Electrothermal Limitations on the Current Density of High-Frequency Bipolar Transistors

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Abstract—In this paper, electrothermal consequences of downscaling bipolar transistors, reducing the emitter resistance and implementing substrate modifications are examined by means of electrical measurements, numerical simulations and analytical calculations. A formulation is given for the optimum current density that can be run through the device and still maintain both sufficient transconductance and thermal stability. This expression sets a theoretical limit on the current density and therefore also on the speed of the given technology node. Particularly the lowering of the emitter resistivity is a trade-off between transconductance and thermal stability, and the optimum choice can be estimated from these results along with the maximum emitter area that will allow unconditional thermal stability.

Index Terms—Bipolar transistors, emitter resistance, high-frequency (HF) technologies, silicon-on-glass, thermal instability.

I. INTRODUCTION

TO INCREASE the speed and overall performance of high-frequency (HF) silicon bipolar devices and circuits, the microelectronics industry is continually investing in the downscaling of devices fabricated on the surface of silicon wafers. The present trends for emitter area downscaling and current densities at maximum cut-off frequency $f_{T,\max}$ are displayed in Fig. 1, where it is clear that there is an almost linear relationship between the current density J_C at $f_{T,\max}$ and the $f_{T,\max}$ itself. Thus, to achieve the higher speed, higher current densities are being implemented [1]–[8]. The achievable currents are directly limited by the emitter contact series resistance, which is inversely proportional to the emitter area. In bipolar devices it is therefore particularly important to develop techniques that reduce the specific emitter resistivity [9]. However, the trade-offs for high collector current and low emitter resistance are twofold. For the first, the power dissipation and corresponding self-heating in the device is high, and second, in the absence of series resistors the electrothermal feedback is stronger and the device is more prone to thermal breakdown [10].

In this paper, the trade off between device speed and thermal stability is evaluated quantitatively by establishing a set of simplified analytical formulas for the collector current/thermal breakdown relationships. The presented calculations show that the electrothermal limitations on the current density, and thus also the device speed, can become quite severe in future

device generations. The situation is particularly critical because of the need in HF circuits to eliminate both electrical device and circuit parasitics. Many substrate modification techniques are being introduced to improve transistor speed, improve the quality of integrated passives and reduce crosstalk. These include shallow and deep trench isolation, silicon-on-insulator (SOI) processes and substrate transfer [11], [12]. In all these methods, the electrically conductive silicon is replaced by electrical insulators that, unfortunately, also are very good thermal insulators and the thermal resistance of the devices can become forbiddingly high. The thermal resistance of several different device structures is estimated by simulations and the associated thermal instabilities are evaluated by correlating to measurements of bulk-silicon and silicon-on-glass transistors. The silicon-on-glass NPN BJTs are thoroughly described and experimentally investigated in [13]. Together with data recently published on today's most advanced silicon devices, the experimental results on the silicon-on-glass transistors are used to support the analysis and calculations.

II. SELF-HEATING AND THERMAL BREAKDOWN IN BJTs

In the following, very simple electrothermal relationships are applied to arrive at an equally simple analytical formulation that describes how the current through a device is limited by self-heating and/or emitter resistance. When the structure of the device is well known and the thermal resistance can be accurately determined, it is possible to extend the present analysis by using more accurate but also more complicated formulations of the thermal resistance [14], [15]. Here we limit ourselves to first-order approximations. Hence, the thermal resistance R_{TH} of a bulk bipolar transistor is related to the emitter area A_E and the thermal conductivity k_{bulk} of the bulk material by the simple equation [14]

$$R_{TH} = \frac{1}{4k_{\text{bulk}}\sqrt{A_E}}. \quad (1)$$

The power P dissipated in the device is related to the power density p as $P = A_E p = A_E J_C V_{CE}$, where J_C is the collector current density and V_{CE} the collector–emitter voltage. Thus the temperature increase above ambient ΔT is related to J_C as

$$\Delta T = R_{TH} P = R_{TH} A_E p = \frac{p\sqrt{A_E}}{4k_{\text{bulk}}} = \frac{J_C V_{CE} \sqrt{A_E}}{4k_{\text{bulk}}}. \quad (2)$$

This equation is used to calculate the ΔT at $f_{T,\max}$ in Fig. 1. For a constant power density, a reduction in device size would reduce the self-heating. However, due to the trend to increase power density to achieve higher f_T as shown in Fig. 1, the

Manuscript received June 14, 2004; revised October 11, 2004. The review of this paper was arranged by Editor V.R. Ramgopal.

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Digital Object Identifier 10.1109/TED.2004.839754

Fig. 1. Emitter area A_E , peak cut-off frequency $f_{T,max}$ and approximated temperature increase at $f_{T,max}$, ΔT_{fTmax} , versus current density $J_{C,fTmax}$ at $f_{T,max}$ for recently published Si and SiGe transistors [1]–[8].

self-heating increases despite reduction in the device size. In addition, for most modern devices the R_{TH} cannot be approximated by such simple formulations, since for example effects of shallow and deep trench isolation, and buried oxide have to be taken into account [14]. In order to give an illustration of the effect of the substrate modifications and packaging on the self-heating, two-dimensional numerical thermal simulations are performed in Femlab [16] and the results are shown in Fig. 2. The bulk-silicon technology in Fig. 2A is compared to the bulk-silicon technology with deep trenches in Fig. 2B, SOI technology without and with trenches in Fig. 2C and Fig. 2D respectively, and silicon-on-glass technology [11] in E. It can be seen that as the electrical isolation gets better, the thermal resistance gets undesirably high. Good heat sinking is often implemented in the packaging. This is particularly effective if the bulk silicon is replaced by a better thermal conductor as in F where a silicon-on-glass technology with copper heat-sink is represented. Here the thermal resistance becomes lower than the bulk silicon value. Such a technology is successfully implemented in experimental silicon-on-glass BJTs [12] and silicon-on-glass power MOSFETs [17]. Although the simulated structures are very simplified and three-dimensional effects are not included, the trend in self-heating is overly clear and illustrates the enormous significance of the device geometry

Fig. 2. Numerically simulated temperature increase with respect to ambient for different technologies. The temperatures are calculated for the same input power and normalized to ΔT of A.

Fig. 3. Schematic cross sections of experimentally studied bulk-silicon and silicon-on-glass NPN BJTs from the same processing line. For more details on the silicon-on-glass processing and silicon-on-glass NPN BJT architecture refer to [13].

and surrounding on the electrothermal limitations described below.

The electrothermal interaction in bipolar transistors can lead to thermal instability [18], [19] and dynamic temperature-current positive feedback can even result in destructive thermal breakdown [20]. Experimental Gummel plots of the bulk-silicon and silicon-on-glass NPN BJTs [13] with schematic cross sections given in Fig. 3 and an emitter area A_E of $20 \times 1 \mu\text{m}^2$ are shown in Fig. 4(a). In the silicon-on-glass transistor the thermal breakdown is seen as a sudden increase in the collector and base current. By assuming that the collector current ideality factor is

Fig. 4. Measurements of the transistors shown in Fig. 3. (a) Gummel plots of a bulk-silicon (dashed lines) and silicon-on-glass devices (solid lines), and (b) Gummel plots of the silicon-on-glass device for several externally added emitter series resistors R_E . Emitter area is $20 \times 1 \mu\text{m}^2$.

1, the collector current density at the onset of thermal breakdown, $J_{C,\text{crit}}$, can be calculated by [18]

$$J_{C,\text{crit}} = \frac{I_{C,\text{crit}}}{A_E} = \frac{\frac{V_T}{A_E}}{|\varphi|V_{CE}R_{TH} - R_\Sigma} \quad (3)$$

where $V_T = kT/q$ (≈ 26 mV) is the thermal voltage, φ the base-emitter voltage temperature coefficient (≈ -1 mV/K) and $R_\Sigma = R_E + r_e$ the equivalent electrical emitter resistance, including the internal r_e and externally applied R_E resistance terms. The internal resistance r_e is usually expressed in terms of the specific emitter resistivity $r_{es} = r_e A_E$ in $\Omega\mu\text{m}^2$, which is a technology parameter. From device measurements, the thermal resistance is determined to be about 10 000 and 300 K/W for the silicon-on-glass and bulk-silicon device, respectively. For $V_{CB} = 2$ V and $R_\Sigma = 2 \Omega$ this gives $I_{C,\text{crit}} \approx 1$ mA for the silicon-on-glass device and unconditional stability for the bulk-silicon transistor since $|\varphi|V_{CE}R_{TH,\text{bulk}} - R_\Sigma < 0$.

The series resistance R_Σ introduces negative feedback, which thermally stabilizes devices [10]. This effect is illustrated in Fig. 4(b), in which experimental Gummel plots of the silicon-on-glass device are shown for different R_E s. The voltage drop across the emitter series resistance also reduces the current-normalized transconductance g_m

$$\frac{g_m}{I_C} = \frac{1}{V_T + I_C R_\Sigma}. \quad (4)$$

Fig. 5. Current-normalized transconductance versus collector current density for different values of specific emitter resistance. External emitter series resistance R_E is neglected. $J_{C,\text{max}}$ is highlighted by the filled circles.

For most applications a (g_m/I_C) value of about half the maximum value (for $R_\Sigma = 0$) is still useful. Therefore the quantity

$$G = \left(\frac{g_m}{I_C}\right)_{\min} = \frac{1}{(2V_T)} \approx 20 \text{ V}^{-1} \quad (5)$$

is introduced here as a lower limit on the current-normalized transconductance [21]. The maximum current density at which (g_m/I_C) is above or equal to 20 V^{-1} for a given R_Σ , is evaluated from (4) and (5) as

$$J_{C,\text{max}} = \frac{1 - V_T G}{A_E R_\Sigma G}. \quad (6)$$

From Fig. 5 it is clear that as the series resistance gets higher, the $J_{C,\text{max}}$ gets lower. Therefore, for operation at very high current densities, which is typical for modern HF devices, the series resistance must be minimized [22]. For instance, to reach the highest achieved $f_{T,\text{max}}$ of 350 GHz, the $J_{C,fT\text{max}}$ needs to be as high as $20 \text{ mA}/\mu\text{m}^2$. Even in the absence of any external emitter resistance, i.e., for $R_E = 0$, such a high current density will limit (g_m/I_C) to below 20 V^{-1} if the technology advances do not allow r_{es} to be reduced to $1.2 \Omega\mu\text{m}^2$. For such a low value of r_{es} , the negative feedback in the emitter is almost completely suppressed, which directly means that the electrothermal feedback is significantly increased.

III. ANALYTICAL FORMULATIONS OF $A_{E,\text{crit}}$ AND $J_{C,\text{opt}}$

In the analysis in this section it is assumed that the external emitter resistance R_E is negligible, thus $R_\Sigma = r_e = r_{es}/A_E$. According to (3), the thermal instability occurs only if $|\varphi|V_{CE}R_{TH} - R_\Sigma > 0$. Therefore, with the expression for R_{TH} given by (1), the maximum emitter area $A_{E,\text{crit}}$ for which the device is unconditionally thermally stable for given r_{es} , k_{bulk} and V_{CE} is expressed by

$$A_{E,\text{crit}} = \frac{16}{\varphi^2 V_{CE}^2} k_{\text{bulk}}^2 r_{es}^2. \quad (7)$$

This means that a device with $A_E \leq A_{E,\text{crit}}$ cannot be driven into thermal breakdown. Otherwise, for $A_E > A_{E,\text{crit}}$ the thermal breakdown occurs for $J_{C,\text{crit}}$ defined by (3).

From (3) and (6) it is shown that while lowering the emitter resistance increases $J_{C,\max}$, it will decrease $J_{C,\text{crit}}$. Therefore, there is an r_{es} for which $J_{C,\max} = J_{C,\text{crit}}$. This defines an optimum value for the specific emitter resistivity $r_{\text{es,opt}}$, which optimizes the allowable current density $J_{C,\text{opt}}$ of a bipolar transistor for given A_E , V_{CE} , and R_{TH}

$$r_{\text{es,opt}} = A_E V_{\text{CE}} R_{\text{TH}} \varphi (1 - G V_T) \quad (8)$$

and

$$J_{C,\text{opt}} = \frac{1}{A_E G \varphi V_{\text{CE}} R_{\text{TH}}} \quad (9)$$

The $J_{C,\text{opt}}$ is the optimum current density of a single-finger HF bipolar transistor made in a given technology node. Keeping emitter area constant while reducing the specific emitter resistivity below $r_{\text{es,opt}}$ is not beneficial for the speed of BJTs: for $r_{\text{es}} \leq r_{\text{es,opt}}$ the current is limited by the thermal instability to $J_{C,\text{crit}} \leq J_{C,\text{opt}}$, while for $r_{\text{es}} \geq r_{\text{es,opt}}$ the current is limited by $(g_m/I_C)_{\min}$ to $J_{C,\max} \leq J_{C,\text{opt}}$.

In a multifinger device, the mutual thermal coupling resistance R_M between the neighboring device fingers is very important for the thermal stability. Moreover, in such devices, the $J_{C,\text{crit}}$ depends on the type of biasing [23]. If the thermal interaction between more distant fingers is negligible, (9) can be written to include the effect of R_M

$$J_{C,\text{opt}} = \frac{1}{A_E G \varphi V_{\text{CE}} (R_{\text{TH}} \pm R_M)} \quad (10)$$

where $+$ and $-$ corresponds to voltage-controlled and current-controlled biasing, respectively.

IV. DISCUSSION

In this section, the simple analytical formulations established in (1) to (10) are applied for a number of different device and technology parameters. First, r_{es} is set to $10 \Omega \mu\text{m}^2$, V_{CE} to 2 V and φ to -1 mV/K , and the critical area expressed by (7) is plotted in Fig. 6(a) versus the thermal conductivity of the substrate k_{bulk} . A device with an emitter area smaller than $9 \mu\text{m}^2$ is unconditionally stable for bulk-silicon technology. On the other hand, if a device is completely surrounded by glass, the critical area is almost four to five orders of magnitude smaller. The figure shows that a small device, which is theoretically not prone to thermal breakdown if made in bulk-silicon technology, can experience instability problems if made in the trench-isolated, SOI or especially silicon-on-glass technology. Also, replacing the silicon wafer with a more thermally conducting substrate like copper [24], lowers the thermal resistance and can be beneficial for thermal stability of large transistors.

In Fig. 6(b) $A_{E,\text{crit}}$ is plotted as a function of r_{es} for devices surrounded by either glass or silicon. For the measured silicon-on-glass and bulk-silicon devices from Figs. 3 and 4 the r_{es} is $40 \Omega \mu\text{m}^2$, which corresponds to $A_{E,\text{crit}}$ (silicon) = $144 \mu\text{m}^2$ and $A_{E,\text{crit}}$ (glass) = $0.007 \mu\text{m}^2$. Therefore, the device with $A_E = 20 \mu\text{m}^2$ is unconditionally stable in bulk-silicon technology, while it suffers from the thermal breakdown if made in silicon-on-glass technology. For the most advanced device from Fig. 1 with $A_E = 0.3 \mu\text{m}^2$, $f_{T,\max} = 350 \text{ GHz}$, $J_{C,fT\max} =$

Fig. 6. Maximum emitter area for which a bipolar transistor is thermally stable (a) versus thermal conductivity of the substrate for a fixed specific emitter resistivity and (b) versus specific emitter resistivity for silicon and glass substrate materials.

Fig. 7. Current densities $J_{C,\max}$ (dashed line) and $J_{C,\text{crit}}$ (solid lines) versus specific emitter resistivity for three different emitter areas, and for both silicon and glass substrates.

$20 \text{ mA}/\mu\text{m}^2$ and r_{es} of $1.2 \Omega \mu\text{m}^2$, (3) and (7) yield $J_{C,\text{crit}}$ (silicon) = $41.5 \text{ mA}/\mu\text{m}^2$ and $A_{E,\text{crit}}$ (silicon) = $0.13 \mu\text{m}^2$. In Fig. 7 $J_{C,\text{crit}} - r_{\text{es}}$ and $J_{C,\max} - r_{\text{es}}$ characteristics defined by (3) and (6) are plotted versus r_{es} . For the bulk-silicon device with $A_E = 0.3 \mu\text{m}^2$, (8) and (9) yield $r_{\text{es,opt}} = 1 \Omega \mu\text{m}^2$ and $J_{C,\text{opt}} = 27.5 \text{ mA}/\mu\text{m}^2$. The 350-GHz device has parameters approaching these values.

Fig. 8. Calculated optimum current density of two-finger (solid lines) and single-finger (dotted lines) devices. The effect of the finger pitch d on $J_{C,opt}$ is plotted for two-finger devices in both voltage- and current-controlled biasing conditions.

The mutual thermal coupling R_M from (10) is approximated by a point-to-point thermal resistance [14] $R_M = 1/(2\pi k_{sub}d)$, where d is the pitch between the neighboring fingers. As an example, single-finger transistors with A_E of 20 and $0.3 \mu\text{m}^2$ are compared to two-finger devices with A_E s equal to $2 \times 10 \mu\text{m}^2$ and $2 \times 0.15 \mu\text{m}^2$, respectively. The optimum current densities are calculated versus the finger pitch for both the voltage- and current-controlled biasing, and are compared to $J_{C,opt}$ of the corresponding single-finger transistor in Fig. 8. If a current-controlled biasing is used, splitting a single-finger transistor into a two-finger device results in an increase in the $J_{C,opt}$ regardless of the value of the pitch. For this type of biasing, bringing fingers closer to each other results in a significant increase of $J_{C,opt}$, and is also beneficial for reducing the device area. On the other hand, if a voltage-controlled biasing is used, the $J_{C,opt}$ increases for a large finger pitch, but reducing the distance between the fingers in order to decrease the total area of the device, can result in a decrease of $J_{C,opt}$, which can eventually become lower than that of the single-finger device.

V. CONCLUSION

From the above analysis, it becomes clear that the speed requirements of advanced bipolar transistors is driving the emitter dimensions and resistance into a region where the very high power densities and the significant thermal resistances will lead to significant device self-heating and detrimental electrothermal feedback. These thermal effects set a maximum current for the safe operating region of the device, which can be extremely low for devices isolated on all sides by dielectrics. For more conventional bulk-silicon devices the maximum current is orders higher but the presented theory predicts that the limit on the current density of high-frequency bipolar devices will, before too long, be set by electrothermal effects.

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