P-1-5

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Control of Defect Properties in Ge Heteroepitaxial Layers by Sn Incorporation and H_2-Annealing

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1. Introduction

Heteroepitaxially growth of germanium (Ge) on silicon (Si) substrates is one of key technologies for the development of integrated electronic and optoelectoric devices. Ge is an attractive material with a higher mobility for holes and electrons than Si. However, one of serious problems of Ge epitaxial layers is the formation of electrically active vacancy defects having the shallow acceptor-like-state. These vacancies affect on the carrier concentration and mobility of heteroepitaxial Ge layers. We have to develop the controlling technology of properties of vacancy in Ge layers.

It is reported that a Sn atom in Si matrix preferentially forms Sn-vacancy pairs for the compensation of the local strain around a Sn atom and the acceptor level of a Sn-vacancy pair becomes deeper than that of single Sn atom in Si [1]. Previously, we reported that the Sn incorporation with a Sn content of 2.0~5.8% into undoped Ge layers reduces the hole concentration [2]. On the other hand, it is reported that the point defect in a Ge layer decreased by the H_2-annealing [3]. v In this study, we investigated the impacts of Sn incorporation and H_2-annealing on the electrical properties of Ge epitaxial layers.

2. Experimental procedure

The substrates were used low-doped separation by implanted oxygen (SIMOX) wafers with a resistivity of 20-30 Ωcm and a SOI thickness of 37-47 nm in order to estimate the carrier conduction of a heteroepitaxial $Ge_{1-x}Sn_x$ layer by minimizing the parasitic current conduction though a substrate. After cleaning a substrate, a 200 nm-thick $Ge_{1-x}Sn_x$ layer was grown on a SOI layer at a substrate temperature of 200˚C in molecular beam epitaxy (MBE) chamber. Ge and Sn were deposited by a Knudsen cell. The Sn content was ranging from 0% to 2.0%. Some samples were taken out to atmosphere and then additionally annealed at 500˚C for 60 min in N_2 or H_2 ambient. A sample was cut into a piece of 1 cm square and Al ohmic electrodes were deposited at each corner. Four-point probe and Hall measurements were performed by the Van Der Pauw technique at a temperature range from 20K to 300K. The Sn content and the degree of strain relaxation were also estimated by x-ray diffraction (XRD) analysis.

3. Results and discussion

Figures 1 show the Arrhenius plots of the carrier concentration estimated by the Hall measurement for as-grown and N_2- and H_2-annealed $Ge_{1-x}Sn_x$/SOI samples with various Sn contents. The majority carrier type in all $Ge_{1-x}Sn_x$ layers was determined to be p-type (hole) by this Hall measurement. It is well known that the energy level of a single vacancy in Ge is an acceptor-like-state (E_v+10~20 meV) [4], and it is considered that these holes are related to vacancy defects formed in $Ge_{1-x}Sn_x$ layers epitaxially grown by MBE in this study. The hole concentration obviously decreases after the H_2-annealing regardless of the Sn content.

Figure 2 shows the substitutional Sn content dependence of the hole concentration at 300K for as-grown and N_2- and H_2-annealed $Ge_{1-x}Sn_x$ /SOI samples. The carrier concentration of the Ge layer without the Sn incorporation is as high as 1×10^{18} cm^{-3}. On the other hand, the carrier concentration of the $Ge_{1-x}Sn_x$ layers with a Sn content of 0.1% is effectively reduced to 3×10^{17} cm^{-3}. This result suggests that Sn atoms in $Ge_{1-x}Sn_x$ layers preferentially formed Sn-vacancy pairs to reduce the local strain around a substitutional Sn atom in Ge matrix. The Sn-vacancy pair probably become more electrically inactive with that the energy state the of defect become deeper than that of single vacancy. In addition, the carrier concentration of the $Ge_{1-x}Sn_x$ layers with a Sn content of 0.1% is reduced to 4×10^{16} cm^{-3} after H_2-annealing, while that after N_2-annealing hardly changes. This result indicates that H_2-annealing is also effective to control the properties of defect in Ge and $Ge_{1-x}Sn_x$.

Next, we estimated the activation energy from the slope of the Arrhenius plot for the carrier concentration of $Ge_{1-x}Sn_x$ layers. Figure 3 show the activation energy of hole in $Ge_{1-x}Sn_x$ layers for as-grown and N_2- and H_2-annealed $Ge_{1-x}Sn_x$/SOI samples. The activation energy of $Ge_{1-x}Sn_x$ layers increases compared to that of the Ge layer without the Sn incorporation. This result is the evidence that the Sn incorporation in Ge layers makes the energy state of vacancy deeper in $Ge_{1-x}Sn_x$ layers. In addition, the activation energy of $Ge_{1-x}Sn_x$ layers also increases by H_2-annealing regardless of the Sn content, while the activation energy of samples after N_2-annealing hardly changes. This result means that H_2-annealing also modifies the energy state of defects in Ge and $Ge_{1-x}Sn_x$. The activation energy achieves to 40 meV for the sample with a Sn content of 0.1%.

Figure 4 shows the Hall mobility of $Ge_{1-x}Sn_x$ layers at 300K as a function of the carrier concentration, which was estimated by the Hall measurement. The mobility of bulk Ge at 300K is also indicated by a broken line as a reference [5]. The hole mobility can be improved with decreasing the carrier concentration by the Sn incorporation and H_2-annealing. The carrier concentration dependence of the Hall mobility for samples with Sn contents lower than 0.1% shows the same trend as that of bulk Ge. This result indicates that the incorporation of Sn as low as 1% hardly degrades the mobility behavior.

4. Conclusions

We investigated the impact of Sn incorporation and H_2-annealing on the electrical properties of Ge heteroepitaxial layers. The 0.1%-Sn incorporation reduces the carrier concentration of the $Ge_{1-x}Sn_x$ layer to 3×10^{17} cm^{-3}. In addition, H_2-annealing effectively reduces the carrier concentration to 4×10^{16} cm^{-3}. We found that H_2-annealing increases the activation energy of hole for $Ge_{1-x}Sn_x$ layers especially with the Sn content of 0.1%. The Sn incorporation and H_2-annealing improves on the electrical properties of carriers in heteroepitaxial Ge layers by controlling the electrical behavior of defects. s

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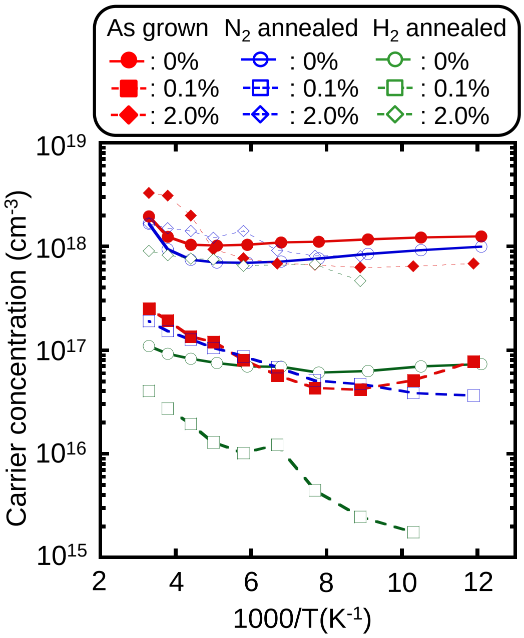

Fig. 1 The Arrhenius plots of the carrier concentration estimated by the Hall measurement for as-grown and N_2- and H_2-annealed $Ge_{1-x}Sn_x$/SOI samples.

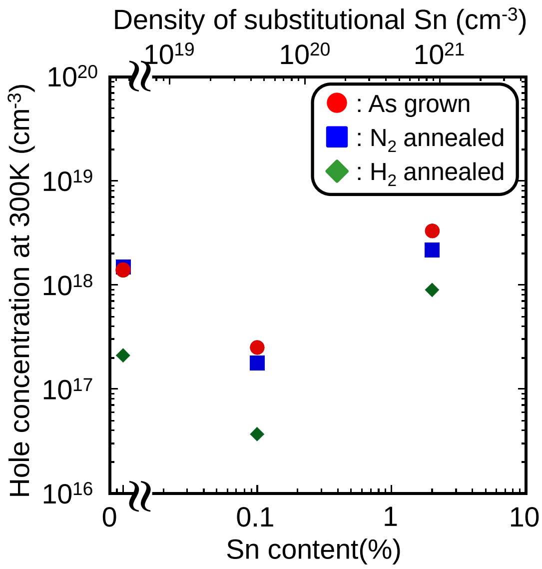

Fig. 2 The substitutional Sn content dependence the hole concentration at 300K for as-grown, N_2- and H_2-annealed $Ge_{1-x}Sn_x$ samples.

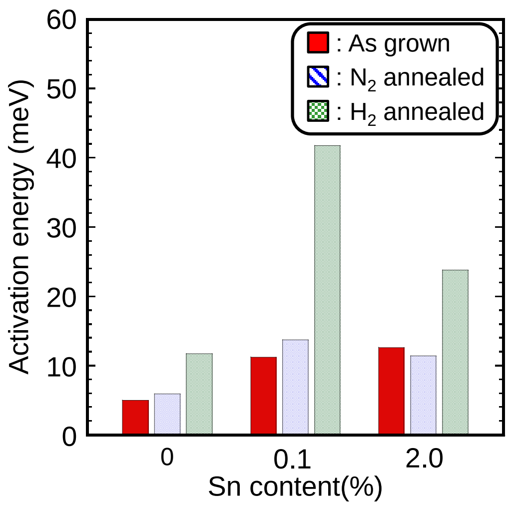

Fig. 3 The activation energy of holes in $Ge_{1-x}Sn_x$ layers for as-grown, N_2- and H_2-annealed $Ge_{1-x}Sn_x$/SOI samples.

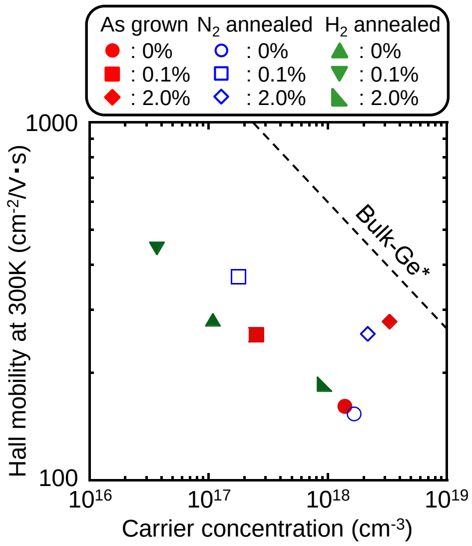

Fig. 4 The Hall mobility of $Ge_{1-x}Sn_x$ layers at 300K as a function of carrier concentration estimated by the Hall measurement. The broken line indicates the mobility of bulk Ge at 300K as a reference.