A high performance 0.18μm BiCMOS technology employing high carbon content in the base layer of the SiGe HBT to achieve low variability of hFE

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Abstract. We present a 0.18μm BiCMOS technology in which hFE variability of Silicon-Germanium Heterojunction Bipolar Transistors (SiGe HBTs) is greatly minimized by means of increased Neutral Base Recombination adding high carbon content in the base layer. In this work, we propose, for the first time, to use a high concentration of carbon in the base of SiGe HBTs as a practical way to increase the base current in a predictable and controlled way. Consequently, variability of hFE is greatly decreased and a significant improvement of device matching can be achieved. Furthermore, to guarantee a sufficiently high value of hFE we propose a Silicon-Germanium cap architecture to increase the collector current. HBTs fabricated using this technology exhibit a peak fT of 90GHz and a peak fMAX of 140GHz with an fTxBVceo of 255GHzV. Together with state of the art 0.18μm CMOS platform and high quality passives this technology is a viable candidate for the design of high frequency analog circuits.

I. Introduction

Addition of carbon in the base layer of SiGe HBTs has been reported as an effective way to achieve high-performance devices [1]. Well-known benefits are the suppression of boron TED [2] and a relaxation of the lattice distortion due to germanium [3]. Emitter junction depth in high performance HBTs ranges typically from 10 to 20nm, so that it is substantially transparent to holes injected from the base. This is the main reason why hFE of poly-silicon emitter HBTs is in general strongly affected by the thickness and uniformity of the oxide formed at the emitter-base interface (IFO). More specifically, the interfacial oxide acts as a potential barrier for holes limiting the base current (I_B) and consequently hFE increases. Since the uniformity of the interfacial oxide is very difficult to control, the random variation of the oxide thickness across the surface together with the random contribution of the interface states, acting as recombination centers, translate into a large dispersion of hFE. This problem is very serious especially in the design of precision analog circuits, which usually rely on good matching of differential pairs. Although specific process steps can be employed in order to minimize the content of oxygen at the interface like an in-situ hydrogen bake in a cluster tool [4], there is still much challenge in the complexity of the process and the necessity to acquire dedicated equipment.

We successfully minimized the contribution of interfacial oxide to the I_B by means of enhanced recombination in the bulk base layer due to a sufficiently high concentration of carbon. The resulting I_B is effectively increased and the mismatch due to variability of hFE (ΔhFE) is significantly decreased. Furthermore, a suitable hFE value has been obtained with the use of a SiGe-cap architecture in order to increase the collector current (I_C).

II. Device Fabrication

The cross section view of the SiGe HBT and simplified fabrication process are shown in Fig. 1and Fig. 2, respectively. The SiGe HBTs have a single poly-Si structure and are fabricated after CMOS module. First, a (100) p type Si substrate receives an arsenic implant to form a buried n^+ collector layer, and then, a silicon n-type layer is epitaxially grown. Proper device isolation is achieved by adding deep trenches (DTI) to the conventional shallow trench isolation (STI) process. After the collector plug is implanted and annealed, the CMOS module follows with implants for n and p-wells. The process is dual gate, employing a 3.5nm thick gate oxide using the nitrided oxide for 1.8V core logic and a 7.5nm gate oxide for 3.3V I/O devices. When the CMOS devices are completely formed, including deep source and drain, a protective layer is deposited and then selectively etched where the HBT must be formed.

A carefully optimized sequence of phosphorus implants fills the gap between the n^+ buried layer and the SiGe:C base to ensure low collector resistance. The layers forming the SiGe:C base are epitaxially deposited by UHV-CVD with a non-selective process. We employ a 12 nm thick highly boron doped base

($3.0X10^{19}cm^{-3}$). A carbon content of 0.5% is incorporated into the base during the epi process. For the emitter we adopt a non-self aligned solution, which guarantees ease of fabrication. After the stacked layers of polysilicon and TEOS are formed, the emitter opening is defined with a mask. TEOS in the emitter is etched by HF solution and then phosphorus in-situ doped polysilicon is deposited and patterned. Phosphorus concentration in the poly-emitter is $5.0X10^{20}cm^{-3}$. Boron implants then follow, self-aligned to the poly emitter to achieve low extrinsic base resistance. We use a final RTA at 910°C for 10sec to activate these last implants, and to drive in the emitter at the same time. The process is terminated with Co salicide formation and a conventional 3 metal levels BEOL process with a MIM capacitor. The third 2μm thick metal is used to obtain high value inductors with sufficiently high quality factor.

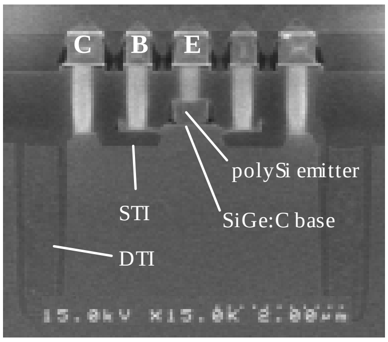

Fig. 1. SEM cross section of the HBT

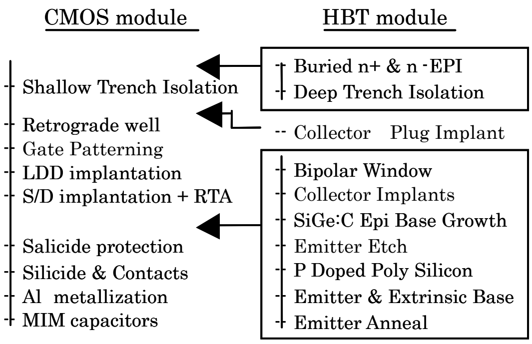

Fig. 2. Simplified fabrication process

III. Electrical Results

We investigated the relations between I_B and the variability of hFE in several experiments varying the carbon content in the base layer and the germanium profile. SIMS profiles for a typical HBT in this technology are shown in Fig. 3. Collector current is controlled by Ge concentration in the plateau located at the emitter base junction through the amount of bandgap narrowing. We investigated the dependences of I_C and I_B over the range of operational V_{BE} on different carbon content (0.2%, 0.5%, 0.8%). Fig. 4 shows typical results for the base current. A net increase of I_B proportionally to carbon content is found and, consequently, hFE becomes smaller as the carbon content increases. Moreover, the hFE variability becomes smaller as the carbon content increases as shown in Fig. 5. We also observed a small decrease in I_C that can be explained by the slight band gap widening due to carbon. It is clear, from these results, that proper hFE values and small ΔhFE can be achieved easily by introducing a sufficiently high content of carbon in the base and by tuning, at the same time, the height of the Ge plateau

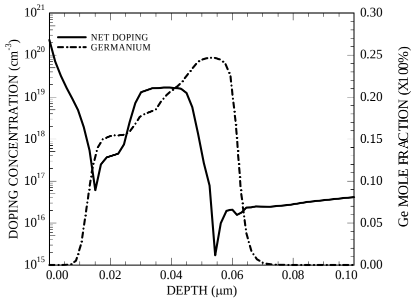

Fig. 3. SIMS profiles for net doping and germanium concentration for a typical HBT

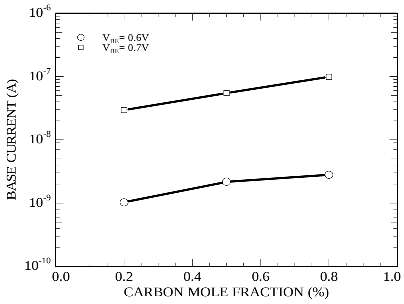

Fig. 4. Measured Base Current at two different Base-Emitter voltages as a function of Carbon Mole Fraction. V_{CB}= 0V

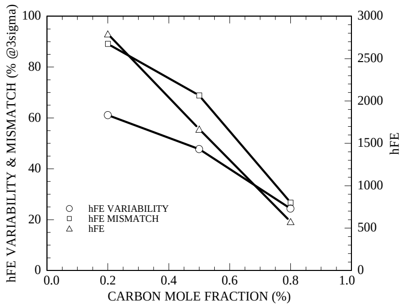

Fig. 5. Measured hFE, together with its variability and mismatch as a function of carbon concentration in the base layer

in the SiGe-cap architecture.

Power spectral density of base current fluctuations, S_{IB}, was measured in the common-emitter configuration. Typical results for different carbon content (0.2%, 0.5%, 0.8%) are shown in Fig. 6. Noise spectral density is larger at higher carbon content, but the increase is negligible for most applications.

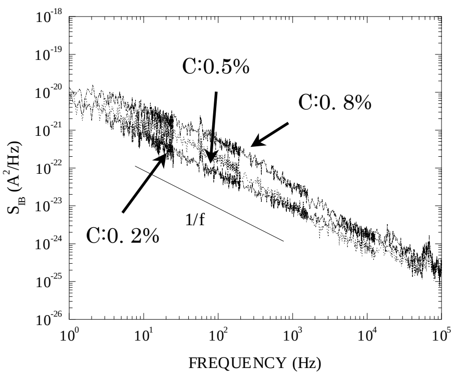

Fig. 6. Power spectral density of base current noise versus frequency for HBTs on different carbon content.
I_B=1μA, Emitter area is 0.2X16X3μm^2

Best results were obtained with a 12nm base thickness with a peak boron doping of 3.0X10^{19}cm^{-3}. Optimal Ge concentration in the cap was found to be 8% and 0.5% was chosen as the carbon mole fraction in the base. The gummel plot of one and 24,000 typical transistors in parallel are shown Fig. 7. The gummel of 24,000 transistors is very well behaved, an indication that no defects were formed in the fabrication process due to high carbon content. ΔhFE is about 14% (3sigma) and a BVceo is 2.8V at this time, confirming that this HBT is suitable for analog applications. AC performance is shown in Fig. 8: peak fT is 90GHz and peak fMAX is in excess of 140GHz. The key element to achieve this performance is that collector current can be sufficiently high without compromising BVceo through a high gain, because carbon is used to independently control I_B to keep hFE at the desired value. Even though this device shows excellent peak performance it is important to note that for several real life applications it is more important that significant performance is achieved at low collector current. In this respect our devices need only 0.5mA to reach 50GHz fT and at this collector current fMAX is already almost 100GHz.

The CMOS section of this technology employs 1.8V NMOS and PMOS transistors with I_{ON} of 600μA/mm and 250μA/mm at a 0.18μm-length gate respectively (Fig. 9). Degradation of CMOS performance with respect to a pure CMOS process is not observed due to the low thermal budget of the HBT module. Precise resistors are formed from p$^+$ polysilicon using boron implantations for standard and high sheet resistances. A high value inductor is achieved using the third 2μm thick metal layer. Together with MIM capacitors using plasma nitrided silicon films as the dielectric and varactors of both pn junction type and MOS accumulation type also available, this process allows the realization of complete RF SOCs (summarized in table1).

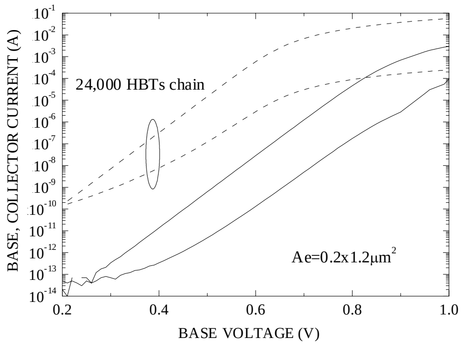

Fig. 7. Typical Gummel plot for one and 24,000 HBTs at V_{CB}=0.
Emitter area is 0.2X1.2μm^2.

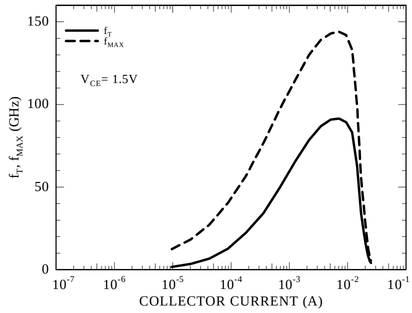

Fig. 8. Cut off frequency and maximum oscillation frequency vs. collector current. Emitter area is 0.2X16μm^2

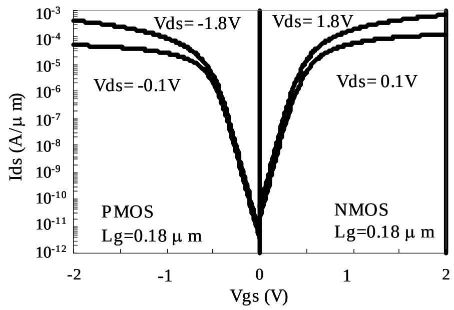

Fig. 9. Drain current (I_{ds}) vs. gate voltage (V_{gs}) characteristics of 1.8-V NMOS and PMOS

IV. Simulations and Discussion

It has been reported that introduction of carbon in silicon alters minority carrier lifetime considerably, already for carbon doses in excess of 4X10^{12}cm^{-2} [5], when carbon is introduced through an implantation step. In the case of implantation, though, it is not easy to determine if the observed reduction of lifetime is due to the damage produced by the implant or the carbon itself. It is common belief however that reduction of lifetime must be associated with the generation of traps close to the valence band of p-type doped silicon acting as recombination centers [6], [7]. We believe that carbon increases recombination in the neutral base region (NBR), resulting in an increased I_B. If NBR becomes the dominant factor in controlling the I_B, instead of recombination of holes at the IFO, we can expect to reduce ΔhFE to the intrinsic small variability associated with epitaxial deposition.

Table1 0.18μm BiCMOS Technology characteristics

NPN HBT	Emitter Area	0.2X16	μm²
	hFE	300	-
	BVceo	2.8	V
	Rbb'	9.5	Ω
	Peak fT/ Peak	91/144	GHz
Core CMOS	VDD	1.8	V
	VT (n/p)	0.32/0.30	V
	IDsat (n/p)	600/250	μA/mm
Resistor	p^+ polysilicon	410/2000	Ω/sq.
Capacito	MIM	1.5	fF/μm²
Inductor	Spiral	9.4/5.7	nH/Q (@1.4GHz)
Varactor	p/n junction	2	Cmax/Cmin
	MOS	3	

To validate our assumption we performed a set of numerical simulations altering the minority carrier lifetime in the base to see if a modified lifetime can account for the increased base current. In order to reproduce experimental data, the maximum lifetime, corresponding to the undoped material (τ_{max}), has been varied.

We found that carbon contents as low as 0.2% have no effect on base current in these particular HBTs. Consistently, simulations show that base current can be reproduced without altering the default τ_{max} value up to a carbon content of 0.2%. If carbon content is further increased to 0.5% lifetime decreases rather abruptly and it is almost one order of magnitude lower for [C]= 0.8% (Fig. 10). Fig. 11 shows the comparison of simulated base current with measurement over the full range of operational base-emitter voltages for the 3 carbon doses investigated.

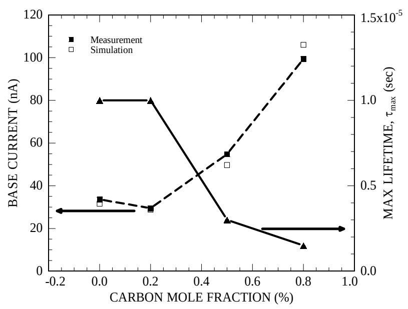

Fig. 10. Simulation results of base current (@ V_{BE}= 0.7V) as a function of carbon dose after tuning of τ_{max}

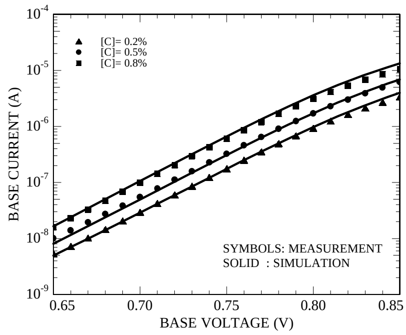

Fig. 11. Simulation of Gummel plots for base current at different carbon

V. Conclusions

We successfully minimized the contribution of interfacial oxide to the base current by means of enhanced recombination in the epitaxial base layer due to a sufficiently high concentration of carbon. The resulting I_B is effectively increased and the mismatch due to variability of hFE is significantly decreased. Furthermore, a suitable hFE value has been obtained with the use of a SiGe-cap architecture in order to increase the collector current. These HBTs show ideal electrical characteristics even for [C] as high as 0.5%, and exhibit 90GHz peak fT, 140GHz peak fMAX and excellent performance also at low collector current with a BVceo of 2.8V. High ideality of current gain has also been obtained. Together with state of the art CMOS and high quality passives this technology is a viable candidate for the design of high frequency analog circuits.

VI. Acknowledgement

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VII. REFERENCES

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