Simulation of Silicon Germanium HBTs Using ATLAS/BLAZE

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The aim of this technical report is to study the suitability of *ATLAS/Blaze* for the simulation of state-of-the-art high-speed SiGe heterojunction bipolar transistors (HBTs) fabricated in close-to-conventional Si-technology. Simulation studies of advanced SiGe HBTs are presented and, where possible, verified with experimental results.

Material Parameters

The incorporation of germanium significantly changes the properties of the base region and the base-emitter and base-collector junctions in a Si/Si$_{1-x}$Ge$_x$/Si HBT. Addition of Ge reduces the bandgap of Si, leading to the narrow bandgap SiGe base of the HBT. The lattice constant of Si$_{1-x}$Ge$_x$ alloy differs considerably from that of Si . Hence, the incorporation of Ge causes strain in the SiGe (compressive in-plane), modifying the energy band structure and density of states in the conduction and valence bands.

The quality of epitaxially grown SiGe/Si heterostructures has improved dramatically in recent years and reported results are very promising in terms of the possibilities offered by the SiGe technology. However, while silicon has been well-characterized over the past 40 years, not nearly as much is known about strained SiGe and many simplifying assumptions are made in the strained-SiGe/Si material parameters.

Simulation of Advanced SiGe HBTs

Since the introduction of SiGe into conventional Si technology, various research groups have demonstrated high performance SiGe base HBTs with different approach to forming the Ge profile in the base. While the IBM group [1] uses graded Ge profiles, the Daimler Benz group [2] focuses on SiGe HBTs with a uniform Ge profile. Recently Harame et al. [1] have developed a high-performance SiGe-base BiCMOS process.

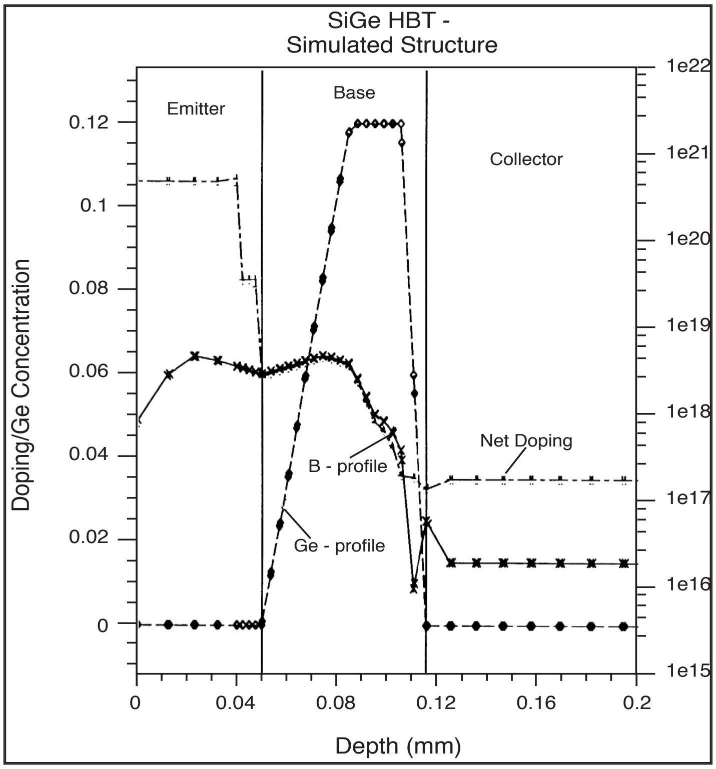

Figure 1. Doping profile and Ge profile (graded base) of a SiGe HBT. Based on Meister et. al. IEDM 95 p. 739.

The highest speed (f$_{max}$) SiGe transistor reported so far appears to be by Schuppen et al. [2]. They used a relatively thick (60 nm) base and heavy doping to reduce the intrinsic base resistance. The base transit time was reduced by a strong electric field with 0 to 15% Ge grading. Meister et al. [3] have reported a SiGe HBT with a 74 GHz f$_{max}$, resulting in a record CML gate delay of 11 ps.

The key issue in this study was to investigate HBT structures which offered both high f$_T$ and f$_{max}$. The simulation results have been compared with the latest reported experimental results [3] as summarized in Table 1. Figure 1 shows the simulated device structure where the Ge profile and doping profiles in various transistor regions

		Experimental	Simulation
Emitter Size	A_E	0.27 x 2.5 μm^2	0.27 x 2.5 μm^2
Current Gain	B	220	210
E-B Breakdown Voltage	B_{VEBO}	3.0	3.0
Early Voltage	V_A	130 V	110 V
Cutoff Frequency	f_T	61 GHz	63 GHz
Max. Osc. Freq.	f_{max}	74 GHz	110 GHz

Table 1. Comparison of simulated and measured data.

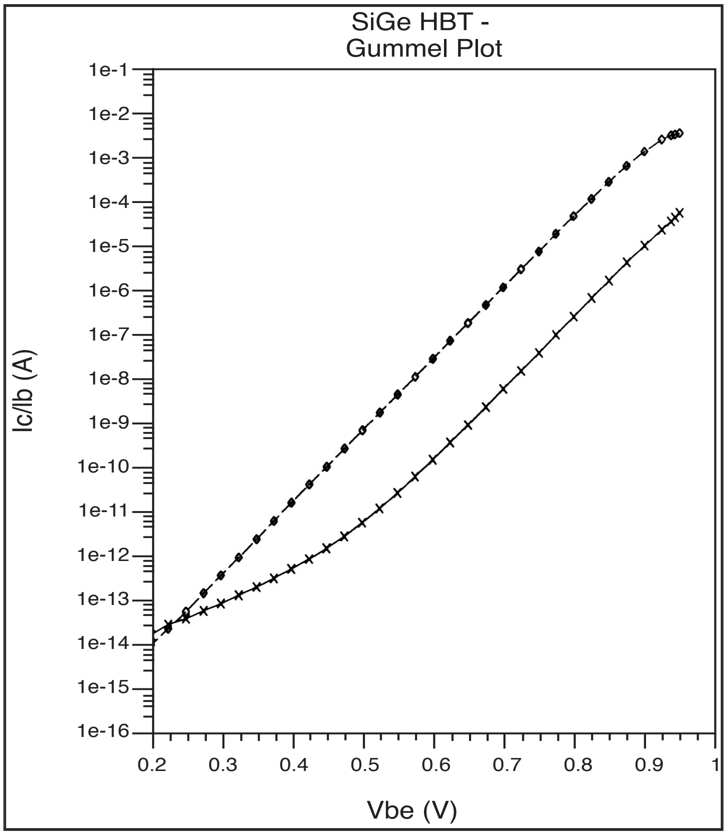

Figure 2. Gummel plot of a SiGe (graded based) HBT. Based on Meister et. al. IEDM 95 p. 739. [3].

are shown. The choice of this structure was made because of the availability of reliable experimental data for such a device.

The Ge concentration in the base has been graded from 0% at the emitter-base junction to 12% at the base-cellector junction. Figure 2 shows the Gummel plot and it is seen that almost ideal base current characteristics are observed. The transistor has a simulated peak dc current gain of about 210, as shown in Figure 3, which compares well with the experimental value of 220. The simulated cutoff frequency f_T is seen to be about 63 GHz while the calculated f_{max} has a value of more than 100 GHz, as shown in Figures 4 and 5 respectively.

In Figure 5 also shown are the small signal current gain β_{ac} extracted from h-parameters and the maximum available gain (MAG). From these curves a unilateral power gain of 22 dB at 10 GHz and an f_{max} of about 110 GHz (MAG) have been obtained at the reverse base-collector voltage of 2 V. In particular this high f_{max} value originates from the integration of the SiGe base, providing both high cutoff frequency and low intrinsic base resistance.

The effect of collector doping on the Early voltage V_A obtained from the simulated output characteristics (I_b = 15 nA) is shown in Figure 6. It is seen that as the doping concentration increases in the collector, the Early voltage decreases. For a collector doping of $5x10^{16}$ cm^{-3}, the predicted V_A is 110 V, giving a high $\beta.V_A$ product exceeding 22000. A Ge fraction of 12% at the base-collector junction has provided the high Early voltage.

Summary

Relatively simple material parameters for strained SiGe layers grown on Si(100) are incorporated in *ATLAS/Blaze*. The carrier mobility models in strained SiGe are very conservative and are similar to silicon. Mobility enhancements due to strain have not been modeled.

As more studies are performed on the electrical properties of SiGe strained layers, the program can easily be modified to include the latest findings. Simulation results for both silicon and SiGe bipolar transistors are in good agreement with reported experimental results available in the literature.

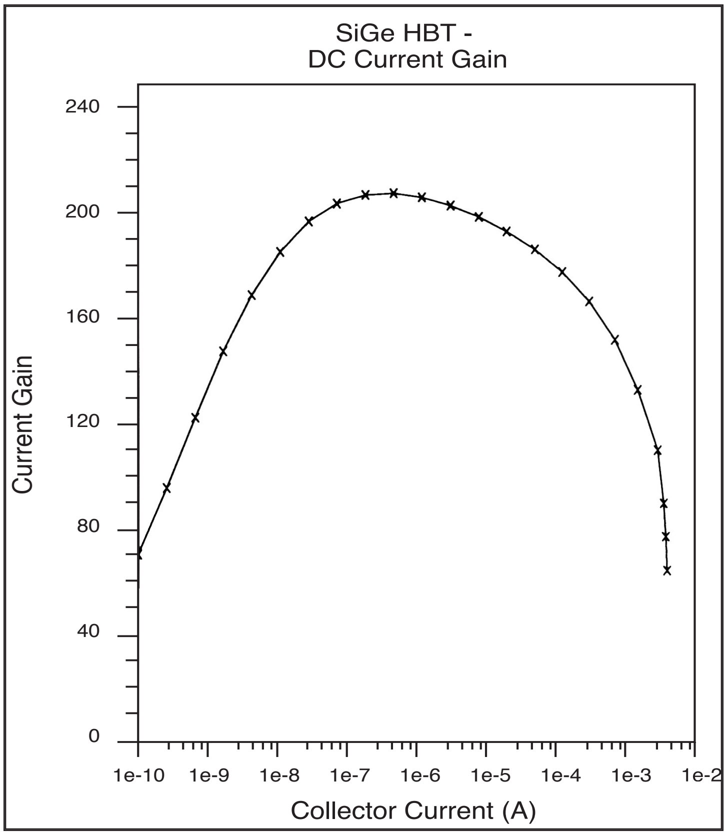

Figure 3. Simulated DC current gain of a graded base SIGe HBT. Based on Meister et. al. IEDM 95 p. 739.

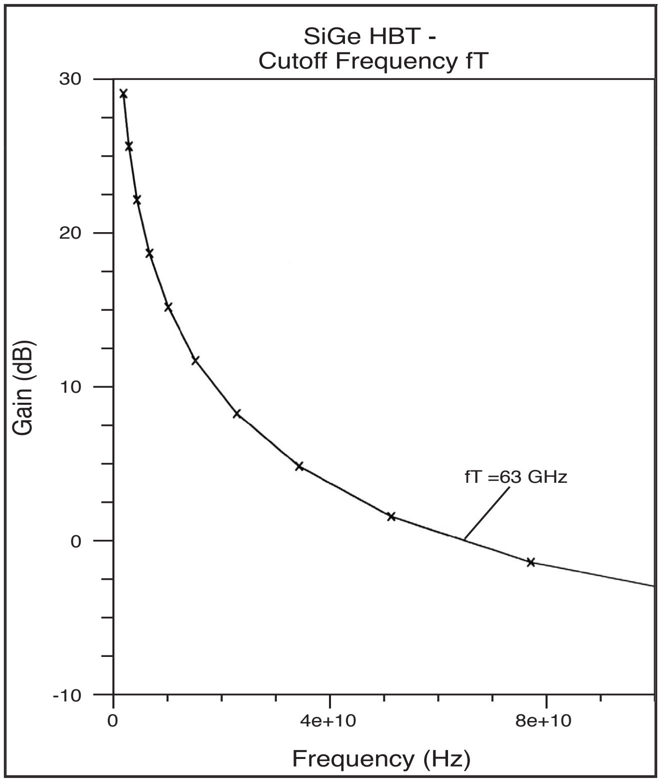

Figure 4. Simulated Frequency (f_T) of a graded base SiGe HBT. Based on Meister et. al. IEDM 95 p. 739.

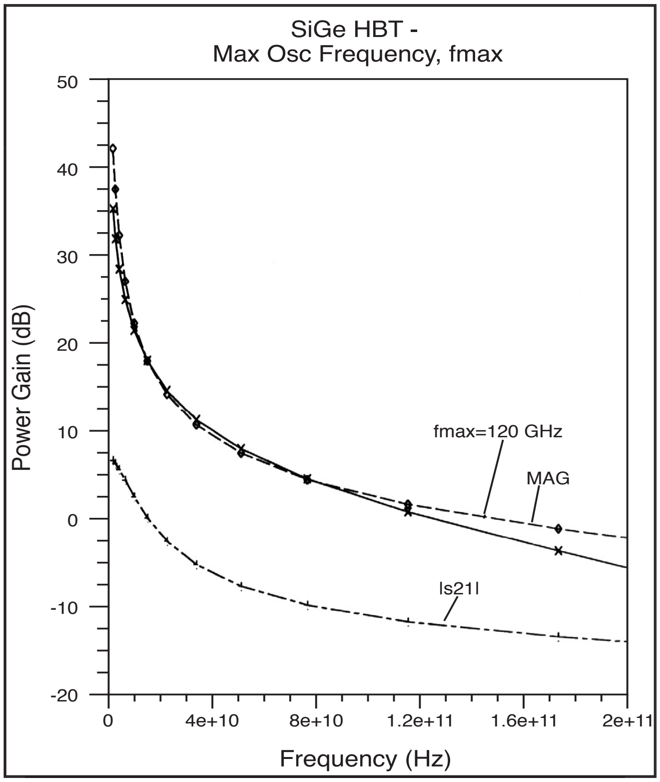

Figure 5. Simulated Frequency of Oscillation of a graded base SiGe HBT. Based on Meister et. al. IEDM 95 p. 739.

SiGe HBTs with a constant (flat) germanium concentration in the base have very large current gains but similar f_T to silicon devices. Unity gain cutoff frequency of over 63 GHz was simulated by *ATLAS* for a graded base SiGe HBT. This is consistent with experimental value of 61 GHz reported by Meister et al. [3]. The projected f_{max} was reported to be about 74 GHz and our simulation results give rather a more optimistic value of over 100 GHz.

References

[1] D. Harame et al., “SiGe HBT Technology: Device and Application Issues”, IEEE IEDM Tech. Dig., pp. 731 - 734, 1995.

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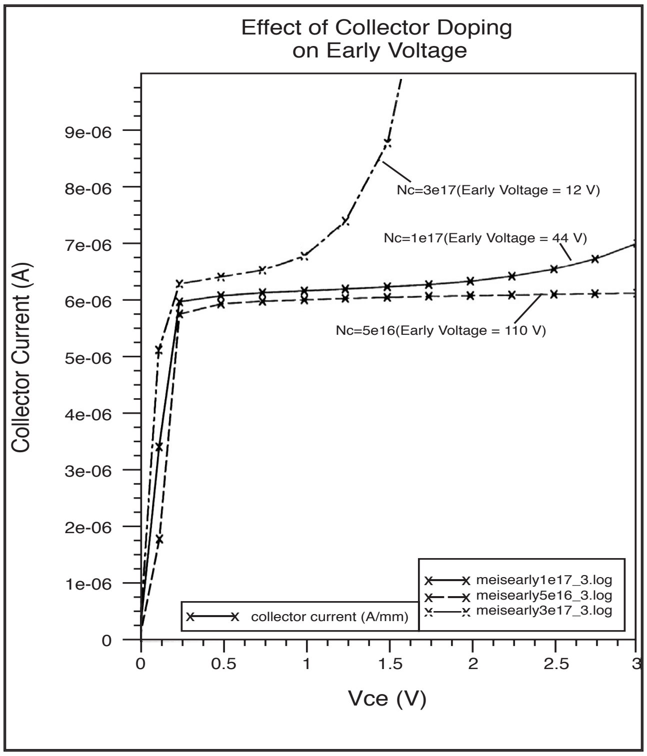

Figure 6. Typical simulated output characteristics of a graded base SiGe HBT as a function of collector doping. Based on Meister et. al. IEDM 95 p. 739.