Announcements

- Labs start tomorrow (Experiment 0).
  - Read lab beforehand
  - Each lab group will get a 331 Lab Kit
  - Bring probes, breadboard, components from 233 (will need to buy if lab group doesn't have enough)
- We finish Chapter 2 material today. Start reading Chapter 3.

Drift Diffusion Equations

$$\mathbf{\nabla} \cdot \mathbf{E} = \frac{\rho(\boldsymbol{x})}{\varepsilon} \quad \Rightarrow \quad \frac{dE}{dx} = \frac{\rho(x)}{\varepsilon} \text{ for 1D}$$

$$\nabla^2 \varphi = -\frac{\rho(\boldsymbol{x})}{\varepsilon} \Rightarrow \quad \frac{d^2 \varphi}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

$$\mathbf{j}_n^{\text{tot}} = qn\mu_n \mathbf{E} + qD_n \mathbf{\nabla} n \Rightarrow \; qn\mu_n E + qD_n \frac{dn}{dx}$$

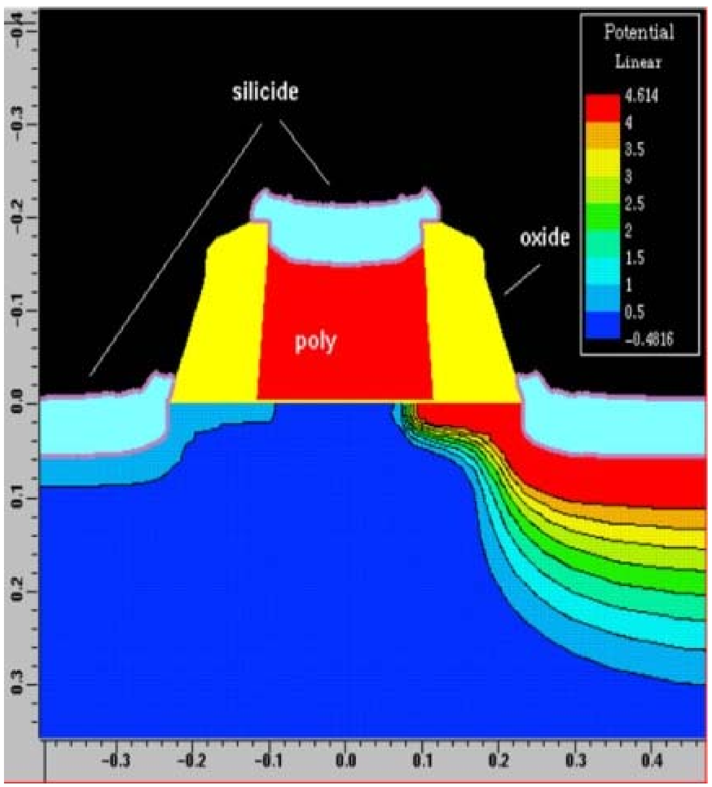
$$\mathbf{j}_p^{\text{tot}} = qp\mu_p \mathbf{E} - qD_p \mathbf{\nabla} p \Rightarrow \; qp\mu_p E - qD_p \frac{dp}{dx}$$

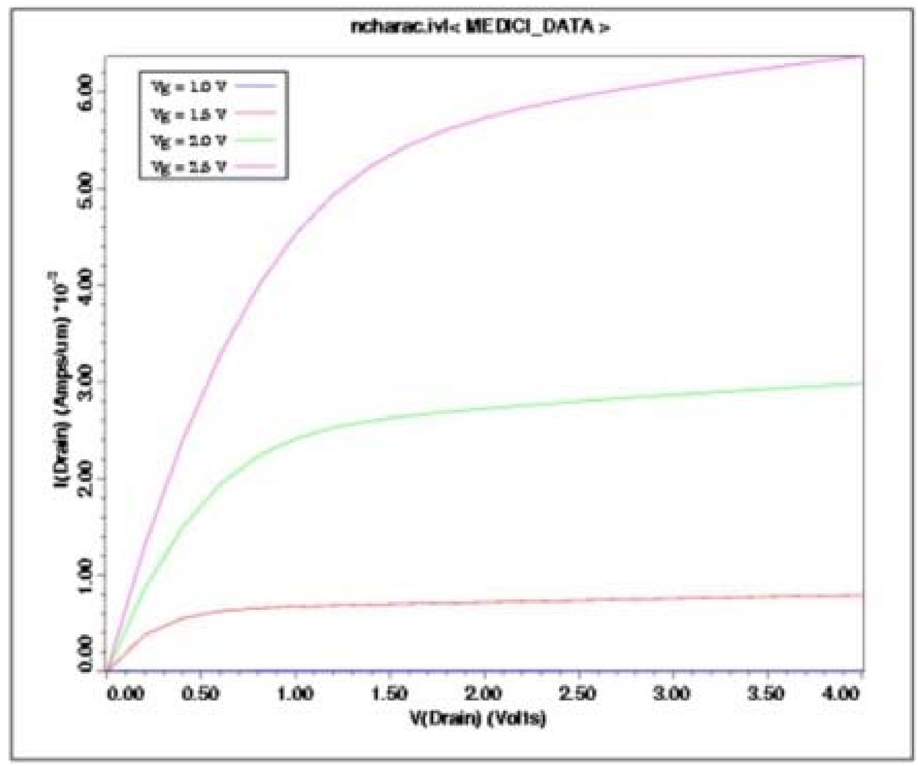
$$\frac{\partial n}{\partial t} = -\, \mathbf{\nabla} \cdot \mathbf{j}_n^{\text{tot}} - \text{R} + \text{G} \quad \text{(G is generation)}$$

$$\frac{\partial p}{\partial t} = -\, \mathbf{\nabla} \cdot \mathbf{j}_p^{\text{tot}} - \text{R} + \text{G} \quad \text{(R is recombination)}$$

Device Analysis and Modeling

- The drift-diffusion equations are the basis for most analysis and design of semiconductor devices.



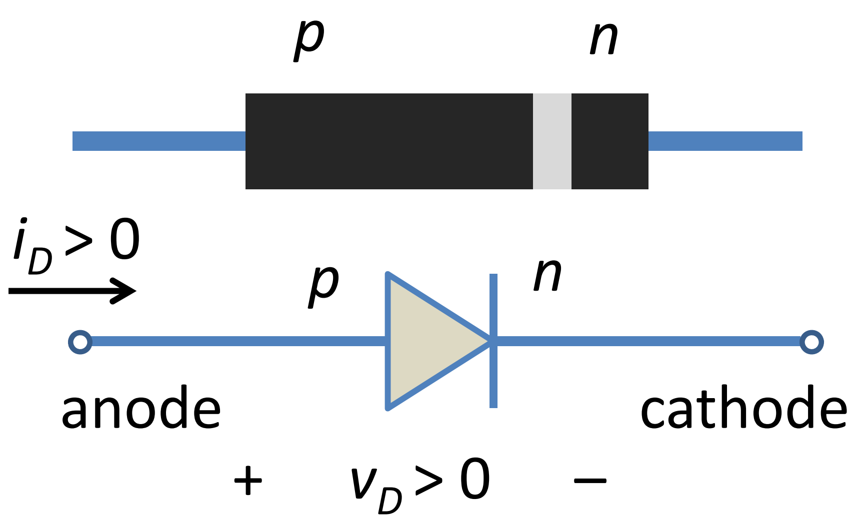


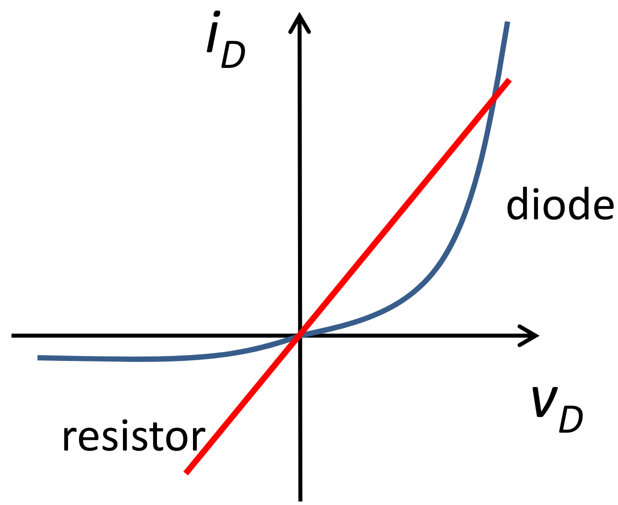
EE 331 Devices and Circuits I

Chapter 3

Diodes – Physics & Characterization

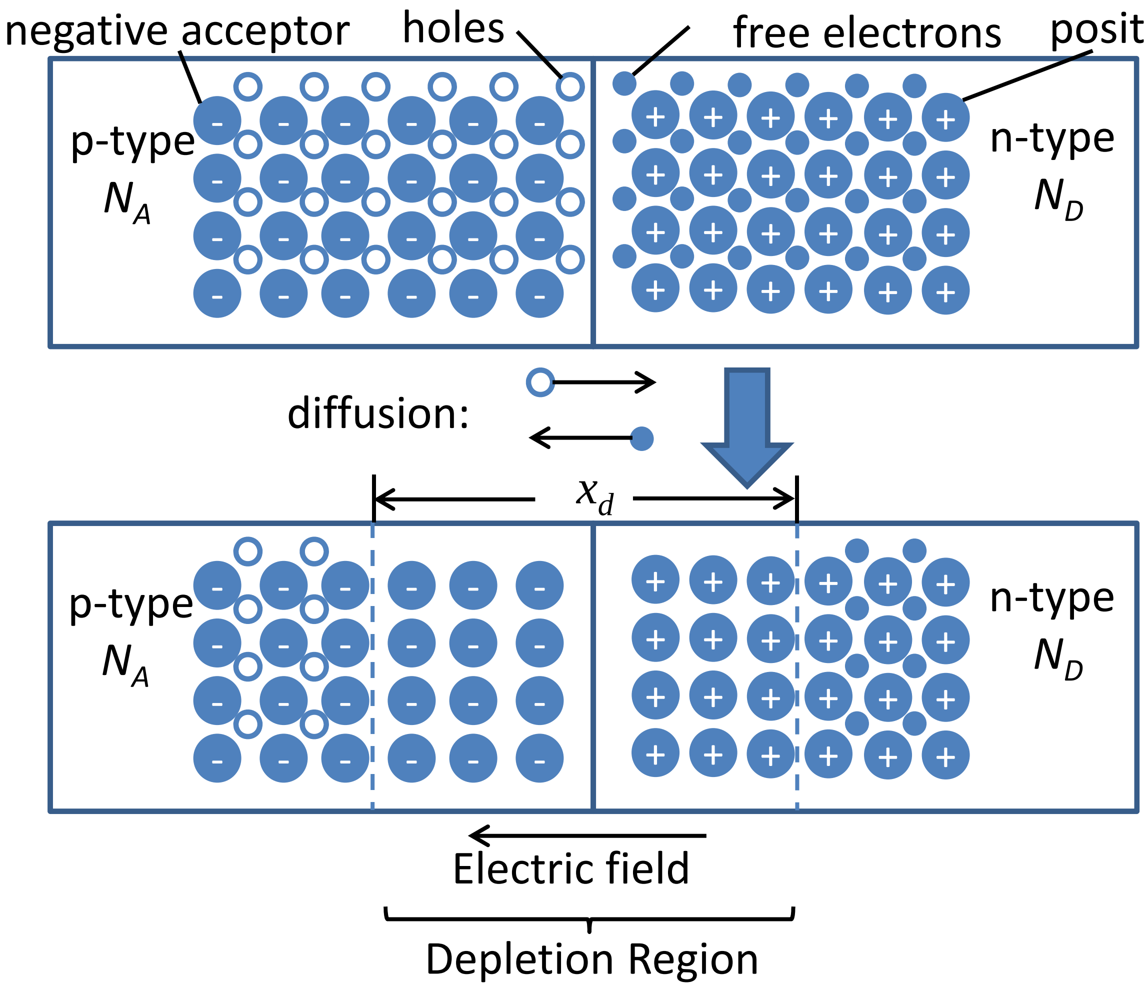
P-N Junction Diodes





- $v_D > 0$, forward bias, $i_D > 0$, large (good forward conduction)
- $v_D < 0$, reverse bias, $i_D < 0$, small (poor reverse conduction)
- Goal: Find function of i_D with respect to v_D.

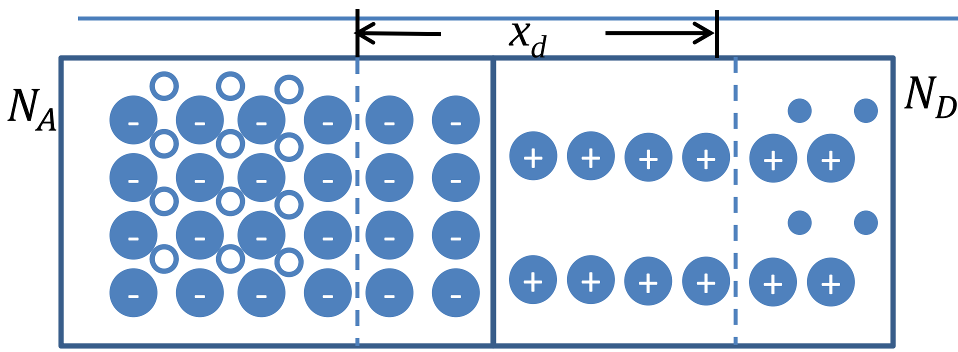
p-n junction – Physical Picture



- Diffusion allows carriers to move from high density to low density
- Immobile ions produce a built-in electric field
- The drift caused by the field prevents the carriers from diffusing further.
- When drift and diffusion are balanced, a metallurgical junction forms
- The junction is featured by a space charge region, also called depletion region (*depleted* of free carriers).

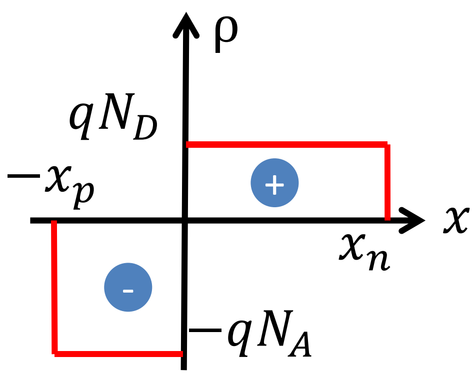
p-n Junction – Electrostatic Analysis

$$N_A > N_D$$

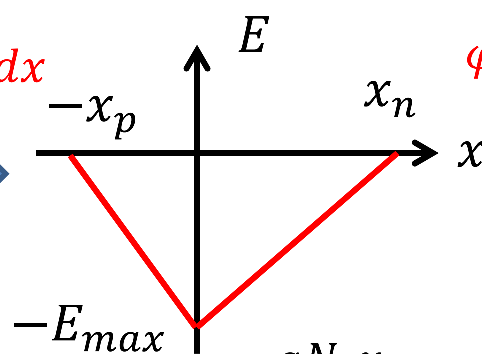


1D Poisson's Equation:

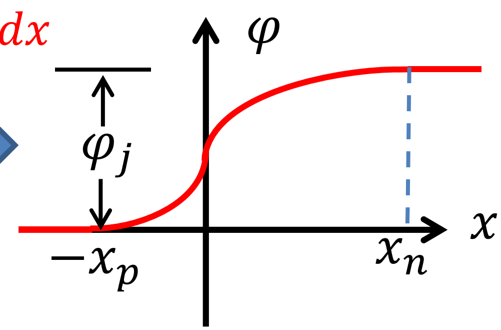
$$\frac{d^2\varphi}{dx^2} = -\frac{dE}{dx} = -\frac{\rho}{\varepsilon}$$



$$E = \frac{1}{\varepsilon}\int \rho dx$$



$$\varphi = -\int E dx$$



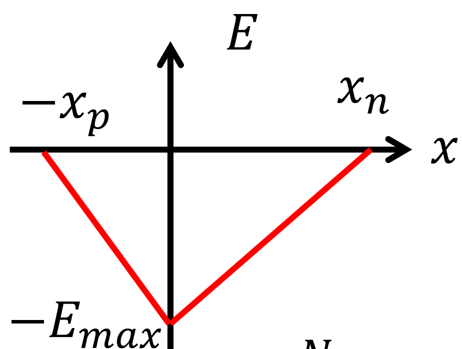
Charges must be equal:

$$x_p N_A = x_n N_D$$

$$E_{max} = \frac{qN_A x_p}{\varepsilon} = \frac{qN_D x_n}{\varepsilon}$$

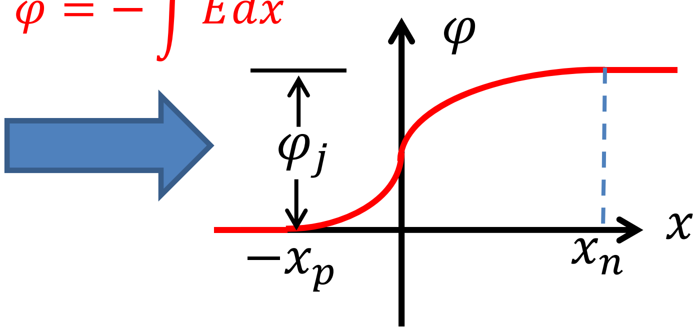
φ_j : built-in voltage

p-n Junction – Electrostatic Analysis



$$E_{max} = \frac{qN_A x_p}{\varepsilon} = \frac{qN_D x_n}{\varepsilon}$$

$$\varphi = -\int E dx$$



- φ_j is the area under E-x curve:
- $\varphi_j = \frac{(x_n + x_p)}{2} |E_{max}| = \frac{qN_A(x_n + x_p)}{2\varepsilon} x_p$
- Combining $x_p N_A = x_n N_D$, we get

$$x_p = \sqrt{\frac{2\varepsilon\varphi_j}{qN_A(1+N_A/N_D)}}$$

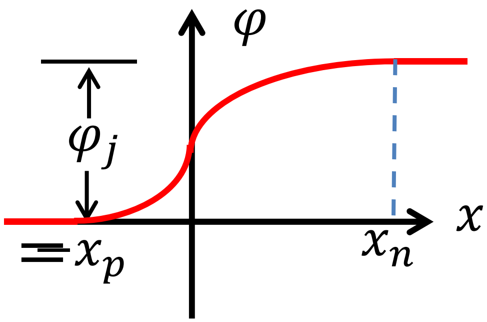
$$x_n = \sqrt{\frac{2\varepsilon\varphi_j}{qN_D(1+N_D/N_A)}}$$

$$x_d = x_n + x_p = \sqrt{\frac{2\varepsilon\varphi_j}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$

Depletion width under zero bias

p-n Junction – Electrostatic Analysis

- How to find φ_j ?



- From detailed balance in equilibrium ($J^{\text{drift}} = -J^{\text{diff}}$):

$$\varphi_j = \frac{kT}{q}\ln\frac{p_0(-x_p)}{p_0(x_n)} = \frac{kT}{q}\ln\frac{n_0(x_n)}{n_0(-x_p)} = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2}$$

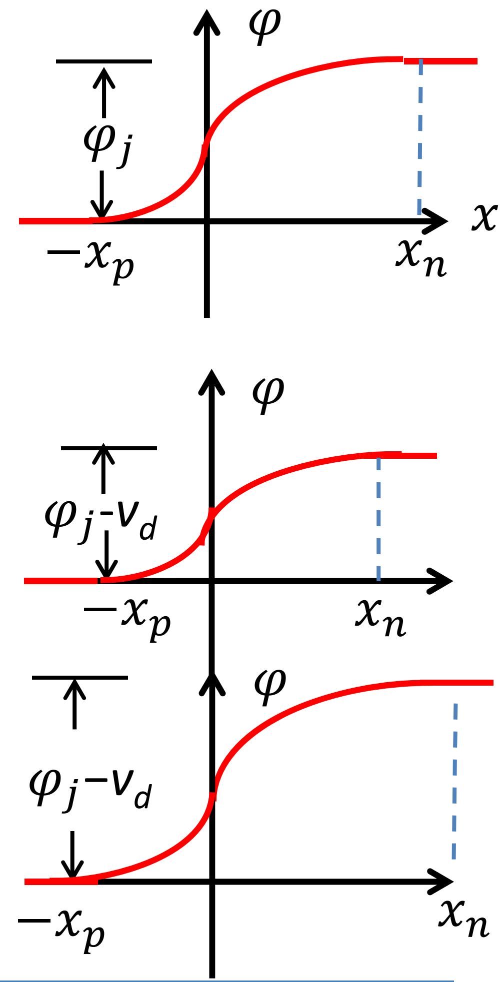
- φ_j depends on
  - Doping concentration on both sides (N_A, N_D)
  - Temperature (kT)
  - Material ($n_i^2 \sim \exp[-E_g/kT]$)

p-n Junction – Applied Voltage

- Applied voltage dropped across x_d.
- Detailed balance still nearly true for $v_d < \varphi_j$ - 0.1 V ($J^{\text{drift}} \cong -J^{\text{diff}}$):

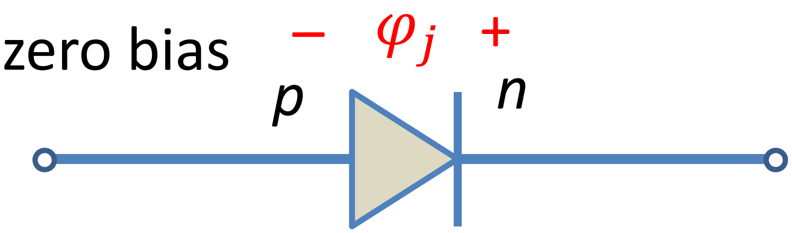
$$\varphi_j - v_d = \frac{kT}{q}\ln\frac{p(-x_p)}{p(x_n)} = \frac{kT}{q}\ln\frac{n(x_n)}{n(-x_p)}$$

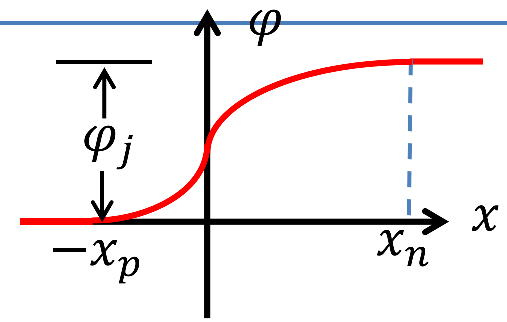
- Forward bias: smaller barrier, narrower depletion region, lower E_{max}.
- Reverse bias: larger barrier, wider depletion region, higher E_{max}.



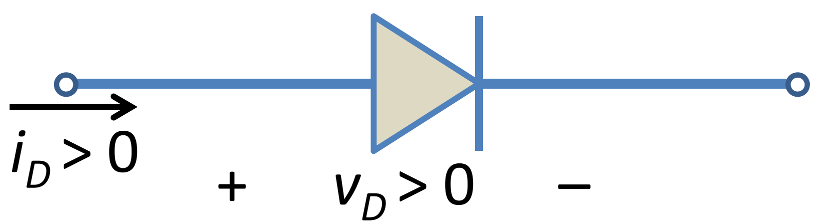
p-n Junction Under Applied Voltage

zero bias

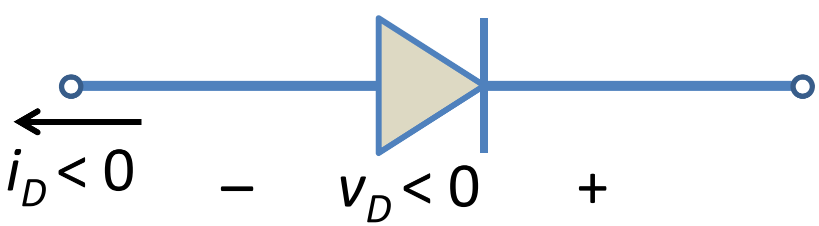




forward bias



reverse bias



- Under bias v_D, replace φ_j with $(\varphi_j - v_D)$. e.g.

$$x_d = \sqrt{\frac{2\varepsilon(\varphi_j - v_D)}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$

- Forward bias, $v_D > 0$, x_d shrinks
- Reverse bias, $v_D < 0$, x_d widens