The Emergence of SiGe:C HBT Technology for RF Applications

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Abstract

In this paper we discuss the design of SiGe:C Heterojunction Bipolar Transistors for RF/IF applications on Motorola's 0.35µm and 0.18µm BiCMOS platforms. High performance devices reaching f_T/f_{MAX} up to 120GHz/125GHz will be described. Additionally, high breakdown voltage devices for power amplifier applications are available having BVCEO > 5V.

INTRODUCTION

In our increasingly mobile society, the demand for wireless devices capable of achieving high bandwidths is becoming progressively more important. With 2.5G devices already prevalent and 3G devices increasing in maturity, the need for technologies to drive the functionality of these next generation products at a low cost is imperative. Silicon-germanium heterojunction bipolar transistors (HBT) have attracted much attention in recent years due to their superior device performance as compared to the silicon BJT counterpart. Additionally, SiGe HBTs are capabale of performance that is competitive with III-V based alternatives. As such, the application space for SiGe devices has rapidly expanded into those areas traditionally dominated by GaAs. In addition to the cost advantage of SiGe-based HBTs, they also have an advantage over their GaAs-based competitors in that they are easily integrated with silicon CMOS analog and digital functions to enable system-on-a-chip solutions.

SiGe HBTs can be tuned to achieve a wide range of performances based upon the specific application. For example, SiGe HBTs having an f_T/f_{MAX} of 350/170GHz [1] have been realized for high bit rate optical networking applications (40Gb/s – 100Gb/s) while HBTs with high breakdown voltages have been demonstrated for power amplifier applications.[2] With increased pressure to improve the versatility of SiGe HBTs to cover diverse application spaces, creative ways to design the intrinsic device become necessitated. Such approaches include the addition of carbon into the base, base profile design, collector design and integration approaches.

BASELINE PLATFORM TECHNOLOGIES

Motorola currently has two generations of SiGe:C HBT technology in production to address wireless applications in the region of 2-6 GHz with enhanced versions of the baseline technologies poised to address higher frequency applications such as WLAN and 24GHz radar. The 0.35µm and 0.18µm baseline platforms share the same basic HBT structure with key differentiators being in design rules, the use of deep trench in the 0.35µm platform versus shallow trench isolation in the 0.18µm platform and a buried layer in the 0.35µm platform (Figure 1). A comparison of the baseline and enhanced HBTs is shown in Tables 1 and 2. In addition to the bipolar and CMOS components of the platforms, a complete suite of passives including polysilicon and thin film resistors, MIM capacitors, gated varactors, and high Q copper inductors are offered to allow high levels of integration.

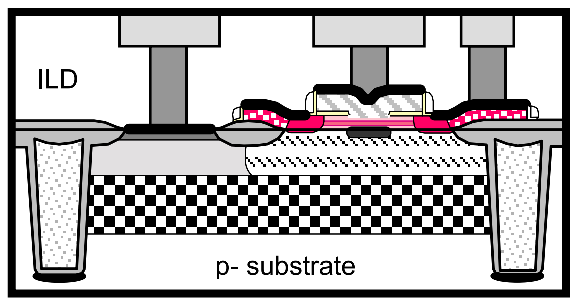

Figure 1. Cross-section schematic of the 0.35µm BiCMOS platform.

Table 1
Comparison of SiGe:C HBT parameters on the baseline and enhanced 0.35µm BiCMOS platforms.

HBT Parameters	0.35µm (std)	0.35µm (enhanced)
Beta	120	250
BVCEO (V)	3.4	2.4
f_T @ Vce = 2V (GHz)	49	80
f_{MAX} @ Vce = 2V (GHz)	86	115
J_c @ peak f_T/f_{MAX} (mA/µm^2)	1.5	2
NF_{min} @ 2GHz	0.7	0.3
Minimum W_e (µm)	0.4	0.3
Intrinsic Base R_s (ohms/sq)	1900	2500

Table 2.
Comparison of SiGe:C HBT parameters on the baseline and enhanced 0.18µm BiCMOS platforms

HBT Parameters	0.18µm (std)	0.18µm (enhanced)
Beta	120	450
BVCEO (V)	3.3	2.0
f_T @ Vce = 2V (GHz)	50	120
f_{MAX} @ Vce = 2V (GHz)	110	140
J_c @ peak f_T/f_{MAX} (mA/µm^2)	1.5	4
NF_{min} @ 2GHz	0.76	0.3
Minimum W_e (µm)	0.25	0.25
Intrinsic Base R_s (ohms/sq)	17600	3500

BASELINE SiGe:C HBT

Motorola's SiGe:C BiCMOS platforms integrate a graded Ge profile to enhance carrier transport across the base (reduced τ_b). Additionally, carbon is also incorporated into the base to suppress the diffusion of boron out of the SiGe layer during subsequent thermal cycles. The impact on boron diffusion in SiGe layers with and without carbon has been studied extensively [3-5]. Shown in Fig. 2 is an example of the severity of boron diffusion in the absence of carbon for a moderate anneal of 1000°C for 20 sec. In addition to allowing for additional margin in the thermal budget of the BiCMOS process, the incorporation of carbon can also allow for aggressive scaling of the base width or increased base doping to lower the intrinsic base resistance. Typical AC characteristics for the baseline 0.35µm and 0.18µm technologies are given in Fig. 3. As observed in the figure, f_T is nearly identical between the two technologies due to the similar intrinsic base profiles. The difference in f_{MAX} between the two HBTs is attributed to the reduction in parasitics in the 0.18µm platform resultant from tighter design rule tolerances.

HIGH PERFORMANCE SiGe:C HBT

One of the most straightforward ways to increase f_T is to increase the intrinsic collector doping at the collector-base junction to allow a higher collector current which decreases the effects of the capacitance terms. Shown in Figure 4 is the impact on f_T by a 4x increase in collector doping concentration (0.35µm platform). F_T is increased by only 10-15% (from 50GHz to 56 GHz) as Kirk effect is pushed out to higher currents. However, this approach alone results

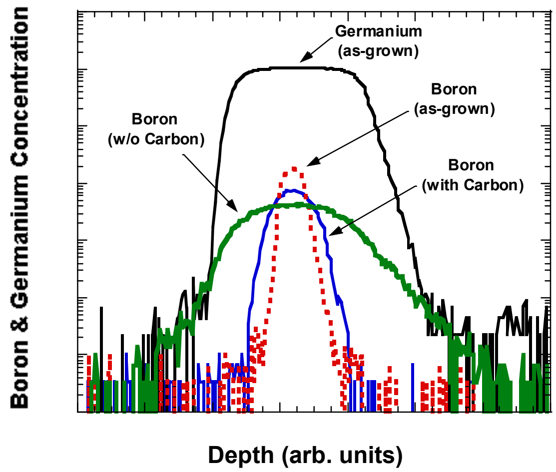

Figure 2. Boron diffusion in a SiGe layer with and without Carbon.

in negligible performance improvement at low currents, degradation in BV_{CEO}, and degradation in the f_{MAX}/f_T ratio due to the increase in collector-base capacitance. Therefore, in order to take full advantage of the benefits of increased collector doping, we must also address the emitter and base delay terms (τ_E and τ_B).

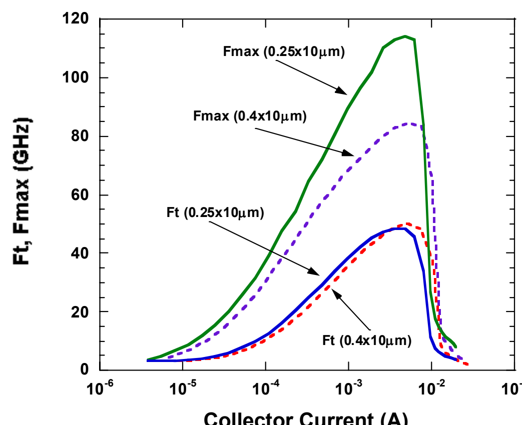

Figure 3. AC characteristics of the standard HBTs on the 0.35µm (0.4x10µm) and 0.18µm (0.25x10µm) BiCMOS platforms.

Also shown in Figure 4 is the influence of reducing the base width (without modification to the collector well profile) with an adjustment to the base position relative to the germanium edge at the emitter-base junction. The increase in Beta through this approach reduces τ_E (reduced V_{BE} for a given I_C) as well as reduces τ_B due to base width reduction. In this approach, a 20% increase in peak f_T is realized (from 50GHz to 61GHz), with a significant improvement in low current behavior. Another approach to modifying the emitter-base junction characteristics is to modify the thickness of the Si capping layer that separates the SiGe:C layer from the As-doped emitter polysilicon layer. Reducing the thickness of this layer is an approach frequently used to reduce both the τ_B (by reducing the base width) and τ_E (by reducing charge storage) terms. Though this approach to optimizing the intrinsic profile represents one option for increasing peak f_T, it also has several potential drawbacks, including degradation in the E-B diode characteristics and the associated HCI reliability, as well as increasing the emitter-base capacitance C_{JE}. Therefore, the extent to which thinning the cap region is a viable approach to improving device performance is dependent upon the particular reliability and performance targets.

Through the optimization of the intrinsic SiGe:C HBT profile (including base width, base position, Si cap thickness and intrinsic collector doping) as well as extrinsic parasitics, we are able to increase the f_T performance of the standard 0.35μm SiGe:C HBT by >50% from 50GHz up to 78GHz. Additionally, the performance of the 0.18μm HBT has also been improved to achieve an f_T of 123GHz while achieving an f_{MAX}/f_T ratio of 1 (see Fig. 4).

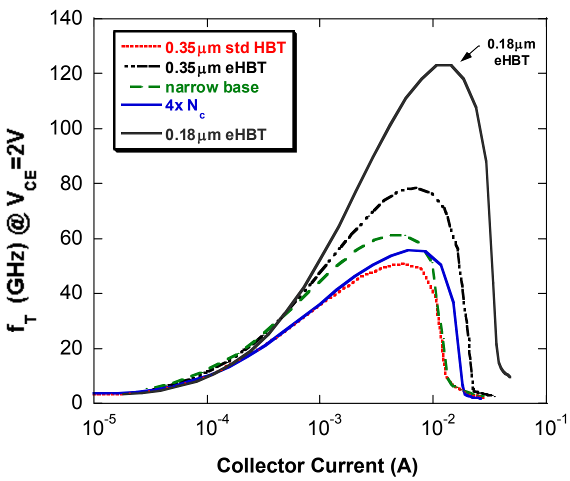

Figure 4. Improvement in peak f_T through various intrinsic and extrinsic profile enhancements.

In order to demonstrate the performance improvement of the enhanced SiGe:C HBT as compared to the standard SiGe:C HBT in an integrated circuit, the MBC13720 Low Noise Amplifier (LNA) was chosen. The MBC13720 is a common-emitter LNA with on chip bias circuitry that allows selectable high and low mode third order intercept point (IP3) operation. The eHBT LNA720 utilized the enhanced SiGe:C HBT process flow and reduced layout rules and was compared to the standard HBT LNA720. All measurements were made using the same application boards and with the same input and output matching designed to tradeoff noise figure (NF), IP3, and return losses with unconditional stability from 100MHz to 10GHz.

We first compared the two versions of the LNA at 1.9GHz with a 2.7V supply voltage and utilized the on chip bias circuitry to set the collector current (see Table 3). Improvement in NF of eHBT over HBT in high IP3 mode is 0.3dB (1.46dB for eHBT, 1.77 for HBT). The current drain of the eHBT is lower by 3mA (7.4mA vs. 10.7mA) in the high IP3 mode and 1mA lower in the low IP3 mode (4.1 vs. 5.2mA). Even at lower current drain in the high IP3 mode the eHBT has comparable OIP3 (22.1 vs. 22.2dBm), P1dB (12.8 vs. 12.3), and s_{21} gain (14.4 vs. 14.6dB). S-parameters for the eHBT and HBT are very similar in both high and low IP3 modes.

Table 3.
Comparison of MBC13720 LNA parameters using the standard 0.35μm SiGe:C HBT process and the eHBT SiGe:C HBT process.

Vcc=2.7 V 1.9 GHz		0.35μm eHBT		0.35μm std HBT	
Parameter	Symbol	High IP3 mode	Low IP3 mode	High IP3 mode	Low IP3 mode
Current	Icc (mA)	7.38 RF	4.11 RF	10.66 RF	5.17 RF
Gain	S21 (dB)	14.4	13.2	14.6	13.8
Noise Figure	NF (dB)	1.46	1.45	1.77	1.52
Input IP3	IIP3 (dBm)	7.9	3.3	8.0	7.0
Output IP3	OIP3 (dBm)	22.1	16.78	22.2	20.6
Output P1dB	P1dB (dBm)	12.8	12.2	12.3	12.6
Input return loss	|S11 |²(dB)	-11.8	-9.7	-13.8	-11.5
Output return loss	|S22 |²(dB)	-11.6	-10.2	-10.7	-9.7
Reverse isolation	|S12 |²(dB)	-18.7	-18.9	-19.3	-19.9

In our second comparison an external bias was used to set the collector current from 3mA to 11mA. With increasing collector current, the NF of the eHBT increased only slightly compared to a larger increase for the standard HBT. At 1.9GHz, the NF of the eHBT varies from 1.38 to 1.41 dB over the current range while the standard HBT increases from 1.52 to 1.8 dB. At 2.5GHz, the NF of the eHBT varied from 1.54 to 1.64dB vs. 1.65 to 2.01dB for the standard HBT. These results show that the enhanced SiGe:C HBT process achieves lower NF and lower current draw, without sacrificing OIP3 and P1dB. Equivalent S-parameters and NF match make the eHBT MBC13720 an attractive drop-in replacement for the current MBC13720.

HIGH BREAKDOWN SiGe:C HBT

While high performance SiGe:C HBTs are able to expand the application space for Si-based mixed signal technologies, there is still a concern over the potential to realize an efficient power amplifier, for the current 1-2GHz market, using these HBTs due to their low breakdown voltage (BV_{CEO}~3.3V) when compared to their GaAs counterparts.

In order to address this concern, we have designed high breakdown voltage SiGe: HBTs that can be integrated on-wafer with the high performance HBT. Cost being one of the constraints to integrating a dual performance HBT on a single wafer, we have utilized a +1 additional mask solution to create the high voltage HBT. One of the integration advantages that SiGe:C HBTs have is that the collector region is primarily formed via implantation (as opposed to the often more complex epitaxial collectors/sub-collectors used in GaAs HBTs). As such, we have tailored the collector implants to achieve both the high performance and high voltage SiGe:C HBT on the same wafer. Through the elimination of the SIC implant (Fig. 1), we are able to realize an HBT having a BV_{CEO} ~ 5.5V. Further collector profile optimization results in a wide range of high breakdown HBTs that can be offered on either the standard or enhanced 0.35μm platform as shown in Fig. 5.

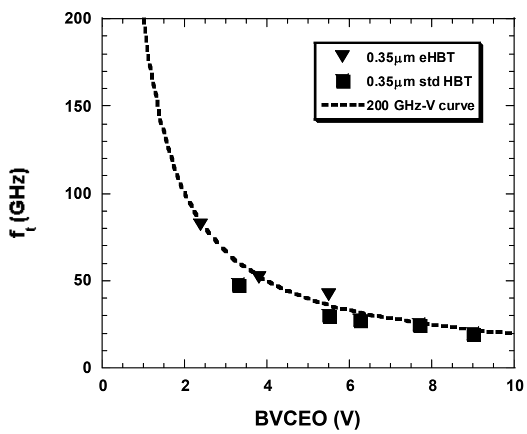

Figure 5. Plot of fT vs. BVCEO for various performance HBTs on the standard and enhanced 0.35μm BiCMOS platform.

Although, SiGe HBT's have been criticized for their low BV_{CEO}, this does not necessary present a true depiction of the device when used in a power amplifier. If the base power supply impedance at DC is low, then the collector-base current will not re-enter the base and avalanche multiplication will not occur. Therefore, BV_{CES} is a more realistic configuration of high voltage HBTs, with BVces typically being 3-5 volts higher than BV_{CEO} (BV_{CEO} can be considered a worst case situation for the HBT). Proper circuit design can improve DC operation near avalanche.

In power amplifier applications, the RF voltage applied to the device can swing above the DC breakdown voltage (BV_{CEO}) without destroying the device. Since avalanche breakdown is a low frequency phenomenon, as long as the half of the RF carrier frequency is greater than the avalanche time constant (typically >2nsec for SiGe HBTs), avalanche breakdown will not occur. Most commercial applications occur at frequencies above 800 MHz and RF sinusoidal voltages will not cause avalanche to occur. However, under high VSWR conditions, the transistor's load can distort the voltage waveform. If the distorted waveform voltage exceeds the avalanche time constant, breakdown will occur.

CONCLUSIONS

While SiGe technology is making tremendous progress in providing solutions traditionally offered only by GaAs technologies and at a lower cost, the two technologies should be considered complementary. There are many technology opportunities in building on strengths of each device technology and to explore new applications. In summary, we review Motorola's 0.35μm and 0.18μm SiGe:C BiCMOS platforms starting with the first generation devices (with f_T/f_{MAX} of 48/80Ghz and 48/114GHz, respectively) having the ability to meet circuit applications in the 2GHz range, followed by the next generations of devices on the platforms (with f_T/f_{MAX} of 78/110Ghz and 123/123GHz, respectively) that expand the application space to include high frequency applications >5-6GHz as well as introduce high breakdown devices having the potential to compete in the power amplifier arena.

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