Int. J. Electron. Commun. (AEÜ) 83 (2018) 398–406

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Regular paper

The current-mode muddle

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ARTICLE INFO

Article history:
Received 19 May 2017
Accepted 6 August 2017

ABSTRACT

With the arrival of monolithic processes for the fabrication of bipolar transistors during the mid-1960s, it seemed like a good time to examine new paradigms for design. Current-mode (CM) was attractive because it suggested that small voltages swings could be used to process analog signals represented as currents; whatever voltages that did arise were treated as *incidental*. These were good ideas at the time. Are they still true today? It is important to know when CM offers a real advantage, to know when it is truly valuable, and to know when it is of only passing and academic interest.

1. Introduction

The year is 1965, about a decade after the conception, by Jean Hoerni at Fairchild, of the planar process for monolithic transistor fabrication; and the year after I joined Tektronix to work on advanced oscilloscope design. The company was now ready to make monolithic circuits in its own dedicated wafer fab. We designers were hardly aware that a revolution in electronics was about to happen.

I was quickly swept up in all the exciting possibilities that monolithic integration afforded; many novel devices and circuits could now be invented and realized. For the first time ever, similar transistors *matched* very well, partly because of the accurate lithography and the fact that they operated at much the same junction temperature. This, in turn, allowed totally new kinds of circuit, compared with what we were used to in discrete form. And unlike vacuum tubes with their lethal supply voltages [1], transistors used safe, low voltages (often with collector-base voltages down even to zero – or even less!) and could handle currents from picoamps up to tens or even hundreds of milliamps.

It was inevitable that, during the coming years, the idea of processing signals exclusively in the current domain took hold. One of the new circuits that quickly gained attention was the ubiquitous current mirror[2], shown in its NPN implementation in Fig. 1a. Here was a simple circuit that could not be realized with tubes, because they were 'depletion mode' devices: they conducted strongly even when their grid-cathode bias was zero. The bipolar junction transistor (BJT) differed in being an 'enhancement-mode' device: hardly any collector current, I_C, flows when the base-emitter voltage, V_{BE}, is zero. And more usefully, I_C increases in a precisely *exponential* fashion as this voltage is increased; this aspect was soon appreciated as the BJT's most potent characteristic. Further, a transistor's collector current can be readily *scaled* higher or lower simply by changing its size. These basic facts, which were apparent years before the arrival of CMOS, were to result in a long list of novel, intriguing and durable cells (see Fig. 2).

As shown, the input of the mirror is the current I_1 and its output is another current, I_2. Textbooks like to point out that $I_2 = I_1 \times A_2/A_1$ where the *A's* are the emitter areas. (Simple analyses assume that the two devices are isothermal, and overlook errors due to the base currents of both devices). But there is an important *voltage* hiding in this 'current-mode' circuit. It appears at the base node, and is generated by I_1 flowing in Q1. This voltage, which falls linearly with temperature (Sec. 2.1) is applied to the base-emitter junction of Q2; which, when isothermal with Q1, generates a scaled output current I_2. Realistically, a positive collector *voltage* at the output will significantly increase this current, due in part to the finite 'Early' voltage of Q2, and sometimes by its own power-induced self-heating. Setting these complications aside for the moment, we can regard this circuit as a 'pure CM' element, because *the input and output are both in current mode.*

But what about that *current source*, I_1? In the literature, it is assumed that one or more of these essential sources can be easily and accurately generated. In fact, they are often lost deep in the analyses, or are accurate only in ratio form. Sometimes, they are *dependent on other currents in the circuit*. They are usually precise only when incidental voltage effects in the CM cells are ignored. And while current sources are widely used for *biasing* purposes, in practice, the need for at least one *voltage* source – the 'supply' – always remains, because there is no way to generate a current

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[1] The two-tube Philbrick op amps used supplies of +/−300 V and consumed 7.4 Watts, mostly in the tube filaments.

[2] Interestingly, tracing the invention of this simple circuit has not found the source. It probably happened at Fairchild soon after their first monolithic process. The author has confirmed that it was neither Dave Fullagar nor Bob Widlar.

https://doi.org/10.1016/j.aeue.2017.08.009
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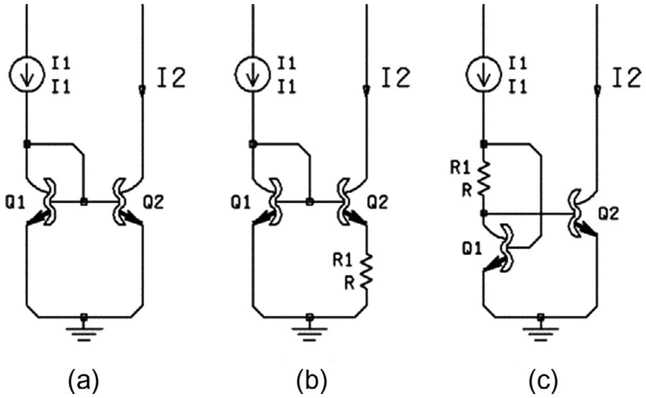

Fig. 1. (a) Basic current mirror (b) First modification (c) Second modification.

without such. It is from such voltages that all of a circuit's currents are derived; which in turn means they are always at the mercy of *ohmic devices* for converting voltages to currents.

Now add a resistor, R, in the emitter branch of Q2 (Fig. 1b). This simple modification is often used when a small current needs to be generated. It forces us to consider the *voltage* across this resistor, because it is *no longer incidental*. Clearly, I_2 will be lower than in the basic current mirror, all things remaining otherwise equal. It transpires that, even with ideal devices, there is no analytic solution for I_2. But when the *desired value for* I_2 is known, a solution for R immediately becomes tractable[3]. Whilst this simple change is useful, we are already beginning to depart from a *pure CM concept*, in view of the fact that, even assuming I_1 is precise, *node voltages* now play an important role in its operation [4].

Moving the resistor from the emitter of Q2 to the collector branch of Q1 (Fig.1c) a simple analytic solution for I_2 is immediately straightforward, given the value of I_1, R and the emitter areas (which for now we will assume to be equal for the two transistors). With this modification, we can make an extremely tiny – nA or less – output current from a substantial sourcing current. But we are now forced to abandon the idea of *pure CM operation*, because we are relying on the specific relationship between the collector *current* and the *voltage* V_{BE}. Before we can analyze this circuit, we need to better understand the BJT. Note in passing that little will be said about MOS realizations of these cell; but such is invariably quite straightforward.

1.1. The ideal BJT transistor

This paper is not intended to discuss subtleties of device physics and behavior, but rather, to reach a general conclusion as to whether there is any special value to CM operation. Accordingly, we will consider the use of the *ideal bipolar transistor* as it relates to the *development of topologies*. The ideal transistor footnote 4 is not limited by its forward current-gain (BF) or Early voltage (VAF); it has no parasitic resistances (RE, RB, RC) nor capacitances (CBE, CBC, CJS). We need to specify the bandgap voltage (EG) and the value of the saturation current (IS) at T = 300 K (it is an extremely strong function of temperature), and we include a finite base transit time (TF) simply to ensure that our circuits are well-behaved in dynamic simulations. Finally, to get $V_{BE}(T)$ closer to a more exact value, we must include the curvature term (XTI). Specific values are provided later.

With its emitter held at zero potential, and the collector-base voltage also close to zero, we apply a small positive voltage V_{BE} to the base terminal and note what happens to I_C. This is called the *normal active region* of operation. The basic relationship [5] is stunningly simple:

$$I_C = I_S \times \exp\left(\frac{V_{BE}}{V_K}\right) \tag{1}$$

Note the symmetry:

I_S is the *scaling current* for I_C while V_K is the *scaling voltage* for V_{BE}. (V_K is the *Kelvin voltage*, or thermal energy, kT/q, approximately 25.85 mV at T = 300 K). But the most notable thing about this expression is the *exponential relationship* of I_C to V_{BE}. This can be regarded as the heart of the BJT; and it has enormous practical value [6].

Why this digression into device theory, in a tutorial discussing the pros and cons of current-mode circuits? The answer (other than wishing to share the sheer beauty of the relationship) is that we find ourselves unavoidably face to face with the concept of *free-mode* design. The BJT is not, as often thought, a current-controlled current source; rather, it is a *voltage-controlled current source*; it is a *transconductance element*, g_m, like a vacuum tube of old (and in typical modes, like CMOS transistors).

Here's another pleasant surprise: by taking the derivative of I_C with respect to V_{BE} we find that the magnitude of the BJT g_m bears this relationship to the collector current:

$$g_m = \frac{I_C}{V_K} \tag{2}$$

Again, we should surely be surprised by the pure simplicity of this statement. Here, even the scaling current I_S is absent. That's good, because it is a messy parameter whose value is minuscule (typically much less than femtoamps) at T = 300 K, and it varies by orders of magnitude over temperature [7]. Most significantly, *the* g_m *is directly proportional to the collector current*, independent of the polarity of the transistor, its physical size, or even the material (germanium, silicon, silicon-germanium, gallium-arsenide, etc.) And we can optionally make this g_m temperature-independent by making I_C proportional to temperature; or, we can make variable-gain cells though controlling this current; and so on.

Eq. (1) can easily be reversed to yield V_{BE} given I_C:

$$V_{BE} = V_K \times log\left(\frac{I_C}{I_S}\right) \tag{3}$$

Refreshed by this 'free-mode' outlook, *attributing equal importance to voltage and current*, we can return to the behavior of the current mirror of Fig. 1c. As before, Q1 is obliged to operate at the supply current I_1; this sets V_{BE1} according to (3). However, the voltage applied to the base of Q2 is reduced by the voltage I_1R. So I_2 has the general form $xe^{-\alpha x:}$

$$I_2 = I_S \times \exp\left(\frac{V_{BE1} - I_1 \times R}{V_K}\right) = I_S \times \exp\left(\frac{-I_1 \times R}{V_K}\right) \tag{4}$$

It is apparent that the output current of this cell can be made tiny for practical values of I_1 and R. Note that, at the unique value $I_1 \times R = V_K$, the output attains its *peak value*: it exhibits a first derivative of zero and thus has no sensitivity [8] to the drive current.

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[3] This is because the describing equation is transcendental; that is, I_2 is equal to a logarithmic term in which I_2 appears again. This simple ruse of reversing Cause and Effect is of great value in numerous cases where the 'forward' analysis hits the transcendental barrier.

[4] Using the standard SPICE names for these basic parameters; of course, we will eventually need to be much more detailed.

[5] Very slightly simplified. At extremely low currents (where V_{BE} V_K) and operating at high temperatures it will be $I_C = I_S$ (exp (V_{BE} / V_K) −1).

[6] William Shockley spent a lifetime considering the complexity of semiconductors materials. That the behavior of the BJT boils down to something so fundamental can only be called remarkable.

[7] If we wish to be sentimental, we might think of I_S as the BJT's 'soul'.

[8] In practice, we can only say that the sensitivity of I_{C2} to I_{C1} is at or near a minimum.