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Optimization of Early Voltage for Cooled SiGe HBT Precision Current Sources

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Abstract: The influence of Ge profile shape on the temperature characteristics of two key analog transistor parameters, Early voltage (V_A) and current gain-Early voltage product (βV_A), in SiGe HBTs have been studied over the temperature range of 300K-77K using SCORPIO, a transistor simulation tool calibrated to measured data [1]. A new version of SPICE that accounts for the temperature dependence of V_A was used to model the various SiGe HBTs simulated and thereby evaluate the cryogenic performance of SiGe HBT precision current sources, which are strongly influenced by the variations in both β and V_A . Results clearly indicate that the cryogenic performance of these SiGe current sources can be significantly improved by using a graded Ge profile instead of a constant Ge profile in the base region of the HBT.

1. INTRODUCTION

Unlike Si BJTs, which suffer performance degradation at low-temperatures due to heavy-doping and freezeout effects, bandgap-engineered SiGe HBTs are naturally suited for cryogenic applications [2]. Small fractions of Ge introduced into the base region of a SiGe HBT cause bandgap offsets that aid the minority carrier injection and its transport through the base region, allowing for the design of high-performance bipolar transistors. Since most of the useful transistor parameters are thermally activated by the amount of bandgap offset introduced in the base region of the SiGe HBT, it is expected that the cryogenic performance of these transistors will be far superior to its room-temperature performance.

Among the many *dc* transistor parameters that need to be optimized for analog applications, the most important ones are β and V_A . The β of a transistor signifies the amount of output current (I_C) available for a given input current (I_B), whereas, the V_A of a transistor accounts for its output resistance. In conventional Si BJTs, β is inversely proportional to the base doping concentration and V_A is directly proportional to the base doping. Therefore, it is difficult to simultaneously improve both β and V_A in Si BJTs, and hence βV_A is considered a key figure-of-merit for analog transistors.

It can be shown mathematically that the improvement in V_A and βV_A in SiGe HBTs compared to that in a similarly constructed Si BJT is [3]:

$$\frac{V_{A, \text{SiGe}}}{V_{A, \text{Si}}} = \frac{\exp(\Delta E_{g, \text{Ge}}(\text{grade}) / kT) - 1}{\Delta E_{g, \text{Ge}}(\text{grade}) / kT} \quad (1)$$

$$\frac{\beta V_{A, \text{SiGe}}}{\beta V_{A, \text{Si}}} = \eta \gamma \exp(\Delta E_{g, \text{Ge}}(x = W_B) / kT) \quad (2)$$

Here, $\Delta E_{g, \text{Ge}}(\text{grade}) = \Delta E_{g, \text{Ge}}(x=W_B) - \Delta E_{g, \text{Ge}}(x=0)$, represents the bandgap grading introduced into the base region of a SiGe HBT. Also, $\Delta E_{g, \text{Ge}}(x=0)$ and $\Delta E_{g, \text{Ge}}(x=W_B)$ are the Ge-induced bandgap offsets at

the emitter-base (EB) and collector-base (CB) depletion edges in the base region, respectively. Parameters η and γ represent the ratio of position-averaged minority carrier mobility in the base region of a SiGe HBT compared to that in a Si BJT, and the ratio of position-averaged density-of-states in the base region of a SiGe HBT compared to that in a Si BJT, respectively. Equations (1) and (2) indicate that both V_A and βV_A in SiGe HBTs can be improved by increasing the bandgap grading in the base region. It is also clear that by cooling, an exponential increase in both of these parameters can be obtained for a SiGe HBT when compared to a similarly constructed Si BJT. Previous studies have shown that the experimental data obtained by cooling advanced UHV/CVD SiGe and Si transistors are in agreement with these theoretical expectations [4].

A recently developed 1-D transistor simulator (SCORPIO), calibrated to SiGe HBT data over a wide temperature range, has also confirmed the exponential temperature dependence for both V_A and βV_A in graded Ge profile SiGe HBTs [1]. SCORPIO uses the SIMS doping profile of a transistor as its input to generate the terminal characteristics of the transistor. Advanced parameter models for minority and majority carrier mobilities, density-of-states, and carrier freezeout are incorporated into SCORPIO and each model takes into account the differences between the Si and SiGe material systems.

2. RESULTS AND DISCUSSIONS

Experiment, theory, and simulation results indicate that by introducing a graded Ge profile into the base region of a SiGe HBT one can exponentially enhance the cryogenic performance of the SiGe HBTs. However, the maximum amount of Ge that can be introduced into any epitaxial SiGe layer must comply with the well-known thermodynamic stability constraint [5], as depicted in Fig. 1. Stiffler et al.'s [6] stability curve shown in the same figure is an empirical result for the critical thickness in strained UHV/CVD SiGe epitaxial films. For any given effective thickness of the epitaxial SiGe film, the film will be unconditionally stable (defect free) if the amount of Ge introduced into the film is below the critical limit (lower left region of the figure) and for Ge content above this critical limit a metastable film will result.

Figure 1. Thermodynamic stability constraint applicable to SiGe epitaxial films.

Figure 2. Germanium profiles with varying Ge grading in the neutral base and approximately similar Ge content at the EB depletion edge.

In the present study, in order to quantify the influence of Ge profile shape on the temperature characteristics of precision SiGe current sources, we began by calibrating SCORPIO to measured results for β and V_A in SiGe HBTs. Device characteristics of an advanced UHV/CVD epitaxial Si- and SiGe-

base technology [7] were measured from 300K to 140K. SIMS data of the SiGe HBT was used as a starting point for the calibration of SCORPIO to the measured results. The Ge profile shown as a solid circle in Fig. 2 was the final calibrated Ge profile shape obtained for the simulated SiGe HBT, and showed consistent agreement with all measured dc and ac characteristics of SiGe HBT over the entire temperature range. Reasonable agreement between the simulation and the measured dc characteristics of the Si BJT was also achieved over this temperature range by using the calibrated SIMS profile, with the Ge profile simply removed.

Two different situations in the variation of the Ge profile shape for a fixed effective SiGe film thickness were considered in the present study: (a) constant integrated Ge content (or constant stability), and (b) variable Ge content. In case (a), the profiles considered varied from a 5.5%-box profile to a 11.0%-triangular profile, with all profiles having the same integrated Ge content as the calibrated SiGe HBT profile (see Fig. 3. inset). Fig. 3 shows the simulation results for the ratio of both V_A and βV_A in SiGe HBTs when compared to a similarly constructed Si BJT, obtained at 300K and 77K. As expected, the box profile shows no improvement in V_A with cooling, but, the triangular profile shows a strong increase in V_A at 77K when compared to the 300K value. The increase in βV_A for the box profile SiGe HBT at 77K when compared to 300K is because of the exponential increase in β due to the presence of significant $\Delta E_{g,Ge}$ ($x=0$). In triangular profile SiGe HBT, however, this increase is due to the exponential increase in both β and V_A . It is clear, therefore, that for analog applications requiring SiGe HBTs, a triangular Ge profile will maximize both V_A and βV_A for a given integrated Ge content.

Figure 3. SCORPIO simulation results for the ratio of V_A and βV_A in SiGe HBT compared to a Si BJT, obtained at 300K and 77K. The Ge profile used in the simulation was varied from a box profile to a triangular profile, keeping the integrated Ge content fixed.

Figure 4. The ratio of V_A in SiGe HBTs compared to a Si BJT, as a function of temperature. The integrated Ge in the base region is varied to increase the bandgap grading, keeping $\Delta E_{g,Ge}$ ($x=0$) approximately the same.

In case (b), the integrated Ge content in the base region was varied by changing the Ge grading and maintaining the Ge content in the EB depletion edge approximately the same. We have considered 3 different Ge profiles (see Fig. 2): 2.5%-box, 9%-trapezoid, and 15%-trapezoid, that fall into various regions of the stability space due to their different Ge concentrations (Fig. 1). By maintaining a similar value of Ge concentration at the EB boundary in all of the profiles, the temperature characteristics of β is expected to be similar in all cases. However, the differences in the Ge grading is expected to strongly impact the temperature characteristics of V_A in these transistors. Fig. 4 shows the simulated results for V_A as a function of reciprocal temperature for SiGe HBTs compared to a similarly processed Si BJT. As

expected, the box profile does not enhance the V_A , but the 15% Ge trapezoidal profile has almost 1300 $\times$ improvement in V_A at 77K compared to a Si BJT.

Precision current sources, commonly used in high-precision analog circuits, are required to maintain constant output current for large changes in output voltages, and thus require large R_{out} . Since the R_{out} of such precision circuits is controlled by the V_A (or βV_A) of the output transistor, it is expected that the use of Ge grading in SiGe HBTs will have a strong impact on the temperature characteristics of such high-precision SiGe current sources. In order to quantify this effect, we have modified the conventional SPICE program (PSPICE) by introducing two new parameters, XTVA and XTVB, to accurately model the temperature dependence of V_A and V_B (inverse Early voltage) in SiGe HBTs. Figs. 5 and 6 show the close agreement between the modified SPICE model and the measured dc characteristics of both Si and SiGe transistors. Calibrated SPICE models were also constructed for each of the 3 simulated SiGe HBTs considered in this study.

Figure 5. Gummel characteristics for the SiGe HBT measured at 300K and 140K compared to that obtained from a calibrated SPICE model.

Figure 6. Output characteristics for both SiGe and Si transistors measured at 300K and 140K compared with the results obtained from modified SPICE models.

Figure 7. Ratio of R_{out} of a SiGe HBT cascode current source to that of a Si circuit, as a function of reciprocal temperature. The inset shows the circuit topology for a cascode current source.

In this study, we have considered a cascode current source as an example of a high precision current source in order to compare the enhancement in R_{out} of a SiGe HBT circuit when compared to that of a Si BJT circuit. Cascode current sources, as shown in Fig. 7, employ negative feedback to increase its R_{out} (proportional to the βV_A of Q_0). Fig. 7 shows the ratio of R_{out} of a SiGe HBT current source when compared to that obtained from a similarly constructed Si BJT current source, over a wide temperature range. Observe that the current source employing a box profile SiGe HBT shows only a slight increase in its performance at low temperatures due to the increase in β with cooling. However, both current sources using SiGe HBTs with Ge trapezoids show a significant increase in their R_{out} at low temperatures compared to their Si counterparts. This enhancement is mainly due to the increase in V_A by introducing large bandgap grading in the base region using Ge.

3. CONCLUSIONS

Using SCORPIO and a new version of SPICE, we have investigated the influence of Ge grading on the temperature characteristics of a high-precision cascode current source. Results clearly indicate that the box profile SiGe HBT only provide marginal improvement in the R_{out} of the current source, whereas a graded Ge profile SiGe HBT yields a significantly larger R_{out} at all temperatures. Our studies indicate that for stable SiGe films in SiGe HBTs, any addition of Ge in the form of grading in the base region will significantly improve the low-temperature characteristics of both V_A and βV_A and hence greatly improve the R_{out} of cooled SiGe HBT precision current sources. It was also shown that for any given integrated Ge content in a stable SiGe film, the maximum impact of both V_A and βV_A can be attained by introducing a triangular Ge profile in the base region of SiGe HBTs as opposed to any other profile shape. Thus, for cryogenically operated high precision SiGe HBT current sources, strongly graded triangular Ge profile SiGe HBTs will be optimum.

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