

Lecture 5: Junctions in semiconductors

- Applications of semiconductor devices
- Junctions in semiconductors
- Poisson's Equation
- P-N Junctions:
 - Depletion region
- Example of an unbiased junction

Device requirements: Shopping list

- How can our knowledge of the basic physical phenomena associated with semiconductors be exploited produce (understand) electronic devices?
- Modern devices are required to do:
 - **Information reception/detection**: Semiconductor diodes, transistors and photo detectors serve the role of detecting signals of various kinds.
 - **Information amplification**: Information received from a device may be weak – the signal must be amplified. Bipolar and field effect transistors are extremely useful devices because they are capable of large gain.
 - **Information manipulation**: May involve addition, multiplication or logic decisions such as AND, OR etc. Specialist input/output relationships (high 1 or low 0 for digital applications). Devices must have high gain and a non-linear response.

Device requirements: Shopping list

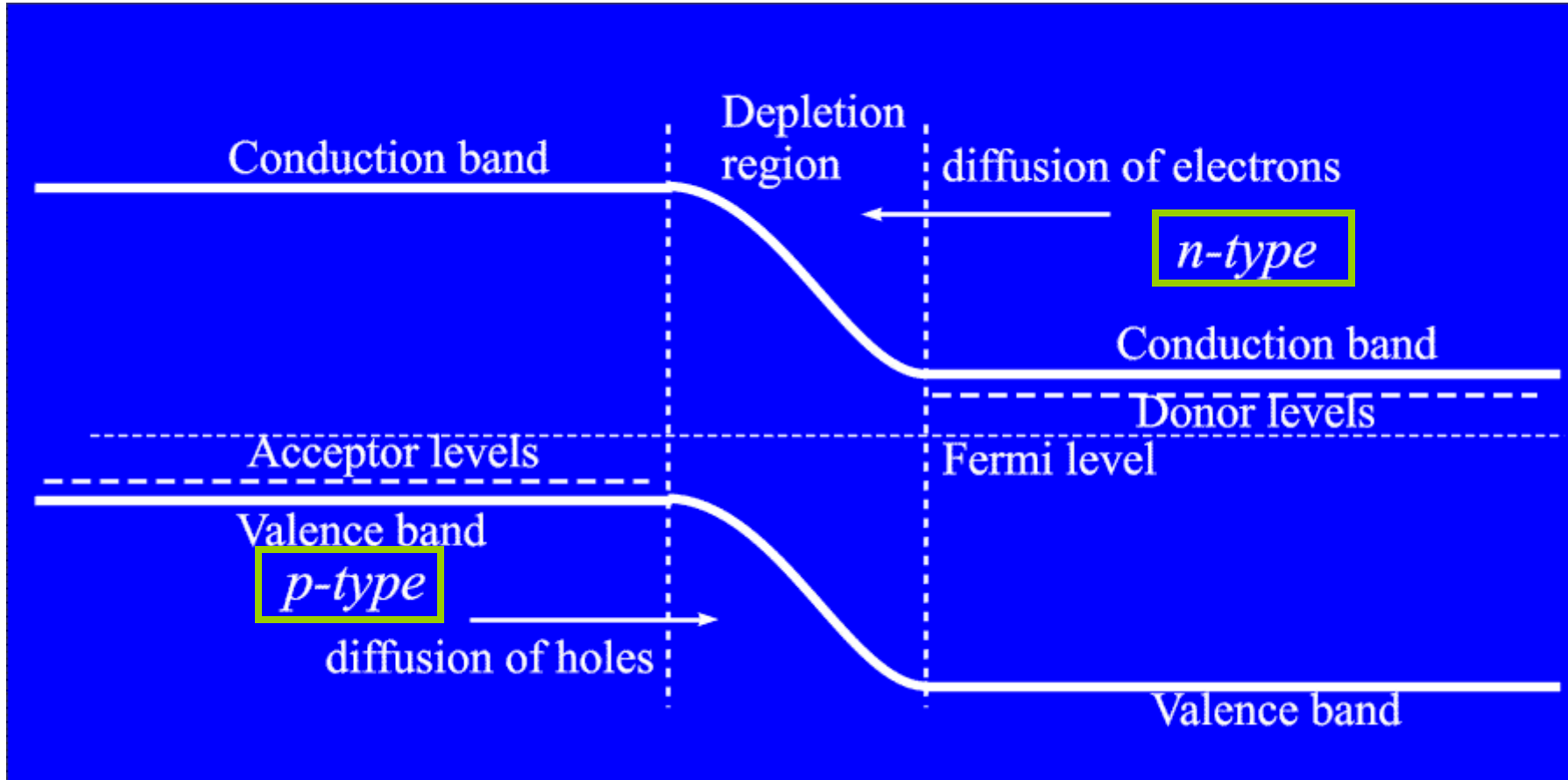
- Modern devices are required to:
 - **Store Information**: Semiconductor memories based on transistors are much faster than magnetic tapes and disks. Rapid cost decreases in the former are increasing market share.
 - **Information Generation**: Take a stream of incoming information and generate an outgoing stream of electronic or optical information. Microwave devices and semiconductor lasers are examples of semiconductor devices that are being used to generate information.
 - **Information Display**: Semiconductor devices such as light-emitting diodes are important devices in the display market.

The need for junctions

- Electric properties of semiconductors can be altered by doping, however we have no ability to instantaneously alter the state of a device.
- If we can use the conductivity of the device, by rapidly changing its value we can define a state.
- An important requirement of good devices is non-linear response. The **rectifying** response is a good example, the flow is easy in one direction and difficult in the other.
- Semiconductors become useful when instead of having a uniform chemical composition, they have spatially non-uniform compositions.
- The idea of a junction is introduced. The most important junction is the **p-n junction**.

- Used as a device in applications as rectifiers, waveform shapers, lasers, detectors etc.
- It forms a key part of the bipolar transistor, one of the most important electronic devices.
- In a p-n junction the nature of the dopants is altered across a boundary to create a region that is p-type next to a region that is n-type.
- Questions:
 - What are the carrier distributions for electrons and holes in the material?
 - What are the physical processes responsible for current flow in the structure when a bias is applied?

The unbiased P-N junction



The unbiased P-N junction

- Three major regions can be identified:
 - **The p-type region**: The material is neutral and the bands are flat. The density of acceptors balances the density of holes.
 - **The n-type region**: Neutral material where the density of donor exactly balances the electron density.
 - **The depletion region**: The bands are bent and a field exists that removes the mobile carriers, leaving negatively charged acceptors in the p-type region and positively charged donors in the n-type region.
- The depletion region, extends a distance W_p and W_n in the p and n regions respectively – an electric field exists.
- A drift current exists that counterbalances the diffusion current, which arises because of the difference in electron and hole densities across the junction.

The unbiased P-N junction

- To describe the junction properties, knowledge of the width of the depletion region, the charge distribution of electrons and holes and the electric field is required.
- Analytical results can be obtained only if some simplifications are made:
 - The physical junction is abrupt and each side uniformly doped.
 - While the mobile charge density in the depletion region is not zero, it is much smaller than the background fixed charges.
 - In order to solve the Poisson equations the assumption is the mobile carrier density is zero – called the depletion approximation.
 - The transition between the bulk neutral n or p-type region and the depletion region is abrupt
- It is necessary us to identify all the current components flowing in the device

The unbiased P-N junction

- There is an **electron drift current** and **electron diffusion current** as well as the hole drift and hole diffusion current.
- When there is no applied bias, these currents cancel each other individually. The hole current density is:

$$J_p(x) = e \left[\underbrace{\mu_p p(x) E(x)}_{\text{drift}} - \underbrace{D_p \frac{dp(x)}{dx}}_{\text{diffusion}} \right] = 0$$

- The drift current density in the depletion region is really $ep(x)v_s(x)$ and independent of E , where v_s is the saturated velocity.
- The field in the depletion region is very large even under equilibrium.

The unbiased P-N junction

- The ratio of μ_p and D_p is given by the Einstein relation:

$$\frac{\mu_p}{D_p} = \frac{e}{k_B T}$$

- As a result of bringing the p and n type semiconductors, a built-in voltage, V_{bi} is produced between the n and the p side of the structure. The built in potential is given by:

$$eV_{bi} = E_g - (E_c - E_F)_n - (E_F - E_v)_p$$

- Where n and p refer to the two sides of the junction.
- With a little rearrangement it can be shown that:

$$V_{bi} = \frac{k_B T}{e} \ln \left(\frac{n_n p_p}{n_i^2} \right)$$

The unbiased P-N junction

- If n_n and n_p the electron densities in the n-type and p-type regions, the law of mass action ($np = \text{constant}$) says:

$$n_n p_n = n_p p_p = n_i^2$$

- Thus, the built in potential $V_{bi} = V_n - V_p$:

$$V_{bi} = \frac{k_B T}{e} \ln \frac{p_p}{p_n}$$

$$V_{bi} = \frac{k_B T}{e} \ln \frac{n_n}{n_p}$$

- The width of the **depletion region** can be determined once we have knowledge of the impurity concentration.
- In the depletion region, the mobile carrier density of electrons and holes is very small compared to the fixed background charge.

- For a p - n junction **Poisson's equation** allows us to determine the value of the potential $\phi(r)$ at any point inside the diode.

$$\nabla^2 \phi(r) = -\frac{\rho(r)}{\epsilon}$$

- Where $\rho(r)$ is the net charge density:

$$\rho(r) = e \cdot n$$

- n is the impurity concentration defined as the difference between the density of donors N_d and the density of acceptors N_a . In one dimension:

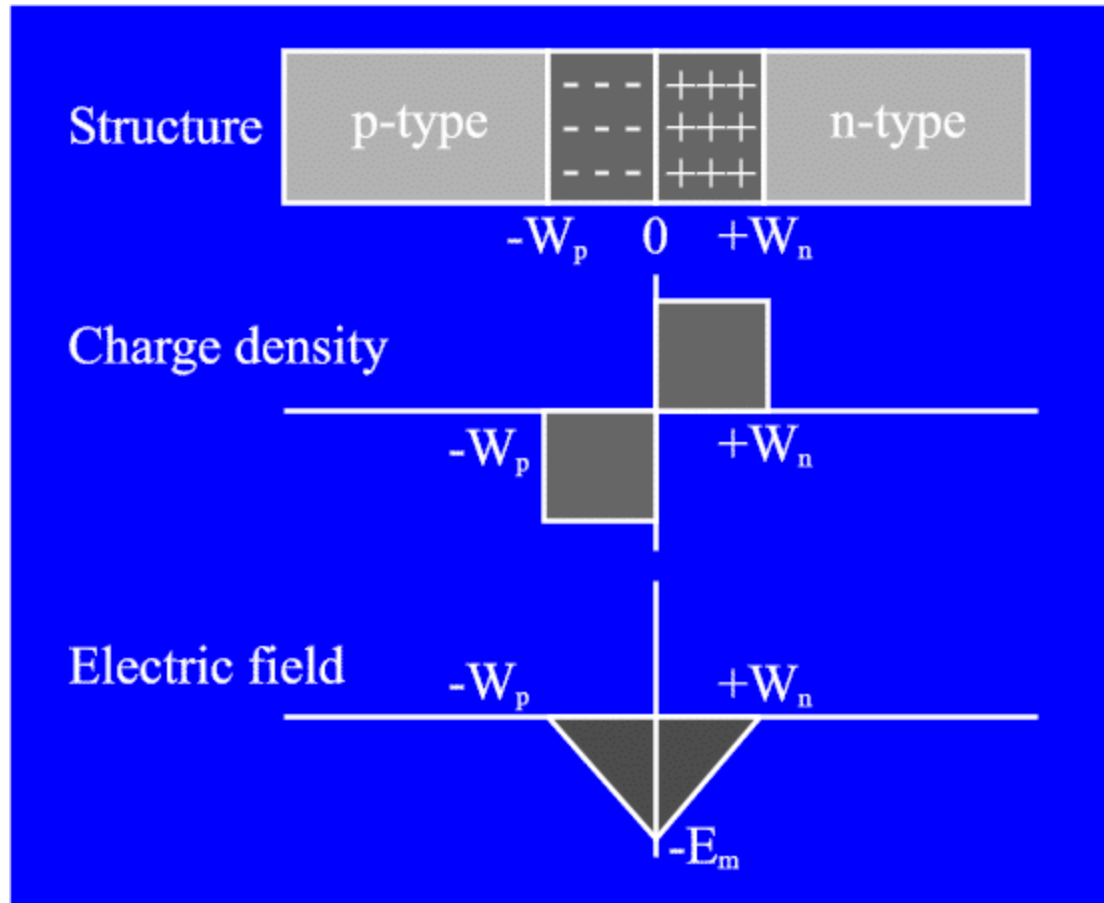
$$\frac{d^2 \phi}{dx^2} = -\frac{\rho(x)}{\epsilon}$$

- Now the shape of the potential across the junction can be obtained by twice integrating the charge distribution profile $\rho(x)$.

The unbiased P-N junction

- The Poisson equation for the depletion region is:

$$\frac{d^2V(x)}{dx^2} = \frac{e}{\epsilon} (N_a - N_d)$$



The unbiased P-N junction

- For the abrupt junction shown on the previous slide, the free carriers are totally depleted so that Poisson's equation simplifies to:

$$\frac{d^2V(x)}{dx^2} = +\frac{eN_a}{\epsilon} \quad -W_p < x < 0$$

$$\frac{d^2V(x)}{dx^2} = -\frac{eN_d}{\epsilon} \quad 0 < x < W_n$$

- The overall charge neutrality of the semiconductor requires that the total negative space charge per unit area in the p-side must equal the total positive space charge per unit area in the n-side:

$$N_a W_p = N_d W_n$$

- The total depletion width W is given by:

$$W = W_p + W_n$$

The unbiased P-N junction

- The electric field shown is obtained by integrating the Poisson's equations:

$$E(x) = -\frac{dV}{dx} = -\frac{eN_a(x + W_p)}{\epsilon} \quad -W_p < x < 0$$

$$E(x) = -E_m + \frac{dV}{dx} = \frac{eN_D(x - W_n)}{\epsilon} \quad 0 < x < W_n$$

- E_m is the maximum field that exists at $x=0$ given by:

$$E_m = -\frac{eN_D W_n}{\epsilon}$$

- Integrating the electric field over the depletion region gives the built-in potential

$$V_{bi} = \frac{eN_D W_n^2}{2\epsilon} + \frac{eN_a W_p^2}{2\epsilon} = \frac{1}{2} E_m W$$

The unbiased P-N junction

- The total depletion layer as a function of the built in potential can hence be written:

$$W_p(V_{bi}) = \sqrt{\frac{2\varepsilon V_{bi}}{e} \left[\frac{N_d}{N_a(N_a + N_d)} \right]}$$

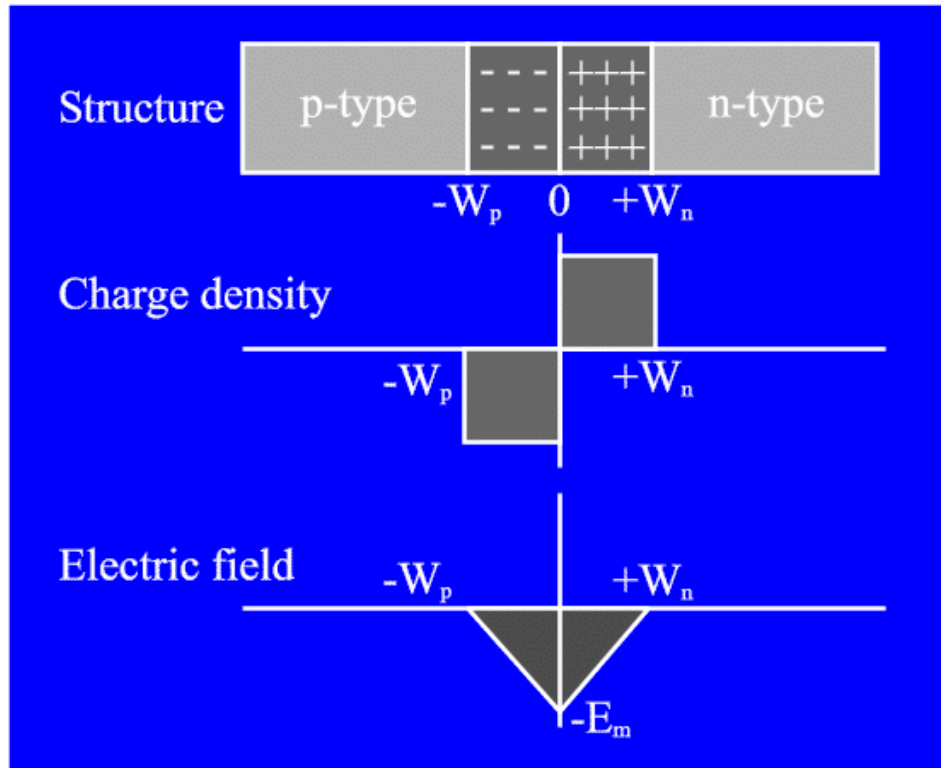
$$W_n(V_{bi}) = \sqrt{\frac{2\varepsilon V_{bi}}{e} \left[\frac{N_a}{N_d(N_a + N_d)} \right]}$$

- And so:

$$W(V_{bi}) = \sqrt{\frac{2\varepsilon V_{bi}}{e} \left[\frac{N_a + N_d}{N_a N_d} \right]}$$

- Important conclusions:
 - **The electric field in the depletion region peaks at the junction and decreases linearly towards the depletion region edges.**
 - **The potential drop in the depletion region has a quadratic form.**

The unbiased P-N junction



The electric field is non-uniform in the depletion region, peaking at the junction.

The depletion in the p and n sides can be different. If $N_a \gg N_d$, the depletion width W_p is much smaller than W_n .

In such abrupt junctions the depletion region exists mainly on the lightly doped side.

Example: Unbiased silicon diode

- An n-type substrate (doping density $N_d=10^{16}\text{cm}^{-3}$) has an indium contact diffused to form a p-type region doped at 10^{18}cm^{-3} . Assuming an abrupt junction and $N_c=2.8\times 10^{19}\text{cm}^{-3}$ and $N_v=1\times 10^{19}\text{cm}^{-3}$ at 300K calculate:
 - Calculate the Fermi level positions in the p- and n-regions.
 - Determine the contact potential.
 - Calculate the depletion widths on the p- and n-side.

Example: Unbiased silicon diode

- The position of the Fermi levels can use any of the equivalent expressions:

$$n_n = n_i \exp\left[\frac{-(E_{Fi} - E_{Fn})}{k_B T}\right] \quad \text{or } n_n = N_c \exp\left[\frac{-(E_c - E_{Fn})}{k_B T}\right]$$

$$p_p = n_i \exp\left[\frac{-(E_{Fi} - E_{Fp})}{k_B T}\right] \quad \text{or } p_p = N_v \exp\left[\frac{-(E_v - E_{Fp})}{k_B T}\right]$$

- $n_n = N_d$; $p_p = N_a$ total free electrons (holes) in conduction (valence) band; n_i, N_c, N_v are the intrinsic carrier concentration, conduction band effective density of states and valence band effective density of states

Example: Unbiased silicon diode

- Calculate the Fermi levels:

$$\begin{aligned}E_{Fn} &= E_c + k_B T \ln \frac{n_n}{N_c} \\ &= E_c - (0.026\text{eV}) \times 7.937 \\ &= E_c - 0.206\text{eV}\end{aligned}$$

$$\begin{aligned}E_{Fp} &= E_v - k_B T \ln \frac{p_p}{N_v} \\ &= E_v + (0.026\text{eV}) \times 2.3 \\ &= E_v + 0.06\text{eV}\end{aligned}$$

- The built-in potential is given by:

$$\begin{aligned}eV_{bi} &= E_g - (E_c - E_F)_n - (E_F - E_v)_p \\ &= E_g - 0.06 - 0.206\text{eV} \\ &= 1.1 - 0.06 - 0.206 \\ &= 0.834\text{eV}\end{aligned}$$

Example: Unbiased silicon diode

- The depletion width on the p-side is given by:

$$W_p(V_{bi}) = \left\{ \frac{2\epsilon V_{bi}}{e} \left[\frac{N_d}{N_a(N_a + N_d)} \right] \right\}^{1/2}$$

$$W_p(0.834) = \left\{ \frac{2 \times 11.9 \times 8.85 \times 10^{-12} \text{ F/m} \times 0.834}{1.6 \times 10^{-19}} \left[\frac{10^{22} \text{ m}^{-3}}{10^{24} \text{ m}^{-3} \times (1.01 \times 10^{24} \text{ m}^{-3})} \right] \right\}^{1/2}$$

$$= 3.2 \text{ nm}$$

$$W_n(V_0) = 0.32 \mu\text{m}$$

- The depletion width on the n-side this therefore 100 times longer.

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