Introduction to Semiconductor Devices
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Lecture – 4.3
Energy Band diagram of PN Junction

This document is intended to accompany the lecture videos of the course "Introduction to Semiconductor Devices" offered by Dr. Naresh Emani on the NPTEL platform. It has been our effort to remove ambiguities and make the document readable. However, there may be some inadvertent errors. The reader is advised to refer to the original lecture video if he/she needs any clarification.

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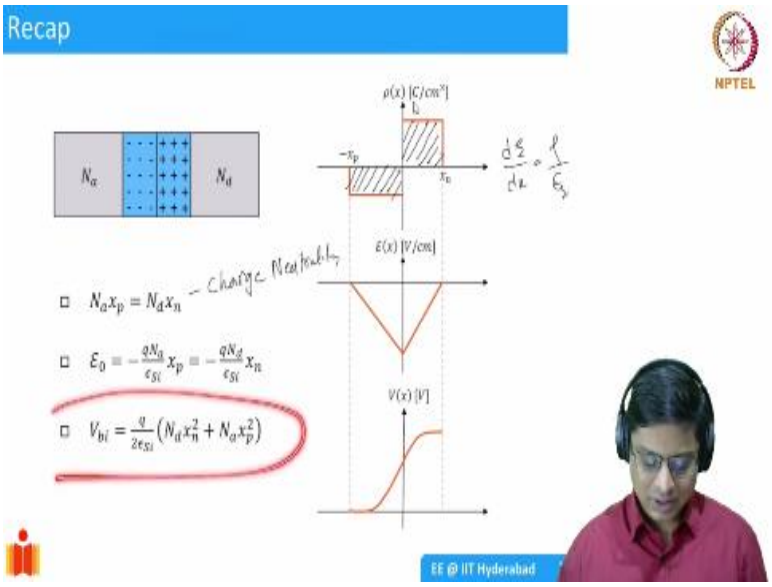

Recap:

We discussed the basic electrostatics of PN junctions. If P type and N type semiconductors are in contact, because of the concentration gradients of holes and electrons respectively, there will be a diffusion of holes and electrons which will leave behind a positively charged space charge here in the N type semiconductor and a negatively charged space charge in the P type semiconductor and named the edge of the depletion regions as x_n and x_p respectively.

Based on Gauss law ($\nabla.D = \rho_v$) as in Eq. (1), the electric field has to be a linear function in x. It has to show a triangular profile (as shown in the above screenshot). And potential is the integral of the electric field.

$$\nabla . E = \frac{dE}{dx} = \frac{\rho_v}{\varepsilon_{si}} \quad (1)$$

$$E = \frac{dV}{dx} \quad (2)$$

Charge neutrality condition is given by

$$x_n N_d = x_p N_A \quad (3)$$

Where in N_a – carrier concentration in the acceptor region (P type), and N_d – carrier concentration in the donor region (N type). When the holes and electrons diffuse, the area on the p side should be equal to the area on the n side. Using the Eq. (2) & (3) obtain the electric field and the potential. Note that the electric field follows triangular profile and the potential follows quadratic function of x.

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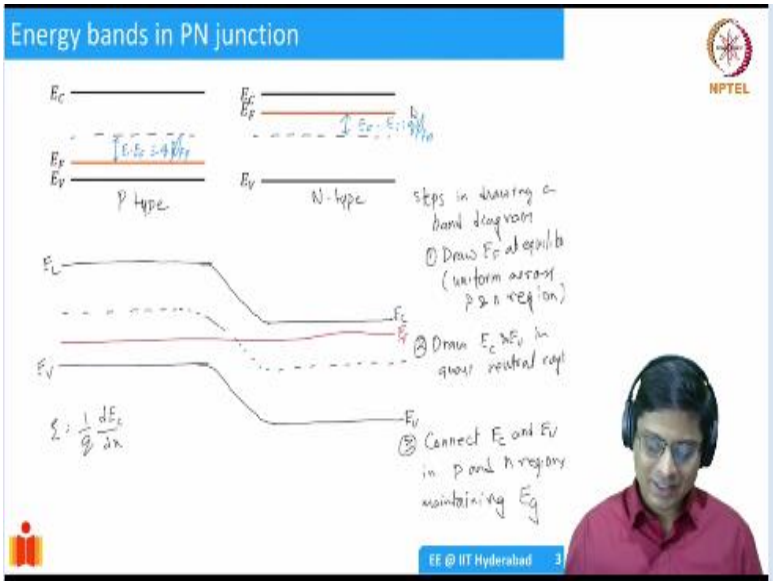

Energy bands in PN junction:

In a PN junction, we have a P type region and a N type region with corresponding doping and has fermi energy (E_F) each. There will be a constant intrinsic fermi energy for both the semiconductors (E_i). The difference in the fermi energy $E_F - E_i$ depends on the fermi potential.

$$E_{Fn} - E_i = q\varphi_{Fn} \quad (4)$$

$$E_i - E_{Fp} = q\varphi_{Fp} \quad (5)$$

At equilibrium, the Fermi level has to be constant and there is no other electric field applied.

Steps in drawing a band diagram:

1. Draw E_i at equilibrium which is uniform across P and N regions. Draw the E_C and E_V Quasi neutral regions that are away from the junction (as shown in the lecture slides).
2. In N region, draw the Fermi level E_F closer to E_C and draw E_V maintaining bandgap. In P region, the Fermi level has to be close to the valence band E_V.
3. Connect the E_C and E_V on both the regions maintaining E_g (material property), thus the band structure looks like in the lecture slide.

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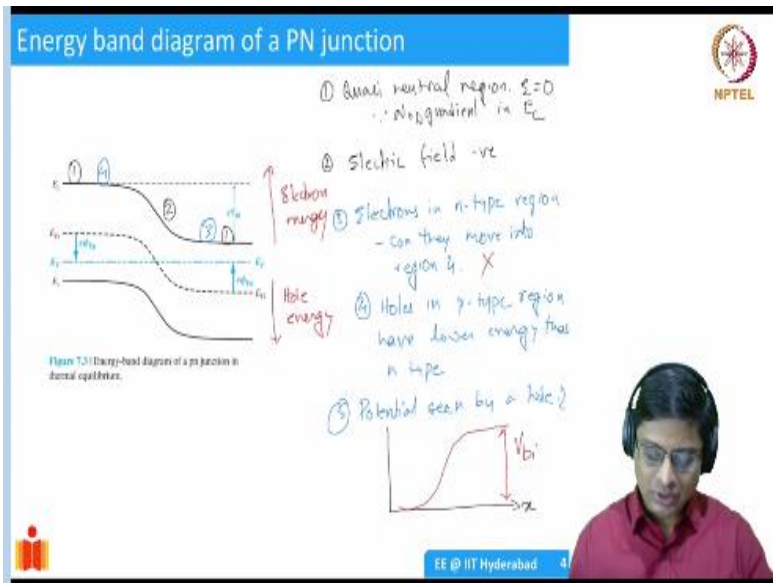

Energy band diagram of a PN junction:

At thermal equilibrium, the energy band diagram of a PN junction is divided into mainly 4 regions.

a. Region 1: Quasi-neutral region. The electric field is zero in this region as there is no gradient in E_C or E_V.
b. Region 2: Depletion region, the electric field is negative as going in –ve x-direction. As we go towards higher energies, electron energy increases and if lower energies, hole energy increases.
c. Region 3, 4: N-type & P-type semiconductor regions. Since the region 4 is at higher energy, there are no transitions from region 3 to region 4. In region 4, holes in P type

region have lower energy than N type and holes stay in the P-type region. Hence there is an energy barrier and not able to go into higher energy regions.

Across the junction, the height of the barrier is known as built in potential (V_{bi}).

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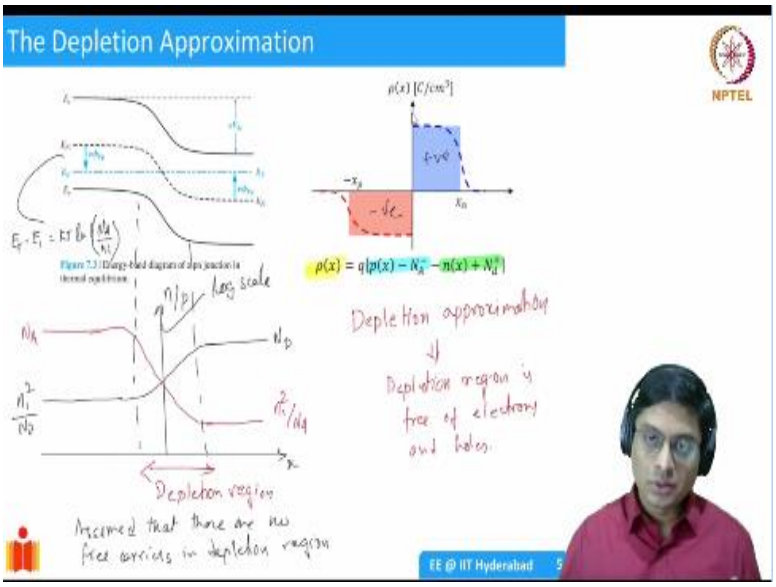

Depletion Approximation:

In the depletion approximation, assume that, the depletion region is free of electrons & holes and the built in potential 'V_{bi}' is calculated across it.

$$E_{ip} - E_F = q\varphi_{Fp} = kT \ln \frac{N_a}{n_i} \tag{6}$$

$$E_F - E_{in} = q\varphi_{Fn} = kT \ln \frac{N_d}{n_i} \tag{7}$$

The carrier concentration field (electron and hole) profiles are shown in the lecture slide (log scale n/p vs position x). On the P-side region, the majority carriers are holes equal to the acceptor doping concentration N_a and the minority carriers are electrons and equal to n_i^2/N_a. Whereas on the N-side region, the majority carriers are electrons and equal to the donor doping concentration N_d and the minority carriers are holes and equal to n_i^2/N_d. In the depletion region or towards the junction, the distance between E_F and E_i is reducing and sweeping, thus there is a smooth variation across the junction.

Note: Since we assume depletion approximation, the values obtained are very close to the approximated values, but not exact, as we have to consider total charge into account. Because it is difficult to solve the equations analytically, if we don't consider approximation. A demo has been shown in the other lecture.

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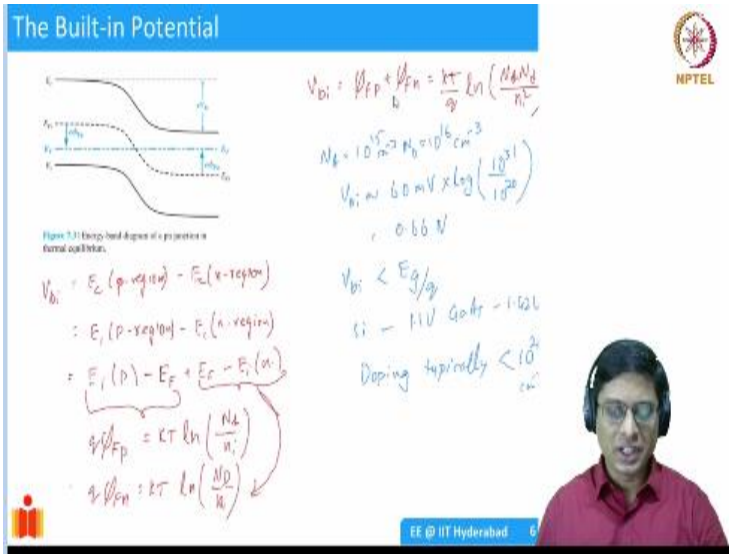

$$qV_{bi} = E_{Cp} - E_{Cn} = E_{ip} - E_{in} = E_{ip} - E_F + E_F - E_{in} \quad (8)$$

$$V_{bi} = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2} \quad (9)$$

At room temperature for a silicon PN junction with n_i~1.5x10^{10} cm^{-3}, $V_{bi} \sim 60\ mV * \ln \frac{N_a N_d}{n_i^2}$ and assume N_a=10^{15} cm^{-3} , N_d=10^{16} cm^{-3}, then V_{bi}~0.66 V.

In case of identical semiconductors, the E_F is continuous and there is no built in potential because there is no junction formed.

The maximum built in potential in any PN junction is equal to the bandgap of the material. This can be obtained by changing the EF closer to the E_V (E_C) on P(N) side. For example, in any Silicon based PN junction, the maximum built in voltage is 1.1 V.

$$qV_{bi} \leq E_g \quad (10)$$

The maximum doping density can be in the orders of 10^{20} cm^{-3}, the rate of Fermi level approaching the band maxima or minima is slowed down. (The reason is the carrier concentrations appear in the log term and there is a small change in the E_F). We assumed that dopants, donors and acceptors are completely ionised so far in this lecture, in this course. If we

go for higher concentrations, the donors and acceptors are not fully ionised. Only some of them are ionised and the ionisation fraction reduces as you go to higher concentrations.

The density of silicon atoms is $5x10^{22}$. If you introduce 10^{20} dopants, essentially, we have one dopant in about 500 atoms which is a lot of doping density and effectively the properties of silicon itself are changed. So, for those reasons, we typically do not prefer to have very high doping.

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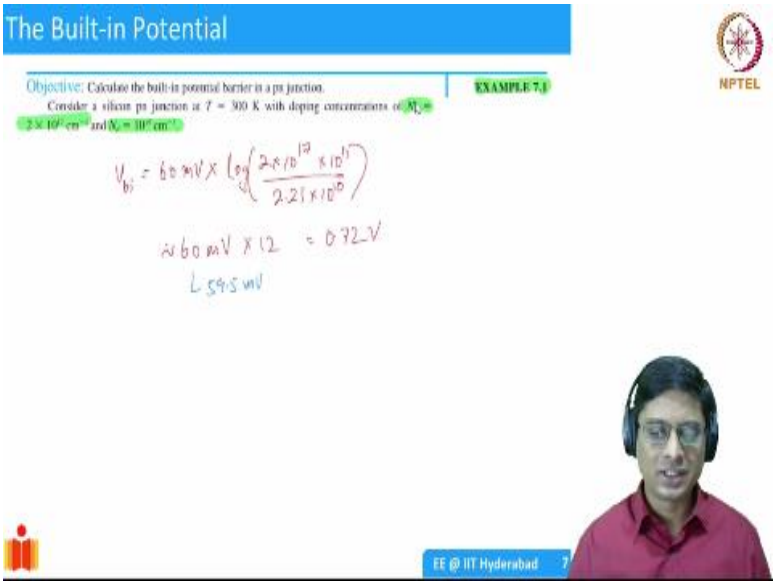

For example, from the textbook problem (refer to example 7.1) calculate the approximate built in potential in the PN junction, which is approximately 0.72 V.

In the next module, will discuss about how to calculate the depletion rates and electric fields.