# Characterization of Si/SiGeC Heterostructures for Device Applications

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## 1. Introduction

With the commercial introduction of the Si/SiGe hetero bipolar transistor (HBT) into mainstream integration technologies, process incompatibilities become an important issue. A basic problem is, for example, the transient enhanced diffusion (TED) of boron out of the SiGe base layer upon thermal activation of the poly-emitter implant. As a remedy, the use of a carbon co-doped base has been proposed, in which a carbon concentration of a few tenths of an atomic percent have been show to very effectively suppress TED. On the other hand, great effort has been dedicated in the past to reduce the carbon concentration in Si ingots as far as possible, because of the propensity of C to form complexes and β-SiC precipitates. In contrast to substitutional C, some of these complexes are known to introduce electrically active states in the band gap. It is therefore important to characterize the microscopic configuration in which C is present after processing of SiGe:C HBTs. In this work, we address this problem with a combination of Fourier Transform Spectroscopy (FTIR), x-ray diffraction (XRD) and SIMS studies.

With the FTIR technique, one is able to probe the local surroundings of carbon atoms in the silicon crystal. In order to detect the absorption from carbon, a silicon reference spectrum has to be subtracted because of the strong Si phonon absorption in the interesting spectral region. The process of subtraction of the Si background is very sensitive to differences in thickness between sample and Si reference, making numerical correction necessary. This is done by measuring the thicknesses by Fabry-Perot interference fringes.

## 2. Measurement of Substitutional Carbon / Silicon Carbide

FTIR is the standard method for the measurement of substitutional C in bulk-Si. Despite the high concentrations in epitaxially grown $Si_{1-y}C_y$ layers, the integrated amount of C is small compared to bulk material. With a method for correction of differences in thickness between sample and Si reference, quantitative measurements on thin layers are possible as shown in Fig. 1.

It is also possible to measure the β-SiC concentration by FTIR. A defined amount of C was deposited on a Si substrate followed by a thin Si cap layer. During an annealing step at 1000 °C, the carbon forms β-SiC, which can be identified by its characteristic phonon absorption.

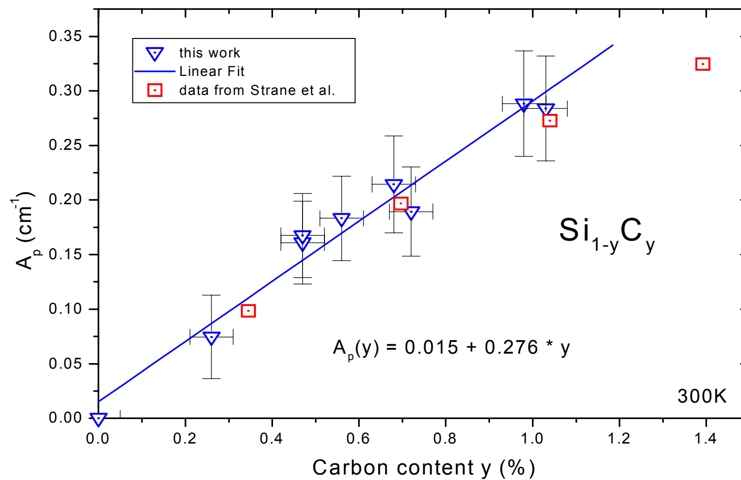


Fig. 1: Dependence of the integrated peak for substitutional carbon from the FTIR measurement as a function of carbon content measured by XRD. The layers are MBE grown with a thickness of 1000 Å.

## 3. Precipitation Behavior

Since the solid solubility of C in Si is about 0.0001%, the epitaxially grown layers are metastable and tend to relax their strain by forming β-SiC precipitates. The process can be studied by FTIR spectroscopy. Substitutional carbon (607 $cm^{-1}$) leaves the lattice and forms small precipitates which are coherently bound to the Si crystal (750 $cm^{-1}$).

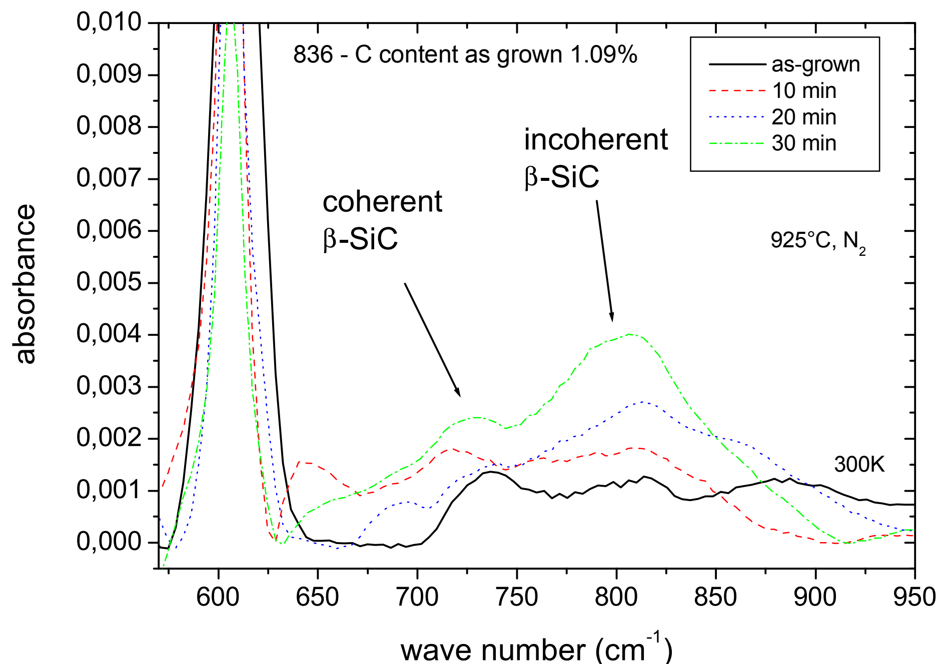


Fig. 2: Time evolution of the different peaks for a 1000 Å thick $Si_{0.99}C_{0.01}$ layer which has been annealed at a temperature of 925 °C for different amounts of time.

If the temperature is high enough, more strain can be relaxed, if the bonds between Si atoms and precipitate break up and the coherence with the neighboring Si atoms is lost. Phonon absorption from β-SiC can then be seen at 820 $cm^{-1}$.

The precipitation process is very sensitive to the as-grown situation. The above figure shows the time evolution of spectra from a $Si_{1-y}C_y$ sample annealed at 925 °C for different periods of time. At the same time, the expansion of the vertical lattice constant can be monitored by XRD.

## 4. Impact of C on TED in a SiGeC: HBT

The influence of C on TED of B was studied for an HBT structure with graded Ge base. Pieces of two samples, one with (0.2%) and one without C doping in the base have been annealed at different RTA temperatures. The slope for the sample with C doping is, within the accuracy of the measurement, constant. TED of B is completely suppressed in this structure. Electrical measurements suggest no negative influence of carbon on device characteristics.

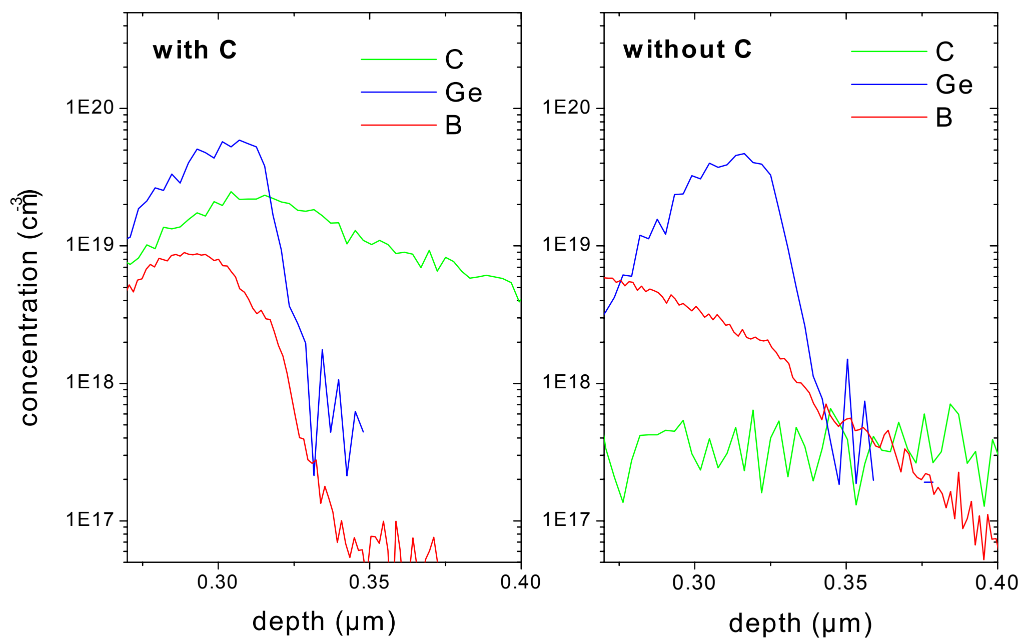


Fig. 3: Comparison of the B profile at the base-collector junction for a SiGe drift-HBT with and without carbon co-doping of the base.

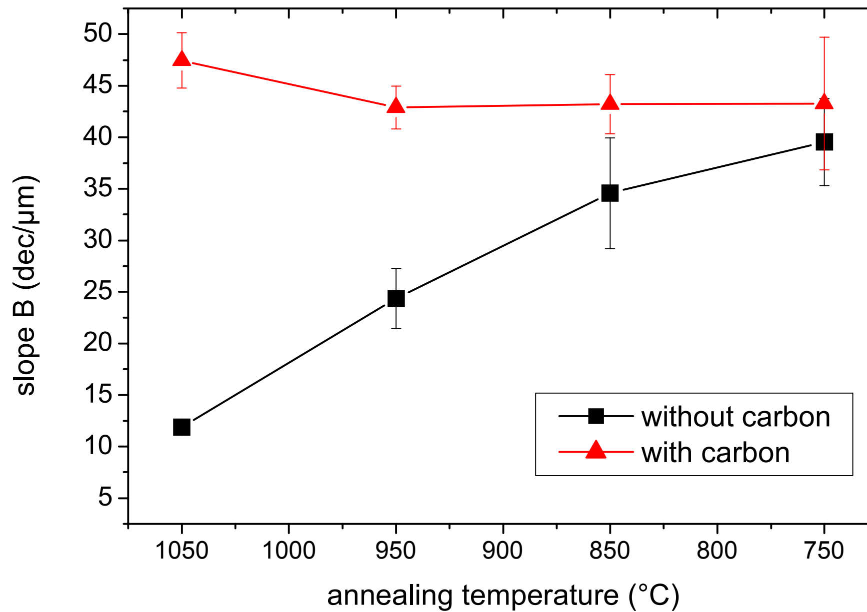


Fig. 4: Slope of the boron profile as a function of annealing temperature for the sample with and without C doping.

## 5. Conclusions

Quantitative measurements of substitutional carbon and SiC were performed on MBE grown $Si_{1-y}C_y$ layers. In the IR transmission spectra, optical absorption from coherent and incoherent β-SiC was observed. The precipitation behavior of C to β-SiC in $Si_{1-y}C_y$ layers was then studied with the FTIR technique.

As a second experiment, the impact of carbon in a SiGeC HBT structure with a poly-Si emitter was studied. Complete suppression of TED of B was obtained by carbon doping of the base with 0.2% subst. C.

## References

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