Examination (PSpice) of BJT (2N3904) Characteristics

Objective
Two semiconductor junctions appropriately joined back-to-back are used to form a transistor. However this is not a matter of simply connecting two discrete diodes. It is essential that there be an intimate coupling between the two junctions provided by forming the junctions close together in the same crystalline environment. In this note the physical relationships that distinguish what are simply separate junctions from a bipolar transistor are discussed qualitatively, and from this discussion the terminal characteristics of the Bipolar Junction Transistor (BJT) are inferred. Static terminal characteristics of a representative transistor (2N3904) are examined in a PSpice computer analysis using an accurate nonlinear model for this device.

Bipolar Junction Transistor
Two semiconductor junctions connected back-to-back are used to form a transistor. However this is not a matter simply of connecting two diodes. It is essential that the background crystalline atomic forces for both junctions are continuous, and moreover for effective transistor operation it is essential that the width of the region separating the two junctions be quite narrow.

There are two orientations in which back-to-back junctions can be arranged; in one case (NPN) the junctions share a common P region, and in the other case (PNP) they share a common N region. This common region is the ‘base’ of the device, and its doping uniquely characterizes the transistor type. The nature of the transistor phenomena is formally the same for both orientations; the distinction between the two is the interchange of the roles of electrons (principal carrier for NPN) and holes (principal carrier for PNP). There are important practical distinctions however with respect to terminal voltage polarities, and there are differences in material parameters. For the present purpose a specific NPN device, 2N3904, is used for illustration.

In normal operation one junction, the emitter junction, is ordinarily forward-biased and is used to inject carriers primarily into the central (base) region. This junction is optimized (and identified as such) by the device manufacturer to perform this injection function. For a NPN device, for example, the N side of the emitter junction is heavily doped n-type compared to the base to provide a large number of electrons that will be injected into the base and diffuse towards the other junction. Conversely the base side of the emitter junction is relatively lightly doped p-type to reduce the hole flow out of the base. This preferential injection of carriers into the base towards the other junction is characteristic of a ‘good’ transistor emitter. (Note: reverse the roles of the carriers for a PNP device, i.e., preferentially inject holes into the n-type base.)

Ordinarily the electrons injected into the base, as they penetrate into the base, would be quickly trapped by holes provided by base acceptor impurities. However if the base width is made sufficiently (very) narrow encounters between electrons and acceptors become relatively infrequent and virtually no trapping occurs before the injected electrons reach the second ‘collector’ junction (also optimized and identified by the manufacturer as the collector). This junction is normally operated in reverse-bias so that the intrinsic collector junction current is just the very small reverse-bias current. Recall that this intrinsic reverse bias current is comprised of carriers that randomly wander into the collector junction where the junction electric field sweeps them across into the collector. Ordinarily the reverse-bias current is small because there are few electrons on the base side of the junction and few holes on the collector side of the junction. However the junction electric field present does not distinguish between electrons present from one source or another, and the sweeping action through the collector junction also applies to the injected electrons transported across the narrow base from the emitter.

What makes this arrangement of particular interest is that the emitter junction current (composed primarily of electrons injected into the base) can be varied over a large range with small changes of emitter junction voltage. This is usual forward bias junction behavior except for the special emphasis placed by appropriate doping in favor of electron injection into the base over hole flow from the base. Since virtually all the carriers injected at the emitter reach the collector junction (the base width is made very narrow to
assure this) the collector current is essentially just the emitter current (neglecting the comparatively small intrinsic leakage current). This augmented reverse-bias current is not sensitive to the collector voltage (provided that collector junction remains reverse-biased and out of reverse-breakdown). Hence a small amount of power expended at the emitter junction can control a much larger power (same current, larger voltage range) at the collector.

There are various second-order effects and other concerns for a more complete appreciation of transistor operation but it is the current control mechanism described that is the essential capability of the transistor. The transistor behaves closely as a controlled current source with a sensitive dependence on emitter junction voltage. The type of transistor described is called a Bipolar Junction Transistor (BJT) because unlike devices described elsewhere both electrons and holes are involved in forming the junctions.

The icon used to represent a NPN transistor is shown below. The names have a historical origin in experiments that led to the development of the device. As indicated in the figure the emitter is identified readily as the only lead with an arrow. The emitter arrow always points P -> N, from the base out in the case of the NPN device. The icon for a PNP device is identical, except that the arrow points from the emitter into the base.

Common Base 2N3904 BJT Collector Characteristics (PSpice Model)
What follows is a computer analysis comparing a PSpice nonlinear model of the 2N3904 (NPN) BJT with a piecewise linear (Ebers-Moll) model of the same device. Concurrently the qualitative description of device phenomena is used to compare the ‘experimental’ computer data with what would be expected. The transistor is connected in a ‘common base’ configuration, meaning simply that the base provides the common terminal between the input and output ports. To illustrate the basic device performance the ‘collector’ characteristics are computed. These are a set of parametric curves showing collector current vs. collector voltage, with a fixed emitter current for each curve. The netlist on the right, below, provides the PSpice input corresponding to the circuit drawn on the left. The collector-base voltage is swept for several parametric values of the emitter current.
The PSpice output is plotted below

We start examination of the plot with the characteristic for $I_E = 0$; since the emitter junction is OFF this is essentially the collector junction diode characteristic. Since essentially no electrons are injected into the base there is no transport across the base and no augmentation of the collector junction current. (Because the collector junction normally operates in reverse-bias the polarity conventions used for the transistor are such as to make collector junction forward-bias current negative; the exponential part of the junction characteristic thus appears on the left side of the transistor plot. This puts what will be the more interesting part of the characteristics in the first quadrant.)

Now note that the other characteristics essentially are displacements of the $I_E = 0$ characteristic, i.e., the injected current (actually a slightly smaller amount) simply adds to the intrinsic collector junction current. The current displacement increment is slightly smaller than the emitter current increment because there is a small loss of injected carriers to hole recombination as they cross the base. However generally the loss is unlikely to be as large as 5% and more than likely will be closer to 1% of the carrier flow.

In the 'normal' operating mode (emitter junction forward-biased, collector junction reverse-biased) the characterization of the transistor as a controlled current source is clearly appropriate. Actually the collector junction can be slightly forward-biased before current is injected by the collector back into the base; a junction has very small forward current for a forward bias below a ‘knee’ voltage of roughly 0.5 volt (for silicon).

**Ebers-Moll Model**

A widely used first-order representation of the BJT (Ebers-Moll model) assumes independent operation of two ‘back-to-back’ junctions, one to provide the carrier injection mechanism and the other to provide the carrier collection mechanism. (See figure below.) To this is added, and this is what distinguishes a transistor from a back-to-back diode connection, a controlled current source to represent the ‘transistor action’, i.e., the mechanism by which carriers injected into the base through a forward-biased emitter junction almost all reach and pass through the reverse-biased collector junction to add to the collector current.

The circuit below (netlist to the right) models the Ebers-Moll BJT representation as two independent ‘back-to-back’ diodes and a controlled current source added to represent the emitter junction carrier injection into the base and subsequent collection by the collector junction. (Strictly speaking there should be a current source across the emitter junction reflecting possible ‘reverse’ operation, i.e., using the designated emitter junction as a collector and vice versa. Since the collector junction is a poor emitter and the emitter junction is a poor collector this 'reverse' operation is rarely if ever used, and reflecting this disuse the emitter current source simply is omitted for simplicity.)
Two computations are made. The first uses a 1N4004 PSpice nonlinear diode model as representative of ‘real’ diode characteristics. This reflects the physics of the BJT on which the Ebers-Moll model is based. (Note: The VBE voltage source is inserted for later use; it strength is set to 0 and so is effectively a short-circuit for this particular computation.) It should be recognized that the model does not account for all the operating characteristics of the nonlinear BJT model; more advanced considerations such as frequency response, saturation, and temperature sensitivity are some omissions. The controlled current source ‘gain’ parameter (corresponding to the transistor current gain $\alpha$) is 0.99; this value is obtained from 2N3904 manufacturer’s specification. Note from the preceding collector characteristic that $\alpha$ is substantially constant. The computed characteristics (see below) closely match the previous results. As noted before the BJT model as shown actually is valid only for normal forward operation since reverse transistor action is not accounted for. (To do so add a controlled current source representing injection at the collector junction; the gain parameter will be smaller however. However also as noted before the BJT is not likely to be operated in reversed mode and this current source will have no effect on the computations in normal mode.)

The computed collector characteristics of the model are shown below. Comparison of the diode-modeled BJT and the more precise nonlinear model collector characteristics are left as an exercise.

**Idealized Diode Model**

For computational simplicity idealized diode models may be used rather than nonlinear diode models. This use is primarily for hand calculations, but for pedagogical purposes a computer simulation of idealized diode models is useful on occasion. Thus DIDEAL in the netlist below modifies the diode emission parameter N (as described elsewhere) to model the idealized diode. The nominal emitter junction bias is accounted for by VBE (set to 0.7 volt) since the knee voltage of the idealized model has been made negligible artificially. Note that a similar allowance for the collector junction is not made, as a
A comment about the sweep voltage range lower limit is appropriate. The diode model forward current is an exponential function of the forward voltage, and with the reduced emission parameter the current will double for about a nanovolt voltage change. Thus very small forward voltages correspond to very large forward currents. A plot of current data may unintentionally hide desired information because of an inappropriate scale used to cover a theoretically artificial very large range. Use Probe range scaling to set a suitable range for data of interest.

The modified netlist and a plot of the computed characteristics follow. Of course the use of idealized diodes makes the model a PWL approximation, as is clear from the computer plot. Here also the comparisons are left as an exercise.

*2N3904 CB Characteristics
* E-M MODEL Idealized diodes $\alpha = 0.99$

<table>
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<tr>
<th>Symbol</th>
<th>Port 1</th>
<th>Port 2</th>
<th>DC Value 1</th>
<th>DC Value 2</th>
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<tr>
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<td>3</td>
<td>1</td>
<td>DC</td>
<td>0.7V</td>
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<td>2</td>
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<td></td>
</tr>
<tr>
<td>DBE</td>
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<td>3</td>
<td>DIDEAL</td>
<td></td>
</tr>
<tr>
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<td>0</td>
<td>DC</td>
<td>-0.1V</td>
</tr>
<tr>
<td>FVIE</td>
<td>2</td>
<td>0</td>
<td>VBE</td>
<td>0.99</td>
</tr>
</tbody>
</table>

.Model DIDEAL D(N = 1U, RS = .001 )
.DC VCB -0.8V 10V .1V IEMITTER 0 .012 .002
.PROBE
.END

Common Emitter Collector Characteristics (2N3904)

There are surprises for the unwary when interpreting transistor characteristics. For example the CB current gain parameter $\alpha$ is substantially but not exactly constant. There is a second-order effect that causes small changes of $\alpha$, too small to be easily discerned in the CB presentation of collector characteristics. But even second-order effects can become important in circumstances that de-emphasize the first-order effects ordinarily masking them. This is particularly well illustrated by computing the Common Emitter collector characteristics of precisely the same nonlinear 2N3904 model used before. It is worth emphasizing (repeatedly) that the transistor model for the CE data presentation is identical to that used for the CB presentation. The performance of the device is precisely the same as for the CB computation. Only the manner in which the information is presented is different, and it is simply the presentation which emphasizes the second-order effects.
The particular second-order effect considered here is called the Early Effect, and is associated with a change in the electrical width of a semiconductor junction as the junction voltage changes. While this happens at the emitter as well as the collector junction it is the latter junction that is the important one; in normal operation the forward-biased emitter voltage changes very little even for large forward current changes.

The junction width increases slightly as reverse bias on the collector junction is increased, with two consequences. First, widening of the collector junction width decreases the base width across which carriers injected at the emitter have to cross to reach the collector junction. The base is a hostile region for these carriers. Electrons injected into the base of a NPN device, for example, are in a p-type region in which they can be attracted to and trapped by the relatively high hole concentration. This possibility, while made very small by design, is decreased slightly more because of the decreased exposure time of the injected carriers, and so the collector current increases slightly. Hence there will be a very small dependence of the collector current on collector-base voltage. There also is a slight increase (for widening of the collector junction width) in carrier transport across the base. The base transport mechanism is primarily a diffusion; widening the junction width and so decreasing the base width tends to increase slightly the carrier concentration gradient and so the collector current.

Suppose you are making measurements to obtain data with which to plot a given CB characteristic, and have just completed readings for a point on the characteristics. To obtain data for the next point you increase the collector-emitter voltage; since the emitter junction voltage is more or less constant this means the reverse-bias across the collector junction increases. The Early Effect then causes a slightly more efficient current transfer across the base. The base current decreases; fewer carriers are lost in the base transit. And that is all of the Early Effect, and all of the very small collector current increase that shows up in the characteristic curves. But unlike the CB presentation the CE curves are for fixed base currents. Hence to complete the measurement for the plot the base current source strength is increased to restore the current level appropriate for the curve for which data is being taken. Then, because of this base current increment, the collector current increases, and this latter increase is not because of the Early Effect. The small change associated with the transistor physics is “amplified” artificially to suit the way the data is plotted. The data as plotted display a much more substantial increase of collector current with collector voltage because the base current must be maintained constant.

The nonlinear PSpice BJT model accounts for the Early effect, and that model is used to illustrate the preceding discussion. Again note that this is precisely the same transistor model used for the earlier calculations. The circuit as analyzed is drawn to the left; the base current is stepped to provide a set of CE parametric curves for IC vs. VCE and these are shown below. The plot is made over a large collector voltage range to emphasize the Early effect, which appears as a noticeable slope to the characteristic curves. The curves extrapolate to a common intercept on the voltage axis called the Early voltage, a value appearing as part of the manufacturer’s specifications for the device. The several curves shown are extrapolated to determine an Early voltage of about -74 volts.

*2N3904 Collector Characteristics
IBASE 0 1 DC 10U
RBASE 1 0 10MEG
Q1 2 1 0 Q2N3904
VCC 2 0 10
.LIB EVAL.LIB
.DC VCC -50V 50V .1 IBASE 0 50U 10U
.PROBE
.END

For many purposes no particular accounting need be made for the Early effect; it is built into the nonlinear model appropriate for computer analysis, and generally is not particularly important for the approximate PWL models used for making estimates and identifying important relationships. (Of course it can be accounted for in a PWL model by in various ways if desired.)
The figure below plots the same data over a smaller collector voltage range to provide a better perspective on the influence of the Early effect over a more usual range of operation. Note that outside of the 'saturation' operating range (i.e., for VCE > 0.4 volt or so) the curves approximate the theoretically expected parallel equally spaced (for equal base current increments) lines, modified by a slope corresponding to the Early effect.

For some applications details of the CE saturation region are useful. Saturation occurs as the collector junction becomes forward-biased, injecting carriers into the base and back towards the emitter. This reduces the net current into the collector, more and more as the collector voltage decreases. Recognize that the collector junction voltage is the difference between the collector-emitter voltage and the forward-biased emitter junction voltage. Hence the collector junction begins to be forward-biased for a collector-emitter voltage of roughly 0.7 volts. Allow an additional decrease of a few tenths volt to get past the diode ‘knee’, and on this basis anticipate that saturation begins to be apparent for collector-emitter voltages of a few tenths volt. The following figure (see below) emphasizes the saturation range of operation.

Finally, the next figure indicates the current amplification factor as a function of the base current; each curve is at constant collector voltage (vertical line on the collector characteristics). Except at lower base currents (where the leakage current of the collector junction makes a significant contribution) \( \beta \) (defined on the figure) is relatively insensitive to changes either in collector current or collector voltage.
PieceWise Linear CE BJT Model
For many if not most basic hand calculations an idealized diode simplification of the Ebers-Moll model makes important analytical insight into BJT circuit performance accessible with simplified calculations. For that reason it is worthwhile reviewing and expanding on the previous discussion of the Ebers-Moll model. The basic model (NPN version) as introduced above is reproduced in the figure below, left. Diode icons are filled simply to indicate that the exponential diode characteristic is implied.

Consideration of the internal physics of the device make the expression of the collector current in terms of
the emitter current quite natural. However in terms of circuit use it turns out to be more convenient
generally to replace the emitter current by the base current as a descriptor of the transistor characteristics.
This is essentially a matter of choice since Kirchoff’s Current Law requires IE = IC + IB. The redefinition
is made to the right of the E-M model, and to emphasize the change the circuit is redrawn interchanging the
orientations of the base and emitter in the drawing. Again this is a matter of preference, without electrical
consequence. Note particularly the re-expression of the controlled source current in terms of IB.

The final simplification is to use idealized diode models in place of the 'exponential' diodes. The emitter
diode replacement also includes recognition of the nominal forward bias voltage of the emitter junction,
although this is ordinarily omitted for the collector junction. The final PWL model, the diodes now are
idealized diodes, is shown on the right.

Normal 'forward' operation corresponds to the emitter diode closed and the collector diode open;
I_B = \beta I_B. This requires a base voltage \geq VBE and a collector voltage greater than the base voltage.
Cutoff (emitter diode open) corresponds to a base voltage \leq VBE, and saturation corresponds to a collector
voltage equal to the base voltage. Since the model is not valid for 'reverse' operation' the collector-emitter
voltage is assumed to be positive.

A detailed examination of the characteristic curves predicted by the model is left for an exercise.
PROBLEMS

1) The 2N3906 is the PNP counterpart to the NPN 2N3906. Compute (plot) the collector characteristics of this transistor. PSpice model parameters are given below.

```
.MODEL Q2N3906 PNP(Is=1.41f Xti=3 Eg=1.11 Vaf=18.7 Bf=180.7 Ne=1.5
+ Ise=0 Ikf=80m Xtb=1.5 Br=4.977 Nc=2 Isc=0 Rc=2.5 Cjc=9.728p
+ Mjc=.5776 Vjc=.75 Fc=.5 Cje=8.063p Mje=.3677 Vje=.75 Tr=33.42n
+ Tf=179.3p Itf=.4 Vtf=4 Xtf=6 Rb=10)
```

2) The PWL transistor models the transistor action with a collector current source proportional to the base current. Compute and plot collector current as a function of base current; refer to the diagram for a test circuit. Then sketch a representative PWL model characteristic estimating an appropriate value for β.

3) Modify the circuit for problem 2 by changing the base current source IB to a voltage source VB. Compute the collector current as a function of base voltage (0.1 volt to 0.8 volt in .01 volt steps). From a plot of log(I(IB(Q1))) vs. VB observe that the collector current is closely an exponential function of the base voltage. Plot the derivative of the logarithm to evaluate the exponent.

4) The ‘diode-connected’ transistor (VCC ≥ 0) is a circuit connection often used in integrated circuits (for reasons to appear later). Compute the volt-ampere characteristic using the 2N3904 transistor. Discuss briefly how this two-terminal connection differs from a diode. Does the transistor operate saturated? What is the relation between the current supplied by VCC and the emitter current? Note: The PWL approximation on the right may be helpful in evaluating the circuit performance.

5) A composite ‘transistor’ is formed by connecting NPN and PNP devices as shown. The NPN device provides the base current for the PNP device. Estimate the current amplification factor for the combined devices from the individual device β values. For 0 ≤ IB ≤ 1µamp compute the PNP emitter current I. Compare the slope with your estimated β.

6) A combination of two transistors (NPN devices here) is shown in what is called a Darlington connection. The input device provides an amplified base current drive for the second device. Estimate the current amplification factor for the combined devices from the individual device β values. For 0 ≤ IB ≤ 1µamp compute the collector current IC. Compare the slope with your estimated β.

7) A ‘push-pull’ transistor connection is shown. Make a qualitative estimate of V_o vs V_i, and compare the estimate with the computed characteristic.