5.1 BJT Device Structure and Physical Operation

Reading Assignment: pp. 377-392

Another kind of transistor is the Bipolar Junction Transistor (BJT).

BJTs are analogous to MOSFETs in many ways:

1. 
2. 
3. 
4. 

The two types of BJTs are npn and pnp (analogous to NMOS and PMOS).

A BJT is a “Silicon sandwich” – one type of Si sandwiched between two layers of the other.
HO: BJT Structures and Modes of Operation

HO: The npn BJT in the Active Operating Region

HO: The npn BJT in the Saturation

HO: The npn BJT in the Cutoff
BJT Structure and Modes of Operation

First, let's start with the npn Bipolar Junction Transistor (BJT). As the name implies, the npn BJT is simply an hunk of p-type Silicon sandwiched between two slices of n-type material:

Each of the three Silicon regions has one terminal electrode connected to it, and thus the npn BJT is a three terminal device.

The three terminals are named:

1. Collector
2. Base
3. Emitter
Note that this *npn* BJT structure creates *two* *p-n* junctions!

* The junction between the *n-type collector* and the *p-type base* is called the *Collector-Base Junction* (CBJ).

Note for the CBJ, the anode is the base, and the cathode is the collector.

* The junction between the *n-type emitter* and the *p-type base* is called the *Emitter-Base Junction* (EBJ).

Note for the EBJ, the anode is the base, and the cathode is the emitter.

Now, we find that the *pnp* BJT is simply the complement of the *npn* BJT—the *n*-type silicon becomes *p*-type, and vice versa:
Thus, the pnp BJT likewise has three terminals (with the same names as the npn), as well as two p-n junctions (the CBJ and the EBJ).

* For the pnp BJT, the anode of the CBJ is the collector, and the cathode of the CBJ is the base.

* Likewise, the anode of the EBJ is the emitter, and the cathode of the EBJ is the base.

Note that these results are precisely opposite that of npn BJT.

Now, we know that each p-n junction (for either npn or pnp) has three possible modes:

1. forward biased
2. reverse biased
3. breakdown

We find that breakdown is not generally a useful mode for transistor operation, and so we will avoid that mode.

Given then that there are two useful p-n junction modes, and two p-n junctions for each BJT (i.e., CBJ and EBJ), a BJT can be in one of four modes!
<table>
<thead>
<tr>
<th>MODE</th>
<th>EBJ</th>
<th>CBJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reverse</td>
<td>Reverse</td>
</tr>
<tr>
<td>2</td>
<td>Forward</td>
<td>Reverse</td>
</tr>
<tr>
<td>3</td>
<td>Reverse</td>
<td>Forward</td>
</tr>
<tr>
<td>4</td>
<td>Forward</td>
<td>Forward</td>
</tr>
</tbody>
</table>

Now, let's give each of these four BJT modes a name:

<table>
<thead>
<tr>
<th>MODE</th>
<th>EBJ</th>
<th>CBJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutoff</td>
<td>Reverse</td>
<td>Reverse</td>
</tr>
<tr>
<td>Active</td>
<td>Forward</td>
<td>Reverse</td>
</tr>
<tr>
<td>Reverse Active</td>
<td>Reverse</td>
<td>Forward</td>
</tr>
<tr>
<td>Saturation</td>
<td>Forward</td>
<td>Forward</td>
</tr>
</tbody>
</table>

We will find that the Reverse Active mode is of limited usefulness, and thus the three basic operating modes of a BJT are Cutoff, Active, and Saturation.
The *npn* Transistor in the Active Operating Region

We know that the base-emitter junction of an *npn* BJT in the active region will be forward biased, while the collector-base junction will be reversed biased. In other words:

\[ v_B - v_E \approx v_{BE} \approx 0.7 \ V \quad \text{and} \quad v_C - v_B \approx v_{CB} > 0 \ V \]
Q: OK, if the collector-base junction is reverse biased, then no current will flow through the collector-base junction, meaning $i_C$ must be zero and $i_B=i_E$, right??

A: NO! A BJT is more complex in its operation than that. Recall the base is very thin. This causes something unusual to happen!

* Recall that if the collector-base junction is reversed biased, then the barrier voltage is large and the diffusion current will drop to zero.

* However, recall also that the drift current is unaffected by the barrier voltage, so drift current does flow across the collector base junction!

Q: Pft! This diffusion current is really small, right? Like $10^{-12}$ A!?

A: NO! Again, this is true for a junction diode, but not for a npn transistor.
* Recall that the base-emitter junction is forward biased, and therefore the diffusion current across this junction is large.

* The emitter region of an npn transistor is heavily doped (n++), so that the diffusion current primarily consists of free electrons moving from the emitter into the base.

* Normally, these free electrons would move to the base electrode, and some still do. But most get swept across the collector base junction by the electric field in the depletion region.
In other words, the large number free electrons in the emitter **diffuse** across the base-emitter junction into the base, then **drift** across the collector-base junction into the collector.

We say that emitter **emits** free electrons, and the collector **collects** them.

If the base is **thin**, then for every free electron that **diffuses** across the base-emitter junction, we find that 100 or more are collected (i.e, drift across the CBJ) by the collector!
The npn Transistor in Saturation

We know that for an npn BJT in saturation, both the BEJ and CBJ will be forward biased. In other words:

\[ v_B - v_E = v_{BE} \approx 0.7 \text{ V} \quad \text{and} \quad v_C - v_B = v_{CB} \approx -0.5 \text{ V} \]
Recall that diffusion current flows in the opposite direction of drift current.

As a result, diffusion and drift current tend to cancel each other.

Therefore in saturation, the total collector current (i.e., drift minus diffusion) is less than that of drift alone.
The npn BJT in Cutoff

We know that for an npn BJT in cutoff, both the BEJ and CBJ will be reverse biased. In other words:

\[ v_B - v_E = v_{BE} < 0.0 \text{ V} \quad \text{and} \quad v_C - v_B = v_{CB} > 0.0 \text{ V} \]

If both p-n junctions (CBJ and EBJ) are reverse biased, then no current will flow! I.E.:

\[ i_B = i_C = i_E = 0.0 \text{ for a BJT in Cutoff} \]