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# UHV/CVD i-Si epitaxy and ion implantation doping for sub-micrometer $N^-$Collector of SiGeHBT

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**A method for sub-micrometer $N^-$collector layer fabricated by Ultra-High Vacuum Chemical Vapor Deposition i-Si epitaxy and ion implantation doping is presented in this paper. The characteristics of this sub-micrometer $N^-$collector layer are investigated. The Spreading Resistance Probe figures show that the transition region of the $N^-$collector dopant profile is steep and the measure by an Atomic Force Microscope shows that the surface roughness is strongly related to the growth condition of the i-Si. The rocking curve by X-Ray Diffraction and the performance of SiGe Heterojunction Bipolar Transistor device demonstrate the good quality of the SiGe layer grown on this kind of $N^-$collector layer. The $BV_{cbo}$ of the SiGeHBT with this sub-micrometer $N^-$collector is 23.5V high, and the $f_T$ is 11 GHz.**

**Key words: UHV/CVD, Si Epitaxy, Ion Implantation, SiGe, HBT.**

## Introduction

The thickness of an $N^-$collector layer should be designed to meet the requirements of the BC junction breakdown voltage, $BV_{cbo}$, of an NPN Silicon Germanium Heterojunction Bipolar Transistor (SiGeHBT). It is also one of the parameters that influence the cutoff frequency, $f_T$, of a transistor. There is a thick transition region of the dopant profile at the interface between the heavily-doped $N^+$Si substrate and the $N^-$Si epitaxial layer by Atmospheric Pressure Chemical Vapor Deposition (APCVD) because of the effect of solid state diffusion and vapor phase self-doping of impurities from the heavily-doped substrate resulting from the high temperature of about 1100 °C. The valid thickness of an $N^-$collector layer will be significantly decreased while the thick transition region exists, resulting in a lower $BV_{cbo}$ of a SiGeHBT than the designed $BV_{cbo}$. Measured by a Spreading Resistance Probe (SRP), the dopant profile of an about 1.2 μm thick $N^-$collector layer by APCVD is shown in Fig. 1 and there is a distinct thick transition region in it. The transition region consists of two parts [1]: a solid state diffusion region (line OB in Fig. 1) and a vapor phase self-doping region (line BC in Fig. 1). In an Ultra-High Vacuum Chemical Vapor Deposition (UHV/CVD) system, the vapor phase impurity in the deposition chamber from the substrate will be easily removed because of the long mean free path of the gas molecules, so that the solid state diffusion from the heavily-doped substrate is the dominating source of the transition region. If ignoring the influence by the vapor phase self-doping, the transition region in Fig. 1 resulted from solid state diffusion of impurities from the heavily-doped substrate is 0.37 μm (line $B_2A$ in Fig. 1), almost the one third of $N^-$collector layer thickness. The Reduced Pressure Chemical Vapor Deposition (RPCVD) and UHV/CVD both with in situ doping are usually used for a thinner transition region [2, 3]. In this paper, the method of UHV/CVD intrinsic-Silicon (i-Si) epitaxy and ion implantation doping is used to obtain sub-micrometer $N^-$collectors in order to avoid the cross-contamination by doping with boron and phosphor in the same UHV/CVD chamber [4].

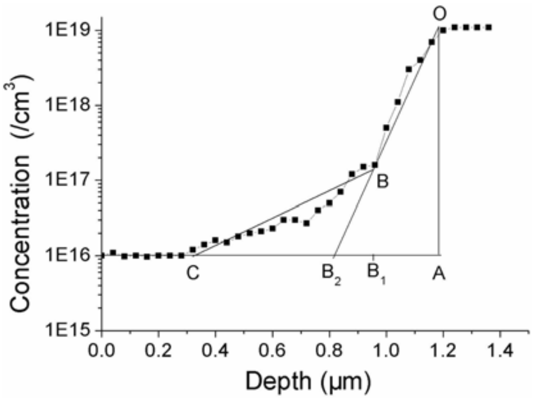


**Fig. 1.** The dopant profile in an $N^-$collector layer grown by APCVD.

## The Experiment and Results

The N<100> Si substrate used in the experiment was heavily doped with arsenic to a resistivity 0.001-0.005

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**Table 1.** The i-Si growth rate varies with the growth temperature and flux of $SiH_4$

| Flux / Growth rate / Temperature | Flux of $SiH_4$ 6 (sccm) | 10 (sccm) | 15 (sccm) |
|---|---|---|---|
| 650 °C | 7.5 nm/minute | | |
| 700 °C | 12 nm/minute | 15.5 nm/minute | 18 nm/minute |
| 750 °C | 12.5 nm/minute | 19.5 nm/minute | 28.5 nm/minute |

**Table 2.** The roughness of i-Si grown in different growth conditions

| Flux of $SiH_4$ (sccm) | 6 (sccm) | 10 (sccm) | 15 (sccm) |
|---|---|---|---|
| Temperature (°C) | Roughness of i-Si (nm) | | |
| 700 | 1.55 | 3.28 | 6.51 |
| 750 | 0.23 | 0.91 | 1.19 |

Ω.cm. The 0.7 μm thick i-Si epitaxy is completed in the UHV/CVD system designed by Tsinghua University [5]. The growth rate of i-Si increases while the temperature and flux of $SiH_4$ increase, as shown in Table 1. The roughness of i-Si layers grown in different conditions are shown in Table 2 measured by an Atomic Force Microscope (AFM) which demonstrate that the roughness increases as the flux of $SiH_4$ increases or the temperature decreases. The minimum roughness of i-Si is obtained in the growth conditions of 750 °C and 6 sccm $SiH_4$ flux.

The dose and energy of ion implantation depend on the designed $BV_{cbo}$ value of a SiGeHBT. Phosphors were implanted into i-Si with a dose of 1.6E12/cm$^2$ and energy of 125 KeV. Also Rapid Thermal Annealing (RTA) at 1050 °C for 20 seconds was used to get sufficient activation. The dopant profile simulated by Athena process simulation software and the real dopant profile measured by SRP are shown in Fig. 2. The transition regions by solid state diffusion from the heavily-doped substrate are respectively 0.05 μm thick in the simulated profile and 0.12 μm thick in the measured profile, corresponding to an impurity concentration of 1E16/cm$^3$.

A SiGe layer was grown in UHV/CVD after finishing the N$^-$collector layer. The longitudinal structure of the SiGe epitaxy consisted of five layers: 10 nm undoped buffer Si, 10 nm undoped $Si_{0.85}Ge_{0.15}$, 40 nm Boron-doped ($1\times10^{19}$/cm$^3$) $Si_{0.85}Ge_{0.15}$, 10 nm undoped $Si_{0.85}Ge_{0.15}$, and 20 nm undoped Si cap. The detailed growth process was described in the other paper [6]. The characteristics of SiGe layers on APCVD N$^-$ collectors and on implantation doped N$^-$collectors were investigated by X-Ray Diffraction (XRD) and there is no obvious difference in the XRD rocking curves shown in Fig. 3.

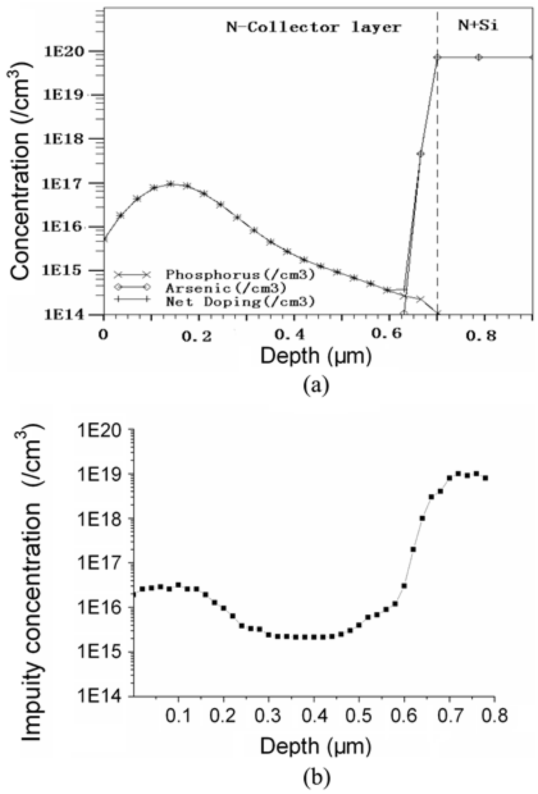


**Fig. 2.** (a) The simulated dopant profile; (b) The measured dopant profile by SRP.

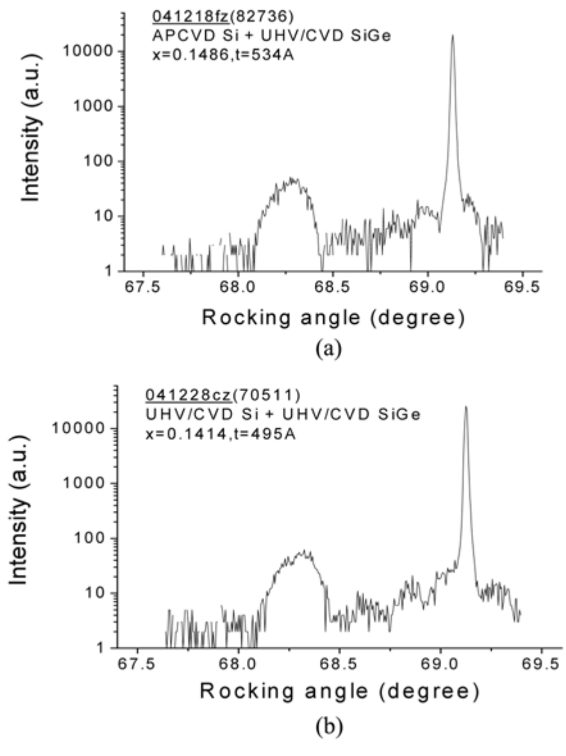


**Fig. 3.** The XRD rocking curves of (a) the SiGe on an N$^-$collector by APCVD; (b) the SiGe on an N$^-$collector by UHV/CVD i-Si epitaxy and ion implantation.

The SiGeHBTs were fabricated with polycrystalline

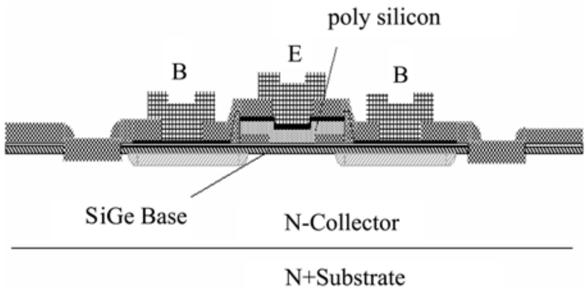


**Fig. 4.** The structure of the SiGeHBT.

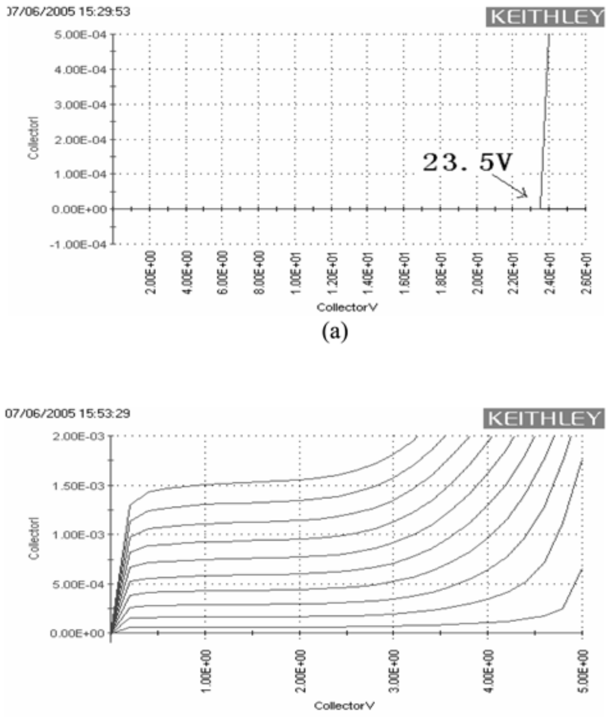


**Fig. 5.** Characteristics of the SiGeHBT with an N⁻collector by UHV/CVD i-Si epitaxy and ion implantation doping (a) reverse BC junction I-V plot; (b) output characteristics.

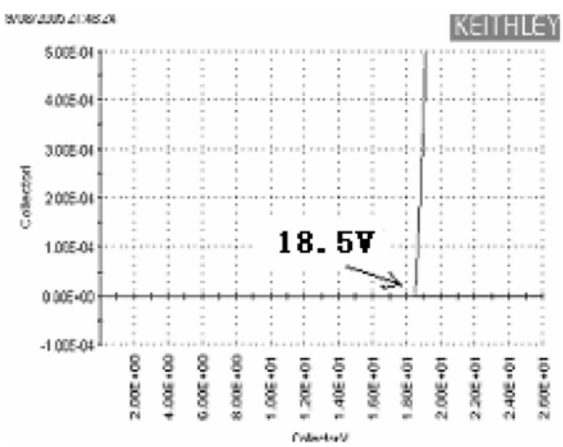


**Fig. 6.** Reverse BC junction I-V plot of the SiGeHBT with an N⁻collector grown by APCVD.

silicon emitters and a quasi-self-aligned process with a feature size of 1 μm. The structure of an SiGeHBT is shown in the Fig. 4. The N⁻collector layers were respectively 0.7 μm thick by UHV/CVD i-Si epitaxy and ion implantation doping and 1.2 μm thick by APCVD. The DC characteristics of the SiGeHBTs are shown in Fig. 5 and Fig. 6. The $f_T$ of a 5-finger SiGeHBT with a 0.7 μm N⁻collector packed in a metal-ceramic package type ST-32 is 11 GHz measured by a HP8510C network analyzer.

## Discussion

It is obvious from the above results that the transition region is steep in the sub-micrometer N⁻collector layer prepared by the method presented in this paper. Also in this method it is understandable that the solid state diffusion from the heavily-doped substrate is mostly resulted during the annealing process because the thermal budget during annealing is much higher than that of i-Si growth, so the solid state diffusion can be effectively controlled by a very short annealing time of RTA. The higher $BV_{cbo}$ of 23.5 V and thinner N⁻collector layer of 0.7 μm reveal better characteristics of this sub-micrometer N⁻collector layer than that of the 1.2 μm N⁻collector layer by APCVD.

Based on the measured dopant profile in Fig. 2(b), it is possible to obtain a flexible contour of the dopant profile by multi-implantation with a higher energy and the optimized thickness of the sub-micrometer N⁻collector layer will rely on the highest energy of the ion implanter. The accuracy of the ion dose and energy will keep the process for sub-micrometer N⁻collector layer fabrication with good uniformity and repeatability.

Though the BC junction performance of the SiGeHBT on the 0.7 μm N⁻collector layer grown in the condition of 750 °C and 15 sccm flux of $SiH_4$ by UHV/CVD is excellent to be acceptable with 23.5V of $BV_{cbo}$ and 0.6 nA of reverse leakage current at 22.5V, attention should be paid to the surface roughness of this sub-micrometer N⁻collector layer which is strongly related to the i-Si growth temperature and flux of $SiH_4$. The roughness increases as the flux of $SiH_4$ increases and the temperature decreases according to the experimental results in Table 2.

## Conclusions

The method for sub-micrometer N⁻collector fabrication by UHV/CVD i-Si epitaxy and ion implantation doping is introduced and the characteristics of this sub-micrometer N⁻collector layer are investigated by SRP, AFM and XRD in this paper. The performance of the SiGeHBT fabricated with this sub-micrometer N⁻collector also shows a good performance. This method provides an option to obtain a sub-micrometer N⁻collector layer. The advantages of this method are as follows: first of all, the thin transition region in the dopant profile can be obtained by a low thermal budget in this process; secondly, the contour of the dopant profile can be easily controlled by different combinations of multi-implantation; thirdly, the precision of ion energy and dose will ensure a process with good repeatability and uniformity; finally, cross–contamination is avoided in the case of in situ doping different impurities in the same UHV/CVD chamber.

## Acknowledgements

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