SiGe - Key Technology for Economic Solutions in High Frequency

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ABSTRACT

The demonstrated potential of SiGe is reviewed and a performance and cost effective production technology SiGe1 is presented. This process is oriented to RF-solutions between 1 and 10 GHz, including all the active and passive devices needed for those applications. Transistors with 50 GHz f_T and f_{max} are complemented by 30 GHz f_T, 6 V U_{CE0} transistors for power amplifiers showing a power added efficiency of 60 %. The manufacturability and reliability of SiGe1 is demonstrated and as first product a DECT frontend IC is shown with a noise figure of 1.6 dB for the LNA , and 28 dBm output power for the PA with up to 47% PAE, measured on packaged devices at 1.9 GHz.

INTRODUCTION

The mobile communication market and especially the high volume wireless handset market is a strong technology driver with high pressure on performance- and cost effective semiconductor solutions.

In the last 5 years SiGe has shown its potential in performance with demonstrations of record values for HBTs of f_T = 130 GHz by Oda et al (1) and f_{max} = 160 GHz by Schüppen et al (2), RF noise figures of 0.5 dB at 2 GHz and 1 dB at 12 GHz by Schumacher et al (3), and LF noise corner frequency down to 300 Hz by Gruhle et al (4). Additionally now available production technologies, by Harame et al (5) and Schüppen et al (6), manufactured on standard Si production lines, allow for low cost combined with high manufacturability and excellent reliability.

SiGe has started his introduction at the RF-frontend side with the capability of low RF noise for LNAs, low phase noise for VCOs, low power consumption for the whole frontend-IC and high output power combined with good power added efficiency for the PA`s. All this features are delivered on the cost level of pure silicon technology. But beside the ability for cost-effective solutions on the frontend side SiGe has the option to merge with state of the art CMOS to a „system on chip" enabling technology.

TECHNOLOGY AND PERFORMANCE

There exist two basic concepts for improving bipolar RF-transistors with the use of SiGe: The SiGe drift-transistor with a doping profile similar to that of an epitaxial base homojunction transistor by Harame et al (5), and the SiGe HBT with a doping profile similar to that of a III-V HBT by Schüppen et al (6). The schematic comparison in Fig. 1 shows the differencies in emitter- and base-doping level and the different Ge content.

TEMIC uses the HBT approach with low doped emitter and high doped base for low base resistivity, improved RF noise and power gain. The complete layer stack for the intrinsic transistor is realized by single wafer CVD-epitaxy. A combined schematic and SEM-crossection is shown in

Fig.2. Details of the process flow are already reported by Schüppen et al. (6). This process is a real integrated technology for mobile communication applications including npn HBT`s with and without selectively implanted collector for high speed and power respectively. Beside a lateral pnp transistor and ESD- and varactor-diodes there are in addition all needed high quality passives like MIM nitride capacitors, spiral inductors and polysilicon resistors. The parameters of the complete device arsenal are summarized in Table 1.

The principal advantages of SiGe can be demonstrated with measurement results of the SiGe1 technology: The high f_T and f_{max} values are achieved at quite low current densities and give a high frequency response with high gain and linearity (Fig.3). The low base resistance of the HBT is responsible for very low RF noise figures and maximum oscillation frequency already at moderate emitter width (Fig.4). The lower U_{BE} value makes it interesting for low voltage designs. The low value of the 1/f noise corner frequency corresponds to low phase noise of VCO`s and are ideal for high frequency direct conversion receivers (Fig. 5) . The highly doped base is responsible for high Early voltage and achievable gain.

A special feature of our HBT approach is power amplification demonstrated in Fig. 7 with a load pull result from on wafer measurement. The device with 10 emitter stripes 1.6x30 μm^2 achieved an output power of 20 dBm with power added efficiency of 62 % at a supply voltage of 3.6 V and 1.9 GHz. The measured collector current showed a positive self biasing effect. For more detailed result see Seiler et al. (7).

MANUFACTURABILITY

Introducing SiGe into the production environment does not mean to have to deal with a new semiconductor material. It is an add on modul to the mainstream Si technology and production takes place on the existing Bipolar- or CMOS-line. For the essential SiGe epitaxy we use the same single wafer CVD equipment as for the Si collector epitaxy, only with a change in process-gases and-temperatures. The substrates are standard Si substrates, 150 or 200 mm, as in RF bipolar or BiCMOS processes. For all that reasons the SiGe manufacturing costs are comparable to pure Si technology.

Because the SiGe base layer has to remain a strained layer to maintain the HBT action, with mismatch to Si-substrate and –caplayer, there are some restrictions. Depending on the thickness of the layer and the Ge content there are limitations to the absolute temperature and the temperature budget. But these requirement fit quite well with that of state of the art CMOS processes. To demonstrate the good yield of our process, Fig. 6 shows a wafer map of gummel plots with each curve representing an array of 10 000 HBTs with the current scale down to 1 pA.

To ensure the quality and lifetime of SiGe products we have done extensive reliability tests on transistor and circuit level with positive results even with a DECT PA monitored in RF-cw-mode at 1.9 GHz.

CIRCUITS

On research level a couple of circuits were investigated in the last few years, e.g. a digital to analog converter (DAC) from IBM in 1993 by Harame et al. (8), an optical transmitter circuit from NEC in 1994 by Hashimoto et al. (9), VCOs at 26GHz and 40 GHz from Daimler-Benz in 1995 by Gruhle et al. (10), and a frequency divider by Hitachi in 1998 by Masuda et al. (11). However, at the moment the biggest market share for SiGe will be in wireless communication systems in the 1 - 6 GHz range. Hence, mixers, GSM power modules, dual band frontends for GSM and PCS1800 and DECT frontends are in the focus and were designed with different customers in the SiGe1 process. Additionally, LNA circuits over a wide frequency range were designed by the University of Ulm and achieved an asssociated gain of up to 26 dB. The relatively

small band width of the 5.8 GHz LNA is an advantage for mobile communication systems, reducing the expense for the input filter. LNAs with noise figures of 1.6 dB at 5.8GHz were recently fabricated using the present SiGe1 technology (Fig.8).
The first commercial product is a DECT frontend including a LNA with 1.6dB noise figure and 20dB gain combined with a 28dBm power amplifier with 47% PAE over the whole packaged device, as shown in Fig.9 and 10. This DECT frontend is now production ready.

CONCLUSION

We have demonstrated that SiGe technology is a well suited performer for RF-circuits and mobile communication systems. Additionally SiGe technology combines manufacturability at competitive costs with high integration capability. Our SiGe1 process offers 50 GHz f_T and f_{max} with rf noise figures far below 1dB at 2 GHz and PAE values of 60% at 2GHz and 3.6 V were achieved.

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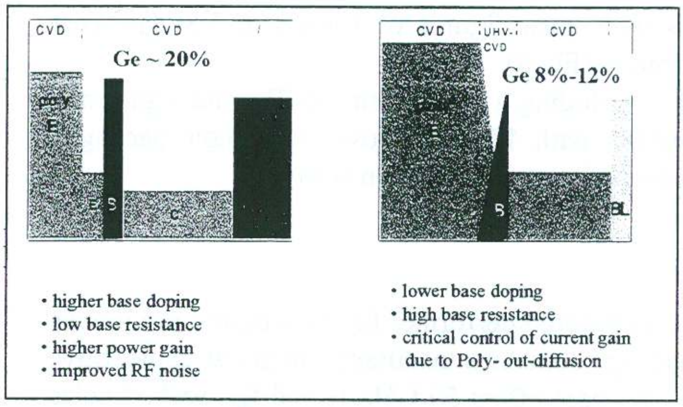

- higher base doping
- low base resistance
- higher power gain
- improved RF noise

- lower base doping
- high base resistance
- critical control of current gain due to Poly- out-diffusion

Fig.1: Comparison of schematic doping profiles of box-shaped SiGe-HBT and triangle-shaped SiGe Drift-transistor

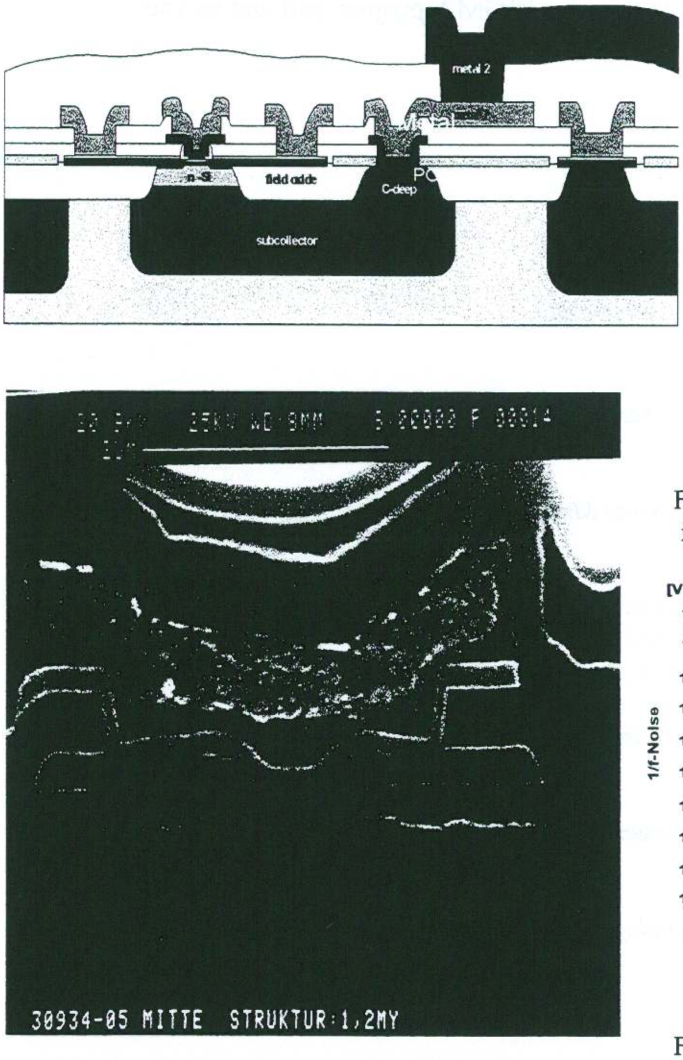

Fig.2: Schematic and SEM cross-section of SiGe1

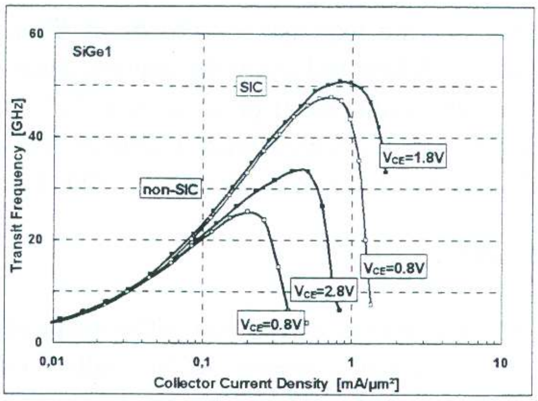

Fig.3: RF-performance of SiGe1-HBTs with and without SIC: f_T = 50GHz, BV_{CE0}= = 3V and f_T = 30GHz, BV_{CE0}= = 6V on the same wafer

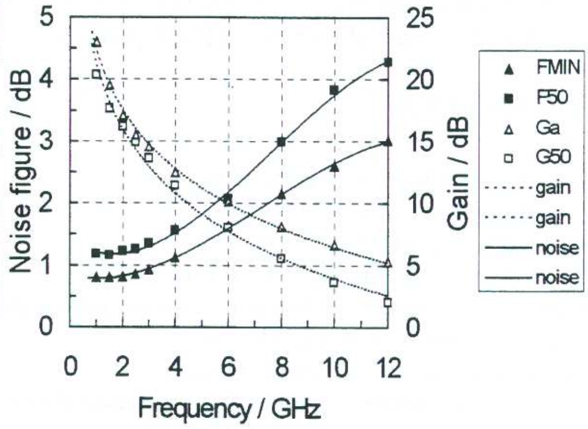

Fig.4: RF noise behaviour of a 3 emitter SiGe-HBT, having a minimum noise figure of 0.8 dB at 2 GHz

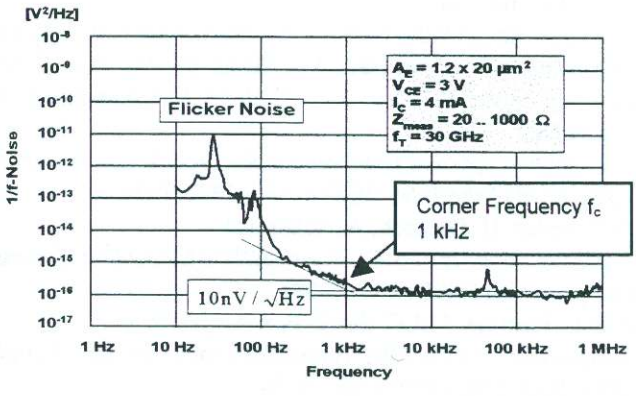

Fig.5: Low frequency noise behavior of 1 emitter SiGe-HBT showing 1khz 1/f corner frequency

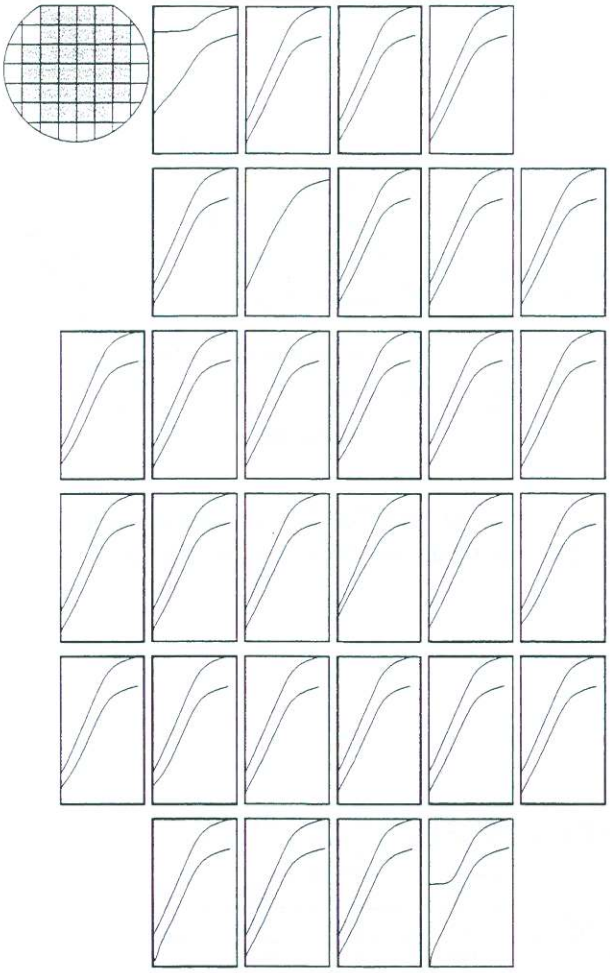

Fig.6: Gummel plot wafer mapping of 10k transistor arrays with $0.8 \times 1.6 \mu m^2$ SiGe-HBTs: y-axis: 1pA-100mA, x-axis: 0.2-1V

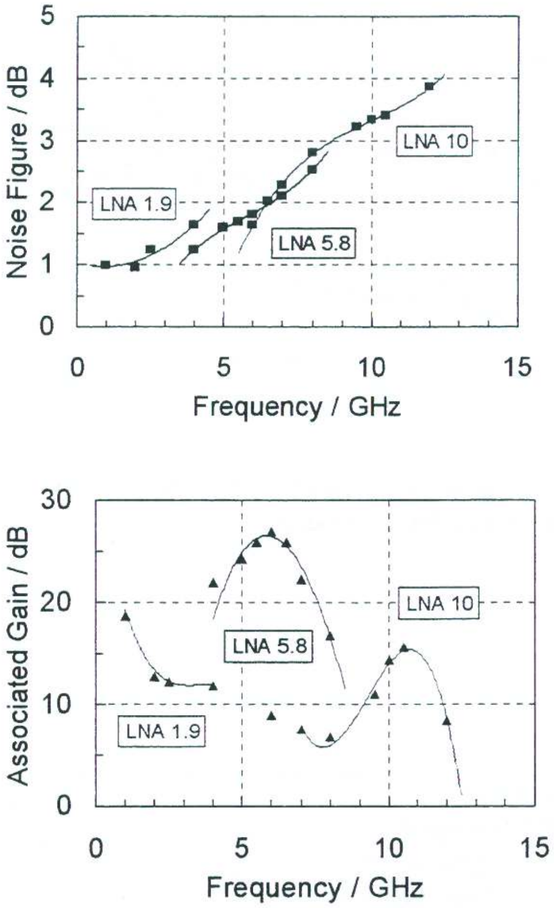

Fig.8: RF-noise figures and associated gain of high performance LNAs at 1.8, 5.8 and 10 GHz

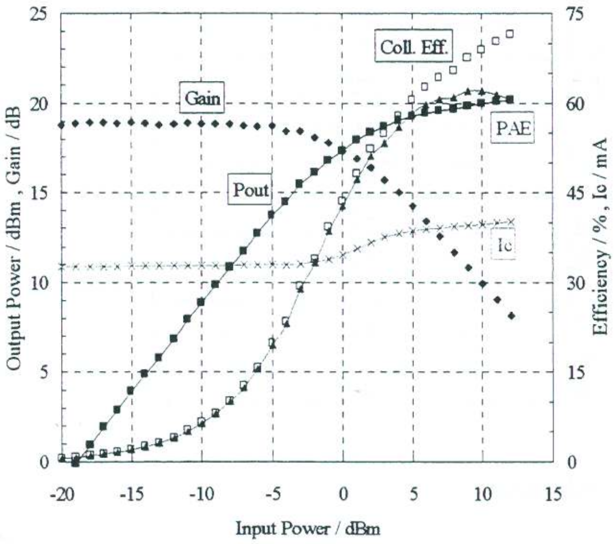

Fig.7: Load pull measurement at 1.9 GHz of a SiGe Power HBT with $10 \times 30 \mu m^2$ emitter area. DC operation point is $V_{CE} = 3.6V$, $I_C = 32$ mA, class AB

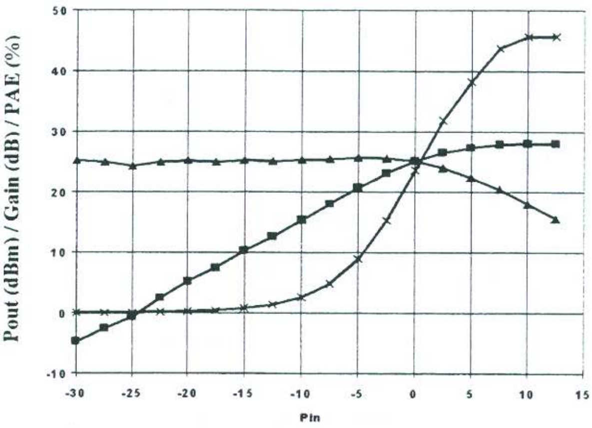

Fig. 9: Completely 3 stages DECT-PA for 2.7-3.6V operation in a SSO20 package

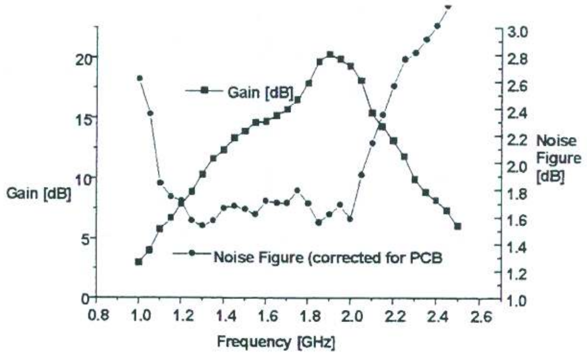

Fig. 10: LNA of the SiGe1 DECT front-end with 1.6dB noise figure and 20 dB associated gain

Parameter	[unit	non–SIC	SIC
NPN transistor			
Transit frequency	f_T [GHz	30	50
Max. frequency of oscillation	f_{max} [GHz	50	50
Current gain	h_{FE} [	180	180
Early voltage	V_A [V	>40	>40
Collector emitter breakdown voltage	BV_{CE0} [V	6.0	3.0
Collector base breakdown voltage	BV_{CB0} [V	15	12
Noise figure at 2 GHz	F_{min} [dB	1.0	1.0
LPNP			
Collector emitter breakdown voltage	BV_{CE0} [V	7	
Current gain	h_{FE} [	5	
Typical collector current	I_{CP} [µA	40	
Passive devices			
High ohmic poly resistor (poly1)	R_H [Ω/sq	400	
Medium ohmic poly resistor (poly2)	R_M [Ω/sq	110	
Low ohmic poly resistor (poly1–$TiSi_2$)	R_L [Ω/sq	4.5	
Precision MIM capacitor	c_{SPEC} [fF/µm²	1.1	
Spiral inductor 4 nH, Q–value at 2 GHz	Q [	7	
ESD Zener diode, Zener voltage	V_Z [V	6.2	
Zener diode, parasitic capacitance	[pF	5.5	
RF–ESD diode, parasitic capacitance	[pF	0.3	

Table1: Summary of the essential parameters of the SiGe1 technology