Analog Design
Kevin Aylward B.Sc.
The Voltage Controlled Bipolar Junction Transistor

Back to Contents

Abstract

This paper attempts to rectify a very common misconception or misunderstanding regarding the basic operation of the Bipolar Junction Transistor. This misconception is the erroneous, but very commonly held, notion that the bipolar transistor is a current controlled current source (CCCS). That is, that the collector and emitter current of the bipolar transistor is in some way *casually* determined by the base current. This notion is false.

It may be stated, without reservation, that the Bipolar Junction Transistor is a voltage controlled device, and to a good approximation a voltage controlled current source (VCCS).

Many elementary, layman or Bantam paperback type references, and unfortunately, even some rare semi academic books often give generic reference to the base current *controlling* the collector or emitter current. The argument for this usually involve no use of semiconductor physics, and rests on various ad hoc arguments on the the notion of the collector current being equal to hfe/beta times the base current. The root cause of this misconception is often the inability to distinguish a *functional* relation from a *causal* relation. That is, whilst it is certainly true that in a practical transistor base current must exist, transistor action is not *causally* dependant on such current. Base current is an *effect* that results from an application of a voltage at the base emitter junction.

The Voltage Controlled Bipolar Transistor

The bipolar transistor is, fundamentally, a voltage controlled device and this principle is usually not open to much debate in academic environments. Any reasonably advanced academic physics text book directly shows that the currents of the transistor are *causally* related to the device terminal *voltages*. To this authors knowledge, there are no technical physics arguments that derive transistor collector and emitter currents from direct knowledge of the base current.

Verification of this view can be obtained by referring to, arguably, one of the foremost papers on modeling the bipolar junction transistor, the paper "An Integral Charge Control Model Of Bipolar Transistors" by H.K. Gummel and H.C. Poon":

"We present in this paper a compact model of bipolar transistors, suitable for network computer programs. Through the use of a new charge control relation linking junction voltages, collector current and base charge, the model includes high injection effects..."

Indeed, the more advanced VBIC model dispenses with the concept of the current gain Beta/hfe entirely:

"...From the physical analyses above, it is clear that the collector current primarily depends on the base doping, and the base current depends primarily on recombination and generation in the emitter region. Consequently, very different physical mechanisms control the collector and base currents. Relating them via a phenomenological parameter such as Bf, which is done in the SGP model, is therefore undesirable, and causes problems for statistical BJT modeling (McAndrew, 1997). This is why VBIC explicitly separates the base and collector current modeling...."

Fundamentally, having a small current directly control a large current violates conservation of energy. It is equivalent to throwing a small pebble at a large rock and attempting to make that rock travel at the same speed as the pebble.

Gummel-Pool Model

Unfortunately, the nature of the "Gummel-Poon" "charge control model" model is very often misunderstood. The "charge control" aspect of the model is the principle that the collector current of the transistor is a causal effect of the charge in the base region. However, this base region *charge*, by construction of the model, is *caused* by the terminal *voltages* of the transistor. The model does not assume or rely in any way on any notion that the charge in the base region is actually caused by charge injected via the base terminal. Indeed, the model explicitly calculates the base region charge by calculating the charge injected from the *emitter*. It is this principle that leads to the very name "Emitter" for the bipolar transistor. It is the Emitter that emits (injects) the majority of the charge into the base region, however, and somewhat unfortunately, a small amount of this charge leaks away via the base terminal as base current. However, any base current is simply a side effect of applying a voltage to the base emitter junction and just reflects the fact that the collector is unable to suck up all of the charge that is injected from the emitter region. This is illustrated in the Gummel-Poon model by the following:

The second page of the Gummel-Poon paper, noted as page 828, states:

"…The new charge control relation arises from the treatment of the transport equation for the carriers that pass between emitter and collector. Use is made of the fact that recombination has only a very small effect on the junction-voltage dependence of the current passing from emitter to collector (later called the dominant current component). Hence for this dependence, but of course not for the base current, recombination is neglected. A direct closed-form solution of the transport equation from inside the emitter to inside the collector is possible…"

In other words, the base current (recombination in the base) is neglected (initially) in the Gummel–Poon method, and base charge is calculated for the "junction-voltage dependence of the current passing from emitter to collector". That is, the 1st order calculation of the base charge is not effected or reliant on base terminal current, but by the terminal voltages. Thus, the bipolar transistor is inherently described as a *voltage controlled* device.

It is further noted that once the 1st order charge and currents have been determined, the Gummel–Poon model goes on to calculate and include the effects of base current as a 2nd order term, for example, by calculating the effective base emitter voltage by allowing for the voltage drop across the internal base resistance due to this base current.

Basic Transistor Operation

The emitter current of a bipolar transistor is generated in the same way as that of the current in a simple diode. That is, applying a voltage to the (base emitter) diode junction results in the same current that would flow in a normal diode. That is:

$$I_e = i_o e^{\frac{V_{be}}{V_t}}$$

However, unlike in the simple diode case, the (base) current that is required from the generator of this diode junction voltage, (Vbe), is much reduced because most of the injected emitter current gets sucked up into the

Collector region due to the electric field at the Collector. A key factor for this to occur is that the base region is very thin.

There is thus an effective functional relationship between collector current and this reduced base current described by ß (beta or hfe), the common-emitter current gain, which is the ratio of collector current to base current. It is typically greater than 100 for small-signal transistors but may be smaller in transistors designed for high-power applications. Beta is not linear in general, and depends on the emitter current and collector-emitter voltage. For the typical case of larger current gains, the base current loss is negligible and has minimal effect on collector current, such that the collector current is simplified to IC= Io.exp(q.VBE/kt). 2nd order base current effects may be included by calculating the voltage drop to the internal base-emitter node due to this current and an internal base spreading resistance, by ib.rbb'.

The summary of this is:

1) The base emitter junction is a diode junction.

2) It can be shown that the current in a diode is causally related to the voltage across it. The relation is:

$$I_e = i_o(e^{\frac{V_{be}}{V_t}} - 1) \text{ - (1)}$$

where Vt is KT/q, and I_o is a constant dependant on temperature.

This equation dictates that however Vd is achieved, Id through the junction will be related by the above equation.

3) A voltage instigated via the base and emitter of the transistor is, essentially, equal to Vd of (1), therefore the current that exists through such junction must be related by (1).

That is, the emitter emits charge into the base region of the transistor, due to the application of Vbe.

4) The emitted charge, once in the base experiences the influence of the voltage at the collector, and as the base is very thin, collects the charge at the collector terminal and thereby prevents most of the charge flow that would over wise attempt to exit out of the base terminal. Some charge does in fact "leak" out of the base, but this is incidental to the notion that the emitter current is, essentially, a causal function of applied Vbe, via the diode equation. As most of this current is collected by the collector, the collector current may also be said to be a direct casual function of the applied base emitter voltage.

5) It can also be stated that is electric field that, ultimately, is what causes charges to move, by virtue of the Lorentz force F=qE. It is thus, the electric field due to the base-emitter voltage that causes charges to be emitted into the base region, and the electric field due to the collector voltage that attracts those charges to the collector region.

Summary

The bipolar transistor is described as a voltage controlled device that is spoilt by a non-linear resister across its base emitter junction. For some simple applications one might consider in a very loose way that the collector current is "caused" by a base current as there is indeed a functional relation, but this is only a descriptive approach of limited value that is difficult or impossible to apply in general situations.

Indeed, if one looks at ones watch and the motions of the planets, we can usually say that the sun will reappear when we see the watch hands rotate twice, but this functional relation is certainly not causal. Stopping the hands moving wont stop the sun moving!

References

McAndrew, C. C., Bates, J., Ida, R. T., and Drennan, P. (1997) “Efficient statistical BJT modeling, why b is more than Ic/Ib.” Proc. IEEE BCTM.

Website last modified 14th March 2015
www.kevinaylward.co.uk
