Lecture 7 - Bipolar Junction Transistors - Outline

- **Announcements**

  First Hour Exam - Oct. 7, 7:30-9:30 pm; thru 10/2/09, PS #4

- **Review/Diode model wrap-up**

  Exponential diode: $i_D(v_{AB}) = I_S\,(e^{qv_{AB}/kT} - 1)$ **(holes)** **(electrons)**

  with $I_S \equiv A\,q\,n_i^2\,[(D_h/N_{Dn}\,w_n^*) + (D_e/N_{Ap}\,w_p^*)]$

  Observations: Saturation current, I_S, goes down as doping levels go up

  Injection is predominantly into more lightly doped side

  Asymmetrical diodes: the action is on the lightly doped side

  Diffusion charge stores; diffusion capacitance: **(Recitation topic)**

  Excess carriers in quasi-neutral region = Stored charge

- **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

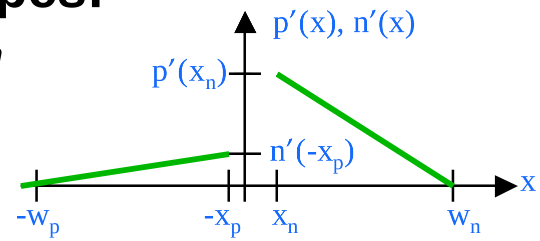
  3. Design objectives

  Operation in forward active region, $v_{BE} > 0$, $v_{BC} < 0$: δ_E, δ_B, β_F, I_{ES}

Biased p-n junctions: current flow, cont.

The saturation current of three diode types:

I_S's dependence on the relative sizes of w and L_{min}

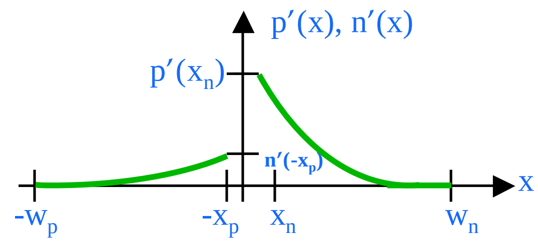


Short-base diode, $w_n << L_h$, $w_p << L_e$:

$$J_h(x_n) = q\frac{n_i^2}{N_{Dn}}\frac{D_h}{(w_n - x_n)}\left[e^{qv_{AB}/kT} - 1\right]$$

$$J_e(-x_p) = q\frac{n_i^2}{N_{Ap}}\frac{D_e}{(w_p - x_p)}\left[e^{qv_{AB}/kT} - 1\right]$$

$$i_D = Aqn_i^2\left[\frac{D_h}{N_{Dn}(w_n - x_n)} + \frac{D_e}{N_{Ap}(w_p - x_p)}\right]\left[e^{qv_{AB}/kT} - 1\right]$$



Long-base diode, $w_n >> L_h$, $w_p >> L_e$:

$$J_h(x_n) = q\frac{n_i^2}{N_{Dn}}\frac{D_h}{L_h}\left[e^{qv_{AB}/kT} - 1\right]$$

$$J_e(-x_p) = q\frac{n_i^2}{N_{Ap}}\frac{D_e}{L_e}\left[e^{qv_{AB}/kT} - 1\right]$$

$$i_D = Aqn_i^2\left[\frac{D_h}{N_{Dn}L_h} + \frac{D_e}{N_{Ap}L_e}\right]\left[e^{qv_{AB}/kT} - 1\right]$$

General diode:

$$i_D = Aqn_i^2\left[\underbrace{\frac{D_h}{N_{Dn}w_{n,eff}}}_{\text{Hole injection into n-side}} + \underbrace{\frac{D_e}{N_{Ap}w_{p,eff}}}_{\text{Electron injection into p-side}}\right]\left[e^{qv_{AB}/kT} - 1\right]$$

Hole injection into n-side **Electron injection into p-side**

Note: $w_{n,eff} \equiv L_h \tanh(w_n - x_n)$, $w_{p,eff} \equiv L_e \tanh(w_p - x_p)$

Asymmetrically doped junctions: *an important special case*

Current flow impact/issues

A p+-n junction ($N_{Ap} >> N_{Dn}$):

$$i_D = Aqn_i^2\left[\frac{D_h}{N_{Dn}w_{n,eff}} + \cancel{\frac{D_e}{N_{Ap}w_{p,eff}}}\right]\left[e^{qv_{AB}/kT} - 1\right] \approx \underbrace{Aqn_i^2\frac{D_h}{N_{Dn}w_{n,eff}}}_{\text{Hole injection into n-side}}\left[e^{qv_{AB}/kT} - 1\right]$$

An n+-p junction ($N_{Dn} >> N_{Ap}$):

$$i_D = Aqn_i^2\left[\cancel{\frac{D_h}{N_{Dn}w_{n,eff}}} + \frac{D_e}{N_{Ap}w_{p,eff}}\right]\left[e^{qv_{AB}/kT} - 1\right] \approx \underbrace{Aqn_i^2\frac{D_e}{N_{Ap}w_{p,eff}}}_{\text{Electron injection into p-side}}\left[e^{qv_{AB}/kT} - 1\right]$$

Note that in both cases the minority carrier injection is predominately into the lightly doped side.

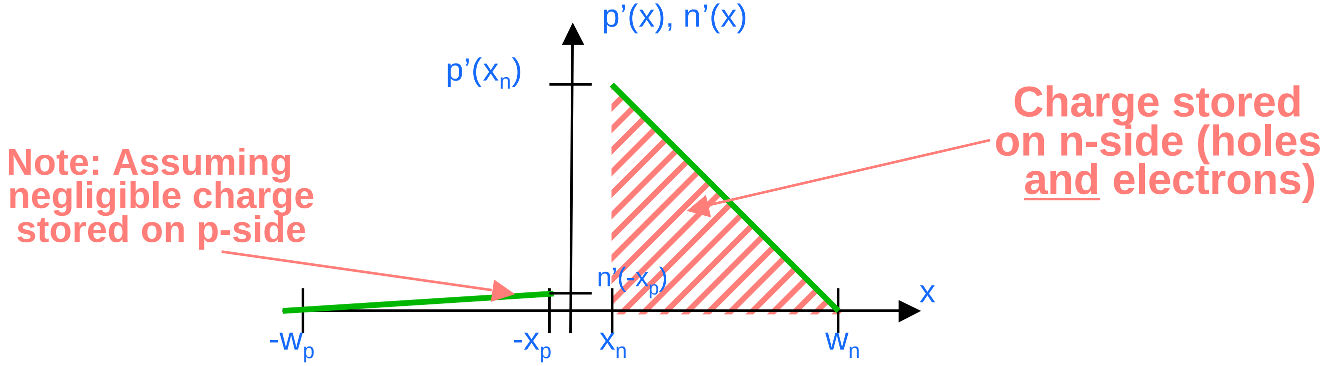
Note also that it is the doping level of the more lightly doped junction that determines the magnitude of the current, and as the doping level on the lightly doped side decreases, the magnitude of the current increases.

Two very important and useful observations!!

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

Diffusion charge store, and diffusion capacitance:

Using example of asymmetrically doped p+-n diode



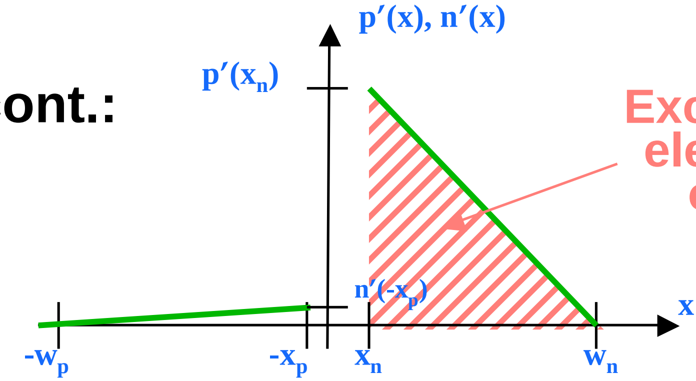
Notice that the stored positive charge (the excess holes) and the stored negative charge (the excess electrons) occupy the same volume in space (between $x = x_n$ and $x = w_n$)!

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

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.:



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

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

To do this, first divide C_{df} by I_D to get:

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

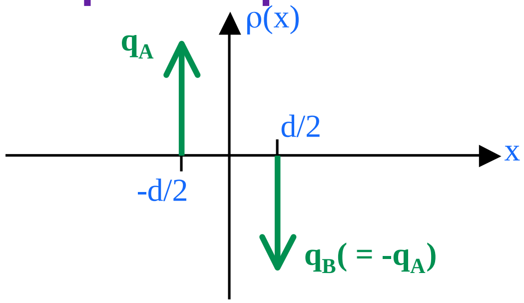
Isolating C_{df}, we have:

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

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

Comparing charge stores; small-signal linear equivalent capacitors:

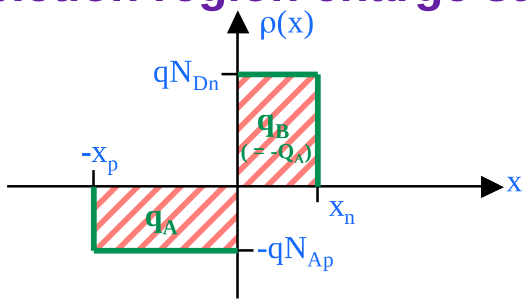
Parallel plate capacitor



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

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

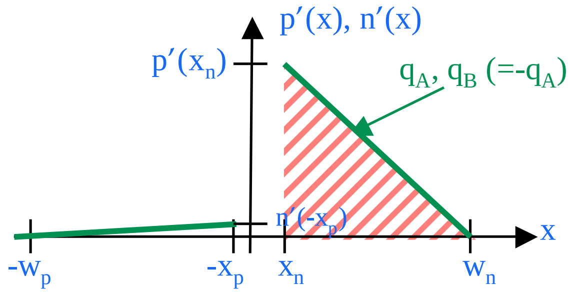
Depletion region charge store



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

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

QNR region diffusion charge store



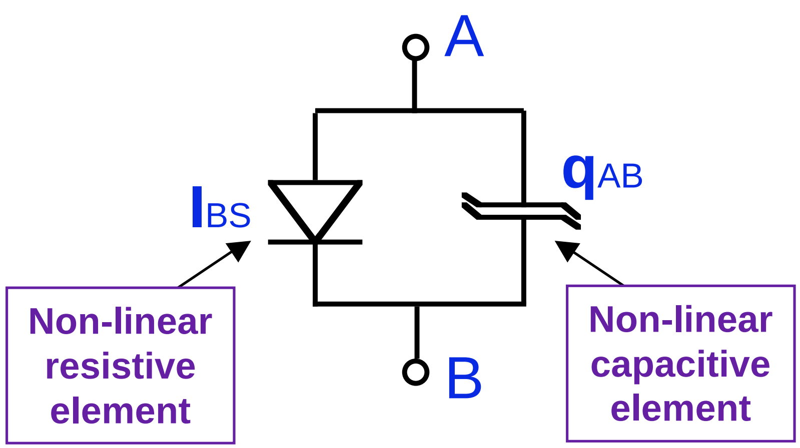
$$q_{AB,DF}(v_{AB}) \approx Aqn_i^2\frac{D_h}{N_{Dn}w_{n,eff}}\left[e^{qV_{AB}/kT}-1\right]$$

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

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

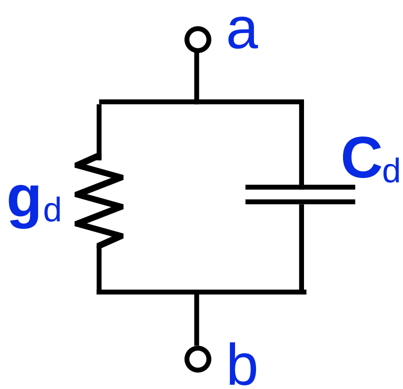
$$C_{df}(V_{AB}) \approx \frac{w_{n,eff}^2}{2D_h}\frac{q\,I_D(V_{AB})}{kT}$$

p-n diode: *large signal model including charge stores*



q_{AB}: Excess carriers on p-side **+** excess carriers on n-side **+** junction depletion charge.

small signal linear equivalent circuit

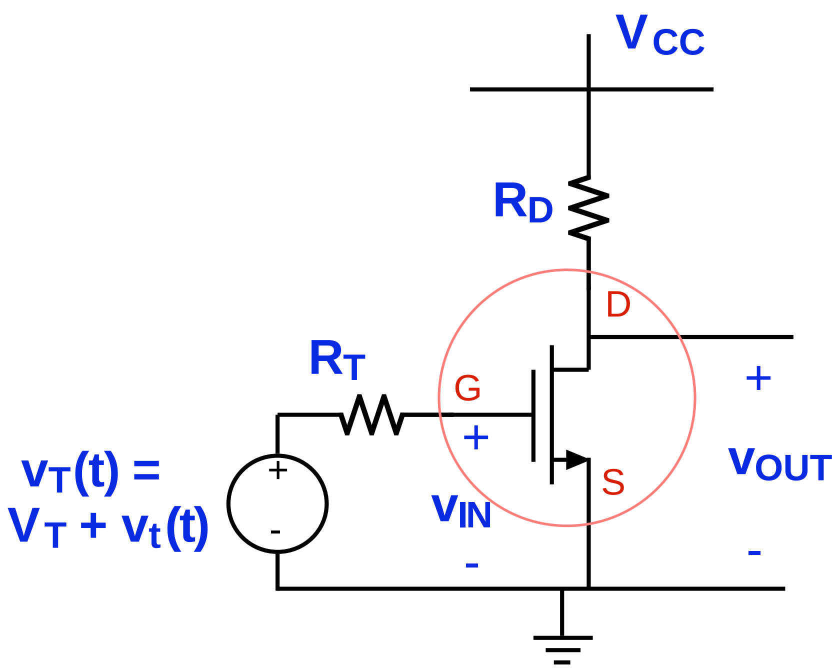


$$g_d \equiv \left.\frac{\partial i_D}{\partial v_{AB}}\right|_{v_{AB}=V_{AB}} \approx \begin{cases} 0 & \text{for} \quad V_{AB} < 0 \\ \dfrac{qI_D}{kT} & \text{for} \quad V_{AB} >> kT/q \end{cases}$$

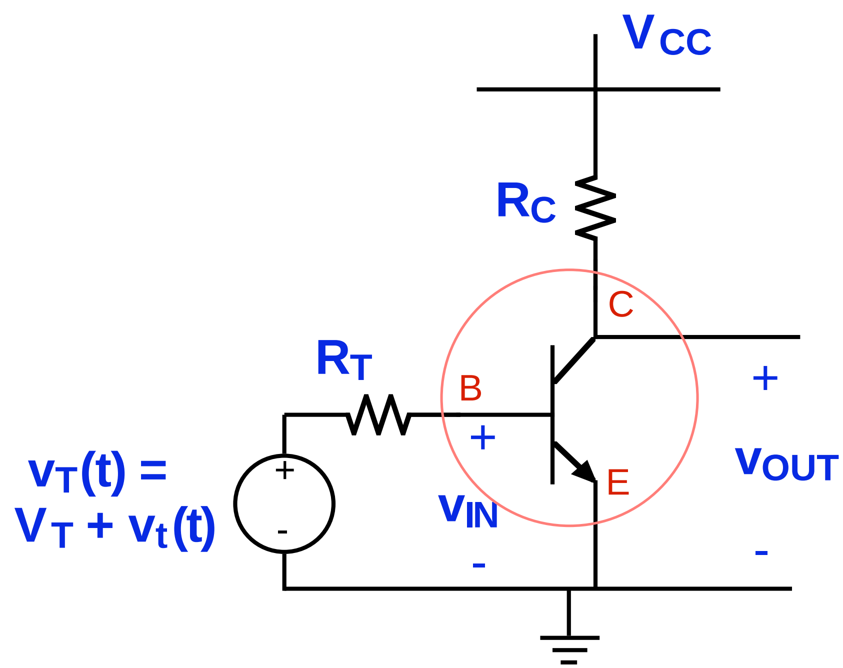
$$C_d(V_{AB}) \equiv \left.\frac{\partial q_{AB}}{\partial v_{AB}}\right|_{v_{AB}=V_{AB}} \approx \begin{cases} C_{dp}(V_{AB}) & \text{for} \quad V_{AB} < 0 \\ C_{dp}(V_{AB}) + C_{df}(V_{AB}) & \text{for} \quad V_{AB} >> kT/q \end{cases}$$

Moving on to transistors!

Amplifiers/Inverters: *back to 6.002*



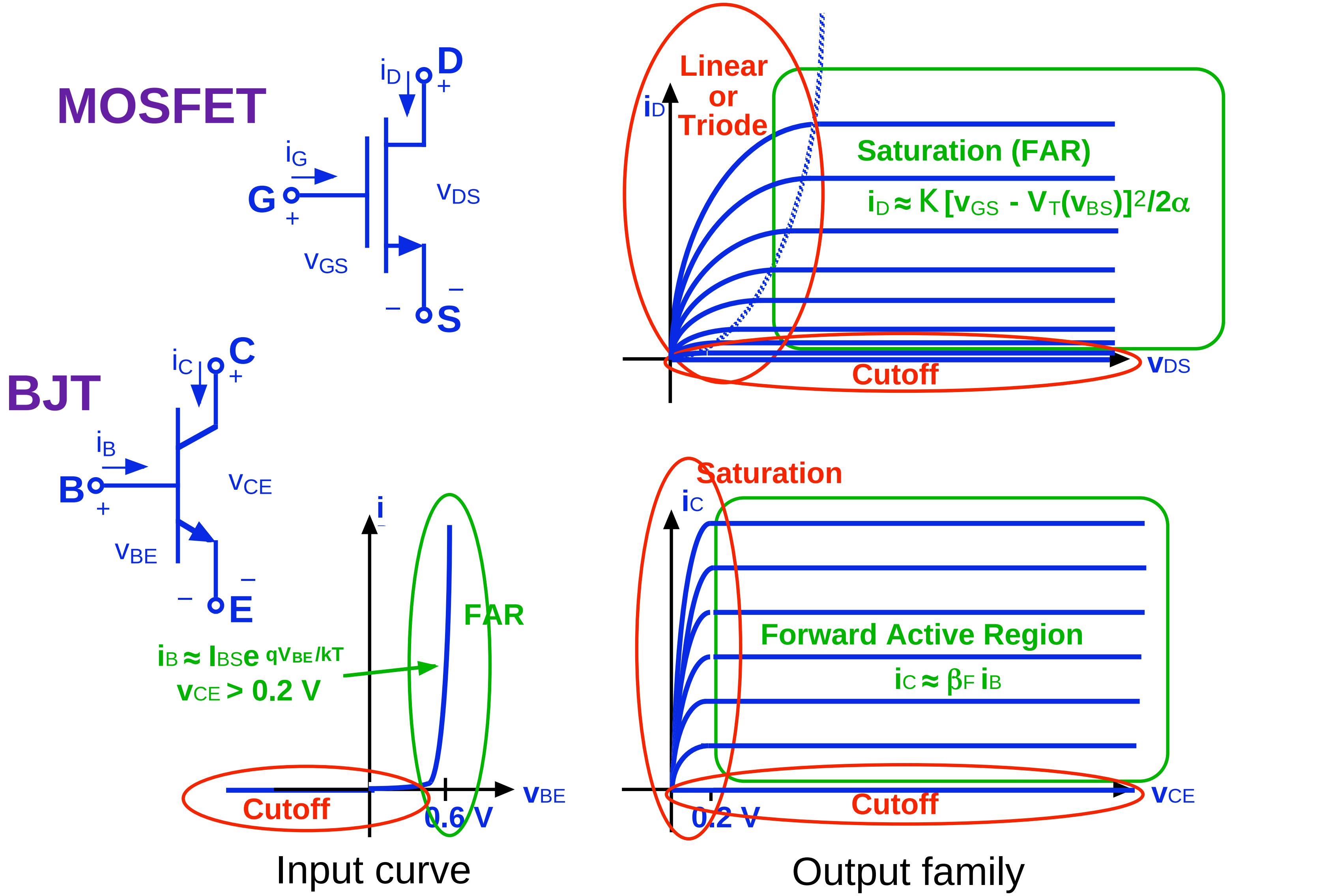
An MOS amplifier
or inverter:
the transistor is an
n-channel MOSFET



A bipolar amplifier
or inverter:
the transistor is an
npn BJT

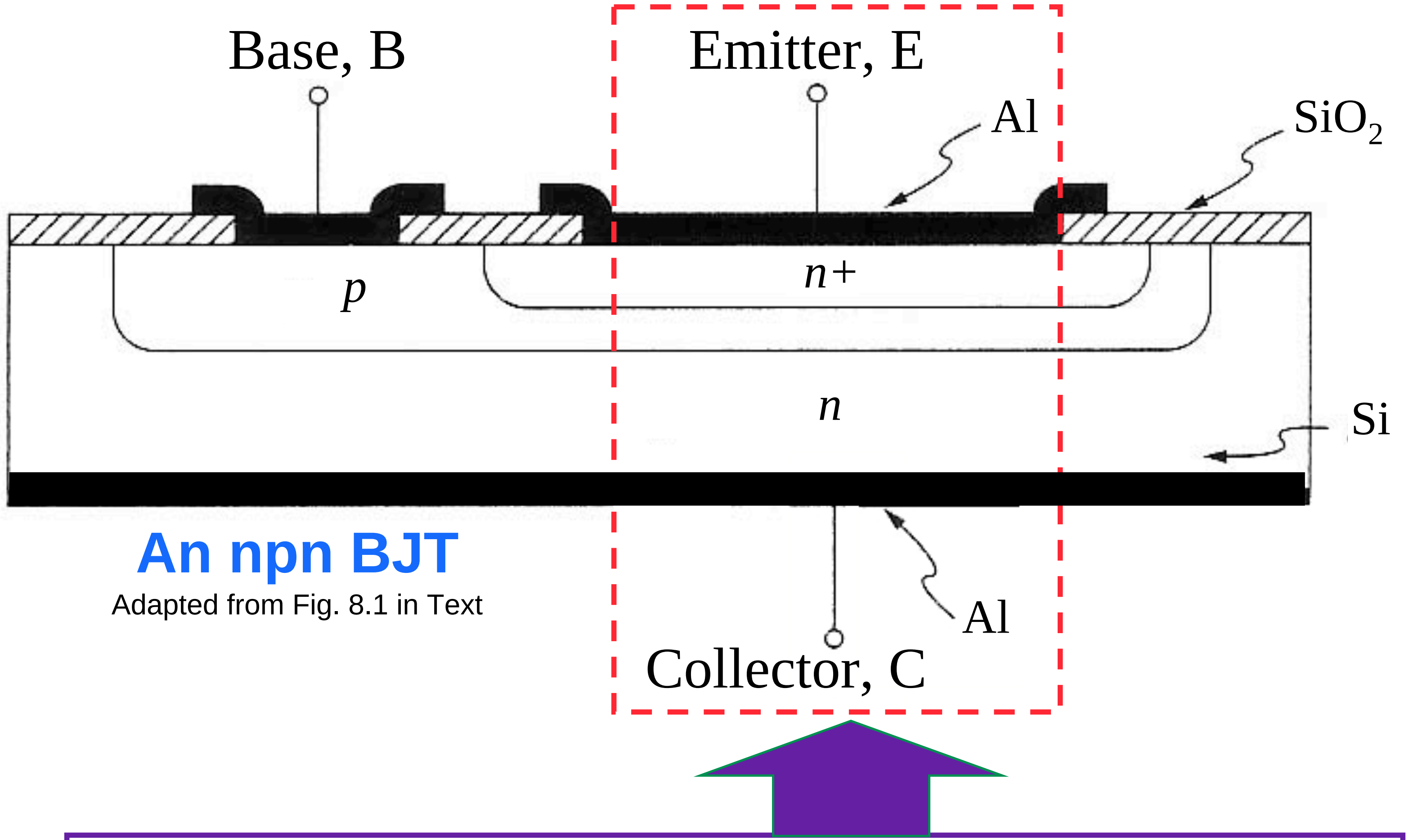
npn BJT: Connecting with the n-channel MOSFET from 6.002

A very similar behavior*, and very similar uses.



* At its output each device looks like a current source controlled by the input signal.

Basic Bipolar Junction Transistor (BJT) - *cross-section*



An npn BJT

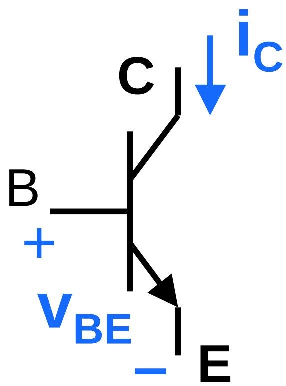
Adapted from Fig. 8.1 in Text

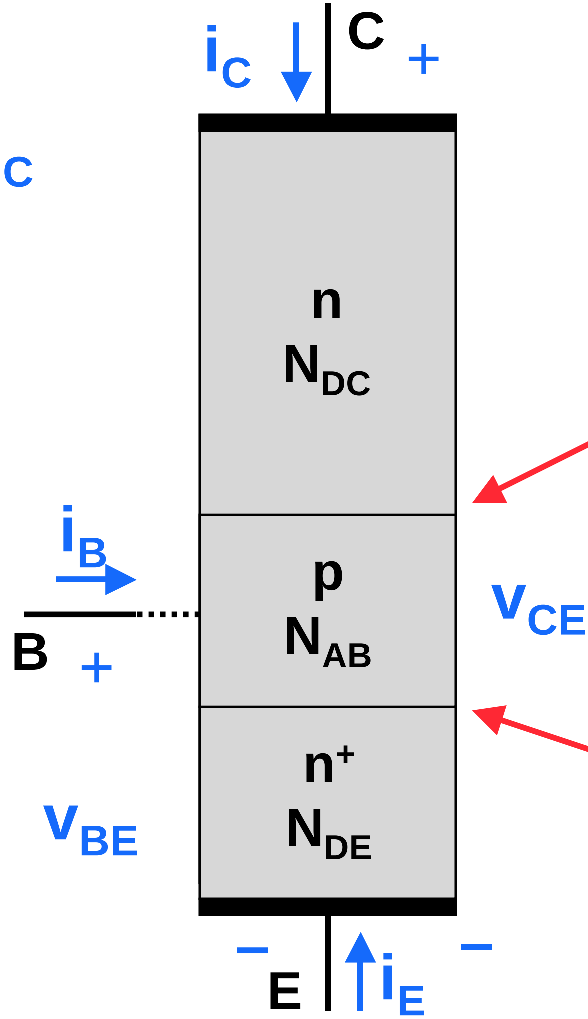
The heart of the device, and what we will model

How does it work?

Bipolar Junction Transistors: basic operation and modeling…

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





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

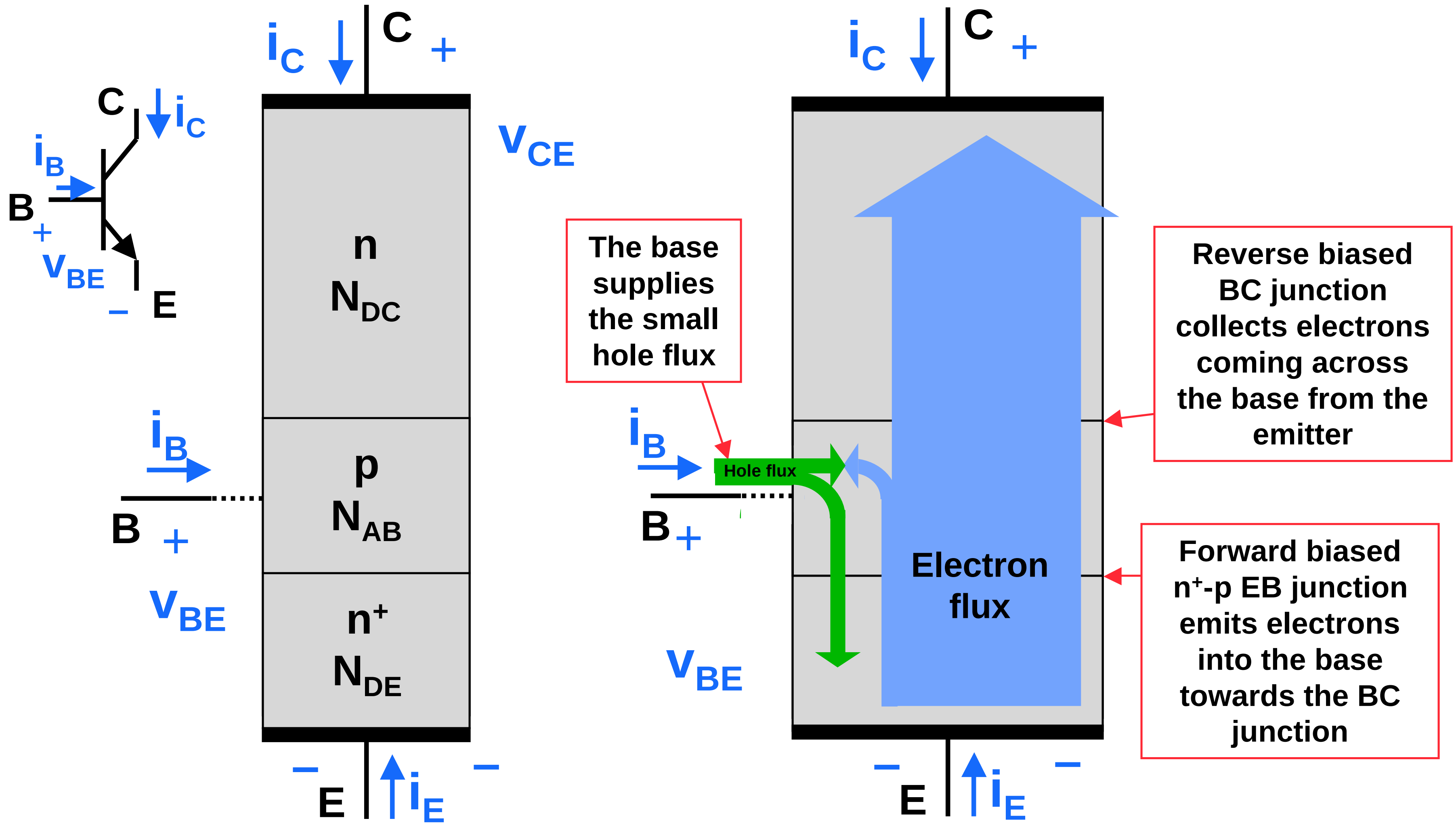
Forward biased

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.

A good way to envision this is to think "carrier fluxes":

Next foil

Bipolar Junction Transistors: the carrier fluxes through an npn

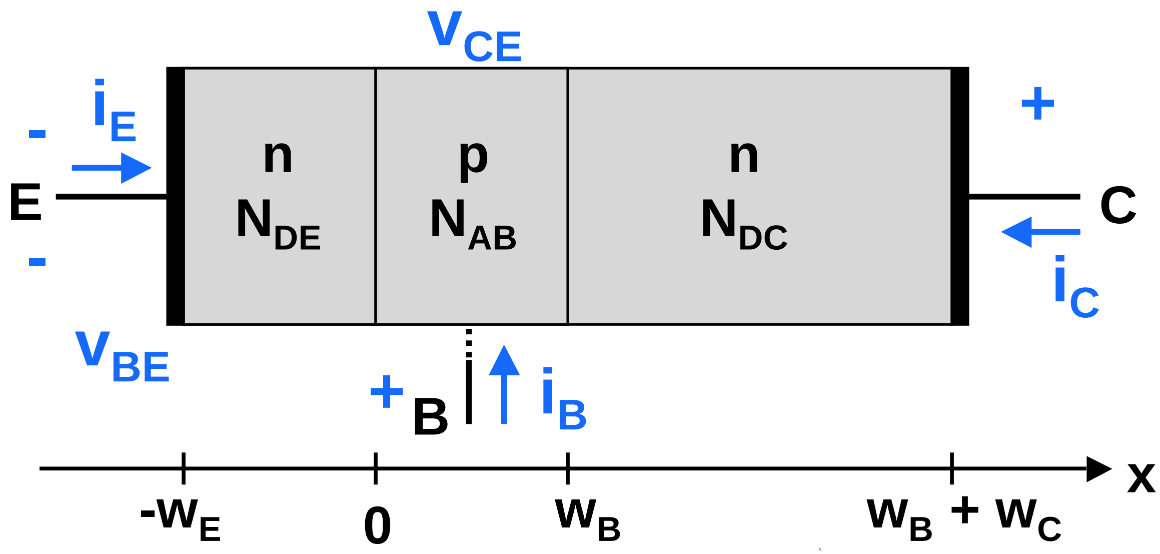


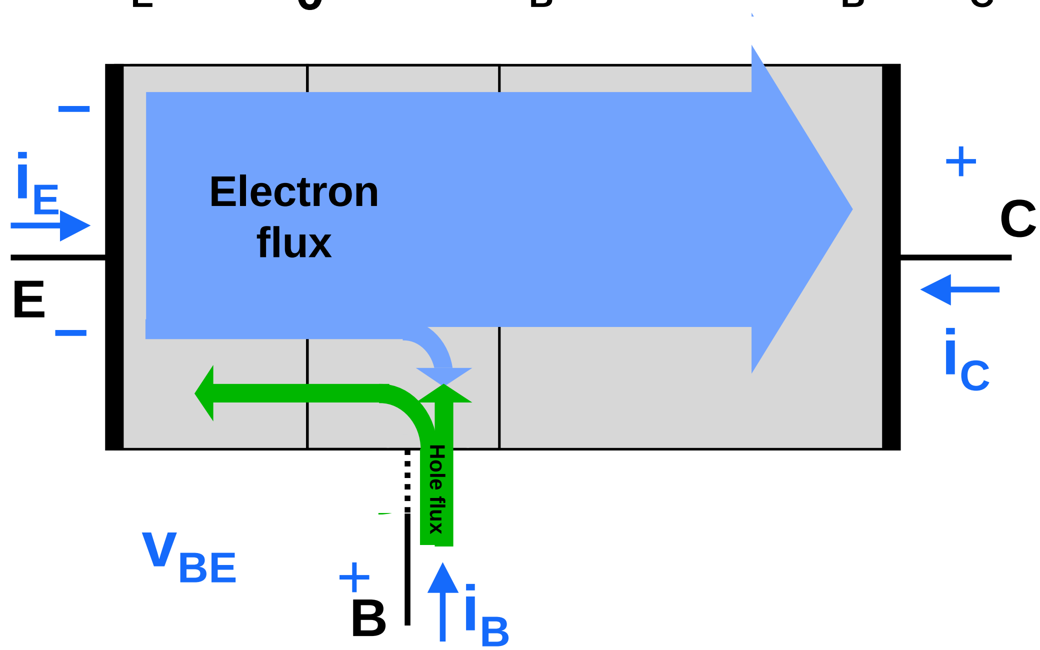
Our next task is to determine:

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

Bipolar Junction Transistors: basic operation and modeling…

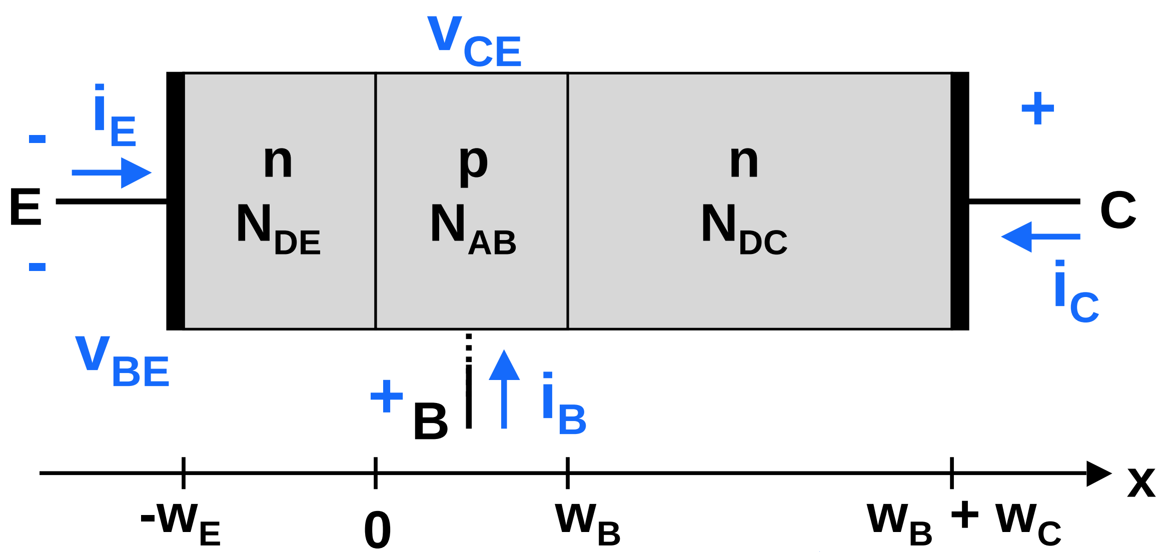
… how the base-emitter voltage, v_{BE}, controls the collector current, i_C



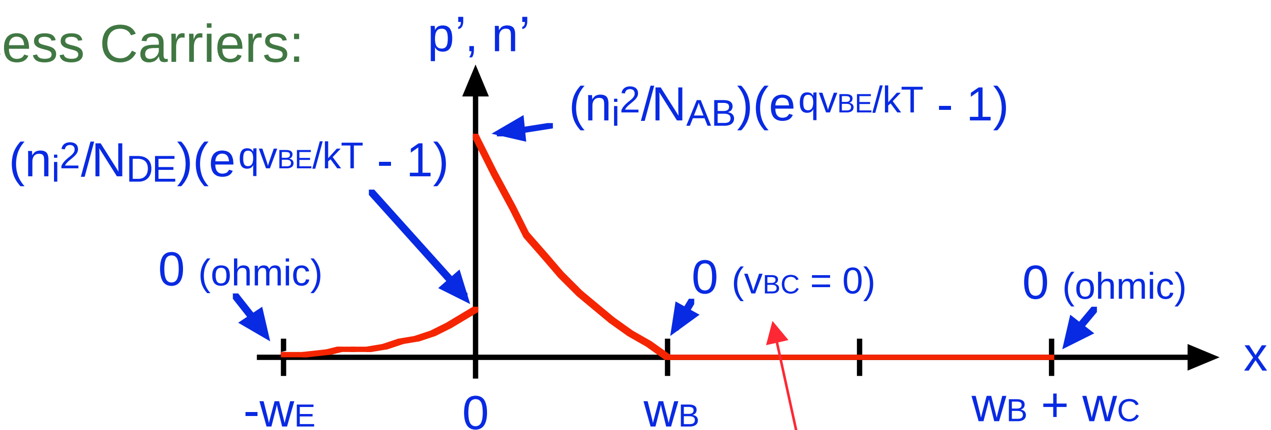


Bipolar Junction Transistors: basic operation and modeling…

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



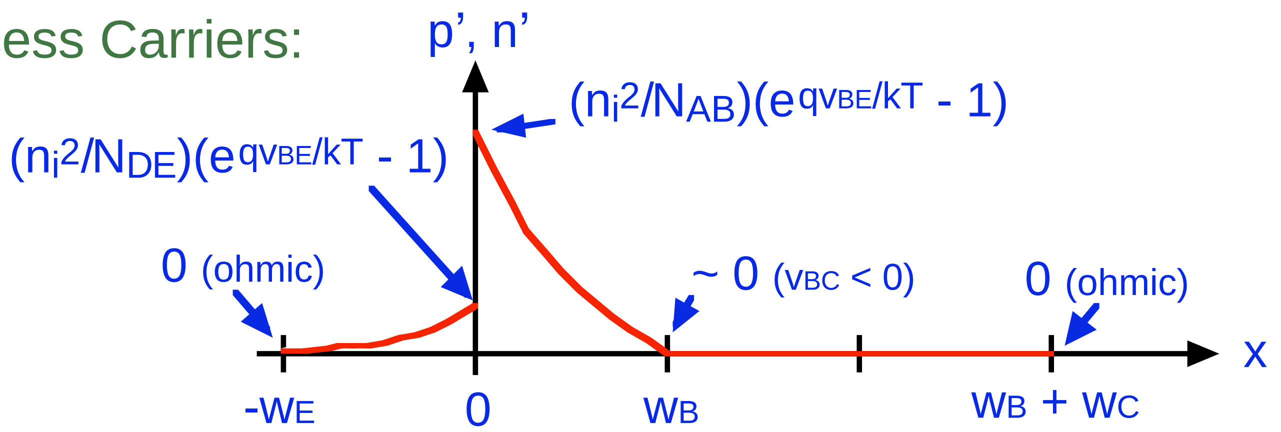
Excess Carriers:



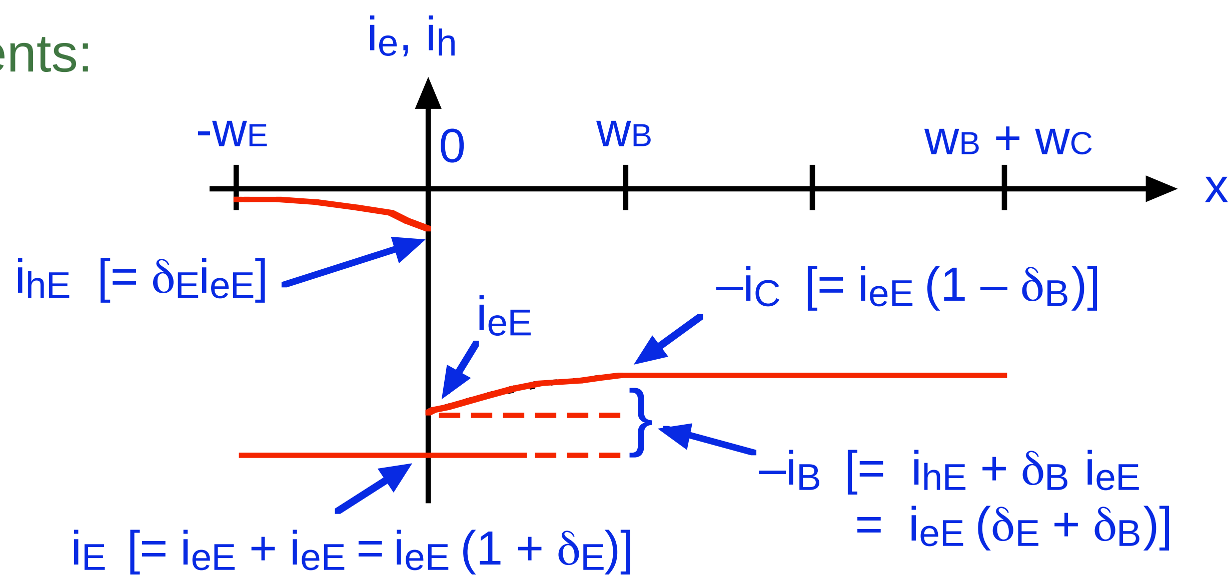
This is rigorous for $v_{CB} = 0$, but also very good when $v_{CB} > 0$.

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

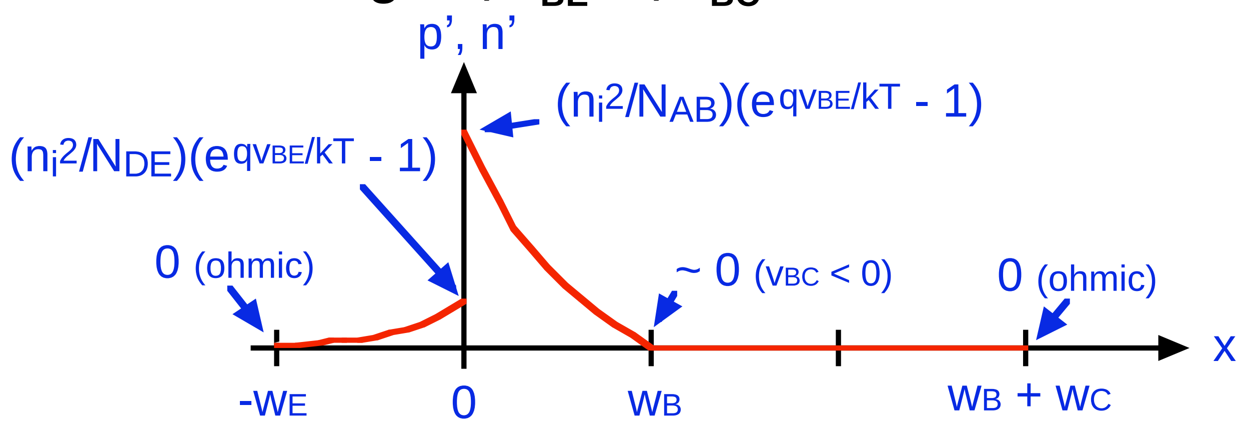
Excess Carriers:



Currents:



npn BJT: Approximate model for $i_E(v_{BE},v_{BC})$ and $i_C(v_{BE},v_{BC})$ in forward active region, $v_{BE}>0$, $v_{BC}<0$



The emitter current, i_E

Begin with the good current, the electron current into the base, i_{eE}:

$$i_{eE} = -Aqn_i^2 \frac{D_e}{N_{AB} w_{B,eff}} \left[e^{qV_{BE}/kT} - 1 \right]$$

Next find the bad current, the hole current back into the emitter, i_{hE}:

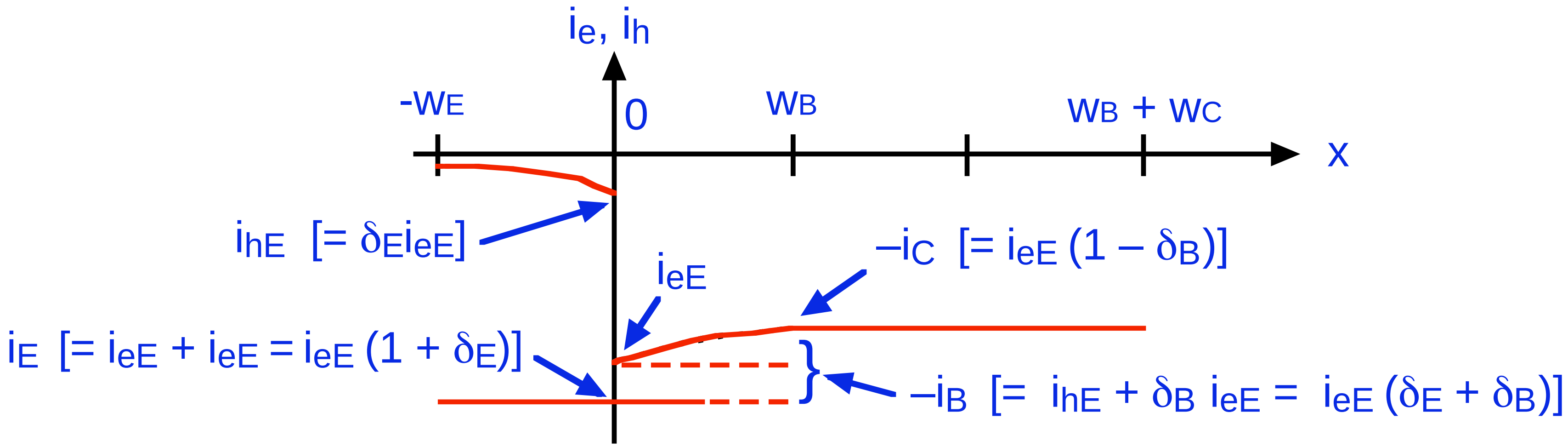
$$i_{hE} = -Aqn_i^2 \frac{D_h}{N_{DE} w_{E,eff}} \left[e^{qV_{BE}/kT} - 1 \right]$$

and write it as a fraction of i_{eE}:

$$i_{hE} = \frac{N_{AB} w_{B,eff}}{D_e} \frac{D_h}{N_{DE} w_{E,eff}} \; i_{eE} = \delta_E \, i_{eE}$$

We'll define δ_E on the next foil.

npn BJT: Approximate forward active region model, cont.



The emitter current, i_E, cont.

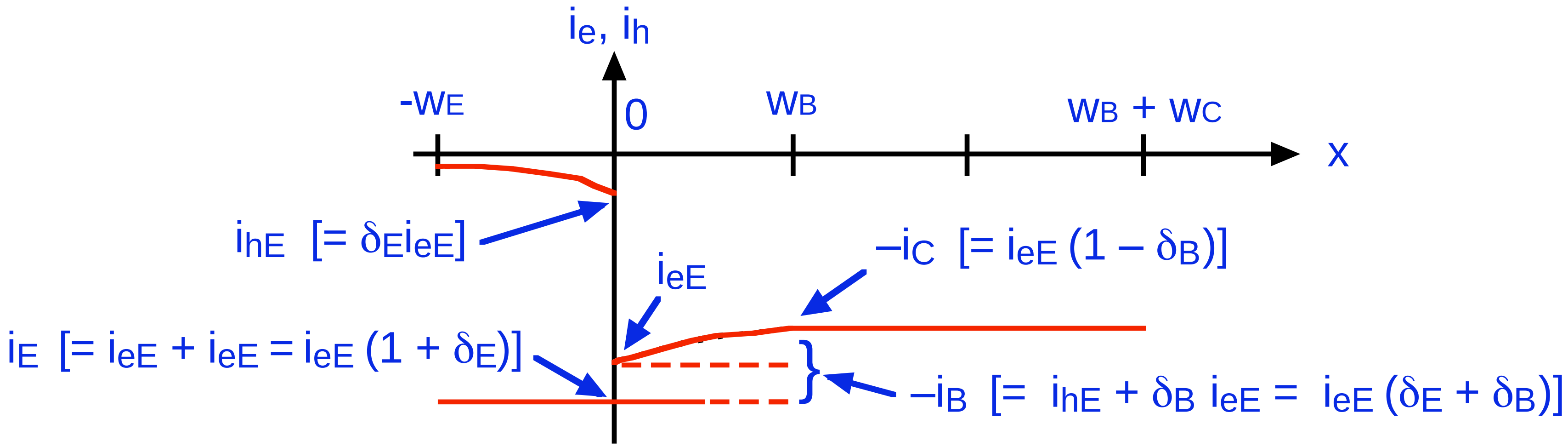
In writing the last equation we introduced the emitter defect, δ_E:

$$\delta_E \equiv \frac{i_{hE}}{i_{eE}} = \frac{D_h}{D_e} \cdot \frac{N_{AB}}{N_{DE}} \cdot \frac{w_{B,eff}}{w_{E,eff}}$$

To finish for now with the emitter current, we write it, i_E, in terms of the emitter electron current, i_{eE}:

$$i_E = i_{eE} + i_{hE} = \left(1 + \frac{i_{hE}}{i_{eE}}\right) i_{eE} = \left(1 + \delta_E\right) i_{eE}$$

npn BJT: Approximate forward active region model, cont.



The collector current, i_C

The collector current is the electron current from the emitter, i_{eE}, minus the fraction that recombines in the base, $\delta_B i_{eE}$:

$$i_C = (1 - \delta_B)\, i_{eE}$$

To find the fraction that recombine, i.e. the <u>base defect</u>, δ_B, we note that we can write the total recombination in the base, $\delta_B i_{eE}$, as:

$$\delta_B\, i_{eE} = -Aq\int_0^{w_B} \frac{n'(x)}{\tau_{eB}}\, dx$$

npn BJT: Approximate forward active region model, cont.

The base defect, δ_B

If the recombination in the base is small (as it is in a good BJT) then the excess electron concentration will be nearly triangular and we can say:

$$\int_0^{w_B} n'(x)dx \approx \frac{n'(0)w_{B,eff}}{2} \quad \text{and} \quad i_{eE} \approx -Aq\,D_{eB}\frac{n'(0)}{w_{B,eff}}$$

Thus

$$\delta_B = \frac{-Aq\int_0^{w_B}\frac{n'(x)}{\tau_{eB}}dx}{i_{eE}} \approx \frac{-Aq\frac{n'(0)w_{B,eff}}{2\tau_{eB}}}{-Aq\,D_{eB}\frac{n'(0)}{w_{B,eff}}} = \frac{w_{B,eff}^2}{2D_{eB}\tau_{eB}} = \frac{w_{B,eff}^2}{2L_{eB}^2}$$

The collector current, i_C, cont.

Returning to the collector current, i_C, we now want to relate it to the total emitter current:

$$\left.\begin{aligned} i_C &= -(1-\delta_B)\,i_{eE} \\ i_E &= (1+\delta_E)\,i_{eE} \end{aligned}\right\} \quad i_C = -\frac{(1-\delta_B)}{(1+\delta_E)}\,i_E = -\alpha_F\,i_E$$

with $\alpha_F \equiv \dfrac{(1-\delta_B)}{(1+\delta_E)}$

npn BJT: Approximate forward active region model, cont.

So far...

We have:

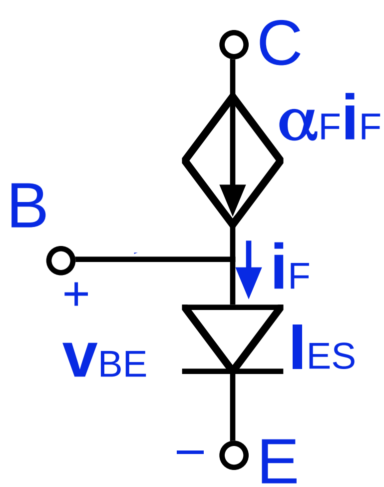
$$i_E = -Aqn_i^2\left(\frac{D_h}{N_{DE}w_{E,eff}} + \frac{D_e}{N_{AB}w_{B,eff}}\right)\left[e^{qV_{BE}/kT} - 1\right]$$

$$= -I_{ES}\left[e^{qV_{BE}/kT} - 1\right] \qquad \text{with} \quad I_{ES} = Aqn_i^2\left(\frac{D_h}{N_{DE}w_{E,eff}} + \frac{D_e}{N_{AB}w_{B,eff}}\right)$$

...and we have:

$$i_C \propto i_E: \qquad i_C = -\alpha_F i_E \quad \text{with} \quad \alpha_F \equiv -\frac{i_C}{i_E} = \frac{(1-\delta_B)}{(1+\delta_E)}$$

These relationships can be represented by a simple circuit model:



$$i_E = -i_F \quad \text{with} \quad i_F = I_{ES}\left(1 - e^{qv_{BE}/kT}\right)$$

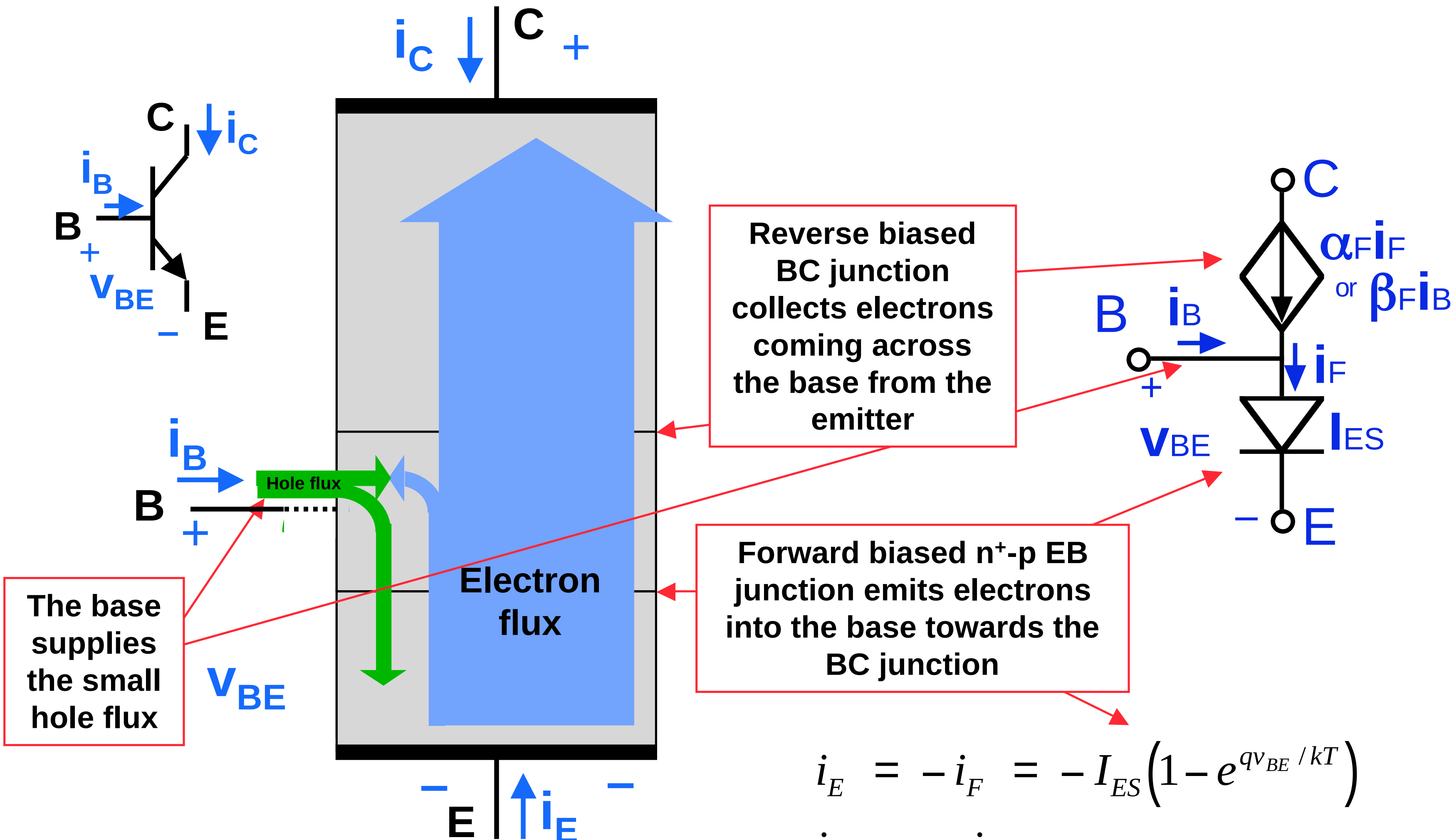
$$i_C = \alpha_F i_F \quad \text{with} \quad \alpha_F \equiv -\frac{i_C}{i_E} = \frac{(1-\delta_B)}{(1+\delta_E)}$$

$$i_B = -i_E - i_C = (1-\alpha_F)i_F$$

Note: $i_F = -i_E$.

Looking at this circuit and these expressions, it is clear that to make i_B small and $|i_C| \approx |i_E|$, we must have $\alpha_F \approx 1$. We look at this next.

npn BJT: Approximate forward active region model, cont.



$$i_E = -i_F = -I_{ES}\left(1 - e^{qv_{BE}/kT}\right)$$

$$i_C = \alpha_F i_F$$

$$i_B = -i_E - i_C = (1 - \alpha_F) i_F$$

npn BJT: What our model tells us about device design.

We have:

$$\alpha_F = \frac{(1-\delta_B)}{(1+\delta_E)}$$

and the defects, δ_E and δ_B, are given by:

$$\delta_E = \frac{D_h}{D_e}\cdot\frac{N_{AB}}{N_{DE}}\cdot\frac{w_{B,eff}}{w_{E,eff}} \quad \text{and} \quad \delta_B \approx \frac{w_{B,eff}^2}{2L_{eB}^2}$$

We want α_F to be as close to one as possible, and clearly the smaller we can make the defects, the closer α_F will be to one. Thus making the defects small is the essence of good BJT design:

$$\text{Doping: npn with } N_{\text{DE}} >> N_{AB}$$

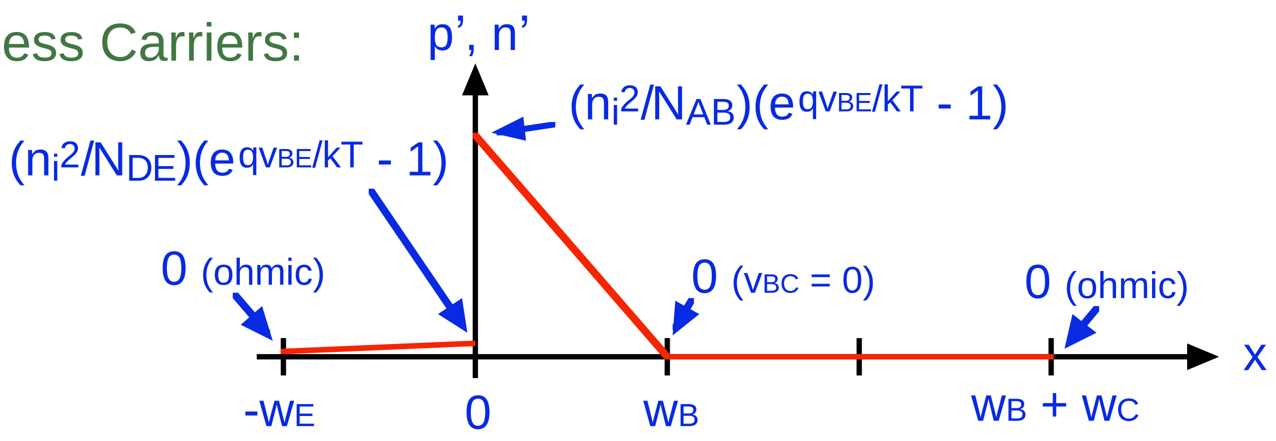
$$w_{B,eff}: \text{ very small}$$

$$L_{eB}: \text{ very large and } >> w_{B,eff}$$

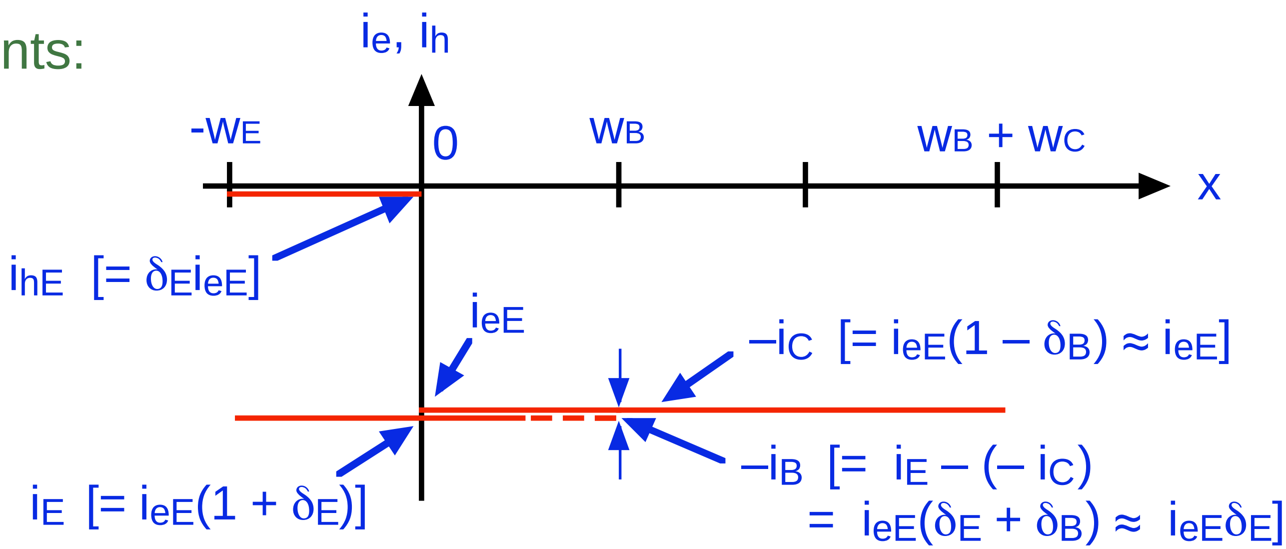
npn BJT: Well designed structure (Large β_F, small δ_E and d_B)

δ_E and δ_B are small and α_F is ≈ 1 when $N_{DE} >> N_{AB}$, $w_E << L_{hE}$, $w_B << L_{eB}$

Excess Carriers:



Currents:



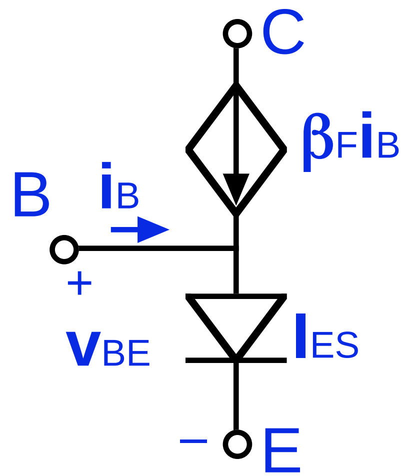
npn BJT,cont.: more observations about F.A.R. model

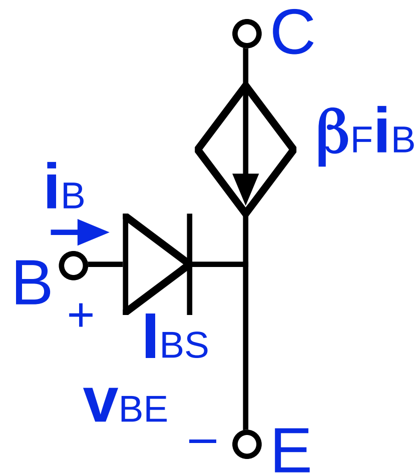
It is very common to think of i_B, rather than i_E, as the controlling current in a BJT. In this case we write i_C as depending on i_B:

$$\left.\begin{aligned} i_E &= -i_F = -I_{ES}\left[e^{qV_{BE}/kT} - 1\right] \\ i_C &= \alpha_F i_F \\ i_B &= (1-\alpha_F) i_F \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} i_B &= (1-\alpha_F) I_{ES}\left[e^{qV_{BE}/kT} - 1\right] = I_{BS}\left[e^{qV_{BE}/kT} - 1\right] \\ i_C &= \frac{\alpha_F}{(1-\alpha_F)} i_B = \beta_F i_B \\ i_E &= -i_C - i_B = (\beta_F + 1) i_B \end{aligned}\right.$$

with $\beta_F \equiv \dfrac{\alpha_F}{1-\alpha_F} = \dfrac{(1-\delta_B)}{(\delta_E + \delta_B)}$ **and** $I_{BS} \equiv (1-\alpha_F) I_{ES} = \dfrac{I_{ES}}{(\beta_F + 1)}$

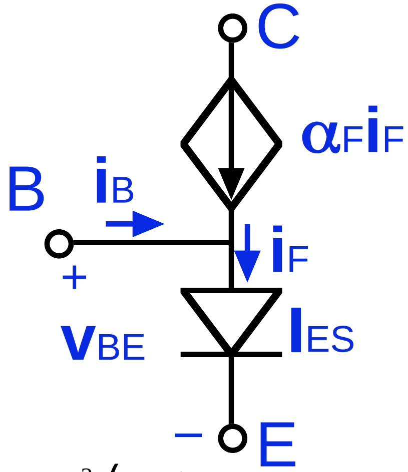
Two circuit models that fit this behavior are the following:

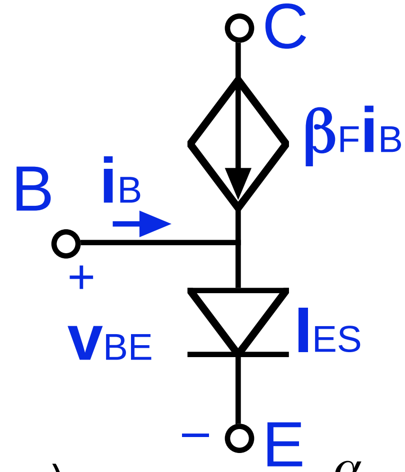


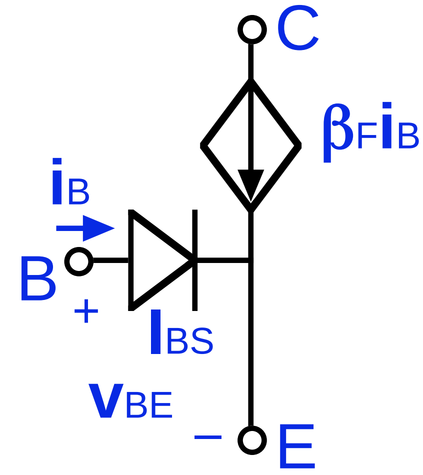


Note: $\alpha_F = \dfrac{\beta_F}{(\beta_F + 1)}$

npn BJT: Equivalent FAR models







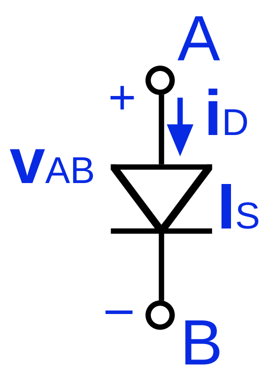
$$I_{ES} = Aqn_i^2\left(D_h/N_{DE}w_{E,eff} + D_e/N_{AB}w_{B,eff}\right)$$

$$\alpha_F = \beta_F/(\beta_F + 1)$$

$$\beta_F = \frac{\alpha_F}{(1-\alpha_F)}$$

$$I_{BS} = I_{ES}/(\beta_F + 1)$$

A useful model using a break-point diode:



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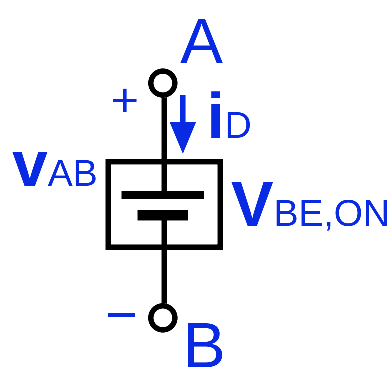
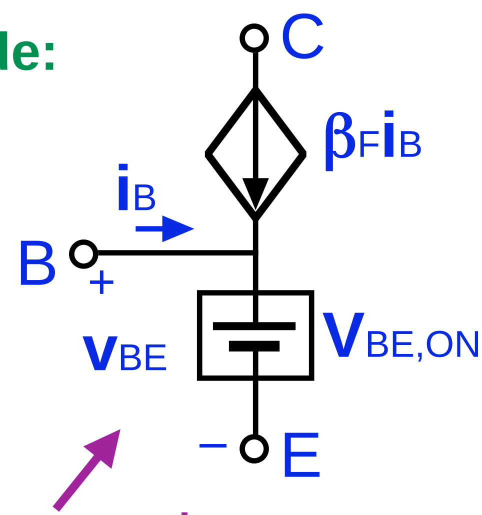


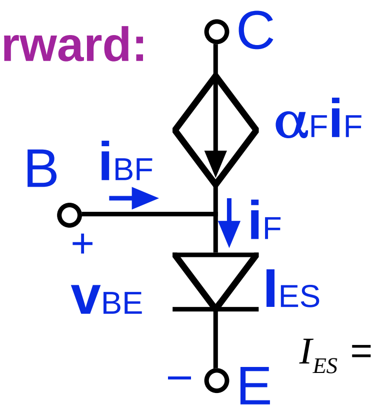


This is a very useful model to use when finding the bias point in a circuit.

npn BJT: The Ebers-Moll model

The forward model is what we use most, but adding the reverse model we cover the entire range of possible operating conditions.

Forward:

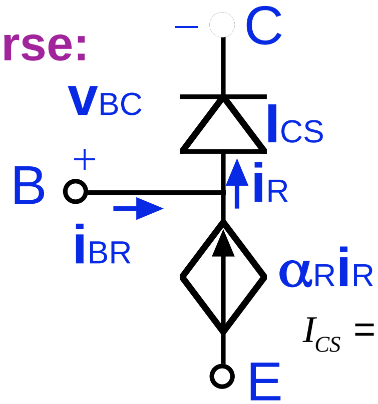


$$I_{ES} = Aqn_i^2\left(\frac{D_h}{N_{DE}w_{E,eff}} + \frac{D_e}{N_{AB}w_{B,eff}}\right)$$

$$\beta_F = \frac{(1-\delta_{\mathbf{B}})}{(\delta_E + \delta_{\mathbf{B}})}, \qquad \alpha_F = \frac{(1-\delta_{\mathbf{B}})}{(1+\delta_E)}$$

$$\delta_E \equiv \frac{i_{hE}}{i_{eE}} = \frac{D_h}{D_e}\cdot\frac{N_{AB}}{N_{DE}}\cdot\frac{w_{B,eff}}{w_{E,eff}}, \qquad \delta_B \approx \frac{w_{B,eff}^2}{2D_e\tau_e} = \frac{w_{B,eff}^2}{2L_e^2}$$

Reverse:



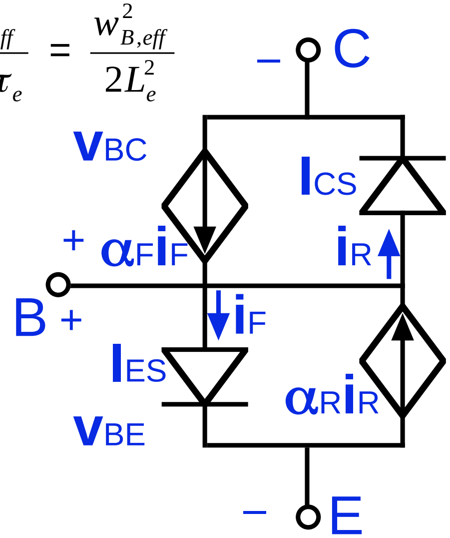
$$I_{CS} = Aqn_i^2\left(\frac{D_h}{N_{DC}w_{C,eff}} + \frac{D_e}{N_{AB}w_{B,eff}}\right)$$

$$\beta_R = \frac{(1-\delta_{\mathbf{B}})}{(\delta_C + \delta_{\mathbf{B}})}, \qquad \alpha_R = \frac{(1-\delta_{\mathbf{B}})}{(1+\delta_C)}$$

$$\delta_C \equiv \frac{i_{hC}}{i_{eC}} = \frac{D_h}{D_e}\cdot\frac{N_{AB}}{N_{DC}}\cdot\frac{w_{B,eff}}{w_{C,eff}}$$

$$\delta_B \approx \frac{w_{B,eff}^2}{2D_e\tau_e} = \frac{w_{B,eff}^2}{2L_e^2}$$

Combined they form the full Ebers-Moll model:



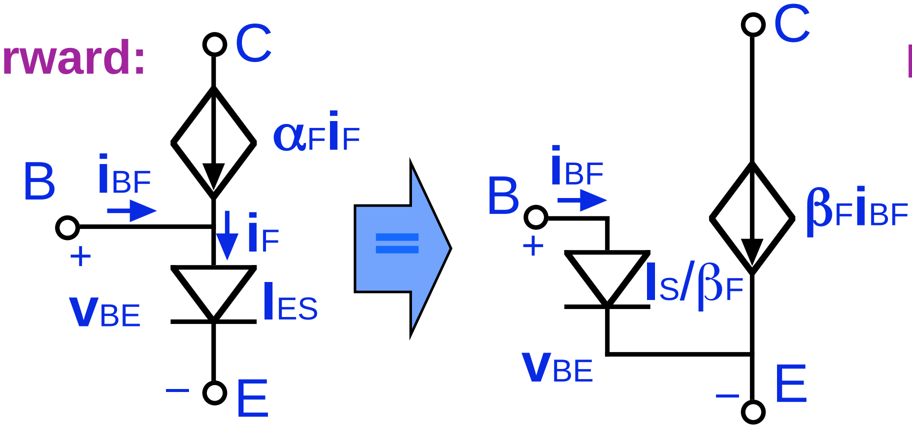
Note: $i_F = -i_E(v_{BE},0)$ and $i_R = -i_C(0,v_{BC})$.

You are not responsible for this model.

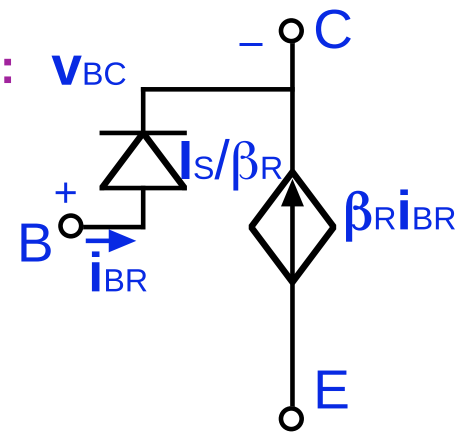
npn BJT: The Gummel-Poon model

Another common model can be obtained from the Ebers-Moll model is the Gummel-Poon model:

Forward:



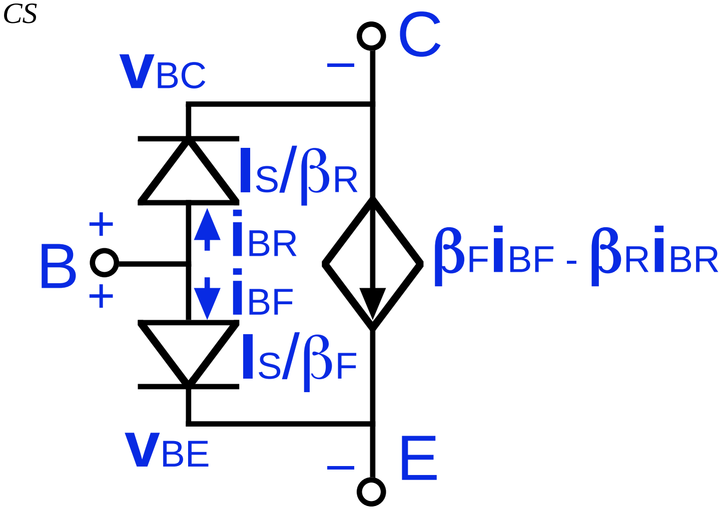
Reverse:



$$I_S \equiv \frac{\beta_F}{(\beta_F+1)} I_{ES} = \frac{\beta_R}{(\beta_R+1)} I_{CS}$$

$$= \alpha_F I_{ES} = \alpha_R I_{CS}$$

Combined they form the Gummel-Poon model:



- Aside from the historical interest, another value this has for us in 6.012 is that it is an interesting exercise to show that the two forward circuits above are equivalent.

You even less responsible for this model.

Lecture 7 - Bipolar Junction Transistors - Summary

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

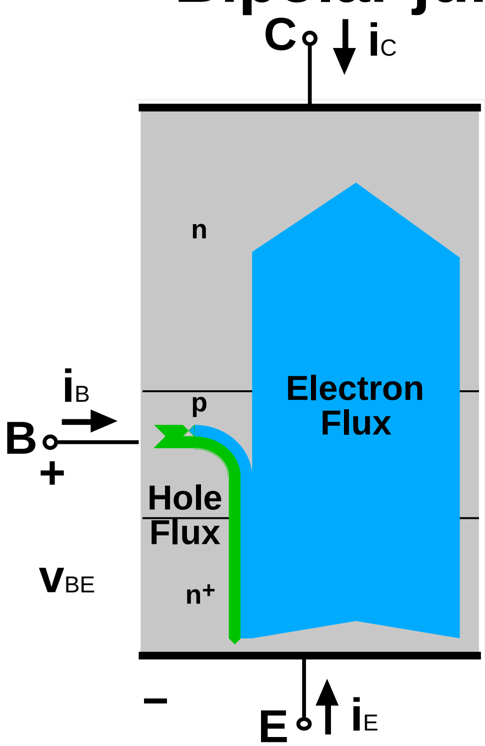
  Refer to "Lecture 6- Summary" for a good overview

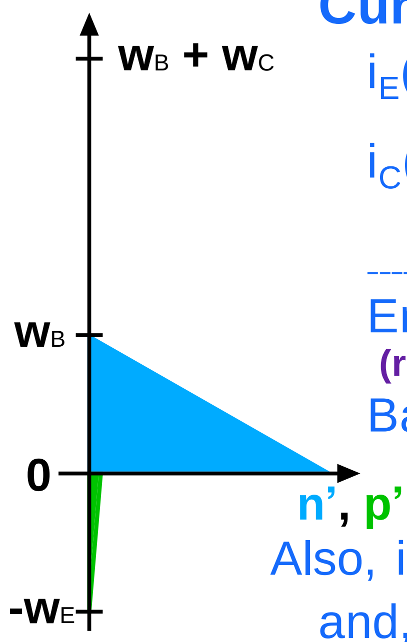
  Diffusion capacitance: adds to depletion capacitance **(p^+-n example)**

  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, $i_B(v_{BE},0) = [(d_E + d_B)/(1 + d_E)]\, i_E(v_{BE},0)$

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

with b_F º $a_F/(1 - a_F) = [(1 - d_B)/(d_E + d_B)]$

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