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High Speed Performance of Si Homo- and $Si/Si_{1-x}Ge_x$ Heterojunction Bipolar Transistors

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Abstract

One intention of our investigations was to compare devices with base profiles resulting from different types of base formation. The first type of base profiles used in the simulations (type I) is fabricated conventionally by ion implantation [1], the second by epitaxial growth of Si (type II). An epitaxially grown base offers the possibility of profiles which show a significantly increased gradient of the base dopant concentration towards the collector. This is the feature which we are mainly interested in. In terms of numbers this means 17 nm/decade in the case of an epitaxial base (even 10 nm/dec are possible) compared to a minimum of 40 nm/dec with an implanted one, as seen in Fig. 1.
A larger collector-side gradient of the base profile results in a thinner base necessary to reach a certain doping level starting from a given level at the collector-base junction, where we assumed a figure of $1.8 \cdot 10^{17}\,cm^{-3}$ for all our devices. A thinner base reduces base transit time. The grading also causes an accelerating electric field in the quasi-neutral base, which further reduces base transit time.
In fixing the value of the base sheet resistance, the base transit time τ_B can be reduced by raising the doping level in the base and simultaneously shrinking its width. This is explained by the fact that the base transit time depends much more strongly on the base

1. Introduction, Doping and Germanium Profiles

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In fixing the value of the base sheet resistance, the base transit time τ_B can be reduced by raising the doping level in the base and simultaneously shrinking its width. This is explained by the fact that the base transit time depends much more strongly on the base

width than on the reduction of the diffusion constant, due to more dopant which alone would increase it. Yet the distance required to reach a certain base doping level is determined by the gradient of the base profile as stated above. If the base width is made smaller, the sheet resistance cannot be maintained. Other limits are given by the rise of EB-junction capacitance and reduction of EB-breakdown voltage with an increase of base doping level. We therefore consider profiles with a maximum doping level in the base which is not higher than $5 \cdot 10^{18}$ cm^{-3}.

For the epitaxially grown base, we discuss the improvements made possible by introducing linearly graded Ge into the base, reaching a maximum content of 20% (type III). The addition of Ge to the base gives rise to a much higher I_C at the same emitter base bias, resulting in a much lower emitter transit time τ_E. By grading the Ge content over the base layer, i.e. increasing its concentration from emitter to collector, an additional electric field in the base can also lower τ_B. The higher the Ge content at the emitter-sided edge of the base (or rather the increase over the emitter-base depletion region), the higher is I_C. But the maximum Ge content is limited by the permitted thickness of the strained SiGe-layer, for thicker layers might relax, leading to degradation of the device. Thus the higher the Ge content at the emitter-sided edge, the shallower the grading in the base. This results in the compromise of reducing both τ_E and τ_B in order to get opimal device performance for case III.

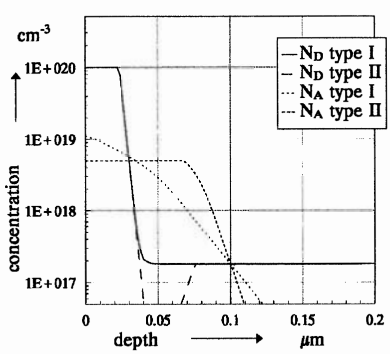

Fig 1: Doping profile of device types I and II

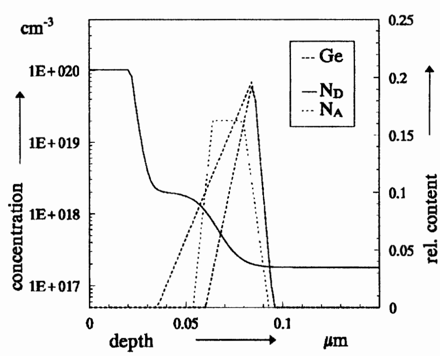

Fig 2: Doping and Ge profile of device type IV

In addition to these devices, we also present performance data of an advanced HBT with a lightly doped emitter layer at the emitter base junction (type IV), similar to the device presented in ref. [2]. With the aid of Ge in devices like thse of type III, the reduction of τ_E is much more noticable than that of τ_B. To make the most out of the addition of Ge, a device is to be bulit where τ_B is reduced to a comparable extent. This can be done by fully utilizing the possibilities of very steep and highly doped - almost box-like - base profiles, which can be fabricated by epitaxial growth. The very high doping of the base leads to base layers with very low sheet resistance - even when they are very shallow. This is another important characteristic of high-speed bipolar junction transistors. But the very thin space charge region of two highly doped layers succeeding one another (emitter and base in this case) leads to unwanted leakage currents [3]. To get rid of them a more lightly doped layer

in the emitter can be introduced. In our studies we used a doping concentration of $2 \cdot 10^{18}$ cm^{-3} for this layer. Its width has an important influence on τ_E and thus on f_T. Therefore it will be made as small as permitted by the leakage currents [3].
With this type of profile f_T is much more sensitive to variations of the starting point of the Ge grading (Fig. 2), representing the inevitable compromise when trying to reduce both τ_E and τ_B.
The simulations are performed by running an extended version of a conventional one-dimensional drift-diffusion equation solver [4], which has been adapted for Si/SiGe heterostructures [5]. The device parameters are extracted from the quasistatic device internal steady state distributions of electrons and holes.

2. Results

For a device of type I holding the base sheet resistance at the value of 10 kΩ and taking the stated limits into consideration the base width be cannot reduced below 70 nm. This leads to a f_T of 43 GHz, compared to 32 GHz with a base width of 100 nm. The corresponding numbers for type II are 48 nm instead of 84 nm with an improvement in f_T from 33 to 54 GHz (Fig. 3), for a 10 nm/dec base profile gradient 63 GHz are reached.

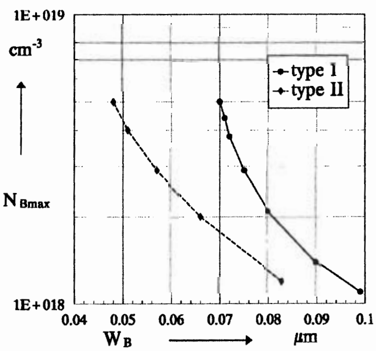

Fig. 3 : Boron doping concentration N_B vs. basewidth W_B at a fixed value of intrinsic base sheet resistance R_{pi} of 10 kΩ for device type I and II

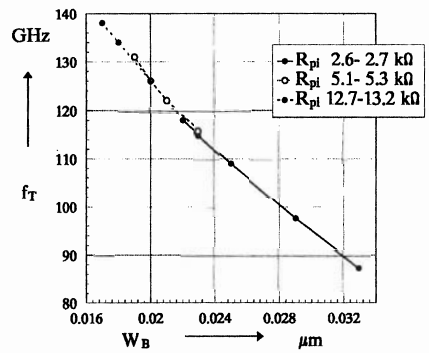

Fig. 4: Maximum f_T vs. baswidth for various values of intrinsic base sheet resistance for device type IV

A similar study was also performed with device IV. For a base sheet resistance of about 2.6-2.7 kΩ a range for f_T can be covered which extends from as low as 87 GHz up to values of 120 GHz, representing doping values of the base ranging from $1.5 \cdot 10^{19}$ cm^{-3} to $5 \cdot 10^{19}$ cm^{-3}. The limits here are again set by the height of the maximum base doping which can be reached for a given base width. For about 13 kΩ sheet resistance even 140 GHz are possible (Fig 4) for $3.4 \cdot 10^{19}$ cm^{-3} base doping.
As mentioned above an important factor for device IV is the inevitable compromise of simultanously lowering τ_E and τ_B. The position in the emitter where the Ge grading starts is measured as the (negative) distance to the metallurgical emitter base junction. As can be

seen in Fig. 5, an optimum of 95 GHz for this parameter at about -15 nm can be achieved, when $2 \cdot 10^{19}$ cm^{-3} is assumed as the doping level of the base.
Now the four types of profile can be compared by considering the variation of maximum transit frequency f_T with base sheet resistance R_{pi} (representing the changing of base width) for a maximum base doping of $5 \cdot 10^{18}$ cm^{-3} for technology I-III and $2 \cdot 10^{19}$ cm^{-3} for IV. The results are plotted in Fig. 6. As can be seen, a moderate improvement in f_T for a given R_{pi} is obtained due to the steeper slope of the epitaxial base compared to the implanted one. A significantly higher f_T can be achieved by grading Ge over the base of the transistor. This is further enhanced by the significantly shallower and higher doped base, accompanied by a steeper Ge concentration gradient in device IV.

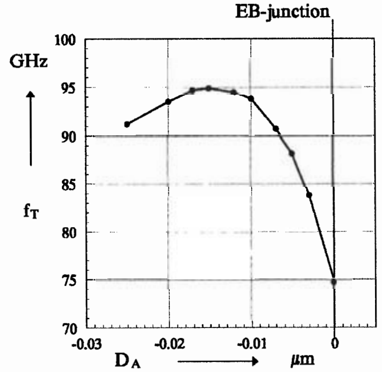

Fig 5: Maximum transit frequency f_T vs. distance D_A of the starting point of Ge grading

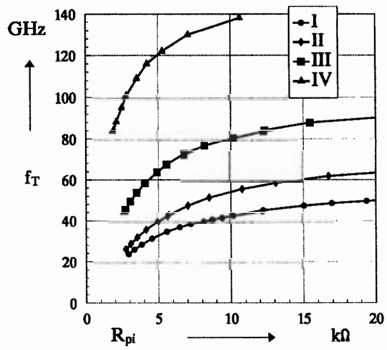

Fig. 6: Maximum transit frequency f_T vs. pinched base sheet resistance R_{pi} for different types of processing

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