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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.

The highest speed ($f_{\text{max}}$) 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 $f_{\text{max}}$, 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 $f_{\text{max}}$. The simulation results have been compared with the latest reported experimental results [3] as summarized in Table 1.

Table 1. Comparison of simulated and measured data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter Size</td>
<td>$A_E$</td>
<td>0.27 x 2.5 $\mu$m$^2$</td>
</tr>
<tr>
<td>Current Gain</td>
<td>$B$</td>
<td>220</td>
</tr>
<tr>
<td>E-B Breakdown Voltage</td>
<td>$V_{\text{EBO}}$</td>
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<tr>
<td>Early Voltage</td>
<td>$V_A$</td>
<td>130 V</td>
</tr>
<tr>
<td>Cutoff Frequency</td>
<td>$f_T$</td>
<td>61 GHz</td>
</tr>
<tr>
<td>Max. Osc. Freq.</td>
<td>$f_{\text{max}}$</td>
<td>74 GHz</td>
</tr>
</tbody>
</table>

Figure 1. Doping profile and Ge profile (graded base) of a SiGe HBT. Based on Meister et. al. IEDM 95 p. 739.
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 $5 \times 10^{16} \text{ cm}^{-3}$, 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.

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

