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Thermally induced current bifurcation in bipolar transistors

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Abstract

Thermally induced current bifurcation in multifinger bipolar transistors is studied by means of three novel and efficient methods that are based on the same electrothermal model for the low to medium current operation of the device: the limit model, the perturbation model and the FEAT simulation program. The results are substantiated by experimental measurements and numerical simulations. The new analysis techniques have been used to supply detailed information on which parameters, both individual and coupled, influence the current bifurcation and the behavior around the bifurcation point, particularly for the case of two-finger devices. In addition, different bipolar technologies and device designs are compared with respect to electrothermal feedback. It is shown that transistors with a negative temperature coefficient of the current gain (such as SiGe-base devices) made on thermally conductive substrates (such as silicon-on-copper technologies) can be designed to have an electrothermal stability superior to that of other Si bipolar technologies.

Keywords: Bipolar transistor; Current bifurcation; Electrothermal effects; Thermal instability; Thermal resistance

1. Introduction

Electrothermal effects can impose serious limitations on the performance and reliability of bipolar junction transistors (BJTs). When the electrothermal feedback is significant, different forms of thermal instability can be observed, such as thermal runaway [1] or collapse of current gain [2], depending on device nature (homojunction or heterojunction), complexity (single-finger, two-finger, or multifinger) [3–6] or type of biasing (voltage or current control) [4,7,8]. In single-finger transistors, the positive current–temperature feedback can create conditions in which device currents are not controlled by the applied voltages. This can cause an enormous increase in current, which is referred to as "thermal runaway" or "thermal breakdown". The electrothermal behavior is particularly intricate in multifinger structures, where the temperature profile and current distribution are governed by thermal coupling between elementary transistors (individual fingers) and structural asymmetries. This leads to a non-uniform current distribution between the fingers, which in turn can lead to a thermal instability where the hottest finger drains all current from the other fingers. The point at which this occurs is commonly known as the bifurcation point. Measurements show that even for symmetrical structures like two-finger devices, the total current is not equally divided between the fingers for every biasing condition. For optimization of device and circuit designs, it is essential to understand and control the mechanisms that lead to thermally unstable operation.

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In this paper three novel methods, each with a different level of accuracy and complexity, are presented for studying thermally induced current instability in two-finger bipolar transistors that are operated in the low to medium current regime. All three methods are based on the same simple and accurate electrothermal model that is designed to account for thermal coupling effects and temperature dependence of the current gain. The first and most straightforward method is analytical and uses the so-called "limit" model. It retains the simplicity of previously proposed analytical methods, such as given in [3], but since it is based on a much more complete electrothermal model it gives a very accurate prediction of the bifurcation point. For this calculation ideally matched fingers must be assumed and in this case there is an abrupt transition from stable to instable operation at the bifurcation point. The second more complex but still analytical method uses a perturbation model in such a way that it is possible to calculate the influence of physical differences between the fingers on the bifurcation point. Thirdly, an efficient and versatile computer program, FEAT (Fast Electrothermal Analysis of bipolar Transistors), for electrothermal simulations of multifinger BJTs has been developed. With this program the electrothermal behavior can be predicted in the whole region of operation, and it is specifically used in this paper to substantiate the results of the two analytical methods as well as to give insight into the significance of the bifurcation points predicted by the models. The results of the computer program are supported by numerical simulations performed by Silvaco's 2-D ATLAS simulator [9] and experimental measurements on silicon-on-glass NPN bipolar transistors. These devices can be surrounded entirely by materials such as oxide and glass that are both electrically and thermally isolating. The resulting high thermal resistance has in the past also been used with profit to study electrothermal effects [6,10–13]. Here we particularly investigate the influence of device model parameters, design and technology on electrothermal stability. Different device categories are studied: both Si and SiGe devices are characterized and a comparison is made between bulk-silicon, silicon-on-insulator, silicon-on-glass [14], and silicon-on-copper [15] technologies.

2. Experimental procedures

To support the modeling, measurements are performed on silicon-on-glass NPN BJTs, a schematic cross section of which is given in Fig. 1. The electrical parameters of the BJT model were extracted from isothermal (pulsed) characteristics of single-finger devices with an emitter area of $20 \times 1\ \mu m^2$, while the self-heating thermal resistance and the mutual thermal coupling resistance have been measured on two-finger test structures with an emitter area of $2 \times (20 \times 1)\ \mu m^2$ using the lock-in measurement technique proposed in [16]. All the measurements are performed on a Cascade probing station equipped with a temperature-controlled chuck, an HP4156B parameter analyzer, and an Agilent 85124A pulse-measurement system.

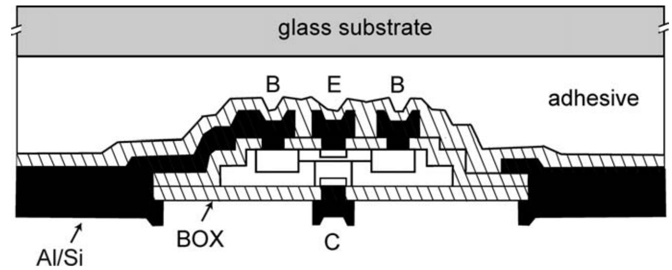

Fig. 1. Schematic cross section of a silicon-on-glass NPN bipolar transistor.

3. Electrothermal model

In Fig. 2 a schematic of the basic BJT device nomenclature (a) is given along with a block diagram of a two-finger bipolar transistor (b). Moreover, this figure includes a graph illustrating the behavior that is typical of the currents I_{C_1} and I_{C_2} versus the total collector current I_{CTOT} in a current-controlled two-finger transistor (c).

The electrothermal interactions in BJTs operated in forward active mode are modeled in this paper specifically through effects of the temperature on the base current I_B

$$I_B = I_{B0} \exp\left(\frac{V_{BEI} + \varphi_{BE}\Delta T}{nV_{T0}}\right), \tag{1}$$

and the current gain β_F

$$\beta_F = \beta_F(T_0) + K_\beta \Delta T = \beta_{F0} + K_\beta \Delta T. \tag{2}$$

The collector and emitter currents I_C and I_E, respectively, are related to I_B and β_F as

$$I_C = \beta_F I_B, \tag{3}$$

$$I_E = I_C + I_B. \tag{4}$$

The V_{BEI} is the internal base–emitter voltage which, according to Fig. 2(a), can be expressed as

$$V_{BEI} = V_{BE} - r_B I_B - R_B I_B - r_E I_E - R_E I_E, \tag{5}$$

where r_E and r_B are the internal (parasitic) emitter and base series resistances, and R_E and R_B the external (ballasting) emitter and base resistors. I_{B0} is a temperature-independent pre-exponential factor, $V_{T0} = kT_0/q$ the thermal voltage at room temperature T_0, $\Delta T = T - T_0$ the increase of the junction temperature, n the ideality factor, $\varphi_{BE} = \left|\frac{\partial V_{BEI}}{\partial T}\Big|_{I_B}\right|$ the absolute value of the temperature coefficient of V_{BEI} for a fixed I_B, $\beta_{F0} = \beta_F(T_0)$ the current gain at room temperature and K_β is a fitting parameter [5]. In silicon homojunction transistors, β_F increases with temperature at medium currents due to bandgap narrowing in highly doped emitters [17,18]. On the other hand, in most heterojunction bipolar transistors (HBTs) it decreases with temperature due to the difference in bandgap of the emitter and base materials [19–26]. Typically, the gain dependence on temperature can be accurately described through an exponential relationship. Assuming that the devices under analysis operate in a limited range of temperatures and