Lecture 16: Bipolar Junction Transistors. Large Signal Models.

Transistors perform key functions in most electronic circuits. This is certainly true in RF circuits, including the NorCal 40A.

There are two basic families of transistors: (1) Bipolar junction transistors (BJTs) and (2) Field effect transistors (FETs).

In the NorCal 40A we will use the following transistors:

- *npn* BJT. Q1 is an example.
- *pnp* BJT. Q4 is an example.
- Junction FET (JFET). Q5 is an example.

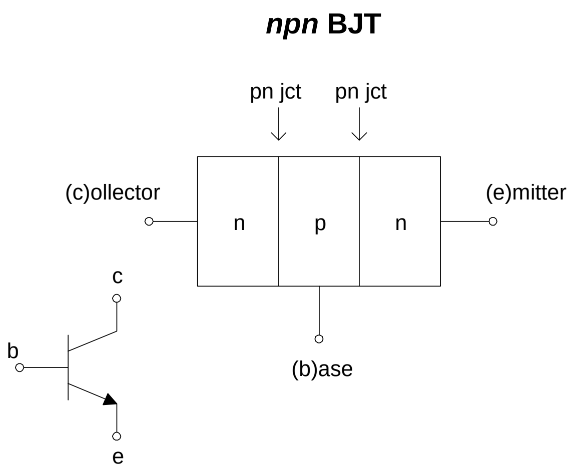
These transistors will be used to perform a plethora of functions in the NorCal 40A transceiver including:

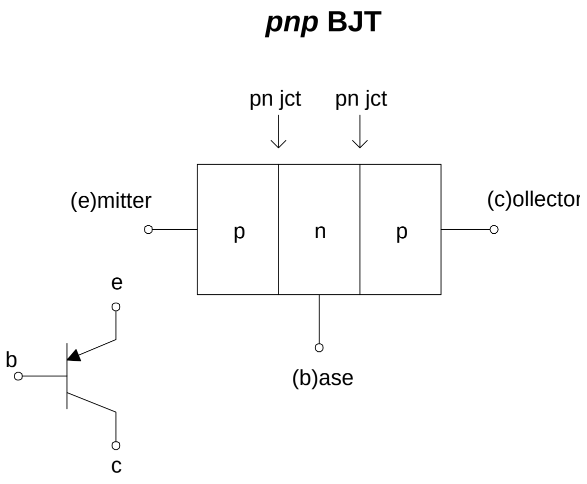
- ✓ Electronic switching (Q1 and Q4).
- ✓ Time-varying voltage amplifiers:
    - o Small signal amplifier (Q6),
    - o Power amplifier (Q7).
- ✓ Buffer amplifier (Q5).
- ✓ Voltage controlled variable resistance (Q2 and Q3).
- ✓ Oscillator (Q8).

We will first consider the operation of the BJT. At the end of the next chapter in the text, we will consider the JFET.

Bipolar Junction Transistors (BJTs)

The BJT can be drawn in simplified sketches as





BJTs actually look a bit different than this when manufactured. Most importantly, they are usually not symmetric devices.

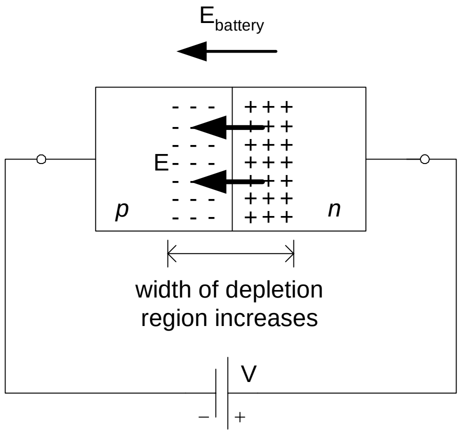
There are four basic modes of operation for a BJT depending on the states of the two *pn* junctions of the transistor:

Mode	**Emitter-Base Jct.**	**Collector-Base Jct.**
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward
Reverse Active	Reverse	Forward

Reverse and Forward Biased Junction

There are two important states for a *pn* junction, as discussed earlier in Lecture 3. These are the reversed biased and forward biased states.

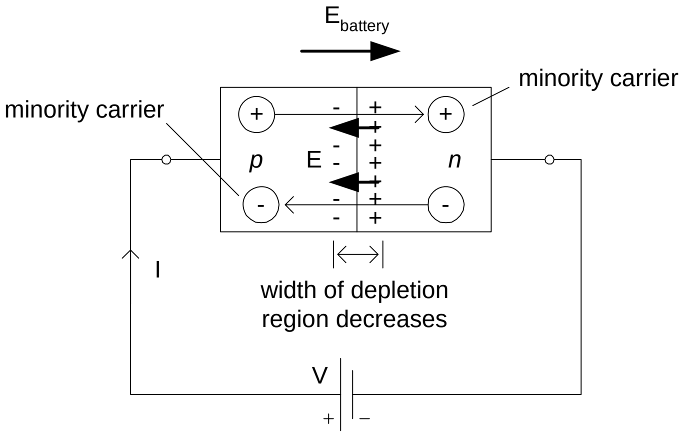
(1) Reversed biased state:



The electric field produced by the battery E_{battery} adds to the electric field of the space charge E in the depletion region. This increases the width of the depletion region.

Little current flows (only the drift current I_S) unless the junction breaks down. This occurs when E_{battery} is strong enough to strip electrons from the covalent bonds of the atoms, which are then swept across the junction.

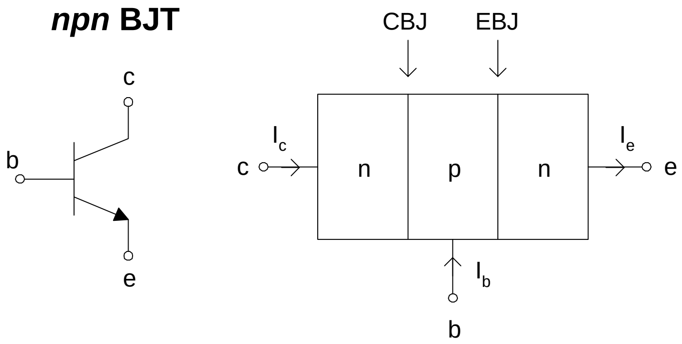
(2) Forward biased state:



When V is large enough so that $E_{\text{battery}} > E$, then (i) holes are swept from the p to n regions, and (ii) electrons are swept from the n to p regions. We now have current!

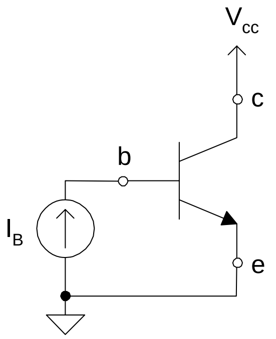
Bipolar Junction Transistor (BJT)

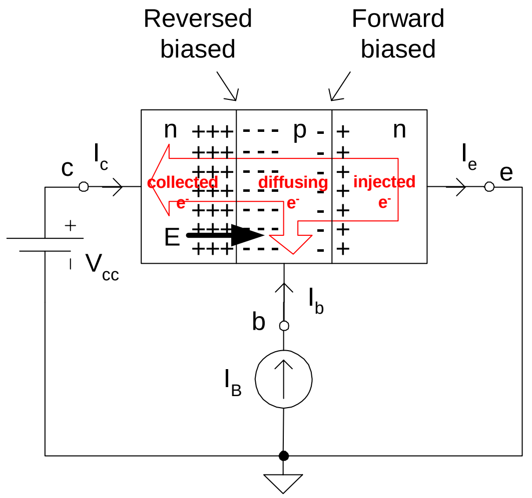
As shown earlier, the BJT is formed from two back-to-back *pn* junctions:



Measuring the dc resistance from c to e would indicate a very large value since we have two back-to-back *pn* junctions. This would occur regardless of the polarity of the measurement since one of the junctions will be reversed biased.

However, we can observe an interesting effect when there is a current into the base and a voltage applied to the collector (so that it is biased in the active region):





The EBJ is forward biased and electrons are injected into the *p* region just as with a forward biased diode.

However, the base is very thin and many diffusing electrons "make it" to the CBJ without recombining with holes in the base. Here at this second junction, the strong electric field (of the reversed-biased CBJ) sweeps the negatively charged electrons across the junction into the collector where they contribute to I_c.

The proportion of electrons from the emitter that "make it" to the collector is called the collector efficiency, α

$$\alpha \equiv \frac{I_c}{I_e} \quad \text{or} \quad \boxed{I_c = \alpha I_e} \tag{8.1}$$

α typically ranges from 0.98 to 0.99. This relationship (8.1) is **ONLY** true if the device is operating in the active mode.

From KCL for the BJT $I_c + I_b = I_e$ or

$$I_b = I_e - I_c = (1-\alpha) I_e \tag{8.2}$$

With $\alpha \approx 1$, then I_b will generally be much, much smaller than I_e (again, in the active mode).

The ratio of the collector current to the base current is called the current gain, β

$$\beta \equiv \frac{I_c}{I_b} \quad \text{or} \quad \boxed{I_c = \beta I_b} \tag{8.3}$$

This relationship (8.3) is **ONLY** true if the device is operating in the active mode.

Dividing (8.1) by (8.2) we find that

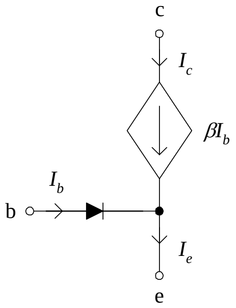
$$\frac{I_c}{I_b} = \frac{\alpha}{1-\alpha} \quad \text{or} \quad \boxed{\beta = \frac{\alpha}{1-\alpha}} \tag{8.4}$$

With $\alpha \approx 0.99$, then $\beta \approx 100-200$ in the active mode. (Note that β is often called h_{fe} in data sheets.)

In the active mode, we can think of the BJT base current as controlling the collector current (since $I_c = \beta I_b$). Because β is a large number in the active region, then a small I_b change produces a much larger I_c change. We've made an amplifier where the base is the input and the collector is the output!

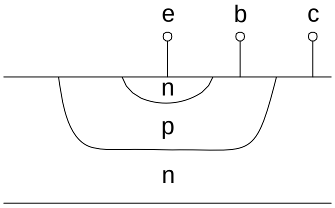
Large Signal BJT Models

Based on our discussions in this lecture, we can now construct a large signal model of the *npn* BJT as (Fig. 8.3a):

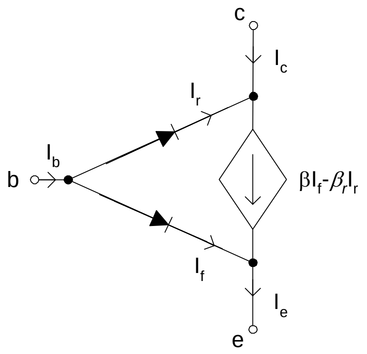


We've modeled only the EBJ with a diode. We can also include the effect of the CBJ as shown in Fig. 8.3(b) of the text. In that case, we use the reverse active current gain $\beta_r \neq \beta$.

These β's are not equal since BJTs are generally not manufactured symmetrically:



The model in 8.3(b) is called the Ebers-Moll model and is used in SPICE.



$$\begin{aligned} I_r + I_c &= \beta I_f - \beta_r I_r \\ I_c &= \beta I_f - \beta_r I_r - I_r \\ &= \beta I_f - (1+\beta_r) I_r \end{aligned}$$

BJT Regions of Operation

There are four distinct regions of operation of a BJT, as mentioned at the beginning of this lecture. These regions are defined by the state of the EBJ and CBJ as listed in Table 8.1:

Region	V_{be}	V_{bc}	V_{ce}	I_c
Active	Forward biased	Reversed biased	??	βI_b
Saturation (“on”)	Forward biased	Forward biased	0.2-0.3 V	$< \beta I_b$
Cutoff (“off”)	Reversed biased	Reversed biased	??	0
Reverse Active	Reverse biased	Forward biased	??	$I_c = \beta I_f - (1+\beta_r) I_r$ $= -(1+\beta_r) I_b$

In the next lecture, we will consider the saturation and cutoff regions of operation. These are the “on” and “off” states of the BJT when it is used as an electronic switch.