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Growth of 100 GHz SiGe-HBT Structures

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The complete structure of high frequency SiGe-HBTs is grown in one run by a Si-MBE process. The thickness of the double heterojunction SiGe base layer was reduced from 65 nm to 25 nm. The electronic quality of the material is confirmed by excellent high frequency performances. The transit frequencies f_T span from 20 GHz (thicker SiGe layers) to 100 GHz for the transistors from thinner SiGe layers.

1. Introduction

Bipolar junction transistors need an emitter higher doped than the base for the desired emitter efficieny (current gain). This layer design restriction is eliminated by the concept of the heterobipolar transistor (HBT) where the emitter made from a larger bandgap material provides enough efficieny for a nearly unrestricted choice of the doping levels of emitter and base. A modification of this concept relies on a small band gap base material with a double heterojunction (emitter/base and base/collector). Several groups have now succeeded to realize silicon based heterobipolartransitors with a SiGe base (SiGe-HBT). The layer design freedom gained by the SiGe-HBT can be advantageously used to improve the speed of silicon based transistors. At least three groups demonstrated SiGe-HBT's with f_T = 50 GHz - 91 GHz /1-3/. Very recently /4/ an IBM group and our group reported to have overcome the 100 GHz limit.

2. Device fabrication

The layer designs and the transistor fabrication schemes of the various groups differ considerably with respect to Ge content, Ge grading, base sheet resistivity, growth technique and post epitaxial processing. We used here a processing scheme which is based on:

(i) Growth of the complete structure (collector, base, emitter, emitter contact) in one epitaxy run.
(ii) Simple device definition by double mesa etching /5/
(iii) No postepitaxial heat processes above 600 °C.

This processing scheme allows rather easy and rapid tests of HBT-structures but is limited to small scale IC's.

3. Growth of the complete layer sequence

The complete layer sequence of the SiGe-HBT is grown in one run by MBE on top of a p -substrate with an appropriate n^+ -buried layer (arsenic doped with a sheet concentration of $2 \cdot 10^{16}/cm^2$). The MBE equipment used (Si-MBE B) was already decribed /6/. Here we only report about the different doping techniques applied for the realization of the npn transistor and the n^+ emitter contact (the n^+ -collector contact is provided by the buried layer). Table 1 gives an overview about the growth temperatures and the applied doping techniqes which are mainly determined by the selected growth temperature regime. Growth started at 650 °C (collector) and finished at 325 °C (emitter contact). Before and after growth annealing temperatures of 900 °C and 600 ° C were utilized for substrate cleaning and crystal ordering, respectively. Antimony is used as n-type dopant material.

TABLE 1: Growth temperature and doping methods [4]

Process step	Temperature (°C)	Doping method
Substrate cleaning	900	-
Si collector	650	Sb, DSI
$Si_{1-x}Ge_x$ base	530	B, elemental
Si emitter	450	Sb, PBU
Si emitter contact	325	Sb, LTD
Anneal	600	-

DSI, doping by secondary implantation: LTD, low temperature doping: PBU pre-build-up.

Si atoms ionized at the electron beam evaporator and accelerated by a substrate voltage of typically few hundred volts helped to incorporate adsorbed Sb atoms at 650 °C growth temperature when spontaneous incorporation is nearly negligible. The method is called doping by secondary ions (DSI /7/). Doping levels of $10^{18}/cm^3$ can be obtained by the pre-build up (PBU) of a submonolayer Sb adatom layer at lower growth temperatures (450 °C) when Sb incorporation is small. Nearly complete incorporation of the impinging Sb atoms is provided at lower growth temperatures (325 °C) when segregation of Sb adations is suppressed by kinetic reasons (LTD low temperature doping). Boron is used as p- type dopant material. In the equipment used the boron atom beam is generated by evaporation of elemental boron from a special high temperature effusion cell /8/. Boron is easily incorporated at a growth temperature of 530 °C.

The general structure of the HBT is shown in Table 2. The layer sequence starts with the n-type collector doped with Sb. The highly boron doped base (several $10^{19}/cm^{-3}$) is clad on both sides by intrinsic layers with thicknesses of a few nanometer. These intrinsic layers allow for a small segregation or outdiffusion of boron and should therefore be designed in accordance with the complete processing scheme. The following emitter and emitter contact layers are Sb-doped to about $10^{18}/cm^3$ and $10^{20}/cm^3$, respectively.

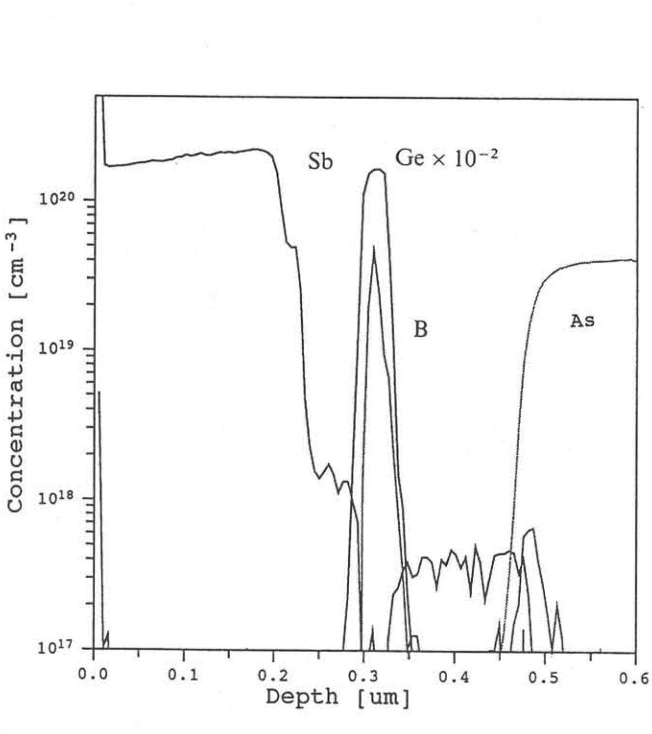

Fig. 1: SIMS profile of sample B2640. From right to left; subcollector (As), collector (Sb), base (Ge $\cdot$ 10^{-2} B), emitter (Sb), emitter contact (Sb).

In the one series we are mainly reporting here the thicknesses of the SiGe layer were decreased from 65 nm to 25 nm. Simultaneously the thicknesses of the boron doping were decreased from 50 nm to 10 nm. The transit frequencies f_T increased from 20 GHz to 100 GHz partly due to a lower base transit time.

TABLE 2: As-grown layer sequence of the $Si_{1-x}Ge_x$ heterobipolar transistor where the specific values given are from sample 2640

Function	Thickness	Doping ($10^{17}/cm^3$)	Ge content x
Collector	130	Sb (4)	0
Cladding	15	i	0,28
Base	10	B (600)	0,28
Cladding	2	i	0,28
Emitter	70	Sb (20)	0
Emitter-contact	230	Sb (2000)	0

The specific layer parameters of the sample (B2640) with the highest f_T (101 GHz) are summarized in table 2. A very thin intrinsic cladding layer (2 nm) between base and emitter is realized besides the small boron doping layers. SIMS analysis (Fig. 1) essentially confirms a chemical structure which was grown by MBE very similar to the intended one. Furtheron an analytical problem is the measurement of the intrinsic layer widths (cladding layers) and of the boron profile on a nanometer scale.

4. X-ray analysis

Bragg-case X-ray diffraction is a powerful fast analytical tool which is extremely employed for characterization of semiconductor heterostructures. The method is highly sensitive to lattice parameter differences, layer thicknesses, an crystal disorder. For the assessment of the HBT's we used a high resolution X-ray diffractometer equipped with a four - crystal monochromator (Philips MPD 1880 HR).

In figure 2a the rocking curve of the HBT sample B 2640 is given showing well resolved the diffraction lines from the Si substrate, the $Si_{1-x}Ge_x$ base, and the Sb doped, emitter contact layer surrounded by the pendellösung oscillations resulting from the respective layer thicknesses.

Important layer parameters like Ge content in the base and layer thicknesses can be gained by a simple, graphical evaluation of a rocking curve. A full interpretation, however of an experimental diffraction pattern requires the comparison with computer simulations of model structures because with this method additional details like interface sharpness, layer homogeneity and crystal perfection are taken into account. The computer simulation of a model HBT (figure 2b) consisting of a 27 nm $Si_{0.715}$ $Ge_{0.285}$ base, a 75 nm Si emitter, and a 235 nm thick Si contact cap (~ 3 $\cdot$ $10^{20}/cm^3$ Sb doped) yields a virtually perfect fit to the experimental curve indicating excellent structural quality.

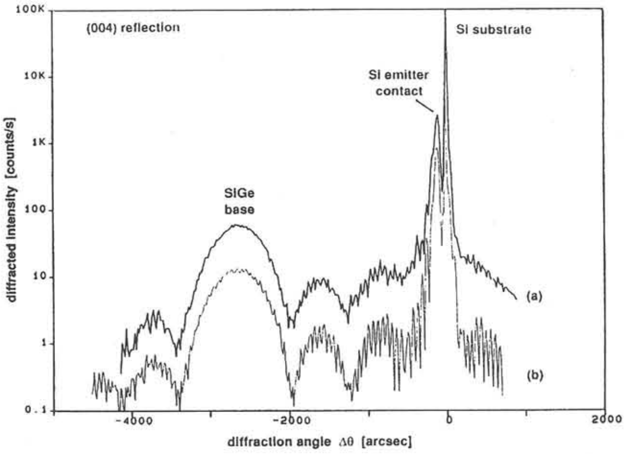

Fig. 2: X-ray diffractions profile from the same structure as in Fig. 1. (a) Measurement, (b) Simulation.

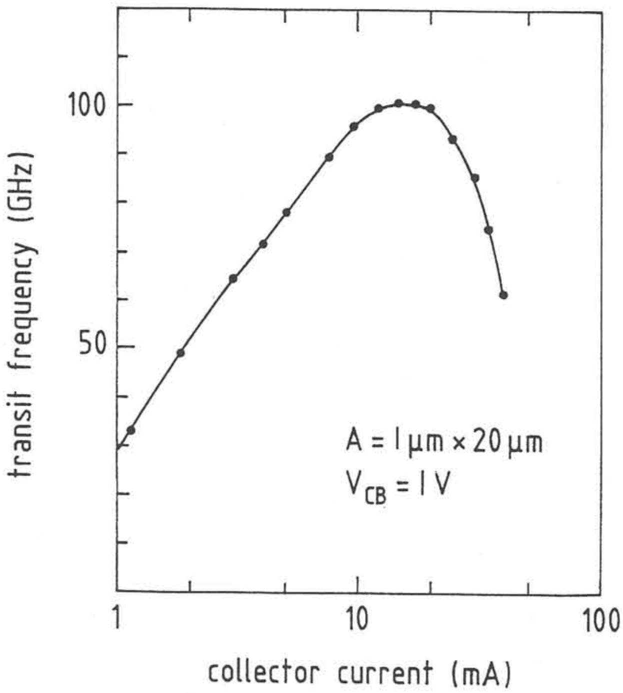

Fig. 3: Transit frequency as function of the collector current. For sample data see Tab. 2

5. Conclusion

We have grown the complete HBT layer and doping structure (collector, base, emitter, emitter contact) in one run by a Si-MBE process. The substrate temperature was chosen to decrease from 650 °C to 325 ° C during growth. The excellent electronic quality of this structure was proven by the fabrication of high frequency SiGe - HBTs with f_T ranging from 20 GHz to 100 GHz. The increase in f_T beyond the silicon transistor limits was obtained by a systematic decrease of the SiGe layer thickness from 65 nm to 25 nm. Simultaneously a high boron doping level (6 $\cdot$ 10/^{19}cm^3) of the base yielded extremely low base sheet resistivities (0.7 kΩ/□for f_T = 50 GHz, 1.6 kΩ/□ for f_T = 100 GHz). Good prospectsfor further rapid progress are expected because the given approach is based on flat profiles within each layer.

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