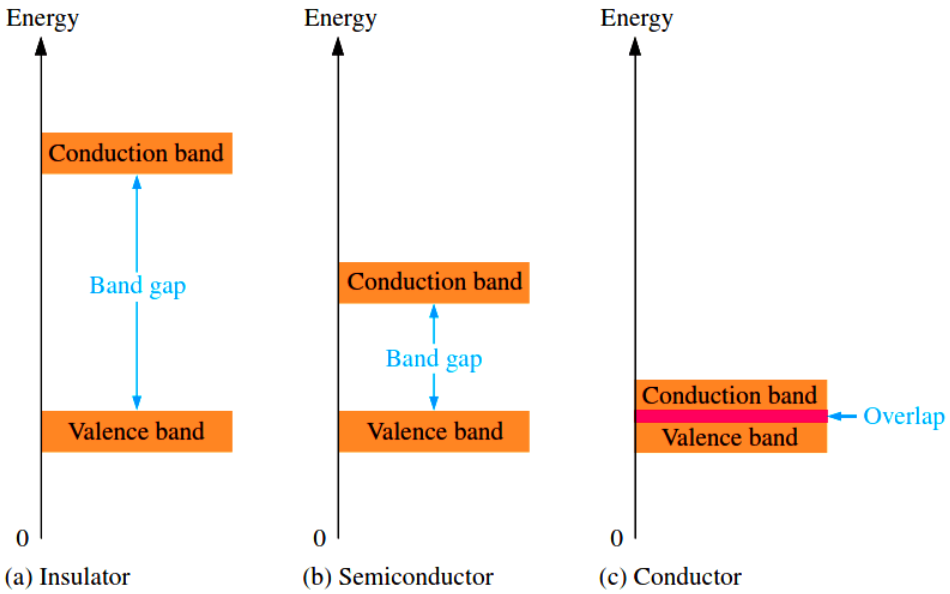

Figure 1.2: Bandgaps in different type of material

The number of free electrons and number of holes per cm^3 in a pure semiconductor is known as the intrinsic carrier concentration, which depends on temperature and bandgap size.

Chapter 2

Carriers

2.1 Doping

The carrier concentration inside semiconductors can be boosted by adding impurities (different elements) into the pure crystal lattice. This takes two forms: n-type and p-type doping. Note that because electrons are typically more mobile than holes, n-type conduction is better than p-type.

2.1.1 N-Type

N-type doping injects impurities that have >4 electrons in their valence band (Group V of the periodic table), and are referred to as "donors." Because semiconductors like Silicon have 4 valence electrons they only require 4 bonds to form the crystal lattice, meaning the impurity can only bond 4 times (becoming ionized) and leaves an electron out. This "odd man out" electron is at a new energy level close to the conduction band, and at room temperature almost all of these move to the conduction band and is free to move.

N-type Carrier: Electron

2.1.2 P-Type

P-type doping injects impurities that have <4 electrons in their valence band (Group III of the periodic table), and are referred to as "acceptors." Because semiconductors like Silicon have 4 valence electrons they need 4 bonds, so there is a "hole" in the bond of the doping material. Electrons move from other levels, causing holes to propagate throughout the system. This looks like a flow of positive charge from atom to atom.

P-type Carrier: Holes

2.1.3 Combinations

If there are multiple dopants inside a semiconductor they "cancel" each other out, and the dopant with the higher concentration will dominate and determine the overall semiconductor type with a final dopant concentration that can be calculated according to section 2.2.3.

2.2 Carrier Concentration

2.2.1 Fermi-Dirac Distribution

The Fermi-Dirac distribution describes the probability of having one electron at an energy level E.

$$\boxed{f(E) = \frac{1}{1+e^{\left(\frac{E-E_f}{KT}\right)}}}$$

Where E_f is the Fermi level, K is the Boltzmann constant, and T is the temperature (in Kelvin). Note that the distribution ignores the fact that electrons cannot exist in the bandgap. This distribution can be found at https://www.desmos.com/calculator/vhp6rlm4i9.

2.2.2 Carrier Levels

The amount of holes and electrons can be calculated from the Fermi-Dirac distribution, giving us

$$\boxed{n_o = n_i e^{\frac{E_f - E_i}{KT}}}$$

$$\boxed{p_o = n_i e^{\frac{E_i - E_f}{KT}}}$$

At certain temperatures in some semiconductors the product of holes and electrons is constant regardless of doping. So for intrinsic levels n_i and p_i

$$\boxed{n_o p_o = n_i p_i = n_i^2}$$

Where we get n_i^2 from the fact that $n_i = p_i$ for an intrinsic semiconductor whose fermi level is about halfway between the conduction and valence bands. If we know the intrinsic carrier level at one temperature, we can find it for the other as

$$\boxed{\frac{n_i(T_1)}{n_i(T_2)} = \left(\frac{T_1}{T_2}\right)^{3/2} e^{\left(\frac{-E_g}{KT_1} + \frac{E_g}{KT_2}\right)}}$$

If $T_1 > T_2$, which shows at high temperatures semiconductors lose doping properties.

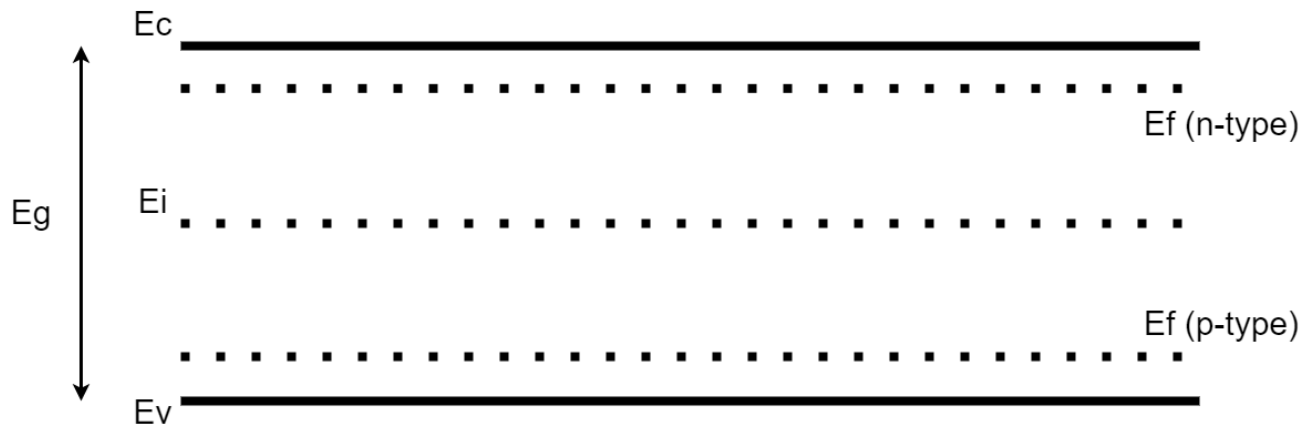

Figure 2.1: Fermi levels of an intrinsic semiconductor (Ei) compared to the shifted levels of doped materials.

2.2.3 Doped Carrier Concentrations

Carriers come from the semiconductor itself (intrinsic) and from dopants. In shallow doping, every atom of dopant releases 1 carrier. The concentrations of each dopant is labeled as N_a for acceptors and N_d for donors. There are two cases to consider:

1. $\boxed{|N_a - N_d| >> n_i \text{ , then majority carrier concentration } \approx |N_d - N_a|}$

2. $\boxed{|N_a - N_d| \approx n_i \text{ , then majority carrier concentration is found by solving charge neutrality equation}}$

2.2.4 Charge Neutrality Equation

When semiconductors are doped the dopants release either a positive or negative charge, and then are ionized as the opposite charge. This means the total material is still electrically neutral, with positive/negative charges being made of ions and carriers. Equating positive and negative gets us

$$N_d + p_o = N_a + n_o$$

When combining this with $n_o p_o = n_i^2$, we can solve the system for the amount of electrons/holes in a semiconductor. End up with quadratic.

Chapter 3

Mobility

3.0.1 Carriers

Electrons have random motion which results from lots of collisions. However when in an electric field, they electrons have a net movement opposite to the field and reaches some terminal velocity because of the collisions. This is described as

$$\boxed{\langle v \rangle = \mu \mathcal{E}}$$

where $\langle v \rangle$ is the average velocity, and μ is the mobility of the carrier.

3.0.2 Conductivity

The definition of Resistance gives us

$$R = \frac{V}{I} = \rho \frac{L}{A} = \frac{L}{A\mathcal{G}}$$

Where ρ is the resistivity of a material and $\mathcal{G}$ is the conductivity, which we can put in terms of semiconducting material

$$\boxed{\mathcal{G} = q\mu_p p_o + q\mu_n n_o = \frac{1}{\rho}}$$

Where q is the charge of an electron (1.6 x 10^{-19}). We can also find the current density, J, as

$$J = \mathcal{G}\mathcal{E}$$

3.0.3 Hall Effect

When a magnetic force is applied to a semiconductor by some $\vec{B}$ field it forces carriers to build up onto one side, creating an electric field that matches the magnetic one.

$$F_E = F_M$$

The carriers available depend on the type of semiconductor; for n-type electrons move and leave behind positive ions, for p-type holes move and leave behind negative ions. These carriers move with a velocity proportional to the applied forces

$$\langle v \rangle \beta = \mathcal{E}_H \ ; \ \langle v \rangle = \mu \mathcal{E}_V$$

Where $\mathcal{E}_V$ is the electric field generated b a test voltage. With a hall voltage proportional to the semiconductor width we get

$$V_H = \mathcal{E}_H W$$

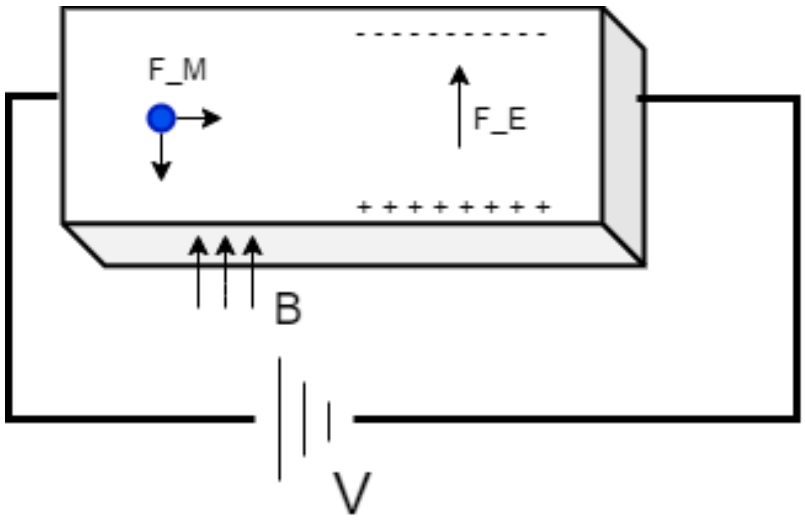

Figure 3.1: Illustrated Hall Effect, with F_E being the electric force and F_M being the magnetic force.

Chapter 4

Excess Carriers

4.0.1 Optical Excitation

The energy of a photon is

$$\boxed{E_{ph} = \frac{ch}{\lambda} = hf}$$

Where h is Planks Constant, λ is the wavelength, c is the speed of light, and f is the frequency. If the energy given is $> E_g$, then photons can excite electrons in a semiconductor, causing them to jump from the valence to conduction band and forming an electron hole pair. Just because the energy is higher than a S.C's bandgap does not mean that every photon is absorbed, the thickness of a material matters. This interaction is described by the following differential equation, where $I(x)$ is the intensity of light as a function of x, the length inside the semiconducting material.

$$\frac{dI(x)}{dx} = -\alpha I(x) \Rightarrow \boxed{I(x) = I_{in}e^{-\alpha x}}$$

I_{in} is the initial intensity of light coming into the semiconductor, and α is the absorption coefficient, a property of a semiconductor. We can use this to find the intensity of light leaving the semiconductor, I_{out}, and then find

$$I_{abs} = I_{out} - I_{in}$$

And the optical generation rate g_{opt}

$$\boxed{g_{opt} = \frac{I_{abs}}{E_{ph} \times t}}$$

Where t is the thickness of the semiconductor.

4.0.2 Carrier Recombination

Electrons can also fall in energy. When this happens the difference in energy is released as either a photon (direct bandgap) or phonon (indirect bandgap). This can occur when falling from the conduction band to valence band, and is called "recombination" because the electron-hole pair is recombined. The recombination rate is given as

$$\boxed{R_{\text{rate}} = \alpha_r \times n \times p}$$

Semiconductor carriers get excited by the temperature in the room as well. This thermal generation rate at steady state has to be equal too the recombination rate $g_T = R_{\text{rate}}$. However when carriers are generated we get a change in the number of carriers from the original level, described as

$$\delta_n(t) = \delta n_0 e^{-t/\tau} \; ; \; \tau = \frac{1}{\alpha_r(n_0 + p + 0)}$$

where the time constant is the "carrier lifetime." If we have constant exposure to light the amount of carriers reaches an equilibrium, and we can find this amount by solving

$$\boxed{\frac{\delta_n^2}{\tau(n_0+p_0)} + \frac{\delta_n}{\tau} - g_{\text{opt}} = 0}$$

If injection is low ($\delta_n << (n_0 + p_0)$) then this can be approximated as $\delta_n = \tau g_{\text{opt}}$. If $\delta_n = \delta_p$, then we can solve for the conductivity as

$$\boxed{\mathcal{G} = \theta_0 + \Delta\mathcal{G} = (q\mu_n n_0 + q\mu_p p_0) + (q\delta_n(\mu_n + \mu_p))}$$

where θ_0 is the non-excited S.C conductivity, and $\Delta\mathcal{G}$ is the change in conductivity due to the optical excitation. Also important to note is that the Fermi level "splits" under optical generation, becoming different for n and p carriers.

4.0.3 Carrier Diffusion

When there is an uneven concentration of carriers inside a system they naturally want to even out. This movement is called carrier diffusion, and makes up part of the total current density of carriers. Other movement is caused by an electric field and is called drift. Combined we get carrier current as a function of distance as follows

$$\boxed{J_n(x) = q\mu_n n(x)\mathcal{E}(x) + qD_n\frac{dn(x)}{dx} \; ; \; J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p\frac{dp(x)}{dx}}$$

$$J(x) = J_n(x) + J_p(x)$$

Where $D_{(n \text{ or } p)}$ are the diffusion coefficients. The first term is due to drift and the second due to diffusion. At equilibrium these two terms have to even out, leading us to Einsteins Relation and giving us the diffusion coefficients

$$\boxed{D_p = \frac{kT}{q}\mu_p \; ; \; D_n = \frac{kT}{q}\mu_n}$$

4.0.4 Diffusion and Recombination

When combining diffusion and recombination the change in carriers is different from both individual cases. At steady state we get a relationship for the change in number of carriers as follows

$$\boxed{\delta_p(x) = \delta_{p_0}e^{\frac{-x}{L_p}} \; ; \; \delta_n(x) = \delta_{n_0}e^{\frac{-x}{L_n}}}$$

Where L_p and L_n are the diffusion lengths, described as

$$\boxed{L_p = \sqrt{D_p\tau_p} \; ; \; L_n = \sqrt{D_n\tau_n}}$$

Chapter 5

PN Junctions

A PN Junction consists of a P-type semiconductor and an n-type semiconductor right next to each other, which is formed through crystal growth or doping.

5.0.1 Static

When a PN Junction is first formed carriers diffuse across both side, leaving behind ions. The donors leaves behind positive ions and the acceptors leave negative ions, leading to a separation of charges and an electric field as shown

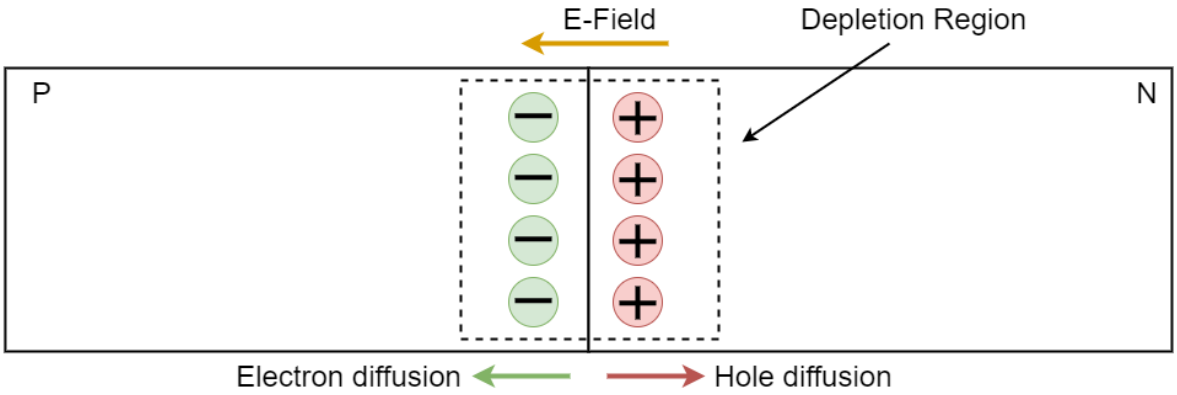

Figure 5.1: The depletion region of a PN junction forming

The diffusion currents oppose the charge flow created by the electric field, eventually leading to an equilibrium and forcing out all charges in between. This region with no charges is called the depletion region. The width of the depletion region depends on the doping levels of the PN junction, and can be found with

$$\boxed{W = \sqrt{\frac{2\epsilon V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}}$$

Where ϵ is the dialectric constant and V_0 is the initial voltage created by ion charge seperation. This voltage can be found with

$$\boxed{V_0 = \frac{KT}{q}\ln\left(\frac{N_a N_d}{n_i^2}\right)}$$

We can find the internal electric field's strength with

$$\boxed{\mathcal{E}_0 = \frac{2V_0}{W}}$$

The charge distribution of the ions in the depletion region can be visualized by a charge vs distance graph. These charges have to be equal on both sides, and this depends on the doping level

$$Q^-_{\text{tot}} = Q^+_{\text{tot}} \Rightarrow X_p N_a = X_n N_d$$

Integrating this gets us the electric field. The area under the electric field is the intial voltage, and the slopes of the graph are proportional to both doping levels.

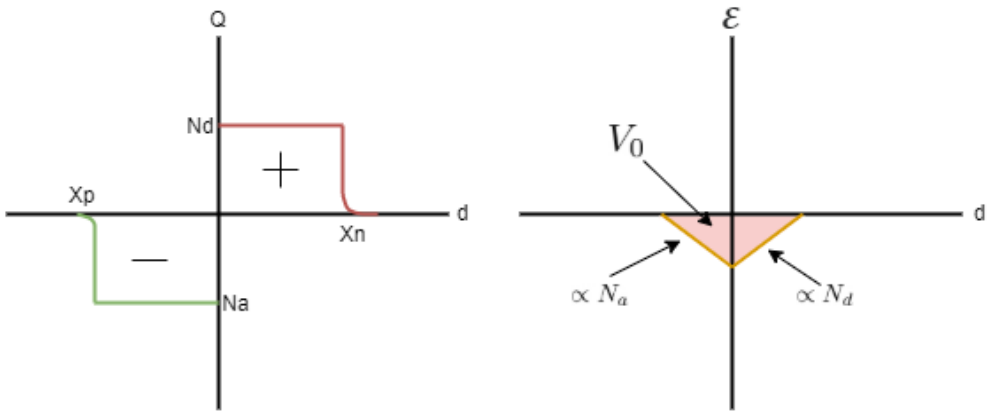

Figure 5.2: Charge distributions inside the depletion region

The depletion region forming also effects how the fermi diagrams look. Initially the fermi levels have a gap; they start at different places for the differently doped material. However as the region forms, the fermi diagram "bends," looking as follows.

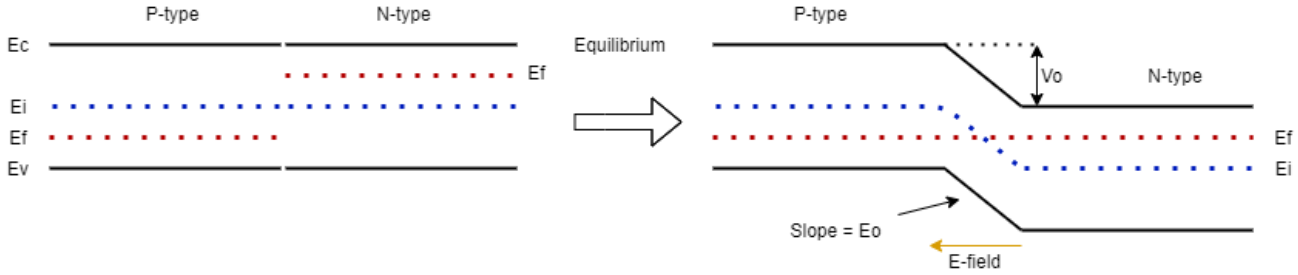

Figure 5.3: Fermi diagram of PN junction

The Fermi level wants to equalize leading to the band diagram bending. As the depletion region forms its electric field causes different energies on the n-side: electrons want to move opposite to the electric field so the energy to conduct drops there; they kind of "roll down" the conduction band from high to low.

5.0.2 Reverse Biasing

If a positive external voltage is applied to a PN junction from N to P, the junction is said to be reverse biased. The electric field caused by this voltage aids the intrinsic electric field across the depletion region,

making it larger and further opposing carrier diffusion. The depletion region widens, and the charge graphs increase because of it. The new width can be calculated as

$$\frac{V_0 + V_r}{V_0} = \frac{W'\mathcal{E}'}{W\mathcal{E}} = \left(\frac{\mathcal{E}'}{\mathcal{E}}\right)^2 = \left(\frac{W'}{W}\right)^2$$

Carriers can still diffuse into or generate in the depletion region and are then swept out by the electric field. This leads to an intrinsic current called the reverse saturation current, calculated as

$$\boxed{I_0 = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)}$$

Breakdown

Breakdown occurs when the the built in electric field reaches a certain level, causing current flow in a reverse biasing scheme. This field is higher for junctions with lower doped material, and vice versa.

Avalance breakdown is when the carriers in the depletion region accelerate to extremely high speeds, ionizing atoms upon impact causing an exponential speedup in electron flow. This happens in lightly doped PN junctions.

Zener breakdown occurs where there is a very narrow depletion region. When this happens electrons can quantum tunnel from valence to conduction band, causing current flow. Usually this is meant to happen, and PN junctions are designed with this effect in mind.

5.0.3 Forward Biasing

If a positive external voltage is applied to a PN Junction from P to N, the junction is said to be forward biased. The electric field caused by this voltage opposes the intrinsic electric field across the depletion region, making it smaller and causing diffusion to occur again. As carriers move through the junction, the voltage source replaces them leading to a steady current flow. A smaller depletion region width leads to changes in the charge distribution graphs; they both become smaller. The new width can be calculated as

$$\frac{V_0 - V_f}{V_0} = \frac{W'\mathcal{E}'}{W\mathcal{E}} = \left(\frac{\mathcal{E}'}{\mathcal{E}}\right)^2 = \left(\frac{W'}{W}\right)^2$$

The current across the junction now increases with the applied voltage. This relationship is shown as

$$\boxed{I = I_0\left(e^{\frac{qV_E}{KT}} - 1\right)}$$

Where V_E is the externally applied voltage, K is the Boltzmann constant, and T is the temperature in Kelvin.

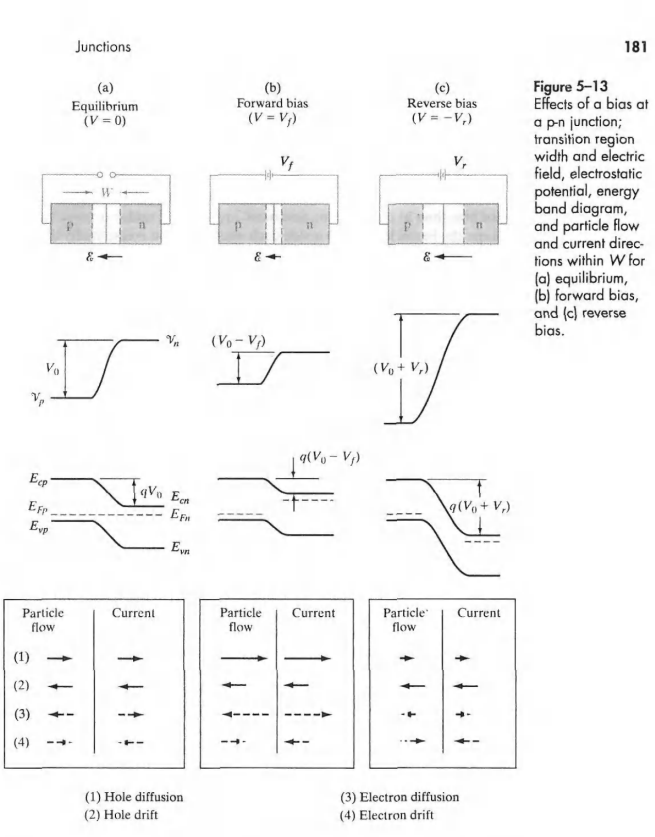

Figure 5.4: PN Junction under different biases

5.0.4 Depletion Region Capacitance

The ions form charges on either side of the depletion region, leading to some capacitance. This can be found as

$$\boxed{C_J = \frac{\epsilon A}{W}}$$

Where A is the cross-sectional area of the junction.

5.0.5 Metal and Shottkey Barriers

Metals can be thought of as very highly doped p-type materials. So when we make contact between a metal and an n-type S.C, a depletion region forms and we get a PN junction like structure. To avoid this interaction, use correct metal with a lower work function or use a very highly doped S.C depletion region to make the depletion size on S.C side low, causing low breakdown.

Chapter 6

Bipolar Junction Transistors

A Bipolar Junction Transistor is a 3-terminal device that acts like a dependent current source. Its structure is composed of three regions of alternately doped material, either NPN or PNP.

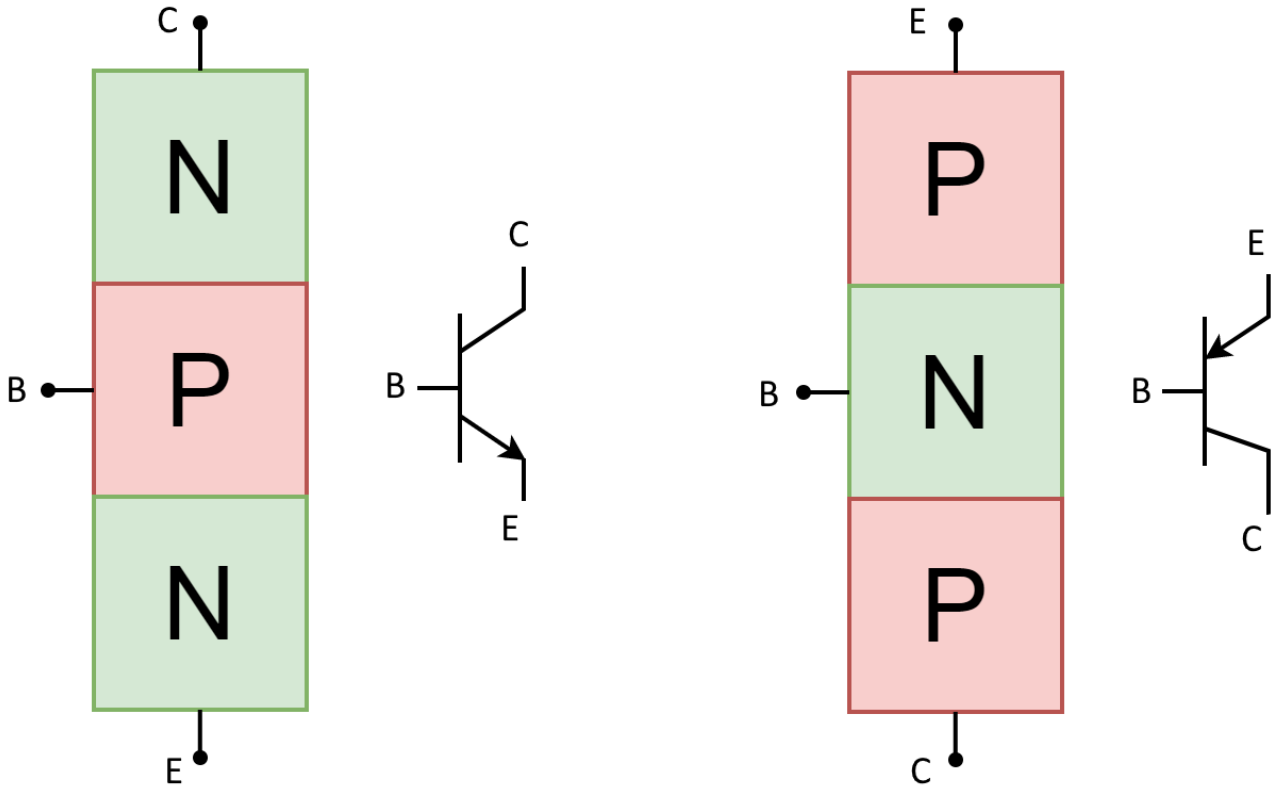

Figure 6.1: PNP/NPN transistors and their circuit symbols

Essentially there are two back-to-back PN junctions.

6.0.1 Active Operation

In normal operation of this transistor we want one PN junction forward biased, and the other reverse biased. For example in an NPN transistor

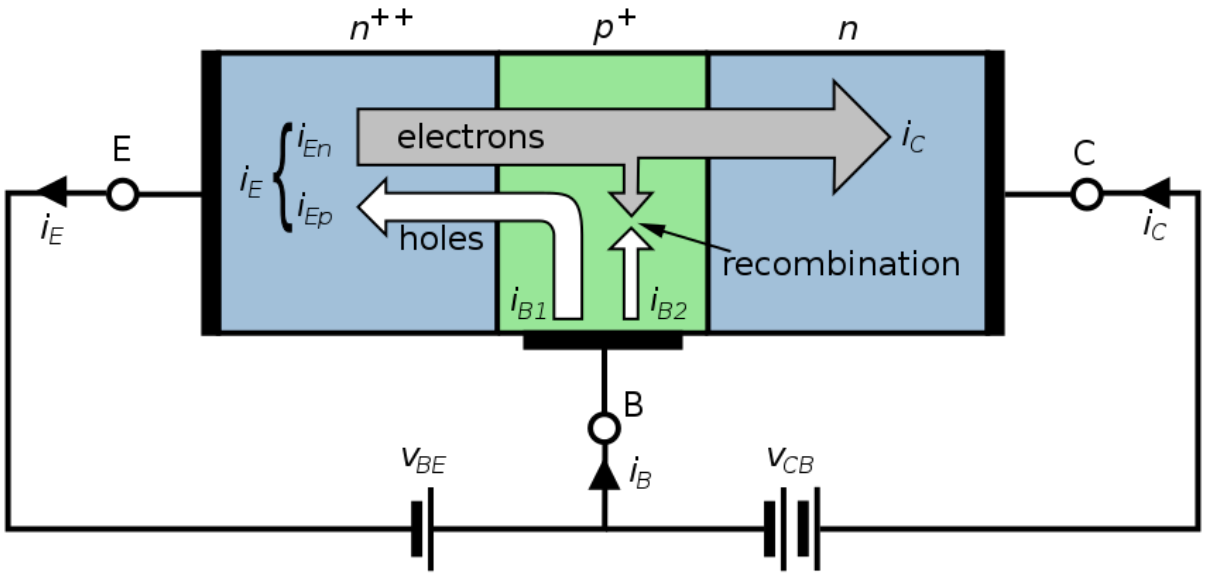

Figure 6.2: NPN BJT in the active region

The BE junction is forward biased, while the BC junction is reverse biased. We dope the E region highly to allow for a large flow of electrons to the base when forward biased. Some of these electrons recombine in the base region, but we make this very narrow to limit this effect. These electrons are then caught in the depletion region field of the reverse biased BC junction and swept out through the collector. The relationship between the collector, base, and emitter currents can be shown as

$$\boxed{I_C = I_S\left(e^{\frac{V_{BE}}{V_T}} - 1\right) = \beta I_B = \alpha I_E}$$

Where β is the current gain, the expression for I_C comes from the PN junction current equation (given by the forward biased BE junction) and $\alpha = \frac{\beta}{\beta+1}$, also called the current transfer rate. We can also write some of these variables in a different way

$$\alpha = \beta\gamma$$

Where γ is the emitter injection efficiency. Ideally we want these characteristics maximized. For β max, we want the base width $<< L_p$. For γ max, we want $\mu_E >> \mu_B$. We can also find γ using some formula (not listed here) that depends on the physical characteristics of each region.

6.0.2 Early Effect

It seems like our collector current is solely dependent on the V_{BE}, giving us a really nice voltage controlled current source; however, this is not exactly how it works. If V_{CE} increases, the depletion region increases as well due to the junction being more reverse biased. Therefore the base region effectively becomes narrower, and β increases. While normally this is what we want, this is happening due to something other than the control signal (V_{BE})!

Chapter 7

Field Effect Transistor

The FET controls current flow through an electric field. Like the BJT it uses interactions between separately doped material to create this effect, however the mechanics work differently. There are different types of FET's, but here we will focus on the Metal Oxide S.C FET.

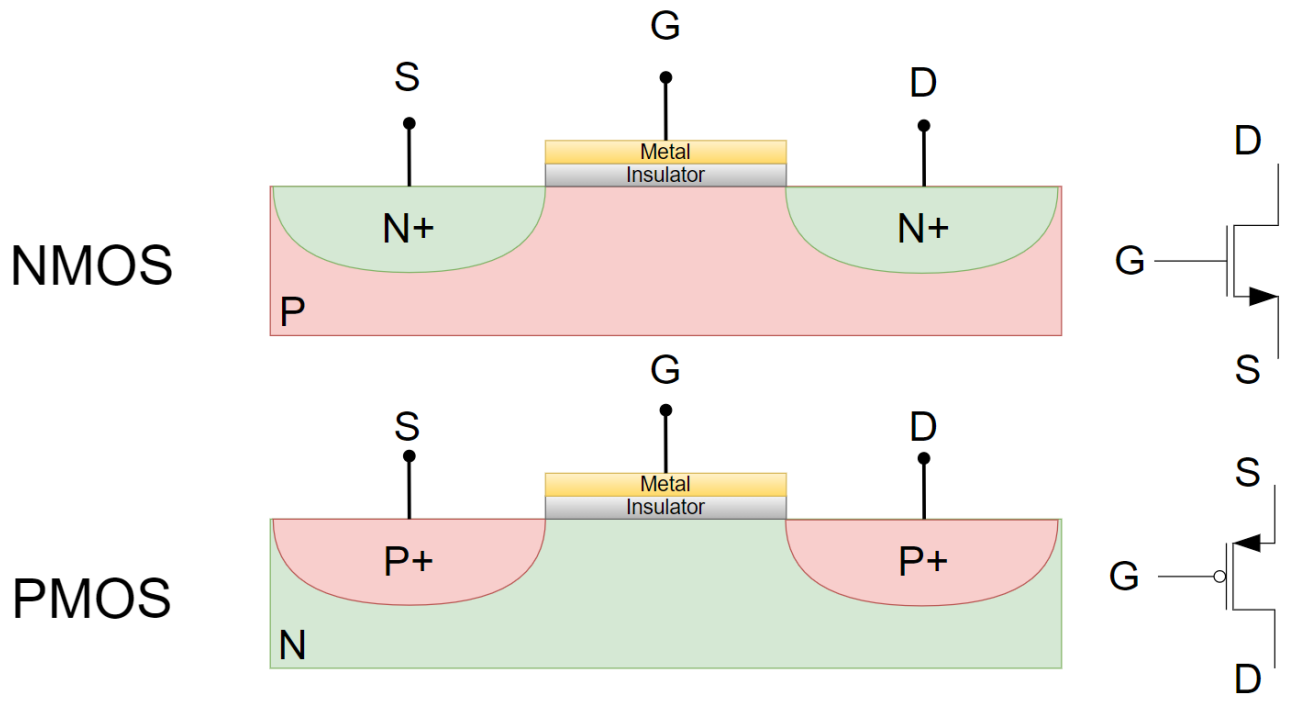

Figure 7.1: NMOS and PMOS structure

7.0.1 Active Operation

Looking at the NMOS, if we apply a positive voltage across the gate with respect to the substrate then the positive charges build up on the metal, repelling holes from underneath the gate region and forming a negatively charged depletion region. If this voltage keeps on increased at some threshold V_T electrons accumulate underneath the gate essentially turning the region into an n-type material. This effect is called inversion, and allows for conduction between the source and drain of an NMOS transistor. A similar effect happens for PMOS; a negative voltage repels electrons and eventually accumulates holes.

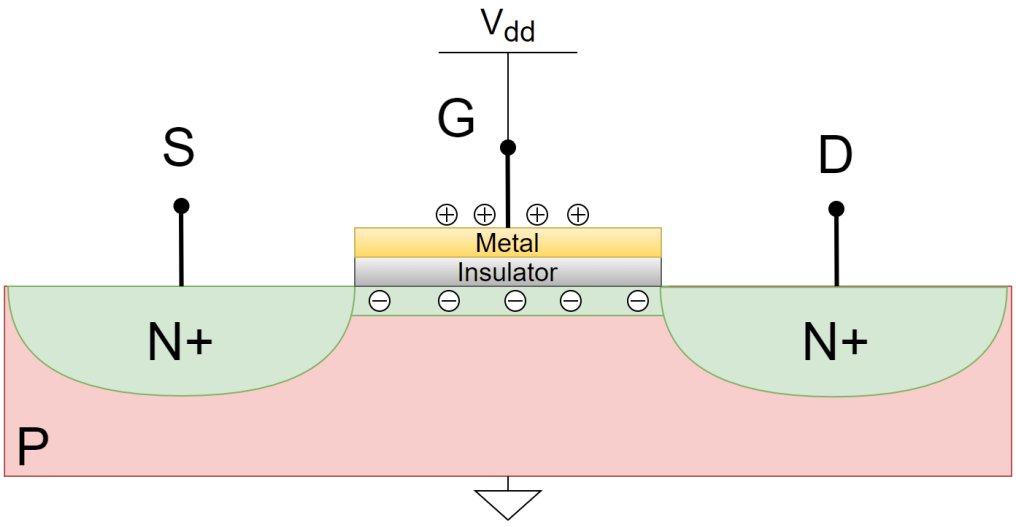

Figure 7.2: Full inversion in an NMOS transistor

However this just gives us a variable resistor. If we now increase the drain voltage the area close to it is at a higher potential. This can take it out of the inversion region, causing the channel to shrink anda depletion region to form. Carriers can stillbe swept along this region, however the current is now controlled by the voltages applied to the NMOS giving a voltage controlled current source.

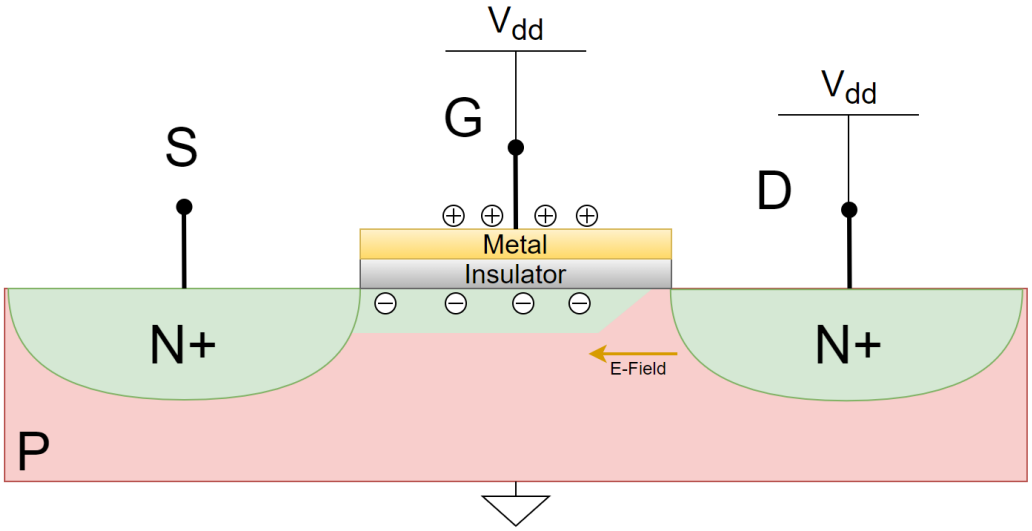

Figure 7.3: NMOS in saturation

Using this principle we can look at the voltages on each of the three terminals to determine what region of operation a MOSFET is in.

Type	On	Linear	Saturation
NMOS	$V_{GS} > V_{TH}$	$V_{GD} > V_{TH}$	$V_{GD} < V_{TH}$
PMOS	$V_{SG} > V_{TH}$	$V_{DG} > V_{TH}$	$V_{DG} < V_{TH}$

Table 7.1: Determining MOSFET region of operation