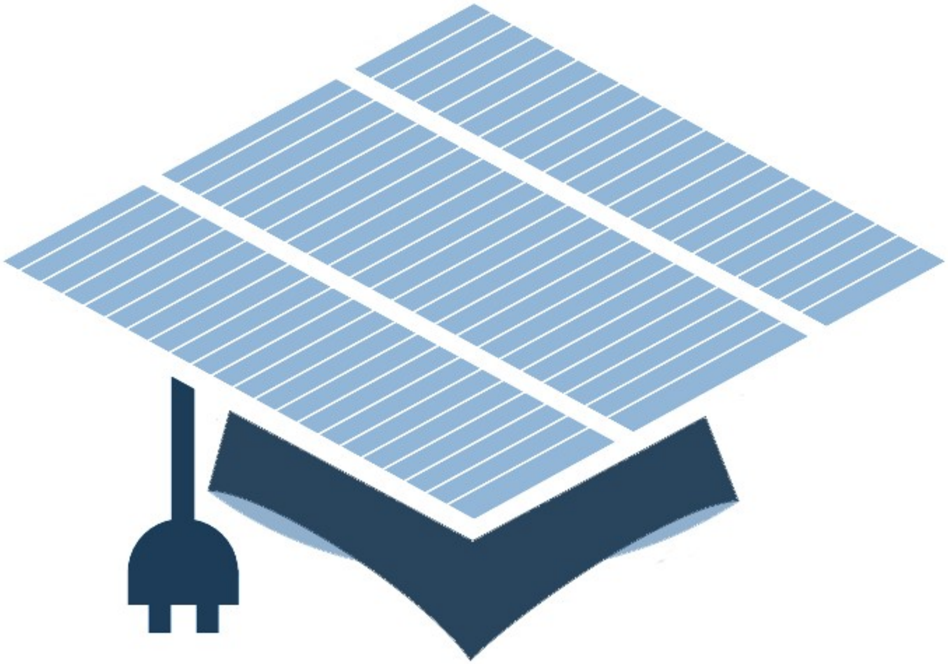


Lecture 5
Junctions!

R. Treharne

Nov 6th 2014

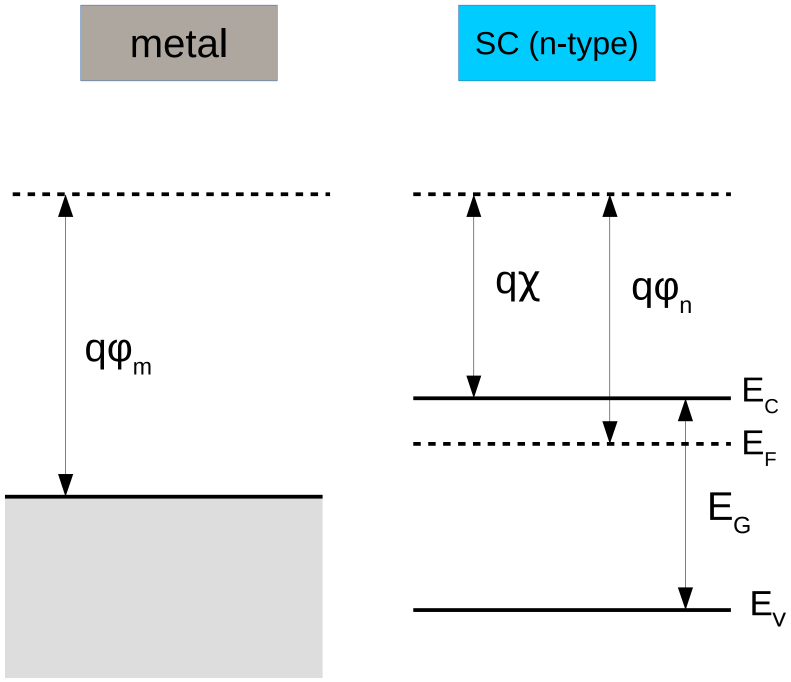
UNIVERSITY OF LIVERPOOL

Lecture Outline

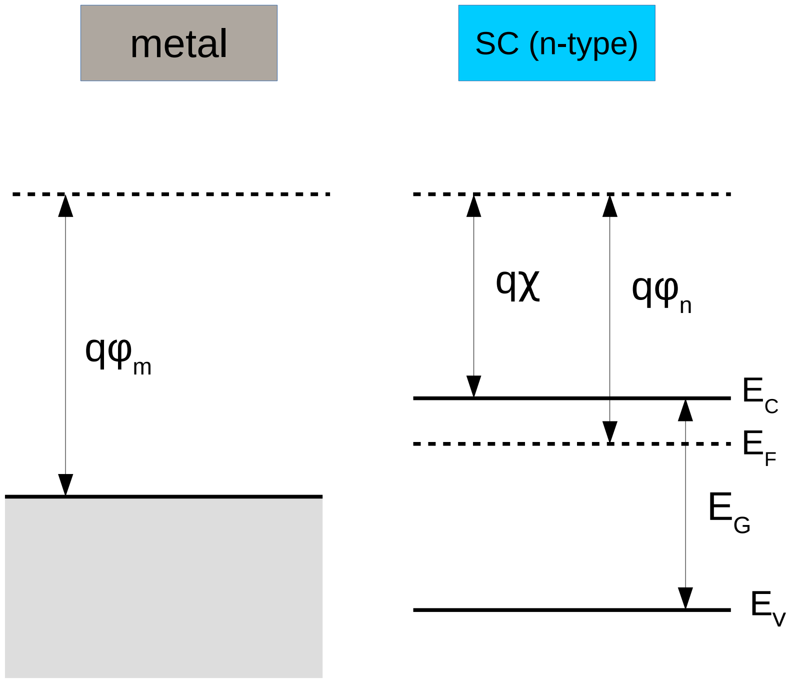
- Drawing Junctions
- Junction Formation – A Physical Picture
- Abrupt Junction
- Deriving Important Junction parameters
- Deriving diode equation
- Ideality Factor - Recombination

Metal-Semiconductor

Schottky Junction



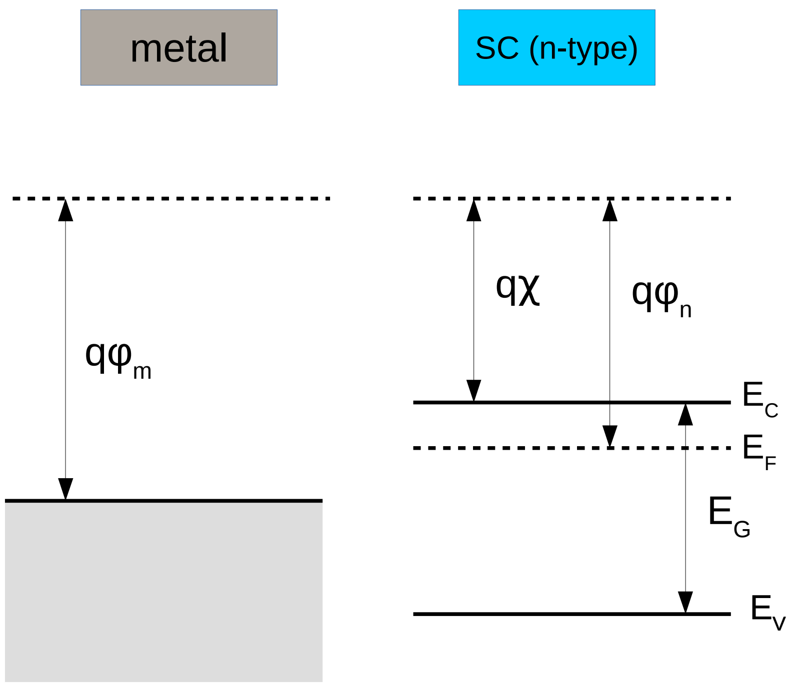
Metal-Semiconductor



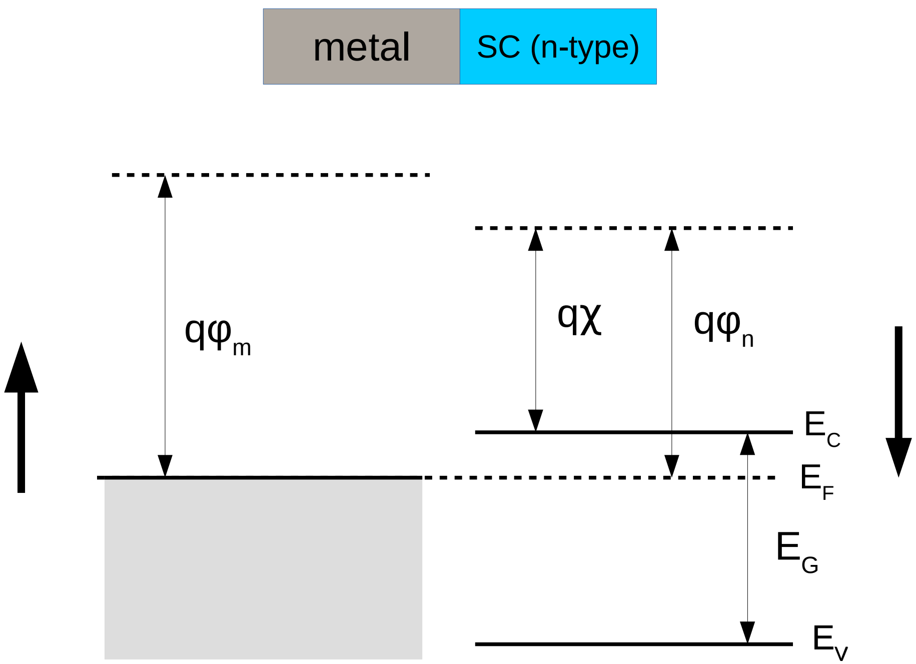
One Rule!

- Fermi level must be in equilibrium

Metal-Semiconductor



"Intimate Contact"



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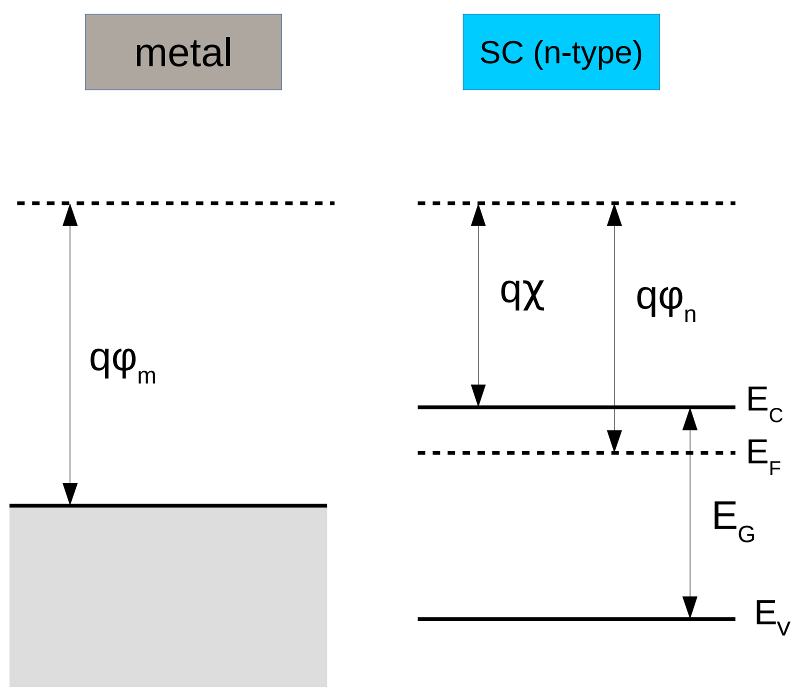
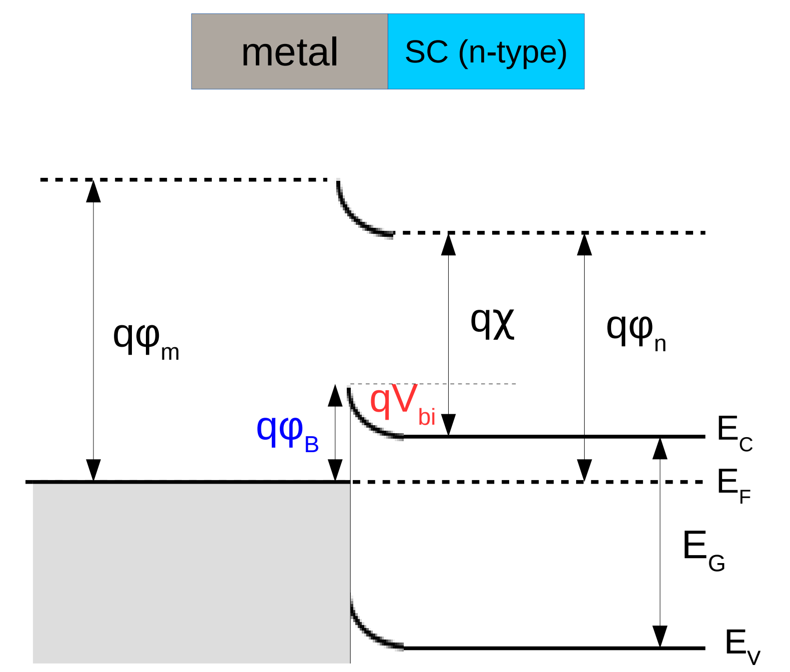
Metal-Semiconductor



BAND BENDING!



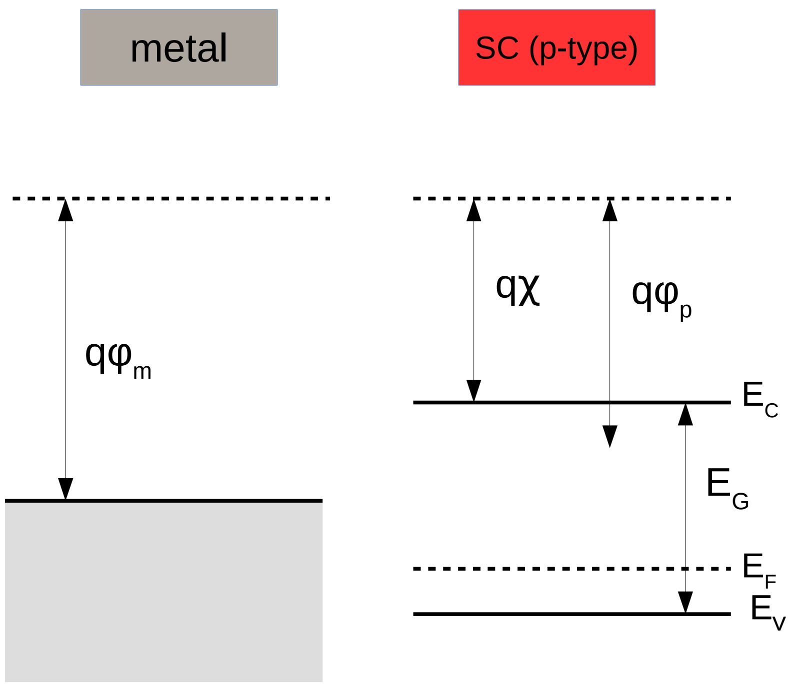
"Built-in Voltage"

$$V_{bi} = \varphi_m - \varphi_s$$

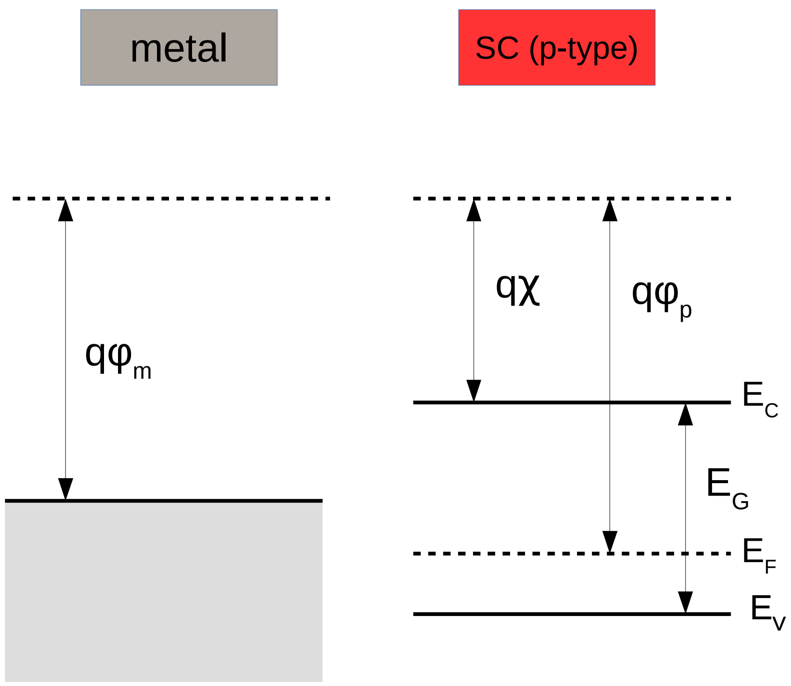
$$\varphi_B = \varphi_m - \chi$$

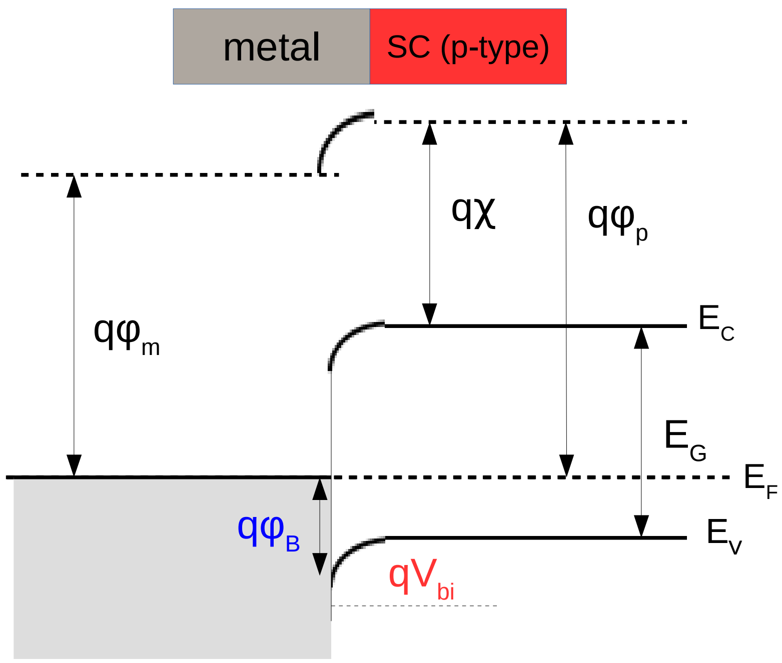
Barrier Height

Metal-Semiconductor



Metal-Semiconductor



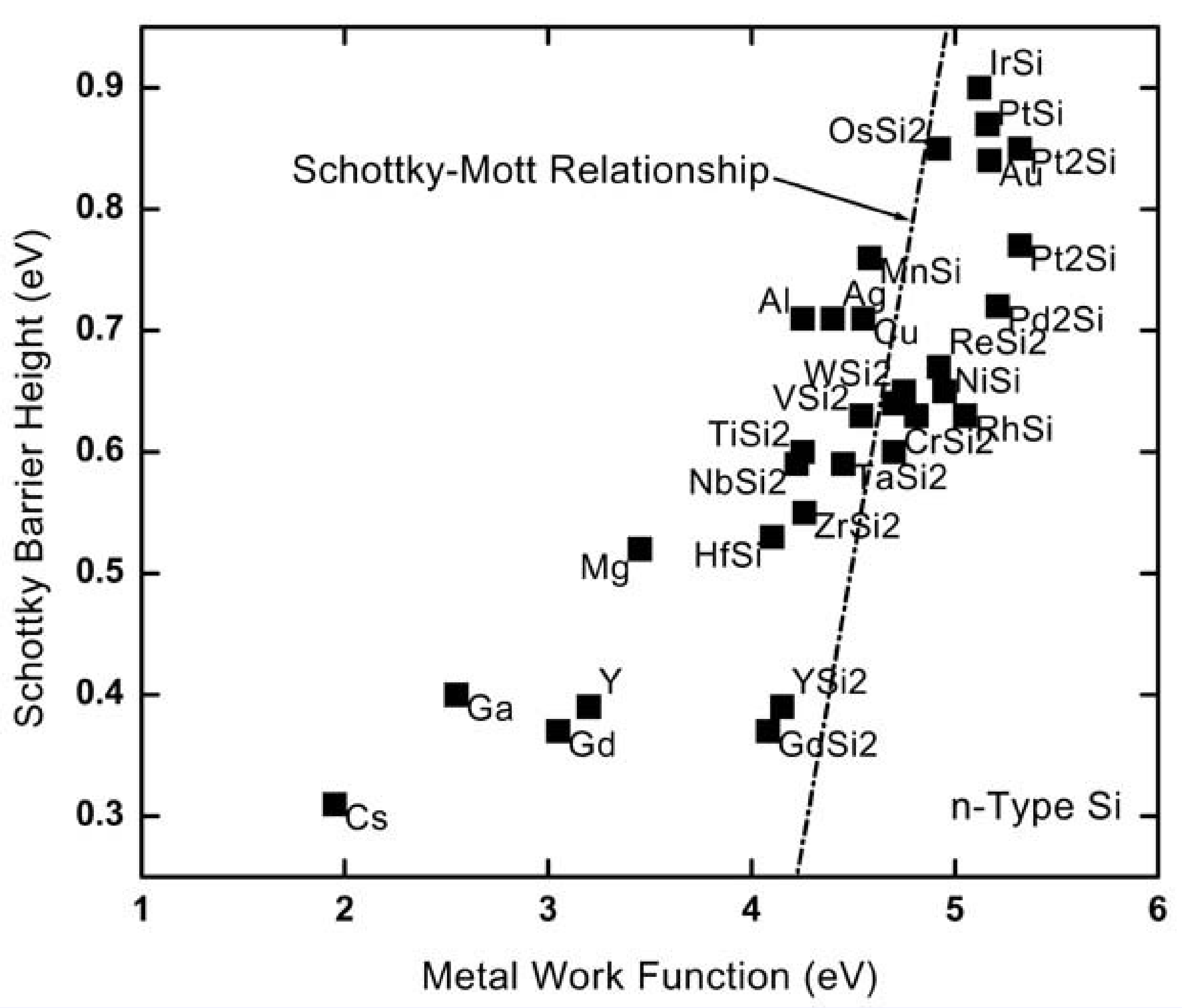


$$V_{bi} = \varphi_m - \varphi_p$$

$$\varphi_B = E_G/q - (\varphi_m - \chi)$$

Metal-Semiconductor

$\varphi_B = \varphi_m - \chi$ → Why doesn't this rule hold?

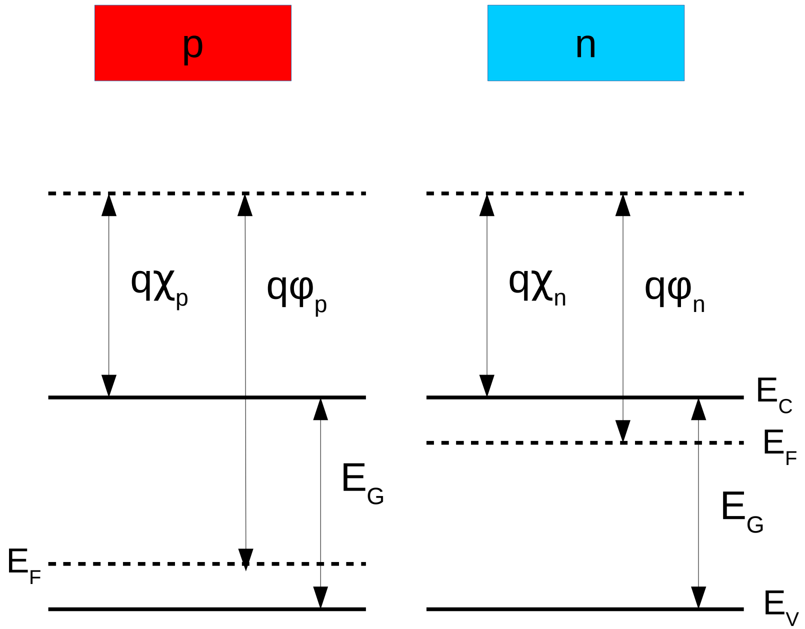


Metal – SC interface effects

- Lattice Mis-match
- High density of defects
- Interface states in gap

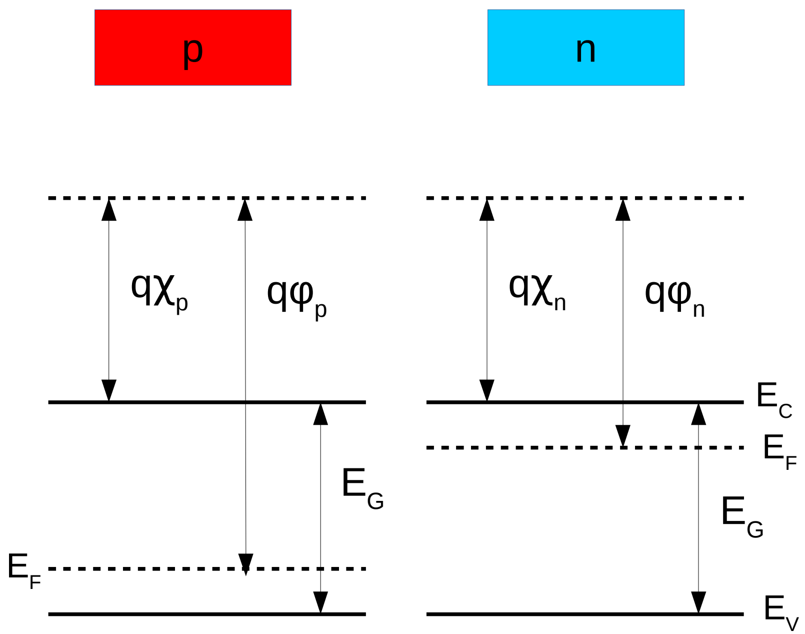
Semiconductor-Semiconductor

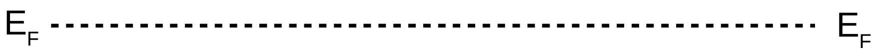
p-n homojunction



Semiconductor-Semiconductor

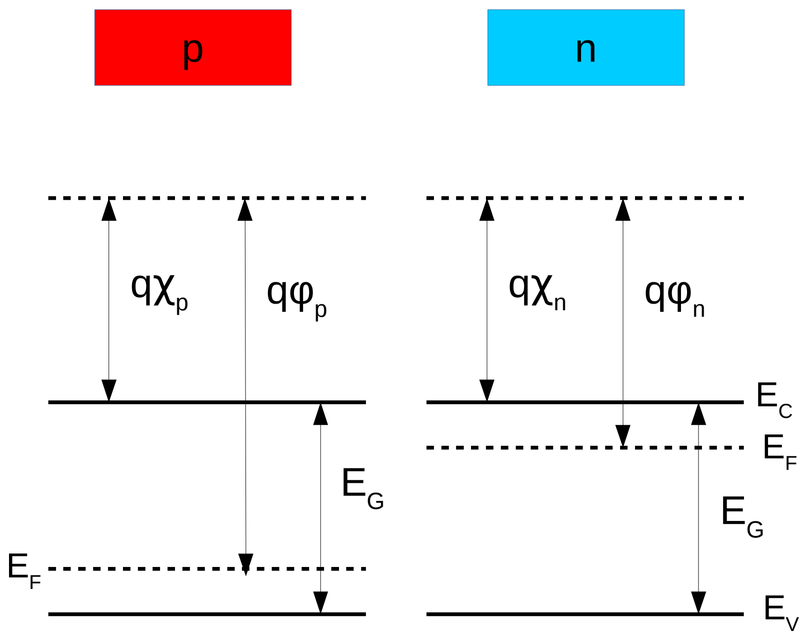
p-n homojunction

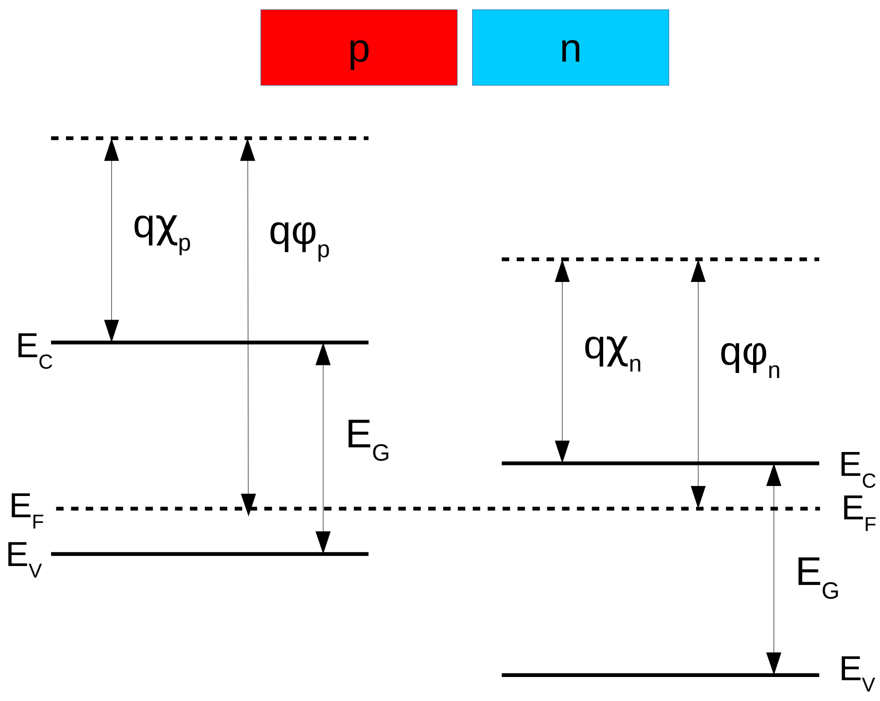




Semiconductor-Semiconductor

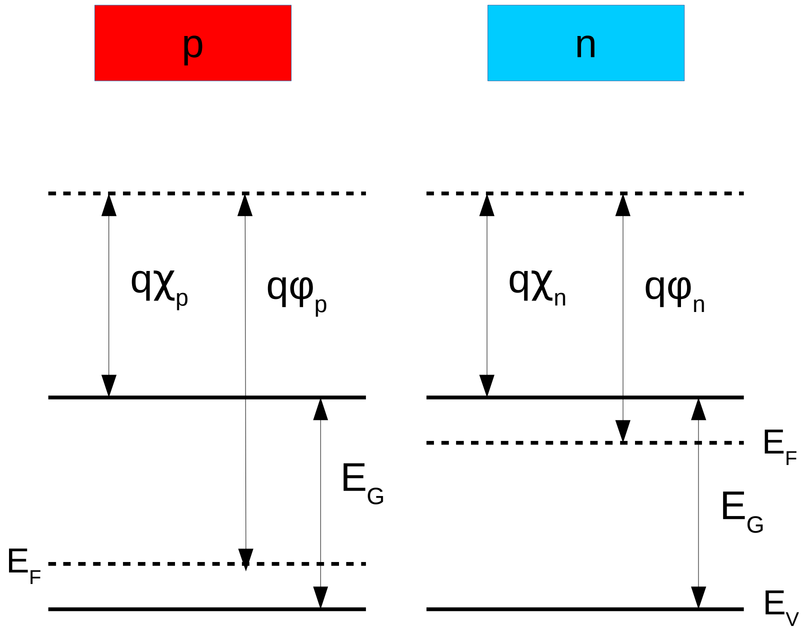
p-n homojunction

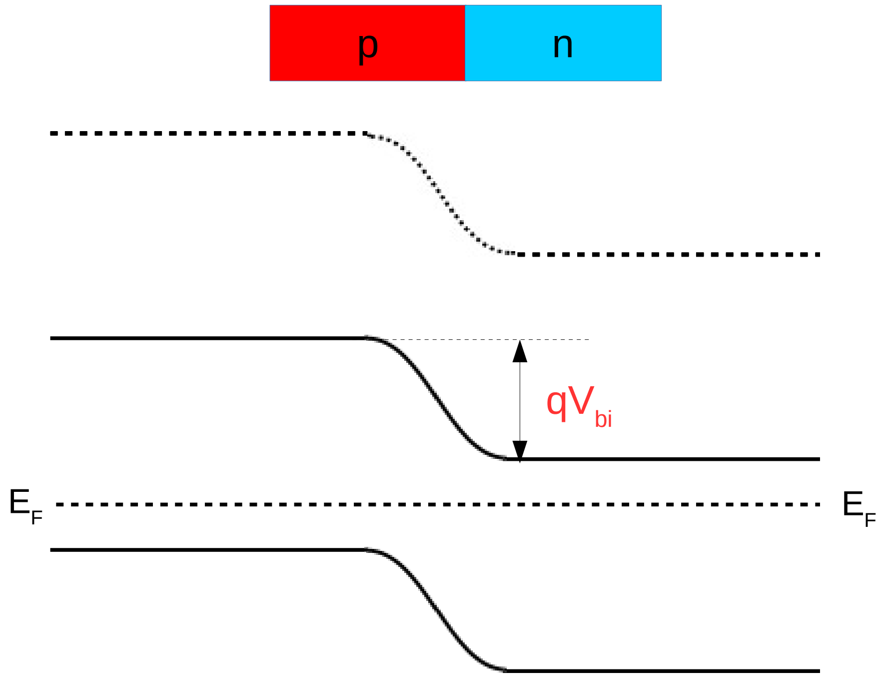




Semiconductor-Semiconductor

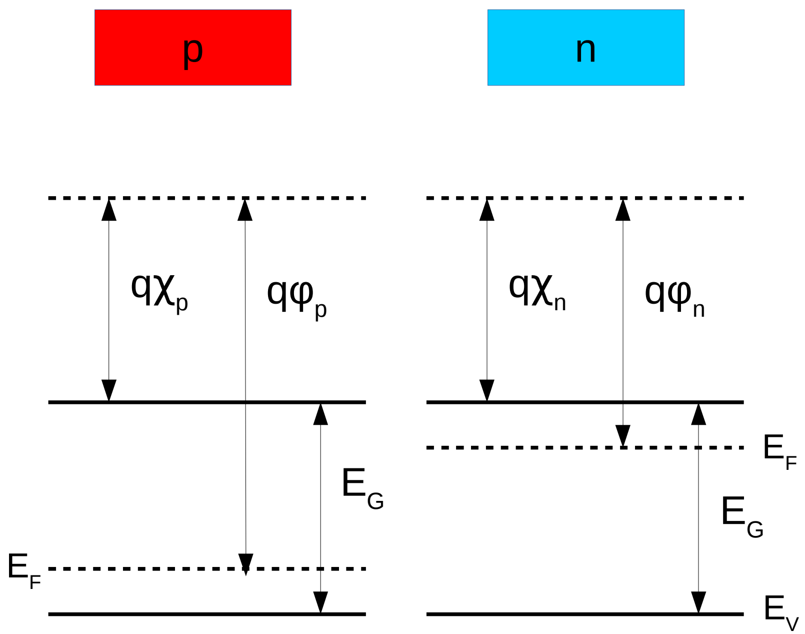
p-n homojunction

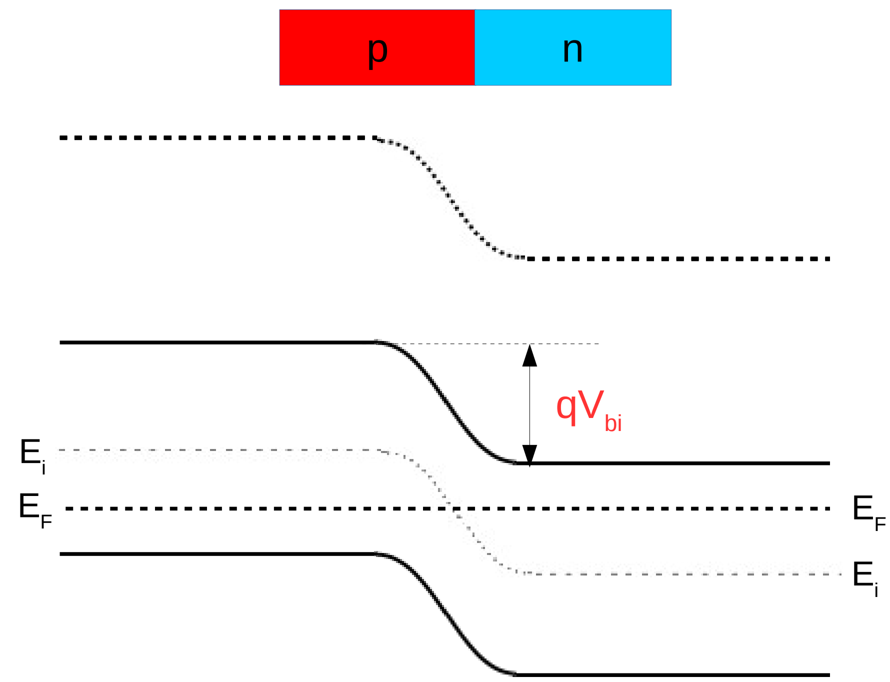




Semiconductor-Semiconductor

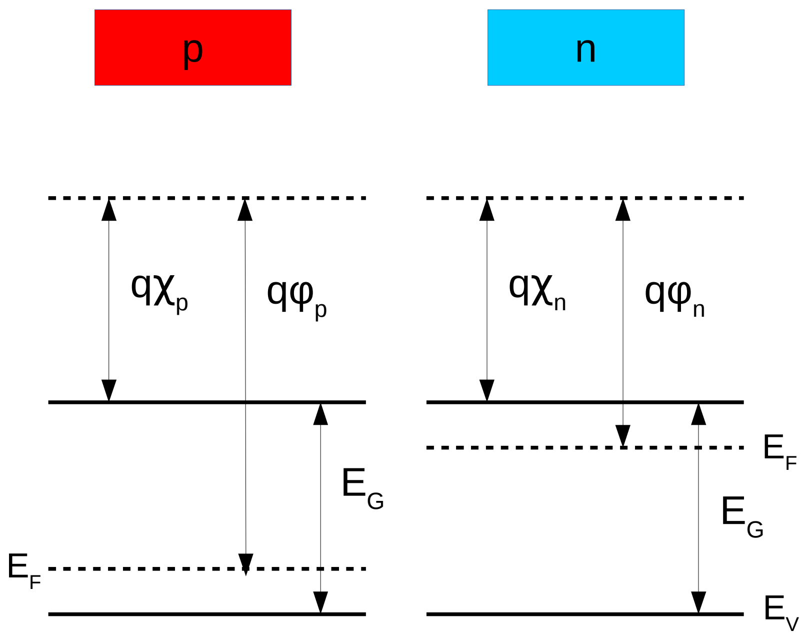
p-n homojunction





Semiconductor-Semiconductor

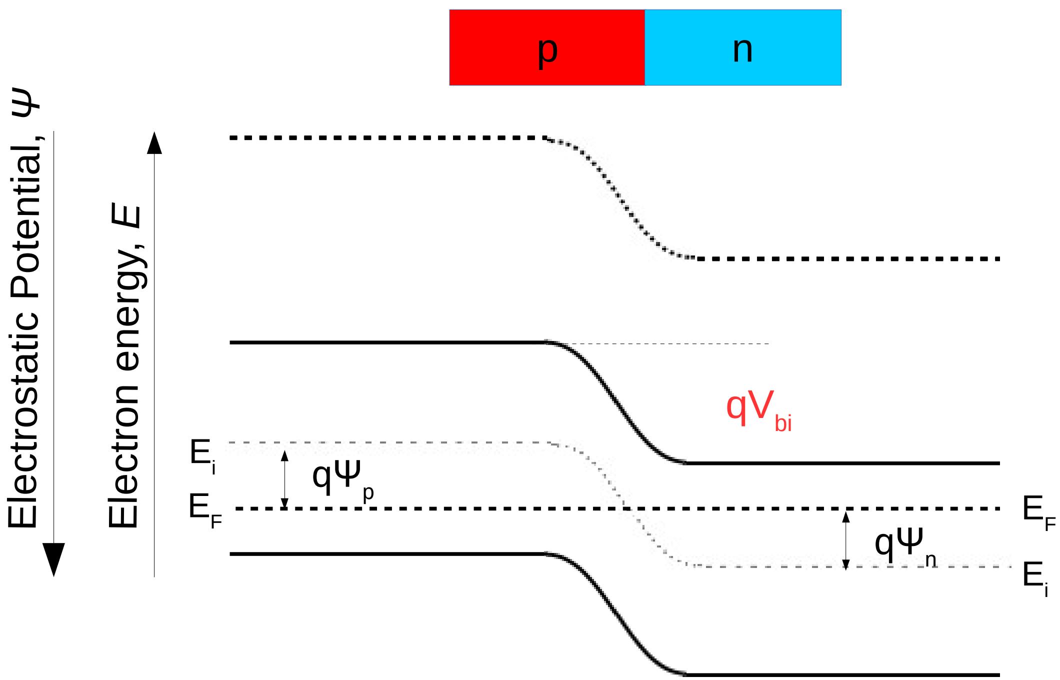
p-n homojunction



KNOW HOW TO DRAW THIS!

Defining Electrostatic potential, Ψ, for a SC

- Difference between E_i and E_f



$$\boxed{V_{bi} = \Psi_n - \Psi_p}$$

Coming back here shortly to get a more physical picture

Semiconductor-Semiconductor

Everybody's favourite homojunction - Silicon

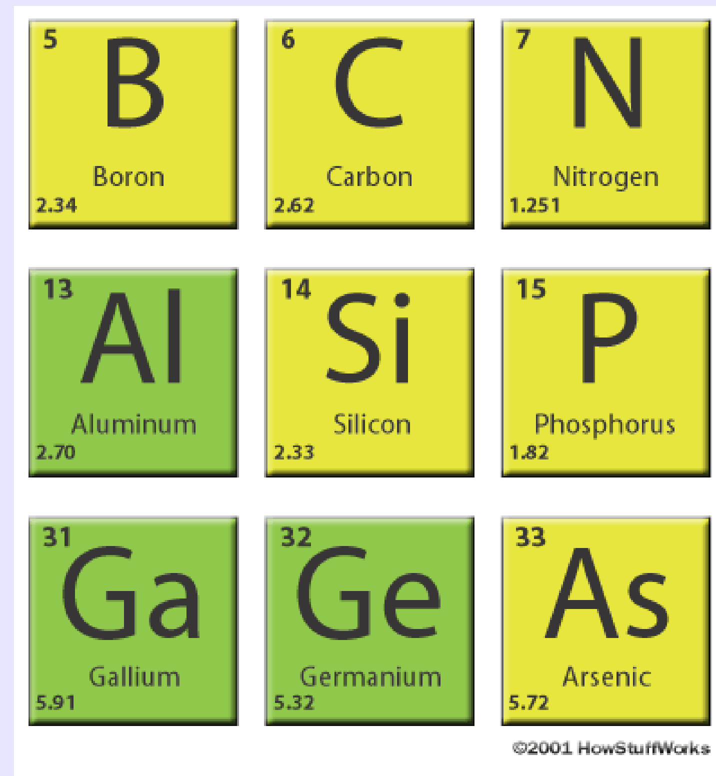
Every bit of electronics you own is jam packed with silicon homojunctions

iPhone 5:
1 billion transistors!
~ 45 nm wide

Mono-C solar cells
~750 μm thick
cell size = 1 cm^2

Extrinsically doped

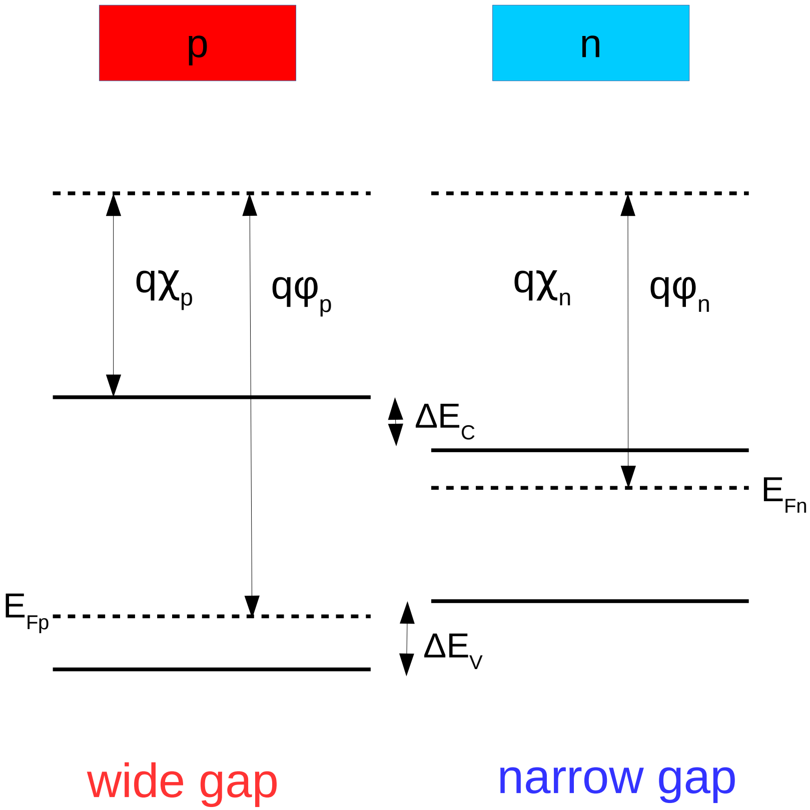
p-type n-type



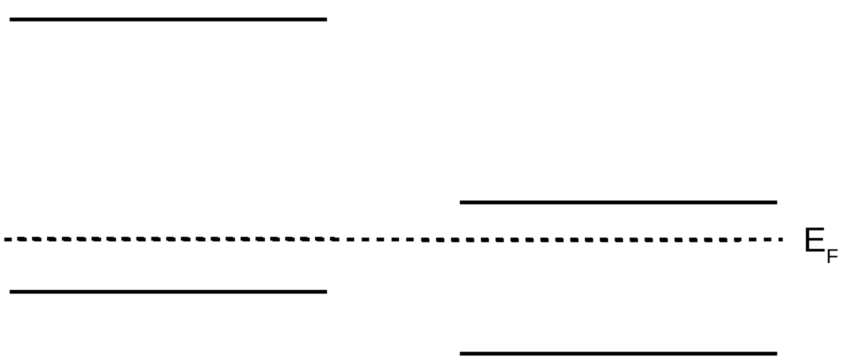
http://electronics.howstuffworks.com/diode1.htm

Semiconductor-Semiconductor

p-n heterojunction: **Different band gaps**

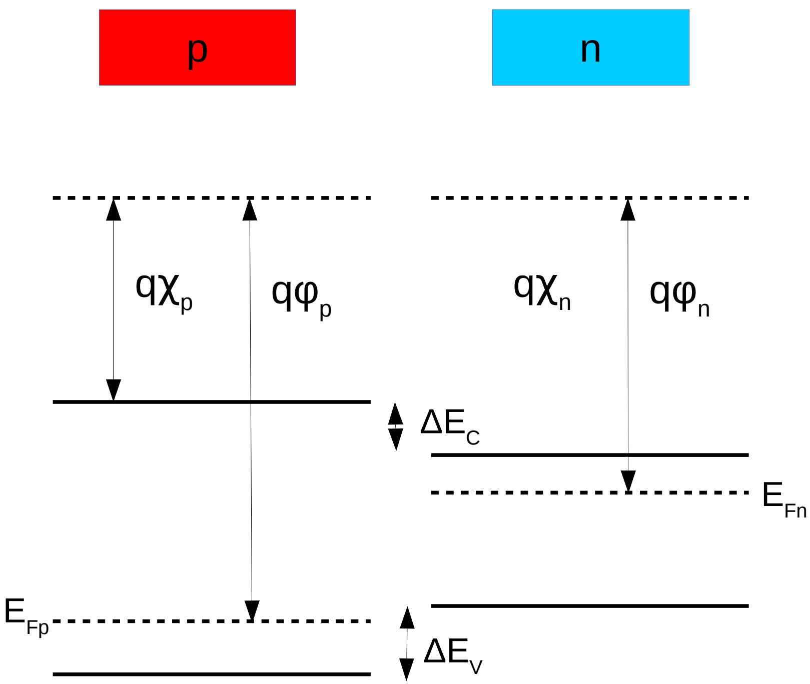


1. Align the Fermi level. Leave some space for transition region.



Semiconductor-Semiconductor

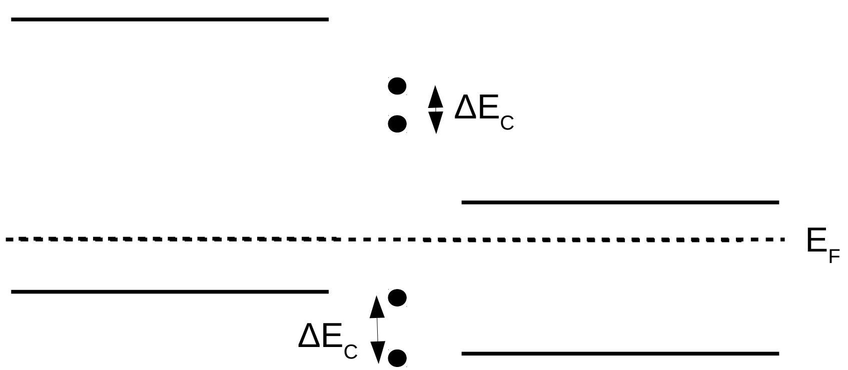
p-n heterojunction: **<u>Different band gaps</u>**



wide gap

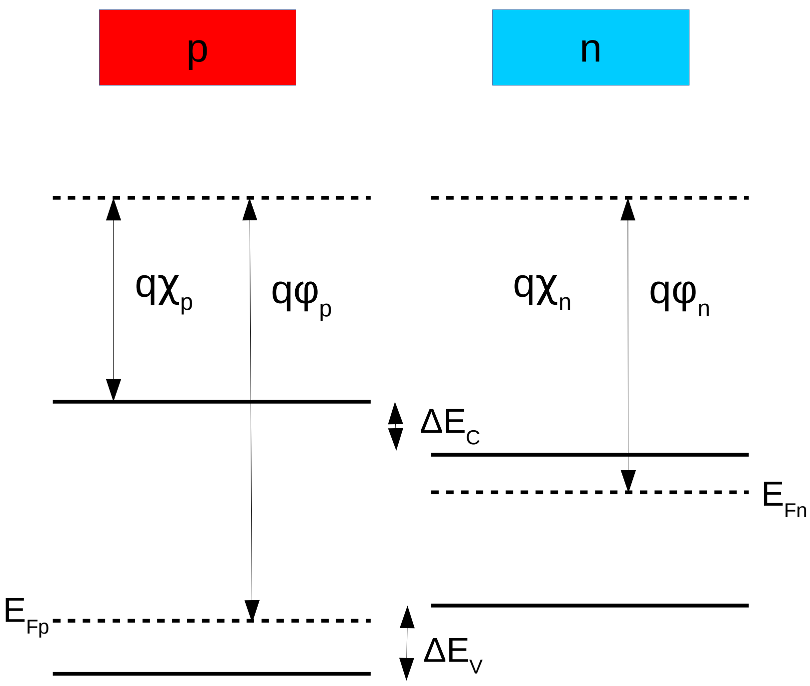
narrow gap

2. Mark out ΔE_C and ΔE_C at mid-way points



Semiconductor-Semiconductor

p-n heterojunction: **<u>Different band gaps</u>**

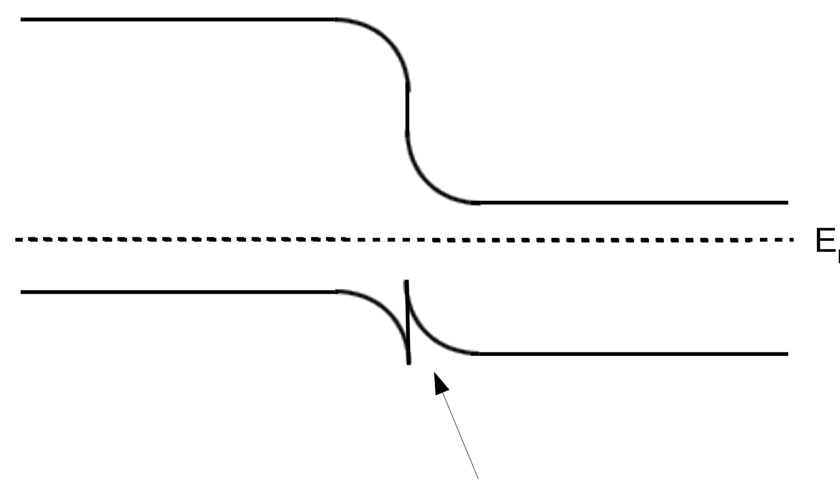


wide gap

narrow gap

3. Connect the C.B. and V.B. keeping the band gap constant in each material

Difference in band gaps give rise to **discontinuities** in band diagrams. This limits the carrier transport by introducing potential barriers at the junction

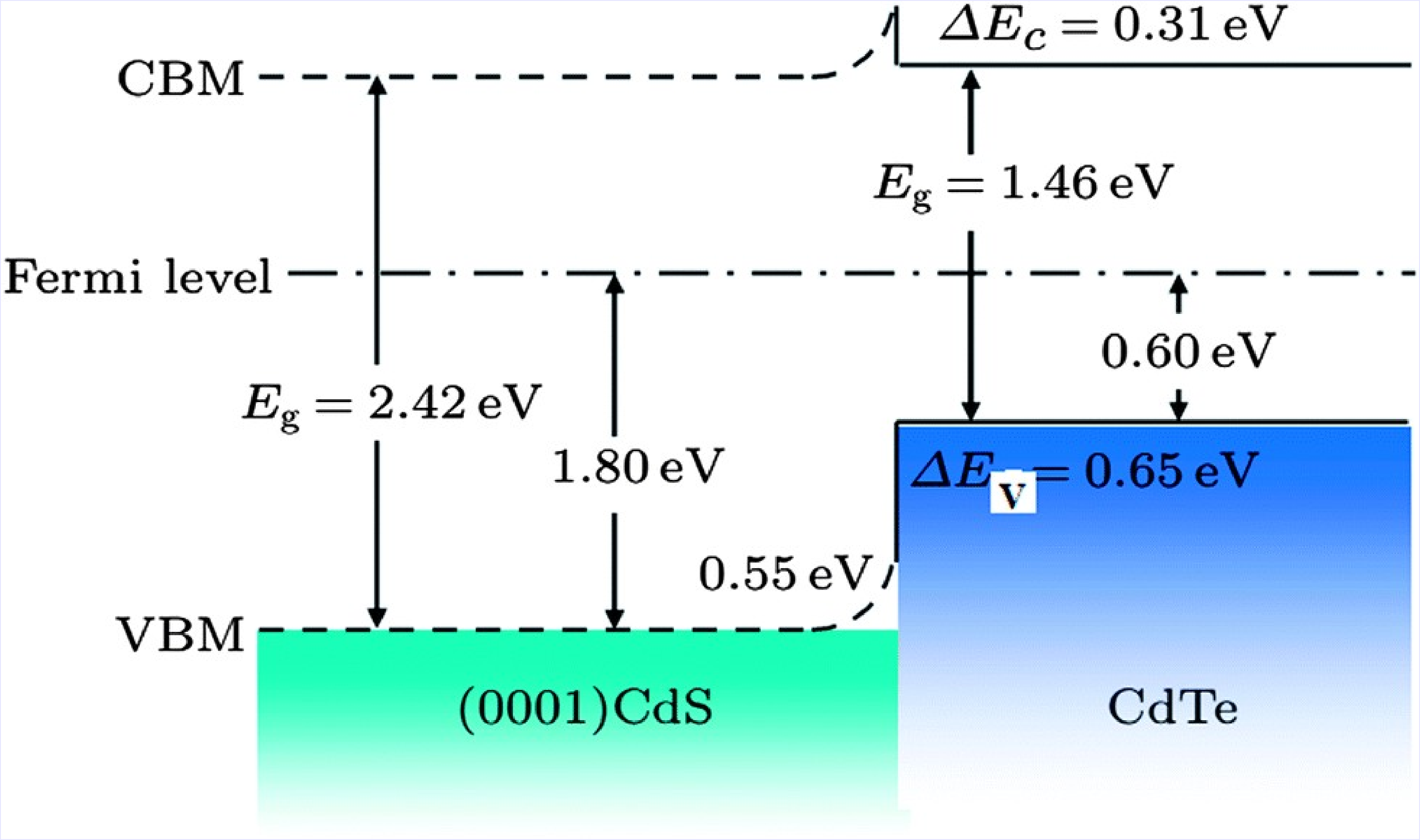


Barrier to hole transport

Semiconductor-Semiconductor

Examples of p-n heterojections

Most thin-film PV technologies

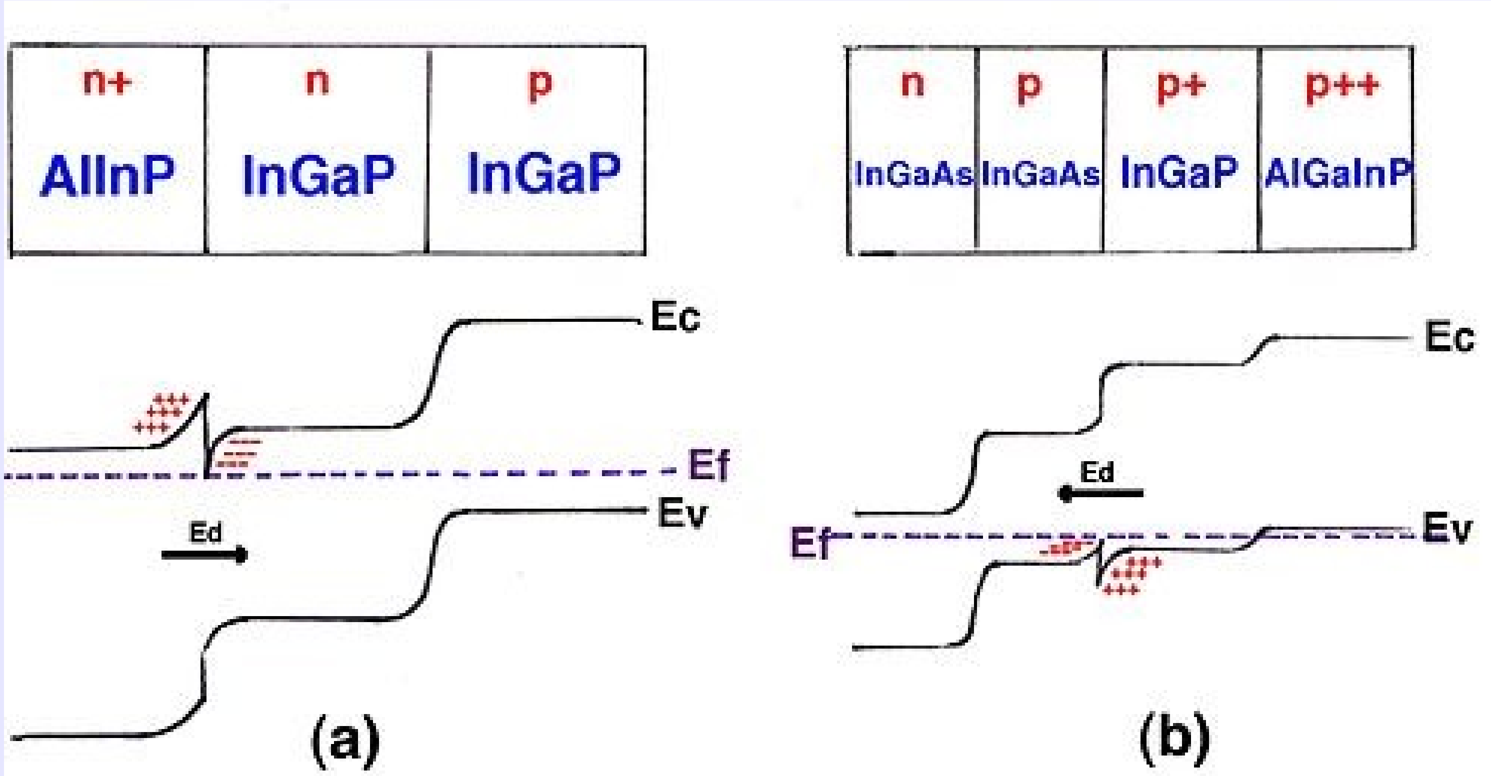


http://pubs.rsc.org/en/content/articlehtml/2013/ee/c3ee41981a#cit111

Semiconductor-Semiconductor

Examples of p-n heterojections

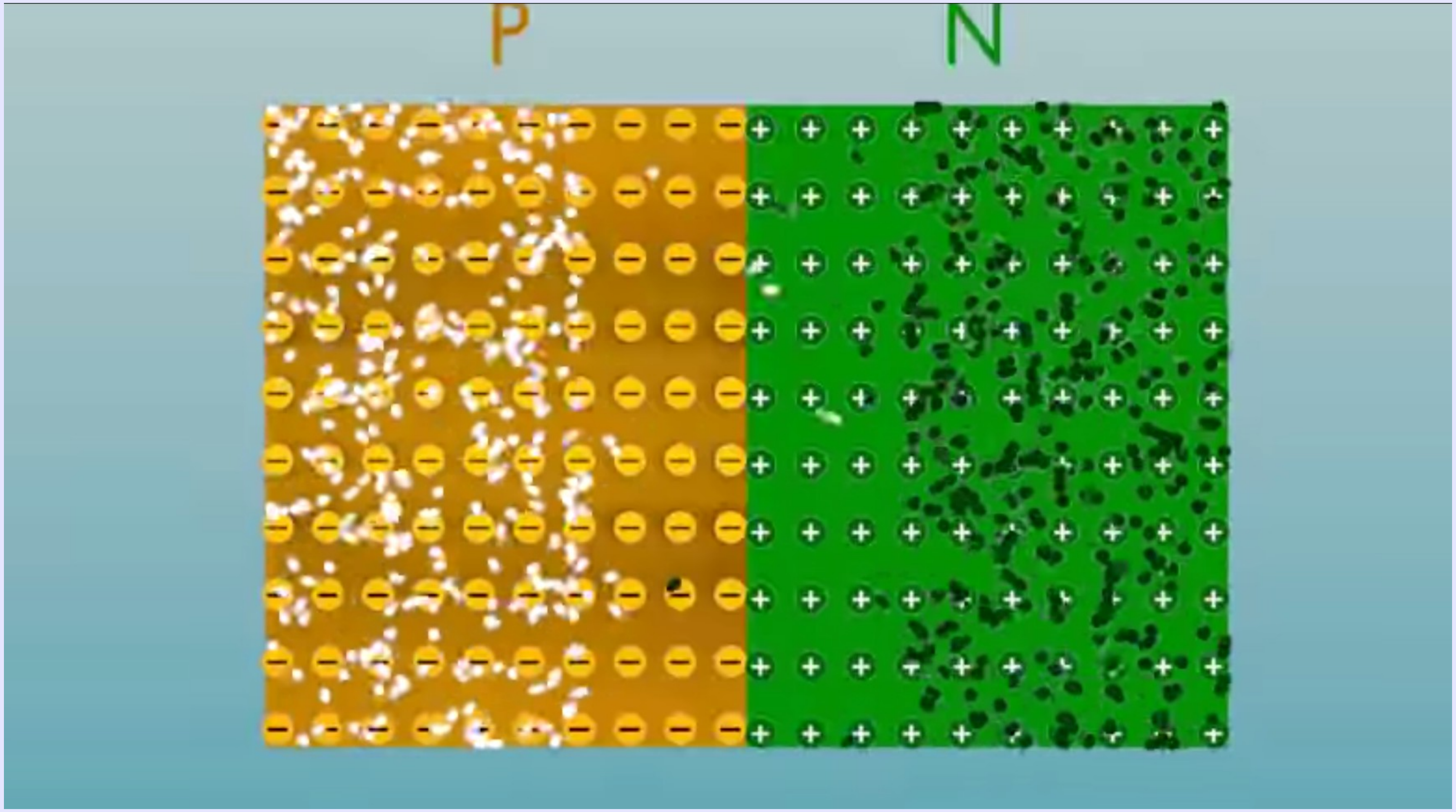
III-V multi-junction devices



Being able to control the band offsets of a material can help eliminate barriers

Physical Picture

Drawing band schematics for junctions all day is fun, but what is actually going on here?



http://www.youtube.com/watch?v=JBtEckh3L9Q

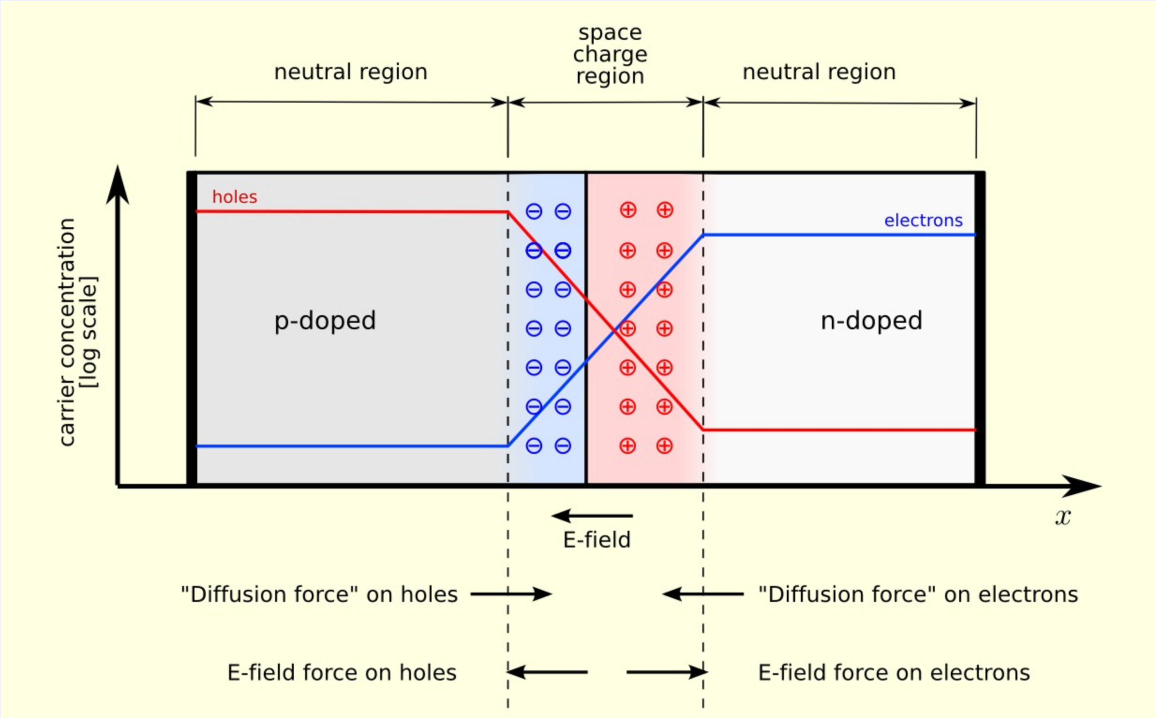
Excellent qualitative description

6:27 – Didactic Model of Junction formation

Physical Picture

Equilibrium Fermi Levels – Explained – our one rule for drawing band schematics!

In thermal equilibrium, i.e. steady state: not net current flows



notice position of “metallurgical” junction. Usually call this **x=0**

$$J = J\left(drift\right) + J\left(diffusion\right) = 0$$

http://en.wikipedia.org/wiki/File:Pn-junction-equilibrium.png

Physical Picture

Lets look at hole current first:

$$
\begin{aligned}
J_p &= J_p(drift) + J_p(diffusion) \\
&= q\mu_p p \xi - qD_p \frac{dp}{dx}
\end{aligned}
$$

Physical Picture

Lets look at hole current first:

$$J_p = J_p(drift) + J_p(diffusion)$$

$$= q\mu_p p \xi - qD_p \frac{dp}{dx}$$

mobility:

$$\mu_p = \frac{e\tau}{m_h}$$

hole distribution:

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

OK to use Boltzmann as
approx to Fermi-Dirac

$$\frac{dp}{dx} = \frac{p}{k_B T}\left(\frac{dE_i}{dx} - \frac{dE_F}{dx}\right)$$

will use this shortly

e-field:

$$\xi = \frac{1}{e}\frac{dE_i}{dx}$$

diffusion coefficient

$$D_p = (k_B T / e)\mu_p$$

Einstein relation

Physical Picture

$$
\begin{aligned}
J_p &= J_p(drift) + J_p(diffusion) \\
&= q\mu_p p\xi - qD_p \frac{dp}{dx} \\
&= \mu_p p \frac{dE_i}{dx} - \mu_p p \left(\frac{dE_i}{dx} - \frac{dE_F}{dx} \right) \\
0 &= \mu_p p \frac{dE_F}{dx}
\end{aligned}
$$

Condition for steady state

TA DA!

$$\boxed{\frac{dE_F}{dx} = 0}$$

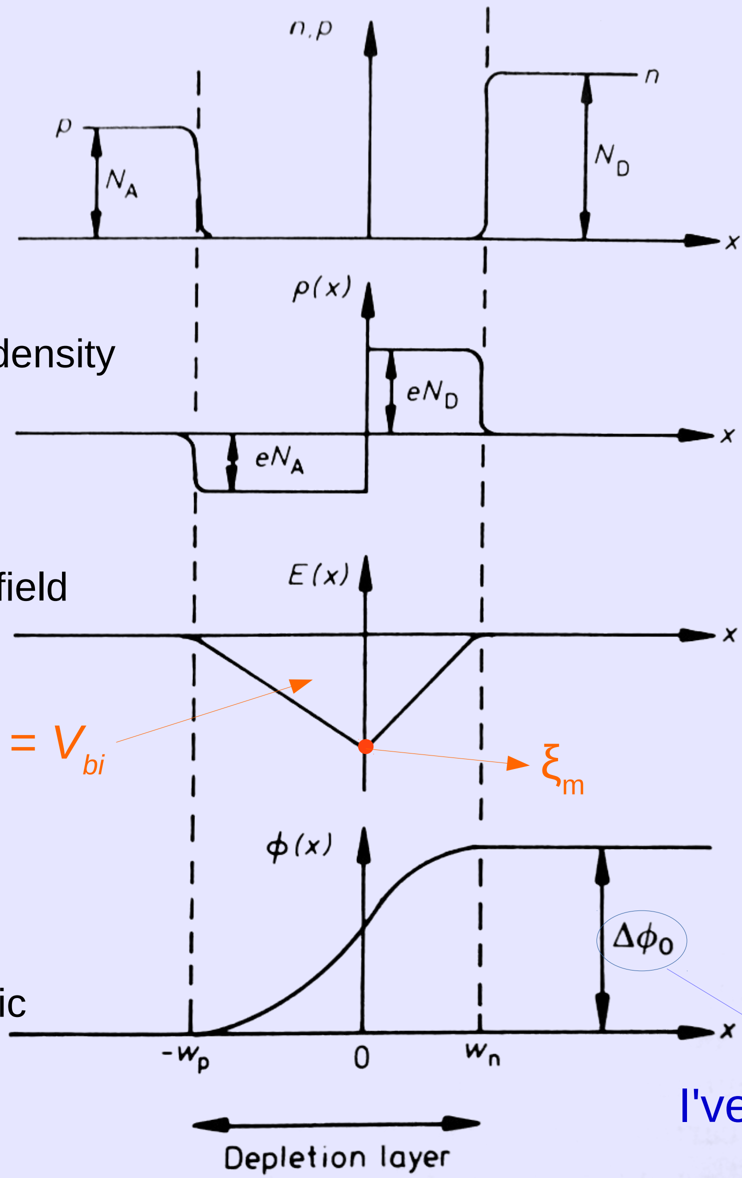
The same is true from consideration of net electron current, J_n

Abrupt Junction

charge density

electric field

electrostatic
potential



outside depletion region:

$$p = N_A \text{ and } n = N_D$$

Space-charge condition

$$N_A w_p = N_d w_n$$

i.e. areas of rectangles must be the same

Max field (at x=0):

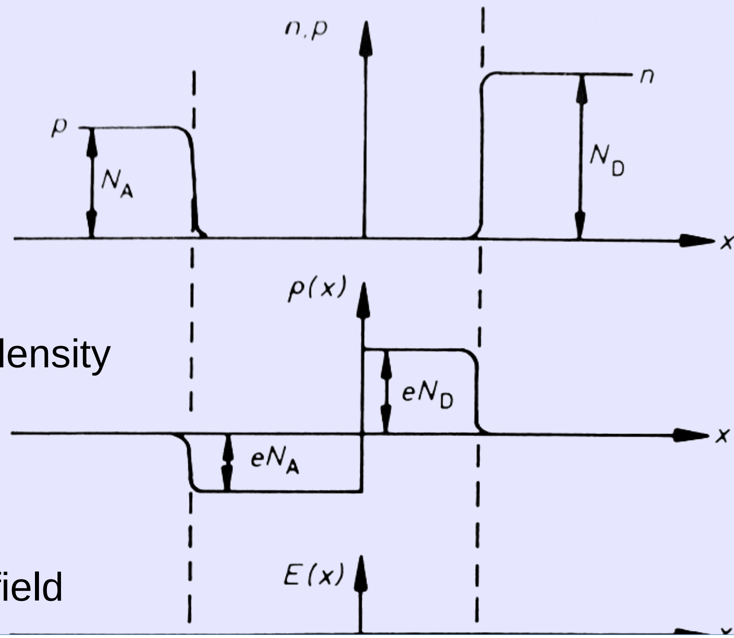
$$\xi_m = qN_D x_n/\varepsilon_s = qN_A x_p/\varepsilon_s$$

$$V_{bi} = \varphi_n - \varphi_p = \frac{k_B T}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

I've already called this V_{bi}

Hook & Hall, *“Soild State Physics”*, 2nd ed. Chap 6, p. 171

Abrupt Junction



charge density

electric field

Are

electros
potentia

Depletion layer

Lets derive this!
(but skip if I'm being slow)

outside depletion region:

$$p = N_A \text{ and } n = N_D$$

Space-charge condition

$$N_A w_p = N_d w_n$$

i.e. areas of rectangles must be the same

Max field (at x=0):

$$\xi_m = qN_D x_n/\varepsilon_s = qN_A x_p/\varepsilon_s$$

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eady called this V_{bi}

Hook & Hall, *“Soild State Physics”*, 2nd ed. Chap 6, p. 171

Abrupt Junction

From Earlier:

$$\varphi = -\frac{1}{e}\left(E_i - E_F\right)$$

What is φ in p and n regions away from junction?

Here

$$p = n_i e^{(E_i - E_F)/k_B T} \quad \text{and} \quad n = n_i e^{(E_i - E_F)/k_B T}$$

$$\varphi_p \equiv -\frac{1}{e}\left(E_i - E_F\right)\Big|_{x \leqslant -x_p} = -\frac{k_B T}{e}\left(\frac{N_A}{n_i}\right)$$

$$\varphi_n \equiv -\frac{1}{e}\left(E_i - E_F\right)\Big|_{x \geqslant -x_n} = -\frac{k_B T}{e}\left(\frac{N_D}{n_i}\right)$$

S. M. Sze, "Semiconductor Devices: Physics and Technology", Chap 4, p.90

Abrupt Junction

Hence:

$$\boxed{V_{bi}=\varphi_n-\varphi_p=\frac{k_B T}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)}$$

want to know what this is for Si?
Go to: http://pveducation.org/pvcdrom/pn-junction/intrinsic-carrier-concentration

Next Question:

How do I calculate φ in the depletion region? (And why would I want to?)

Must solve Poisson's Equation

Go read some electrostatics if you're interested

$$\boxed{\nabla^2\varphi=-\frac{\rho}{\varepsilon}}$$

Abrupt Junction

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon}$$

$$\rho(x) = \begin{cases} -N_A e & -w_p < x < 0 \\ +N_D e & 0 < x < w_n \\ 0 & elsewhere \end{cases}$$

INTEGRATE ONCE

$$\xi = -\frac{d\varphi}{dx} = \begin{cases} -\frac{N_A e}{\varepsilon}\left(x + w_p\right) & -w_p < x < 0 \\ \frac{N_D e}{\varepsilon}\left(x + w_n\right) & 0 < x < w_n \end{cases}$$

INTEGRATE TWICE

$$\varphi(x) = \begin{cases} -\frac{N_A e}{2\varepsilon}\left(x + w_p\right)^2 & -w_p < x < 0 \\ \frac{N_D e}{2\varepsilon}\left(x + w_n\right)^2 & 0 < x < w_n \end{cases}$$

Abrupt Junction

$$V_{bi}=\varphi(x=w_n)-\varphi(x=-w_p)$$

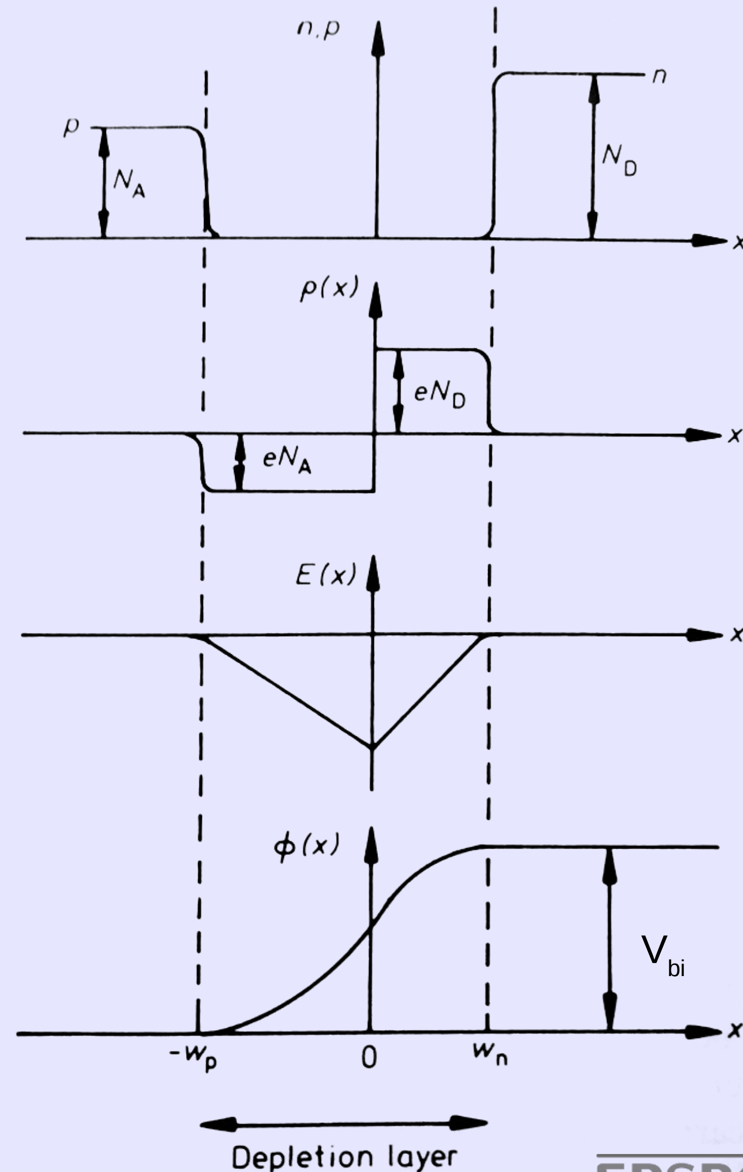
$$V_{bi}=\frac{e}{2\varepsilon}\left(N_A w_p^2+N_D w_n^2\right)$$

using result: $N_A w_p = N_D w_n$

$$\boxed{w_n=\sqrt{\frac{2\varepsilon N_A V_{bi}}{eN_D(N_A+N_D)}} \qquad w_p=\sqrt{\frac{2\varepsilon N_D V_{bi}}{eN_A(N_A+N_D)}}}$$

and with some jiggery pokery:

$$\boxed{W=w_p+w_n=\sqrt{\frac{2\varepsilon}{e}\left(\frac{N_A+N_D}{N_A N_D}\right)}}$$

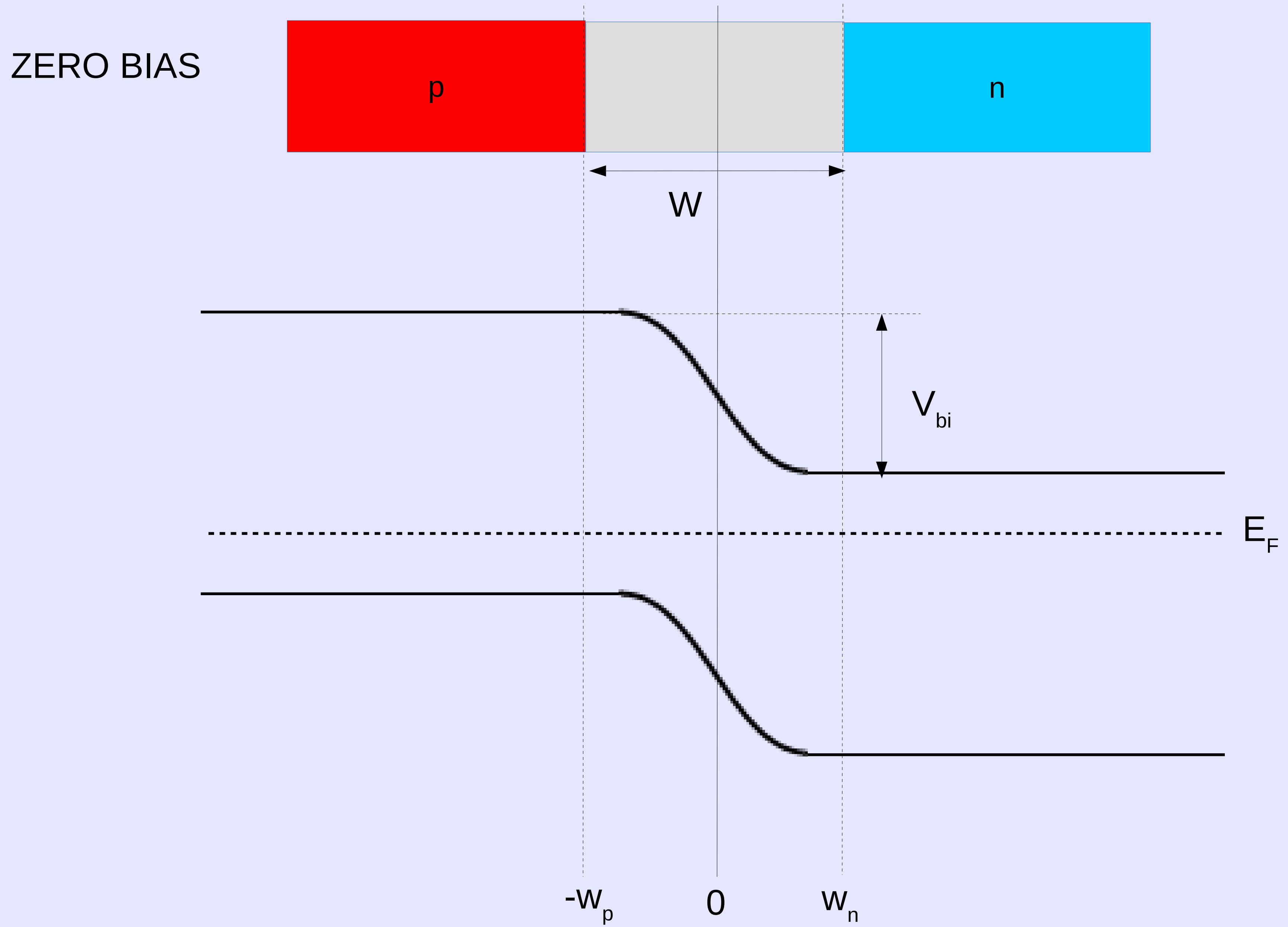


What happens to our ideal p-n junction if we put a forward or reverse bias across it?

CENTRE FOR DOCTORAL TRAINING
NEW AND SUSTAINABLE
PHOTOVOLTAICS

L5

Under Bias



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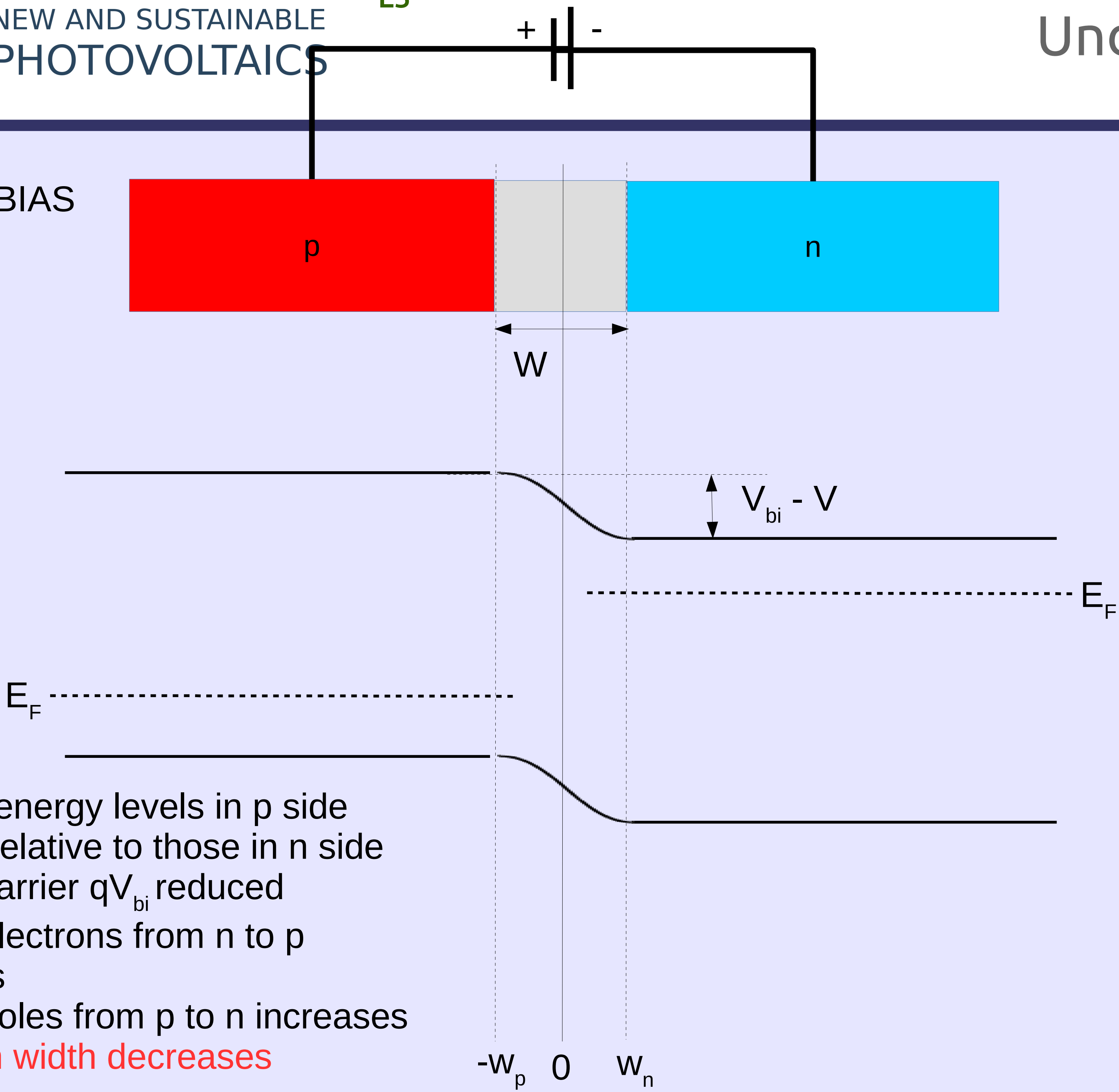
Under Bias

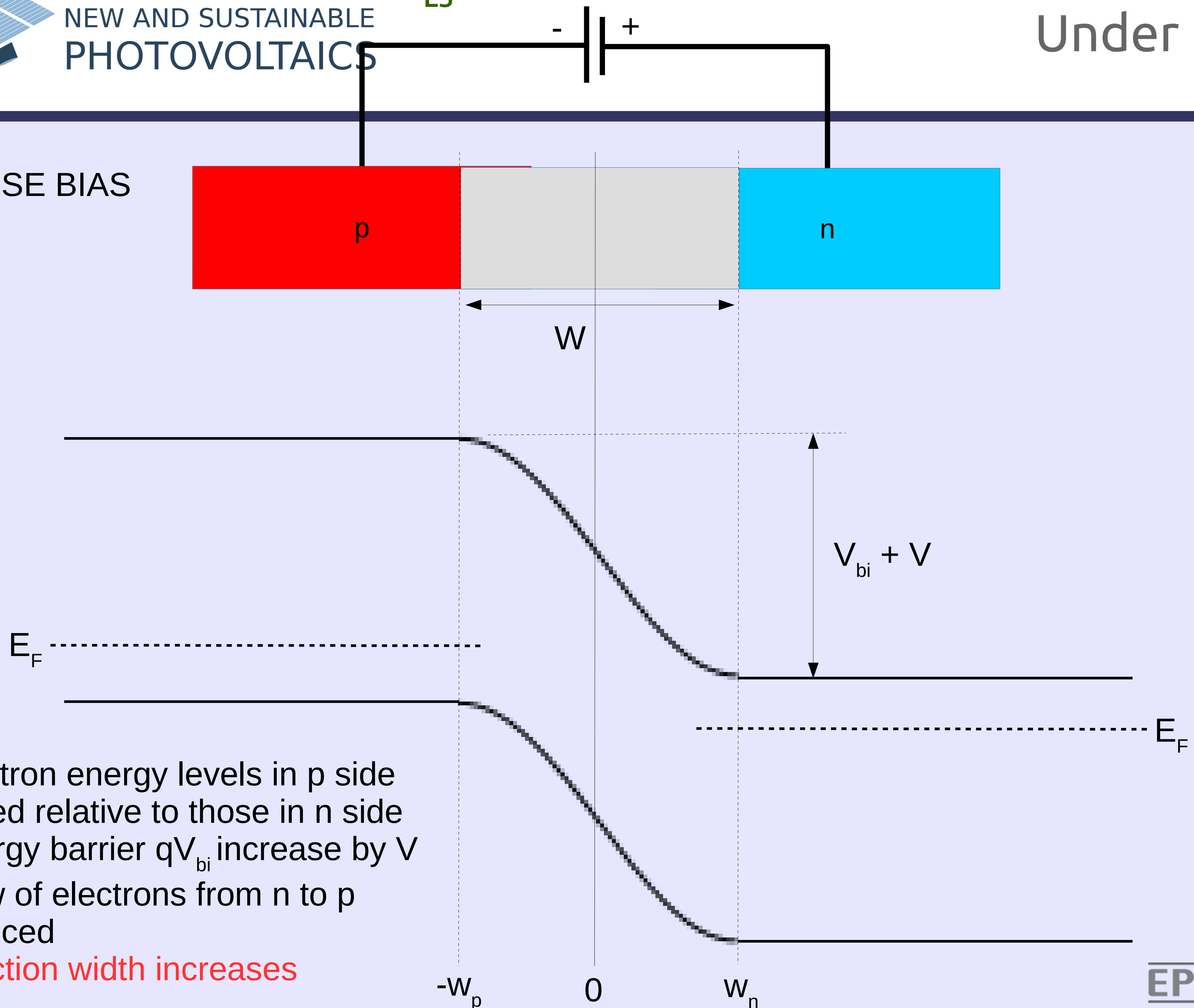
FORWARD BIAS



- Electron energy levels in p side lowered relative to those in n side
- Energy barrier qV_{bi} reduced
- Flow of electrons from n to p increases
- Flow of holes from p to n increases
- Depletion width decreases

Under Bias

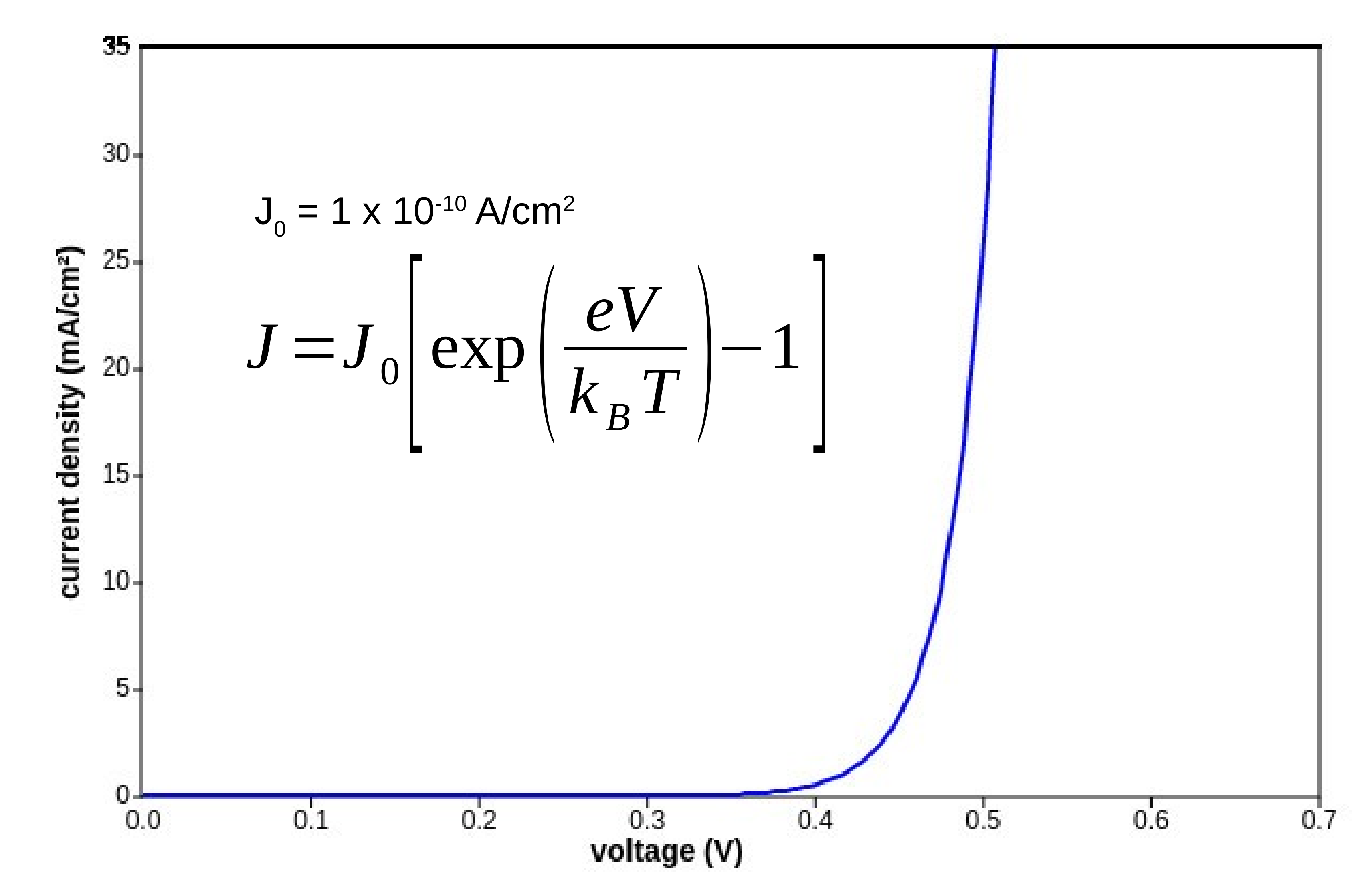
REVERSE BIAS



- Electron energy levels in p side raised relative to those in n side
- Energy barrier qV_{bi} increase by V
- Flow of electrons from n to p reduced
- Junction width increases

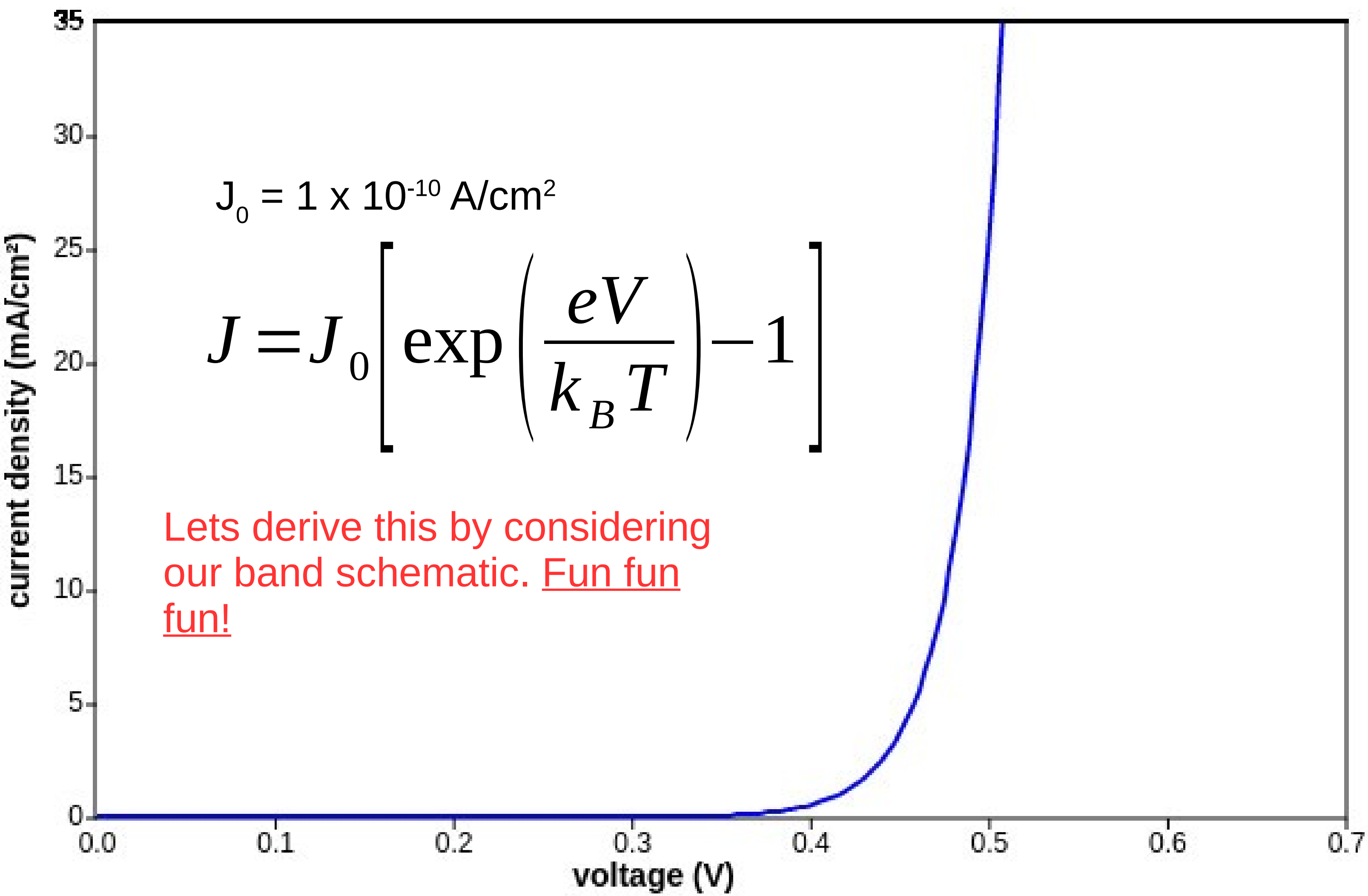
Of course, you already know all about this:

Ideal dark *JV* curve



http://pveducation.org/pvcdrom/pn-junction/diode-equation

Ideal dark *JV* curve



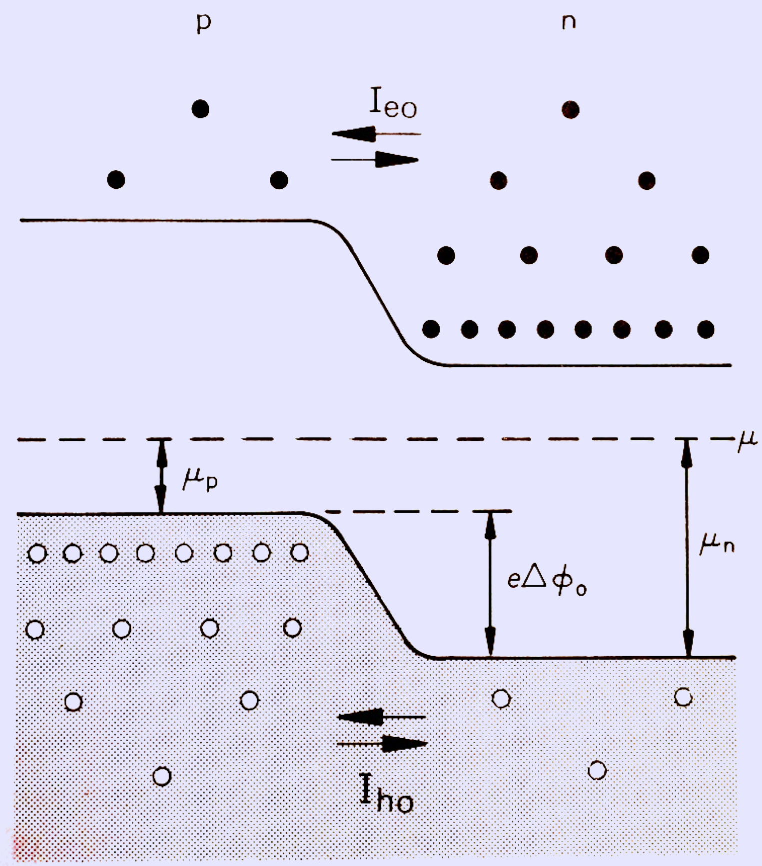
$J_0 = 1 \times 10^{-10}$ A/cm^2

$$J = J_0\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

Lets derive this by considering our band schematic. <u>Fun fun fun!</u>

http://pveducation.org/pvcdrom/pn-junction/diode-equation

Deriving Shockley Equation

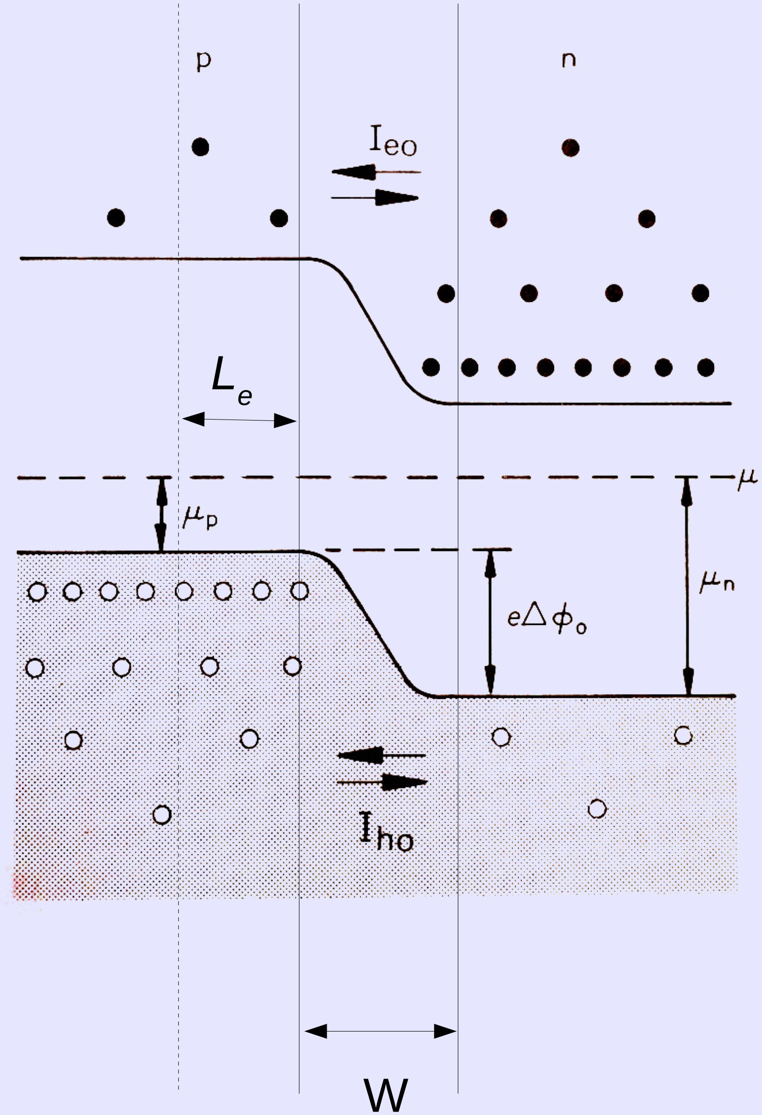


Steady State again (i.e. no bias)

Consider electron drift current

- I_{eo} from p to n

Deriving Shockley Equation



<u>Steady State again (i.e. no bias)</u>

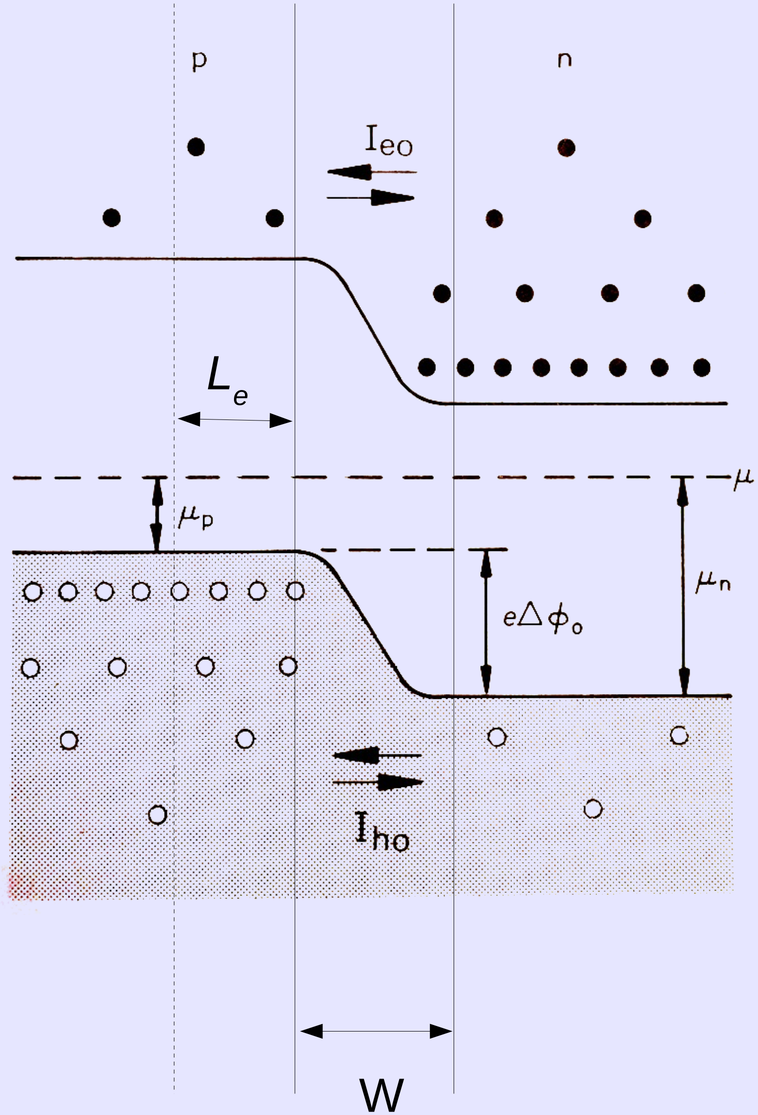
Consider electron drift current

– I_{eo} from *p* to *n*

$$I_{e0} = e \times (generation\ rate / volume) \times (volume\ within\ L_e\ of\ depletion\ zone)$$

$$J_{e0} = e\left(\frac{n_p}{\tau_p}\right) L_e$$

Deriving Shockley Equation



<u>Steady State again (i.e. no bias)</u>

Consider electron drift current

– I_{eo} from *p* to *n*

$$I_{e0} = e \times (generation\ rate / volume) \times (volume\ within\ L_e\ of\ depletion\ zone)$$

number of electrons on p side

$$J_{e0} = e \left(\frac{n_p}{\tau_p} \right) L_e$$

electron lifetime

diffusion length $L_e = \sqrt{D_e \tau_p}$

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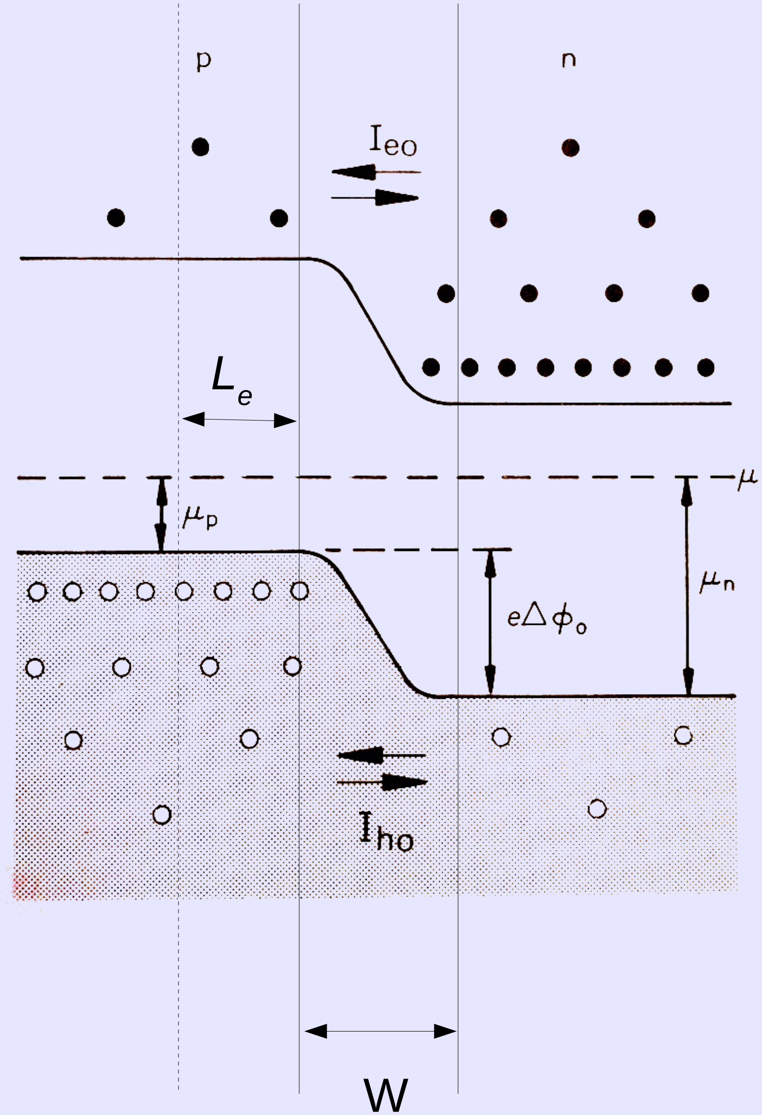
Deriving Shockley Equation



<u>Steady State again (i.e. no bias)</u>

Consider electron drift current

- I_{eo} from p to n

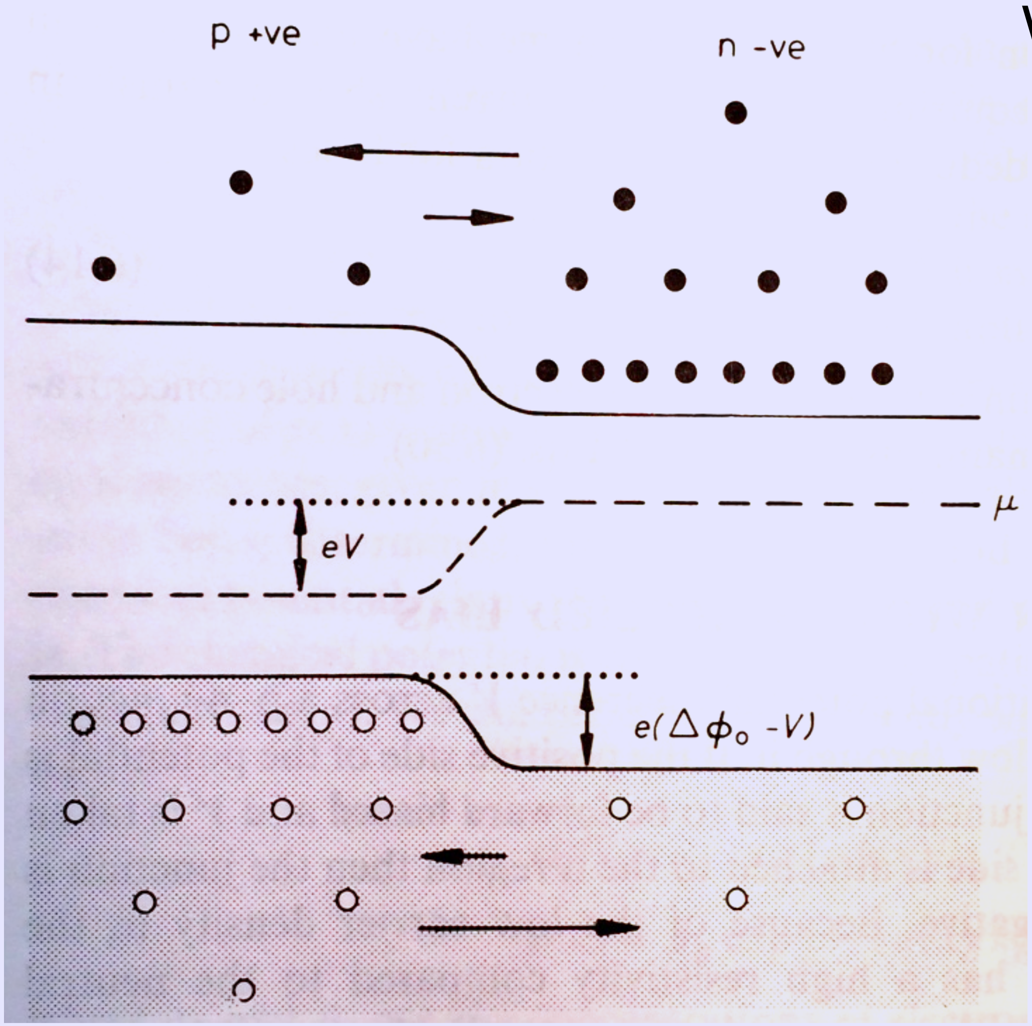
By assuming that all acceptors on p side are ionized:

$$n_p = \frac{n_i^2}{p_p} = \frac{n_i^2}{N_A}$$

can re-write J_{e0} as:

$$J_{e0} = \frac{eD_e n_i^2}{L_e N_A}$$

Deriving Shockley Equation



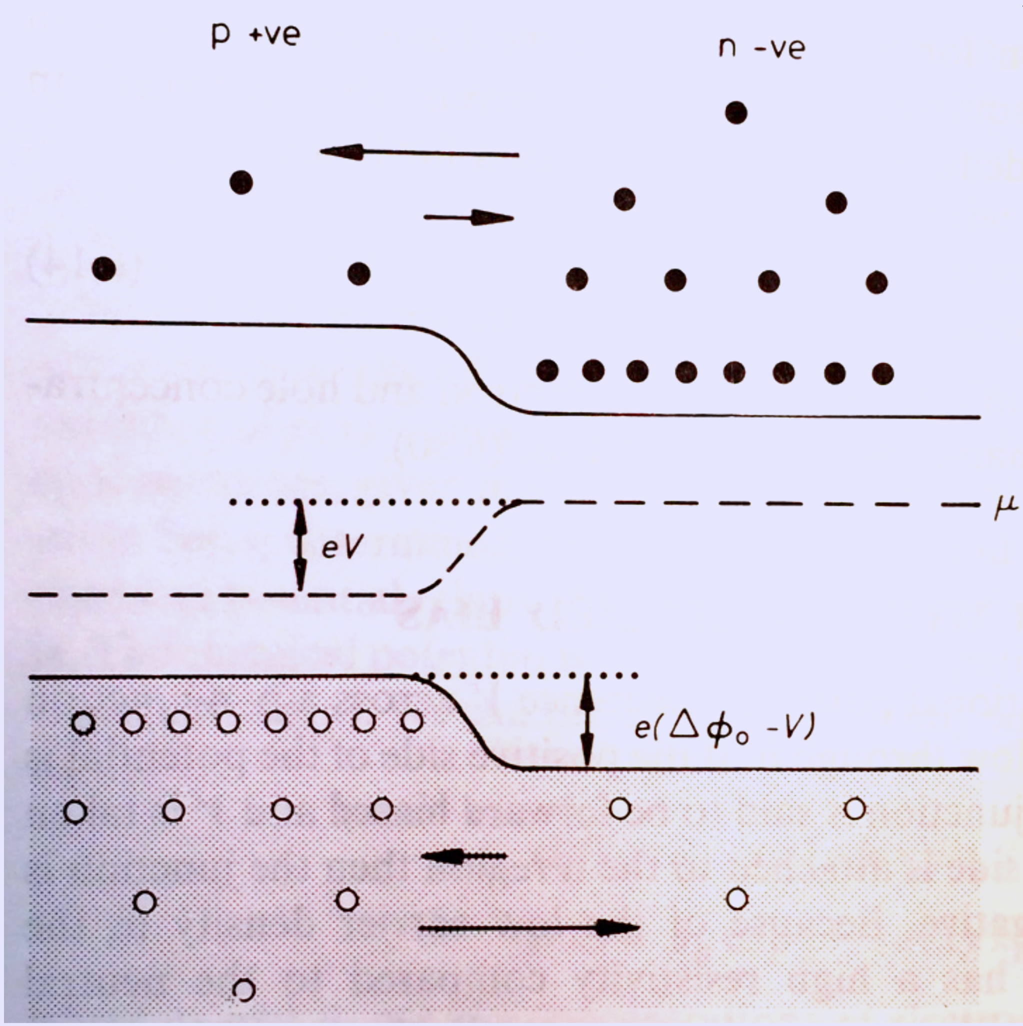
What happens **under forward bias**?

- Drift (p to n)? - Nothing. No potential barrier in this direction
- Diffusion (n to p)? - Increases by exponential factor:

$$\exp\left(\frac{eV}{k_B T}\right)$$

If we assume occupation of states in CB is given by Boltzmann distribution

Deriving Shockley Equation



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Net electron current:

$$\begin{aligned} J_e &= -J_{e0} + J_{e0}\exp\left(\frac{eV}{k_B T}\right) \\ &= J_{e0}\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right] \end{aligned}$$

Deriving Shockley Equation

Can do the same for the net **hole** current:

$$J_h = J_{h0}\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

where

$$J_{h0} = \frac{eD_H n_i^2}{L_h N_D}$$

Deriving Shockley Equation

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Therefore: **Net Current!**

$$\boxed{J = J_e + J_h = J_0\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]}$$

ideal diode equation

$$\boxed{J_0 = J_{e0} + J_{h0} = en_i^2\left(\frac{D_e}{L_n N_A} + \frac{D_h}{L_h N_A}\right)}$$

reverse saturation current,
a.k.a “dark current”

Deriving Shockley Equation

Previous derivation ignores the recombination and generation of carriers **within the depletion layer** itself!

$$J = J_0 \left[\exp\left(\frac{eV}{n k_B T} \right) - 1 \right]$$

Deriving Shockley Equation

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ideality factor – a complete FUDGE

Worth reading up about – but don't stress out about it.

- S. M. Sze, *"Semiconductor Devices"*, 2nd ed. Chap 4, pp 109 – 113
- Hook & Hall *"Solid State Physics"*, 2nd ed. Chap 6, pp 178 – 179

  I have these books if you want them.

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Lecture Summary

- Drawing Junctions
- Junction Formation – A Physical Picture
- Abrupt Junction
- Deriving Important Junction parameters
- Deriving diode equation
- Ideality Factor - Recombination