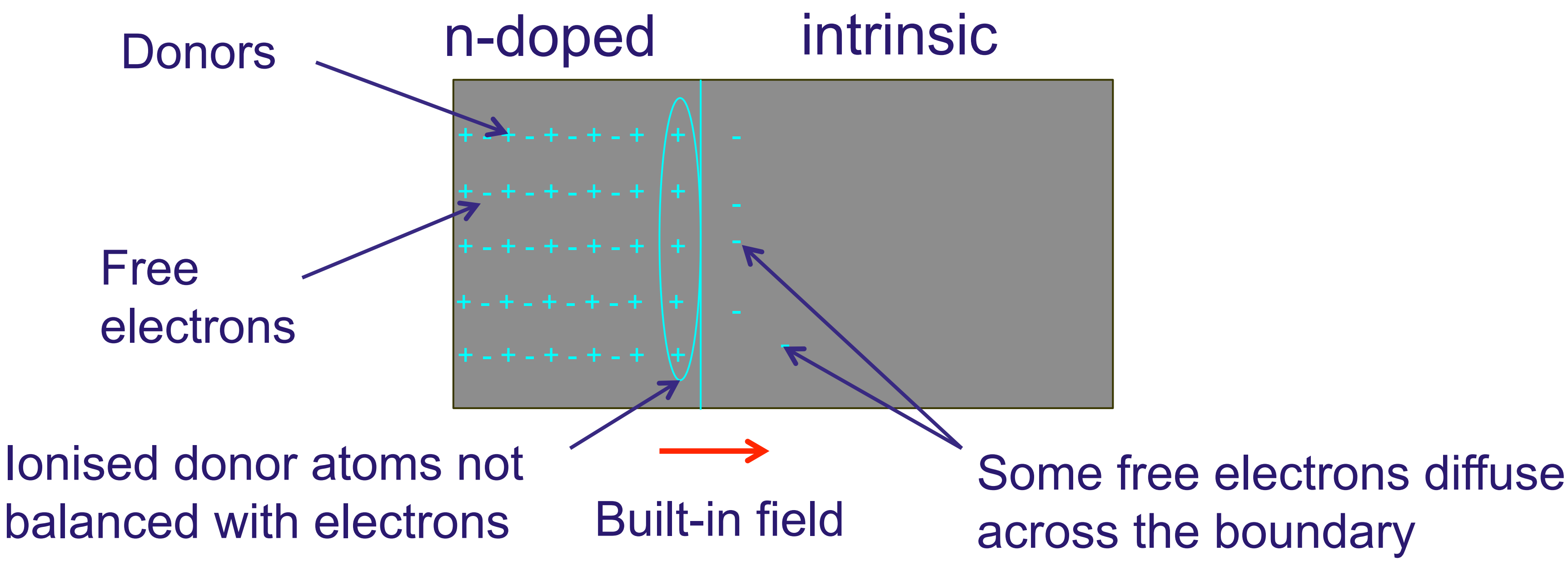
Lecture 10

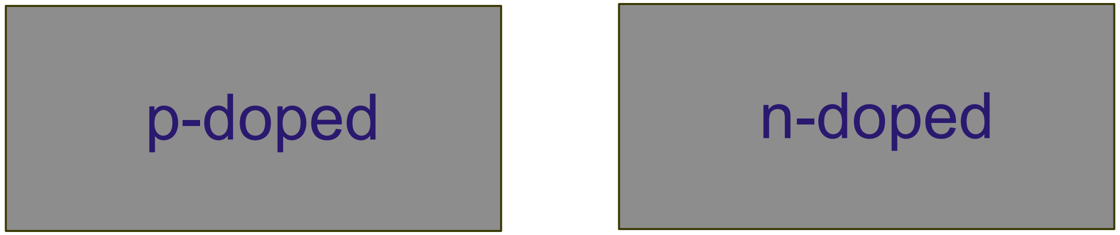
- p-n Junction (diode)
  - Bringing together n and p doped material
- Built in Potential
  - Derivation
- Band Structure p-n junction

Built-in field - first look at n-type in contact with intrinsic

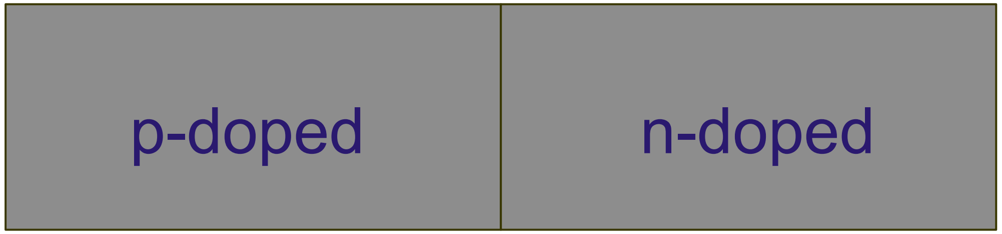


- Free electrons from the n-doped region diffuse into the un-doped region
- A built-in electric field is set up to counter this and establish equilibrium

Bringing Two Blocks of Semiconductor into contact (p-n junction)



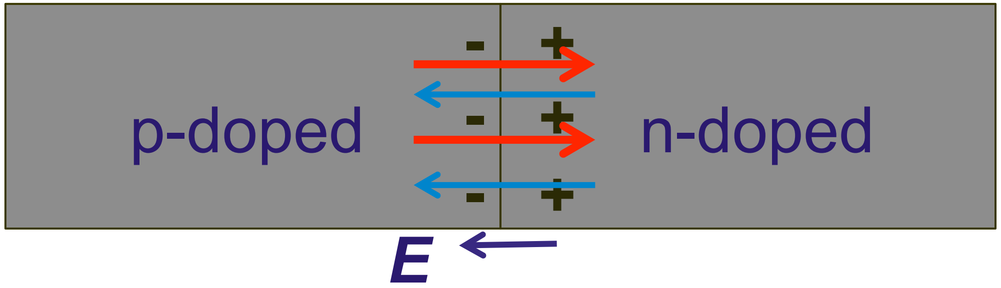
2 isolated n and p doped blocks (constant doping in each) of semiconductor



Bring them into contact – we now have a non-uniform carrier concentration at the junction of the two - what happens?

J must be zero….

- we cannot have any net current since there is no circuit



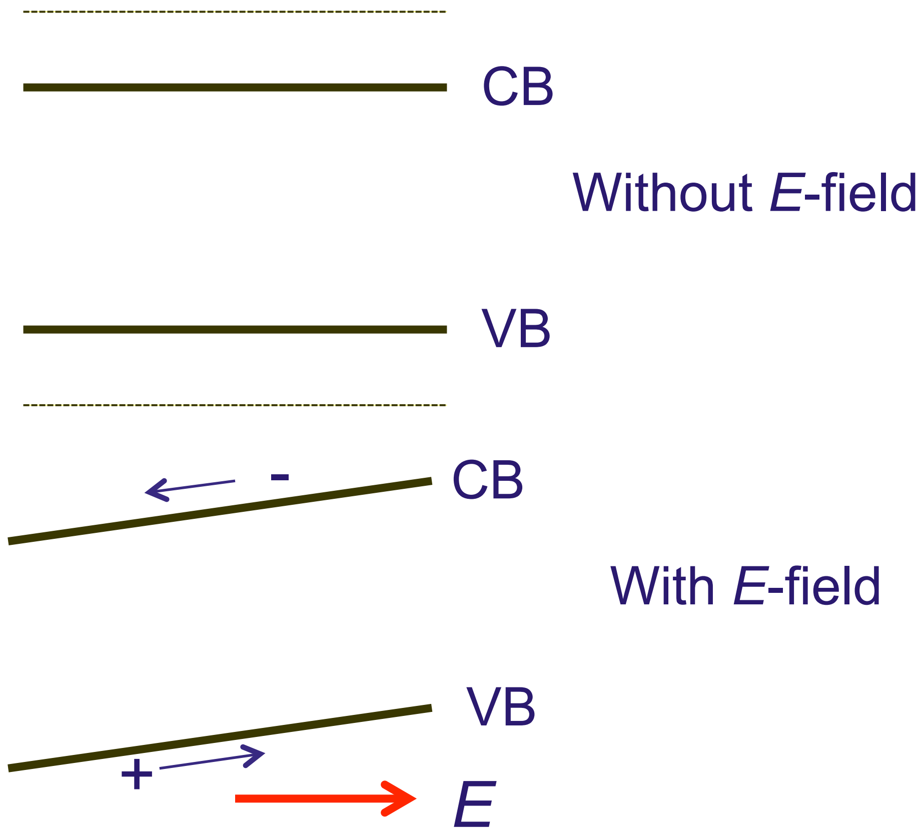
- Initially diffusion will occur, holes (red arrows) – L to R, electrons (blue arrows) – R to L
- Fixed dopant atoms near the interface form a ‘space charge’
- An electric field must be generated to oppose the diffusion and create a drift current which is equal and opposite to the diffusion current i.e. net $J = 0$ – note that the ‘built-in’ field direction opposes both electron and hole diffusion current
- This electric field will appear as a built-in potential, V_0, within the junction
- We will now calculate the magnitude of V_0 and see what factors influence it….

Energy Band Picture of Electric Fields

Instead of drawing energy bands as before we can consider only the edges

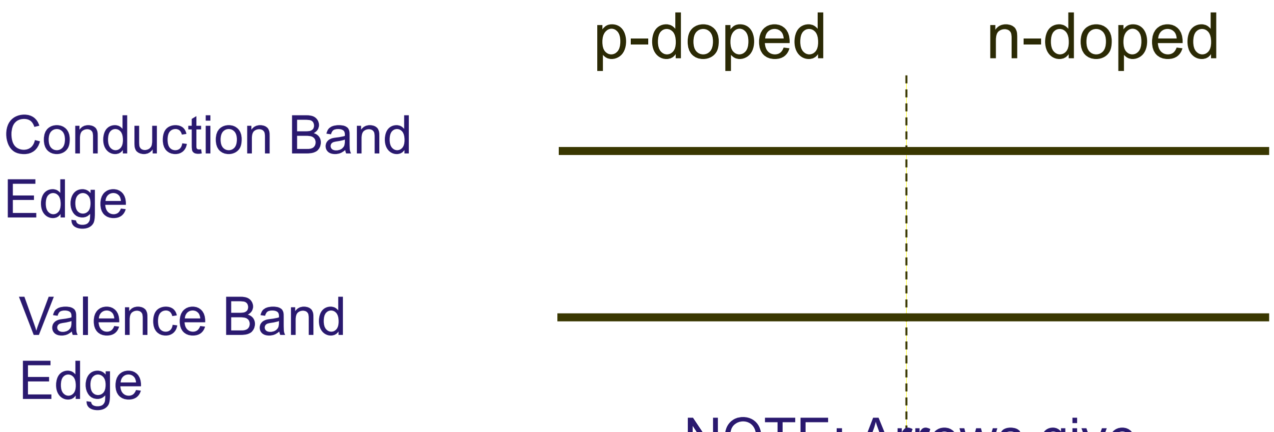
Conduction Band (CB)
Bottom Edge

Valence Band (VB)
Top Edge



- E-field results in a slope in CB and VB
- Electrons move ‘downhill’
- Holes move ‘uphill’

Returning to PN Junction - assume no internal field yet



NOTE: Arrows give current direction

$$J_h^{diffusion}$$

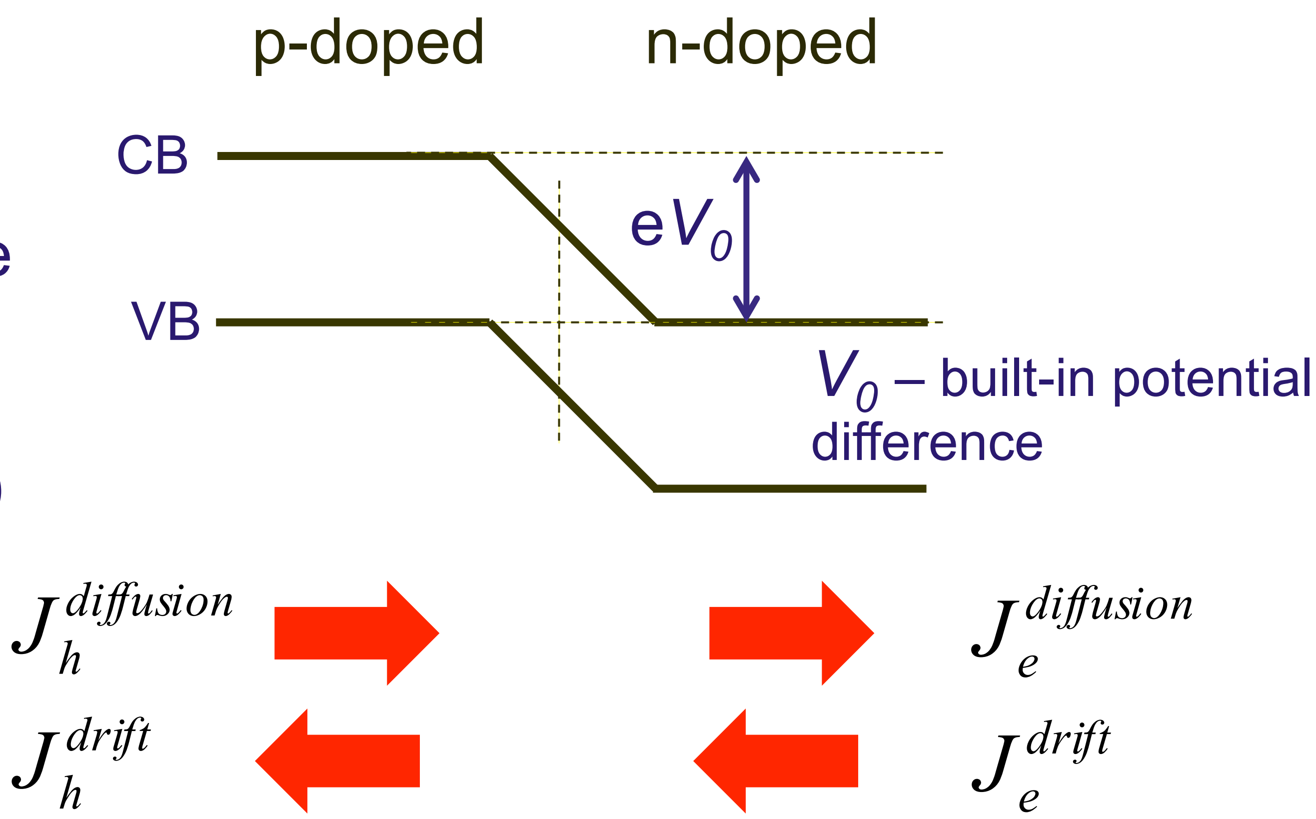
$$J_h^{drift} = 0$$

$$J_e^{diffusion}$$

$$J_e^{drift} = 0$$

Built-in Field at the Junction

Built-in field is established to exactly balance the drift and diffusion currents (J = 0)



Free Carrier Diffusion

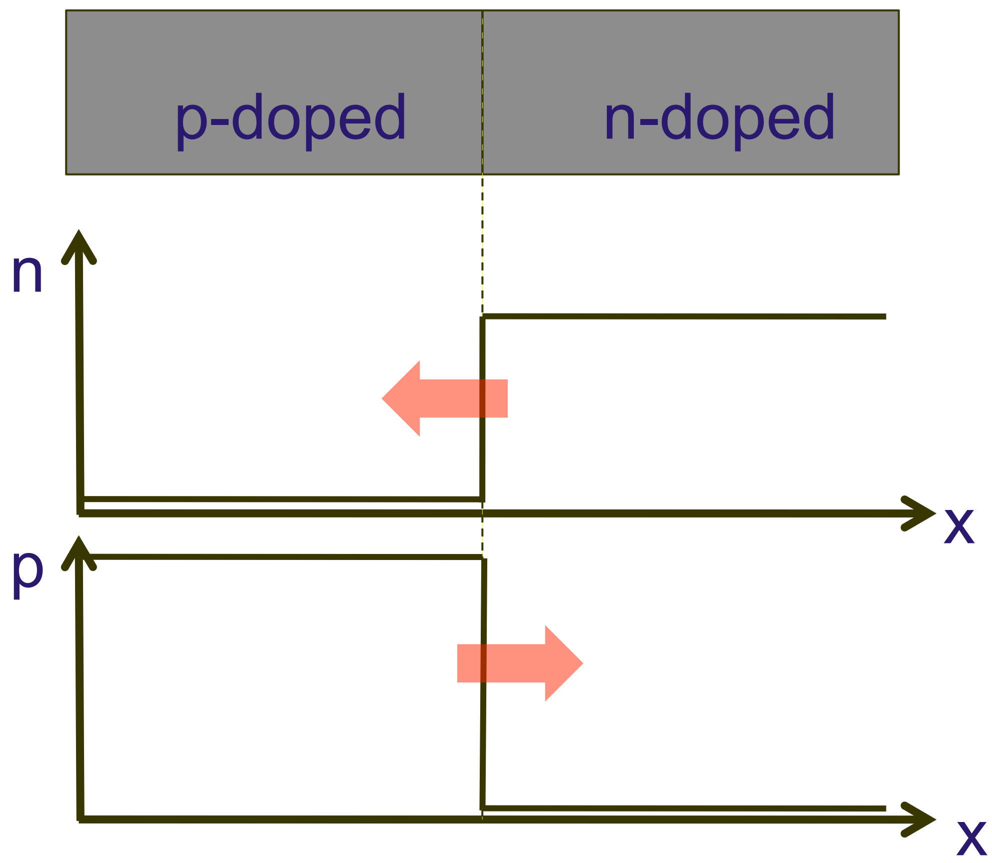
(Just after connection)

• Holes diffuse into n-material where they are minority carriers and recombine with electrons

• The holes leave behind ionized (-ve) acceptors in p-region

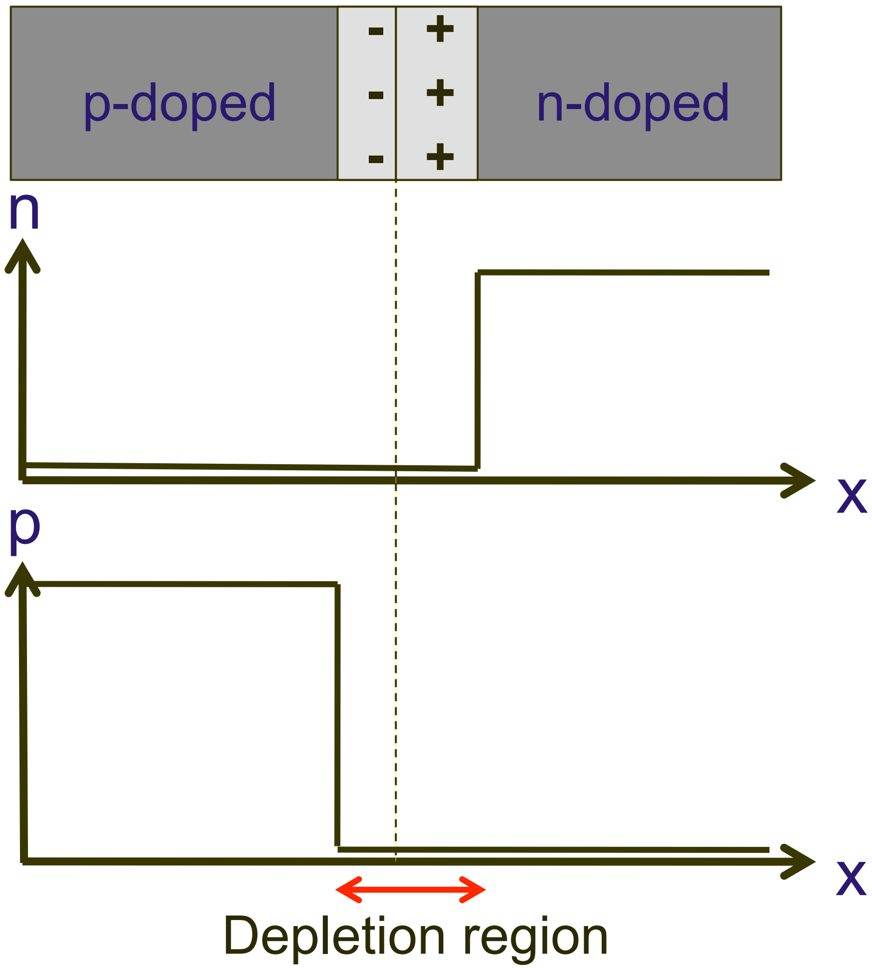
• Similar behaviour for electrons

• Get *depletion* of free carriers at junction



Depletion Region

- Electron diffusion right to left (current left to right)
- Hole diffusion left to right (current left to right)
- At equilibrium there must be no net current so an ***E***-field is generated
- Results in a potential difference V_0 between n and p regions



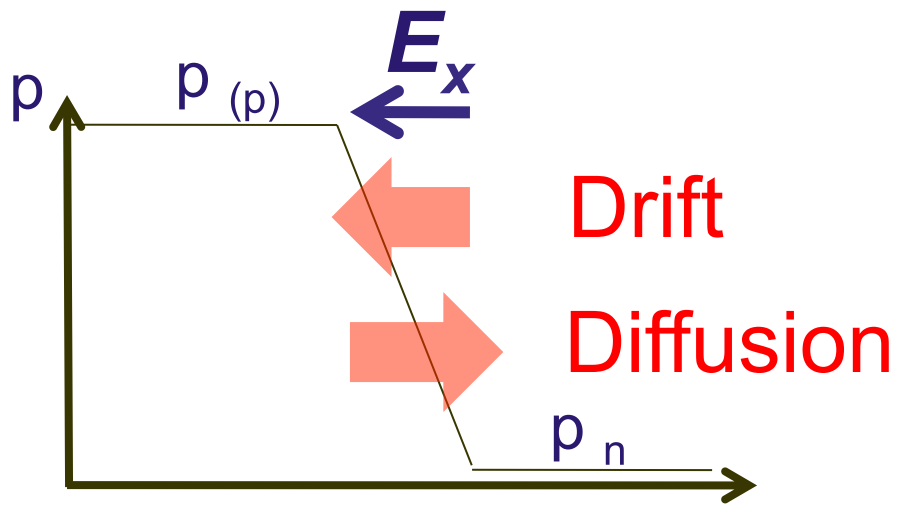
V_0 - consider holes

From discussion on drift and diffusion

$$J_h^{total}(x) = J_h^{drift} + J_h^{diffusion} = e\mu_h E_x p - eD_h \frac{dp}{dx} = 0$$

Rearranging

$$E_x = \frac{D_h}{\mu_h p} \cdot \frac{dp}{dx}$$



Note: in this example *dp/dx* is negative

V_0 Continued..

Recall Einstein relationship for diffusion coefficient $$D_h = \frac{k_B T}{e} . \mu_h$$

Gives $$E_x = \frac{k_B T}{e} . \frac{1}{p} . \frac{dp}{dx}$$

Remember that $$V = -\int E. \, dx$$

Combining these gives $$V_0 = -\frac{k_B T}{e} \int_{p_{(p)}}^{p_n} \frac{dp}{p}$$

Integration yields $$V_0 = \frac{k_B T}{e} ln\left(\frac{p_p}{p_n}\right)$$

Same analysis gives for electrons $$V_0 = \frac{k_B T}{e} ln\left(\frac{n_n}{n_p}\right)$$

V_0 Continued (2)..

Remembering

$$n_i^2 = n_p p_p \quad \Rightarrow \quad V_0 = \frac{k_B T}{e} ln\left(\frac{p_p n_n}{n_i^2}\right)$$

All terms are known, or can be calculated

T = Temperature
p_p = acceptor doping density
n_n = donor doping density
n_i = intrinsic carrier density

V_0 Continued (3)..

Which terms are dominant ?

Rearranging $$V_0 = \frac{k_B T}{e}\left[ln\left(p_p n_n\right) - ln\left(n_i^{\,2}\right)\right]$$

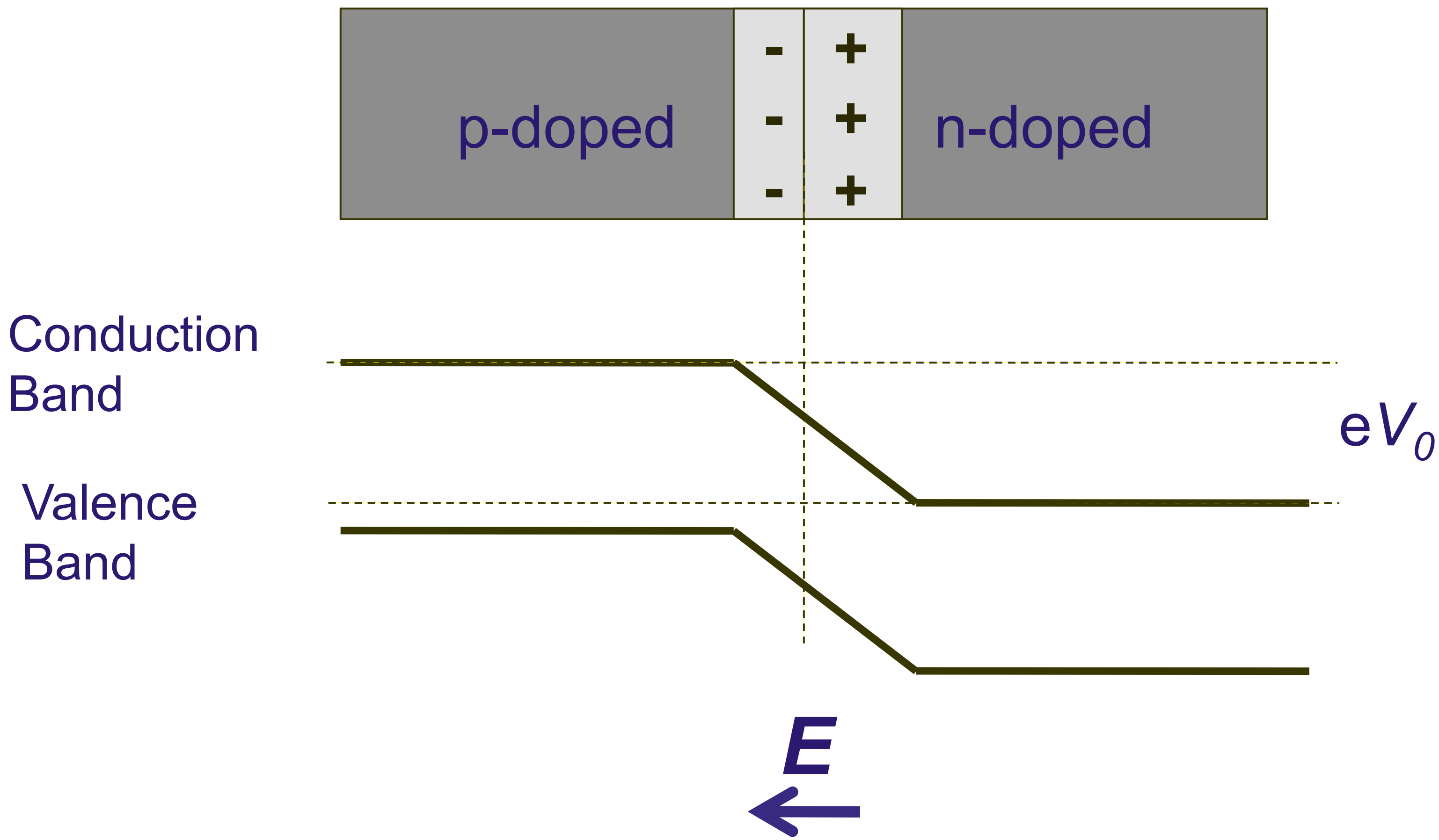
Substituting for n_i $$V_0 = \frac{k_B T}{e}\left[ln\left(p_p n_n\right) - ln\left(CT^{3/2}\right)^2 + \frac{W_g}{k_B T}\right]$$

$$V_0 = \underbrace{\frac{k_B T}{e}\left[ln\left(p_p n_n\right) - ln\left(CT^{3/2}\right)^2\right]}_{} + \frac{W_g}{e}$$

Small compared to band-gap energy term, W_g/e

This means $eV_0 \approx W_g$

Band Structure picture



Summary

- In a p-n junction electrons and holes will diffuse across the junction and recombine as minority carriers
- The acceptor and donor ions are left behind and cannot move
- In equilibrium the diffusion and drift currents must result in no net current
- An *E*-field is formed to exactly balance the currents
- There is a built in voltage, V_0, in the junction
  - This is an internal barrier to current flow
  - We cannot measure this directly at the terminals

Summary (2)

- The built in voltage expressed as eV_o is close to the band-gap energy, W_g
- The temperature dependence of the built in voltage comes from the temperature dependence of the band-gap

