PHYSICS OF FUTURE ULTRA HIGH SPEED TRANSISTORS – PART 1: HBT

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Abstract — An overview about current status of SiGe-HBT production is given. Advanced SiGe-HBTs are predicted to reach in near future f_T=200 GHz. Design examples are given.

I. INTRODUCTION

Continous shrinkage of device dimensions and rather recently application of heterostructures have increased the frequency limits of silicon based devices into the mm-wave region (>30 GHz). We concentrate in this article on progress caused by silicon based heterostructures.

Part I is devoted to the heterobipolartransistor (HBT) which gained confidence for heterojunction devices since entering volume production. A scheme of a modern self-aligned bipolar junction transistor (BJT) is given in Fig.: 1.

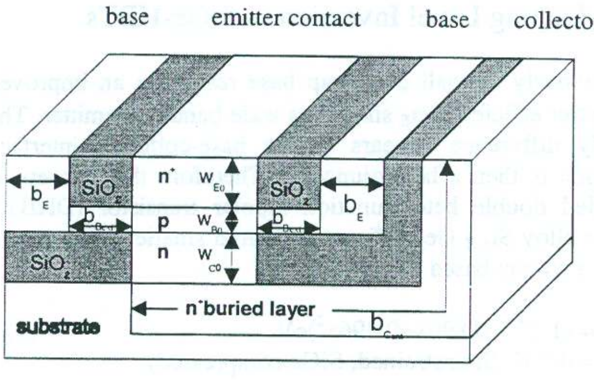

Fig.1: Scheme of an integrated bipolar transistor with poly-Si contacts and oxide isolation [1].

II. CONCEPT OF HETEROBIPOLAR TRANSISTOR

The proposal of a heterojunction bipolar transistor (HBT) was made by Shockley in 1948 [2]. Several years later, Krömer formulated the current gain relations of the HBT by a diffusion model [3].

The basic idea was the use of a wide-gap emitter in the emitter/base junction to provide a higher emitter efficiency – that is, a higher current gain in a HBT than in a homojunction bipolar transistor with the same doping levels. Wide band gap emitter HBTs were realized in the group III/V material system (for a review, see [4]). A corresponding principle – the use of a narrow band gap base in a double heterostructure bipolar transistor (DHBT) – can be realized in the material system SiGe/Si. Probably, our group was the first proposing a SiGe-DHBT in 1977 [5].The SiGe-base (Fig. 2) is nearly ideal because the band offset is almost completely in the valence band as needed for perfect DHBT operation.

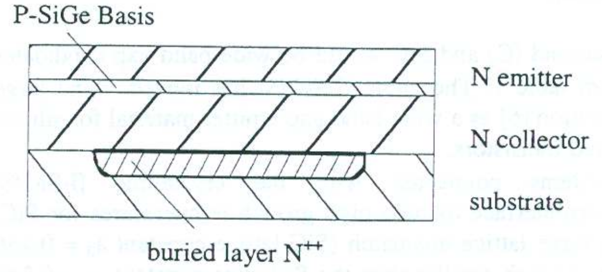

Fig. 2: Layer sequence of the SiGe-DHBT. Reproduced from the 1977 patent application [5]

The emitter of a bipolar junction transistor is much higher doped than the base to get a reasonably high current gain β in a common emitter configuration. In a common base configuration the current gain α then approaches unity (α→1 for β→∞).

$$\alpha = \alpha_E \,.\, \alpha_T \qquad (1)$$

$$\alpha_E \cong 1-((D_P.w_B.N_A)/(D_n.L_P.N_D))(e^{-\Delta E_g/kT})$$

Emitter efficiency α_E, transport factor α_T, base width w_B, diffusion coefficient D and diffusion length L, doping density N, kT = 26 meV at room temperature.

The approximation above given is also valid under some simplifying assumptions for a heterojunction bipolar transistor (HBT) with an emitter material of larger band gap (ΔE_g) than that of the base material as can be seen from equation (1).

In a HBT the doping level N_A can be increased by a proper choice of ΔE_g without sacrificing the good emitter efficiency α_E near unity. The HBT concept gives a higher freedom for the layer design of a bipolar transistor. This freedom can be used for a higher current gain β, for a lower Early voltage V_{EA}, for a higher transit frequency f_T and/or a lower base sheet resistivity R_{bi}.

A. Wide Band Gap Emitter

A wide variety of semiconductor materials exists with band gaps larger than the gap of Si (1.12 eV at room temperature). However, for a broad application in silicon based circuits the compatibility with silicon technology should be given where group IV materials would be preferred. The search for appropriate group IV materials follows two different routes. One route relies on single crystalline materials. The band gap (Table 1) of diamond lattice group IV materials decreases with increasing atomic number.

	C	β-SiC	Si	Ge	α-Sn
E_g	5.48	2.2	1.12	0,66	-
a_0	0.357	0.436	0.543	0.566	0.649
ε	5.7	6.5	11.9	16.2	(24)

Table 1: Indirect band gap E_g (eV), lattice constant a_0(nm) and dielectric constant ε for group IV materials (diamond lattice).

Diamond (C) and SiC would be wide band gap candidates from table 1. The cubic β-SiC/Si has indeed found large attention [6] as a wide band gap emitter material for silicon based transistors.

Problems connected with the crystalline β-SiC/Si heterointerface include high growth temperatures for SiC, the large lattice mismatch (SiC lattice constant $a_0 = 0.436$ nm is much smaller than the Si lattice constant $a_0 = 0.543$ nm) and a typ I band offset. A type I band offset results in an electron energy spike at the interface for the n/p^+-junctions of an HBT. Usually, this spike is avoided by a gradual transition which is not possible in the SiC/Si – system. The other route utilizes the band gap modulation with phase changes (hydrogenated amorphous silicon, a-Si:H) or with strong localization/quantization (microcrystalline silicon, μ-Si). The heterophase boundary (a-Si/Si or μ-Si/Si) can be used for the HBTs because μ-Si (E_g = 1,4 eV) and a-Si (E_g = 1,7 eV) exhibit larger band gaps than single crystalline silicon (E_g = 1.12 eV). Doping of a-Si:H and low mobility and therefore high emitter resistances cause the main problems within this heterophase route. Absorption in a-Si is much stronger than in crystalline Si which could be used in some optoelectronic applications.

Remaining problems of wide band emitter solutions with technology, parasitics and material quality shifted activities to small band gap base solutions.

B. Carrier Drift through the Base

In high frequency bipolar transistors the base transit time τ_B contributes essentially to the total transit time $(1/(2\pi f_T))$ measured by the transit frequency f_T. For a pure diffusion current the base transit time is given by

$$\tau_B = W_B^2 / 2D_n \qquad (2)$$

with base width w_B and minority carrier diffusion coefficient D_n. E. g. for w_B = 100 nm, D_n = 5 cm²/s the transit frequency will be below 15 GHz. The transit time τ_B can be reduced by an internal electrical field (carrier drift). A Ge content gradient through the base provides the necessary electrical field. With homogeneous doping (Fig.3) the mean electric field strength E is roughly given by $\Delta E_g/e\, w_B$ leading to reduced transit times.

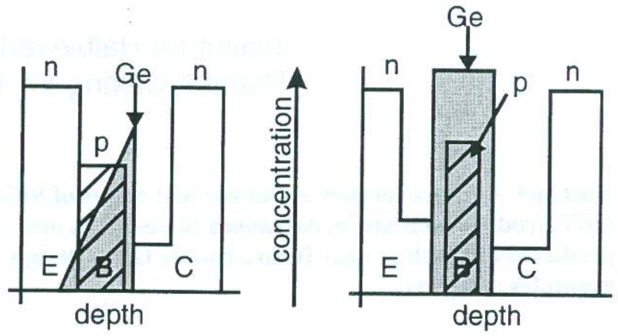

Fig. 3: Scheme of a drift field transistor with a graded SiGe base (left side) and of the double heterojunction bipolar transistor (right side).

The main advantages of the SiGe drift base are given by an easy implementation into existing technologies and by a low Ge content stable structure [7]. The implementation into existing bipolar technologies leaves the drift transistor with a drawback common to high frequency BJT's. Base sheet resistivities increase with decreasing base widths because of low base doping/high emitter doping.

C. Doping Level Inversion in SiGe-HBTs

Obviously a small band gap base results in an improved emitter efficiency α_E similar to wide band gap emitter. The only difference appears at the base-collector interface which is then a heterojunction. Therefore this concept is called double heterojunction bipolar transistor (DHBT). The alloy $Si_{1-X}\,Ge_X$ offers the desired smaller band gap E_g for a silicon based DHBT [8].

$$E_g = (1.17 - 0{,}896x + 0.396x^2)\text{eV} \qquad (3)$$

(T = 4.2 K, Si unstrained, SiGe compressed)

But in pseudomorphic structures on Si (no misfit dislocations) the obtainable band gap differences ΔW_g are limited to below 150meV-200meV because of the lattice mismatch η between SiGe and Si.

Lattice mismatched material may grow completely strained up to a critical thickness which strongly decreases with increasing mismatch η. For typical base widths (15 nm – 50 nm) of high frequency HBTs the critical thickness criterion limits the choice of SiGe alloys to Si rich (x=0.3–0.2) ones. Nevertheless, it was demonstrated that the improved emitter efficiency allows a complete inversion of the doping levels in such strained SiGe-DHBTs [10]. Instead of doping the emitter very high as in bipolar junction transistors (BJT) now the base is doped to much higher doping levels than the emitter (Fig. 3). The DHBT-concept provides therefore very thin base layers with acceptable or even improved base sheet resistivities (typical 1kΩ/□ to 7kΩ/□) leading to excellent high frequency properties, low noise, high current gain and low Early voltages.

The DHBT concept may be combined with a Ge gradient to further reduce the base transit time τ_B. Several groups have now obtained with specific layer structures transit frequencies f_T or maximum oscillation frequencies f_{max} well beyond 100 GHz [11-13]. Several integrated circuits for microwave applications were demonstrated [14,15] which open the route to monolithic microwave integrated circuits based on silicon transistors [16].

III. INDUSTRIAL AVAILABILITY

Mainly two industrial groups pushed SiGe as a commercial technology [17], namely IBM and Daimler Benz/TEMIC. IBM´s SiGe HBT technology for wireless communications went into high-volume production autumn 1998. A range of products, including low-noise amplifiers, voltage-controlled oscillators and low-noise transistors are being fabricated at IBM´s Advanced Semiconductor Technology Center in East Fishkill, New York, and Burlington, Vermont.

With its eyes on future applications in cellular phones, GPS products and fibre-optic networks, IBM has joint development agreements with Hughes Electronics (Malibu) and Nortel (Ottawa).

The fruits of Daimler-Benz´s research (now Daimler-Chrysler) have been implemented by Temic Semiconductors, originally a microelectronic component off-shoot from Daimler-Benz, but since late last year a subsidiary of Atmel. It`s front-end IC U7004B SiGe chips for cordless DECT phone applications, offering lower noise, higher switching speed and lower power consumption, have been on the market since October 1998. Series production at Temic´s semiconductor plant in Heilbronn, Germany, uses progressive and automated line for 6" wafers guaranteeing high quality.

Over 30 companies around the world are now developing SiGe IC`s. A recent device market forecast [18] predicts a strong increase of the SiGe-HBT market to USD 1800 M in 2005. According to this study applications such as wireless and satellite-based voice and data services are expected to drive 80 percent of the demand in 2002, whereas high-speed computer networking applications, consumer, industrial and military uses will account for the remaining 20 percent.

Let us sketch the development from the idea to the volume production on the example of Temic, a specific selection, because of the European based production in South Germany (Heilbronn). When Erich Kasper and Peter Russer filed a patent application [5] in 1977 the device technology was by far not ready to realize this SiGe HBT. Twelve years later (1989) the rapid progress in semiconductor technology allowed to process true HBT structures [19]. In this early days, the competing efforts of an IBM group were more devoted to a SiGe drift transistor [20] which was easier to implement in the available excellent bipolar technology of this company. Within the following few years the speed of the true HBTs jumped beyond 50 GHz (1992, [21]) and 100 GHz (1994, [22]), respectively.

The transfer [23] in the production started with a feasibility study 1993 and was intensified since 1996.

Temic offers since 1998 a first production technology, called SiGe1, including npn HBTs with and without selectively implanted collector (SIC) on the same wafer.

The main important issue of the technology is the differential growth of the SiGe layer after a standard recessed LOCOS process. The SiGe-poly is used for the base contact and for two of the three resistor types. The emitter has an inside and an outside spacer and an additional alpha-silicon layer in order to perform the emitter and the collector contact. A cross section of the first generation of SiGe-HBTs is given in Fig. 4

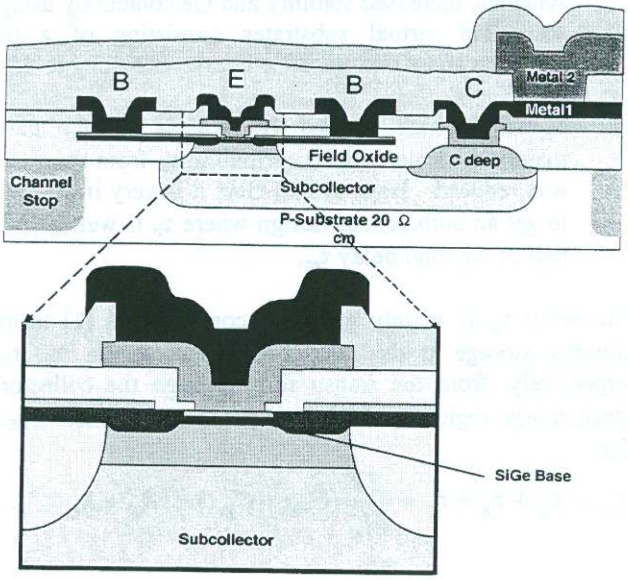

Fig. 4: Cross section of a commercial SiGe-HBT (SiGe1 technology of Temic Atmel [23])

In addition, spiral inductors, nitride capacitors, three types of poly resistors, a LPNP, rf- and dc- ESD protection and varactor diodes are incorporated in the present technology.

The SiGe 1 technology is comparable in terms of masks and costs to a standard double poly Si BJT process. Therefore this technology is well suited for large scale integration (LSI), as nicely demonstrated by a wafer mapping of the 10k transistor arrays over a typical 6 inch wafer. In addition, a couple of lifetime tests on single HBTs and complete packaged circuits were all positive and were summarized in a special qualification report. The process was recently qualified.

The SiGe HBTs reveal transit frequencies f_T of 30 GHz with a collector emitter breakdown voltage of BV_{CEO}=6V and 50GHz with BV_{CEO}=3V, respectively.

SiGe1 is used for RF low noise amplifiers and power amplifiers in mobile phones, e.g. DECT, GSM, DCS1800, CDMA, TDMA. In addition, gain blocks, dualband transceivers and mixer circuits for base stations are in the product portfolio.

The quality and the reproducibility of the technology were demonstrated by highlights as functioning 10k arrays over whole wafers and lots, by 0.5W power HBTs revealing 72% PAE at 900 MHz and 64% at 1.8GHz, a LNA at

5.8GHz with a record noise figure of 1.6dB and 26dB associated gain, and a 2:1 multiplexer showing a clear eye diagramm at 40 Gbit/s.

IV. FUTURE TRENDS

We will see in the near future a lot of activities in at least three directions.

(i) Integration efforts for more complex circuits and circuits with higher frequencies up to the mm-wave region.

(ii) Technology efforts to facilitate easier manufacturing. Low temperature processing, suppression of transient enhanced diffusion, refined integration schemes, increased stability and Ge content by using so called virtual substrates consisting of a Si substrate and a relaxed SiGe overlayer belong to this point.

(iii) Speed increase beyond f_T=200GHz. In the past mainly the time delay contribution τ_B from the base was reduced. Beyond 100 GHz it is very important to get an outbalanced design where τ_B is well below half of the total delay τ_{ec}.

The delay τ_{ec} is mainly given by contributions [1] from minority storage at the emitter and base region, τ_E, τ_B respectively, from the transit time through the collector space charge region τ_C, from load times of capacities C_{BE}, C_{BE}.

$$\tau_{ec} = \tau_E + \tau_B + \tau_C + \frac{\beta T}{qI_C}(C_{BE} + C_{BC}) + (R_E + R_C)C_{BC}$$

where the contributions τ_B, τ_C are given for a proper designed flat profile by

$$\tau_B = W_B^2 / 2D_n \qquad \tau_C = W_C / 2v_S$$

with w_B, w_C widths of base and collector, respectively, and D_n, v_s diffusion constant of electrons, and saturation velocity of electrons, respectively. The delay time τ_E often may be neglected with HBTs. In our design for a 200 GHz transistor [24] we spend roughly 1/3 of the total delay for τ_E, 1/4 for τ_C and the rest for loading of the capacities. The proposed layer structure is given in Table 2. Even for a relaxed layout (1µm emitter finger, 2µm base width) the SiGe-HBT should reach the 200 GHz limit. Without considering velocity overshoot effects a transit frequency of f_T=185GHz is calculated [24].

n^{++}-buried layer:	$d_{Sub} = 4$ µm	$\rho = 2$ mΩcm	
n-collector :	$d_k = 45$ nm	$N_c = 1\ 10^{17}$ cm^{-3}	
n^+SiGe-Spacer:	d = 5 nm	$N_D = 1\ 10^{18}$ cm^{-3}	$Si_{0,72}Ge_{0,28}$
p^{++}SiGe-Basis:	d = 17.5 nm	$N_A = 8\ 10^{19}$ cm^{-3}	$Si_{0,72}Ge_{0,28}$
i-SiGe-Spacer :	d = 5 nm		$Si_{0,72}Ge_{0,28}$
n-emitter :	d = 25 nm	$N_D = 4\ 10^{17}$ cm^{-3}	
n^+-emitter :	d = 25nm	$N_D = 3\ 10^{18}$cm^{-3}	
n^{++}-emitter :	d = 15nm	$N_D = 3\ 10^{20}$cm^{-3}	

Table 2: Proposed layer structure for a 200GHz SiGe-HBT

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