Benefits of SiGe over Silicon Bipolar Technology for Broadband Mixers with Bandwidth above 10 GHz

student paper

Sabine Hackl[1,2], Martin Wurzer[1], Josef Böck[1], Thomas F. Meister[1], Herbert Knapp[1], Klaus Aufinger[1], Sabine Boguth[1], Ludwig Treitinger[1], Arpad L. Scholtz[2]

[1] Infineon Technologies AG,
Otto-Hahn-Ring 6, D-81730 Munich, Germany,
Tel.: +49 89 234-41217, Fax.: +49 89 234-47069,
E-Mail: sabine.hackl@infineon.com

[2] Institute of Communications and Radio-Frequency Engineering,
Vienna University of Technology, Gusshausstrasse 25, 1040 Vienna, Austria

Abstract **Future broadband wireless services will use carrier frequencies in the range of 10 GHz to 40 GHz. This raises the question which semiconductor technologies are suited for realization of the key RF building blocks like LNAs, mixers, oscillators and, in a later phase, for the complete monolithic integration of receivers and transmitters. This work investigates the benefits of SiGe bipolar technology in comparison to silicon at identical feature size for broadband mixers with bandwidth in the range mentioned above.**

I. Introduction

SiGe bipolar technology is one of the most attractive candidates for the emerging field of broadband wireless services. It combines the potential to fulfill the technical specifications with the cost advantages, integration, and manufacturing capabilities of standard silicon technologies. Therefore it is of primary interest to investigate the realization of key building blocks as precondition for the monolithic integration of complete subsystems. This work discusses the benefits of SiGe for analog functions with bandwidth larger than 10 GHz. By simulation, design, and electrical characterization of active broadband mixers the benefits are identified, evaluated, and related to the relevant technology parameters.

II. Technologies

The mixers were fabricated in advanced silicon and SiGe bipolar technologies, using a double-polysilicon self-aligned emitter base configuration with effective emitter width of 0.25 μm. The wiring capacitances are small due to the use of four metallisation layers. The main difference between the two technologies is found in the formation of the active base:

The base of the silicon transistors is formed by low-energy ion implantation with subsequent diffusion using rapid thermal processing. The resulting base width is only 50 nm with sheet resistance of 12 k$\Omega/\square$. Cut-off frequency f_T of 52 GHz, maximum oscillation frequency f_{max} of 65 GHz, and ECL gate delay τ_d of 12 ps are achieved [1].

The SiGe base is integrated by selective epitaxial growth. The Ge profile is linearly graded across the base with a maximum Ge fraction of 15 %. The intrinsic base sheet resistance is 4k$\Omega/\square$ at base width of 50 nm. The transistors manufactured in this technology offer a cut-off frequency $\mathrm{f_T}$ of 80 GHz, maximum oscillation frequency $\mathrm{f_{max}}$ of 97 GHz, and CML gate delay time τ_d of 8 ps. A further improved version is published in [2]. Figure 1 shows a schematic cross section of the SiGe transistors, the main transistor parameters for both technologies are summarized in table 1.

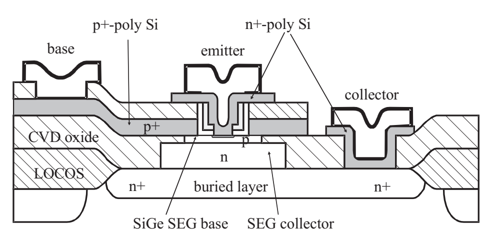

Fig. 1. Schematic cross section of the SiGe transistor.

TABLE 1. Main transistor parameters of Si and SiGe.

technology	Si	SiGe
min. lith. feature size	0.5 μm	0.5 μm
max. f_T	52 GHz	80 GHz
max. f_{max}	65 GHz	97 GHz
min. gate delay	12 ps	8 ps

The advantage for SiGe HBTs is the additional degree of freedom for further optimizations introduced by the bandgap engineering. It can be used for further vertical scaling leading to higher transit frequency and/or reduction of the base resistance both giving lower noise and larger bandwidth.

III. Circuit Design

The presented mixers are based on the Gilbert cell concept [3]. Figure 2 shows the simplified circuit diagram of the mixers. They have a double-balanced structure and connect the RF signal to the cross-coupled quad and the LO signal to the emitters of the lower transistor pair. The circuits have open-collector outputs to allow for a wide range of different applications. For the measurements presented in section V matching to 50 Ω is done off chip with an LC network to achieve optimum gain. The transistor sizes have been optimized individually for low noise and high bandwidth. Figure 3 shows the chip micrograph. The chip size is 0.45 mm x 0.45 mm. The mixer cell itself only takes about 1 % of the whole chip area.

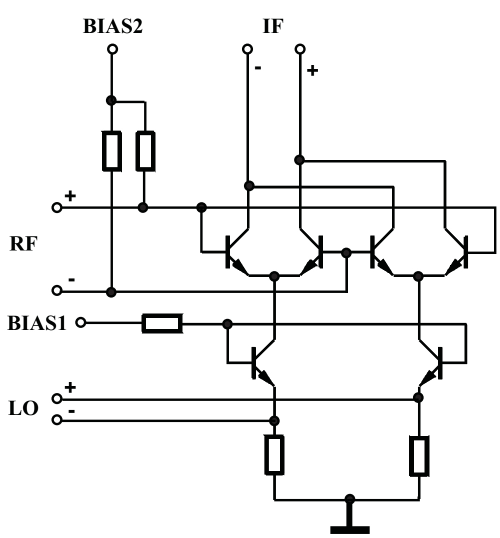

Fig. 2. Simple circuit diagram of the mixer.

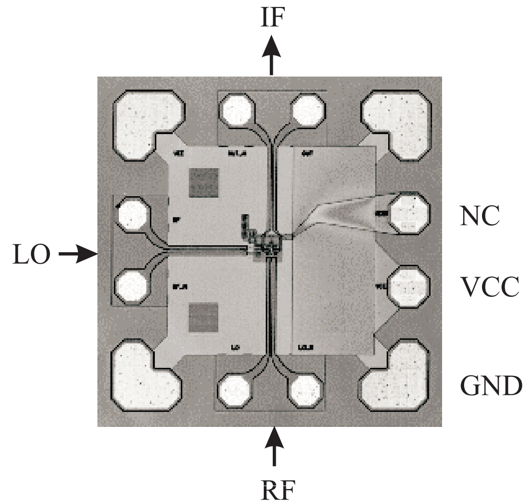

Fig. 3. Chip micrograph (size: 0.45 mm x 0.45 mm).

IV. Simulation

The same circuit layout is used in different technologies with different layer type resistors. This results in lower resistor values in the SiGe circuits. If the mixers operate with the same supply voltage of 5 V the SiGe circuits work with higher current densities leading to a higher conversion gain. Simulations show this influence on the gain to be about 3 dB at DC decreasing for increasing frequencies (figure 4).

Further investigations have shown that the mixer circuits are sensitive on the emitter resistance which has influence on the mixer gain. The process sequence applied to the SiGe transistors causes a much lower emitter resistance compared to the silicon transistors. This leads to an increase in gain by about 2 dB for SiGe.

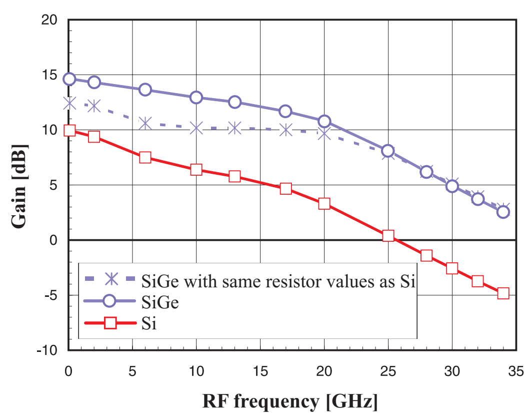

Fig. 4. Simulated conversion gain vs. RF frequency. The IF frequency is 240 MHz, P_{LO} is 0 dBm.

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V. Experimental Results

For electrical characterization the chips are bonded on microwave substrates ($\epsilon_r = 3.38$). An intermediate frequency of 240 MHz is chosen. The local oscillator power is 0 dBm.

Figure 5 shows the measured conversion gain vs. frequency for the mixers in the two technologies, silicon and SiGe. The advantage of SiGe in conversion gain is clearly seen. A smaller advantage can be measured for the bandwidth. At a voltage supply of 5 V, the conversion gain is 13 dB at 2 GHz, and 10 dB at the 3 dB cut-off frequency of 20 GHz in case of SiGe. For silicon the conversion gain is 8.4 dB at 2 GHz, and 5.4 dB at the lower 3 dB cut-off frequency of 17 GHz.

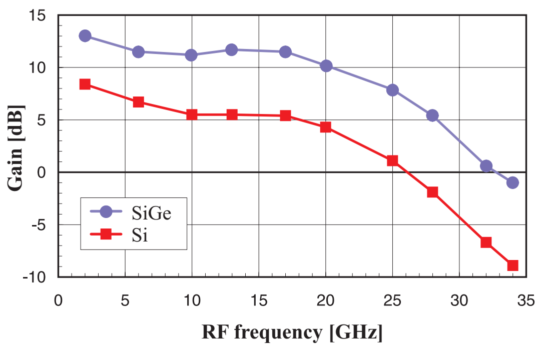

Fig. 5. Measured conversion gain vs. RF frequency. The IF frequency is 240 MHz, P_{LO} is 0 dBm.

Noise measurements show further advantages of SiGe over silicon broadband mixers (figure 6). A low double-sideband noise figure of 6 dB at the 3 dB cut-off frequency of 20 GHz is achieved with SiGe, 8.8 dB have been measured at the cut-off frequency of 17 GHz for mixers realized in silicon, both at a voltage supply of 5 V.

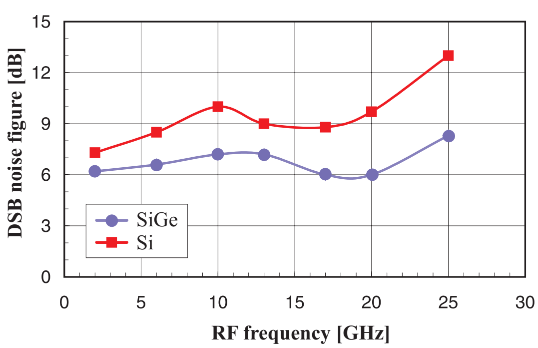

Fig. 6. Measured double-sideband noise figure vs. RF frequency. The IF frequency is 240 MHz, P_{LO} is 0 dBm.

For decreasing frequencies the noise difference between silicon and SiGe mixers decreases. This can be seen in figure 7. The noise difference is 1.1 dB at 2 GHz and increases up to 4.7 dB at 25 GHz.

Figure 7 also shows the advantages of SiGe over Si for gain with increasing frequencies. For circuits measured at 5 V voltage supply this can be seen in a higher gain of 4.6 dB at 2 GHz which is increasing up to 7.9 dB at 34 GHz. As simulations have shown the main advantage of SiGe over Si is explained by the lower transit time and the lower emitter resistance of the present SiGe transistors.

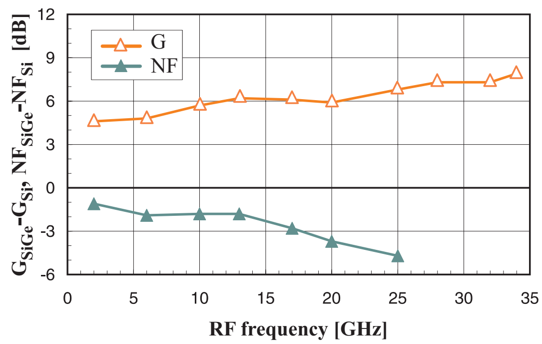

Fig. 7. Comparison between Silicon and SiGe of measured gain and measured double-sideband noise figure. The IF frequency is 240 MHz, P_{LO} is 0 dBm.

The 1 dB compression point and the 3^{rd} order intercept point, both referred to the input at the 3 dB cut-off frequencies, are -19 dBm and -9.9 dBm for silicon and -21 dBm and -11.3 dBm for SiGe.

Because of the different resistor values the current consumption for a single supply voltage of 5 V is 1.4 mA for silicon and 2 mA in case of SiGe. The supply voltage can be varied from about 3 V to about 7 V (figure 8). For about 4 V to 7 V the conversion gain is nearly constant. Lowering the supply voltage is limited by the circuit configuration, the break-down voltage of the transistors is limiting higher voltage supply.
Power consumption of only 7 mW for silicon devices and 10 mW for SiGe devices at 5 V supply voltage is achieved. Because of the low power consumption these mixers are ideal for being integrated in highly integrated frontend ICs. Table 2 summarizes the technical data.

Figure 9 gives the state of the art for broadband mixers in different semiconductor technologies at different frequencies including the data presented above.

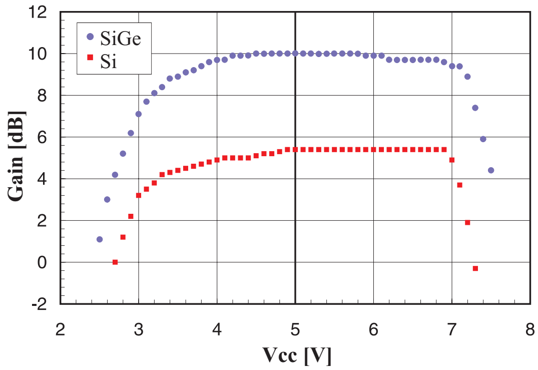

Fig. 8. Conversion gain vs. supply voltage at 20 GHz signal frequency for SiGe and 17 GHz signal frequency for silicon. The IF frequency is 240 MHz, P_{LO} is 0 dBm.

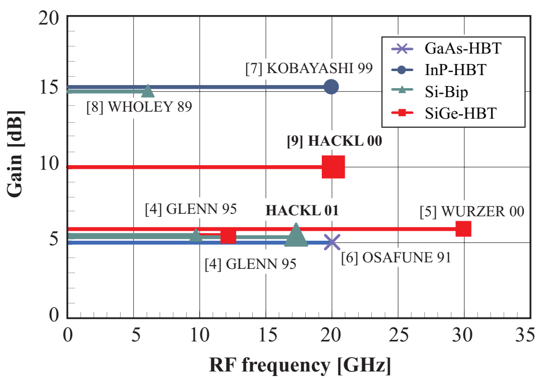

Fig. 9. State of the art for monolithic broadband mixers.

VI. Conclusions

A comparison of active broadband mixers in Si and SiGe technology has been presented and discussed. The silicon based mixer sets a new state of the art for analog monolithic broadband mixers realized in silicon. With SiGe further advantages in gain, noise, and bandwidth can be reached. At frequencies higher than 10 GHz the benefits are increasing. In case of conversion gain the benefit of 4.6 dB at 2 GHz increases up to 7.9 dB at 34 GHz. The advantage in noise figure is 1.1 dB at 2 GHz increasing up to 4.7 dB at 25 GHz. The benefits of gain can be traded against the bandwidth [5]. Due to the fact that SiGe bipolar technologies have still a high potential for further improvements increasing advantages in gain, noise, and bandwidth for active broadband mixers can be expected.

TABLE 2. Technical data at 3 dB cut-off frequency.

technology	52 GHz Si	80 GHz SiGe
3 dB bandwidth	17 GHz	20 GHz
gain (LO=0 dBm)	5.4 dB	10 dB
DSB NF	8.8 dB	6 dB
1 dB CP_i	-19 dBm	-21 dBm
$IP3_i$	-9.9 dBm	-11.3 dBm
supply current	1.4 mA (5 V)	2 mA (5 V)
power consumption	7 mW (5V)	10 mW (5V)

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