# <u>ECE 440: Lectures 27-28</u>

P-N Diode in Equilibrium

**So far:**

- **Energy bands, Doping, Fermi levels**
- **Drift (~n*v), diffusion (~dn/dx)**
- **Einstein relationship (D/μ = kT/q)**
- **“Boring” semiconductor resistors (either n- or p-type)**
- **Majority/minority carriers with illumination**

- **First device: metal-semiconductor (MS) contact**
- **Second device: MOS capacitor**
- **Third device: MOS field-effect-transistors (FET)**

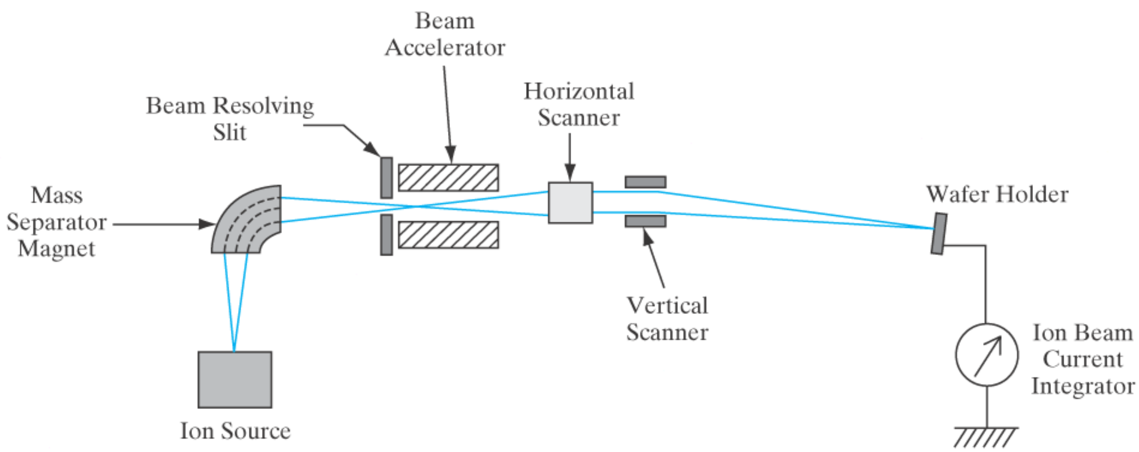
**Today, we start our fourth “useful” device:**

- **The P-N junction diode <u>in equilibrium</u> (external V=0)**
- **Remember, in equilibrium Fermi level must be <u>flat</u>**

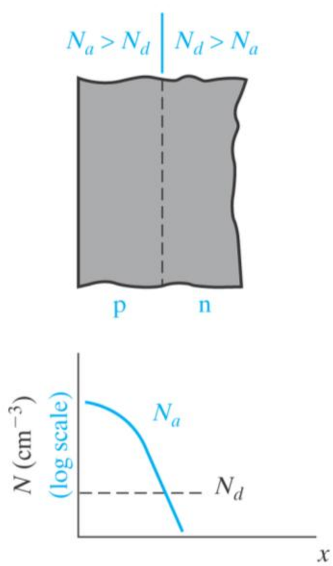
## How is the P-N junction fabricated?

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

2) **Then dope by p-type ion ($B^-$) implantation:**




3) **Result:**



**For more details please:**

- **Read Streetman book section 5.1**
- **Wikipedia**
- **Take ECE 444**

**Back to p-n junction.**

**What happens if I bring a p-type and n-type piece of semiconductor together?**

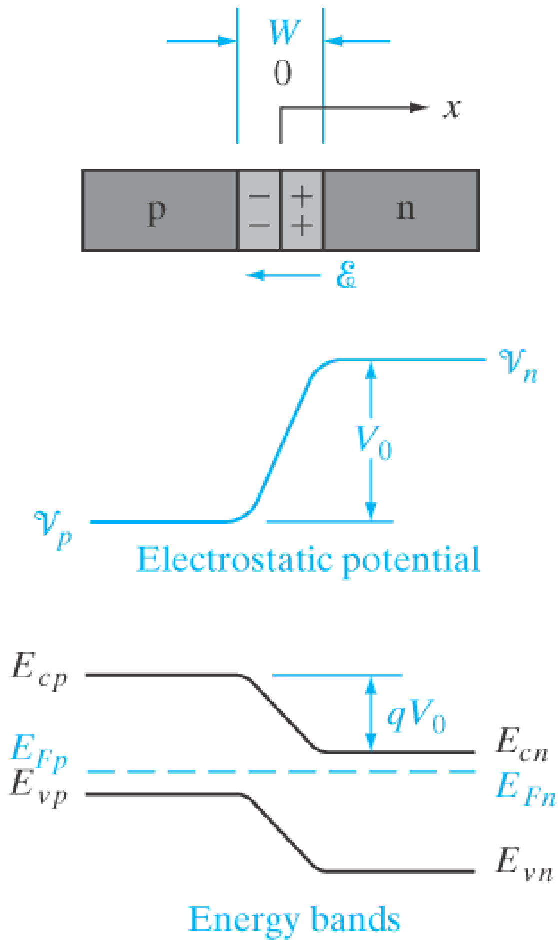
**We already have the tools to analyze this together. Draw isolated band diagrams:**

**What happens to the (huge) electron and hole concentrations on either side of that junction, immediately after they are brought together?**

**What is <u>required of the Fermi level in equilibrium</u>? (why?)**

**So draw the p-n band diagram in equilibrium:**

**What do electrons and holes leave behind at the junction, after they recombine and equilibrium is established?**

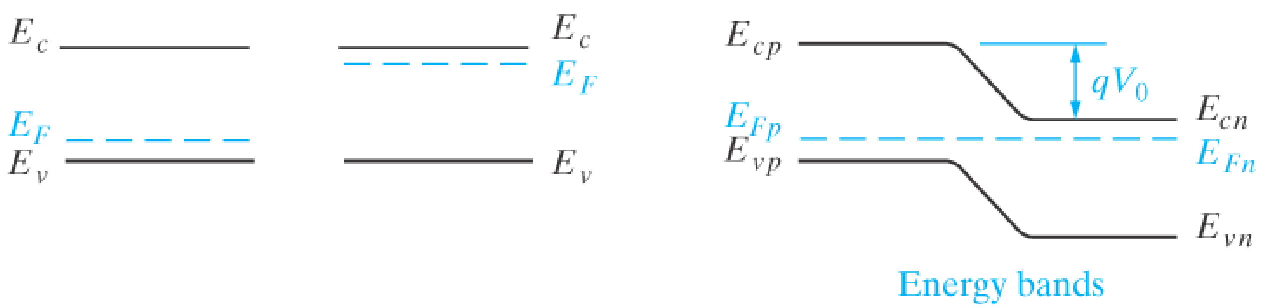



**A:**

**(this is called "space charge")**

**What is required of the currents at equilibrium?**

**What is the built-in potential $V_0$?**




**Can you measure the built-in potential with a voltmeter?**

**Easy to calculate $V_0$ for an abrupt P-N junction:**

1) **First, calculate $E_F - E_i$ on each side of the junction:**

2) **Notice $qV_0 = (E_{Fn} - E_i) + (E_i - E_{Fp})$**

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

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

**From the built-in voltage:**

$$\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0 / kT}$$

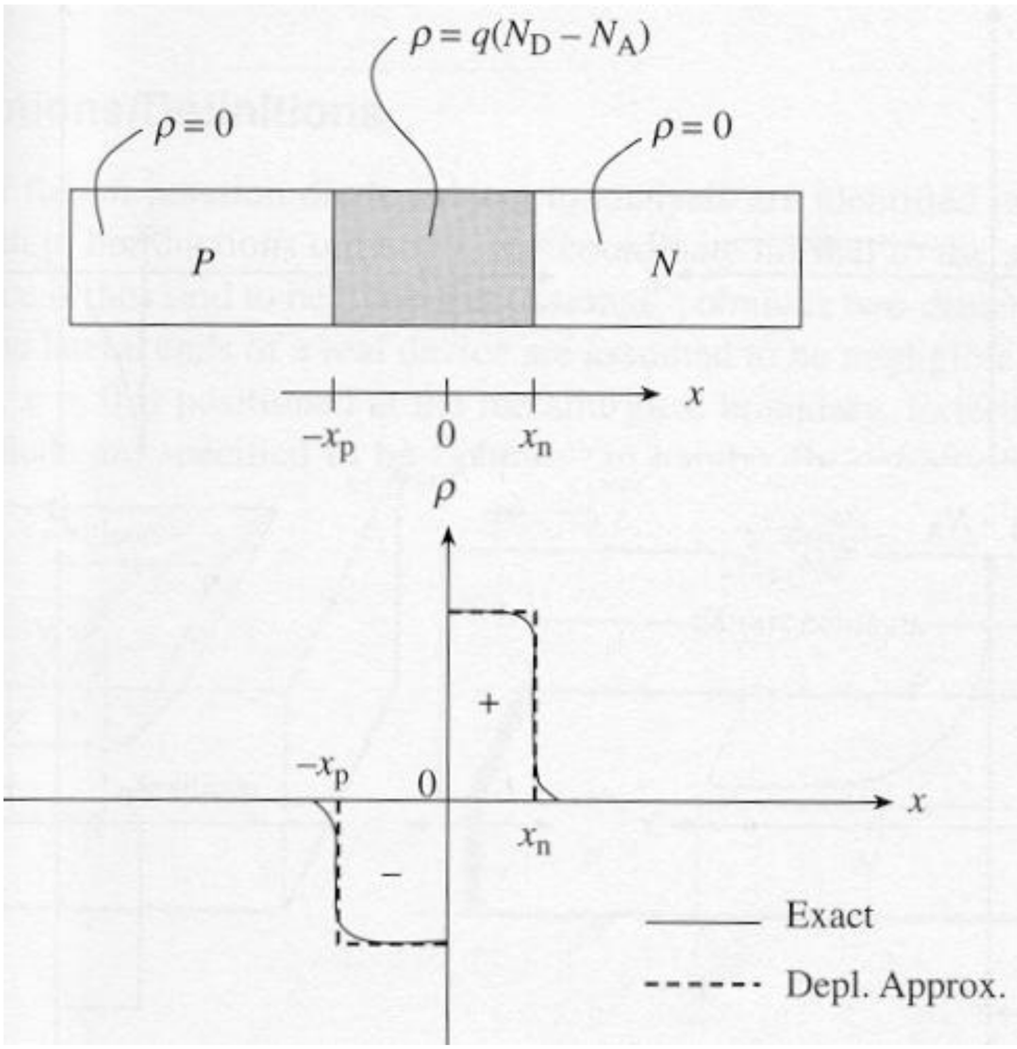
**This relates the majority/minority carrier concentration on either side of the junction. Which becomes more useful next lecture(s) when we apply an external voltage.**

# ECE 440: Lecture 29

Space Charge in P-N Diode

**Example: 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.**

**So far, we talked about p-n junction built-in voltage $V_0$.**
**Today: more about p-n electrostatics.**




**In the middle, where there are huge p-to-n concentration gradients, what happens?**

**What is left in the middle after the electrons and holes there are gone?**

**Note: we will keep making the <u>depletion approximation</u> which means an ______________________________ between the space charge ($N_D$ – $N_A$) region and the two quasi-neutral (n and p) regions.**

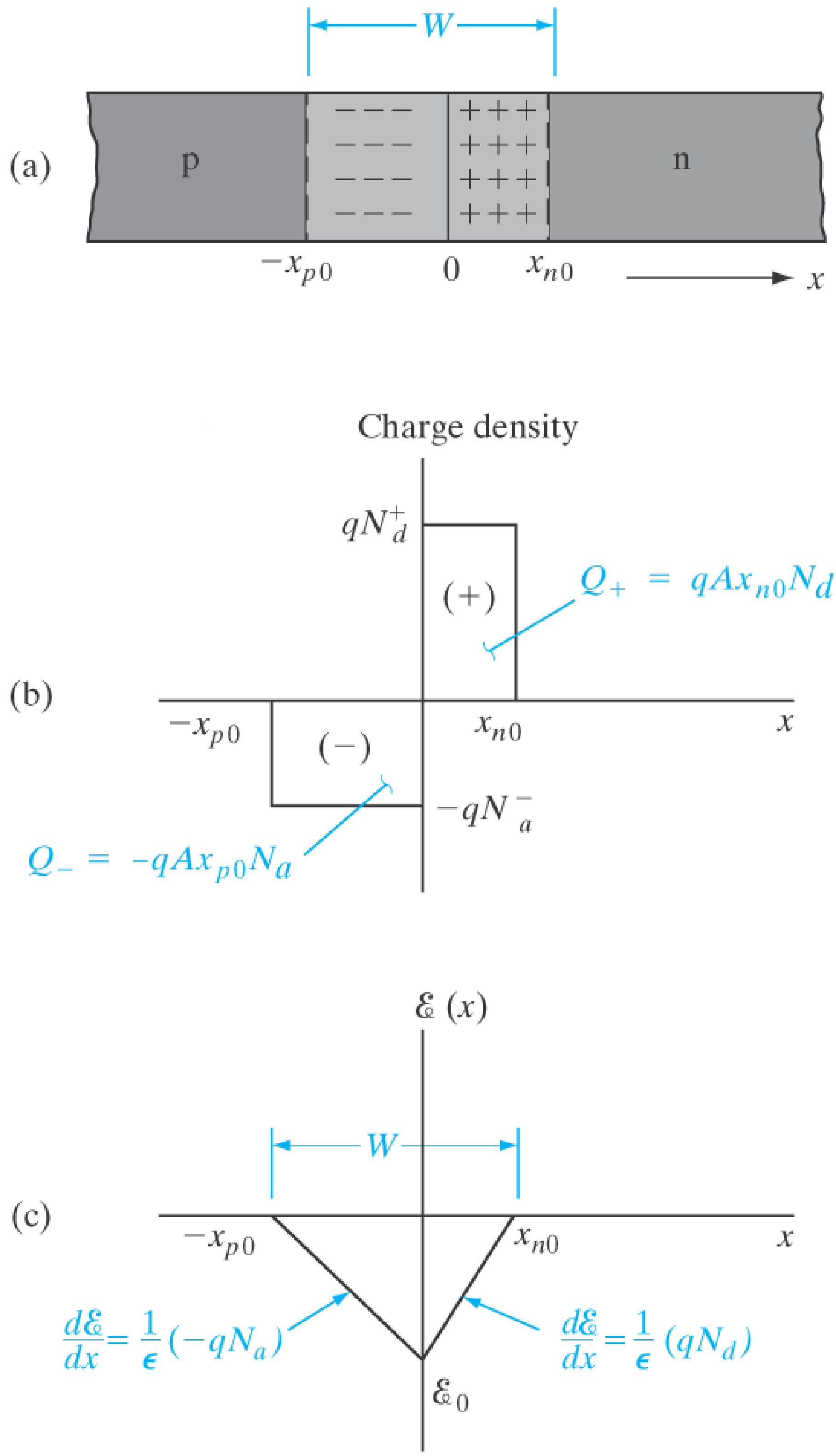
**What is the depletion region?**
**What is the space charge region (SCR)?**
**What are the quasi-neutral regions (QNR)?**

**If the SCR is $W = x_p + x_n$ in width, do the two ($x_p$, $x_n$) sides have to be equal? Why/why not?**

**What's the total charge on either side of the junction?**

- **On the p-side:**
- **On the n-side:**

**OK, let's calculate the depletion widths now.**


W
(a)
p
n
− − −
+ + +
$-x_{p0}$
0
$x_{n0}$
$x$
Charge density
$qN_d^+$
(+)
$Q_+ = qAx_{n0}N_d$
(b)
$-x_{p0}$
(−)
$x_{n0}$
$x$
$-qN_a^-$
$Q_- = -qAx_{p0}N_a$
$\mathcal{E}(x)$
W
(c)
$-x_{p0}$
$x_{n0}$
$x$
$\frac{d\mathcal{E}}{dx} = \frac{1}{\epsilon}(-qN_a)$
$\frac{d\mathcal{E}}{dx} = \frac{1}{\epsilon}(qN_d)$
$\mathcal{E}_0$

**This isn't too hard with the Poisson equation (Gauss' Law).**

**Recall:**

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

**In one dimension, in the depletion region, this is just:**

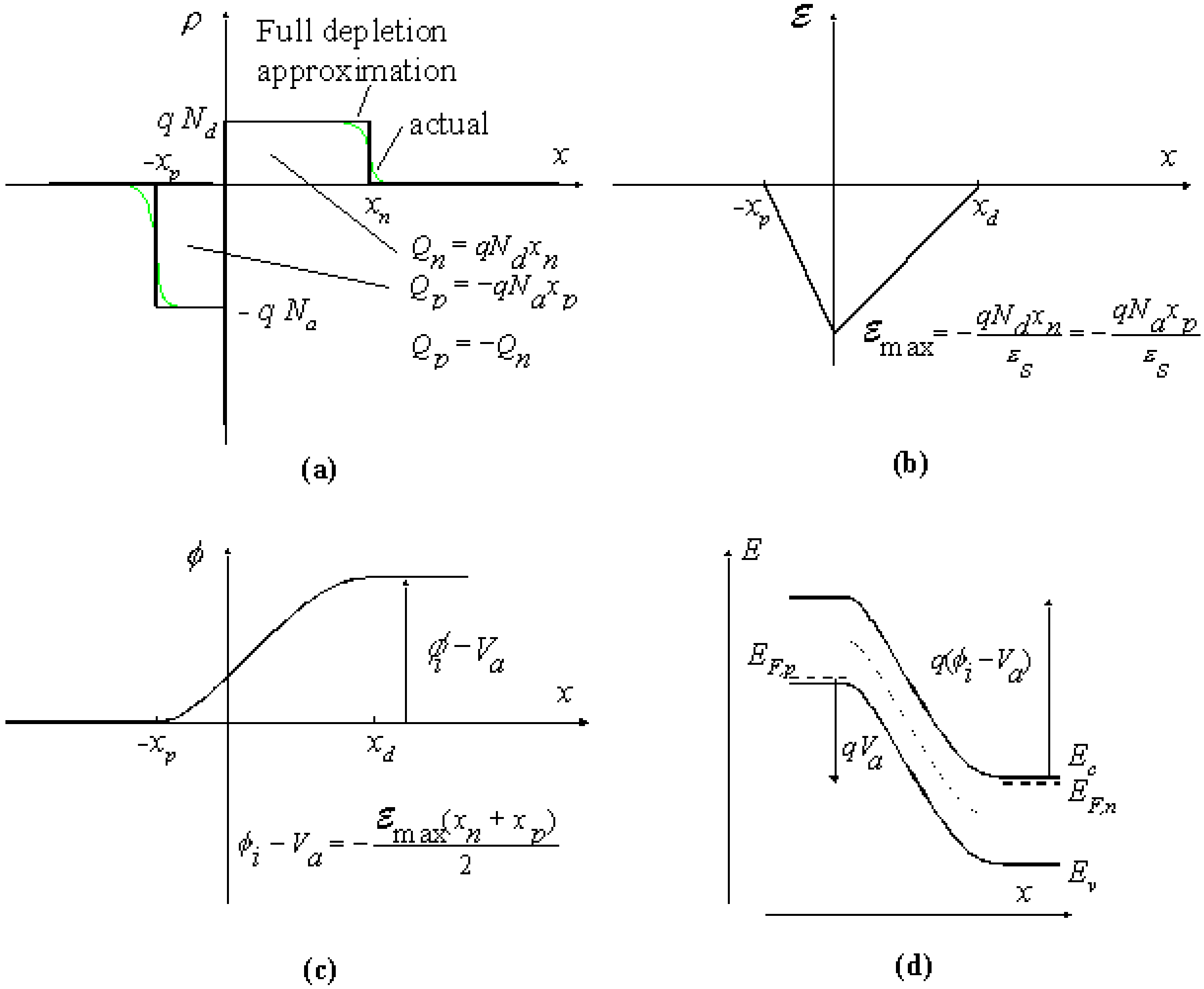
- **On the p-side:**
- **On the n-side:**

**Integrate over the space charge density on either side, and obtain the maximum field at the junction:**

$$E_0 =$$

**The field distribution is triangular, because the charge distribution is rectangular (*depletion approximation*).**

**Now, the built-in potential is easy to calculate.**




**The voltage potential across the junction is just (minus) the integral over the electric field:**

**So the built-in voltage $V_0$ is the area under the electric field triangle.**

**Be careful (a bit):**

**Voltage Potential = -q * Potential Energy**

**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 between Volts and Joules.**

**------**

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

$$V_0 = \frac{q}{2\varepsilon} \frac{N_A N_D}{N_A + N_D} W^2$$

**And from last lecture, from Fermi level alignment:**

$$V_0 = \frac{kT}{q} \ln\left( \frac{N_A N_D}{n_i^2} \right)$$

**Now we can calculate all kinds of things, like the depletion width (W), and the individual depletion regions ($x_p$ and $x_n$).**

**What if I vary 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 ($V_0 - V_{fwd}$) where $V_{fwd} > 0$.**

**A *reverse bias* is – applied to the p-side, which *increases* the built-in voltage barrier ($V_0 - V_{rev}$) where $V_{rev} < 0$.**

***[if we're out of time, use this space to draw the band diagrams, if you need a hint look up Fig. 5-13 in the book]***

**<u>Example</u>: An abrupt silicon p-n junction has p-side $N_A = 10^{16}$ cm$^{-3}$, and n-side $N_D = 5\times10^{16}$ 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.**