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Silicon Based HBT: Comparison of Concepts

E. Kasper
Institut für Halbleitertechnik, Universität Stuttgart, 70049 Stuttgart, Germany

1. Introduction

The emitter of a bipolar junction transistor (BJT)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 ($\alpha \rightarrow 1$ for $\beta \rightarrow \infty$).

$$\alpha = \alpha_E \cdot \alpha_T \qquad (1)$$

$$\alpha_E \cong 1 - ((D_p \cdot w_B \cdot N_A) / (D_n \cdot L_p \cdot N_D)) (e^{-\Delta W_g / kT})$$

Emitter efficiency α_E, transport factor α_T, base width w_B, diffusion coefficient D and diffusion length L, respectively 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 (ΔW_g) than that of the base material (Fig. 1) as can be seen from equation (1).

In a HBT the doping level N_A can be increased by a proper choice of ΔW_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 E_A, for a higher transit frequency f_T and / or a lower base sheet resistivity R_{bi}. In the following section (2) the classical concept of a wide band gap emitter is treated. Sections (3) to (5) deal with SiGe as small band gap base material from the already developed drift transistor to future strain adjusted HBT's with strong doping level inversion.

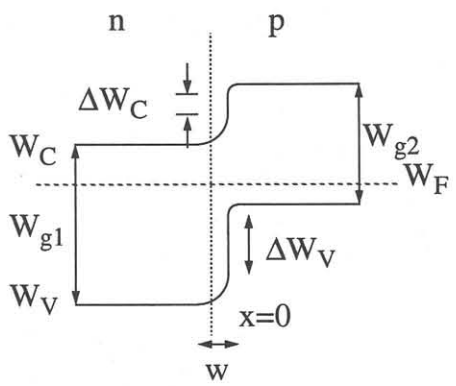

Fig. 1: Band structure of a n / p^+ heterojunction with ideal type II band offsets (staggered) ΔW_C and ΔW_V.

2. 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	a-Si
W_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 W_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 has indeed found large attention /1/ 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 type 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 HBT's because μ-Si (W_g = 1.4 eV) and a-Si (W_g = 1.7 eV) exhibit larger band gaps than single crystalline silicon (W_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 gap emitter

solutions with technology, parasitics and material quality shifted activities to small band gap base solutions which are described in the next sections.

3. 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 cm^2 / 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. 2) the mean electric field strength E is roughly given by $\Delta W_g / e \cdot w_B$ leading to reduced transit times.

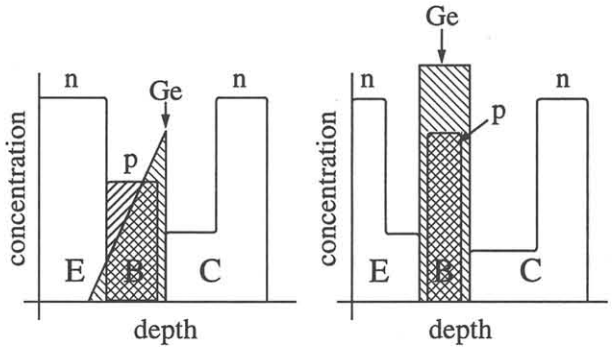

Fig. 2: Scheme of a drift field transistor with a graded SiGe base (left side) and of the double heterojunction bipolar transistor (right side).

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. The first industrial realizations of high speed SiGe transistors and integrated circuits followed this concept /2/ which is mainly driven by work at IBM. 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. The following section shows how to overcome this problem.

4. Doping Level Inversion in SiGe-HBT's

Obviously a small band gap base results in an improved emitter efficiency α_E similar to the 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 W_g for a silicon based DHBT /3/.

$$W_g = (1.17 - 0.896x + 0.396x^2)\ \text{eV} \qquad (3)$$
(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 150 meV-200 meV because of the lattice mismatch η between SiGe and Si. The lattice constant a of SiGe increases with Ge content x /4/.

$$a(x) = (0.5431 + 0.01992x + 0.002733x^2)\ \text{nm} \qquad (4)$$

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 HBT's 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-DHBT's /5/. 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. 2). The DHBT-concept provides therefore very thin base layers with acceptable or even improved base sheet resistivities (typ. 1 kΩ / ❐ to 7 kΩ / ❐) leading to excellent high frequency properties and low noise /6/ or high current gain (up to 5000 was obtained at room temperature) and low Early voltages. The leading industrial proponent of the SiGe-DHBT concept is the Daimler Benz group (with Telefunken microelectronics as their semiconductor branch). With rather conservative lithography rules (1 µm emitter finger width) they realized world record values for both f_T (116 GHz) and f_{max} (90 GHz) of silicon based bipolar transistors /7/. A further improvement also for power transistors should be expected in the near future.

5. Strain Adjustment: Transport Factor as Limiting Effect

Let us consider lattice mismatched material couples like $Si_{1-x}Ge_x$ / Si with a common lattice spacing at the interface which means no misfit dislocation at this interface. The value of this common lattice spacing defines the strain status in both materials. The most common solution is to choose the lattice spacing of the underlying substrate in our case that of silicon. Then and only then the Si layers will be unstrained and the SiGe layers will be compressively strained. From an energetic point of view a strain adjustment with tensile strain in Si and compressive strain in SiGe would be favourable which calls for an intermediate lattice spacing of the

SiGe / Si couple. The „virtual substrate" technique /8/ allows this strain adjustment by placing a relaxed buffer layer between the substrate and the strain adjusted film stack. Strain adjusted film stacks exhibit three general properties of which the first two can be used advantageously for material engineering.

(i) Material properties like band offsets may be tailored by the strain.

(ii) The critical thickness of the pseudomorphic film stack itself may be enhanced considerably by the lower energy of strain adjusted films.

(iii) The relaxed buffer layer causes a misfit dislocation network between buffer and substrate acting as getter inside the virtual substrate.

But state of the art growth techniques require thick buffer layers and degrade the quality of the overlying material by threading dislocations.

A principal scheme of a strain adjusted SiGe-HBT is proposed in fig. 3. The buffer layer is buried within the n^+-doped subcollector. It could consist e.g. of a partly relaxed $Si_{0.6}Ge_{0.4}$ layer with a compressive remaining strain of $\varepsilon = -0.4\%$. The following n-doped $Si_{0.7}Ge_{0.3}$ collector is strain free, whereas the p-base ($Si_{0.4}Ge_{0.6}$) is compressively strained and the n-emitter (Si) is tensily strained. The parameters are chosen to prepare the desired type II emitter-base heterointerface and to increase the Ge-content in the base to 60% for a large band gap difference ΔW_g between emitter and base. For a large band gap difference (e. g. ΔW_g = 300meV) the current gain β could be increased by the improved emitter efficiency α_E to several millions if there would be no other limiting factors. The limiting factor in such heterostructures is the recombination of minority carriers during their transport through the base. The transport factor α_T should be near unity and at least more than 0.98. For minority carrier diffusion lengths L_n larger then the base width w_B the following approximations are valid for the transport factor α_T and the current gain β, respectively (emitter efficiency $\alpha_E = 1$ assumed).

$$\alpha_T = 1 - 0.5\,(W_B / L_n)^2 \qquad (5)$$

$$\beta = 2\,(L_n / W_B)^2$$

For a typical 20 nm base width HBT the diffusion length L_n has to be above 0.1 µm which should be obtained even with the degraded crystal quality of state of the art virtual substrate material.

The strain adjusted SiGe-HBT offers nearly unlimited choice and optimization of the doping levels because current gain is not defined by them up to levels of several $10^{20}/cm^3$. First prototypes will be realized in the near future. A relaxed buffer layer technique with thin buffer thicknesses could enhance the acceptance of this HBT concept.

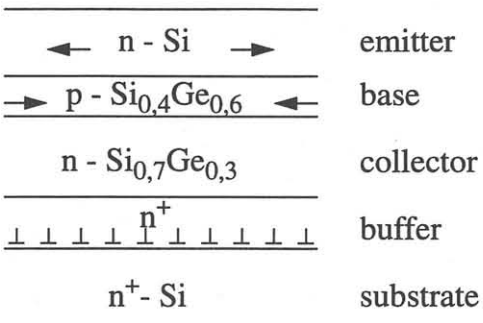

Fig. 3: Layer structure of the strain adjusted SiGe-HBT. Arrows mark the strain, misfit dislocations are indicated by ⊥.

6. Conclusion

Bipolar circuits will benefit from improved silicon based HBT properties especially for high frequency operation. The advantage of the HBT is based on the enhanced freedom for the doping profile design because the necessary emitter efficiency is provided by the heterojunction band offsets. Wide band gap emitters (predominantly SiC and a-Si) require further material research and suppression of parasitic effects to prove their high device potential. SiGe is the chosen material for small band gap HBT's. Both, the early version of a drift field transistor and the more recent one with dopant level inversion have surpassed the 100 GHz f_T-limit. In the author's opinion a strain adjusted version with nearly unlimited choice of doping levels will be the ultimate technical solution. But this needs further progress in epitaxial strain adjustment techniques.

7. References

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