Investigation of Thermal Crunching Effects in Fishbone-Type Layout Power GaAs-HBTs

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Abstract— **Thermal current crunching in power HBTs is investigated by numerical simulation. Compact electro-thermal models are connected in parallel, thermal interaction is accounted for by a thermal resistance matrix. It turnes out that the dominant effect in HBTs of fishbone-type layout is that half of the HBT is effectively switched off. This can only be simulated by a slightly asymmetric model.**

I. Introduction

Thermal current crunching is an important factor that limits the power performance of HBTs. At high dissipated powers, the current concentrates on a small part of the emitter area. The reason is the positive feedback effect, since at constant base-emitter voltage, the current rises with temperature, which in turn increases dissipated power. This leads to a further increase of current, and so on. This hot-spot formation is expected to occur in the centre of a large transistor, since this is the location with worst heat dissipation and thus highest temperature.

Microwave power HBTs are usually composed of small-sized HBT cells connected in parallel. Since these HBT fingers heat up mutually, eventually hot-spot formation takes place [1]–[5]. The hot spots are expected to occur in the center of the device, since the thermal resistance there is higher than at the edges, where the heat is spread to the sides too. However, a certain threshold is necessary for the thermal current crunching to occur.

Several countermeasures are applicable to improve the thermal stability and to increase this threshold. The first one is to introduce a feedback resistor at base or emitter of each HBT finger. This ballasting resistor reduces the internal base-emitter voltage with increasing current, therefore partially compensating the positive thermal feedback effect. Another means is to reduce the HBT's thermal resistance and thereby the self-heating. A comparably simple solution would be to distribute the HBT fingers on a larger area than necessary without thermal effects. The heat then is generated over a larger volume, thermal interaction and also thermal resistance are reduced.

However, reducing thermal interaction is dangerous, as shown in [5]. The reason is that the temperature-current relation is given by a non-linear function which has multiple solutions above a certain temperature. Low thermal interaction allows for high temperature differences between distant parts of the transistor. As a result, the lack of thermal interaction even enhances hot-spot formation. Accordingly, strong thermal coupling of the HBT fingers is necessary to equalize the temperature distribution, by a so-called thermal shunt.

In this paper, a typical fish-bone type power HBT is investigated. In this layout, the HBT fingers are arranged in two parallel rows. Additionally to the thermal crunching due to mutual heating as investigated in [1]–[4], also asymmetric hot-spot formation resulting from insufficient thermal coupling of the two rows is investigated because it plays an important role in this layout.

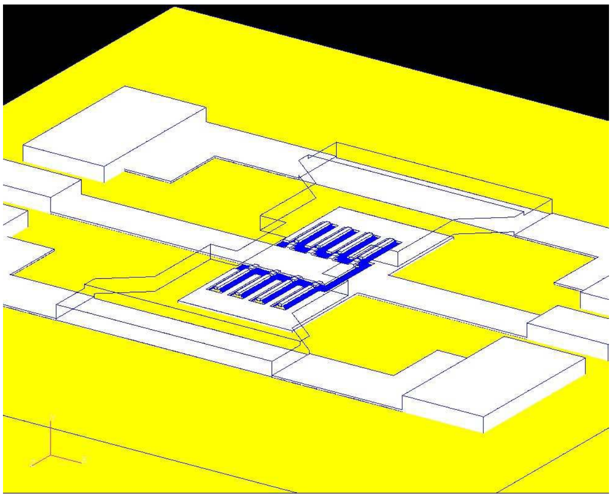

Fig. 1. Schematic of HBT structure in coplanar environment for thermal simulation. The emitter air bridge is transparent so the eight emitter fingers in two rows can be seen.

II. The HBT and its Model

The work focuses on the thermal requirements of power HBTs for base-station applications operating at 27 V, similar to the devices reported in [6]. The high dissipated powers require significantly more care in thermal handling of the devices compared to common 3 V operation. Emitter air-bridges are employed for thermal management, which provide thermal coupling between the fingers and improve heatsinking. Air bridges of 5 μm and 20 μm thickness are investigated. The layout of the HBT is shown in Fig. 1. It consists of eight HBT cells, each with an emitter size of $3{\times}70\,\mu\mathrm{m}^2$, which are electrically connected in parallel. The layout is in two parallel rows, therefore the thermal coupling between the two rows is less than between the HBT cells within a row, depending on the thickness of the emitter air-bridge.

The modelling approach is similar to [1]–[4]. Compact electro-thermal HBT models [7] with each of them describing a single HBT finger are connected in parallel. The thermal interaction is accounted for by a thermal admittance matrix $\mathbf{Z}_{\mathrm{th}}$, see Fig. 2. It connects the vector of the power dissipation of the HBT cells $\vec{P}$ with the vector of temperature offset due to self-heating $\vec{\Delta T}$. Mutual self-heating at known power dissipation is given by: $\vec{\Delta T} = \mathbf{Z}_{\mathrm{th}} \cdot \vec{P}$. The thermal resistance matrix is determined by numerical thermal simulations using a commercial code. The simulated transistor geometry is shown

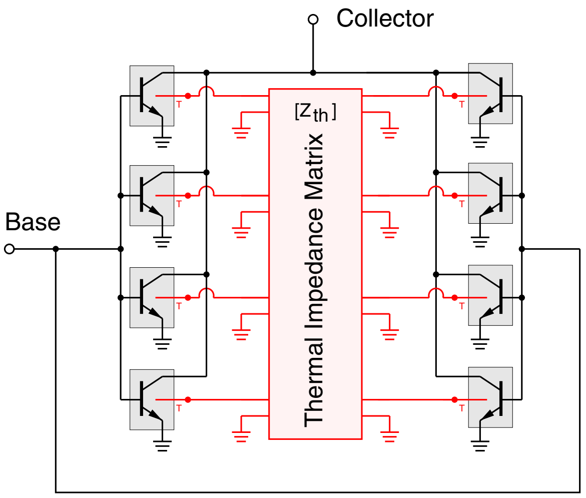

Fig. 2. Circuit diagram of the eight-finger HBT in common emitter configuration. The emitter fingers are connected electrically in parallel, thermal interaction is accounted for by the thermal impedance matrix.

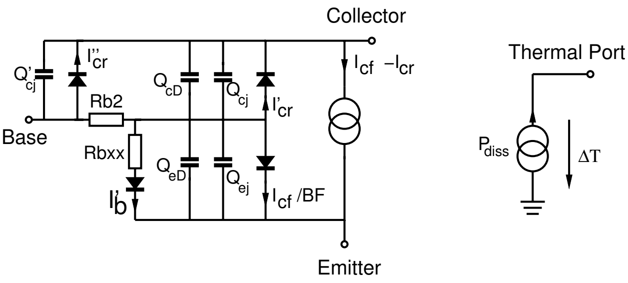

Fig. 3. Equivalent circuit of an intrinsic HBT cell.

in Fig. 1. The matrix elements of $\mathbf{Z}_{\rm th}$ are determined by subsequently introducing an additional heat load to every single HBT finger and simulating the resulting temperature increase at all HBT fingers compared to the case of equal load to all HBT fingers. To enhance the large-signal model stability and to simplify the simulations, constant values for the thermal conductivities κ are assumed. In order to account for the fact that the thermal conductivity increases with temperature, the value of κ at the highest dissipated power levels is employed in all cases. It has been observed that the errors in the simulation at lower dissipated powers are of minor influence. It should be noted that the steep increase in thermal resistance $R_{\rm th}$ which sometimes is observed in parameter extraction for a lumped transistor model, is caused by hot-spot formation. The exponential increase of $R_{\rm th}$ then is due to concentration of the current to the hot-spot, which is an effective reduction of the total emitter area. This effect is accounted for in this distributed model, since it is capable to reproduce the current crunching and hot-spot formation. Thermal capacitances are introduced to decouple the low-frequency signals which contribute to self-heating and the microwave signals which do not. In the present investigation, only the decoupling is important, not an accurate model of the thermal dispersion effects.

The HBT cells are modeled by the FBH HBT model [7], [8], that supports partition of intrinsic and extrinsic base-collector diode, non-ideal base currents, self-heating, current-dependence of base-collector capacitance and collector transit time (i.e. velocity modulation and Kirk effect). The intrinsic equivalent circuit is shown in Fig. 3. The diode currents depend on temperature by the following formula

$$I = I_s\, e^{(V_g/V_{th,0} - V_g/V_{th})} \left(e^{V/(nV_{th})} - 1\right) \qquad (1)$$

with the saturation current I_s, an activation energy $E_g = V_g/q$, the thermal voltage at junction temperature V_{th} and that at a reference temperature $V_{th,0}$, the ideality factor n, and voltage V. The modeled current gain decreases linearly with temperature.

The main effect, however, is that the collector current I_c depends approximately exponentially on temperature. This leads to significant differences in the temperature of the HBT cells, while the applied voltages are fixed for all.

There are two effects that lead to hot-spot formation, resulting in the current crunching effect.

- Self-heating inside the HBT will always be stronger than at the edges. This is simply due to the fact that the outer HBT cells can spread their heat to the surrounding material, while the inner cells are surrounded by other heat sources. This is easily implemented in the model, by means of thermal coupling resistances between the HBT cells, and by higher values of the thermal resistances of the inner cells. It is therefore easily simulated with the distributed thermal model in a circuit simulator. From this effect, one can expect that the two inner cells of both rows (cf. Fig. 1) are at a higher temperature from the beginnig, and take over most of the current beyond a certain threshold. In this case, the effect is symmetrical, and the hot-spot consists basically of two hot-spots centered on both rows.
- The other effect is described in [5]. Above a certain theshold, there is more than one possibility to obtain a certain amount of total collector current from a number of HBT cells which are electrically in parallel. However, it is necessary for the cells to have high differences in temperature in that case. Since the current depends exponentially on temperature, it may be possible for a single cell which is hotter than the others to take over almost all current. This effect is essentially non-symmetrical and will happen in each layout, even in perfectly symmetrical ones, provided that the thermal coupling between the individual HBT cells is weak enough to allow for significant differences in the temperature. The asymetrical hot-spot formation will be dominant in real transistors, but in circuit simulators it might not be discovered. Since the models usually are perfectly symmetrical, the simulator only finds the symmetrical solution without hot-spot, which is in reality highly unstable.

In order to be able to observe the non-symmetrical effect in the simulation, the thermal resistance at one finger was increased by a small amount (less than 3%). This slight asymmetry allows the circuit simulator to prefer an asymmetric current distribution over the perfect symmetrical one whenever possible, as it would happen in reality as well, where slight perturbations of symmetry are always present.

III. Results

Typical output I-V curves of a power HBT are shown in Fig. 4. All curves are simulated using the above-described model for HBTs with the same layout, eight emitter fingers arranged in two rows. The current gain decreases continuously due to self-heating until it drastically breaks down due to current crunching.

Three cases are plotted in this figure: the less thermally stable HBT only has an emitter resistance per emitter finger R'_e of 2.5 Ω, and an emitter air bridge of 5 μm thickness (solid lines). Increasing R'_e to 6 Ω (broken lines) clearly enhances thermal stability. However, the device is thermally stable in the entire range of operation only when the emitter air bridge is increased to 20 μm.

The nature of the current crunching can be investigated observing the current that flows through each of the HBT fingers. Fig. 5 shows the result for the HBT with R'_e of 2.5 Ω and 5 μm thick air bridge. The summation of the currents in this graph yields the middle branch of the IV curve shown in Fig. 4. Three different regions are observed, as indicated in the figure.

1) At lower dissipated powers, the current distribution is symmetrical. But the fingers in the middle of each row have higher thermal resistances and therefore carry more current than those at the edges of each row.
2) If a certain level of dissipated power is reached, the current concentrates on a single row only. The other half of the transistor is effectively switched off, even if the temperature at the hottest spots there was only slightly less than the counterpart on the other side. This is a dynamic process with the result that the warmer fingers on one row are switched off together with the colder ones, while the current through the colder ones of the other row increases. This asymmetric effect as predicted in [5] takes place in real transistors, but is disguised when a perfectly symmetrical model is employed. This is also shown in Fig. 5. The dotted lines represent simulation results obtained from a perfectly symmetrical model. It is observed, that the two fingers in the middle of each row always draw a higher current and therefore are warmer, but the device operation seems to be stable. Only the slight asymmetry of the model reveals that this solution in reality is highly unstable. It is, therefore, crucial to obtain realistic results.
3) If the voltage is further increased, thermal crunching due to mutual heating takes place in the remaining operating row of HBT fingers. Then, the current concentrates on the hottest finger, i.e., the one in the center, which has the slightly increased thermal resistance (no. 3 in Fig. 5). This effect, however, takes place only since the current already flows on one half of the transistor, which means that the dissipated power is doubled there.

There are mainly two ways to enhance the thermal stability, either by increasing the feedback at every emitter cell by a higher value of R'_e, or by increasing the thermal coupling between the two rows of emitter fingers.

Fig. 6 presents results for the same HBT with the emitter resistance per finger increased to $R'_e = 6\,\Omega$ instead of $R'_e = 2.5\,\Omega$. Due to the increased feed-back, the device is more stable. The asymmetric effect takes place at much higher voltages, and further hot-spot formation is not observed within the voltage range considered.

Results obtained for a thicker air-bridge of 20 μm are shown in Fig. 7, solid lines. The results are similar to the case before.

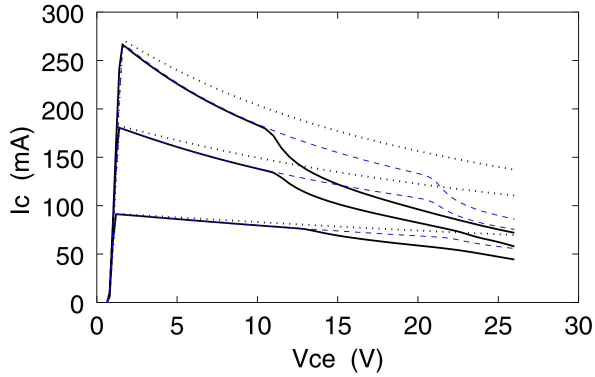

Fig. 4. Simulated I-V of 8-finger power HBT cell. Parameter is the base current. Solid lines: emitter resistance per finger $R'_e = 2.5\,\Omega$, dashed blue lines: $R'_e = 6\,\Omega$, both with 5 μm emitter air bridge. Dotted lines: $R'_e = 6\,\Omega$, 20 μm emitter air bridge.

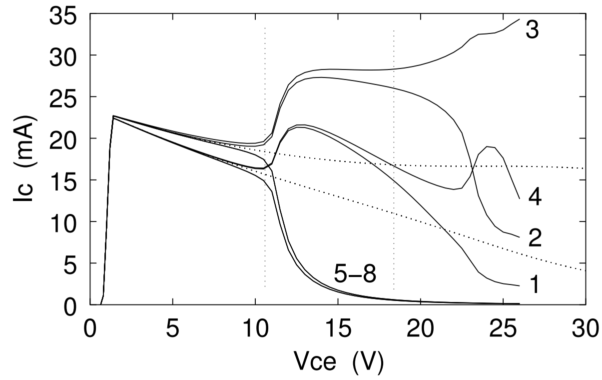

Fig. 5. Simulated currents of the individual emitter fingers of the power HBT cell. $R'_e = 2.5\,\Omega$, 5 μm emitter air bridge. Solid lines: slightly asymmetric model, broken lines: symmetric model. For the numbering of the fingers see inset in Fig. 6.

Again, the asymmetrical hot-spot formation is delayed, but not fully suppressed. Only if the emitter air bridge is increased to 20 μm and a high R'_e of 6 Ω are applied, the device is fully stable, as shown in Fig. 7, dashed lines.

IV. Summary

The different mechanisms leading to thermal current crunching are investigated using an electrothermal model of a power HBT. It turns out that the asymmetrical hot-spot effect is dominant in the fish-bone type layout. This means that one half of the HBT is effectively switched off. While the thermal resistance can be reduced by distributing the HBT fingers on a larger area, this measure also poses the threat of thermal instability. It is necessary to introduce strong thermal coupling in order to equalize the temperature. It is shown that it is possible to simulate the effect using thermally coupled compact models in circuit simulators, if a slight perturbation is introduced to change the symmetry of the thermal resistance matrix.

Acknowledgements

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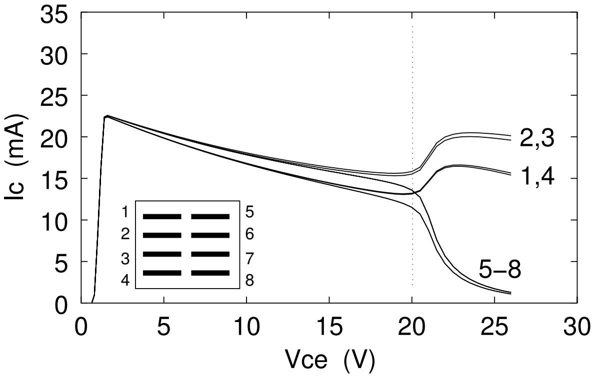

Fig. 6. Simulated currents of the individual emitter fingers of the power HBT cell. $R_e' = 6\,\Omega$, $5\,\mu$m emitter air bridge. For the numbering of the fingers see inset.

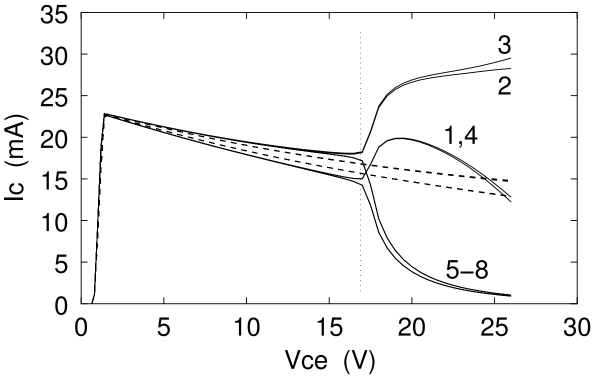

Fig. 7. Simulated currents of the individual emitter fingers of the power HBT cell. Solid lines: $R_e' = 2.5\,\Omega$, dashed lines: $R_e' = 6\,\Omega$. $20\,\mu$m emitter air bridge. For the numbering of the fingers see inset in Fig. 6.

REFERENCES

[1] P. Baureis, "Electrothermal modeling of multi-emitter heterojunction bipolar transistors (HBTs)," in *Dig. INMMC, Workshop on Integrated Non-Linear and Millimeterwave Circuits*, Gerhard-Mercator-Universität, Duisburg, 145 - 148, 1994.

[2] T. Peyretaillade, M. Perez, S. Mons, R. Sommet, Ph. Auxemery, J.C. Lalaurie, R. Quéré, "A pulsed-measurement based electrothermal model of HBT with thermal stability prediction capabilities," in: *IEEE MTT-S Int. Microwave Symp. Dig.*, 1515 - 1518, 1997.

[3] Ch.M. Snowden, "Large-signal microwave characterization of AlGaAs/GaAs HBT's based on a physics-based electrothermal model," *IEEE Trans. Microwave Theory Tech.*, vol. 45, 58 - 71, Jan. 1997.

[4] J. Grajal de la Fuente, V. Krozer, A. Campo, M. Schüßler, "Performance limitations of power HBT devices," in *Dig. GAAS 99*, 98 - 102, 1999.

[5] K. Lu, Ch.M. Snowden, "Analysis of thermal instability in multi-fnger power AlGaAs/GaAs HBT's," *IEEE Trans. Electron Dev.*, vol. 43, pp. 1799 – 1805, Nov. 1996.

[6] P. Kurpas, F. Brunner, R. Doerner, B. Janke, P. Heymann, A. Maaßdorf, W. Doser, Ph. Auxemery, H. Blanck, D. Pons, J. Würfl, W. Heinrich, "High-voltage GaAs power-HBTs for base-station amplifiers" in: *IEEE MTT-S Int. Microwave Symp. Dig.*, 2001, pp. 633 - 636.

[7] M. Rudolph, R. Doerner, K. Beilenhoff, P. Heymann, "Scalable GaInP/GaAs HBT large-signal model," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 2370 - 2376, Dec. 2000.

[8] M. Rudolph, R. Doerner, K. Beilenhoff, P. Heymann, "Unified model for collector charge in heterojunction bipolar transistors," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 1747 – 1751, July 2002.