Improved Performance and Thermal Stability of Interdigitated Power RF Bipolar Transistors with Nonlinear Base Ballasting

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Abstract

A novel base ballasting scheme for interdigitated power RF bipolar transistors has demonstrated improved performance and thermal stability. The nonlinear ballast resistor in series with each base finger is implemented by depletion-mode FET, which requires only minor modification in the fabrication process. Mixed-mode simulation, instead of analytical equations, is used for more universal device analyses.

I. Introduction

The positive feedback from inhomogeneous temperature distribution in interdigitated power bipolar transistors can cause thermal instability or gain collapse [1,2]. Usually emitter ballast resistor is used for prevention, and its optimal value needs to be carefully chosen to ensure good instability protection without severe performance degradation [3]. The design of finger spacing is also a tradeoff in view of thermal management, since its reduction can increase thermal coupling between fingers and hence decrease the current hogging effect [4,5], but this reduction will lead to inefficient heat dissipation for the entire cell [5]. We propose to use a new nonlinear base ballasting scheme that is very effective in thermal instability protection with little performance penalty at normal operating conditions. Since the positive feedback from joule heating can be nearly eliminated, the layout design can also be more aggressive towards total heat dissipation.

II. Power RF device modeling

Power RF devices pose significant challenges to modeling strategies, since both thermal and parasitic effects need to be accurately accounted for. For the power BJT in this study (Fig. 1), mixed-mode device/circuit simulation has been demonstrated as an effective method to model the parasitic elements and to link the detailed doping profiles directly with circuit performance [6]. Unlike analytical approach [3-5], the numerical method can capture all transistor behaviors and electrical couplings with no operation-mode assumption, and hence has a more universal applicability. The modeled T-network and calibrated Gummel plots to measurements at room temperature are shown in Figs. 2 and 3. Measured doping profile is also used for calibration. Extracted values of the parasitic elements are listed in Table 1 [6]. The emitter ballast resistance is about 110 Ω per finger implemented by a p-type diffusion resistor. The f_T as a function of the collector current I_c and the S-parameters are shown in Fig. 4. There is very good agreement between measurements and simulation.

III. Nonlinear base ballasting

It is apparent that a nonlinear ballast resistor will be superior to a linear one, since optimal effective resistance values can be separately designed for operating conditions and instability protection. If the ballast resistor is applied to the base end [5,7], the equivalent resistance can be obtained by multiplying the emitter resistance with the DC current gain β. Although it was argued in [7] that base ballasting can only work for HBT, not BJT, since β increases with temperature T_L for BJT, a more careful analysis in Fig. 5 reveals that the base current I_b still increases with T_L, though not as fast as I_c. Therefore, base ballasting can still prevent thermal instability in BJT, just not as effective as emitter ballasting if the equivalent value is used. A nonlinear emitter ballasting is difficult to implement owing to its small I_{dsat} value and limited area. With a nonlinear base resistor implemented by a depletion-mode MOSFET as shown in Figs. 6 and 7, the saturation region of MOSFET will effectively limit the currents through the hot finger, while the linear region will hardly affect the normal operating point of the cold finger. Modification of layout for the additional MOSFET is shown in Fig. 8. The MOSFET has a channel length and width of $3\mu m$ and $15\mu m$, and a threshold voltage of $-0.45V$. The dimensions of the depletion-mode FET is determined by setting proper I_{dsat} level for optimal circuit performance and instability protection. Other layouts or devices are also applicable as long as the nonlinear resistance values are chosen appropriately (e.x., an enhancement-mode MOSFET with gate connected to V_{cc}). Fig. 9 shows improved temperature dependence of gummel plot by using nonlinear ballasting scheme. Different ballasting schemes are compared in Fig. 10 in view of instability protection. Due to increased effective g_m of nonlinear ballasting scheme, higer f_T is resulted as shown in

Fig. 11. All coupling capacitances have been taken into account. S-parameters with different ballasting scheme is also compared for high frequency characteristics as shown in Fig. 12. It can be seen that the new ballast scheme is strongly favorable to the conventional emitter ballasting.

IV. HBT applications

The proposed ballast scheme is possible to be applied to power HBT applications too. The nonlinear resistor can be obtained by MESFET, although more difficult modification on fabrication is likely. A computational prototype through mixed-mode simulation is built for illustration. The HBT device follows the specification in [7] and the MESFET has a gate length and width of $2\mu m$ and $5\mu m$ and a threshold voltage of $-0.3V$. As shown in Fig. 13, base ballasting using depletion-mode FET is more efficient in HBT due to decreasing β with increasing T_L. With proper operating condition, HBT does not experience β collapse since as T_L of the hot finger increases, collector current decreases due to base current is effectively limited by MESFET so that T_L does not increase anymore as illustrated in Fig. 10.

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