Topic 14: Bipolar Junction Transistor Introduction

Preface:

This set of notes will introduce the theory of the bipolar junction transistor. The mathematical analysis in this section will be light. The goal is to gain an intuitive understanding of how the device works before diving into the equations. We will start by motivating the structure of the device, discussing the modes of operation, the several configurations of the device, the IV characteristic, and the energy band diagram.

Bipolar Junction Transistor:

The BJT is the most natural extension of the PN junction. In its simplest form, the BJT is formed from two back-to-back PN junctions. With two junctions, we can form either an NPN or a PNP BJT. The standard diagram of both devices is provided below.

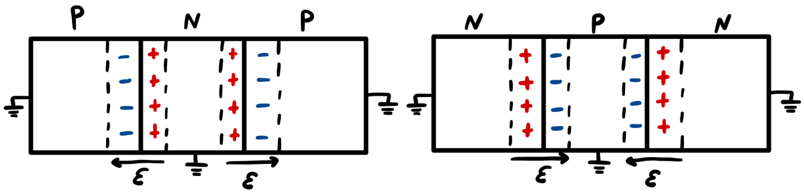

Figure 1: PNP and NPN BJTs under thermal equilibrium.

Each of the three terminals have been grounded to indicate thermal equilibrium. Unlike the PN junction, we now have two junctions, with two built-in voltages. We also have three terminals to differentiate. Hence, we need to give these terminals a name and establish some notations.

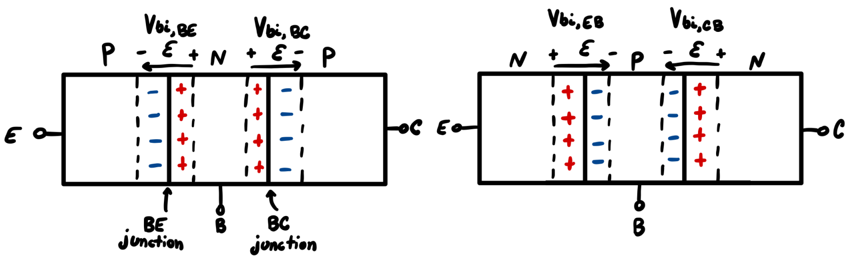

Figure 2: PNP and NPN terminal and junction notation.

We have three terminals, denoted the **emitter**, **base**, and **collector**. As of now, the collector and emitter are interchangeable because the doping concentration differentiates the two. A convenient way to remember that base is that the base type is always opposite the collector and emitter. We have two junctions, denoted the base-emitter and base-collector junction. The terminology is typically the same for NPN and PNP devices since it refers to the physical interface between regions. The difference lies in the notation of the built-in potential.

Note if you have taken an electronics course and have learned BJT circuits, this notation may be opposite to what you are used to with V_{BE} verses V_{EB}. When referencing voltages between two points, we prefer the subscript to be in the order of descending voltage. For example, in the PNP device, the built-in voltage across the base-emitter junction is denoted $V_{bi,BE}$. The built-in field points from the base to the emitter, implying the base is at a higher potential than the emitter. Whereas the same base-emitter built-in voltage is denoted $V_{bi,EB}$ in the NPN case.

We know that both PN junctions are off in thermal equilibrium, so the next natural step is to introduce voltage sources. We will examine the PNP case unless stated otherwise. We must ask ourselves which terminals the voltage sources should connect to? Since we care about the voltage across each junction, we will attach voltage sources across the base-emitter and base-collector. We will use the notation V_{EB} and V_{CB} for the base-emitter and base-collector junctions, respectively. Note that the subscript order matters. If we want to forward bias the base-emitter junction, the positive terminal of the source must be attached to the emitter with the negative on the base. Visually, the source direction is provided below.

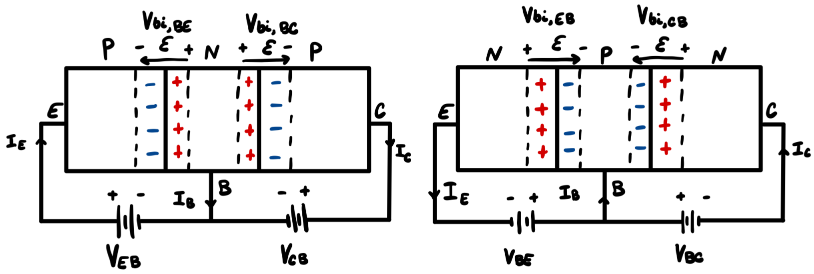

Figure 3: PNP and NPN notation with bias voltages.

This system of subscripts is helpful in that the built-in potential for each junction is opposite the bias voltage subscript implying cancellation. Also, note that each of these voltage sources is assumed to forward bias the junction. However, this does not need to be the case. We have four total modes the device can operate in and we will study three of the four modes.

Modes of Operation:

The four modes of operation are described in the table below. The following subsections will provide a high-level overview of each mode.

V_{EB}	V_{CB}	BE Junction Bias	BC Junction Bias	Mode
> 0	> 0	Forward	Forward	Saturation
> 0	< 0	Forward	Reverse	Forward Active
< 0	> 0	Reverse	Forward	Reverse Active
< 0	< 0	Reverse	Reverse	Cutoff

Table 1: BJT Modes of operation.

We will study saturation, forward active, and cutoff. For reasons described later, there lack practical reasons to operate a BJT in reverse active. Before we can address each mode we must acknowledge the BJT is a three-terminal device and we have current associated with the emitter, base, and collector. The current into each terminal is denoted by I_B, I_C, and I_E for the base, collector, and emitter.

Cutoff:

In cutoff, both junctions are reverse biased. Recall that a reverse bias is for all intents and purposes an open-circuit. Implying that each region, the emitter, base, and collector, are disconnected from each other implying there is no closed path for current to flow. Hence, the net current through the device is zero. If we do not neglect the saturation current, a small leakage current will be present albeit extremely small.

$$I_B = I_C = I_E = 0 \tag{1}$$

There is not much analysis to cutoff, we will do a more quantitative analysis later but for an initial viewing, the mode is sufficient.

Saturation:

Saturation is a metaphorical inverse to cutoff. If cutoff is an open circuit then saturation is a short circuit. Intuitively, we know that the PN junction behaves as a short circuit while forward biased.

Hence, saturation must occur when both PN junctions are forward biased. At this point, we must state that **a BJT is not two back-to-back diodes!** It may seem simple to assume the BJT is simply two diodes but our analysis in the next set of notes will show this is not true.

Forward Active:

As stated in the table above, forward active occurs when the base-emitter is forward biased and the base-collector reverse biased. The table implies that the applied base-emitter voltage is large enough to overcome the built-in potential. With this condition, the depletion region in the base-emitter has shrunken to zero. To remove ambiguity, the figure below visualizes the source polarities in forward active. **Note** the base-emitter depletion region is included to abstract the value of the source.

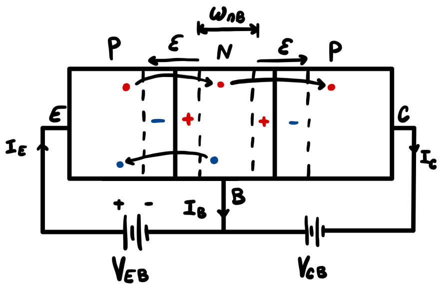

Figure 4: PNP current components under forward active.

In the figure above, let's start by looking at the base-emitter junction. Under forward bias, nothing is blocking the holes in the emitter from diffusing into the base. The hole must then traverse through the neutral base. Since the base is an n-type, the hole becomes the minority carrier and is subject to recombination. However, if the neutral base is significantly thin the hole will pass into the base-collector depletion region and get swept into the collector by the built-in field. A significantly small neutral base implies $w_{NB} \lll L_p$. Where L_p represents the average distance a hole can travel before recombining. If w_{NB} is much less than it L_p it is extremely unlikely recombination will occur.

Under these specific conditions, a complete path is formed within the device. In a PNP device, the hole is able to traverse from the emitter, through the base, and into the collector. It is no coincidence the emitter is called the emitter and the collector is called the collector. With this description, the emitter region emits carriers into the base for the collector to collect. The only difference with an NPN device is that the emitter emits electrons and $w_{NB} \lll L_n$. We must also note that nothing stops electrons in the base from diffusing into the emitter. As the holes pass from the emitter to the base electrons passing from the base to emitter can recombine. Therefore, if we could somehow minimize the base current then the BJT's efficiency would increase.

It is time to address some notation to the various current components. There are five total components within a PNP BJT. Simply reverse the direction for an NPN BJT. The five components of current pertinent to our study are:

1. Diffusion of holes from emitter to base; I_{Ep}.
2. Diffusion of electrons from base to emitter; I_{En}.
3. Movement of holes from base to collector; I_{Cp}.
4. Movement of electrons from collector to base; I_{Cn}.
5. Flow of electrons into base to compensate for losses due to recombination; I_{Bn}.

We may visualize these five currents in the figure below, provided in the Sze text. I particularly like the figure because it shows, with approximate scale, the magnitude of each component.

Beginning with the emitter, the electron and hole current is present. Similarly, the collector has its respective hole and electron current. However, in the base a small electron flow is present. This small flow is due to the aforementioned recombination within the base. If we assume a narrow base width then this component approaches zero but will always be nonzero. The current direction is leaving the base since electrons enter the base from the base terminal and conventional current opposes electron flow.

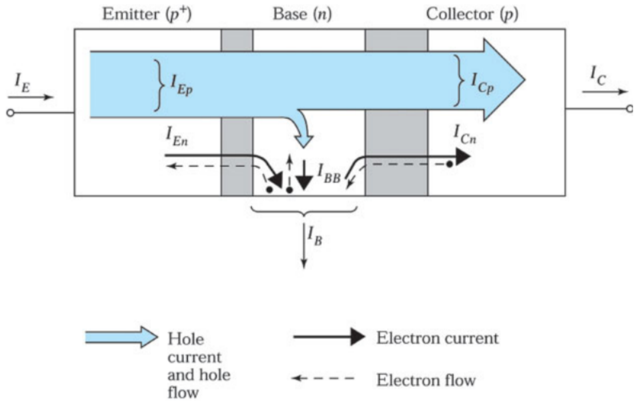

Figure 5: Current components in a forward active PNP BJT. ([2])

It is also worth mentioning that the I_{Cn} component will be incredibly small. The component is purely dependent on free charges randomly making their way into the depletion region and getting swept away by the built-in field.

Combining the components within each region,

$$I_E = I_{Ep} + I_{En} \tag{2}$$
$$I_C = I_{Cp} + I_{Cn} \tag{3}$$
$$I_E = I_B + I_C \tag{4}$$

We can make several observations or assumptions about the size of each component. Regardless of the BJT type, manufacturers will design the device with $N_E \geq N_B \geq N_C$, where N_E, N_B, and N_C are the doping densities in the emitter, base, and collector, respectively. The subscript A or D for the donor type may not be included if the device type is given. However, we can write it explicitly as $N_{AE} \geq N_{BD} \geq N_{AC}$ for a pnp device. The motivation for this doping profile will be discussed later.

$$I_{Ep} \approx I_{Cp} \tag{5}$$
$$I_{Ep} \ggg I_{En} \tag{6}$$
$$I_{Cp} \ggg\ggg I_{Cn} \tag{7}$$

Addressing each of the claims above, in order. The short base assumption implies low recombination. Hence, any holes which enter the base are likely to traverse to the collector. Within the emitter, holes are the predominant carrier. If the emitter is doped fairly larger than the base then hole diffusion will dominate the current through the junction. The holes see a larger drop in concentration, implying more holes will be forced into the base. For the collector, the large number of holes injected from the base will surely dominate the small number of random electrons falling into the base-collector depletion region. With these assumptions, we approximate

$$I_E \approx I_{Ep} \tag{8}$$
$$I_C \approx I_{Cp} \tag{9}$$
$$\Rightarrow I_E \approx I_C \tag{10}$$

Note that we can assume that I_E and I_C are approximately equal, but physically $I_E > I_C$ by the slightest amount. Taking these results back to the base KCL, if $I_E = I_B + I_C$ and $I_E \approx I_C$, then $I_B \approx 0$. That is, the base current is much smaller than either the collector or emitter current. At this point, we can make an incredibly interesting observation. A small current applied to the base may control a larger current passing through the emitter to the collector. This description is the current perspective of the BJT.

Reverse Active:

The reverse active mode is generally disregarded in semiconductor physics and circuit theory. The mode is insignificant because the BJT is an asymmetric device. The way the BJT has been drawn throughout these notes implies that the collector and emitter terminals are named arbitrarily. However, this is not true. The emitter is typically doped much larger than the collector, typically by a factor of 1000. The base doping lies between the emitter and collector doping. However, the relation between the emitter and collector doping matters the most.

Under reverse active, the base-emitter is reverse biased, and the base-collector is forward biased. The voltage polarities are opposite of forward active. Hence, we can take the observations from forward active, and apply them to the reverse active mode. Note, the terminology may seem confusing over the next few paragraphs, I apologize in advance. The forward biased base-collector implies charges will diffuse from the collector into the base. The majority charges in the collector traverse through the base and enter the emitter. The reverse bias of the base-emitter sweeps carriers away into the emitter. Immediately we see an issue regarding the collector doping concentration. The collector, behaving as the emitter, is less effective in reverse active. The smaller donor concentration implies fewer carriers will enter the base under reverse active than forward active. There are also issues regarding recombination in the base. However, other, more prevalent, issues exist.

The practical construction of the BJT also influences the efficiency of the device. Practical BJTs are fabricated in a way that treats the collector as a metaphorical net. The size of the emitter is small compared to the collector. The emitter emits carriers into the base and subsequently the collector. If the size of the collector is small, then it is likely that carriers may recombine before reaching the collector. If we swap the orientation, the emitter makes for an incredibly small net. The smaller "net" immediately reduces the efficiency and paired with the smaller number of carrier emissions the reverse active mode offers few advantages.

Configurations:

Regardless of the mode of operation, we have not chosen a specific point for ground. With three terminals we can place the ground on either the emitter, base, or collector. The way we have drawn the BJT early in the notes indicates the base might be the best option. The two sources V_{BE} and V_{BC} for a PNP device will have both the emitter and collector voltages references with respect to ground. Say we chose the collector for ground, the base-emitter voltage is no longer referenced with respect to ground. Instead, the voltage is referenced with respect to V_{BC}.

Depending on where ground is placed determines the configuration of the device. For example, placing the ground as the base makes a common-base device. Similarly, the ground on either the emitter or collector will be for a common-emitter and common-collector, respectively. The naming is surprisingly straightforward since ground and common are used interchangeably. Each of these configurations has various benefits, which we sadly do not get to discuss. These benefits are a large focus of Electronics 1 and involve parameters like input resistance, output resistance, current gain, and voltage gain of the device.

Common-base:

Under common-base configuration we can make the interesting observation of a two-port network. We can apply some input voltage on the emitter, with respect to ground, and the collector will have some output voltage with respect to ground. Similarly, we have an input and output current at the emitter and collector which are approximately equal. Implying the device has zero current gain in this configuration.

Treating the emitter as the input does provide benefits with respect to the input resistance. The input resistance of a common-base BJT is incredibly small compared to the other configurations. This small input resistance makes the common-base device common throughout radio frequency electronics. The input resistance is on the order of tens of Ohms, which makes impedance matching between circuits to antennas quite easy. Other benefits are present but will not be discussed heavily in these notes.

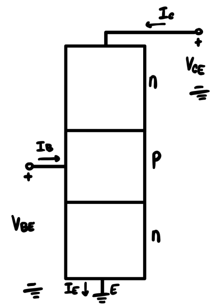

Figure 6: NPN BJT common-emitter configuration.

Common-emitter:

Let's repeat the process with a common-emitter configuration. The emitter is tied to ground, the base becomes the input, and the collector becomes the output. Since $I_C \ggg I_B$ we can transform a small input current into a large output current, effectively amplifying the current. This property is why we say that BJTs may act as an amplifier, and why the common-emitter amplifier composes so much of the Electronics 1 curriculum. The diagram for the common-emitter configuration is provided below.

Note that typically the common-emitter has a collector voltage referenced with respect to ground. If $V_{CE} > V_{BE}$ then the base-collector junction will be reverse biased since a KVL across the device states $V_{BC} = V_{BE} - V_{CE}$.

Common-collector:

The common-collector is the final common-terminal configuration. The configuration is quite similar to the common emitter. The input voltage is provided at the base, V_{BC}, and the output is taken from the emitter, V_{EC}. Note the two subscripts above are reversed from the common-emitter configuration. We will not discuss the common-collector, however, it is mentioned to show that not just the common-base and emitter configuration exist. For the curious, the common-collector configuration is used predominantly for voltage buffering, also called an emitter follower.

Applications:

Let's take a moment to appreciate some of the use cases for BJTs. A device with four modes of operation must have a large range of use cases. Cutoff and saturation form the heart of digital electronics. While BJTs are no longer the standard device for digital VLSI, they can still implement digital logic. Cutoff represents the device is off and saturation represents the device being on. This behavior is identical to a switch! There is more nuance to implementing logic gates with BJTs and ways to encode on and off states but it is beyond the point.

Forward active forms the heart of analog design. Those who have taken Electronics 1 have seen the many ways to bias a BJT to behave as an amplifier. BJTs can be chained together to form extremely high gain amplifiers. They can also implement components like current sources, operational amplifiers, oscillators, and nearly every integrated circuit before the CMOS revolution.

IV Characteristic:

For each of the common-terminal configurations, their benefits may not be immediately evident. By sketching the IV characteristics we will gain some insight into the characteristics of each device. We will not include the I_B vs I_C plots since we know that increasing I_B will increase I_C and the interesting effects come from the second bias voltage.

Common-base:

We may sketch the IV characteristic for the device to gain insight. However, the BJT has two junctions. Which junction should represent the voltage axis? We will let V_{CB} denote the horizontal axis. This is done because a fixed V_{EB} will shift our focus to the base-collector. If we vary V_{CB} the depletion region width changes, allowing more or fewer carriers to pass through the neutral base. Hence, choosing V_{CB} as the horizontal axis will visualize how the base-collector junction varies the current. **Ideally, V_{CB} should not affect the collector current but this is not true**.

In a plot of I_C vs V_{CB} the horizontal axis represents $I_C = 0$. Regardless of V_{CB} the collector current must be zero. Hence, the horizontal axis represents cutoff of the transistor. As V_{CB} becomes sufficiently large, what mode are we in? We assume that V_{EB} is sufficient to forward bias the base-emitter junction, so we have either saturation or forward active. Forward active requires a strong reverse bias on the base-collector, hence this region is forward active. In an ideal transistor, the collector current is independent of V_{CB}. Implying that for large V_{CB} the collector current will be constant since V_{EB} is a constant.

As V_{BC} becomes negative, the base-collector becomes forward biased. As the forward bias increases the device enters saturation. Under saturation, the collector current must drop. When the base-emitter and base-collector junctions are both forward biased holes from the emitter and collector will diffuse into the base. Over time, the total number of holes in the base will saturate since recombination is the primary process of removing these holes from the neutral base. Low recombination results in a large number of holes remaining within the base increasing the concentration. As the concentration increases the rate of diffusion decreases, approaching zero.

Combining these observations into a plot, the IV characteristic is provided below from the Sze text.

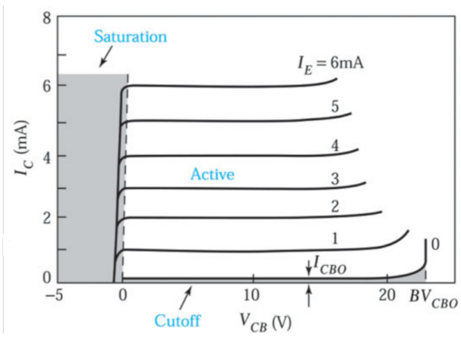

Figure 7: PNP BJT collector IV characteristic plot. ([2])

From this plot, we can note the three distinct regions: cutoff, forward active, and saturation. The cutoff curve is drawn slightly above zero since small leakage currents exist. Also note that breakdown is still an issue and large biasing voltages, BV_{CB0}, will result in a steep increase in current. Above the cutoff curve, several other curves are drawn denoted by: 1, 2, 3, and so on. Each of these curves represents a distinct V_{EB}. Curve 1 has the lowest V_{EB}, curve two has a slightly larger V_{EB} than curve 1, curve three has a slightly large value than curve two, and so on. In general, $V_{EB,1} < V_{EB,2} < V_{EB,3} < \ldots < V_{EB,n}$, where n is the maximum curve drawn. As V_{EB} increases we expect I_C to increase since V_{EB} determines the emitter current, and $I_C \approx I_E$. The approximately equal collector and emitter current is also shown by the $I_E = 6$ mA statement.

The forward active region is nearly flat, as expected for the common-base configuration. Slight curvature is present at the end of each curve since breakdown is an ever-present issue. As for saturation, we can see that from $V_{CB} < 0$ the saturation current drops drastically. It is not until the built-in base-collector electric field begins to weaken that defines saturation. With $V_{CB} = 0$ the base-collector is still reverse-biased albeit weakly when compared to $V_{CB} = 10$. Interestingly, this gives us two forms of forward active, a strong and soft active mode. These modes are not important to us but are important to circuit designers attempting to bias their transistor effectively. **Common-base configuration has unity current gain.**

Common-emitter:

We will use a similar process as the common-base to qualitatively derive the IV characteristic for the common-emitter. Before we start, note that the common-emitter diagram was given for an NPN device. This was done to provide exposure to both device types in this set of notes. To convert to a PNP device, the current direction and subscript orders must switch. Each curve in the plot will correspond to a

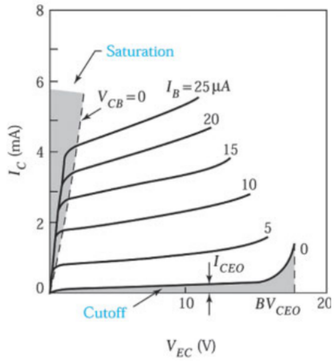

Figure 8: Nonideal PNP BJT common-emitter IV characteristic plot.

fixed V_{EB} and the horizontal axis will represent V_{EC}. Again, a convenient way to remember common configurations voltage directions is that the first subscript is the common terminal.

In the common-emitter configuration V_{BC} is not immediately known. Applying a KVL across the devices results in $V_{EB} + V_{BC} = V_{EC}$, implying $V_{BC} = V_{EC} - V_{EB}$. This equation tells us that the base-collector voltage is offset by the base-emitter voltage. For a fixed V_{EB} the base-collector will remain reverse biased if $V_{EC} \geq V_{EB}$. However, as V_{EC} becomes larger the depletion region width increases. As mentioned, the increased depletion region reduces the size of the neutral base implying more carriers may pass into the collector. Therefore, it is expected that the collector current increases with V_{EC}. For simplicity, let's assume this effect is not present, or that I_C is independent of V_{EC}. Under this assumption, the collector current is constant for large V_{EC}.

Under cutoff, $I_C = 0$, implying the horizontal axis represents cutoff mode regardless of V_{EC}. V_{EB} is assumed to be sufficiently large to forward bias the base-emitter, hence any $V_{CE} \geq V_{EB}$ will reverse bias the base-collector driving the device into forward active. Under forward active, the collector current is ideally constant. As for saturation, the curve is offset by V_{EB}. For $V_{CE} < V_{EB}$ the built-in field is weakened which allows carriers to diffuse. The saturation behavior is identical to the common-base but starts at a different V_{CE} value.

The plot for the non-ideal common-emitter IV characteristic is provided below. The plot is provided in the Sze text and includes the effect of V_{BC} varying the collector current. The effect is quite substantial and something we cannot ignore, however, we will study this effect in detail later. The ideal characteristic is identical in shape to Fig. 7. The difference is the emitter current is no longer the input current, the base current is. The base current is on the order of several μA in the figure

The structure of the plot is identical to the common-base configuration the curves increase vertically along with the V_{EB} value. The values of 5, 10, 15, and such reference to the base current. However, using these labels we can say that $V_{EB,5} < V_{EB,10} < V_{EB,15} < \ldots < V_{EB,n}$, where n is the top-most curve in the plot.

Energy Band Diagram:

The energy band diagram for the BJT may not be presented during the lectures. However, it gives insight into how the various modes of operation occur. Recall from our PN junction discussion that the n-type region has a Fermi level near the conduction band, and the p-type has a Fermi level near the valence band. Within the depletion region, the bands were drawn linearly to connect the two regions. This process may be applied to the BJT since it is formed of PN junctions. We know that at thermal equilibrium the Fermi level must be flat. Hence, we can stitch together the three regions via the Fermi level. For a PNP device, the energy band diagram is provided below.

The distance between the valence band for the collector and emitter should not be identical. We know that the emitter is generally doped much larger than the collector. Hence, the Fermi level will be closer to the valence band in the emitter than the collector. Regardless, the image above visualizes the general structure of the BJT energy band diagram.

The lack of curvature within each region implies a negligible electric field; bulk neutrality assumption.

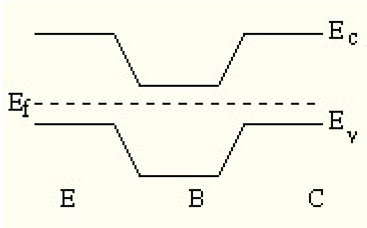

Figure 9: PNP thermal equilibrium energy band diagram. ([1])

At the base-emitter junction, a nonzero slope is present to visualize the depletion region of each junction. If an electron in the emitter were to stumble into the depletion region, it would roll down the "hill" into the base. Inversely, any hole within the base would roll up the hill into the emitter. The device must be under cutoff because the majority of holes in the emitter cannot diffuse into the base. For diffusion to occur the flat level of the base must be above the emitter to satisfy the rolling analogy.

If we were to bias one of the junctions, how would this affect the energy band diagram? We know that putting the negative terminal of a voltage source on a terminal will raise the level in the energy band diagram. Hence, if we place a voltage source with the positive terminal attached to the emitter and the negative terminal attached to the base the height between the base-emitter must decrease. We can confirm this behavior is true because the built-in potential increases from the emitter to the base. If a voltage source is applied opposite to the built-in voltage the depletion region is reduced. Introducing a forward bias on the base-emitter junction and a reverse bias on the base-collector results in the following diagram.

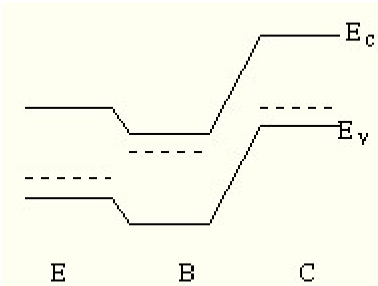

Figure 10: PNP forward active energy band diagram. ([1])

Let's focus on the base-emitter junction first. The height between the base-emitter has been reduced due to the applied voltage. If we imagine a hole in the emitter, the probability the carrier can jump over the barrier, and enter the base is greater than in cutoff. We can also imagine the electron's perspective in the base. The reduced base-emitter height will also allow for electrons in the base to diffuse into the emitter. However, diffusion will not fully be present until the depletion region width is reduced to zero. When the depletion region width is zero the height between the base and emitter is zero.

The large slope in the base-collector is due to the reverse bias base-collector junction. When we reverse bias the base-collector the positive terminal of the source is attached to the base and the negative terminal to the collector. Under this configuration, the bands in the collector are raised vertically and the base-collector height is increased. Let's imagine the holes which traverse into the base from the emitter. When the carrier reaches the end of the neutral base, a large slope is seen. The large slope will cause the carrier to be swept away into the collector. Recall in forward active the base-collector depletion region collects carriers injected by the emitter and prevents majority carriers in the base from diffusing into the collector. The electrons in the base see a large barrier to enter the collector, effectively blocking them. Whereas holes in the base see a drop encouraging entering the base.

We can continue this process for saturation and reverse active, however, we will leave that for you. This section is somewhat optional, but it is helpful in visualizing the various modes from a different perspective. The equations derived in the next set of notes are useful, however, the energy band diagram provides a concise visualization.

Early Effect (Optional)

This section will serve as a short introduction into the Early effect. In the IV characteristics above, an increasing base-collector reverse bias increases the current slightly. This phenomenon is called the Early effect, discovered by James M. Early. For those who have taken Electronics 1, this is where V_A comes from.

The early affect is due to modulations in the base-collector depletion region. Imagine for a fixed V_{BC}, let's say 5 V. We know the depletion region will have some width associated with it. If we increased the reverse bias to 6 V the depletion region width must also increase. However, what happens when the depletion region width increases? Recall from our PN junction analysis the conservation of charge. As the depletion region expands more space charge is present in the depletion region. If we were to continue increasing the base-collector voltage would the depletion region grow forever? No. Our analysis with a **short base** region assumed the base is significantly narrow. Increasing the base-collector depletion also reduces the width of the neutral base. Hence, less carriers are recombined in the neutral base which increases the collector current.

Conclusion:

This set of notes has introduced the bipolar junction transistor and its theory of operation. By combining two PN junctions the number of modes and configurations increased greatly from the PN junction. The cutoff, saturation, and forward active modes were discussed heavily, with slight mention of reverse active. As well as the three configurations the BJT may be wired under common-base, common-emitter, and common-collector configurations. These three configurations have different properties with respect to voltage and current gain, as well as circuit parameters such as the input and output resistance of the device. With each of these configurations, the IV characteristic curve was discussed qualitatively. We noted some nonidealities in the common-emitter configuration which we will study later in the course. The notes ended with a brief discussion of the energy band diagram to wrap the large number of observations made throughout the notes. The next set of notes will be focused on the quantitative analysis of the BJT.

References

[1] P. Roblin. *bjtflow.t*. URL: http://www2.ece.ohio-state.edu/%7Eroblin/test432/bjt/testall.html.

[2] Lee M. K. Sze S. M. *Semiconductor Devices: Physics and Technology 3rd edition*. Wiley. (2012).