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Silicon Heterostructure by Germanium Ion Implantation

Akira Fukami, Ken-ichi Shoji, and Takahiro Nagano

Hitachi Research Laboratory, Hitachi, Ltd.
4026 Kuji, Hitachi, Ibaraki 319-12, Japan

Formation of SiGe/Si heterostructure by germanium ion implantation and subsequent solid phase epitaxy is investigated. Two kinds of crystalline defects are observed. One is a misfit dislocation and the other is a residual dislocation caused by the ion bombardment. The p-n junction formed in the SiGe layer has a leakage current three orders of magnitude larger than that of a pure Si p-n junction. Carbon doping in the SiGe layer improves its crystalline quality and the junction's characteristics.

1. INTRODUCTION

Recently, studies have been reported on the fabrication of SiGe/Si heterojunction bipolar transistors with various growth techniques[1-4]. For example, deposition of SiGe with molecular beam epitaxy can optimize control of impurity profiles[1]. However, considering the compatibility with current silicon integrated circuit fabrication lines, it would be difficult and costly to merge any of these techniques with a standard process.

Ion implantation is a technique highly compatible with any standard silicon process and is expected to be suitable for fabricating a SiGe alloy. In this study, SiGe/Si heterostructures are fabricated using germanium ion implantation into silicon and subsequent solid phase epitaxy. The microstructure of the implanted layer as well as the electrical characteristics of p-n diodes formed are examined. A technique for improving the crystalline quality of the SiGe layer is suggested. Instead of using boron as reported previously[5], a carbon ion implant is added to the process to compensate for the lattice mismatch between the silicon substrate and the implanted layer. Our results show improvements in both crystallinity and junction properties.

2. FABRICATION PROCEDURES

Germanium ions were implanted into n-type Si(100) through a thermally grown 10-nm oxide at an energy of 50 keV with a dose of $2.5\times10^{16}cm^{-2}$. The peak germanium concentration is about $8\times10^{21}cm^{-3}$. For some samples, carbon ion implantation was subsequently carried out at an energy of 15 keV with a dose of $3.0\times10^{15}cm^{-2}$. These samples were then furnace-annealed in an N_2 ambient at 600°C for 24 h. Rapid thermal annealing (RTA) at 1000°C for 10 s was also performed on some samples.

In order to evaluate the crystalline quality electrically, a planar p-n junction structure was utilized. Figure 1 shows a schematic of the device geometry. The area of the n^{++}-region is 1×5 μm^2. Germanium ions were implanted into p-type Si(100) at 120 keV with a dose of $5\times10^{16}cm^{-2}$. In some samples, carbon ions were subsequently implanted at 33 keV with a dose range of $3\text{-}12\times10^{15}cm^{-2}$. Boron ion implantation then followed to form the p^+-region. Two annealing steps were carried

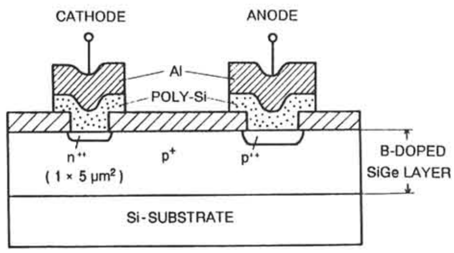

Fig. 1. Schematic cross section of a SiGe n^{++}-p^+ junction.

out. First, low-temperature annealing at 600°C for 24 h followed by annealing at 950°C for 10 min. Then a SiO_2 overlayer was added, diffusion windows were opened, and a poly-Si film was deposited. Arsenic ions were implanted to form the n^{++}-region and boron ions were implanted to form the p^{++}-region. Furnace annealing at 950°C for 10 min followed. Finally, aluminum deposition was made to form the metal contacts.

3. RESULTS AND DISCUSSION

Germanium concentration profiles for samples as-implanted and after annealing, with the dotted curve indicating the simulation result are shown in Fig. 2. The as-implanted shows a higher concentration at the surface and a deeper penetration than the simulation. These differences are attributed

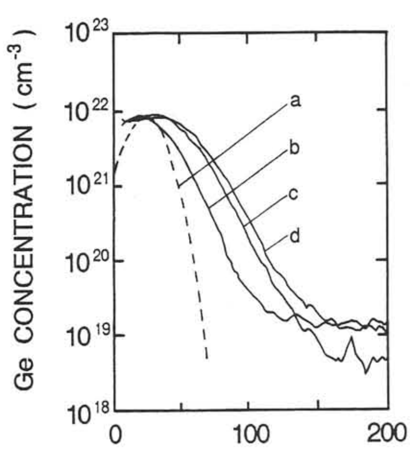

Fig. 2. SIMS profiles of Ge in Si: (a) as-implanted (simulation), (b) as-implanted (experiment), (c) annealed at 600°C for 24 h, (d) same as (c) followed by RTA at 1000°C for 10 s.

to diffusion during ion implantation as a result of beam heating. Upon annealing at 600°C for 24 h, germanium ions diffused about 25 nm further into the substrate.

XTEM micrographs of the as-implanted sample and of the furnace-annealed sample are shown in Fig. 3. Figure 3(a) shows that an amorphized layer was formed to a depth of about 100 nm. As shown in Fig. 3(b), there are some defects under the surface and at the original amorphous-crystalline interface.

Figure 4 shows high resolution XTEM micrographs of the furnace-annealed sample, as viewed from the [110] direction. The interface between the recrystallized layer and the substrate is shown in Fig. 4(a). There are dislocations due to the residual germanium ion damage. Figure 4(b) shows the surface region. The lattice image reveals that the top layer is still amorphous even after annealing at 600°C for 24 h. However, these two lattice images show that the recrystallized region is a solid phase epitaxial (SPE) layer. Furthermore, there are many defects at the sub-surface. These defects form about 60° angle to the surface. In view of the high concentration of

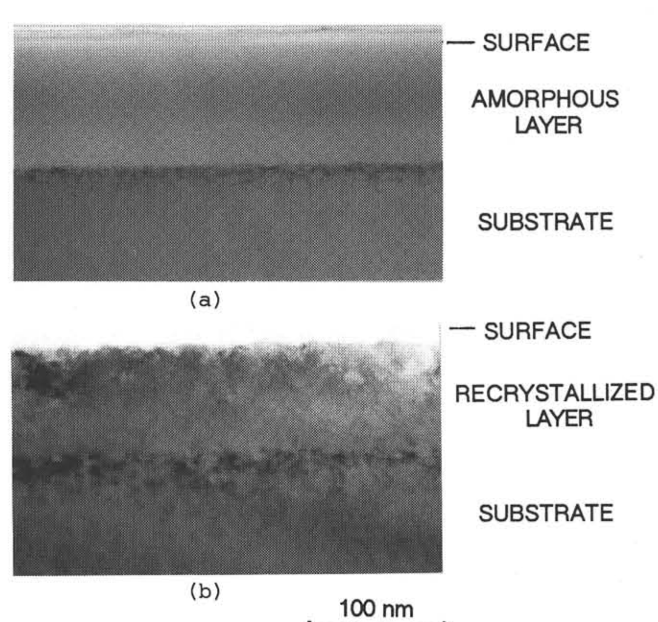

Fig. 3. XTEM images of SiGe/Si: (a) as-implanted, (b) annealed at 600°C for 24 h.

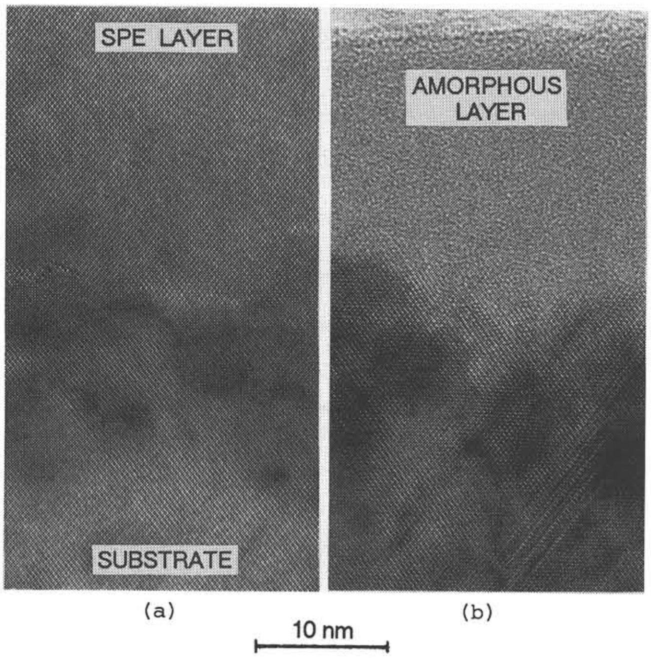

Fig. 4. High resolution XTEM images of SiGe/Si: (a) interface between recrystallized layer and substrate of sample annealed at 600°C for 24 h, (b) sub-surface region of sample in (a).

germanium near the surface (Figure 2), these defects are probably similar to the misfit dislocations observed in a molecular beam epitaxial SiGe/Si heterostructure[6].

The RTA process at 1000°C for 10 s was added to grow the entire region epitaxially and to reduce the dislocations at the interface. Furthermore, carbon implantation was added to reduce the misfit dislocations near the surface. As shown in Fig. 2, the germanium atoms diffused only 10 nm during the RTA. Figure 5 shows two XTEM micrographs, one of a sample implanted with Ge^+ and one implanted with both Ge^+ and C^+. No amorphized layer exists under the surface. Some of the dislocations at the interface were removed by the RTA. The defects near the surface are reduced considerably by the presence of carbon.

Figure 6 summarizes results of room-temperature current-voltage measurements for three diodes. A comparison of forward current-voltage characteristics is shown in Fig. 6(a). Both the SiGe and the carbon-

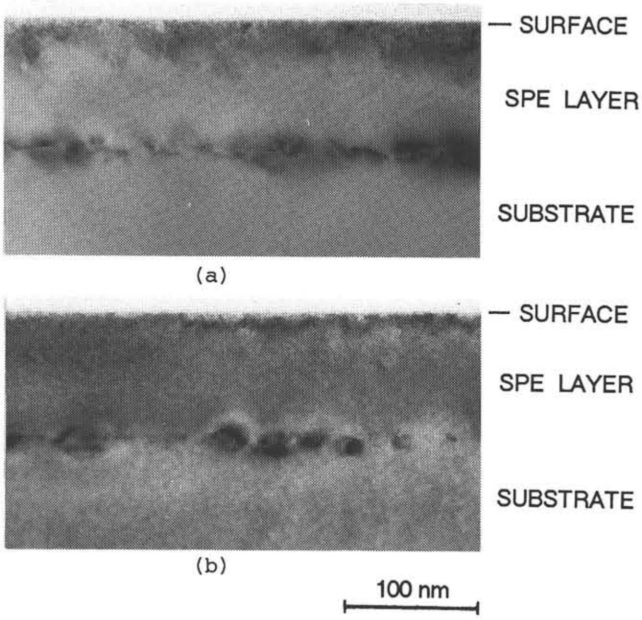

Fig. 5. XTEM images of SiGe/Si annealed at 600°C for 24 h followed by RTA at 1000°C for 10 s: (a) without carbon doping, (b) with a C^+ dose of $3\times10^{15}cm^{-2}$.

doped SiGe diodes exhibit larger currents and smaller slopes than the pure Si diode. This is attributed to carrier recombination associated with defects near the SiGe surface. The forward current decreases as carbon ions are added. However, the slope does not change. This parallel downward shift corresponds to an increase of about 0.06 eV in bandgap due to carbon doping. Figure 6(b) displays the reverse current-voltage characteristics. The leakage current of the SiGe diode is about three orders of magnitude larger than that of a pure Si diode. As in the forward-bias case, this difference is due to a larger generation current associated with defects in the SiGe layer. The leakage current decreases as carbon ions are added. This decrease is a result of improvement in crystalline quality. Figure 6(c) shows the dependence of the breakdown voltage on the carbon ion dose. For reference, the values of the SiGe diode and the pure Si diode are also plotted. The SiGe diode has the lowest breakdown voltage. However, the breakdown voltage increases with an increase in carbon ion dose.

4. SUMMARY

SiGe heterostructures were formed by germanium ion implantation followed by thermal annealing. There are two kinds of defects in the recrystallized SiGe layer. One is a misfit dislocation due to the high germanium content which forms 60° angle to the surface. The other is a residual dislocation at the recrystallized-layer/substrate interface caused by the germanium ion bombardment.

P-n junctions were fabricated in the SiGe layer. The forward current is larger than that of a pure Si diode and is attributed to additional recombination centers across the diode. The reverse leakage current decreases as carbon ions are added. The breakdown voltage increases with an increase in carbon ion dose. Therefore, carbon doping improves the SiGe crystalline quality and consequently the diode characteristics.

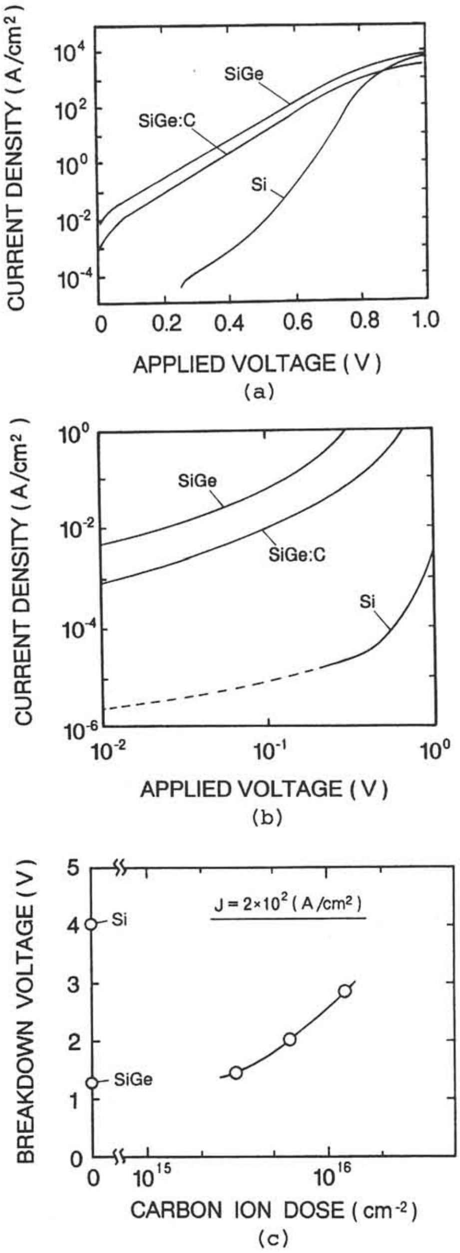

Fig. 6. Comparisons of diode current voltage characteristics: (a) forward bias, (b) reverse bias. The carbon dose in the SiGe:C diode is $1.25\times10^{16}cm^{-2}$. (c) shows the dependence of reverse-bias breakdown voltage on C^+ dose.

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