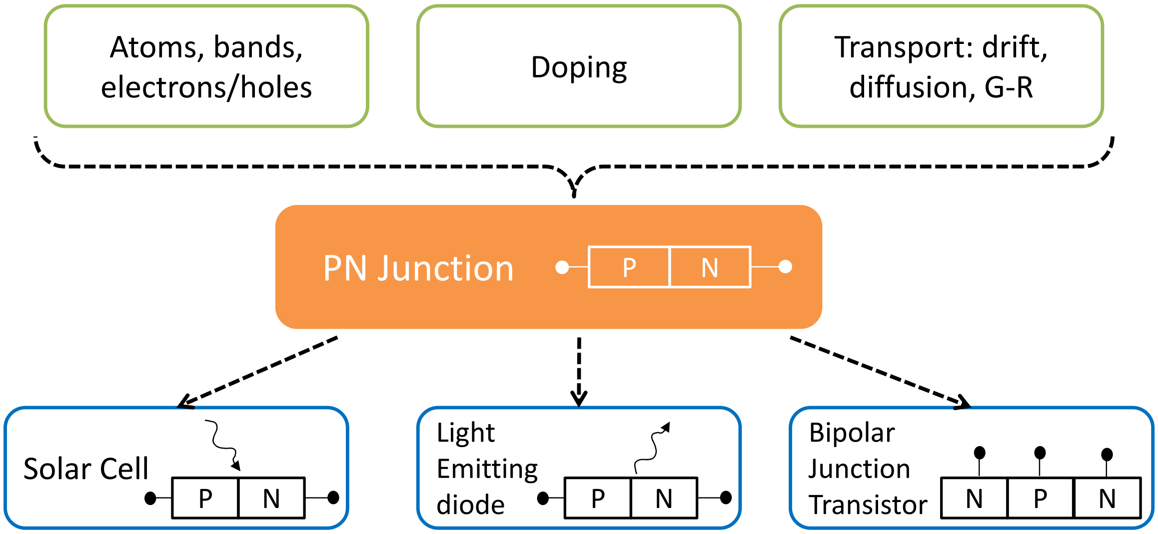
ECE 116 Lectures 18-19

P-N diode in equilibrium

- https://truenano.com/PSD20/contents/toc4.htm
- Read: BVZ Ch. 4.1, 4.2 and 4.3.1 to 4.3.3
- Where we are in 116 topics:



Atoms, bands, electrons/holes

Doping

Transport: drift, diffusion, G-R

PN Junction

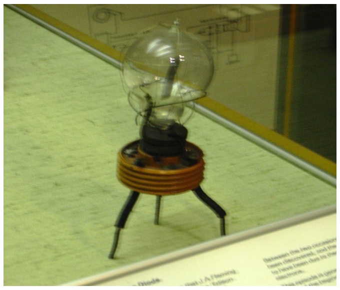
Solar Cell

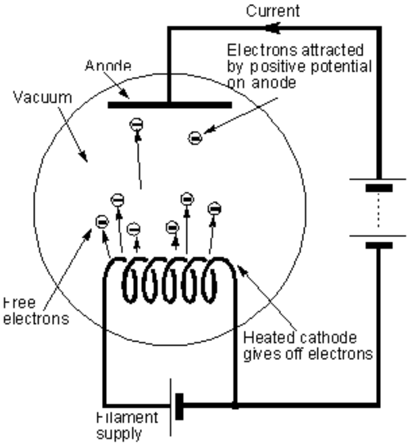
Light Emitting diode

Bipolar Junction Transistor

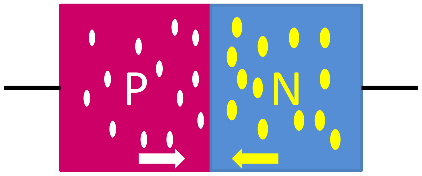
- So far we studied:
    - Energy bands, doping, Fermi levels
    - Drift (~n*v), diffusion (~dn/dx)
    - Einstein relationship ($D/\mu = kT/q$)
    - “Boring” semiconductor resistors (either n- or p-type)
    - Majority/minority carriers with illumination
- Today we start our first “useful” device:
    - The p-n junction diode in equilibrium (external V=0, lights off)
    - Remember, in equilibrium Fermi levels must be flat

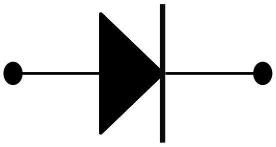
- Diodes: from vacuum tube to semiconductors



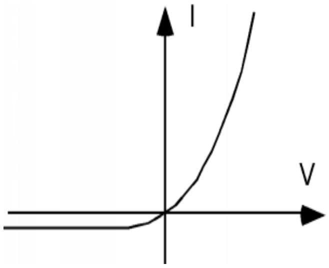


http://www.circuitstoday.com/vacuum-diodes





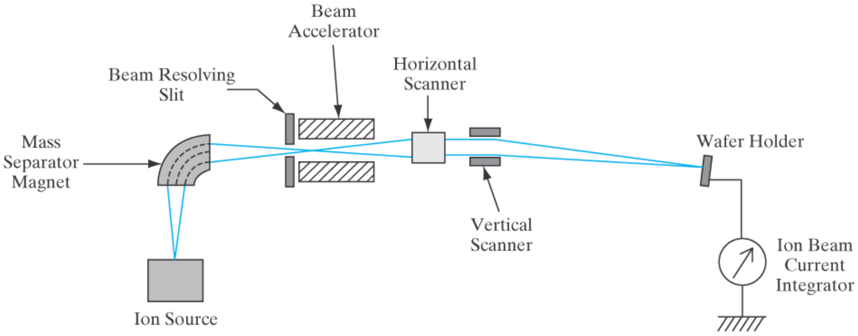
Basic function is rectification



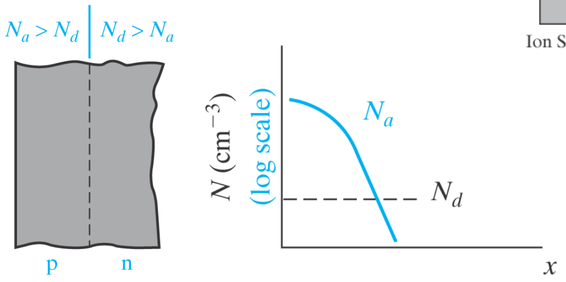
- How is the p-n junction fabricated?

1) Start with, say, n-type Si wafer

2) Then dope by p-type ion (e.g. B^-) implantation:

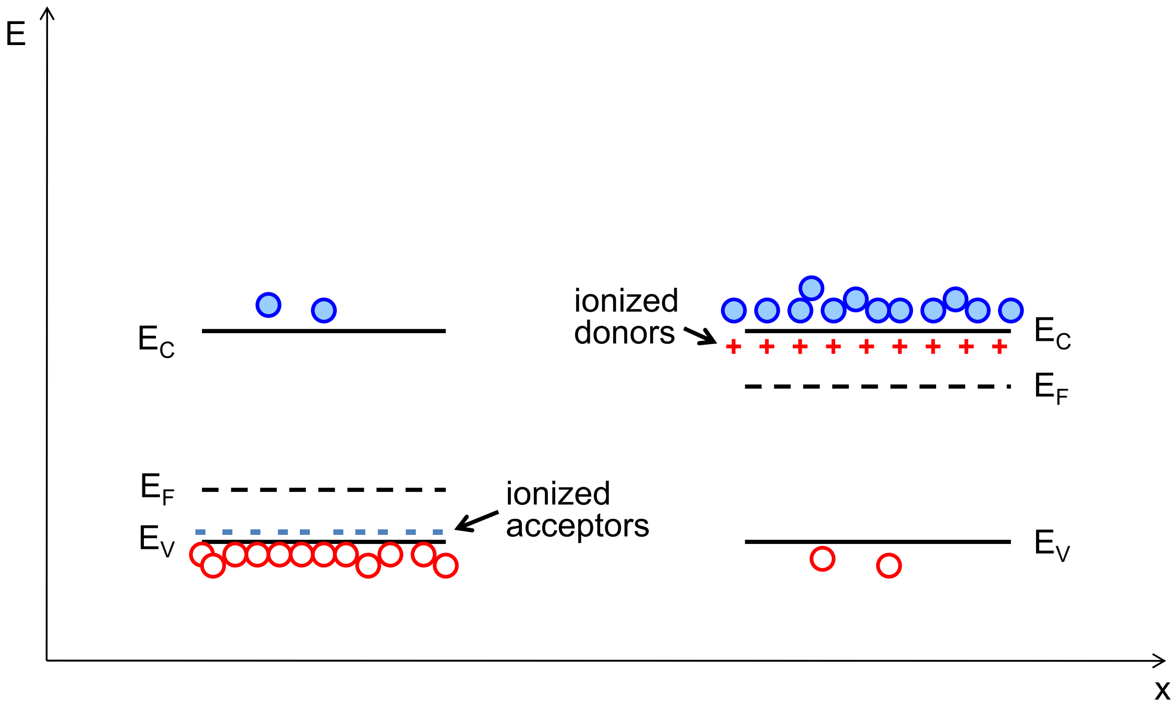


3) Result:

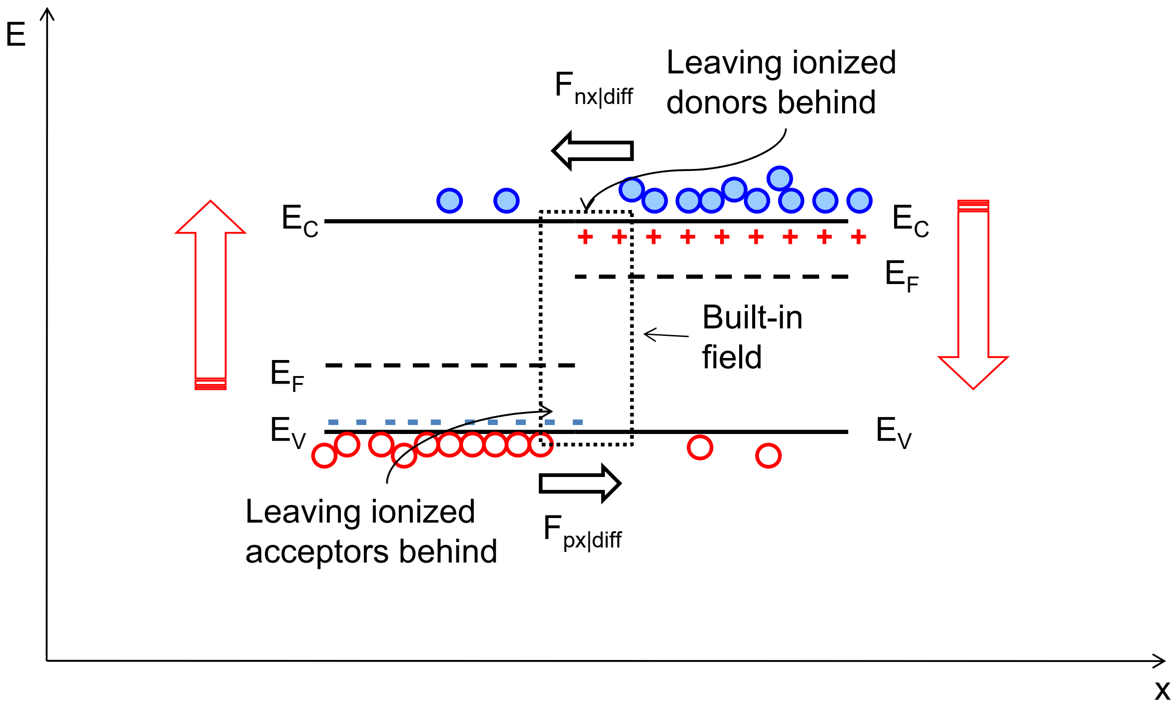


For more fabrication details please:
- Read Streetman book Ch. 5.1
- Take EE 212 and 312

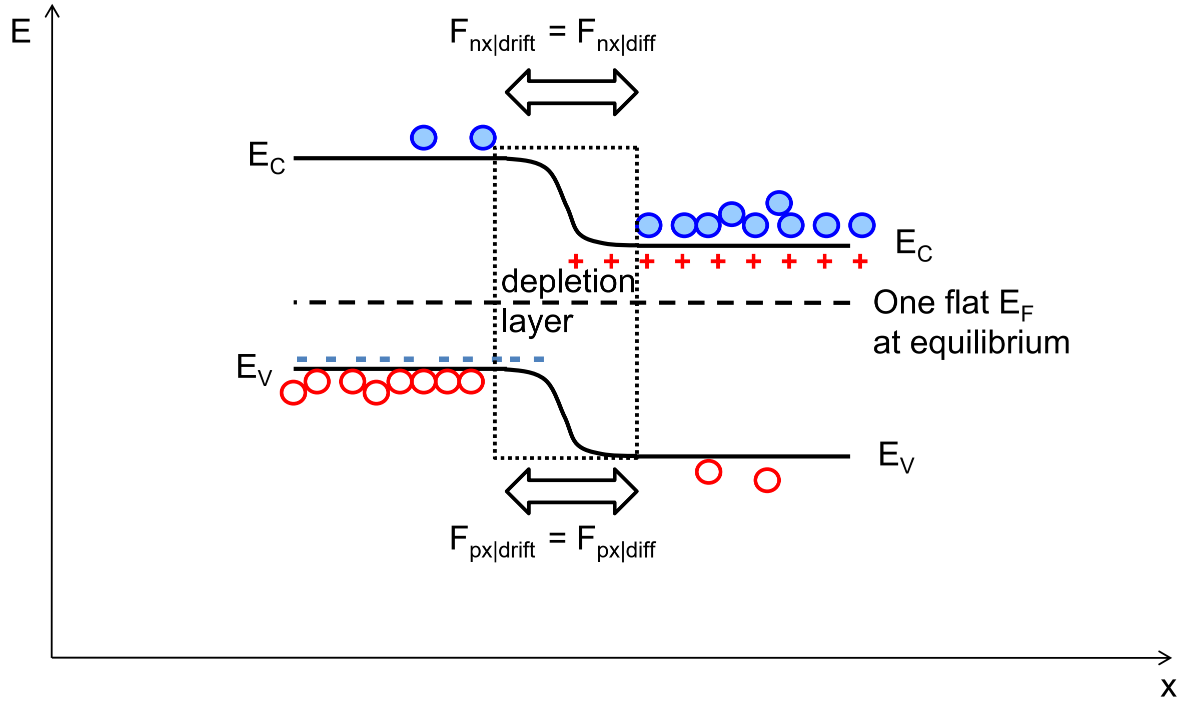
- Bring a p-type and n-type piece of semiconductor “near” each other. Draw separated p and n regions:



- Non-equilibrium diffusion and recombination (HUGE p and n gradients when two regions are brought together)



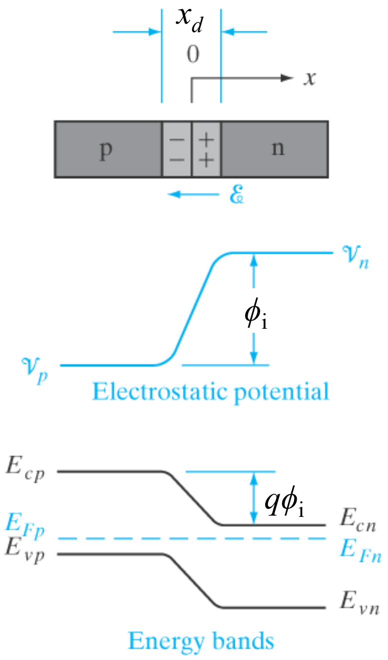
- Establish equilibrium (E_F flat):



- Q: what do electrons and holes leave behind at the junction, after they recombine and equilibrium is reached?

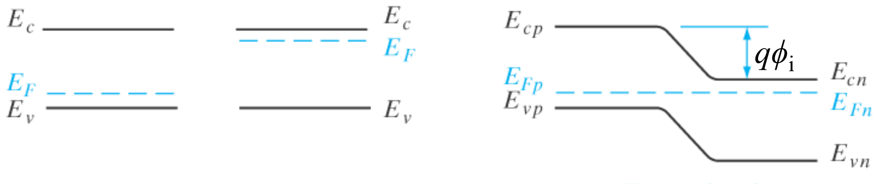
- A: depletion layer with fixed dopants

(also called “space charge region”)



- What is required of the currents at equilibrium?

- What is the built-in potential ϕ_i?



Energy bands

- Can you measure the built-in potential with a voltmeter?
- Easy to calculate ϕ_i for an abrupt p-n junction:
  - 1) First calculate $E_F - E_i$ on each side of the junction:
  - 2) Notice $q\phi_i = (E_{Fn} - E_i) + (E_i - E_{Fp})$

- Recognize that, say, on the p-side majority carrier: $p_p = N_A$
- And far into the n-side of the junction $n_n = N_D$

- Using $np = n_i^2$ on p-side, minority carriers there $n_p = n_i^2/N_A$

- From the built-in voltage: $\dfrac{p_p}{p_n} = \dfrac{n_n}{n_p} = e^{q\phi_i/kT}$

- This relates the majority/minority carrier concentration on either side of the junction. Which becomes more useful next lecture(s) when we apply an external voltage.

- **Ex:** (p^+)-n junction with $N_A = 10^{20}$ cm^{-3} and $N_D = 10^{15}$ cm^{-3}. Calculate Fermi levels and built-in potential at equilibrium.

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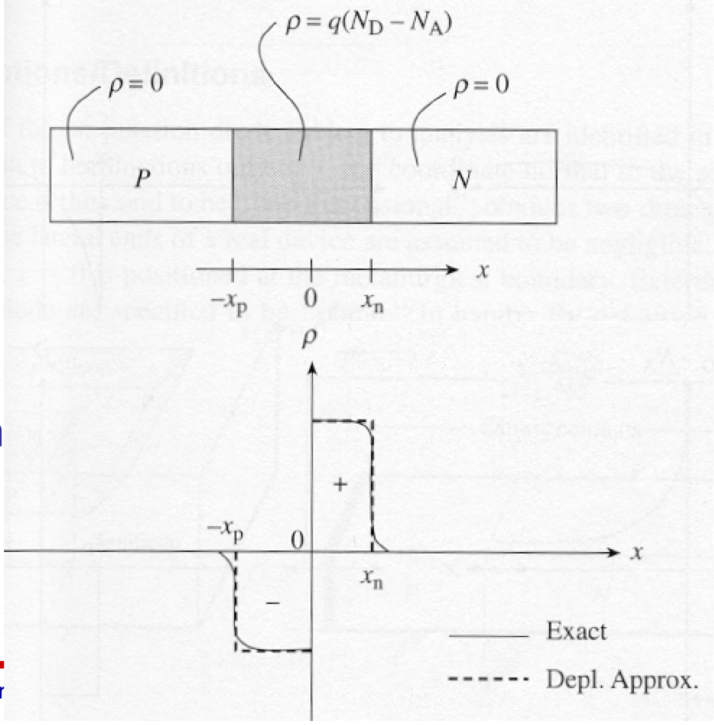
Space charge in a p-n diode

- So far we talked about p-n junction built-in voltage ϕ_i
- Now, more about electrostatics.



- In the middle, where there are huge concentration gradients, what happens?

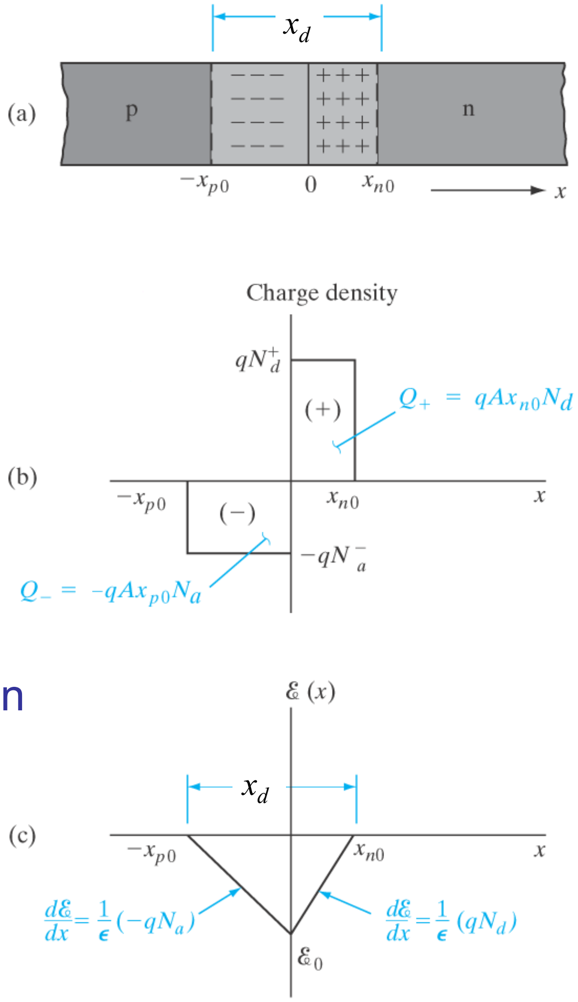
- What is left in the middle after the electrons & holes there recombine and are gone?

- Note: we will keep making the depletion approximation which means an abrupt (“step”) transition between the space charge ($N_D – N_A$) region and the two quasi-neutral (n and p) regions

- What is the depletion region?
- What is the space charge region (SCR)?
- What are the quasi-neutral regions (QNR)?

- If the SCR width is $x_d = x_p + x_n$, do the two (x_p, x_n) sides have to be equal? Why or why not?

- What is the total charge on either side of the junction:
  - On the p-side:
  - On the n-side:



- OK, let’s calculate the depletion widths x_n and x_p now

- This isn't too hard with the Poisson equation (Gauss' law)
- Recall:

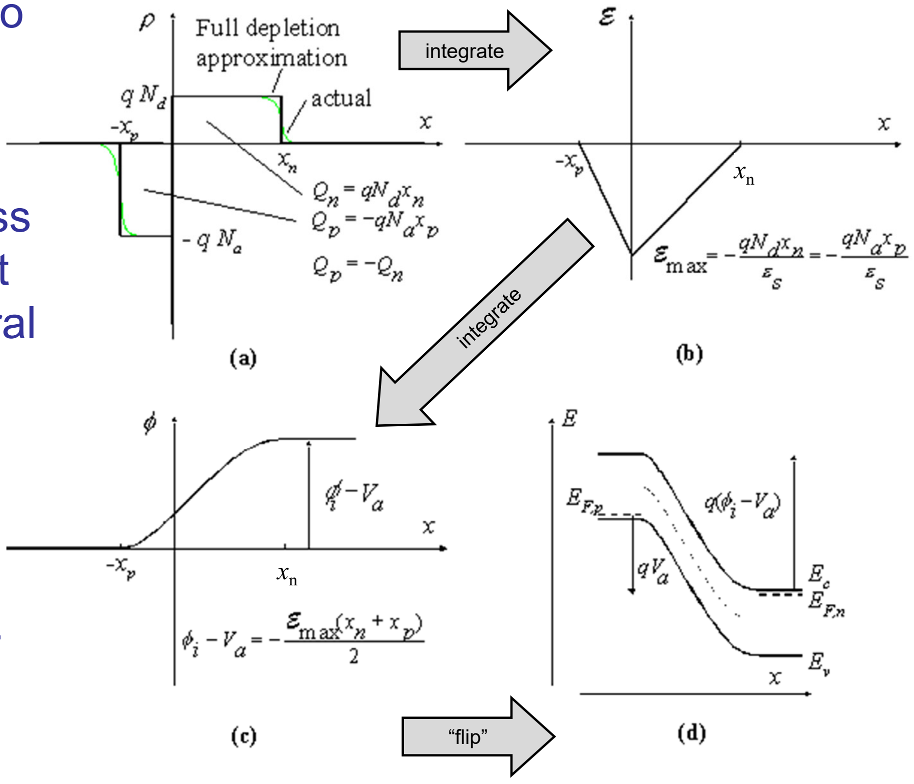
$$\nabla \cdot E = -\nabla^2 V = \frac{\rho}{\varepsilon} = \frac{q}{\varepsilon}\left(\qquad\qquad\qquad\qquad \right)$$

- In one dimension, in the depletion region, this is just:
  - On the p-side: $\frac{dE}{dx} = -\frac{q}{\varepsilon} N_A \quad \text{for } -x_p < x < 0$
  - On the n-side: $\frac{dE}{dx} = +\frac{q}{\varepsilon} N_D \quad \text{for } 0 < x < x_n$
- Integrate over the space charge density on either side, and obtain the maximum field at the junction:

$$E_{\max}(x=0) = -\frac{qN_A x_p}{\varepsilon} = -\frac{qN_D x_n}{\varepsilon}$$

- The field distribution is "triangular" because the charge distribution is "rectangular" (*depletion approximation*)

- Now, the built-in potential is easy to calculate.
- The voltage across the junction is just (minus) the integral over the E-field
- So the built-in voltage ϕ_i is the area under the E-field "triangle"



- Be careful (a bit):

Potential Energy = –q * Voltage Potential

- Although if we use “eV” units for energy (so q = 1 electron) then the two are equivalent numerically (with a minus sign)
- If we use “Joule” units for energy (so q = 1.6 x 10^{-19} C) then of course you need to be careful multiplying by q to convert from Volts to Joules.

- Back to the built-in voltage, we now have from electrostatics:

$$\phi_i = \frac{q}{2\varepsilon}\frac{N_A N_D}{N_A + N_D} x_d{}^2$$

- But earlier we obtained from energy level (e.g. E_C) misalignment:

$$\phi_i = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

- Now we can calculate: $x_d = x_n + x_p = \sqrt{\frac{2\varepsilon_S}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(\phi_i - V)}$
- And the individual depletion regions:

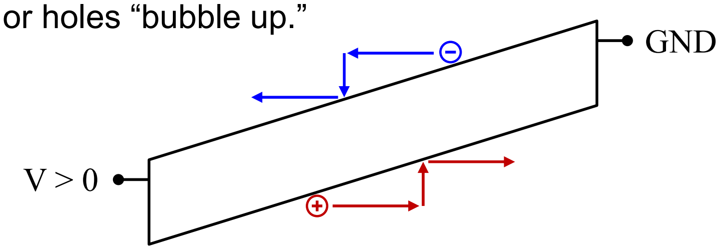
$$x_n = \frac{N_A}{N_A + N_D}x_d \qquad x_p = \frac{N_D}{N_A + N_D}x_d$$

- The maximum electric field at the junction:

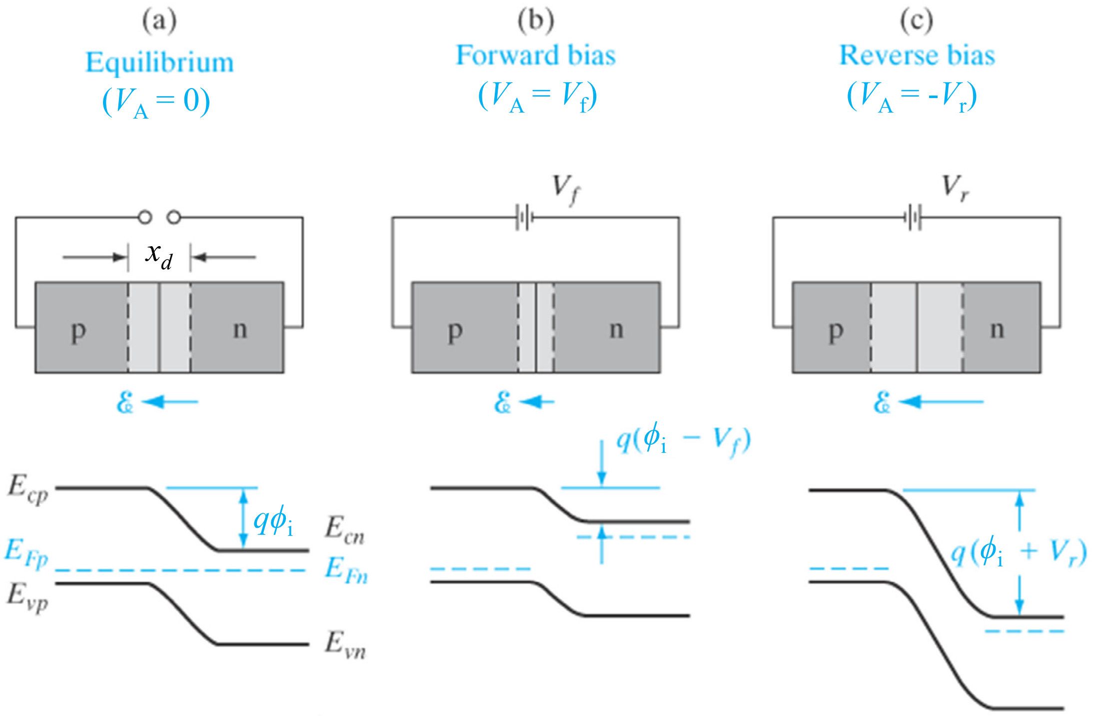
$$|E_{\max}| = |E_0| = \frac{2(\phi_i - V)}{x_d}$$

- Note what happens when $N_A >> N_D$ or $N_D >> N_A$
- And remember the dielectric constant $\varepsilon_S = \varepsilon_{r,s}\varepsilon_0$
- Be careful with units! E.g. if ε is in F/cm then q should be in C, if kT is in eV then q should be “1 e”, etc.

- Note V (= V_A) is the externally applied voltage
  - Remember, a positive outside voltage "grabs" the Fermi level on the side it's applied on and drags it down. (negative pulls it up).
  - How do we remember this? Think of the simple resistor band diagram, which way the electric field points (external + to -) and which way the electrons "slide down" or holes "bubble up."



- A *forward bias* is + applied to the p-side, which *lowers* the built-in voltage barrier ($\phi_i - V_A$) where $V_A > 0$
- A *reverse bias* is – applied to the p-side, which *increases* the built-in voltage barrier ($\phi_i - V_A$) where $V_A < 0$
- Now draw the band diagrams (Fig. 4.2.4 in the book)


(a) Equilibrium ($V_A = 0$)

(b) Forward bias ($V_A = V_f$)

(c) Reverse bias ($V_A = -V_r$)

- What about forward bias when $V_A = \phi_i$?
- Can we have $V_A > \phi_i$?

- **Ex:** An abrupt silicon p-n junction has p-side $N_A = 10^{16}$ cm^{-3}, and n-side $N_D = 5\text{x}10^{16}$ cm^{-3}. A) What is the built-in voltage. B) How wide is the depletion region with applied V = 0, 0.5 and -2.5 V. C) What is the maximum electric field, and D) the potential across the n-side for these external V's.