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Strain Relaxation Enhancement of $Ge_{1-x-y}Si_xSn_y$ Epitaxial Layer on Ge Substrate Using Ion-Implantation Method

Hidetaka Sofue[1], Masahiro Fukuda[1], Shigehisa Shibayama[1], Shigeaki Zaima[1,2], and Osamu Nakatsuka[1,3]

[1]Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
[2]Graduate School of Engineering, Meijo University, 1-501, Shiogamaguchi, Tempaku-ku, Nagoya 468-8502, Japan
[3]IMaSS, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
Phone: +81-52-789-3819 e-mail: nakatuka@alice.xtal.nagoya-u.ac.jp

Abstract

We demonstrated that the strain relaxation enhancement of both $Ge_{1-x-y}Si_xSn_y$ and $Ge_{1-x}Sn_x$ epitaxial layers on ion-implanted Ge substrate and the reduction of critical energy for strain relaxation. This fact supports a mechanism of reducing a static friction from substrate side by ion implantation. This possibility is discussed based on Raman spectroscopy analysis.

1. Introduction

$Ge_{1-x-y}Si_xSn_y/Ge_{1-x}Sn_x$ double heterostructure with type-I energy band structure and direct transition $Ge_{1-x}Sn_x$ are promising structure for future optoelectronic and transistor applications [1,2]. We previously demonstrated the enhancement of the photoluminescence intensity of a $Ge_{1-x}Sn_x$ layer formed by $Ge_{1-x-y}Si_xSn_y/Ge_{1-x}Sn_x/Ge_{1-x-y}Si_xSn_y$ double heterostructure pseudomorphically grown on Ge substrate. However, the $Ge_{1-x}Sn_x$ layer is still indirect transition due to a large compressive strain. It looks generally difficult to form a direct transition $Ge_{1-x}Sn_x$ with the pseudomorphic growth on Ge substrate since a very high Sn content more than 16% is required to a compressive-strained $Ge_{1-x}Sn_x$ [3]. To decrease the required Sn content, the increase of a lattice constant of under layer to reduce the strain of $Ge_{1-x}Sn_x$ is a possible solution.

Since the $Ge_{1-x}Sn_x$ layer is grown on a $Ge_{1-x-y}Si_xSn_y$ layer, the strain relaxation method of $Ge_{1-x-y}Si_xSn_y$ layer is examined in this study. It was reported that the ion implantation to Si substrate successfully enhance the strain relaxation of $Si_{1-x}Ge_x$ epitaxial layer on Si substrate [4]. Thus, we examined ion-implantation method to Ge substrate before $Ge_{1-x-y}Si_xSn_y$ growth. As a result, the strain relaxation of $Ge_{1-x-y}Si_xSn_y$ layer is sufficiently enhanced on an ion-implanted Ge substrate [5]. In this report, to obtain a general guideline for controlling the strain relaxation of group-IV semiconductor materials, we also discussed the mechanism of the strain relaxation enhancement of not only $Ge_{1-x-y}Si_xSn_y$ but also $Ge_{1-x}Sn_x$ epitaxial layers on ion-implanted Ge substrate.

2. Experimental

B ions were implanted on Ge(001) substrate after removing surface native-oxide. Ion doses were 1×10^{14} cm^{-2} and 3×10^{14} cm^{-2} and the ion implantation energy was 20 keV. Subsequently, the ion-implanted Ge(001) wafer was cleaned with chemical solutions and then thermally cleaned at 430 °C in ultrahigh vacuum. A 100-nm-thick $Ge_{1-x-y}Si_xSn_y$ or $Ge_{1-x}Sn_x$ layer was grown on the substrate at 100 °C using molecular beam epitaxy system. The target Si and Sn contents in $Ge_{1-x-y}Si_xSn_y$ layer were 10% and 13%, respectively. The Sn content in $Ge_{1-x}Sn_x$ layer was ranging from 5% to 12%. The crystalline structure was characterized with X-ray diffraction 2-dimensional reciprocal space mapping (XRD-2DRSM). Also, Raman spectroscopy measurement was performed to analyze the effect of ion implantation on the strength of Ge-Ge bonds.

3. Results and discussion

Figure 1 shows XRD-2DRSM results for the $Ge_{1-x-y}Si_xSn_y$ layer grown on (a) Ge substrate without ion implantation and (b) Ge substrate after the ion implantation of an ion dose of 3×10^{14} cm^{-2}. The strain relaxation is clearly observed for the $Ge_{1-x-y}Si_xSn_y$ layer grown on the ion-implanted substrate, while not for the sample without ion-implantation.

From XRD-2DRSM results, the in-plane lattice constant and the degree of strain relaxation (DSR) were esti-

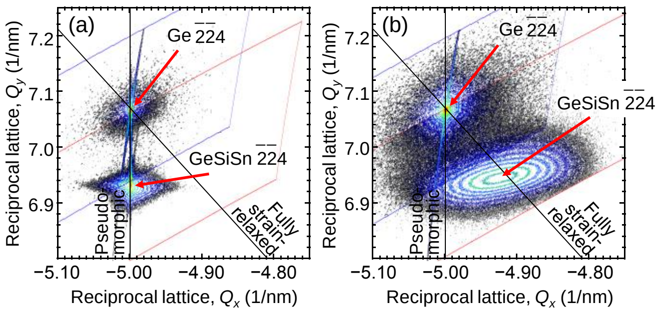

Fig. 1. XRD-2DRSM results around the Ge reciprocal lattice for samples of $Ge_{1-x-y}Si_xSn_y$ grown on (a) un-implanted and (b) ion-implanted substrate. The ion dose was 3×10^{14} cm^{-2}.

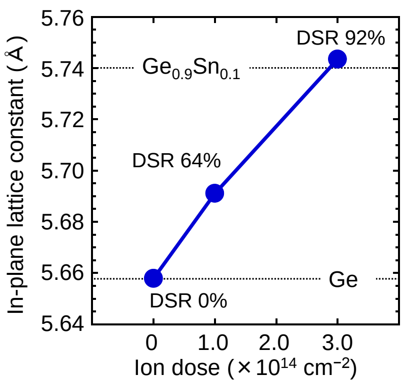

Fig. 2. In-plane lattice constants and DSR of $Ge_{1-x-y}Si_xSn_y$ layers as a function of the ion dose.

mated. **Figure 2** shows the in-plane lattice constant of $Ge_{1-x-y}Si_xSn_y$ layers as a function of the ion dose. The in-plane lattice constants of Ge and $Ge_{0.9}Sn_{0.1}$ are indicated with dotted lines. The DSR value of each $Ge_{1-x-y}Si_xSn_y$ layer is also shown in **Fig. 2**. It is observable that both the in-plane lattice constant and DSR of $Ge_{1-x-y}Si_xSn_y$ layer increase with the ion dose. For the ion dose of 3×10^{14} cm^{-2}, we achieved a large DSR value of 92% and large in-plane lattice constant more than 5.74 Å, which is comparable to the lattice constant of $Ge_{0.9}Sn_{0.1}$.

Next, we discuss the strain relaxation mechanism of $Ge_{1-x-y}Si_xSn_y$ layer on ion-implanted Ge substrate from the macroscopic viewpoint that is a strain energy. According to our previous work [6], there is a critical strain energy for the strain relaxation of $Ge_{1-x}Sn_x$ on Ge substrate ($E_{c,GeSn}$), which was roughly estimated to be 3~5 J/m^2. This value is independent on the substrate orientation regardless that strain relaxation mechanisms of $Ge_{1-x}Sn_x$ such as Sn precipitation and dislocation propagation should be complexly related each other. Thus, we investigated the effect of the ion-implantation method on $E_{c,GeSn}$. To discuss that, we examined to grow a $Ge_{1-x}Sn_x$ layer on the ion-implanted Ge substrate with an ion-dose of 3×10^{14} cm^{-2}. **Figure 3** shows the DSR of $Ge_{1-x}Sn_x$ layers on ion-implanted and un-implanted Ge substrates as a function of the Sn content. The strain energy, E_{strain} of $Ge_{1-x}Sn_x$ layer was estimated with the following equation,

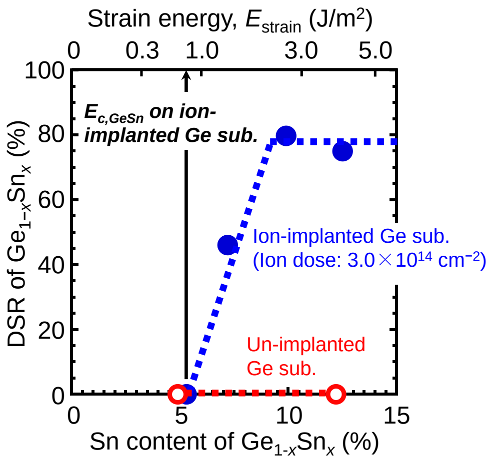

Fig. 3. DSR of $Ge_{1-x}Sn_x$ grown on un-implanted and ion-implanted Ge substrates as a function of the Sn content, corresponding to the strain energy. The ion dose was 3×10^{14} cm^{-2}.

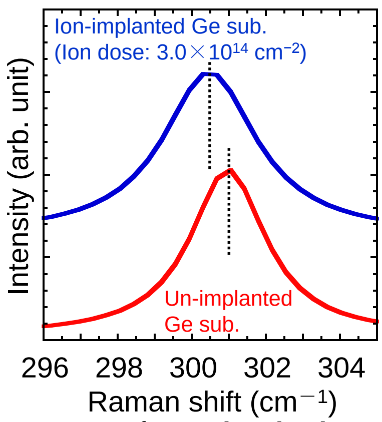

Fig. 4. Raman spectra of un-implanted and ion-implanted Ge substrate with ion dose is 3×10^{14} cm^{-2}.

$$E_{strain} = M_{001}\varepsilon^2 h \tag{1}$$

Here, M_{001} is the biaxial modulus of 001 orientation, h is the thickness of $Ge_{1-x}Sn_x$ layer, ε is the strain estimated from the Sn content assumed by the pseudomorphic growth of $Ge_{1-x}Sn_x$ on Ge, respectively. As shown in **Fig. 3**, the strain relaxation of $Ge_{1-x}Sn_x$ on the ion-implanted substrate occurs with increasing the Sn content higher than 5%, while that on the Ge substrate without ion implantation still does not even at a Sn content of 12%. This result indicates that $E_{c,GeSn}$ is effectively reduced to be less than 1 J/m^2 by ion implantation. We expected that the decrease of $E_{c,GeSn}$ is due to the reduction of the static friction from the Ge surface.

Finally, to investigate the effect of ion-implantation on the static friction, Raman spectroscopy analysis was carried out. **Figure 4** shows Raman spectra of Ge substrate without and with the ion implantation with an ion dose of 3×10^{14} cm^{-2}. The peak position of the ion-implanted Ge substrate shifts by 0.5 cm^{-1} from that without ion implantation. Also, the full width of half maximum value increases from 2.4 to 2.8 cm^{-1} by the ion-implantation. We confirmed that peak shift and broadening are located only at the surface side by combining chemical etching method (*not shown*). If this peak shift is caused by only the strain, the tensile strain with 1.0% is applied to Ge substrate. But the estimated strain value from XRD is just 0.5%, meaning that the observed Raman peak shift is not only from the strain. The remained possible mechanisms are crystal damage or softening of Ge-Ge bonds. Although we have not distinguished these two mechanisms yet, the similar Raman peak shift and broadening are verified for heavily Ga-doped Ge formed by the in-situ doping technique (*not shown*). Since Ge-Ge bond softening can be caused by increasing hole carrier concentration [7], this result is reasonable. In our presentation, we will also discuss the $Ge_{1-x-y}Si_xSn_y$ growth on a p^+-Ge substrate.

4. Conclusions

We demonstrated that the formation of 92% strain-relaxed $Ge_{1-x-y}Si_xSn_y$ epitaxial layer with a lattice constant of 5.74 Å. Also, we found that $E_{c,GeSn}$ is reduced to be less than ~1 J/m^2 on the ion-implanted Ge substrate. This mechanism is expected to be the reduction of the static friction of the substrate side due to the crystal damage or softening of Ge-Ge bonds according to Raman spectroscopy analysis, which have not been distinguished yet. The possibility of phonon softening induced strain relaxation is a worth to be further investigated to realize the growth of strain-relaxed $Ge_{1-x-y}Si_xSn_y$ layer with a high crystallinity for the practical applications.

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