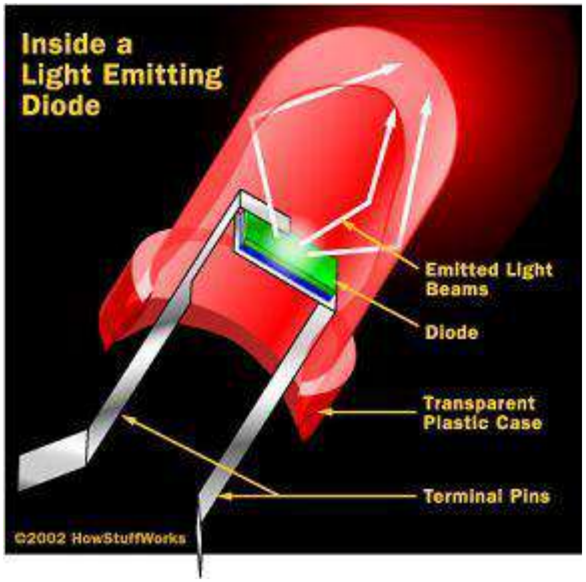
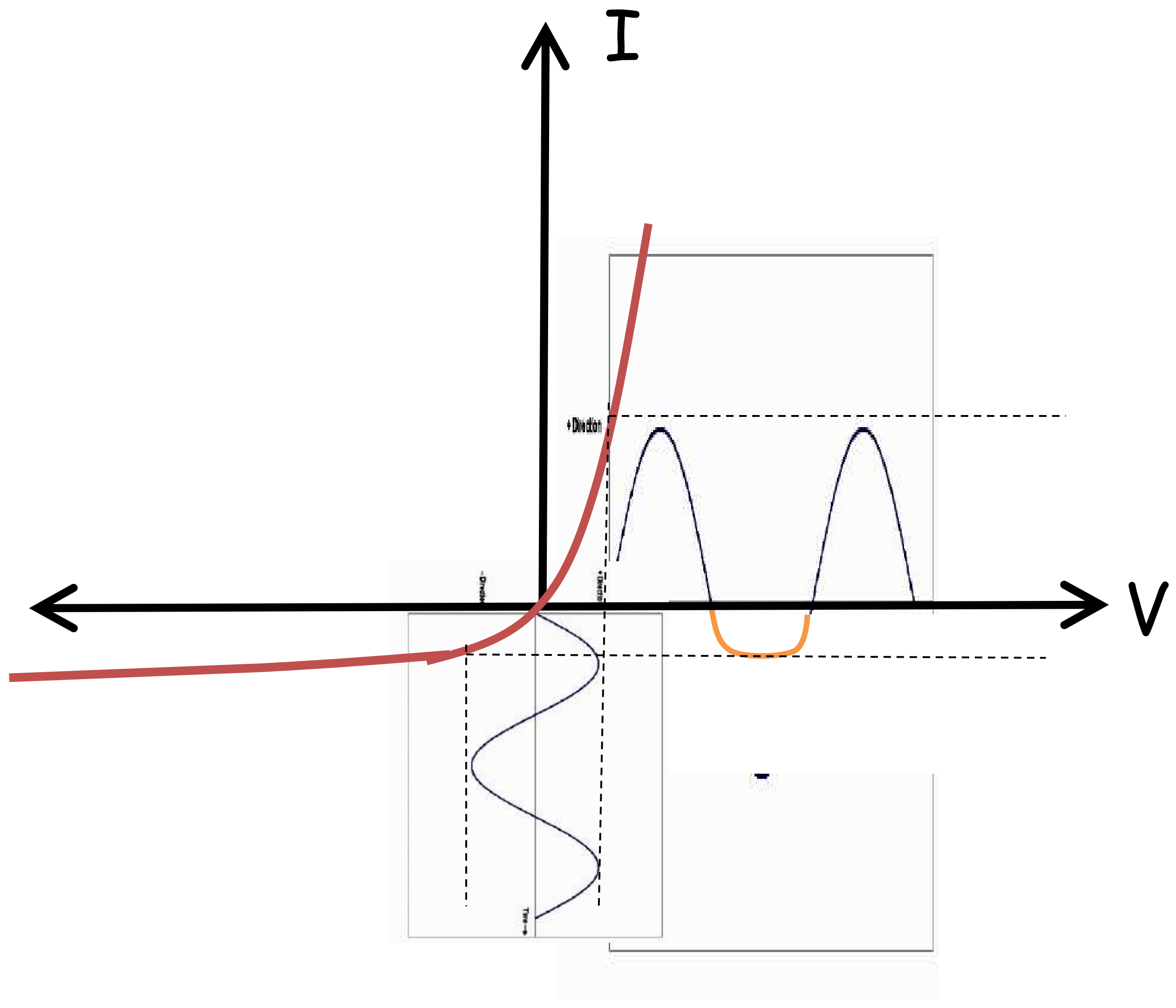
P-N Junctions



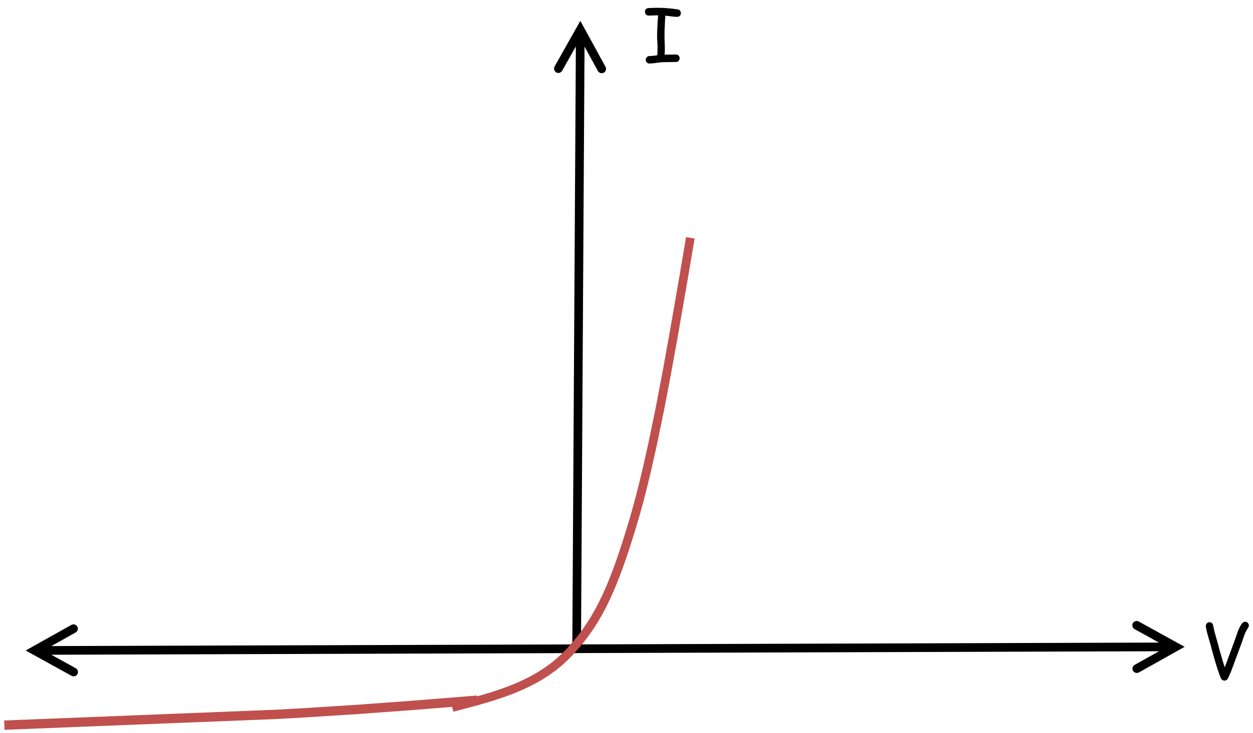
- So far we learned the basics of semiconductor physics, culminating in the **Minority Carrier Diffusion Equation**
- We now encounter our simplest electronic device, a diode
- Understanding the principle requires the ability to draw band-diagrams
- Making this quantitative requires ability to solve MCDE (only exponentials!)
- Here we only do the equilibrium analysis

P-N junction diode



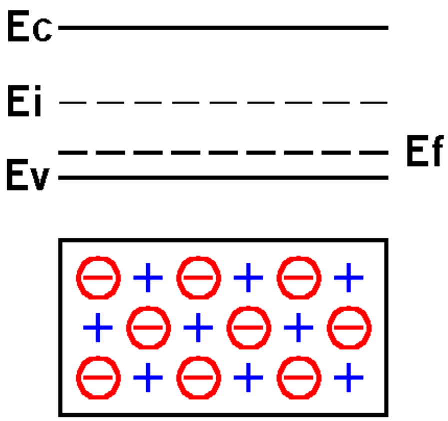
SEMICONDUCTOR DIODE

P-N junction diode



$$I = I_0(e^{qV/\eta kT} - 1)$$

P-N Junctions - Equilibrium

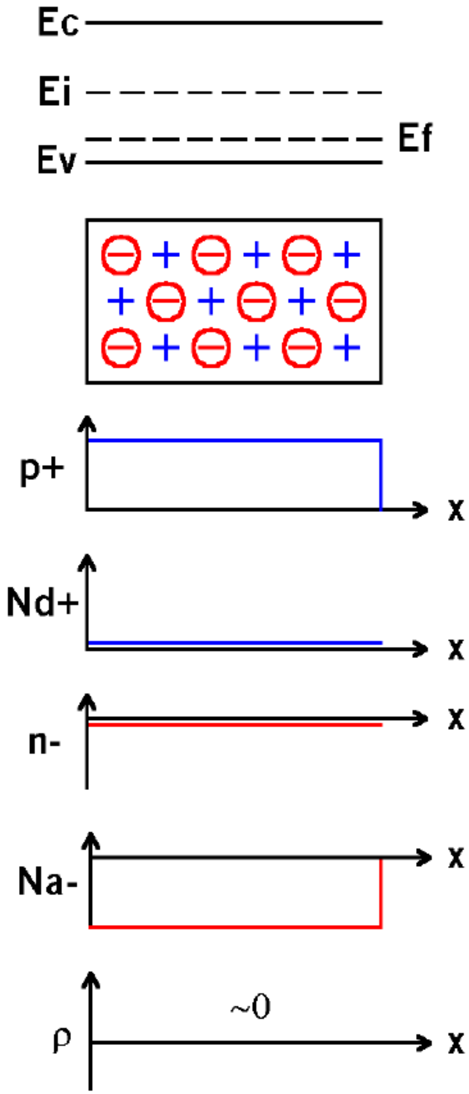


What happens when these bandstructures collide?

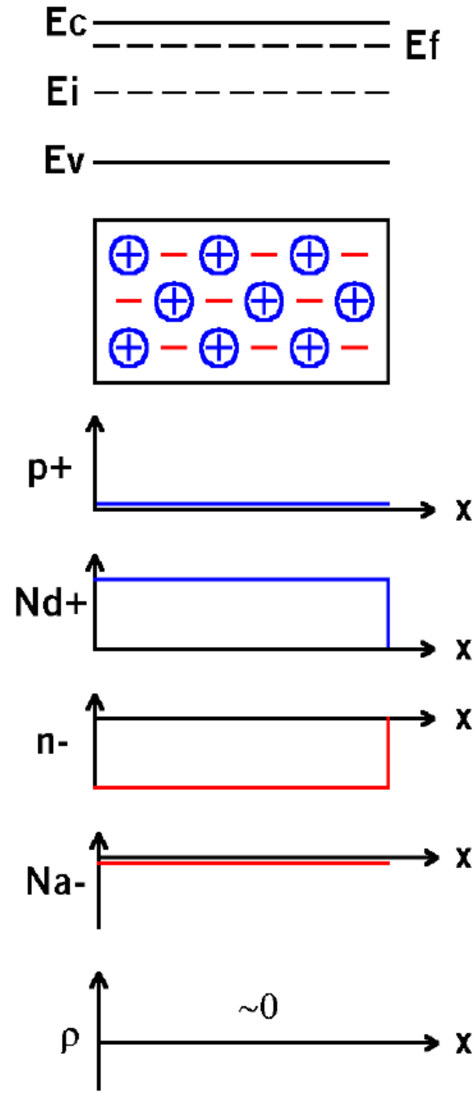
- Fermi energy must be constant at equilibrium, so bands must bend near interface
- Far from the interface, bandstructures must revert

Time < 0: Pieces separated

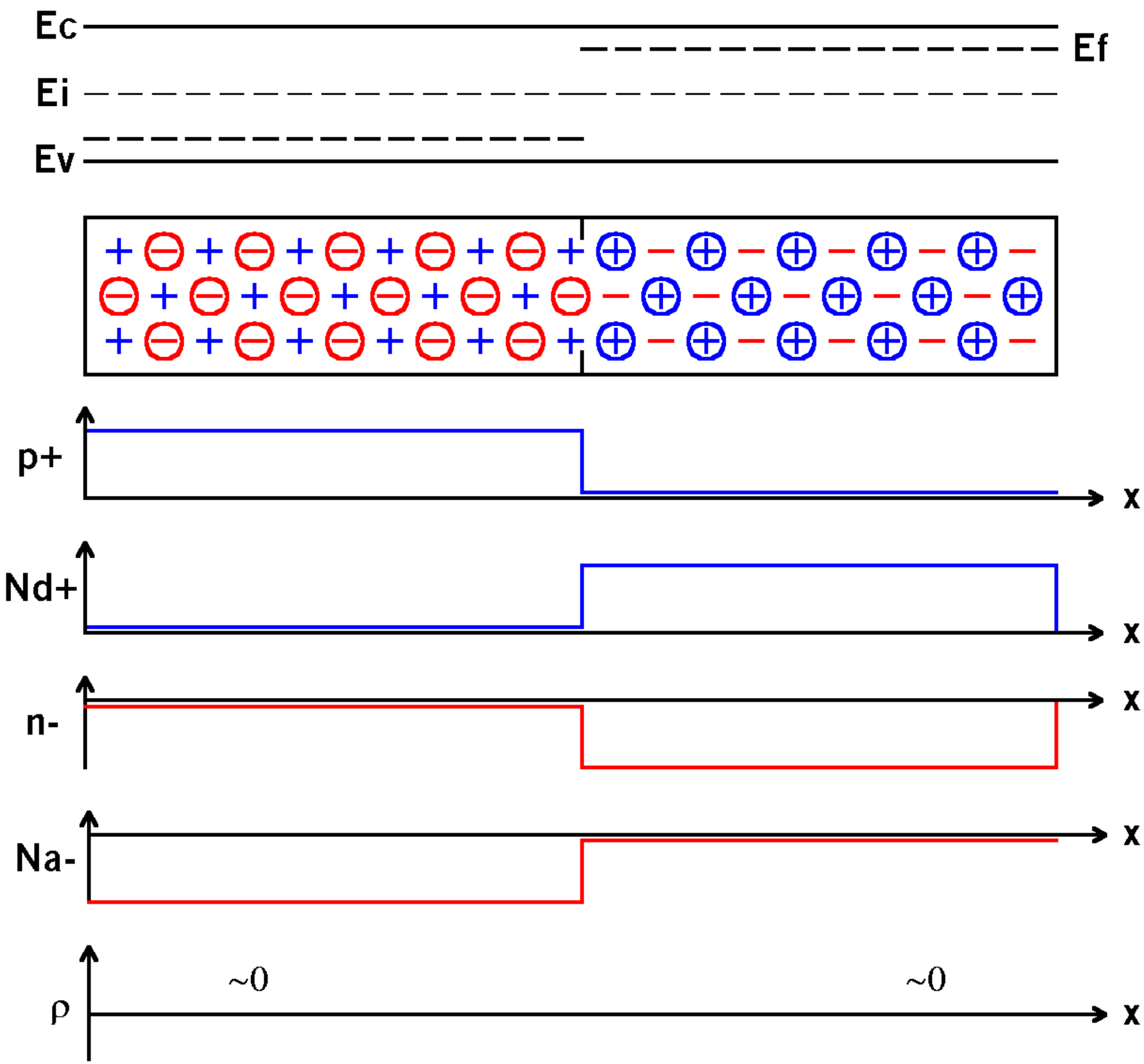
P-type piece



N-type piece

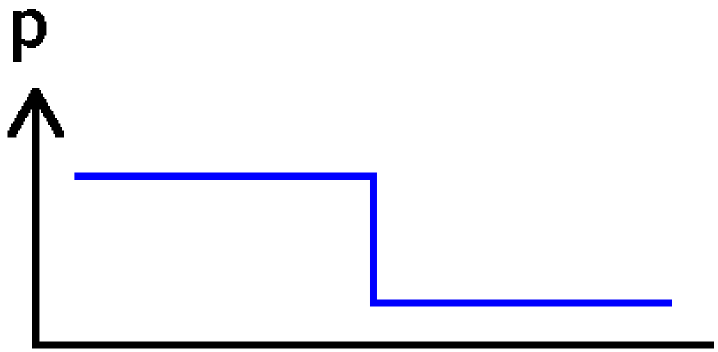


At time = 0, slam the two pieces together



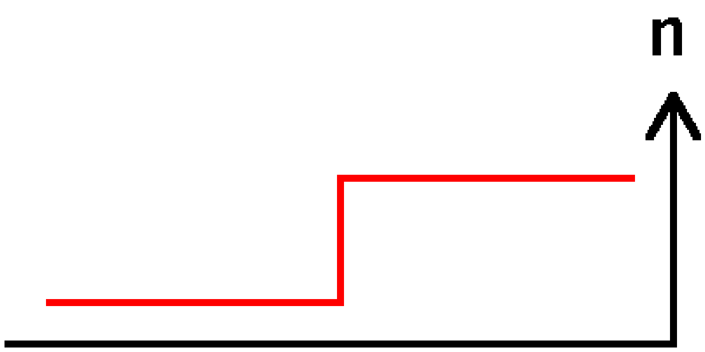
Gradients drive diffusion

Hole gradient



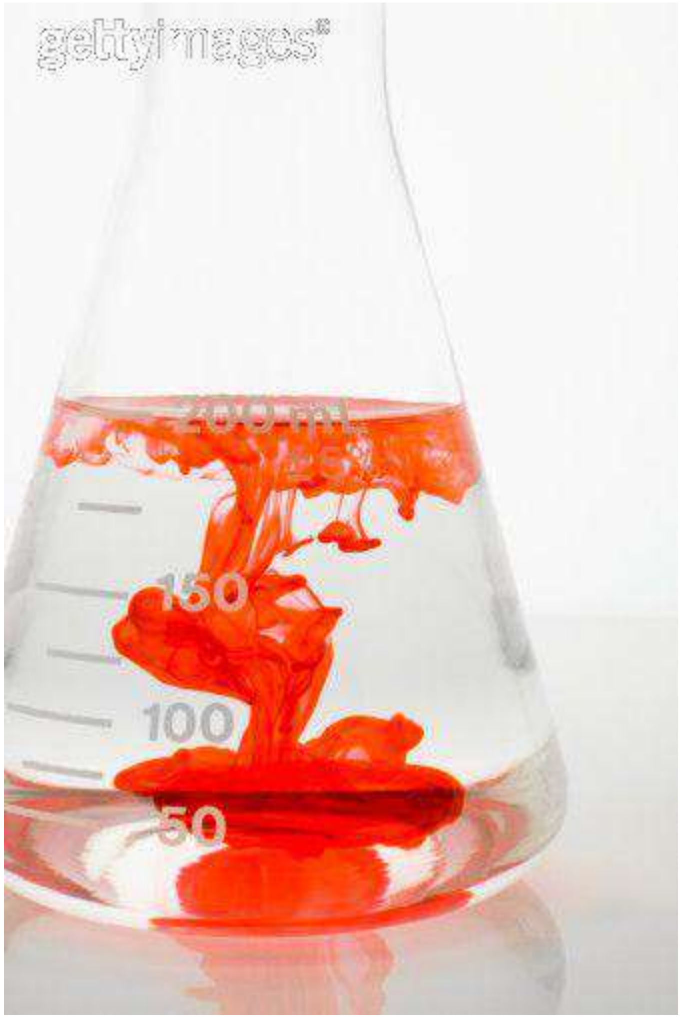
$J_{p,\,diffusion} = -qD_p\, dp/dx$ = current right, holes right

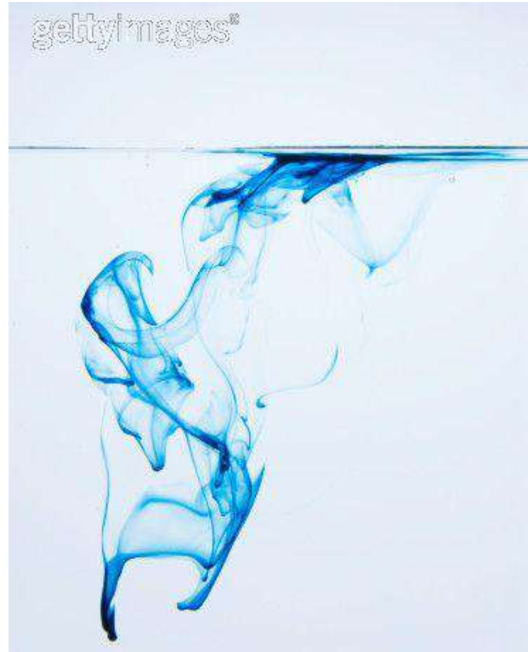
Electron gradient

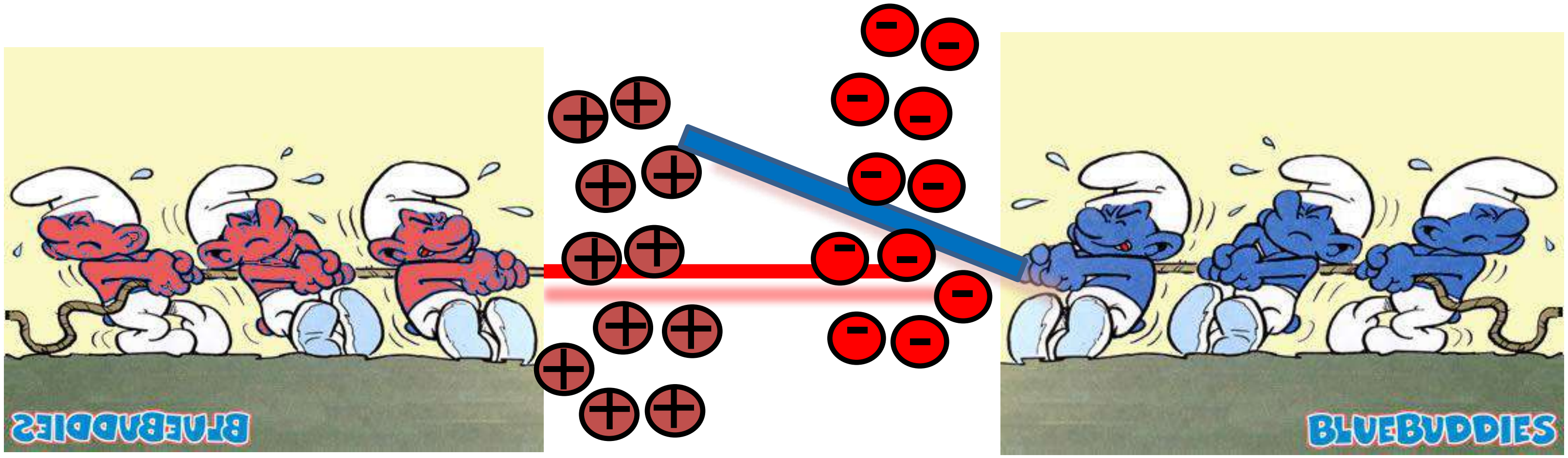


$J_{n,diffusion} = qD_n\, dn/dx$ = current right, electrons left

Gradients drive diffusion

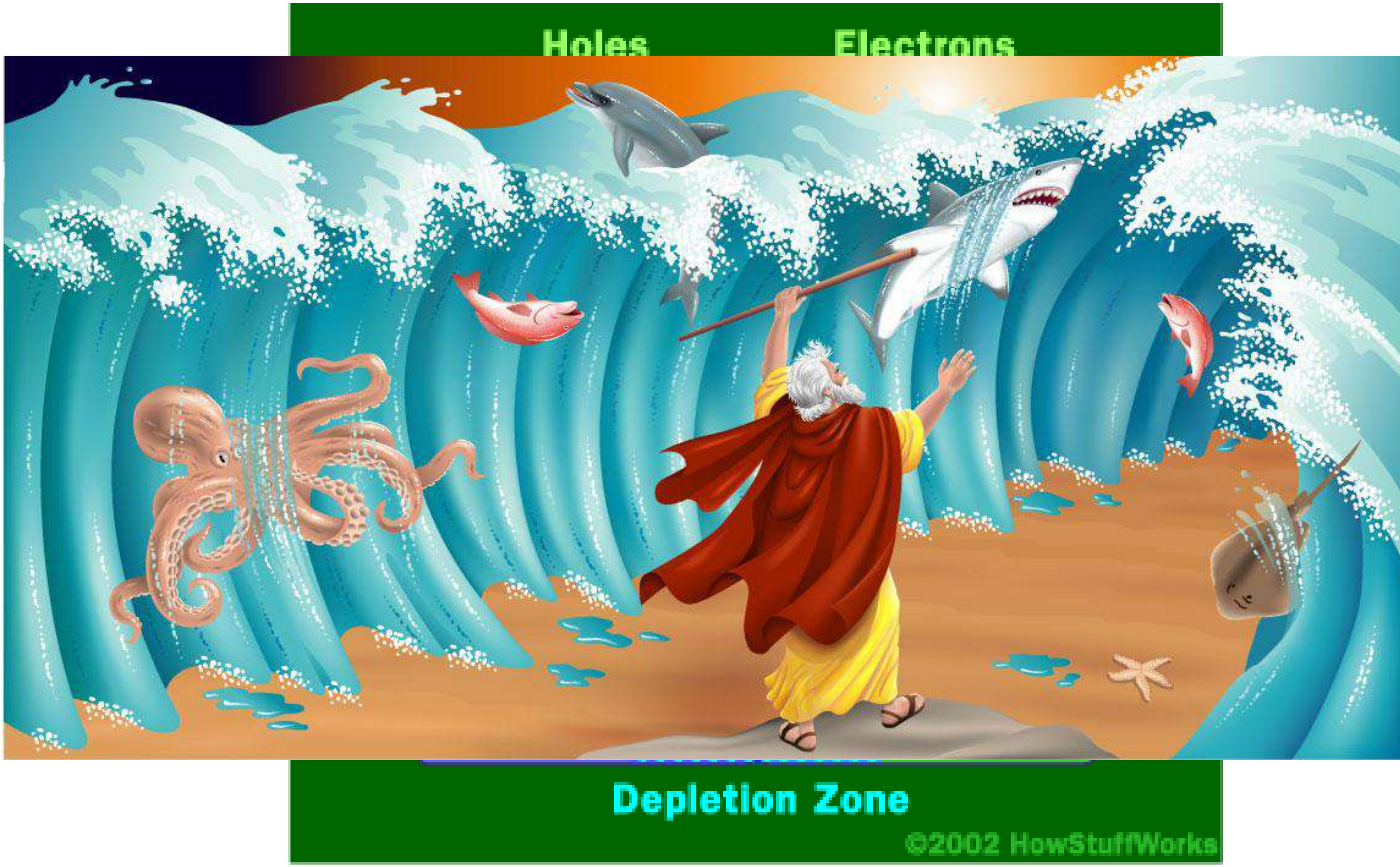






But charges can't venture too far from the interface because their Coulomb forces pull them back!

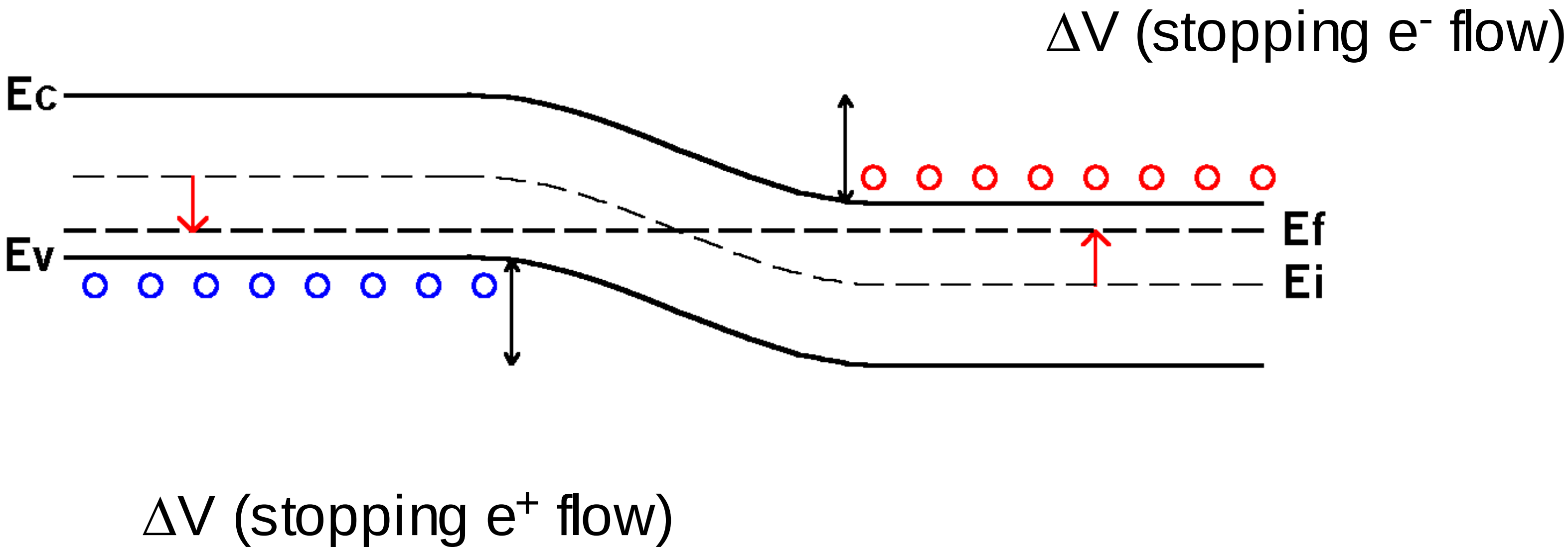
Separation of a sea of charge, leaving behind a charge depleted region

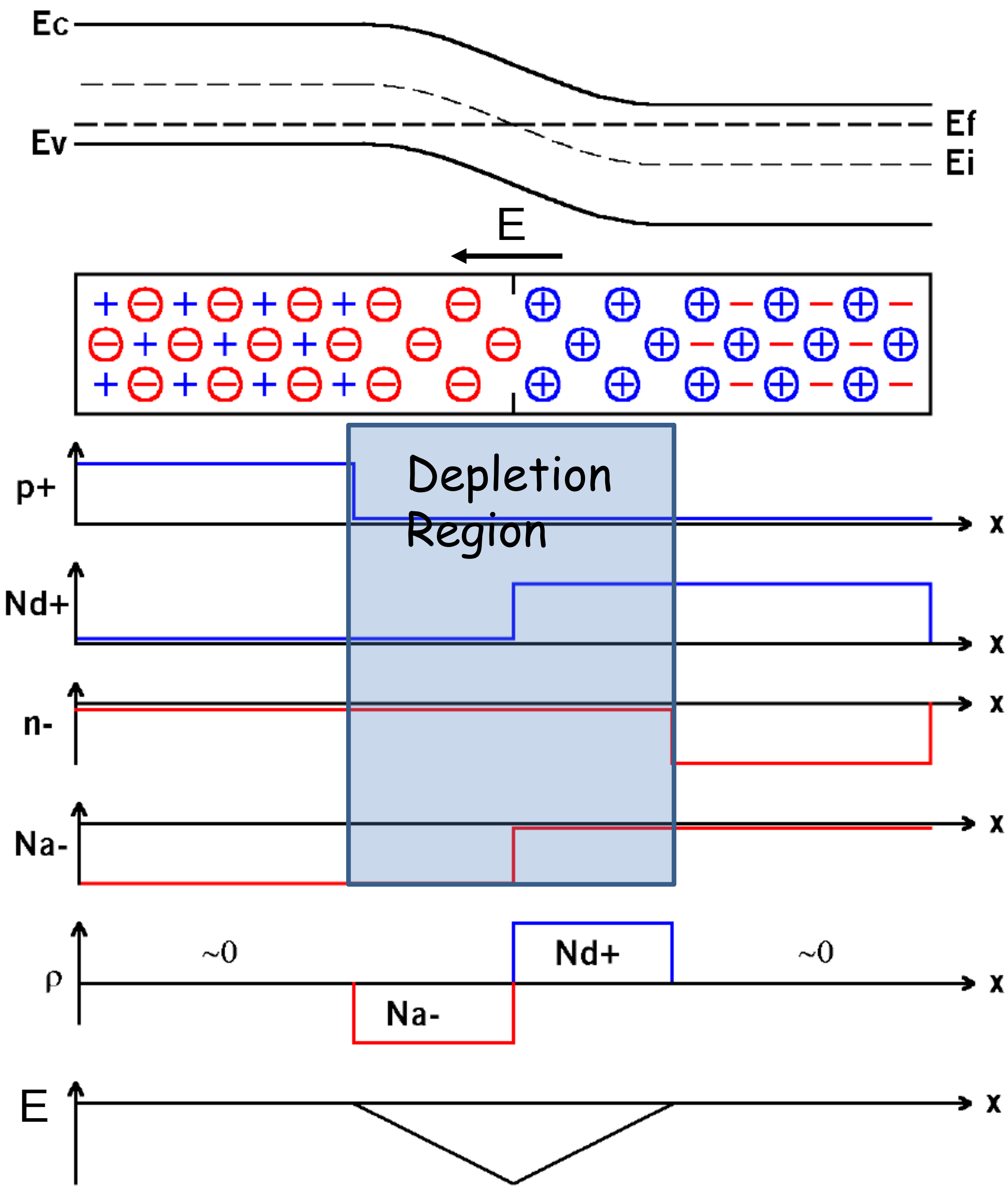


SEMICONDUCTOR DIODE

http://scott.club365.net/uploaded_images/Moses-Parts-the-Red-Sea-2-782619.jpg

Resulting in a barrier across a depletion region

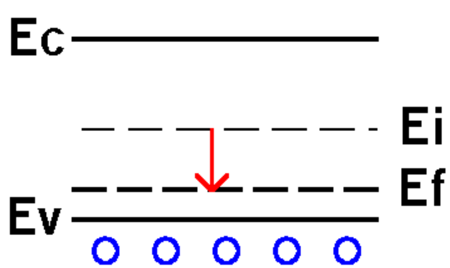



Ec
Ef
Ev
Ei
E
Depletion
Region
p+
x
Nd+
x
n-
x
Na-
x
ρ
~0
Nd+
~0
x
Na-
E
x

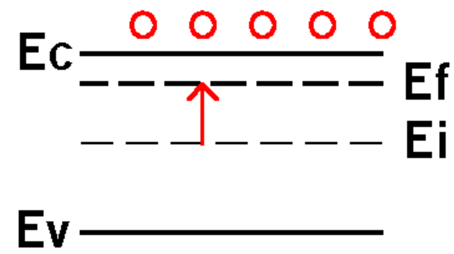
How much is the Built-in Voltage?

$$qV_{bi} = (E_i - E_F)_{Left} + (E_F - E_i)_{Right}$$

P side



N side



$$p \approx N_a$$

$$N_a = n_i e^{(E_i - E_F)/kT}$$

$$(E_i - E_F)_{Left} = kT \ln\left(\frac{N_a}{n_i}\right)$$

$$n \approx N_d$$

$$N_d = n_i e^{(E_F - E_i)/kT}$$

$$(E_F - E_i)_{Right} = kT \ln\left(\frac{N_d}{n_i}\right)$$

How much is the Built-in Voltage?

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_a}{n_i}\right) + \frac{kT}{q}\ln\left(\frac{N_d}{n_i}\right)$$

$$\Rightarrow V_{bi} = \frac{kT}{q}\ln\left(\frac{N_a N_d}{n_i^{\,2}}\right)$$

N_a acceptor level on the p side

N_d donor level on the n side

Special case: One-sided Junctions

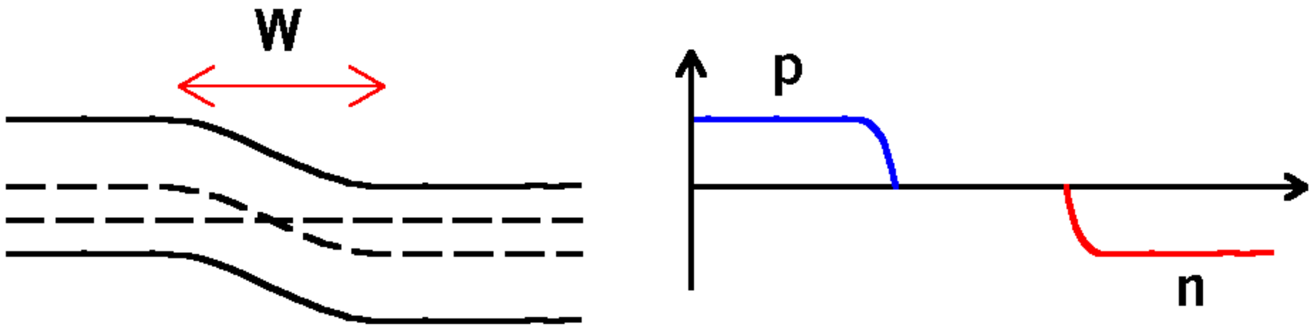
- One side very heavily doped so that Fermi level is at band edge.
- e.g. p^+-n junction (Heavy B implant into lightly doped substrate)

$$(E_i - E_F)_{left} \approx (E_C - E_V = E_G)/2$$

$$(E_F - E_i)_{Right} = kT \ln\left(\frac{N_D}{n_i}\right)$$

$$\Rightarrow V_{bi} = \frac{E_G}{2q} + \frac{kT}{q}\ln\left(\frac{N_d}{n_i}\right)$$

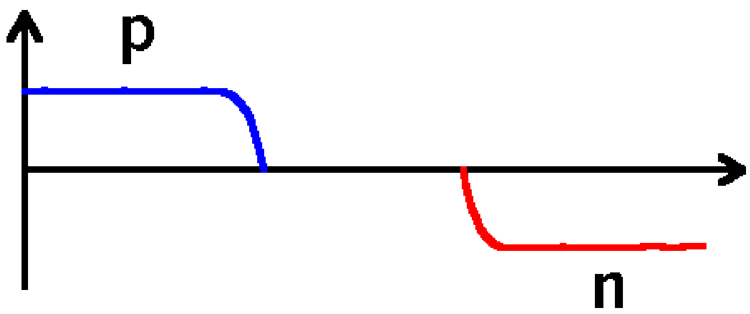
How wide is the depletion region?

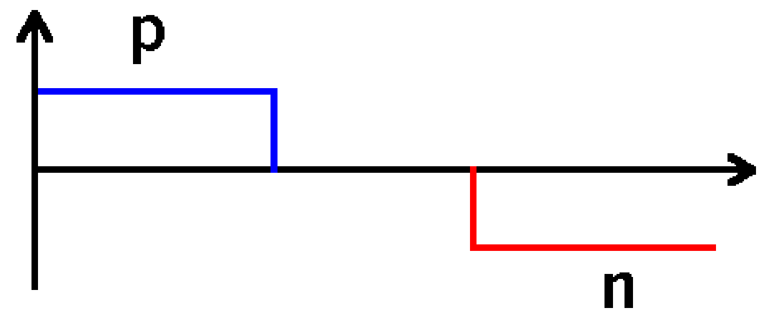


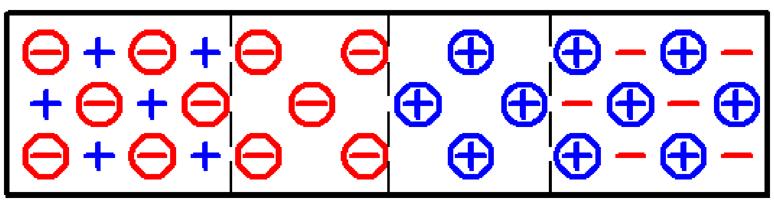
$$p = n_i e^{(E_i - E_F)/kT}$$

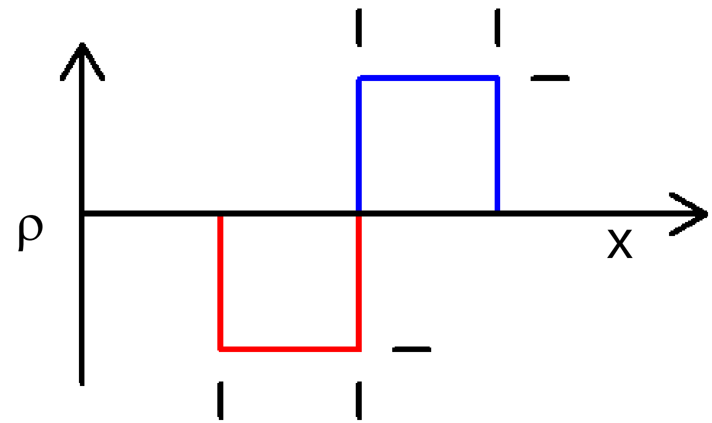
$$n = n_i e^{(E_F - E_i)/kT}$$

Depletion Approximation-step junction

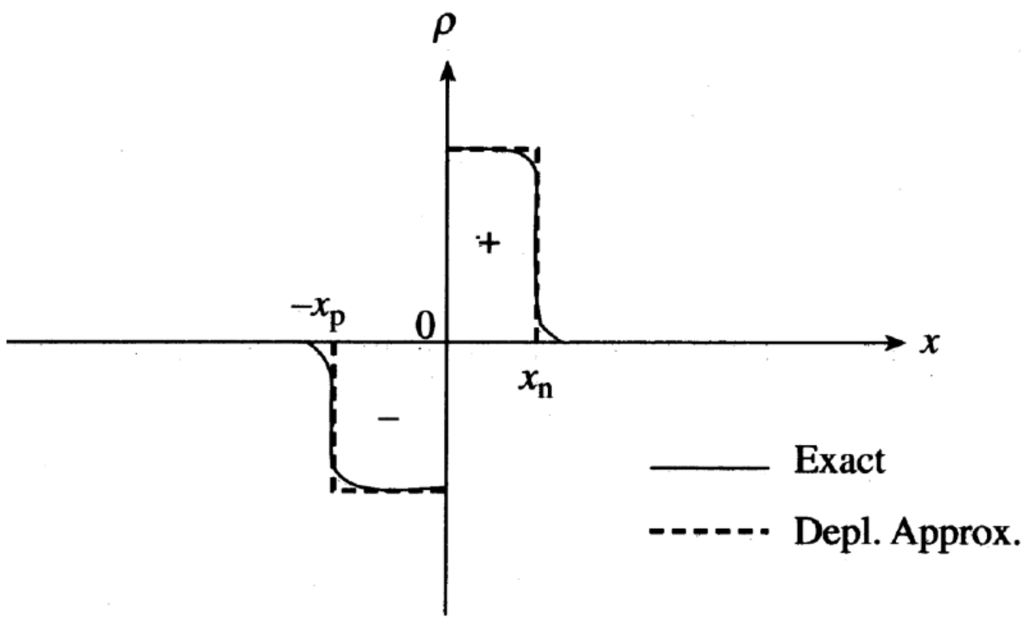




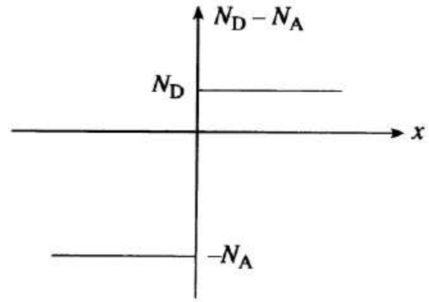




Depletion approximation-step junction



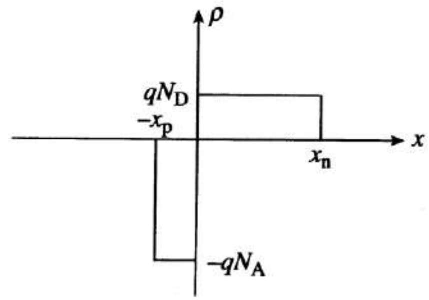
Exponentials replaced with step-functions



(a)

Doping

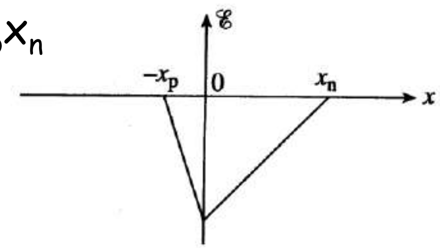
$N_A x_p = N_D x_n$
$= W_D/(N_A^{-1} + N_D^{-1})$



(b)

Charge Density

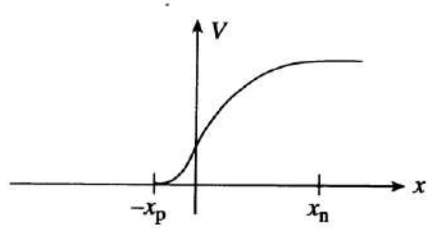
$K_s \varepsilon_0 E_m = -qN_A x_p = -qN_D x_n$
$= -qW_D/(N_A^{-1} + N_D^{-1})$



(c)

Electric Field

$V_{bi} = \frac{1}{2}|E_m|W_D$



(d)

Electrostatic Potential

R DIODE

Depletion Width

$$\Rightarrow W = \left[\frac{2K_S\varepsilon_0}{q} \frac{(N_A + N_D)}{N_D N_A} V_{bi} \right]^{1/2}$$

Maximum Field

$$E_m = \sqrt{2qV_{bi}/k_s\varepsilon_0(N_A^{-1}+N_D^{-1})}$$

How far does W_d extend into each junction?

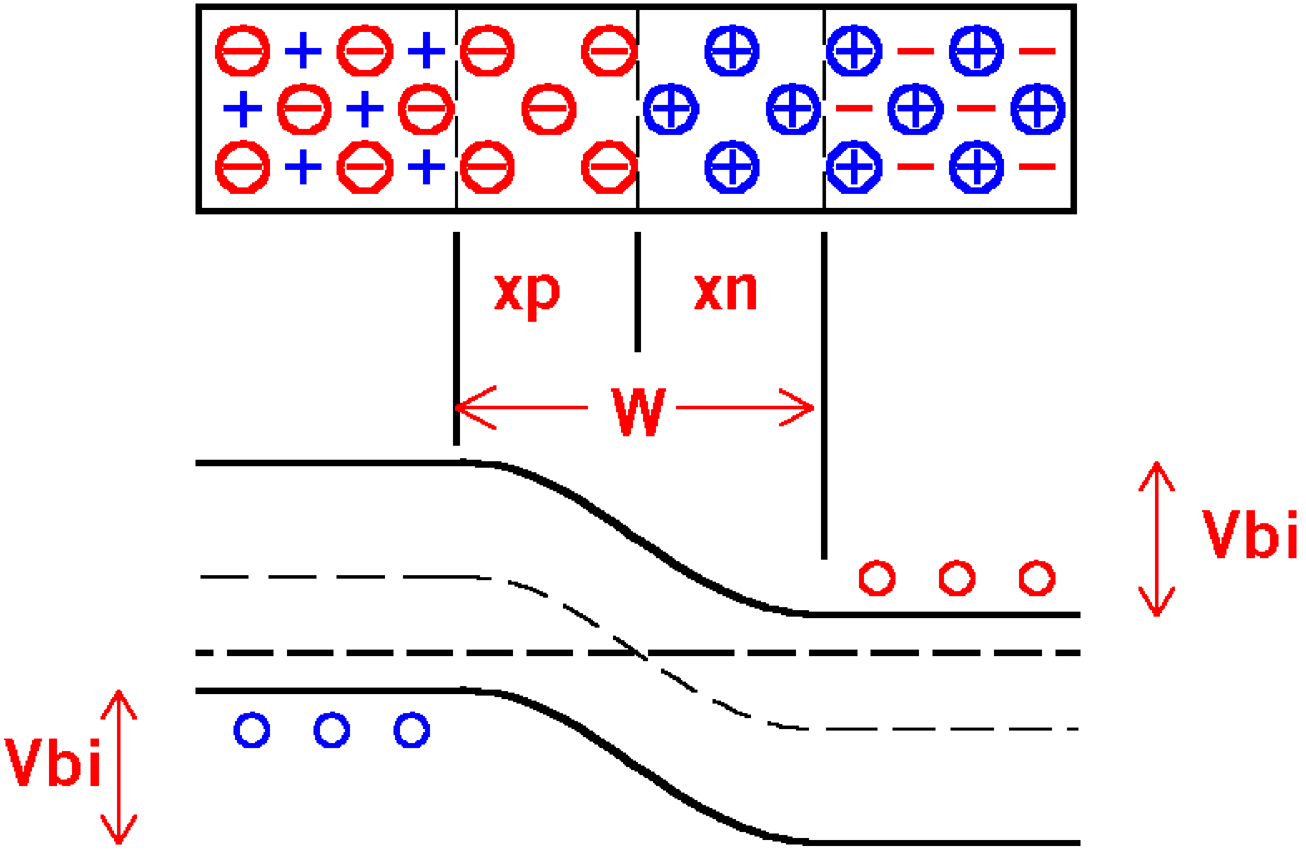
$$W = x_n \left(\frac{N_A + N_D}{N_A} \right)$$

or

$$x_n = W \left(\frac{N_A}{N_A + N_D} \right) \qquad x_p = W \left(\frac{N_D}{N_A + N_D} \right)$$

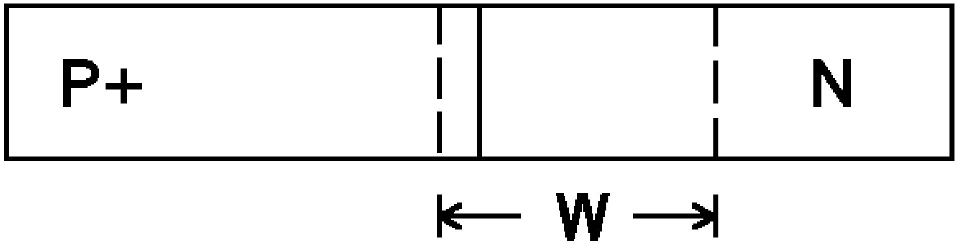
Depletion width on the n-side depends on the doping on the p-side
Depletion width on the p-side depends on the doping on the n-side

e.g. if $N_A >> N_D$ then $x_n >> x_p$ *One-sided junction*

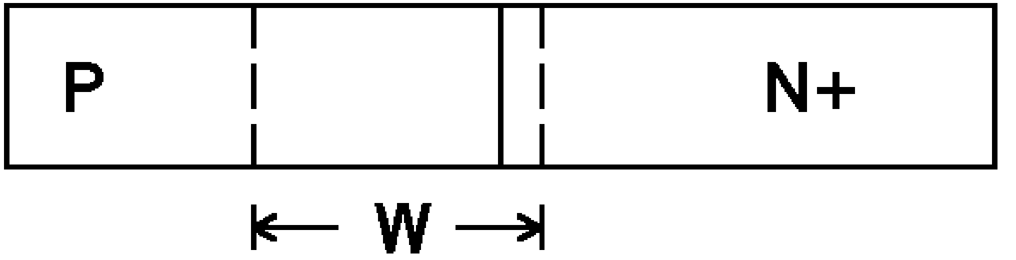


SEMICONDUCTOR DIODE

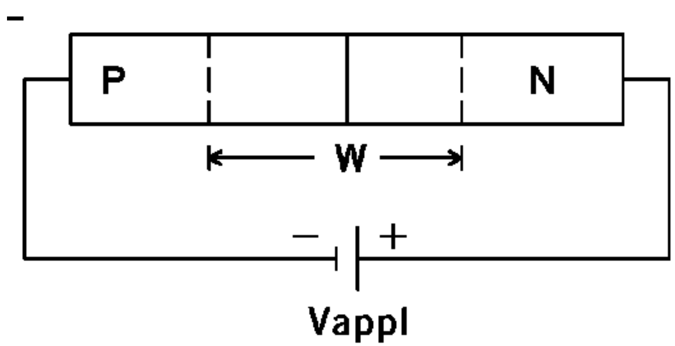
"P^+ - N" => $N_a >> N_d$

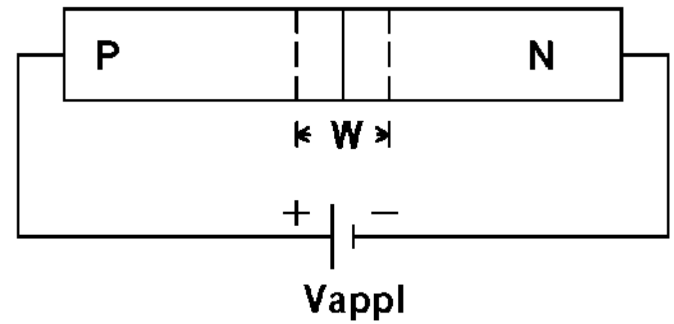


"P - N^+" => $N_a << N_d$



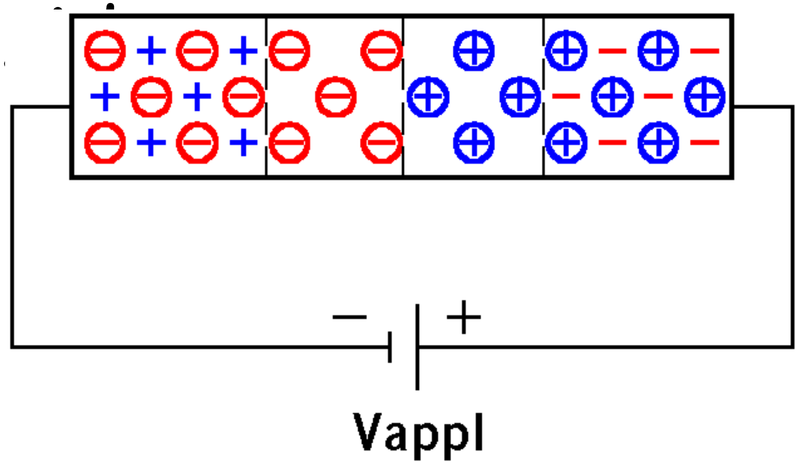
P-N Junction with applied voltage





Reverse Bias

- +Voltage to the n side and -Voltage to the p



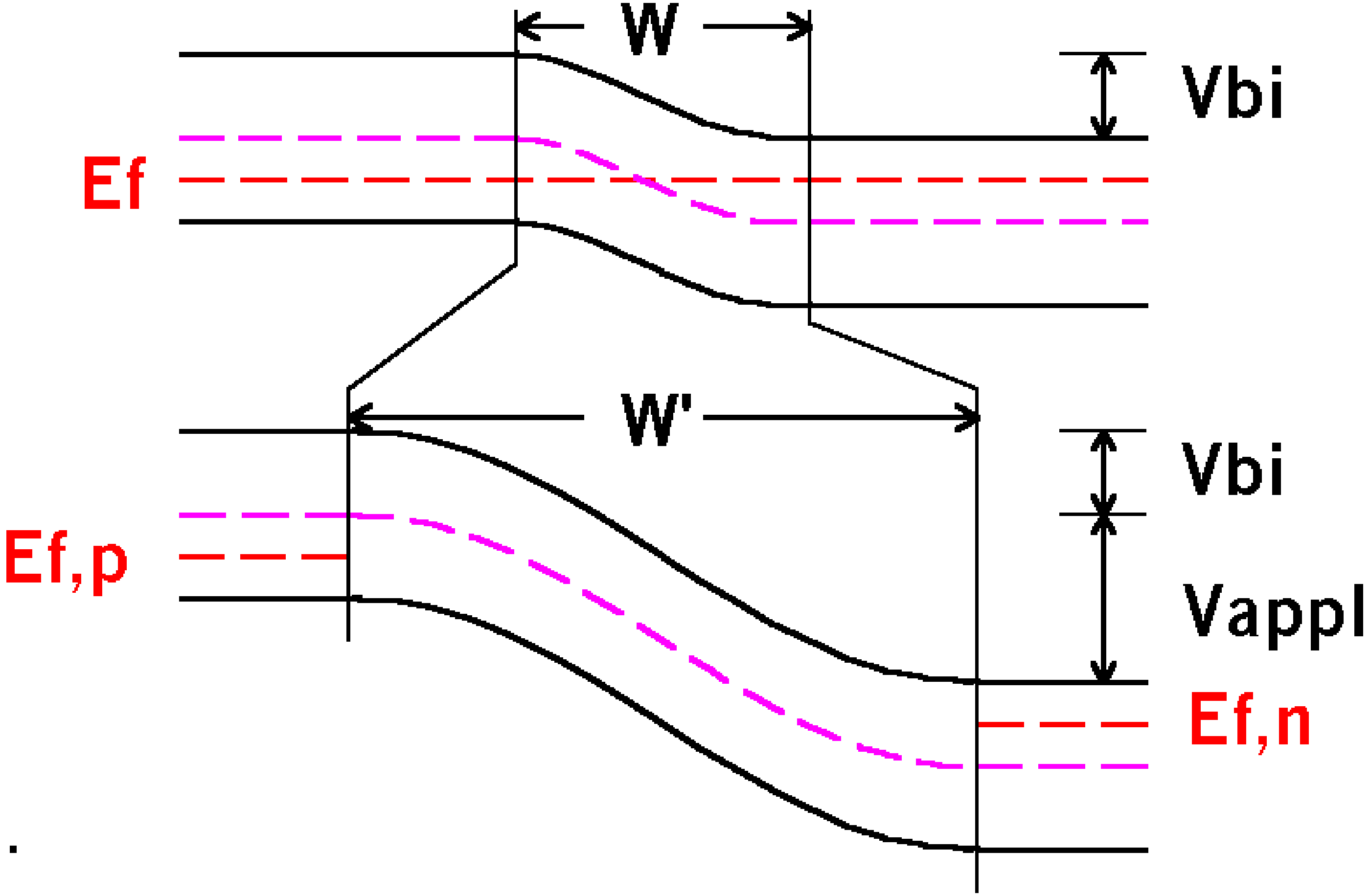
Vapplied is sucking more:

holes (+) out of P-side

electrons (-) out of N-side

Depletion region will be larger

Reverse Bias Band Diagram



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Reverse Bias depletion

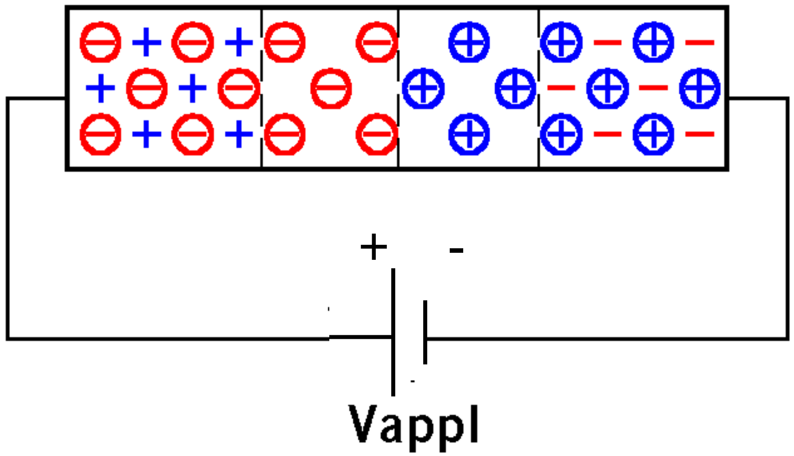
$$W = \left[\frac{2K_S\varepsilon_0}{q} \frac{(N_A + N_D)}{N_D N_A} (V_{bi} + V_{rev}) \right]^{1/2}$$

$$x_n = W(V_{rev}) \left(\frac{N_A}{N_A + N_D} \right) \qquad x_p = W(V_{rev}) \left(\frac{N_D}{N_A + N_D} \right)$$

Applied voltage disturbs equilibrium E_F no longer constant

Reverse bias adds to the effect of built-in voltage

Forward Bias



Negative voltage to n side positive to p side

More electrons supplied to n, more holes to p

Depletion region gets smaller

Forward Bias Depletion

$$W = \left[\frac{2K_S\varepsilon_0}{q} \frac{(N_A + N_D)}{N_D N_A} (V_{bi} - V_{fwd}) \right]^{1/2}$$

$$x_n = W(V_{fwd}) \left(\frac{N_A}{N_A + N_D} \right) \qquad x_p = W(V_{fwd}) \left(\frac{N_D}{N_A + N_D} \right)$$

General Expression

- Convention = V_{appl}= + for forward bias

  V_{appl}= - for reverse bias

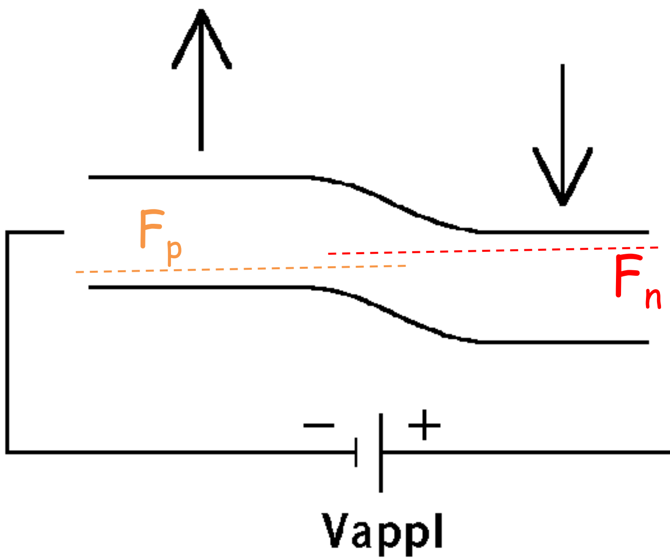
$$W = \left[\frac{2K_S\varepsilon_0}{q} \frac{(N_A + N_D)}{N_D N_A} (V_{bi} - V_{appl}) \right]^{1/2}$$

$$x_n = W(V_{appl}) \left(\frac{N_A}{N_A + N_D} \right) \qquad x_p = W(V_{appl}) \left(\frac{N_D}{N_A + N_D} \right)$$

Positive voltage pulls bands down- bands are plots of electron energy

Bands = plots of electron energy

Voltage = potential energy per (+) charge



$$n = n_i e^{(F_n - E_i)/kT}$$

$$p = n_i e^{(E_i - F_p)/kT}$$

Fermi level is not constant ⇒ Current Flow

In summary

A p-n junction at equilibrium sees a depletion width and a built-in potential barrier. Their values depend on the individual doping concentrations

Forward biasing the junction shrinks the depletion width and the barrier, allowing thermionic emission and higher current. The current is driven by the splitting of the quasi-Fermi levels

Reverse biasing the junction extends the depletion width and the barrier, cutting off current and creating a strong I-V asymmetry

In the next lecture, we'll make this analysis quantitative by solving the MCDE with suitable boundary conditions