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Characterization of BF_2^+ ion-implanted layers in strained-silicon/SiGe heterostructures

Yohei Ishidora [a], Koji Koyama [a], Jun Morioka [a], Taroh Inada [a,*], Nobuyuki Sugii [b]

[a] Graduate School of Engineering, Hosei University, Koganei, Tokyo 184-8485, Japan
[b] Central Research Laboratory, Hitachi Ltd., Kokubunji, Tokyo 185-8601, Japan

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Abstract

BF_2^+ implanted strained silicon/SiGe was characterized with the aim of maximizing the performance of strained-silicon pMOSFETs. Recovery of implantation damage in the strained-silicon layer was achieved by annealing at 900 °C or higher, but end-of-range defects remained in the SiGe layer after annealing. Germanium recoil and vacancy-enhanced redistribution of germanium caused by BF_2^+ implantation are not negligible issues in strained-silicon MOSFET fabrication. Boron diffusion during annealing was retarded in SiGe compared to that in silicon, and as a result, a higher-concentration and shallower boron-doped region than that in silicon can be formed in strained silicon/SiGe. Hole mobility in boron-doped strained silicon is about 30% higher than in silicon. These results suggest that lower source and drain resistance can be achieved in the strained-silicon pMOSFET than in the silicon pMOSFET.

Keywords: Strained silicon; Mobility; Boron; Ion implantation

1. Introduction

The strained-silicon MOSFET is a promising device structure to improve the performance of the scaled-down CMOS because of its high carrier mobility [1–6]. While miniaturizing the gate length and increasing mobility of the channel, reducing parasitic resistance of source and drain regions becomes crucial for improving the performance of the MOSFETs. The fraction of parasitic resistance in a scaled-down CMOS of a 45-nm node is estimated to reach roughly 25% of total resistance based on data cited in the ITRS 2004 roadmap [7]. The source and drain region of the strained-silicon MOSFET contains a strained silicon/SiGe heterointerface, and it is necessary to optimize impurity profiles near this interface to maximize the performance of the MOSFET. Investigation of fundamental properties of ion-implanted strained-silicon/SiGe heterostructures is thus an important part of developing strained-silicon technology.

We have investigated the n^+ strained-silicon/SiGe layers formed by implantation of As^+ ions [8,9]. In this work, we study crystallization, redistribution of boron, fluorine, and germanium atoms, and electrical activation of BF_2^+ ion-implanted p^+ layers.

2. Experimental

A schematic cross-section of bulk strained silicon/SiGe layers used in this experiment is shown in Fig. 1. The strained-silicon, the relaxed $Si_{1-x}Ge_x$ buffer layer of 1.0–1.5 μm thick, and a graded SiGe buffer layer of 2.0 μm thick (not shown) were grown on a p-type silicon substrate (not shown) by low-pressure chemical-vapor deposition. The strained-silicon thicknesses and germanium fractions, x, of the relaxed $Si_{1-x}Ge_x$ buffer layer of were 34, 16, and 23 nm and 0.1, 0.2, and 0.3, respectively. The substrate was implanted with 50 keV BF_2^+ ions (projected range: Rp = 45 nm) with a dose of 2×10^{15} cm^{-2} at room temperature. After the implantation, the substrates were subjected to 10 s of rapid-thermal annealing (RTA) in nitrogen at a temperature of 900 or 1000 °C. The heating rate of the RTA was about 50 °C/s.

We examined the crystallographic properties of the samples with Rutherford backscattering spectrometry (RBS) and cross-sectional transmission electron microscopy (XTEM). The energy of the $^4He^+$ ions for the RBS measurement was 1.5 MeV, and the backscattering angle was 150°. The depth

* Corresponding author. Tel./fax: +81 42 387 6122.
E-mail address: taroh@ionbeam.hosei.ac.jp (T. Inada).

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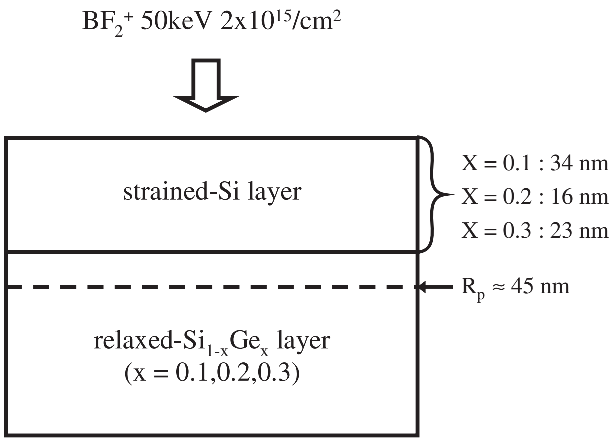

Fig. 1. Schematic cross-section of bulk strained-silicon/SiGe substrates. BF_2 ions were implanted into SiGe layer (projected range (Rp): 45 nm) through the strained-silicon layer.

profiles of boron, fluorine, and germanium were evaluated with secondary-ion mass spectroscopy (SIMS). The primary ions were Cs^+ or O_2^+. We used the stripping Hall measurement of Van der Pauw geometry to measure the depth profiles of carrier density and mobility.

3. Results and discussion

3.1. Crystallization of BF_2-implanted layers by annealing

RBS spectra for virgin, implanted, and annealed strained-silicon/SiGe samples are shown in Fig. 2. The germanium fraction, x, of the relaxed $Si_{1-x}Ge_x$ buffer layer is 0.1. Aligned-yield spectra of virgin, as-implanted, and 900 °C-annealed samples are indicated by a line, squares, and circles, respectively. Random-yield spectra are identical for all the samples of the different treatments and are indicated by dots. After the implantation, the aligned yield increases due to the implantation-induced defect formation. After the RTA at 900 °C, aligned yield decreased and came close to the virgin sample's level indicating recovery from defects.

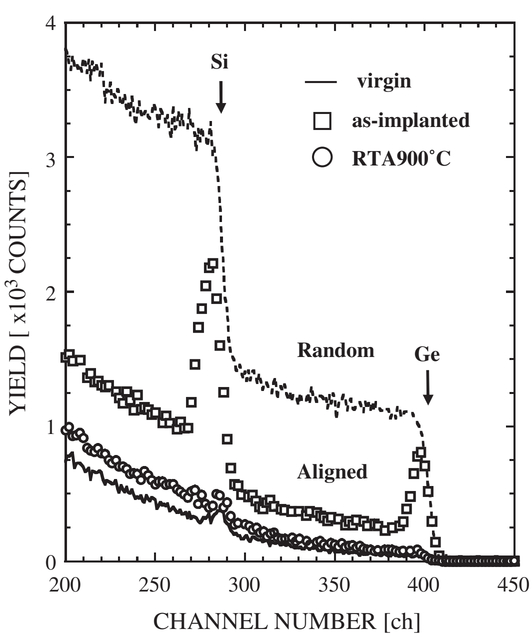

Fig. 2. RBS spectra of strained-silicon/SiGe samples (germanium fraction, x=0.1). Aligned-yield spectra of virgin, as-implanted, and 900 °C-annealed samples are indicated by a line, squares, and circles, respectively. Random-yield spectra were identical for all samples of different treatments.

An XTEM image of the 900 °C-annealed sample (x=0.1) is shown in Fig. 3. A dark strain-induced contrast at depths of 20–40 nm is near the strained silicon/SiGe interface, and no defects are seen in the strained-silicon layer. This suggests that the strained-silicon layer is completely recrystallized by RTA. At a depth of about 60 nm (in the SiGe layer), end-of-range defects are seen in the SiGe layer. A slight increase in the RBS aligned yield from the virgin state may be due to these defects. This type of defect was not observed for the arsenic-implanted samples [8,9]. A SIMS depth profile (not shown) indicated that there is a fluorine pileup at the same depths of the end-of-range defects. We presume that incomplete amorphization caused by BF_2 implantation with low kinetic energy made it difficult to anneal out the end-of-range defects and release fluorine atoms from this region.

3.2. Germanium redistribution during implantation

SIMS depth profiles of germanium for virgin, as-implanted, 900 and 1000 °C-RTA samples are shown in Fig. 4. The germanium fraction, x, of the relaxed $Si_{1-x}Ge_x$ buffer layer is 0.3. The implantation itself caused recoil of germanium atoms into the strained-silicon layer, which results in interface broadening. The same phenomenon was observed in the arsenic-implanted samples [8,9]. The amounts of recoiled atoms estimated from the SIMS depth profiles are in good agreement with the estimate by the SRIM [10] simulation. More significant interface broadening during RTA was observed. Vacancy-enhanced diffusion plays a role in interface broadening during RTA. The strained-silicon layer employed in the strained-silicon MOSFET is as thin as 20 nm. Recoiled and redistributed germanium atoms reach more than 10 nm (concentration higher than 10^{20} cm^{-3}). This redistribution might degrade the gate-oxide integrity if the implantation is done near the gate electrode during the formation of the extension region. Careful control of ion implantation (depth, angle, and dose) and annealing is thus an important require-

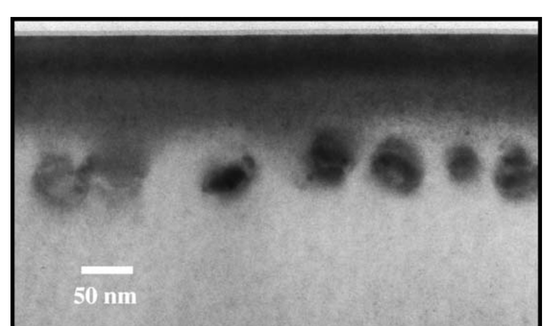

Fig. 3. XTEM image of 900 °C-annealed sample (germanium fraction, x=0.1).