6.012 - Electronic Devices and Circuits

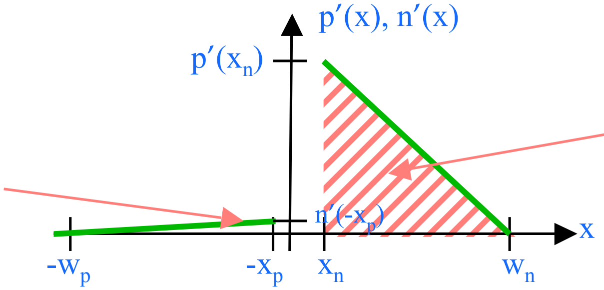
Lecture 8 - <u>Bipolar Junction Transistor Basics</u> - Outline

- **Announcements**
  - Handout - Lecture Outline and Summary; Old exam 1's on Stellar
  - First Hour Exam - Oct. 8, 7:30-9:30 pm; thru p-n diodes, PS #4
- **Review/Diode model wrap-up**
  - Exponential diode: $i_D(v_{AB}) = I_S\,(e^{qv_{AB}/kT} - 1)$ (holes) (electrons)
    with $I_S \equiv A\,q\,n_i^2\,[(D_h/N_{Dn}\,w_n^*) + (D_e/N_{Ap}\,w_p^*)]$
  - Short- vs. long-base diodes: effective diode lengths and consequences
  - Observations: Saturation current, I_S, goes down as doping levels go up
    Injection is predominantly into more lightly doped side
    Junctions as injecting and extracting contacts.
  - Diffusion charge stores; diffusion capacitance:
    - Quasi-neutral region excess carriers as charge store
    - Total charge vs. voltage and current; incremental capacitance
- **Bipolar junction transistor operation and modeling**
  - Bipolar junction transistor structure
  - Qualitative description of operation: 1. Visualizing the carrier fluxes
    (using npn as the example) 2. The control function
    3. Design objectives
  - Operation in forward active region, $v_{BE} > 0$, $v_{BC} < 0$: $\square_E$, $\square_B$, $\square_F$, I_{ES}

Biased p-n junctions: excess minority carrier (diffusion) charge stores

Excess minority carrier charge stores; Diffusion capacitance:

Using example of asymmetrically doped p+-n diode



Note: Assuming negligible charge stored on p-side

Charge stored on n-side (holes and electrons)

Diffusion charge store, n-side:

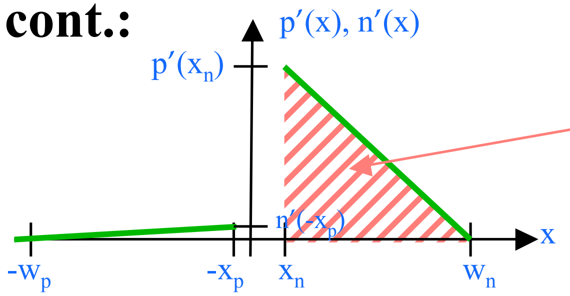
Notice that the stored positive charge (the excess holes) and the stored negative charge (the excess electrons) occupy the same volume in space (between x = x_n and x = w_n)!

$$q_{A,DF}(v_{AB}) = Aq\left[p'(x_n) - p'(w_n)\right]\frac{\left[w_n - x_n\right]}{2} \approx Aq\frac{n_i^2}{N_{Dn}}\left[e^{qv_{AB}/kT} - 1\right]\frac{w_{n,eff}}{2}$$

The charge stored depends non-linearly on v_{AB}. As we did in the case of the depletion charge store, we define an incremental linear equivalent diffusion capacitance, $C_{df}(V_{AB})$, as:

$$C_{df}(V_{AB}) \equiv \left.\frac{\partial q_{A,DF}}{\partial v_{AB}}\right|_{v_{AB}=V_{AB}} \approx A\frac{q^2}{2kT}w_{n,eff}\frac{n_i^2}{N_{Dn}}e^{qv_{AB}/kT}$$

Diffusion capacitance, cont.:



Excess holes and
electrons stored
on n-side

A very useful way to write the diffusion capacitance is in terms of the bias current, I_D:

$$I_D \approx Aqn_i^2 \frac{D_h}{N_{Dn} w_{n,eff}} \left[e^{qV_{AB}/kT} - 1 \right] \approx Aqn_i^2 \frac{D_h}{N_{Dn} w_{n,eff}} e^{qV_{AB}/kT} \quad \text{for} \quad V_{AB} >> kT$$

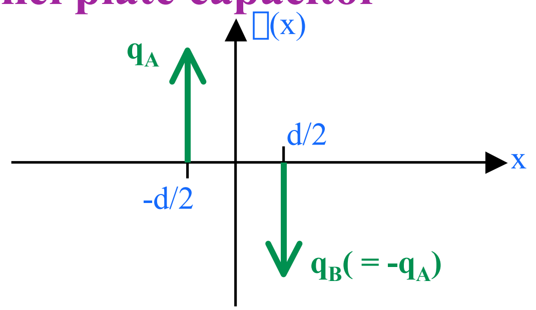
Comparing this to C_{dfF} we find:

$$C_{df}(V_{AB}) \approx A \frac{q^2}{2kT} w_{n,eff} \frac{n_i^2}{N_{Dn}} e^{qV_{AB}/kT} \approx \frac{w_{n,eff}^2}{2D_h} \frac{q\, I_D(V_{AB})}{kT}$$

** Notice that the cross-sectional area of the device, A, does not appear explicitly in this expression. Only the total current!

Comparing charge stores and small-signal linear equivalent capacitors:

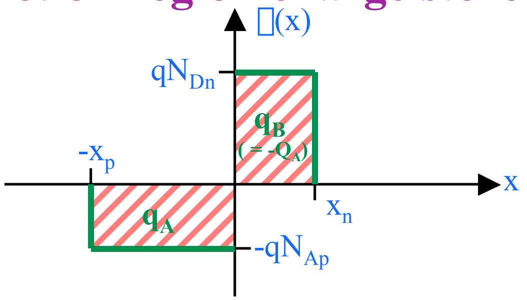
Parallel plate capacitor



$$q_{A,PP} = A\frac{\varepsilon}{d}v_{AB}$$

$$C_{pp}(V_{AB}) \equiv \left.\frac{\partial q_{A,PP}}{\partial v_{AB}}\right|_{v_{AB}=V_{AB}} = \frac{A\varepsilon}{d}$$

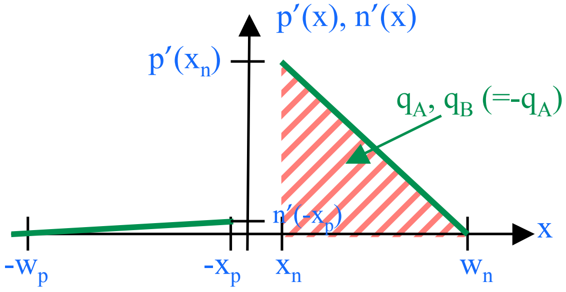
Depletion region charge store



$$q_{A,DP}(v_{AB}) = -A\sqrt{2q\varepsilon_{Si}\left[\phi_b - v_{AB}\right]\frac{N_{Ap}N_{Dn}}{\left[N_{Ap}+N_{Dn}\right]}}$$

$$C_{dp}(V_{AB}) = A\sqrt{\frac{q\varepsilon_{Si}}{2\left[\phi_b - V_{AB}\right]}\frac{N_{Ap}N_{Dn}}{\left[N_{Ap}+N_{Dn}\right]}} = \frac{A\,\varepsilon_{Si}}{w(V_{AB})}$$

QNR region diffusion charge store



$$q_{AB,DF}(v_{AB}) \approx Aqn_i^2\frac{D_h}{N_{Dn}w_{n,eff}}\left[e^{qV_{AB}/kT} - 1\right]$$

Note: Approximate because we are only accounting for the charge store on the lightly doped side.

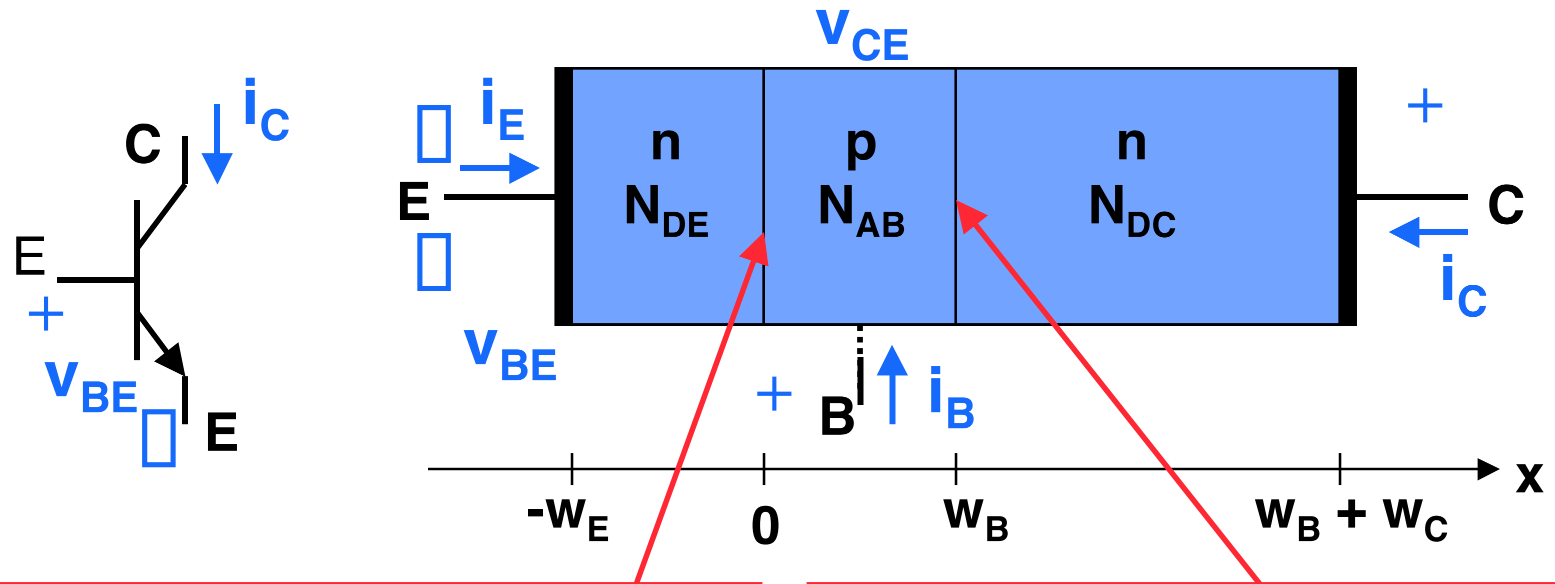
$$= \frac{w_{n,eff}^2}{2D_h}\,i_D(v_{AB})$$

$$C_{df}(V_{AB}) \approx \frac{w_{n,eff}^2}{2D_h}\,\frac{q\,I_D(V_{AB})}{kT}$$

Note: Valid in forward bias where $v_{AB} >> kT/q$

Bipolar Junction Transistors: basic operation and modeling…

… how the base-emitter voltage, v_{BE}, controls the collector current, i_C



Forward biased

v_{BE}, the bias on the emitter-base junction, controls the injection of electrons across the E-B junction into the base and toward the collector.

Reverse biased

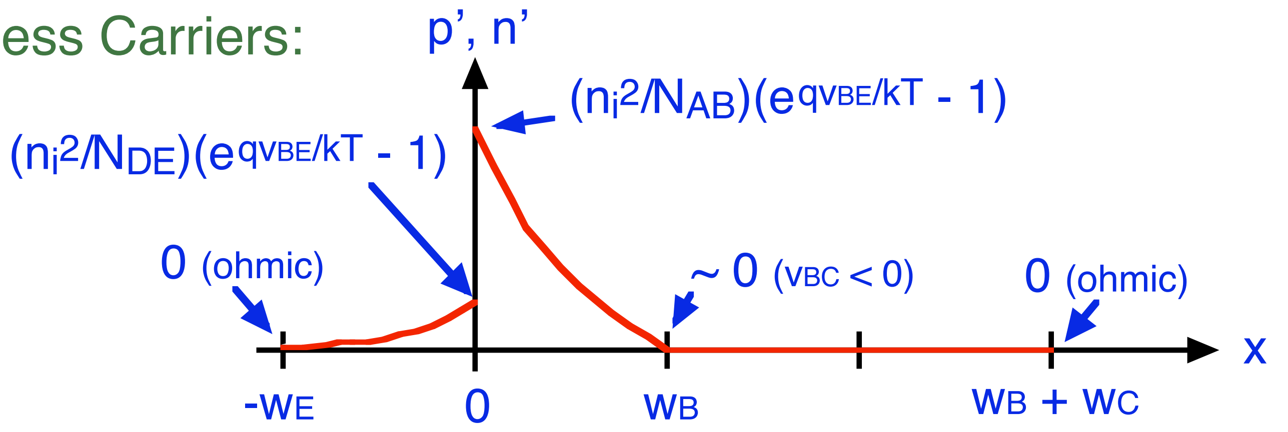
v_{CB}, the reverse bias on the collector-base junction, insures collection of those electrons injected across the E-B junction that reach the C-B junction as the collector current, i_C

Our next task is to determine:

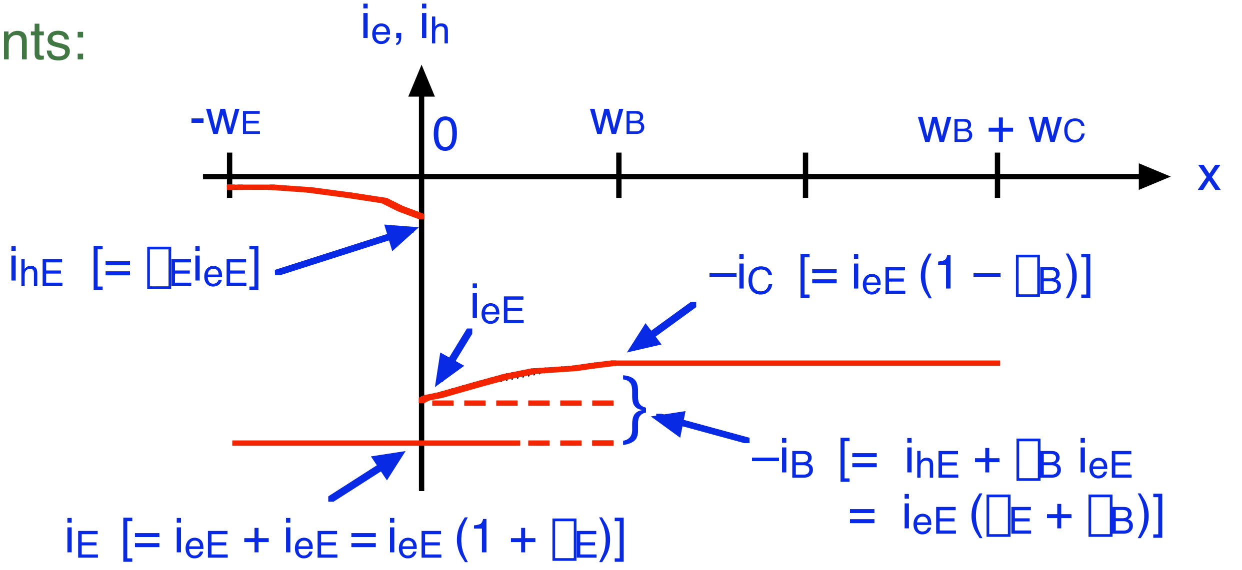
Given a structure, what are $i_E(v_{BE},v_{CE})$, $i_C(v_{BE},v_{CE})$, and $i_B(v_{BE},v_{CE})$?

npn BJT: Forward active region operation, $v_{EB} > 0$ and $v_{CB} \leq 0$

Excess Carriers:



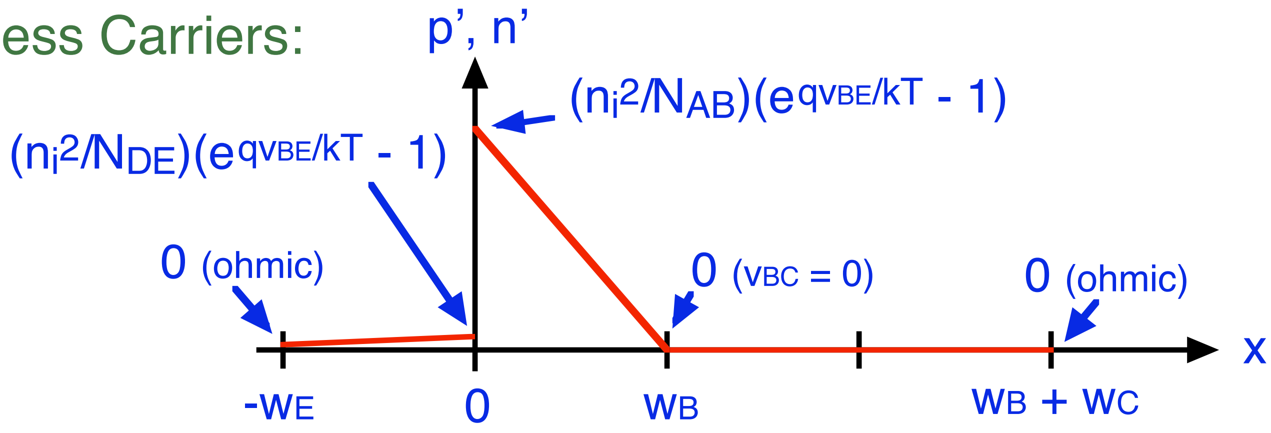
Currents:



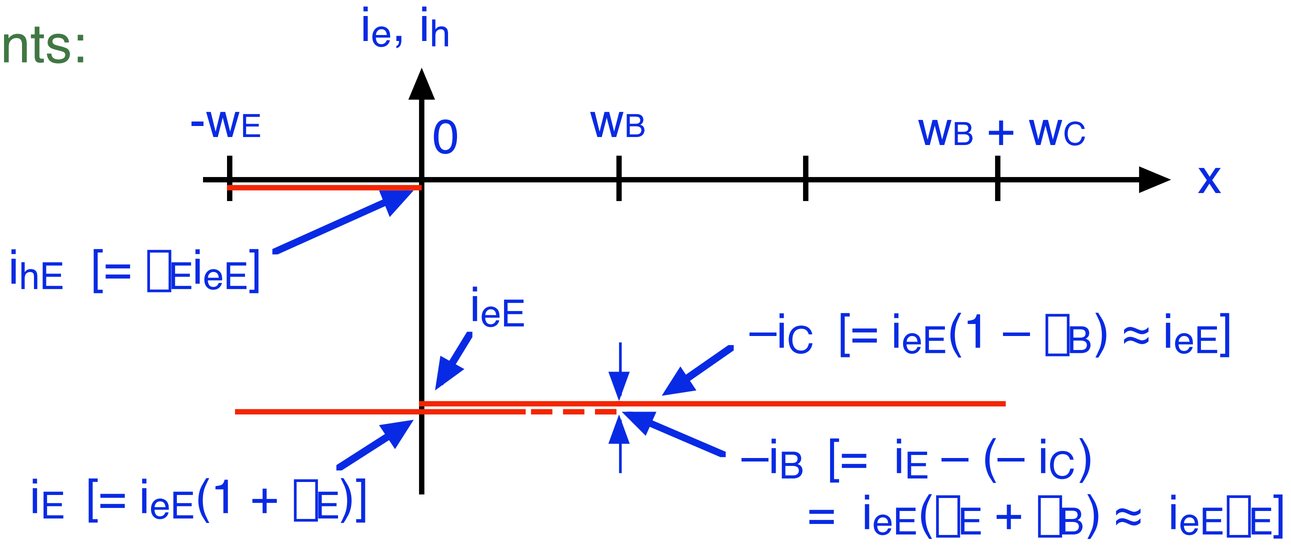
npn BJT: Well designed structure in FAR

$N_{DE} >> N_{AB}, w_E << L_{hE}, w_B << L_{eB}$

Excess Carriers:



Currents:



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Lecture 8 - Bipolar Junction Transistor Basics - Summary

- **Review/Junction diode model wrap-up**

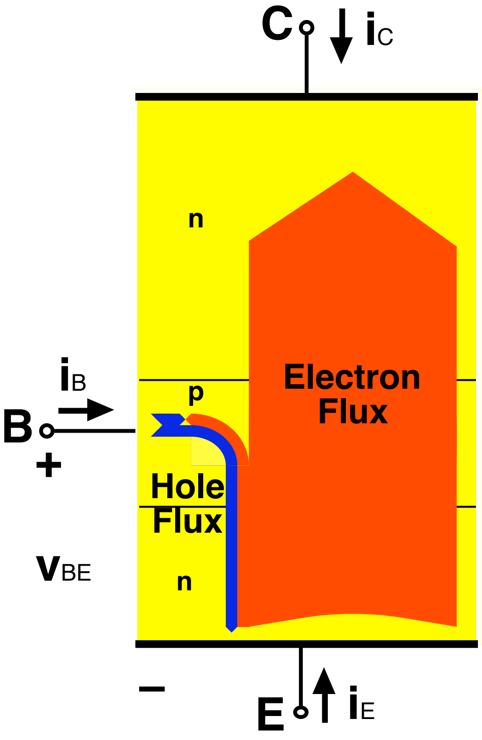
  Refer to "Lecture 7- Summary" for a good overview

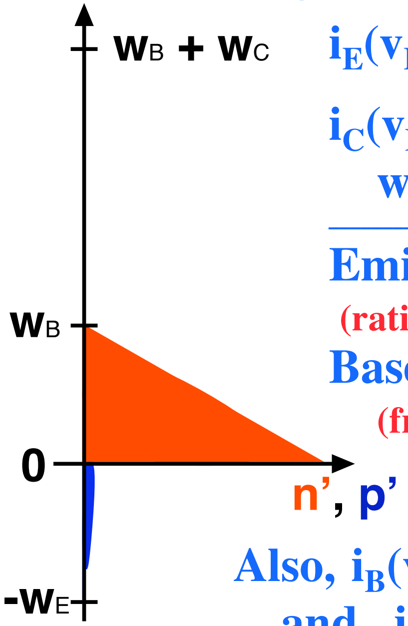
  Diffusion capacitance: adds to depletion capacitance (p$^+$-n example)

  In asym., short-base diodes: $C_{df}(V_{AB}) \approx (qI_D/kT)[(w_n - x_n)^2/D_h]$

  (area doesn't enter expression!)

- **Bipolar junction transistor operation and modeling**





Currents (forward active): (npn example)

$i_E(v_{BE},0) = -I_{ES}\,(e^{qv_{BE}/kT} - 1)$

$i_C(v_{BE},0) = -\alpha_F\, i_E(v_{BE},0)$

with $\alpha_F \equiv [(1 - \delta_B)/(1 + \delta_E)]$

Emitter defect, $\delta_E \equiv (D_h N_{AB} w_B{}^* / D_e N_{DE} w_E{}^*)$

(ratio of hole to electron current across E-B junction)

Base defect, $\delta_B \equiv (w_B{}^2/2L_e{}^2)$

(fraction of injected electrons recombining in base)

Also, $i_B(v_{BE},0) = [(\delta_E + \delta_B)/(1 + \delta_E)]\, i_E(v_{BE},0)$

and, $i_C(v_{BE},0) = \beta_F\, i_B(v_{BE},0)$,

with $\beta_F \equiv \alpha_F/(1 - \alpha_F) = [(1 - \delta_B)/(\delta_E + \delta_B)]$