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Mobility Behavior in $Ge_{1-x}Sn_x$ Layers Grown on SOI Substrates

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1. Introduction

Recently, high-carrier-mobility materials such as strained-Si, $Si_{1-x}Ge_x$ and Ge have been much attracted for realizing the high current drivability and the low power consumption in MOSFET. $Ge_{1-x}Sn_x$ is one of expected materials with a higher mobility for holes and electrons than Ge, since it is mixed crystal between Ge and Sn whose effective mass is smaller than Ge [1]. $Ge_{1-x}Sn_x$ also has a lattice constant larger than Ge, and is expected for a buffer layer of tensile-strained Ge and III-V compound semiconductors [2,3]. We previously reported the formation and the crystalline properties of $Ge_{1-x}Sn_x$ buffer layers for realizing tensile-strained Ge layers [4,5]. However, the electronic properties of the $Ge_{1-x}Sn_x$ layers have not been clearly understood yet.

In this study, we investigated the Hall mobility and the carrier density of un-doped $Ge_{1-x}Sn_x$ layers grown on SOI substrates. We found that the behavior of the mobility for temperature and the scattering process is different between Ge and $Ge_{1-x}Sn_x$ layers.

2. Experimental

Substrates were used low-doped SIMOX SOI wafers with a resistivity of 20-30 Ωcm and a SOI thickness of 37-47 nm in order to minimize the parasitic current conduction. After cleaning a substrate, a 160 nm-thick $Ge_{1-x}Sn_x$ layer was grown on a SOI layer at a substrate temperature of 200ºC in molecular beam epitaxy (MBE) chamber whose base pressure is lower than 1×10^{-8} Pa. Ge and Sn were deposited by a Knudsen cell and an arc plasma gun, respectively. The Sn content of $Ge_{1-x}Sn_x$ layers was ranging from 0% to 5.8%. Then, some samples were additionally annealed at 500ºC for 60 min. 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 estimated by X-ray diffraction analysis.

3. Results and Discussion

The majority carrier type in all $Ge_{1-x}Sn_x$ layers was determined to be p-type (hole) by the Hall measurement. It is well known that the energy level of a vacancy in Ge is an acceptor-like-state (E_v+10-20 meV) [6] and it is considered that these holes are related to vacancies formed in $Ge_{1-x}Sn_x$ layers epitaxially grown by MBE in this study.

The temperature dependences of the measured carrier concentration and the measured mobility are shown in Figs. 1(a) and 1(b), respectively. The carrier concentration in all samples is as high as 10^{18}cm^{-3}, suggesting the formation of many vacancies due to the MBE growth at the low temperature of 200ºC. The carrier concentration decreases and the mobility increases about 1.5 times after the annealing. This result indicates that the decreasing in the density of vacancies due to improving in the crystalline quality of $Ge_{1-x}Sn_x$ layers by annealing.

Figure 2 shows the carrier concentration of $Ge_{1-x}Sn_x$ layers as a function of the Sn content at 300K. The Sn content dependence of the carrier concentration shows a V shape, and that of the $Ge_{0.98}Sn_{0.02}$ layer is the lowest in the samples. It is reported that a Sn atom in Si preferentially forms a Sn-vacancy pair for the compensation of the strain around a Sn atom and the energy level of Sn-vacancy pair becomes deeper than that of Sn in Si [7]. We deduced that Sn atoms in $Ge_{1-x}Sn_x$ layers also preferentially formed Sn-vacancy pairs and the hole concentration decreased due to the formation of the deeper energy state in the $Ge_{0.98}Sn_{0.02}$ sample. On the other hand, in the case of the Sn content over 2%, the carrier concentration increases due to the generation from the energy state formed probably by Sn itself. However, the detail of the energy state of Sn in $Ge_{1-x}Sn_x$ with high Sn content has not been clear yet.

The temperature dependence of the carrier concentration below 50K in Fig. 1(a) becomes very small. This suggests the carrier conduction in the impurity band for a heavily-doped semiconductor with an impurity concentration over 10^{16} cm^{-3} at carrier freeze-out region [8]. Therefore, it is considered that the hole conduction in the valence band is dominant at a temperature over about 100K. The mobility in the $Ge_{0.98}Sn_{0.02}$ layer at 300K is estimated to be 280 cm^2/Vs which is twice larger than that in the Ge layer. This mobility enhancement is roughly considered to be due to the smaller effective mass of hole in $Ge_{0.98}Sn_{0.02}$ than that in Ge, since the effective masses of α-Sn and Ge are $0.195m_0$ and $0.284m_0$, respectively. On the other hand, the measured mobility decreases with the increase in the Sn content in $Ge_{1-x}Sn_x$ samples with a Sn content over 4%. This result suggests the scattering by Sn atoms or Sn-vacancy pairs in $Ge_{1-x}Sn_x$ becomes actual with the increasing in Sn content.

We also resolved the mobility, μ_i and the carrier concentration, p_i of the parallel conduction in the valence band and the impurity band formed by defects such as vacancies by following equation;

$$\sigma = q\left(p_V \mu_V + p_D \mu_D\right), \qquad (1)$$

$$R_H = \frac{p_V \mu_V^2 + p_D \mu_D^2}{q(p_V \mu_V + p_D \mu_D)^2}, \quad (2)$$

where σ is the measured conductance, R_H is the measured Hall coefficient, q is the elementary charge, the suffixes V and D indicate the valence band and the defect states, respectively. Here, we assumed that the carrier concentration and the mobility at 20K were governed only by the conduction in the impurity band.

Figures 3(a) and 3(b) show the carrier concentration and the hole mobility in the valence band, respectively, as a function of temperature. The hole mobility in the Ge layer decreases with the temperature below 200K, suggesting the coulomb scattering due to ionized vacancies. On the other hand, the temperature dependence of the hole mobility in $Ge_{1-x}Sn_x$ samples is small compared to the Ge sample at the temperature below 200K. This result suggests the dominant scattering process is due to neutral sites such Sn-vacancy pairs whose energy level is deeper than that of the vacancy site. The maximum hole mobility is estimated to be 660 cm^2/Vs at 110K in the $Ge_{0.98}Sn_{0.02}$ layer. The hole mobility of Ge_xSn_{1-x} can be probably more enhanced by the reduction in the vacancy density with improving in the crystalline quality.

4. Conclusions

We investigated the behavior of the carrier concentration and the mobility in the $Ge_{1-x}Sn_x$ layers epitaxially grown on SOI substrates. The carrier concentration is estimated to be as high as 10^{18} cm^{-3} despite undoped $Ge_{1-x}Sn_x$ layers, indicating the formation of many vacancies due to the low temperature growth of $Ge_{1-x}Sn_x$ layers, Nevertheless, we found that the hole mobility in the $Ge_{0.98}Sn_{0.02}$ layer is more than twice compared to that in the Ge layer. $Ge_{1-x}Sn_x$ is expected to be a high mobility material for realizing ULSI devices with the high speed and the low power consumption.

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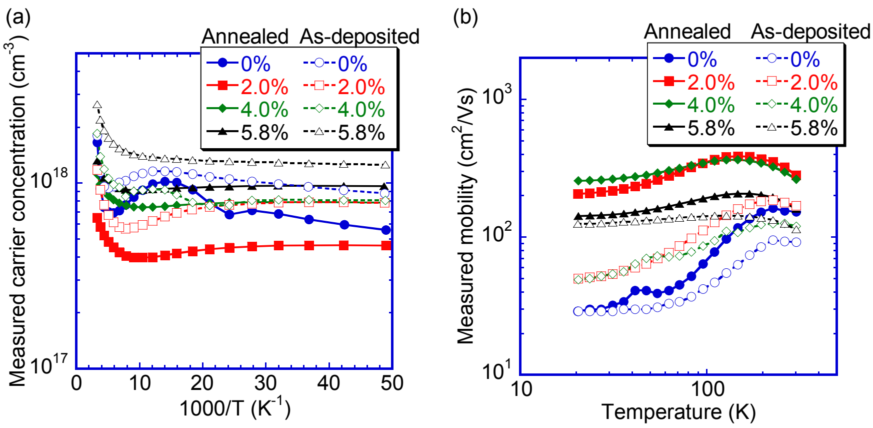

Fig. 1. The temperature dependences of (a) the measured carrier concentration and (b) the measured mobility for as-grown and annealed $Ge_{1-x}Sn_x$ samples

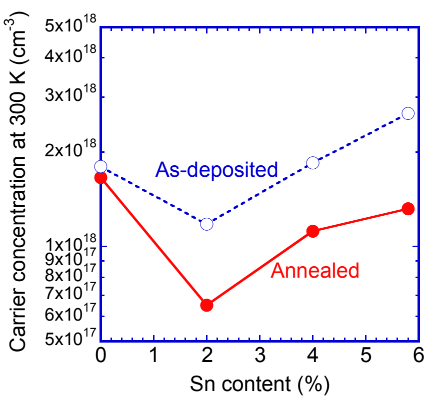

Fig. 2 The carrier concentration of $Ge_{1-x}Sn_x$ layers as a function of the Sn content at 300K for as-grown and annealed $Ge_{1-x}Sn_x$ samples.

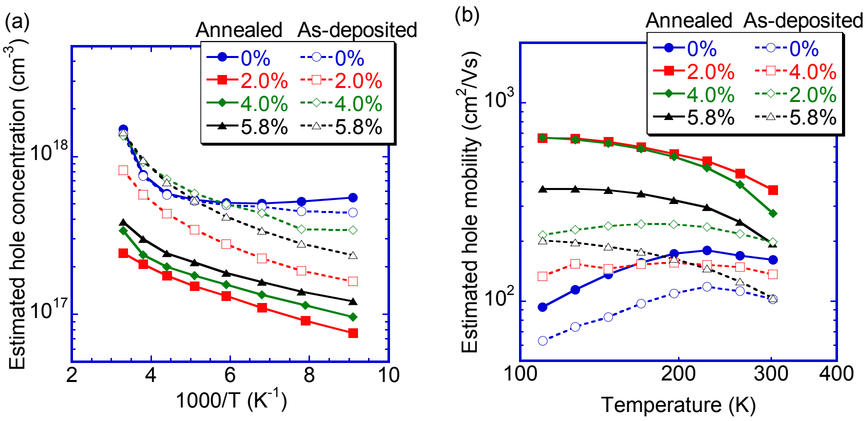

Fig. 3. The temperature dependences of (a) the carrier concentration and (b) the estimated hole mobility in the valence band as a function of temperature for as-grown and annealed $Ge_{1-x}Sn_x$ samples