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Atomic-Layer Doping in $Si_{1-x}Ge_x/Si/Si_{1-x}Ge_x$ Heterostructures by Two-Step Solid-Phase Epitaxy

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1. Introduction

The $Si_{1-x}Ge_x$ / Si / $Si_{1-x}Ge_x$ heteroepitaxy is a key technology for introducing high-speed modulation-doped field-effect transistors (MODFETs) into Si-ULSI [1-8]. We have developed a new growth method for SiGe heterostructures which combines molecular-beam epitaxy (MBE) and solid-phase epitaxy (SPE). This combination produces an atomically flat interface between the $Si_{1-x}Ge_x$ and the Si-channel layers. Due to this smooth interface, we obtained ultrahigh mobility of 5.5×10^5 cm^2/Vs at 4.2 K [9]. However, the carrier concentration in the doped $Si_{1-x}Ge_x$ region could not be properly controlled. This problem must be solved to control the properties of MODFETs.

In line with this, we investigated depth profiles of the Sb dopant in the SPE grown regions and found significant redistribution of Sb atoms. This result triggered the new idea of two-step SPE. This technique successfully realized an atomic-layer doping of Sb in SiGe by eliminating the redistribution of Sb atoms and made a precise control of carrier density possible.

2. Experimental

A schematic cross-section of the SiGe heterostructure is shown in Fig. 1. In the growth procedure of the heterostructures, first, the p-Si (100) substrates were cleaned by chemical etching and introduced into an ultrahigh-vacuum chamber using evaporation sources of Si, Ge, and Sb. A $Si_{1-x}Ge_x$ ($0\leq x\leq 0.2$) compositionally graded buffer layer (2 μm thick) was then grown at 600°C to apply sufficient tensile strain to a Si-channel layer. Next, the Si-channel layer (20 nm thick) was grown at 400°C above this layer. Above this channel layer, a $Si_{0.8}Ge_{0.2}$ spacer layer, an Sb delta-doped layer and a $Si_{0.8}Ge_{0.2}$ cap layer were then formed by two types of SPE processes. In the first, single-step SPE [9]; each layer was deposited below 100°C then crystallized simultaneously by heating to 600°C in approximately 10 minutes. And in the second process, two-step SPE (new method); the $Si_{0.8}Ge_{0.2}$ spacer layer was deposited below 100°C and crystallized by heating to 600°C, cooled to below 100°C, and the Sb delta-doped layer and the $Si_{0.8}Ge_{0.2}$ cap layer were deposited below 100°C then crystallized by heating to 600°C. Lastly, a Si cap layer was grown on the $Si_{0.8}Ge_{0.2}$ cap layer at 600°C.

Quantitative depth-profile analyses of Sb and Ge were made by secondary-ion mass spectrometry (SIMS) on a Physical Electronics 6600 spectrometer using 2-keV Cs^+ primary ions. The carrier density of the samples was evaluated by Hall-effect measurement using van der Pauw geometry.

3. Results and discussion

The SIMS profile obtained from a typical sample grown by single-step SPE is shown in Fig. 2(a). There are two peaks in the depth profile of Sb concentration in this figure. That is, one at the position where Sb is doped (15 nm in depth) and one at the position (30 nm in depth) just above the Si-channel layer. This result suggests that Sb atoms diffused from the original position during the crystallization of the amorphous layer. Because the diffusion coefficient of Sb atoms in the amorphous phase (in the $Si_{0.8}Ge_{0.2}$ layer) is much higher than that in the crystalline phase (in the Si-channel layer), the diffused Sb atoms accumulate on top of the channel layer. This result indicates that the control of Sb concentration profile is difficult by single-step SPE growth of these layers.

To solve this problem, we examined a two-step SPE process. In this process, when Sb atoms are deposited on top of the crystalline phase and covered by amorphous SiGe at low temperature on this layer, redistribution of Sb during the crystallization of covered SiGe is suppressed. This is because Sb atoms are pinned on the regular sites on the crystalline phase. The SIMS profile for the sample grown by two-step SPE is shown in Fig. 2(b). The depth profile of Sb concentration is sharp and remains at the original position (55 nm in depth). This result demonstrates that the accurate control of Sb profile is possible by the two-step SPE technique.

Controllability of carrier density in Sb delta-doped layer by the two-step SPE was investigated by measuring the carrier concentration as a function of Sb concentration. As the activation coefficient of Sb with the atomic-layer doping in SiGe is not well-known, to compare the activation coefficients, we prepared samples in which Sb is doped in Si or $Si_{0.8}Ge_{0.2}$. The sample structures are shown in Fig. 3(a). Sb was deposited on the crystalline Si or $Si_{0.8}Ge_{0.2}$ layer, and then a cap layer was formed by SPE.

The dependence of Sb concentration on the sheet carrier density is shown in Fig. 3(b). In this graph, the solid line corresponds to the dependence of the carrier density when the

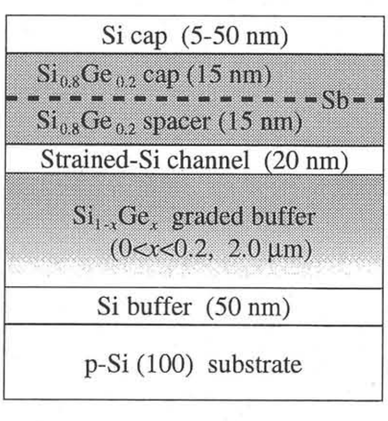

Fig. 1 schematic cross-section of the SiGe heterostructure doped Sb is fully activated, and the dashed line shows the solubility limit of the delta-doped Sb in Si [10]. The activation coefficient is by far lower than unity in the high-concentration region near the solubility limit. As Sb concentration decreased, the activation coefficient increased and reached almost unity around 0.001 ML. The concentration range around 0.001 ML is regularly used in the fabrication of MODFETs. Therefore, control of carrier concentration in the MODFETs is possible by using the two-step SPE technique.

4. Conclusion

We developed a two-step SPE technique for fabricating high-quality $Si_{1-x}Ge_x$ / Si / $Si_{1-x}Ge_x$ heterostructures. SIMS analyses and Hall-effect measurements revealed that the Sb doping profile was sharp and the electrical activation was high. With this technique, both the formation of an abrupt interface between SiGe and Si and the precise doping control in the SiGe layer became possible for the first time. This method will be a powerful tool in developing high-speed MODFETs.

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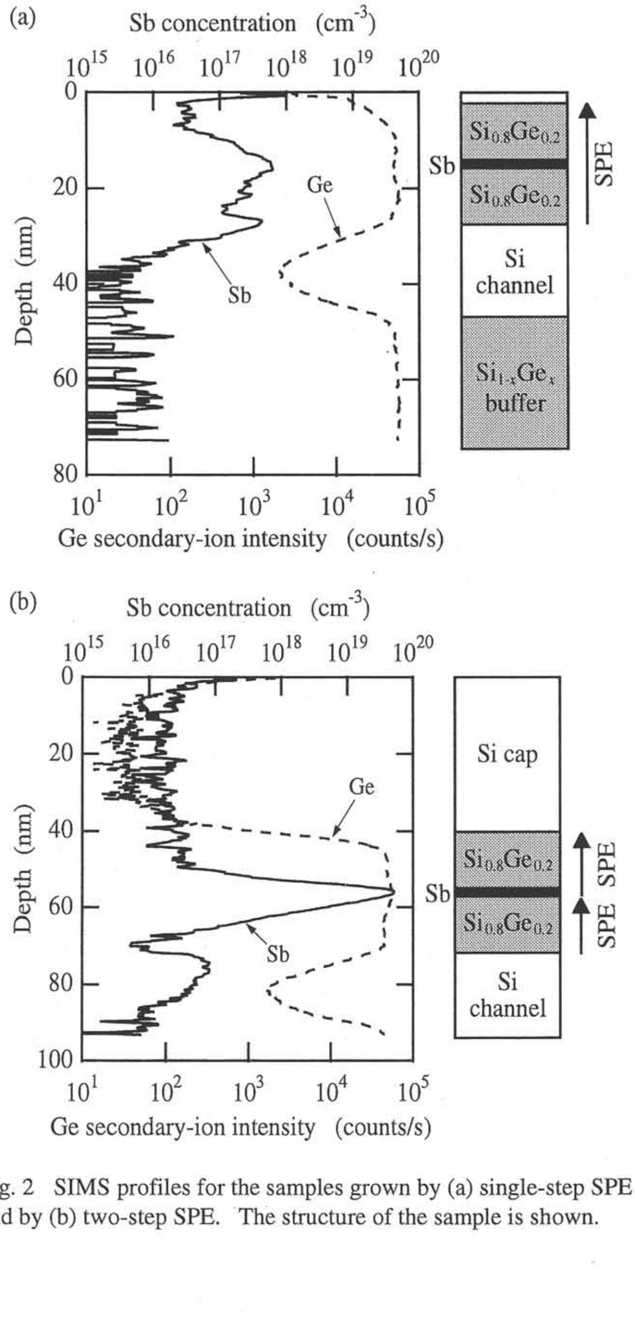

Fig. 2 SIMS profiles for the samples grown by (a) single-step SPE and by (b) two-step SPE. The structure of the sample is shown.

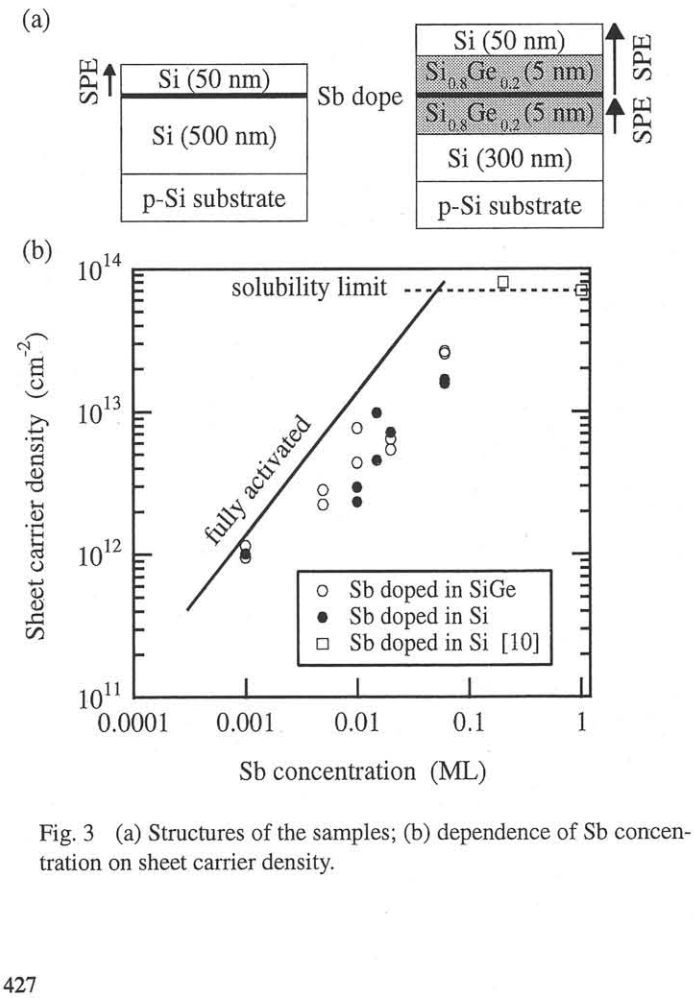

Fig. 3 (a) Structures of the samples; (b) dependence of Sb concentration on sheet carrier density.