A Review of Self-Heating Effects on Bipolar Circuits

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ABSTRACT — General insights into local-heating effects on the large- and small-signal behaviors of bipolar integrated circuits are provided, and the circuit conditions under which self-heating causes significant errors in simulations are discussed.

INTRODUCTION

Thermal effects can be categorized into three different cases; thermal coupling between two transistors on the same chip [1], package thermal effects which raises the overall temperature of the chip [2], and self-heating [3]. This paper focuses on self-heating effects to help engineers understand and quickly apply this knowledge to practical device characterizations and circuit designs.

Self-heating effects are induced by the thermal spreading impedance which is a strong function of device structure and the material. This heating effect is typically confined within the heat generating transistor itself [4].

Self-heating effects tend to be more significant with current trends in bipolar junction transistor (BJT) design such as reduced geometries and device isolation techniques. Scaling tends to increase the thermal spreading impedance as well as the emitter current density leading toward higher device operating temperature. Also, the trends in device isolation (e.g., trench and SOI) makes self-heating more significant because of the poor thermal conductivity of the SiO_2.

For SOI transistors, the errors in large-signal as well as small-signal performances can be large at the transistor's optimum operation currents ($f_T = f_{Tmax}$). Thermal spreading resistances of these transistors are more than three times higher than that of the junction isolated devices [5].

MECHANISM

As is well known, the BJT performance is strongly temperature sensitive. In the forward active region, an approximated expression for the collector current of the BJT can be given as [6]

$$I_C = I_S\left(1 + \frac{V_{CE}}{V_A}\right) exp\frac{V_{BE}}{V_T} \tag{1}$$

where V_A is the Early voltage considering the electrical effects only, V_{CE} the collector-emitter voltage, V_{BE} the base-emitter voltage, and V_T the thermal voltage. In Eq. 1, the saturation current I_S for an NPN transistor can be expressed as

$$I_S = CD_n n_i^2 \tag{2}$$

where D_n is the electron diffusion constant and n_i the intrinsic carrier concentration. The constant C involve only temperature-independent quantities. As is well known, n_i increases strongly with temperature because of the temperature dependent nature of the energy bandgap and the electron occupation probability of the energy state represented by the Fermi-Dirac distribution function. From Eqs. 1 and 2 (for a fixed V_{BE}) increase in n_i tends to dominate the I_C temperature dependence, although the negative temperature coefficients of D_n and the $exp\,(V_{BE}/V_T)$ term tends to counteract as a second order effects. The approximated expression for the fractional temperature coefficient of I_C is given by [7]

$$D_C \cong T^{-1}\,[3 + (V_{GO} - V_{BE})/V_T] \qquad (3)$$

where T is the absolute temperature and V_{GO} is the bandgap potential which is typically around 1.2V. For moderate currents, 6%/K is a good number to use as a typical value for D_C.

For a base driven by a current source, the relation $I_C = \beta I_B$ shows that the temperature coefficient of the collector current is governed by the temperature dependence of the β. β increases towards high temperatures, and it's behavior is usually explained by the bandgap narrowing effect which leads to the simple relation [8]

$$\beta\,(T) \sim exp\,(-\frac{\Delta E_g}{kT}) \qquad (4)$$

where ΔE_g is an effective value of the bandgap reduction in the emitter and k is the Boltzmann constant.

Due to the heavy-doped emitter, β of scaled devices tends to be more sensitive to temperature variation.

Conversely, bandgap narrowing tends to make the base current less temperature sensitive. The fractional temperature coefficient of the base current is given by $D_B = D_C - D_\beta$ where D_β is the fractional temperature coefficient of β which is typically around 0.7%/K [9].

The incremental rise in device temperature is given by $\Delta T = R_{TH}P \cong R_{TH}I_C V_{CE}$ where R_{TH} is the thermal resistance and P is the power dissipated within the device.

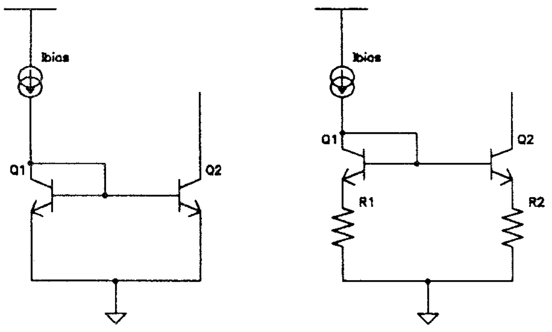
DC

For a base-emitter junction driven by a voltage source, self-heating can significantly increase the collector and base currents as they are controlled by D_C and D_B respectively. If the base is driven by a current source, self-heating increases collector current very slowly because of small D_β while at the same time the base-emitter junction voltage decreases (typically ~ -2mV/K). Therefore, by knowing the thermal resistance, the power dissipated, and the typical values for the temperature coefficient, engineers can easily get a rough estimates of DC errors caused by the self-heating effects.

A simple way to extract the thermal resistance of a transistor is described in [7,10]. The strong dependence of the thermal spreading resistance on the device structure makes a valuable production DC parameter to screen irregularities in device structure (e.g., integrity of the SOI transistor isolation).

As it might be obvious from the above discussion, the presence of resistance at the base and/or emitter terminal tends to reduce the self-heating effects. These resistances have a negative feedback effect to the self-heating effects [11]. In such a case, the temperature sensitivity of the circuit will be somewhere between D_C and D_β depending on the resistance value.

For integrated circuits, DC errors caused by self-heating tends to show predominantly in the bias circuits, especially, the current mirrors [12]. In a simple current mirror, as shown in Fig. 1a, the reference transistor Q_1 provides a fixed voltage. Therefore, transistor Q_2 is in a susceptible condition to self-heating effect. The collector current of transistor Q_2 can be significantly different from what a typical SPICE predicts depending on the current level, collector-emitter voltage, and thermal spreading resistance.



(a) (b)

Fig. 1. Circuit schematics of simple current mirrors.

Often in IC bias circuits, degeneration resistors are included at the emitters of the current mirror (Fig. 1b) to alleviate the process dependent V_{BE} mismatch problem. Note that these emitter degeneration resistors not only help to improve the V_{BE} match and output impedance but also relieves self-heating induced errors.

SMALL-SIGNAL

From a small-signal stand point, the above mentioned DC self-heating effects can be translated into Y-parameters, for a common-emitter structure, given by [9]

$$Y_{mn} = \frac{Y_{mnE} + D_m Z_{TH} I_m I_n}{1 - D_m Z_{TH} P} \qquad (5)$$

where m or $n = 1$ for the base or 2 for the collector, Y_{mnE} is the uncorrected electrical Y-parameter, and Z_{TH} is the thermal spreading impedance. $D_1 = D_B$ and $D_2 = D_C$.

Except at high power levels (although for SOI transistors, even at low power), errors in Y_{11} and Y_{21} induced by self-heating are minor. However, errors in Y_{12} and Y_{22} can be significant even with negligible power and is strongly dependent on collector current [11].

Self-heating effects on Y_{22} can affect the gain as well as stability while Y_{12} can affect the input impedance of an amplifier [13]. Again with base and emitter resistances, the D_m in Eq. 5 is less, so that the net effect on the Y-parameters become less also. The thermally induced components of the Y-parameters eventually becomes negligible as frequency goes up.

From the model parameter extraction point, the self-heating effects on Y_{22}, or g_{22} at low frequencies, can create serious error in Early voltage measurements [14].

It is a common industry practice to measure the Early voltage of the BJTs with the base driven by a current source, while by definition the base-emitter junction should be driven by a voltage source. Considering the electrical effects only, the measured Early voltage for both cases should be close, assuming that the base region recombination current is a negligible portion of the total base current which is true with most of the present BJT technologies. However, in reality, the Early voltage measured under fixed V_{BE} can be significantly lower than the actual electrical Early voltage because of self-heating effects. The time constants of self-heating effects are nano- to microseconds depending on the device sizes. For reasonable size devices, self-heating effects complete in less than 1 milliseconds [14]. Therefore, it is hard to extract the right Early voltage with typical parameter extraction equipments (e.g., HP4145 Semiconductor Parameter Analyzer) avoiding self-heating effects. However, due to the less temperature sensitive nature of BJTs under fixed base current, Early voltage measured in this case can be close to the electrical Early voltage except in the high current region, and that is why the Early voltage is measured with base driven by a current source.

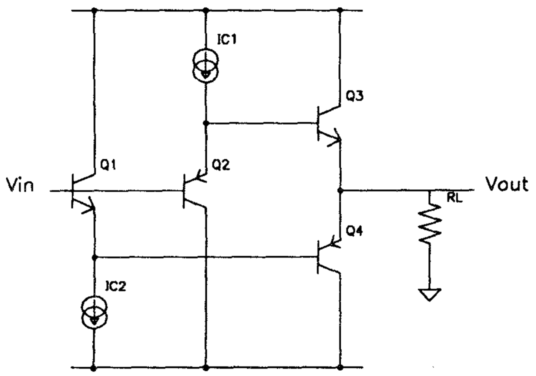


Fig. 2. Circuit schematics of a high speed buffer.

LARGE-SIGNAL

Errors caused by self-heating effects in transient performance of the integrated circuits are mostly limited to precision circuits [11]. However, for some switching circuits, errors can be substantial.

Fig. 2 shows a typical high speed output buffer stage. In Fig. 2, for a step voltage applied at V_{in}, the collector-base voltages of transistors $Q_1 - Q_4$ change by the same amount. The heating or cooling of these transistors change their base-emitter voltages for given collector currents. Therefore, the settling time of this circuit can be significantly degraded by self-heating as thermal transients take a much longer time to settle.

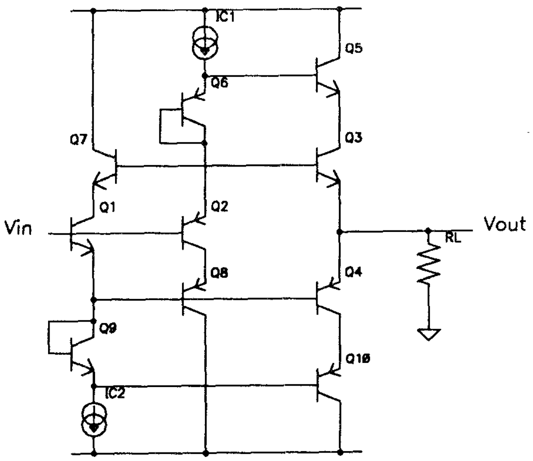


Fig. 3. Circuit schematics of a high speed buffer with self-heating protection.

Fig. 3 shows a buffer circuit mitigating the self-heating problem. As can be seen from the figure, however, the solution hurts the output swing and takes more transistors.

SUMMARY

Self-heating can have significant effects on BJT characterizations and circuit designs. With today's trends of scaling and dielectric isolations in BJT design, knowledge about self-heating effects can be valuable. This paper is written for engineers to help understand the practical aspects of the self-heating effects.

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