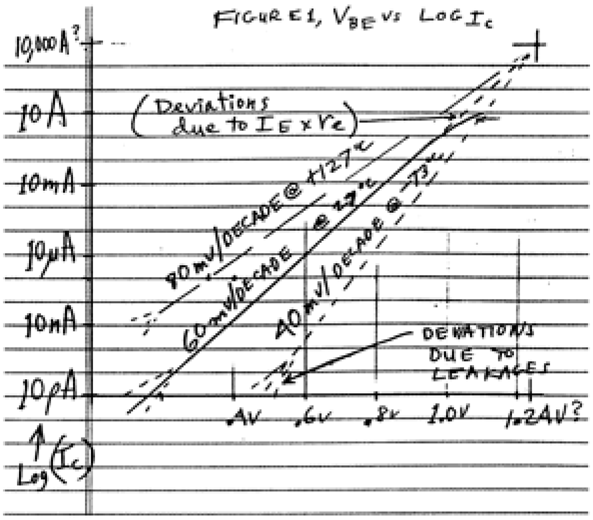
THE BEST OF BOB PEASE

What's All This VBE Stuff, Anyhow?



The other day, I was walking past the Applications Engineering area, when I heard a grouchy debate between a couple of guys over in the corner. As they saw me walk by, they called out, "Bob, come on over here, and maybe you can solve this problem for us." I looked at their problem.

"Bob, we were trying to use the standard diode equation to compute the tempco of a transistor's VBE, and it doesn't seem to make any sense." I looked at their standard equation:

$Ic = i_s \times e^{(qVBE/kt)}$

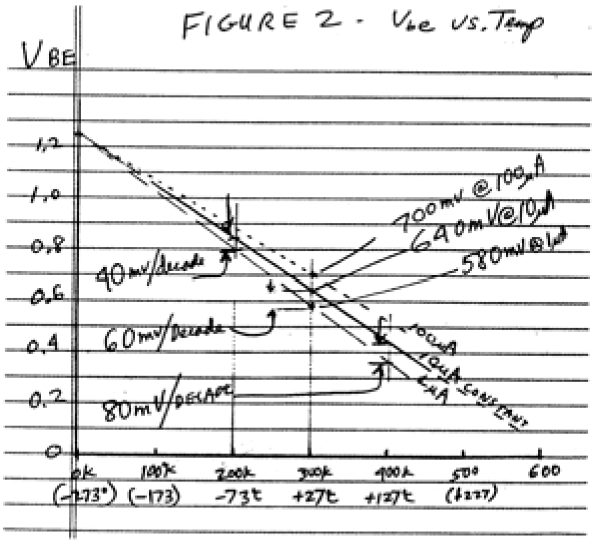
Yes, there was a term for temperature, 't' in there, but it wasn't a very prominent term. Obviously, they had tried to see how this equation responded to temperature. They were puzzled because it does NOT respond properly to temperature. It doesn't give anything *like* -2 mV/degree C. I began assisting them by explaining, "When they give you this equation in school, they neglect to tell you that the i_s isn't a constant, but rather a very wild function of temperature. This function is so wild that they won't tell it to you, because it's not very useful. You can't successfully differentiate it versus temperature. So you're better off NOT having such an unusable equation."

They responded, "Okay, what are we supposed to use?" I replied, "Ah, let's do a graphical approach. Let me make up a couple of sketches." First I scribbled out Figure 1, showing the log of collector current versus VBE.

I went on to explain, "That school-book linear plot of VBE versus Ic isn't very useful, because it just shows a severe knee. I never use that one. Look at the middle line of this plot. It shows that at room temperature, the slope of the log of Ic versus VBE is quite linear over seven, eight, or nine decades of current. Only at high currents does the curve bend, due to emitter resistance. And, only at very small currents do you get errors due to leakages. So, in the whole mid-range, you get a wide range of conformity to the slope of 60 mV/decade." The two guys agreed with what I had said.

After this, I pointed to the upper line. "At a hot temperature such as +127 degrees C, the curve is very similar. But, at a shallower slope, the millivolts per decade is *worse*, very close to 80 mV/decade. Indeed, this number of millivolts per decade is predicted by the diode equation." They further agreed that my explanations seemed correct. Plus, I showed the guys that the lower sloping line is sort of like the curve for -73 degrees C, but it's at a slope of 40 mV/decade -- a rather higher gain, with a higher gm. Fine.

Also, it's possible to see that all the curves tend to converge or extrapolate to a single high point at a *very* high base-emitter voltage, perhaps + 1.24 V, at a *very* high current, maybe 10,000 Amperes. Based on this outrageously high theoretical current at an absurd voltage, one could (theoretically) compute what the VBE is really doing--not very accurately, or usefully.



But I pointed out that this curve is just good for giving a ball-park overview of what goes on. Yes, in concept this could be used for computing the actual VBE of the transistor, at various currents and temperatures. But, it's too crude and too broad to be useful. What we want to use is closer to Figure 2.

I sketched away madly to get this figure, showing the plot of VBE versus temperature. This illustrates the bias of transistors at various constant currents, versus temperature. "THIS," I said, "is *useful*--and let me show you where and why." I stated that it was based on the real data, for a real standard transistor, and it's what I use to compute biases for real precision linear circuits, such as band-gap references or temperature sensors. This and a slide rule (or a little hand-held scientific calculator) lets me compute the operating points I need.

I pointed out the middle, solid, sloping line. "This line is based on some measured data. This transistor, when used in a band-gap reference, has a Magic Voltage of about 1.240 V. That's where the band-gap runs flattest. So this line is drawn in order to go through 1.240 V dc at absolute zero temperature. That's where the VBE extrapolates to--if the transistor were cooled off--and that is not real data."

"The other point of calibration is where it goes through 0.640 V of VBE at 10 uA at room temperature, about +27 degrees C. That's a simple, factual, measured data point." Then one guy asked, "But why +27 degrees C? Why not +25?" 1 replied that +27 C is, with an accuracy better than 0.2 degrees C, exactly 300 degrees Kelvin. Therefore, it makes the math much easier to work with, at +200, +300, and +400 degrees Kelvin. They agreed.

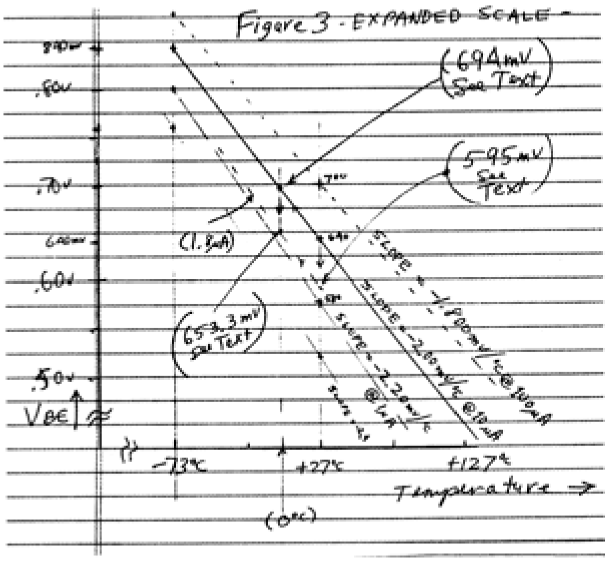
Furthermore, I pointed out that the voltage represented by this line is just the nominal VBE of the transistor versus temperature, at a constant emitter current. This has a nominal slope which is quite close to -2.00 mV/degree C. THIS is a very useful thing to know -- the bias at which the transistor runs at -2.0 mV/degree C -- because we will soon see that at many other operating currents, the tempco is NOT -2.00.

Next I stated to them, that IF the voltage between the solid, slanting line and the horizontal line at 1.240 V is studied, you can see that it's a Voltage Proportional To Absolute Temperature (VPTAT). Therefore, when we want to build a band-gap reference that's 1.240 V, all we have to do is ADD to the VBE a voltage that's VPTAT. Then, we can make a band-gap reference.

This is all you have to do: if you have a VPTAT that's 60 mV at room temperature, and you can amplify this with a gain of 10, then you can add that onto a VBE to make a band-gap reference--as Mr. Widlar proved, about 30 years ago. They agreed, that made sense as well.

I had to admit that the solid, sloping line appears to be nominally linear, and I drew it as more-or-less linear--but it's NOT truly linear. The VBE curve actually is bowed downward at both hot and cold temperatures, perhaps as much as 2 to 4 mV. But for many uses, that's a negligible error, which is easy to make corrections for, later.

I explained further: let's take a look at the upper, dotted line of Figure 2 (and Figure 3). This is for the transistor running at 100 uA. It, too, extrapolates back toward that point at absolute zero. This line does NOT have a slope of -2.000 mV/degree C, but instead -1.800. This line isn't parallel to the other line. It's set above it by 60 mV/decade at room temp, by 80 mV at +127 degrees C, and by 40 mV at - 73 degrees C. This difference is very accurately a VPTAT.



The LOWER dashed line is the line for a bias of 1 uA. It has a slope of -2.200 mV/degree C. It's offset by 60 mV/decade at room temperature, more when hot, and less when cold. The tiny segment of the line is at 0.1 uA, and has a slope of -2.400 mV/degree C (Fig. 3).

So, all lines for VBE at a constant current are all fanned out, radiating from that point at absolute zero. THIS is the curve from which it's easy to compute temperature coefficients and operating points. Now, an expanded plot, Figure 3, depicts only the central portion of Figure 2.

Let's say we want to estimate a VBE at some other biases. I'll take you through some examples. The main point is, though, that you can fairly easily compute the bias for any normal situation.

Okay, we agree that we know the VBE at those specified conditions: 640 mV at 10 uA and +27 degrees C. Let's say I want to compute the VBE of the transistor at the same current, but at a different temperature, like at 0 degree C. In the example shown, the temperature coefficient of VBE is - 2.000 mV/ degree C. A shift of -27 degree C will cause the VBE to increase by (-27) x (-2.0) = +54 mV, up to 694.0 mV. That's not very hard. For any change of temperature, at a constant bias current, simply multiply the change in temperature by the tempco of VBE. But the tempco of -2.0 mV/degree C only applies at 10 uA in this example. At any other current, the tempco will be different. More on this later....

What if we want to start from our initial conditions and move to a different current, such as 1.8 uA at +27 degrees C? For this case, where things are at a constant temperature, you can use the diode equation:

IC1 = Io x e $^{qVBE/kt}$, or its inverse:

VBE1 - VBE2 = kt/q ln(IC1)/(IC2)

The ratio of currents is 0.18, and the natural log of 0.18 is -1.7148. At +27 degrees C, the factor kt/q = 26.06 mV per factor of e, which is the same factor as 60.0 mV/decade.

Therefore, the delta VBE will be - 1. 7148 x 26.06 mV, or -44.7 mV. The VBE will decrease from 640 mV to (640 - 44.7) = 595.3 mV. This isn't a surprise. Any time the collector current of a transistor changes at a constant temperature, the VBE changes in a nice logarithmic way. But that 26.06 mV is only at that value at +27 degrees C. At all other temperatures, it's different, as a linear function of absolute temperature.

Another useful way to look at it, is that any time you change the current by a factor of 10 at room temp (about +27 degrees C), the VBE will shift by 60 mV, up or down, as appropriate. For many cases where decades of current are the important factor, the multiples of 60 mV make calculations simple. No computers or calculators are required.

Now, let's consider the case where you want to compute the VBE when both the current and the temperature are changed. There are two ways to compute this. And, both of these computations had better give the same answer.

Let's say we want to compute the VBE at 1.8 uA at 0 degrees C. You could first change the temperature of the 10-uA transistor to zero degrees at constant current, and then change the current at a constant temperature.

Let's do that: We just agreed that the VBE would be 694 mV at 10 UA at 0 degrees C. How much will VBE change if we then go to 1.8 UA? At 0 degrees C, kt/q isn't 26.06 mV, but 273/300 x 26.06 mV, or 23.712 mV, as the temperature has decreased by that factor. Therefore, as we decrease the current by a factor of 0. 18, the VBE changes by -1.7148 x 23.712 mV, or -40.7 mV, so the VBE decreases to 653.3 mV.

What if we arrive at this point by the other route of first decreasing the current, and THEN decreasing the temperature? We just computed that the VBE at +27 degrees C and at 1.8 UA was 595.3 mV. What is the tempco Of VBE at THIS current? It isn't -2.000 mV/degree C, as it is at 10 uA. And, and it isn't -2.200 mV/degree C like it is at 1 uA. It's at an intermediate value. These slopes are all Proportional To Absolute Temperature, as they intercept absolute zero at 1240 mV. So the slope of (1240 mV - 595.3 mV)/300 degrees C is 644.7 mV/300 degrees C, or -2.149 mV/degree C. If you multiply this tempco by a -27 degree C change, the shift will be 58.02 mV. When you add this to 595.3 mV, the answer is 653.32 mV. So, fortunately, we get the correct answer when we compute it either way.

If you need to know the tempco of VBE, it normally changes - 200 uV/degree C every time the current is reduced by a factor of 10. Thus while the transistor of this example had - 2.000 mV/ degree C at 10 uA, it has - 2.200 mV/ degree C at 1 uA, -2.400 mV/degree C at 0.1 uA, -2.6 mV/ degree C at 10 nA, and -3.0 mV/degree C at 100 PA. While most people don't bias transistors down there, that does NOT mean that the tempco isn't surprisingly well defined down there, and it's a LOT bigger than just -2.0 mV/degree C!

What other factors should we take into account when we want to compute VBE? With monolithic npn transistors, it's fairly safe to assume that the transistors' VBEs are fairly well matched and predictable. We need to only take into account a difference of about 5 or 10 mV, if the transistors are designed with similar geometries. That's even if no special care is taken to match them perfectly. With discrete transistors from the same batch, the matching may be similar, or it might be POOR if the transistors came from different batches. There could be a lot of deviations, but you can't count on that.

As mentioned earlier, the curvature of VBE versus temperature will cause the VBE to be 1 or 2 mV smaller, at 0 degrees C and also at + 70 degrees C, compared to the linear predictions. It could easily be 3 or 4 mV lower at -55 degrees C or +150 degrees C -- it really is quite close to a parabolic eror.

Additionally, Earley Effect will normally cause a low-beta transistor (beta = 50 or 100) to run 1 or 2 mV lower in VBE, if the VCE is as high as 20 V, rather than 0.6 V. On high-beta transistors (beta = 200 or 400), the decrease in VBE may easily run 3 or 4 mV. (At another time, we can discuss the complete ramifications of this Earley Effect. Suffice it to say here, transistors with high beta might have smaller CURRENT errors, but they tend to have correspondingly poorer VOLTAGE errors.)

Of course, if you run the transistor at high currents where V = IE x RE is significant, that effect can be additive (approximately) and is usually fairly linear and predictable (not to mention self-heating). If the IC or IE are small, then the leakages may cause significant deviations. Also, if IE becomes quite small, some transistors may have a rapid fall-off of beta, so you cannot be sure the base current is negligible any more! And if you ever let the transistor saturate, the VBE can rise or fall considerably, depending on how the transistor was made. Still, these graphical techniques can do a pretty good job of helping you to estimate the VBE of a bipolar npn transistor--and of a discrete pnp, too.

Now, you could write a fancy equation to compute all this, but I prefer a graphical approach. That way, I get good insights into what's going on, and I don't get fooled by computational mistakes.

All for now. / Comments invited! RAP / Robert A. Pease / Engineer rap@galaxy.nsc.com -- or:

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P.S. If you really want to use a big unwieldy equation, be my guest:

$$I_C\,(uA) = 99.8 \times 10^9 \times e^{(V_{BE} - I_E \times R_E - 1.240V) \times q/kt}$$

where q/kt = (1/26.06 mV) x (300 degrees Kelvin/t) Of course, your transistor will surely have a scale factor different from 99.8. / rap

(This column was originally published in Electronic Design's *Analog Applications Supplement*, June 26, 2000.)