EEE105 "Electronic Devices"

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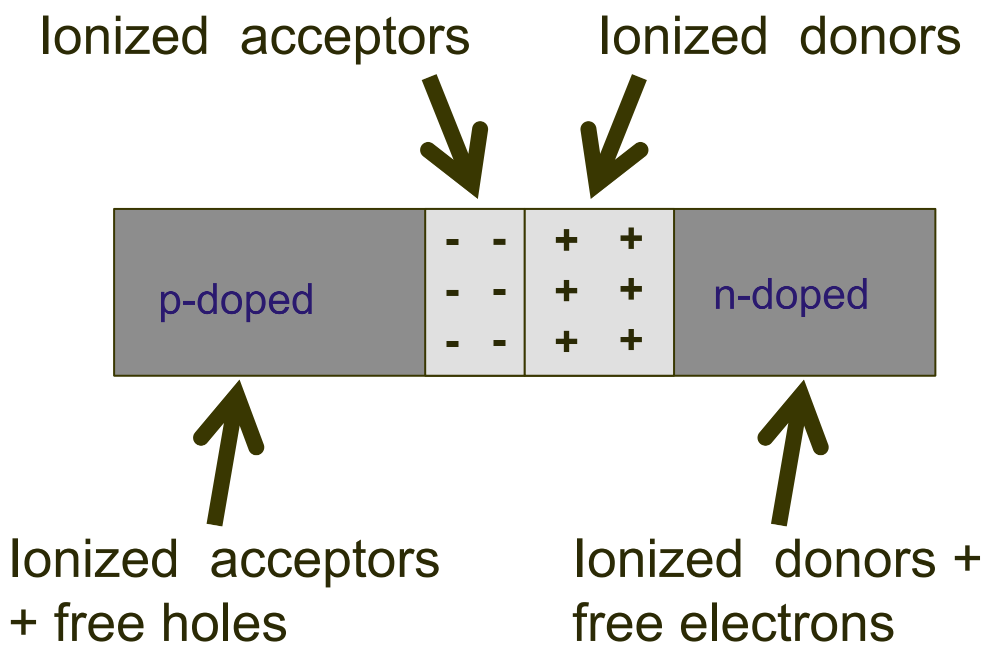
Lecture 13

- Poisson's Equation
- Space charge at the Junction
  - Depletion width
- Disturbing the equilibrium - qualitative
  - p-n junction under zero, forward, reverse bias

Fuller Picture



To fully understand a p-n junction we have to consider blocks of distributed charge – the ionized acceptors and donors

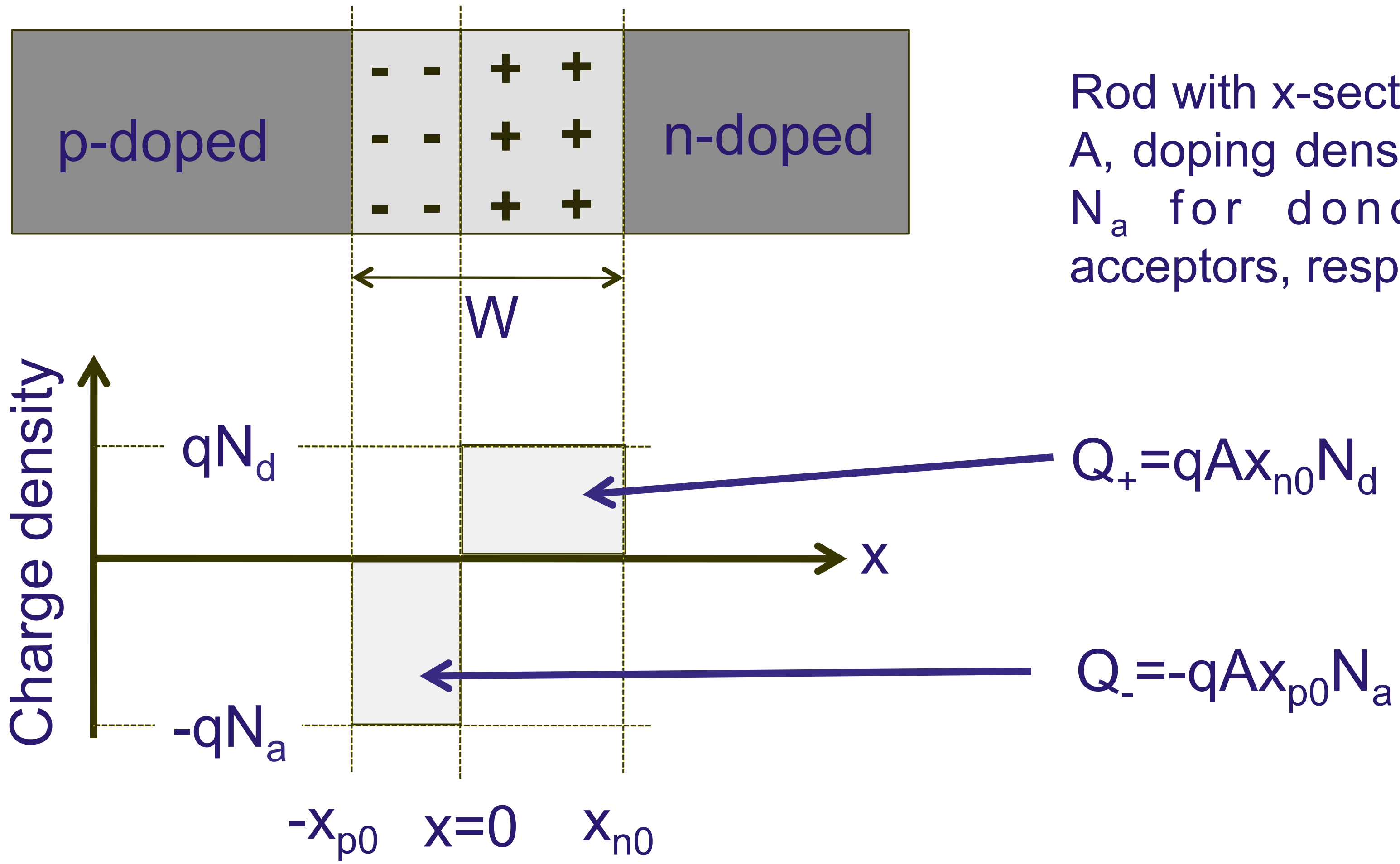
E-Fields – Distributed Charge

- Poisson's equation relates electrostatic potential to charge density (see EEE220)
- In 1D Poisson's equation states $$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon}$$
- As $E = -\dfrac{dV}{dx}$ We can rewrite this as $$\frac{dE}{dx} = \frac{\rho}{\varepsilon}$$

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

- Rate of change of electric field with distance is governed by ρ, the mean charge density and ε the permittivity

Space Charge at a Junction



Rod with x-sectional area A, doping densities of N_d N_a for donors and acceptors, respectively.

Space Charge at a Junction

Assume neutrality outside W

Neglecting carriers within the depletion region charge density is governed by ionized dopants (assume all ionized at room temp)

Total net charge in depletion region is zero

$$qAx_{p0}N_a = qAx_{n0}N_d \quad \text{and} \quad W = x_{p0} + x_{n0}$$

-Extent of depletion in doped regions depends on relative doping levels

Equal doping levels → equal depletion depths,

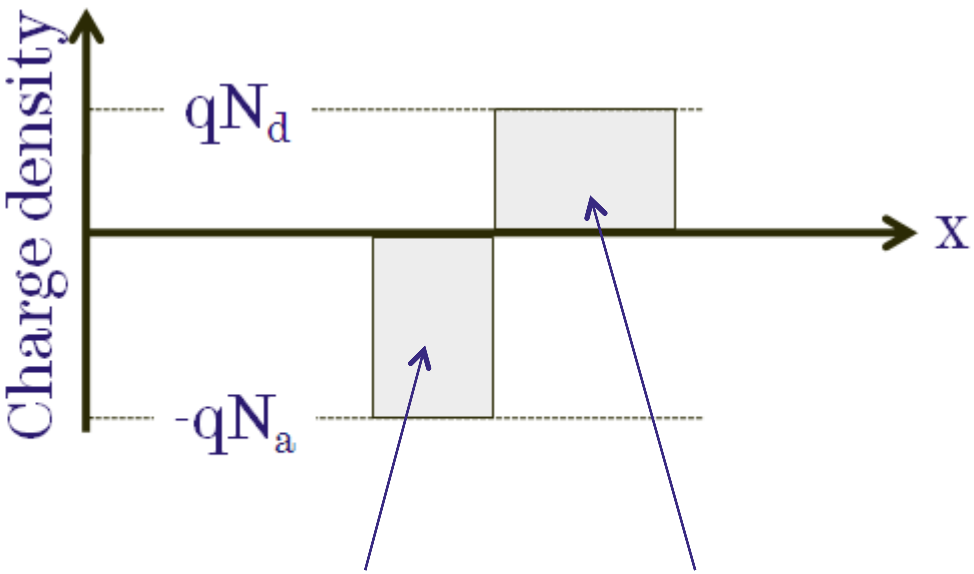
also, cancelling, we get $x_{p0}N_a = x_{n0}N_d$ -we will use this a lot.....

E-fields - Poisson's Equation

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon}$$

So generally

$$\frac{dE}{dx} = \frac{q}{\varepsilon}\left(p - n + N_d - N_a\right)$$



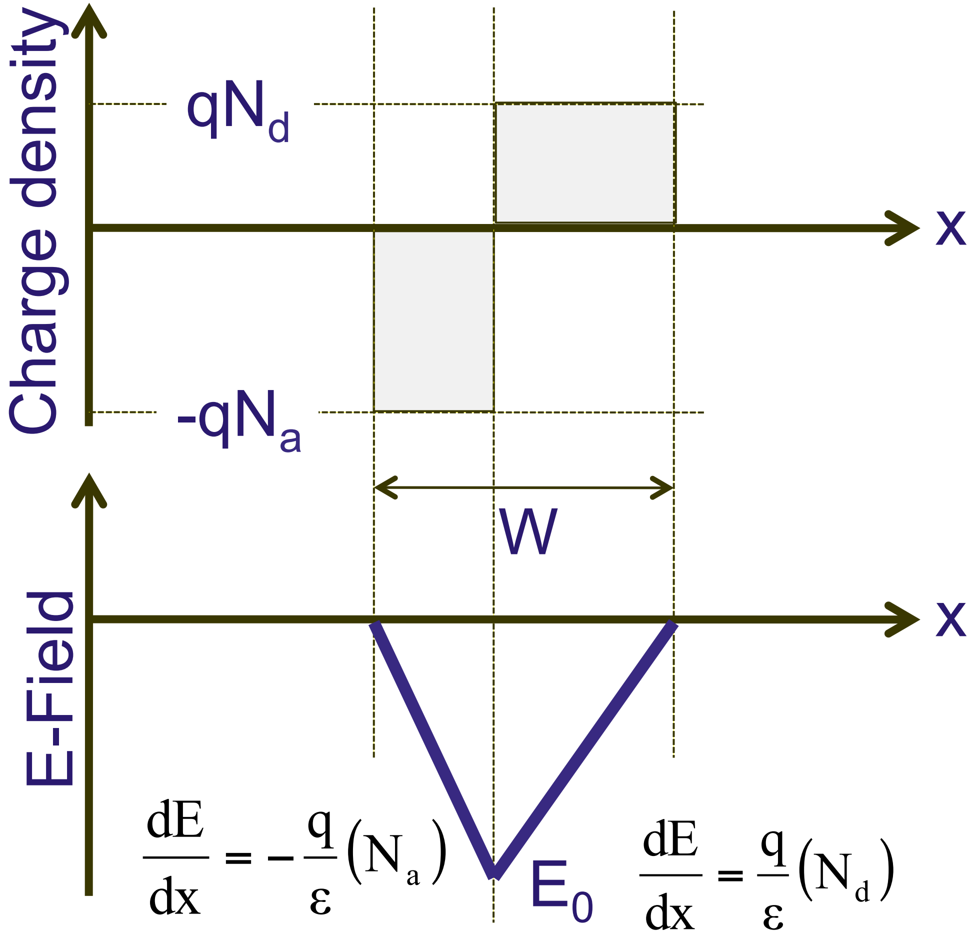
In depletion region

– assume n=p=0,

-only one dopant in a given region

$$\frac{dE}{dx} = -\frac{q}{\varepsilon}\left(N_a\right) \qquad \frac{dE}{dx} = \frac{q}{\varepsilon}\left(N_d\right)$$

E-fields - Poisson's Equation



We knew E-field is negative (in direction of –ve x)

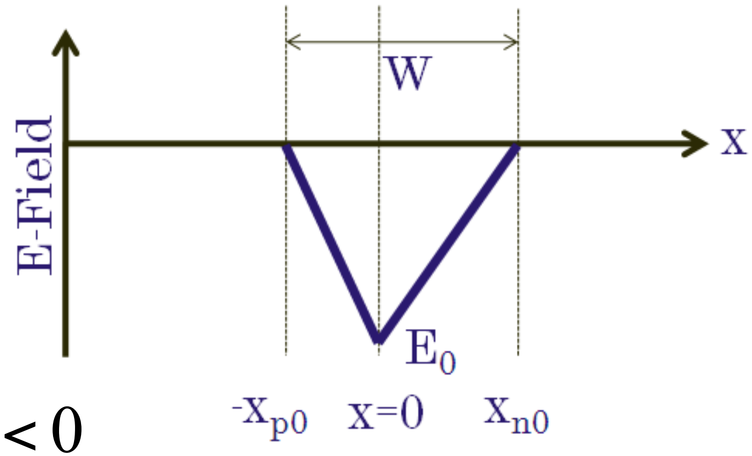
2 regions of +ve and –ve dE/dx

Maximum E-field at physical junction between doped regions

Value of E_0

Can determine E_0 by integration of

$$\frac{dE}{dx} = -\frac{q}{\varepsilon}(N_a) \quad \text{or} \quad \frac{dE}{dx} = \frac{q}{\varepsilon}(N_d)$$



With correct limits e.g.

$$\int_0^{E_0} dE = -\frac{q}{\varepsilon} N_a \int_{-x_{p0}}^{0} dx \qquad \text{for} \quad -x_{p0} < x < 0$$

$$\int_{E_0}^{0} dE = \frac{q}{\varepsilon} N_d \int_{0}^{x_{n0}} dx \qquad \text{for} \quad 0 < x < x_{n0}$$

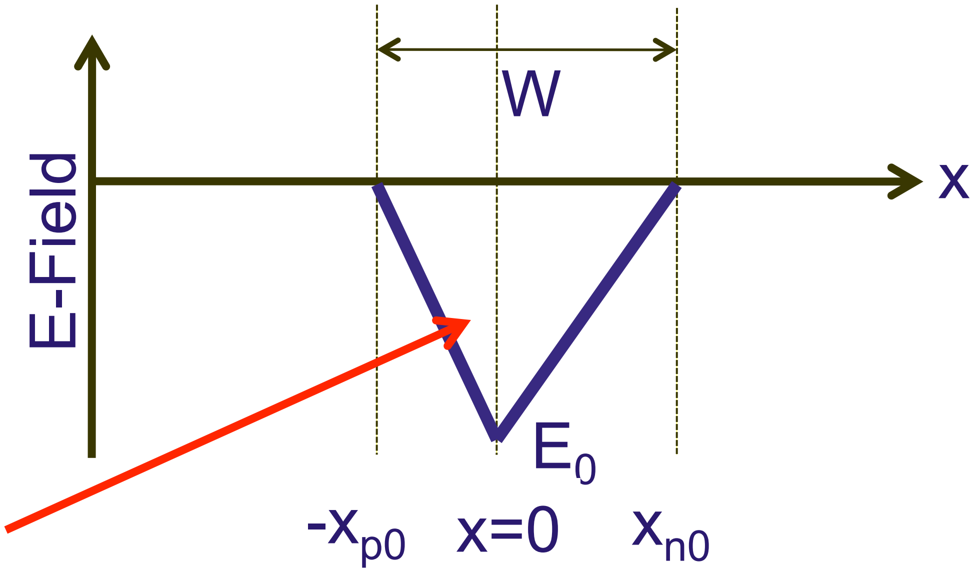
yielding $$E_0 = -\frac{q}{\varepsilon} N_d x_{n0} = -\frac{q}{\varepsilon} N_a x_{p0}$$

Depletion Region Width, W

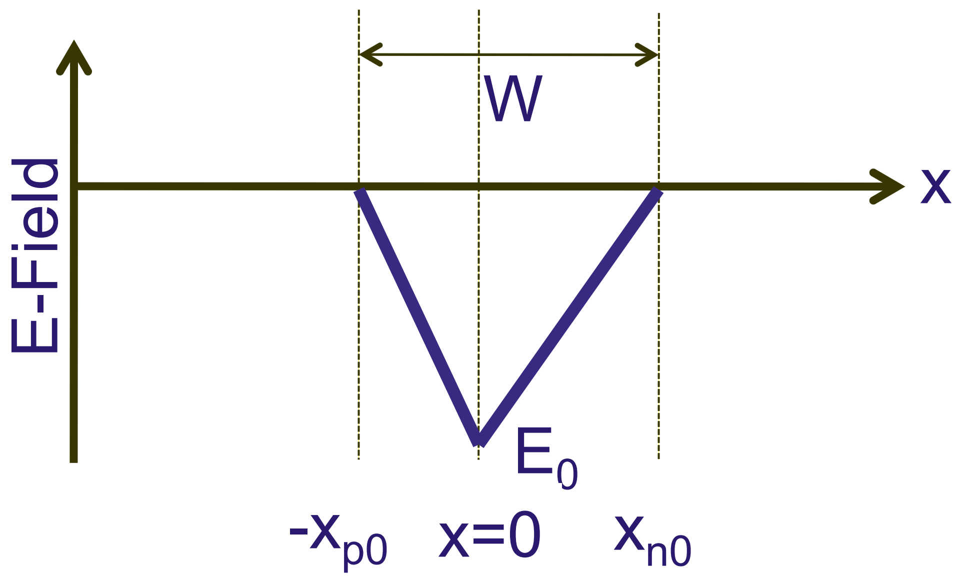
$$E = -\frac{dV}{dx}$$ or alternatively,

$$-V_0 = \int_{-x_{p0}}^{x_{n0}} E(x)\,dx$$

So V_0 is area of this triangle



Depletion Region Width Cont.



$$V_0 = -\frac{1}{2}E_0 W$$

e.g.

$$V_0 = \frac{1}{2}\frac{q}{\varepsilon}N_d x_{n0} W$$

$$x_{n0}N_d = x_{p0}N_a$$

$$V_0 = \frac{1}{2}\frac{q}{\varepsilon}N_a x_{p0} W$$

Eliminating x_{p0}, or x_{n0}

remembering $$x_{p0} N_a = x_{n0} N_d$$

and $$W = x_{p0} + x_{n0}$$

so $$(W - x_{n0}) N_a = x_{n0} N_d$$

$$x_{n0} = \frac{W N_a}{(N_d + N_a)}$$

From, e.g. $$V_0 = \frac{1}{2} \frac{q}{\varepsilon} N_d x_{n0} W = \frac{1}{2} \frac{q}{\varepsilon} \frac{N_a N_d}{N_a + N_d} W^2$$

More Algebra....

$$W = \left[\frac{2V_0\varepsilon}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} = \left[\frac{2\varepsilon\left(V_0 - V_f\right)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

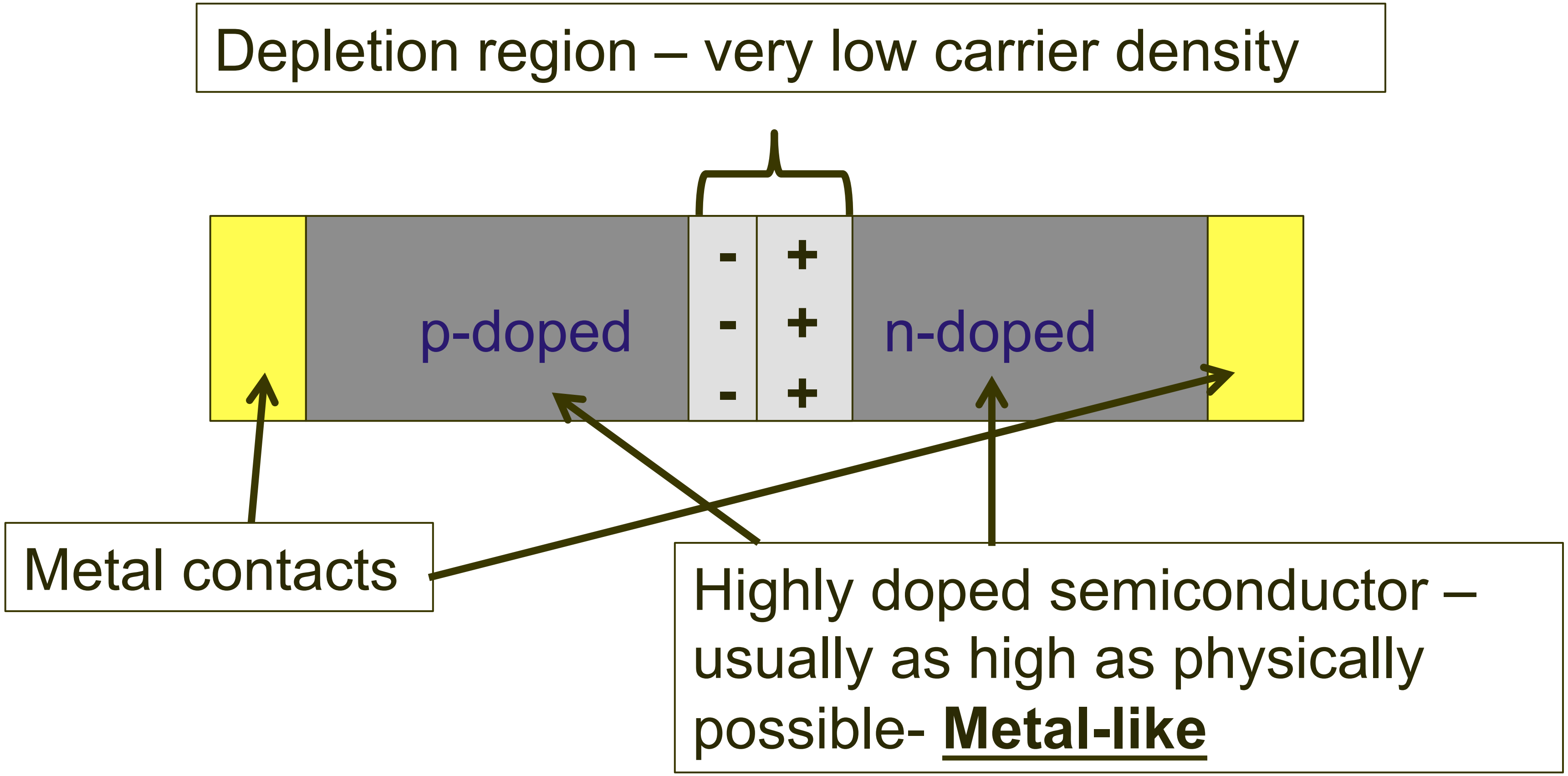
No applied bias

Forward bias

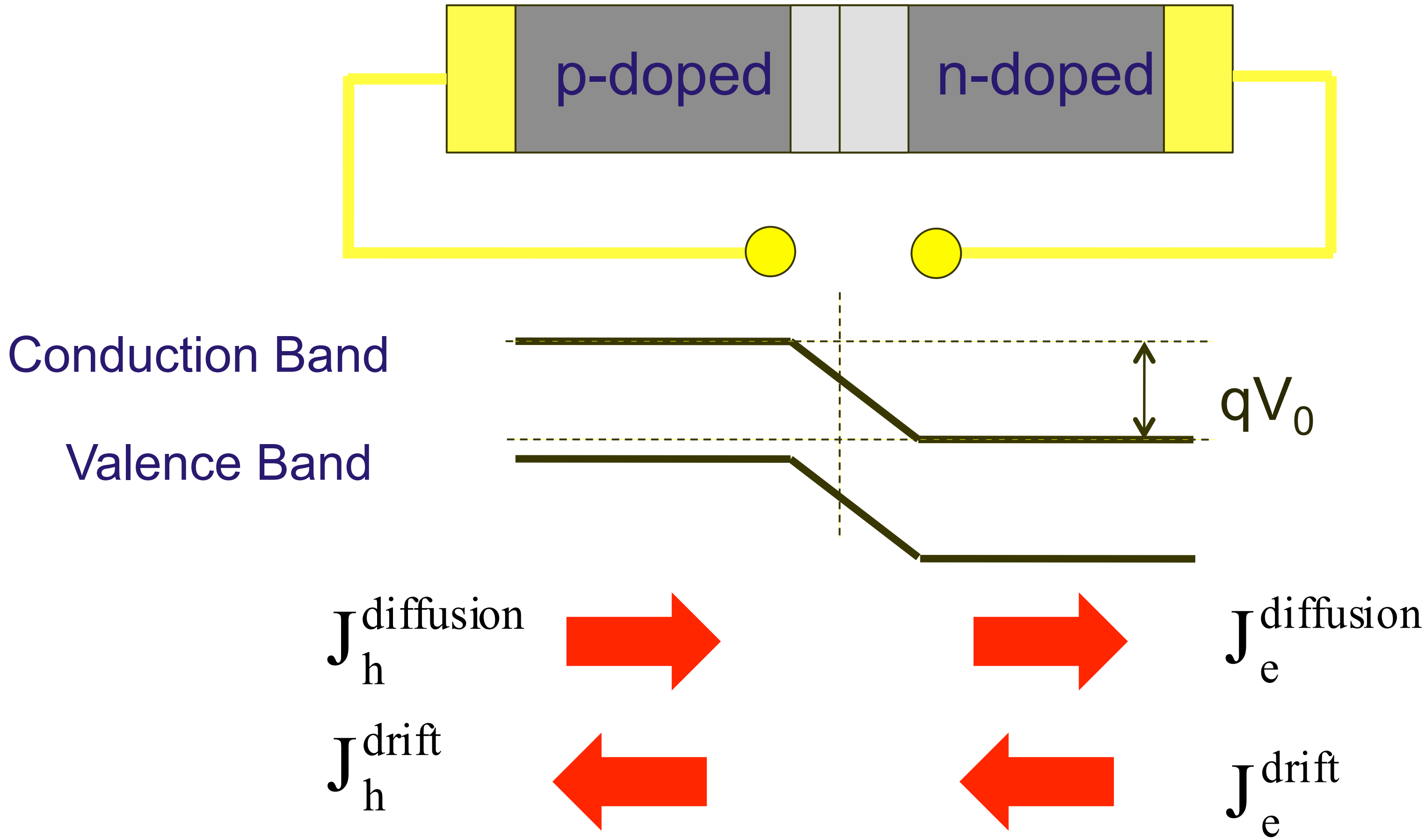
May also substitute for $W = \dfrac{x_{n0}\left(N_d + N_a\right)}{N_a}$ to determine

depletion depths in doped material

Where are potentials dropped?



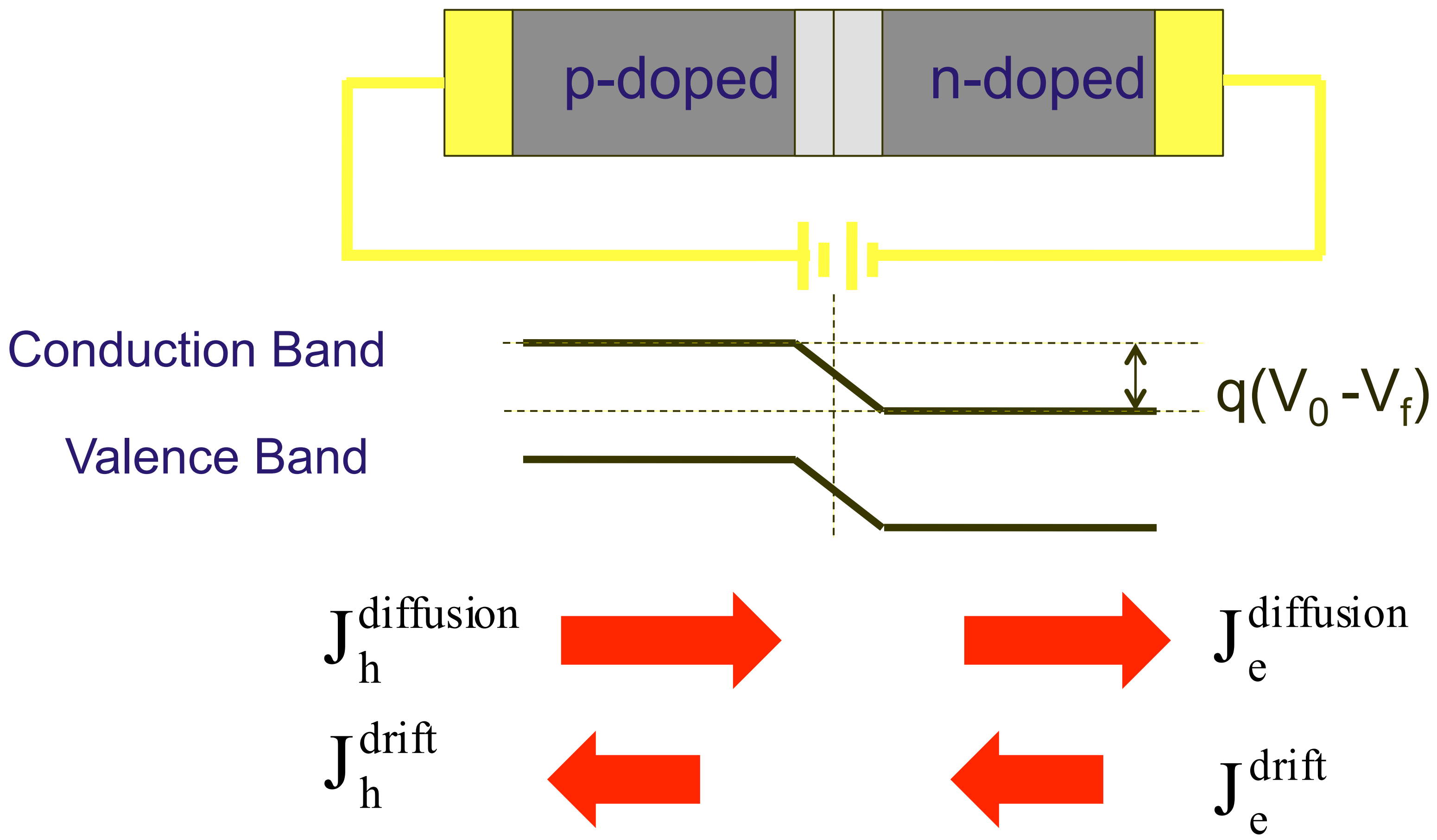
Zero Applied Voltage



Zero Applied Voltage (2)

- Built in E-field to balance diffusion and drift currents so there is no net current
- Depletion region where carrier density is low – consists of fixed ionized donors and acceptors - giving rise to the E-field
- Diffusion Current – Limited by potential barrier – at zero bias small diffusion current
- Drift Current – very few minority carriers to contribute to drift–so very small

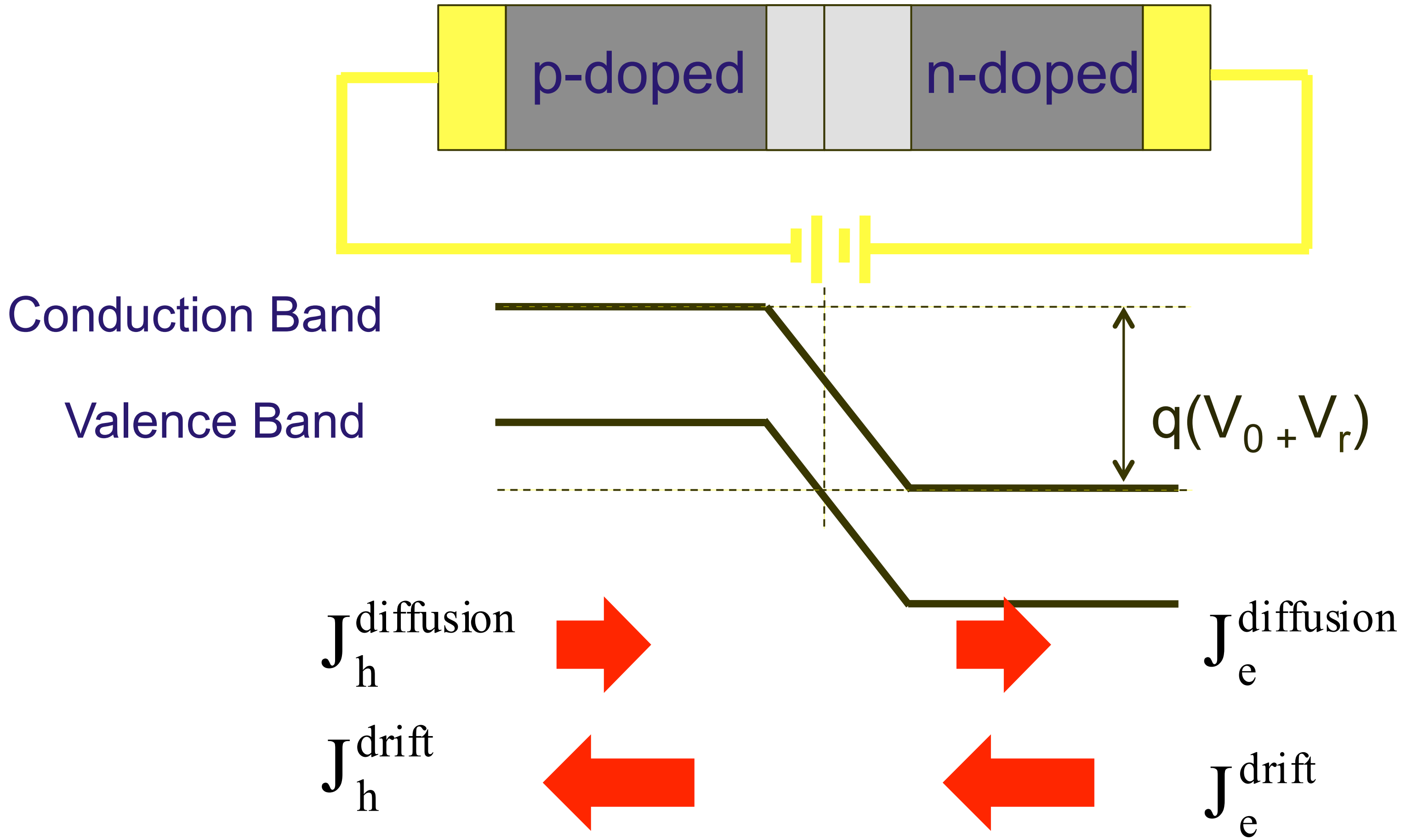
Forward Bias, V_f



Forward Bias, V_f

- Applied voltage changes the potential barrier and thus E-field within junction region - as we have forward bias the potential barrier is reduced
- The electric field in the transition region reduces
- This reduces the transition region width (need fewer "exposed" ionized dopants to achieve this lower E-field
- Diffusion Current – potential barrier smaller – so increased diffusion current
- Drift Current – essentially same as zero bias - very few minority carriers to contribute to drift–so very small

Reverse Bias, V_r



Reverse Bias, V_r

- Applied voltage changes the potential barrier and thus E-field within junction region
- As we have reverse bias the potential is increased
- The electric field in the transition region increases
- This increases the transition region width (need more “exposed” ionized dopants to achieve this higher E-field
- Diffusion Current – potential barrier bigger – so reduced diffusion current – essentially zero
- Drift Current – essentially same as zero bias - very few minority carriers to contribute to drift–so very small

Summary

- Poisson's equation relates electrostatic potential to charges present
- Space charge at the p-n junction determines the depletion region width, penetration into the n and p-doped regions, Electric-field and built in potential
- The operation (drift and diffusion currents) of the p-n diode has been discussed qualitatively for zero, forward and reverse bias