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Carrier Depth Profile of Si/SiGe/Si n-p-n HBT Structural Materials Characterized by Electrochemical Capacitance-Voltage Method

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Abstract: Si/SiGe/Si n-p-n HBT structural materials have been grown by gas source molecular beam epitaxy with disilane, solid Ge, diborane and phosphine as sources. The materials are of good structural properties. The effectiveness of Electrochemical Capacitance-Voltage (ECV) technique on profiling the shallow doped layers of nanometer dimensions has been demonstrated. Compared with spreading resistance probe, the ECV technique is relatively easy to get the carrier distribution profile, especially for the Si/SiGe/Si HBT structural materials with shallow (≤50nm) base regions (p-type SiGe layer, Ge content about 0.2). The results show that n-p-n structures can be obtained by in situ doping.

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1 Introduction

In recent years SiGe Molecular Beam Epitaxy (MBE) has attracted much attention due to its application in researching new elements for high performance CMOS and bipolar technologies[1]. For example, Si/SiGe/Si n-p-n HBT has been attached importance to its investigation for the purpose of high-speed, high-frequency applications[2,3]. It is very important for the device fabrication to get the characterization of SiGe HBT structural materials because the carrier profile is critical for the accurate device performance prediction. However, characterization of the electrical active carrier profiles of heavily doped and shallow (≤100nm) layers presents a challenging task[4] towards the development of various

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semiconductor devices. Recently, the Secondary-Ion Mass Spectroscopy (SIMS) has been proved as a useful method to provide with depth resolution. However, this chemical dopant profile does not always give the indication of the electrical active carrier concentration. In order to measure this concentration, techniques such as Spreading Resistance Profiling (SRP)[5] or Electrochemical Capacitance-Voltage[6,7](ECV) have been employed.

The aim of this paper is to seek an approach to get the accurate carriers profile of Si/SiGe/Si n-p-n HBT structural materials. Preliminary results of SRP and ECV are presented and compared. The latter method is used to get the carrier profiles, mainly in Ⅲ-Ⅴ materials and also in silicon recently. In this work, we try to use ECV method to obtain the carrier distribution in Si/SiGe/Si HBT structures. The results show that n-p-n structures can be obtained by in situ doping.

2 Experiments

Sample growth was carried out in a home-made MBE system, which had been modified for SiGe growth with Ge Knudsen cell and several gas lines[8—10] acting as Gas Source Molecular Beam Epitaxy (GSMBE) system. The sources are disilane, solid Ge, diborane and phosphine. Two-inch (100) Si substrates (n-type, 0.002Ω·cm) were used. Prior to the growth, the background vacuum was 10^{-7}Pa. The substrate was thermally cleaned by annealing at 850℃ for 20 min and the characteristic (2×1) surface reconstruction was routinely observed as what can be seen from the Reflection High-Energy Electron Diffraction (RHEED) pattern. Before SiGe growth, a buffer Si layer of 200—300nm was grown at 800℃. During the growth of SiGe layer, the temperature of Ge cell is 1100℃, disilane flow rate was 4 sccm, and the diborane (1.1% diluted in pure H_2) flow rate was 2 sccm. The substrate temperature was 550℃. During the subsequent Si emitter growth, phosphine (0.1% diluted in pure H_2) flow rate was 0.2 sccm and the substrate temperature was risen to 600℃. During the whole growth process, the vacuum is about 10^{-5}—10^{-3}Pa. The growth rate is about 6nm/min for SiGe layers.

Figure 1 is a typical double crystal X-ray rocking curve for as-grown samples. It can be seen that the epilayer has perfect structural properties. The good quality has been confirmed by Transmission Electron Microscopy (TEM) as shown in Fig. 2. The interfaces are very smooth and free of dislocations. The Si emitter surface is not so smooth as the interface but with some small pits distributed randomly. A two-dimensional to three-dimensional growth mode transition has been observed during the highly P-doped Si growth, and the pits are the reason for the roughening transition[11]. However, it should be noted that the pits have no relationship with the underlined epilayers nor the dislocations or other defects in the structures.

SRP measurements are carried out with ASR-100C/2 spreading resistance probe system. The curvature radius of the probe used is about 2.5μm. SRP involves a lot of time consuming process in sample preparation and data processing, especially the thin films' de-

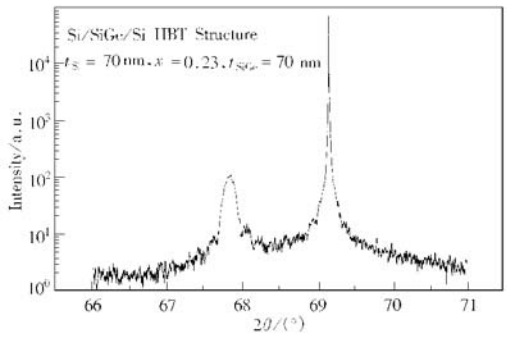

FIG. 1 Typical DCXRD Rocking Curve for n-p-n Si/SiGe/Si HBT Structure

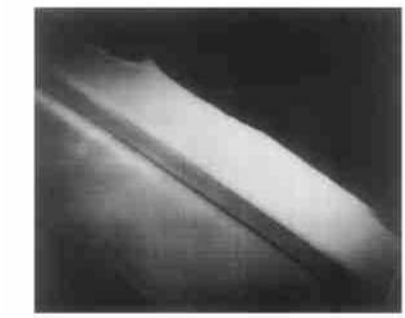

FIG. 2 Cross-Sectional TEM Micrograph of Si/SiGe/Si n-n-p HBT Structure Materials

manding for accurate calculation and good control of bevel angles. The results are also heavily dependent on the operator's skill.

Eletrochemical capacitance-voltage technique provides an elegant idea of the determination of the active dopant concentration. ECV analysis is carried out with a BioRad profiler PN4300PC. In this experiment, the sample size is 5mm×5mm. A good ohmic contact is made as the back of the sample by gallium indium eutectic. The area between the electrolyte contact and the sample surface is a ring with the diameter of 5 mm. The electrolyte used is a 1∶1 mixed solution of $NH_4F \cdot HF$ (0.1M) and HCl (0.5M).

3 Results and Discussion

Sample A and B are both n-p-n Si/SiGe/Si HBT structures with similar buffer and cap Si, but different thickness of SiGe.

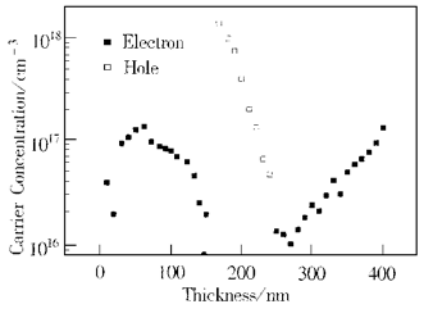

FIG. 3 Carriers' Profile Characterized by SRP of Si/SiGe/Si n-p-n HBT Structure Sample with 80nm SiGe n-Type Layer

Figure 3 is the result of SRP measurement of sample A. It can be seen that the thickness of p-type SiGe layer is about 80 nm. The content of Ge is about 0.10. The carrier profile has been shown, though the accuracy of the carrier concentration is not very satisfactory. Many characterization results show that as for the samples with thicker SiGe layers than 50nm, such as sample A, the carrier depth profiling can been achieved using either SRP or ECV method. Figure 4 shows the results of ECV and SRP measurements of sample B. In this sample, the Ge content is about 0.22 and the thickness of p-type SiGe layer is about 40nm. Same carrier distributions are shown in ECV and SRP, but the absolute values are different.

Samples grown recently are mostly of much thinner SiGe layers, such as 40nm in

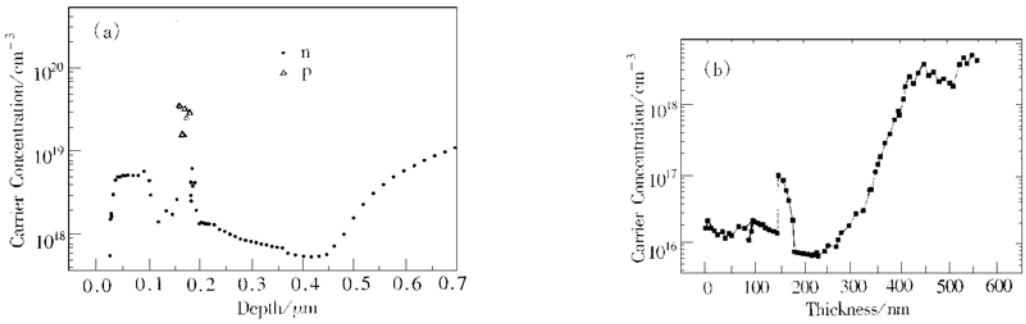

FIG. 4　Carriers' Profile Characterized by (a) ECV and (b) SRP of Si/SiGe/Si n-p-n HBT Structure Sample with 40nm SiGe p-Type Layer

sample B. Sometimes results from SRP measurement can not show any p-type active carrier concentration. As it is known, the curvature radius of the probe used is about 2.5μm. Therefore, such a sharp change in dopant and the carrier profiles represent a challenge to the SRP characterization technique. Considering our samples grown by GSMBE incorporated with the doping steps, which vary according to the orders of magnitude over the distance less than 10 nm, it is easy to explain why SRP fails to measure the carrier concentration of the thin-SiGe-layer samples.

Although the sample with much thinner SiGe layers, as sample B, is prepared with a small bevel angle, it still has a fairly narrow B-doped region for the probe to focus on. Therefore, a probe of 2.5μm curvature radius is rather possible to contact the base region of p-type SiGe with the n-type Si layers. Due to the equation of SRP, we find the mean-value of the resistance is mainly around the probe. Because of the drastic change in the dopant concentration and their narrow distribution, the really high carrier concentration (such as $10^{19}cm^{-3}$) could not be obtained by the SRP measurement. In addition, there are some serious limitations of SRP, including the carrier spilling and crystalline imperfections with the latter leading the noise problems to a small sampling volume. Furthermore, SRP measurements require an accurate knowledge of the effective carrier mobility as a function of the concentration. In our measurements, it is assumed that both n-type Si and p-type SiGe layers have the ideal mobility values of Si bulk materials for electron and hole, respectively, which will certainly cause some system error. Generally, there are a number of factors that limit the SRP profiling of ultrashallow regions, such as the Si/SiGe/Si HBT structural materials with shallow base regions.

In contrast, ECV measurements are not so difficult. Depth profiling is achieved by the electrochemical ecthing of the semiconductor material under an electrolyte "Schottky" contact[12]. It takes the advantage of relations between the applied reverse-bias voltage, the width of the resulting space charge region and the carrier concentration. The carrier concentration is inversely proportional to the derivative of the C-V curve (i.e. dC/dV).

The equations in this method are available in the standard semiconductor texts[13]. Therefore, the data are accurate, providing the carrier concentration of the doped region without any dependence on the mobility. Due to the existance of two heterojunctions in the layer structure, the carrier concentration value in the vicinity of the heterobarries is not totally due to the real variation in carrier distribution, but the artifacts associated with the redistribution of the free charge across the barriers[12]. As the carrier concentration in Si and SiGe are high, and the widths of the space charge layers are small compared with the thickness of SiGe base layers, the carrier concentration far away from the heterojunctions can be regarded as the true concentration in the layers. We have also employed SIMS to make a depth resolution. It comes an agreement between the atomic concentration profile by SIMS and the carrier concentration profiles measured by ECV, though there is a significant difference between the SRP-obtained concentration and the SIMS data.

In summary, Si/SiGe/Si n-p-n HBT structural materials, which are of good structural properties, have been grown by GSMBE using disilane, solid Ge, diborane and phosphine as sources. The effectiveness of ECV technique on profiling the shallow doped layers of nanometer dimensions has been demonstrated. Compared with SRP, the ECV technique is relatively easy to get the carrier distribution profile, especially for the Si/SiGe/Si HBT structural materials with shallow ($\leqslant$50nm) base regions (p-type SiGe layer, Ge content about 0.2). The results prove that n-p-n structures can be obtained by situ doping.

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