Control of Dislocations and Sn Precipitations for Fabrication of Tensile-strained Ge on Ge$_{1-x}$Sn$_x$ Buffer Layer

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We investigated the dependence of strain relaxation and Sn precipitation on the thickness and the growth temperature of the Ge$_{1-x}$Sn$_x$ layer on a virtual Ge substrate. We found that the strain relaxation of the Ge$_{1-x}$Sn$_x$ layers is enhanced by increasing the thickness of the Ge$_{1-x}$Sn$_x$ layers. Additionally, the higher degree of strain relaxation of 87% and higher Sn content of 6.8% were realized by lowering the growth temperature of the Ge$_{1-x}$Sn$_x$ layers. The low temperature growth probably enhances the introduction of point defects contributing to the creation of new misfit dislocations at the Ge$_{1-x}$Sn$_x$/Ge interface. The Ge$_{1-x}$Sn$_x$ layer grown in this study has the potential to induce a tensile strain of 0.86% to the Ge layer.

Key words: germanium, tin, strain, epitaxial growth, dislocation

1. INTRODUCTION

A tensile-strained Ge has been expected for the application to high speed metal-oxide-semiconductor field effect transistors (MOSFET) beyond conventional strained Si MOSFETs. It was calculated that the in-plane tensile-strained Ge has higher mobility than bulk Ge not only for holes but also electrons. According to the calculation, the tensile strain value of Ge has to be higher than at least 1.0% in order to realize a higher effective mobility in tensile-strained Ge than a strained Si for n-type MOSFETs. On the other hand, tensile-strained Ge has also been seen as attractive for use in photonic devices because of its effect of extending the detection range of Ge toward a longer wavelength due to shrinkage of the energy bandgap. Therefore, tensile-strained Ge has good potential to be widely applied in electronic and photonic devices.

We focused strain-relaxed Ge$_{1-x}$Sn$_x$ buffer layers having larger lattice constants than Ge in order to induce a tensile strain into Ge layers. There are two types of strain reduction mechanism of Ge$_{1-x}$Sn$_x$ layers. One is the strain relaxation due to the lateral propagation of misfit dislocations. The strain of Ge$_{1-x}$Sn$_x$ layers is relaxed in the region where the misfit dislocation propagates at the Ge$_{1-x}$Sn$_x$/substrate interface. Previously, we reported that threading dislocations preexisting in a virtual Ge substrate supply nucleus of misfit dislocation to the Ge$_{1-x}$Sn$_x$ layer and effectively enhance the propagation of misfit dislocations at the Ge$_{1-x}$Sn$_x$/Ge interface. As a result, the high degree of strain relaxation (DSR) was realized. On the other hand, Sn precipitation occurs because of the low solid solubility limit in Ge and the strain in the Ge$_{1-x}$Sn$_x$ layer is also reduced by Sn precipitation. In our previous study, we found that there is the critical misfit strain of Sn precipitation. Recently, we also reported that the long time and low temperature annealing is effective to increase the critical misfit strain by suppressing Sn precipitation and to realize a high DSR. Considering the critical misfit strain of Sn precipitation, we proposed the compositionally step-graded called CSG Ge$_{1-x}$Sn$_x$ multilayer structure. In this method, the Sn content in each layer was gradually increased. After the strain relaxation of the 1st Ge$_{1-x}$Sn$_x$ layer, the misfit strain between the 1st and the 2nd Ge$_{1-x}$Sn$_x$ layers can be reduced. As a result, XRD 2dimensional reciprocal space mapping (XRD-2DRSM) observation revealed that a Sn content and a DSR of the top CSG buffer layer achieved to 6.3% and 77%, respectively. A tensile strain value of the Ge layer on this CSG structure achieved to 0.62% for bulk Ge.

However, much larger tensile strain value in Ge is required to realize much higher electron mobility comparable to strained Si. In order to induce a tensile strain over 1.0% in Ge, we have to realize a larger in-plane lattice constant of the Ge$_{1-x}$Sn$_x$ buffer layer by increasing the Sn content and the DSR. There are some key factors for enhancing strain relaxation of the Ge$_{1-x}$Sn$_x$ layers by propagating misfit dislocations without Sn precipitation.

As shown in our previous work, long time and low temperature annealing is effective to enhance the propagation of misfit dislocations with suppressing Sn precipitation. In this study, we focused on other two approaches. One is the thickness of the Ge$_{1-x}$Sn$_x$ layers. Increasing the thickness of the Ge$_{1-x}$Sn$_x$ layers promises larger driving force of propagation of misfit dislocations due to larger stress in the Ge$_{1-x}$Sn$_x$ layer and enhancement of the DSR. Another approach is low temperature growth of the Ge$_{1-x}$Sn$_x$ layers to introduce point defects for the creation of dislocations. In this study, we investigated the dependence of strain relaxation and Sn precipitation on the thickness and the growth temperature of the Ge$_{1-x}$Sn$_x$ layers, in order to establish the growth process of the Ge$_{1-x}$Sn$_x$ layers having large in-plane lattice constants based on these
approaches.

2. EXPERIMENTAL

Ge and Ge$_{1-x}$Sn$_x$ layers were grown by molecular beam epitaxy with a base pressure less than $1 \times 10^{-8}$ Pa. Ge and Sn were deposited using a Knudsen cell and an arc plasma gun, respectively. After the chemical cleaning of Si(001) substrates, the in situ thermal cleaning was performed at 850ºC. A Ge layer was epitaxially grown on the Si substrate and followed by ex situ rapid thermal annealing at 700ºC for 1 min in N$_2$ ambient to completely relax the strain in the Ge layer. We call this structure consisting of a fully strain-relaxed Ge layer on a Si substrate the “virtual Ge substrate (v-Ge)”. Details of the growth and cleaning of v-Ge have been described elsewhere. The Ge$_{1-x}$Sn$_x$ layers were epitaxially grown at 200ºC and 150ºC on v-Ge. The in situ thermal cleaning of the v-Ge substrate was performed at 430ºC. The post-deposition annealing (PDA) at 500ºC for 60 min in N$_2$ ambient was performed after the growth of the Ge$_{1-x}$Sn$_x$ layer for the strain relaxation.

Four-crystal XRD-2DRSM and cross-sectional transmission electron microscopy (XTEM) were used to characterize the crystallinity and the dislocation structure of the epitaxial Ge and Ge$_{1-x}$Sn$_x$ layers.

3. RESULTS AND DISCUSSION

Figures 1(a) and 1(b) show the typical XRD-2DRSM results for the Ge$_{0.946}$Sn$_{0.054}$/Ge/Si samples before and after PDA. We can observe the peaks related to the 224 lattice planes of the v-Ge and the Ge$_{0.946}$Sn$_{0.054}$ layer. In the as-grown sample, the horizontal reciprocal lattice, Q$_x$ of the Ge$_{0.946}$Sn$_{0.054}$ layer corresponds to that of the v-Ge, which means that the Ge$_{0.946}$Sn$_{0.054}$ layer is pseudomorphically grown on the v-Ge. On the other hand, after PDA, the peak position of the Ge$_{0.946}$Sn$_{0.054}$ layer shifts due to the strain relaxation. We can estimate the DSR and the Sn content of the Ge$_{0.946}$Sn$_{0.054}$ from the peak position of XRD-2DRSM.

Figure 2 shows the summary of peak positions of the Ge$_{1-x}$Sn$_x$224 reciprocal lattice points estimated from XRD-2DRSM for samples with a single Ge$_{1-x}$Sn$_x$ layer with thicknesses of 50 and 100 nm on the v-Ge before and after PDA. Horizontal and vertical axes indicate values of reciprocal lattices along the directions of [110] and [001], respectively. The peak position of the reciprocal lattice from a bulk-Ge or an unstrained Ge layer is indicated with “Ge 224” in Fig. 2. Vertical and diagonal lines indicate the reciprocal lattice peak positions for pseudomorphic and fully-strain-relaxed Ge$_{1-x}$Sn$_x$ layers, respectively, with various Sn content. Broken lines in Fig. 2 also indicate the trajectory of the diffraction peak position when the strain relaxation occurs for the Ge$_{1-x}$Sn$_x$ layers with maintenance of Sn contents of 4, 5, and 6%. We can estimate the Sn contents and the DSR of the Ge$_{1-x}$Sn$_x$ layers from the peak position obtained with XRD-2DRSM.

The strain of the Ge$_{1-x}$Sn$_x$ layers was relaxed after the PDA for both samples without Sn precipitation. It should be noted that a higher DSR was realized in the sample with a thickness of 100 nm than 50 nm. This result suggests that the propagation of misfit dislocations at the Ge$_{1-x}$Sn$_x$/Ge interface is promoted due to the large stress from a thick Ge$_{1-x}$Sn$_x$ layer.

Next, we also investigated the dependence of strain relaxation on the growth temperature. Here, we prepared 100 nm-thick Ge$_{1-x}$Sn$_x$ layers with various Sn contents with two different growth temperatures of 200ºC and 150ºC. In the sample grown at 150ºC, it is expected that
Table I. The detail of samples in Fig. 3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Growth temperature (ºC)</th>
<th>Ge$_{1-x}$Sn$_x$ thickness (nm)</th>
<th>Sn content (%)</th>
<th>Annealing condition</th>
<th>Symbol in Figure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>100</td>
<td>5.4</td>
<td>500ºC 60 min</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>6.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4L</td>
<td>150</td>
<td></td>
<td>8.1</td>
<td></td>
<td>■</td>
</tr>
<tr>
<td>5L</td>
<td>8.7</td>
<td></td>
<td></td>
<td></td>
<td>□</td>
</tr>
</tbody>
</table>

many more point defects are induced in the Ge$_{1-x}$Sn$_x$ layer than the Ge$_{1-x}$Sn$_x$ layer grown at 200ºC during the growth of the Ge$_{1-x}$Sn$_x$ layer. The strain relaxation behaviors in these samples were compared after PDA at 500ºC for 60 min.

Figure 3 shows the summary of peak positions of Ge$_{1-x}$Sn$_{224}$ reciprocal lattice points estimated from XRD-2DRSM results for these samples. The symbols and the detail of the samples are summarized in Table I. In all Ge$_{1-x}$Sn$_x$ layers grown at 200ºC, the Sn contents are not higher than 5.5% as a result of Sn precipitation after PDA. This result suggests that the critical misfit strain of Sn precipitation is 7.9×10$^{-3}$ for the growth at 200ºC. On the other hand, in the Ge$_{1-x}$Sn$_x$ layer grown at a lower temperature of 150ºC, a Sn content and a DSR of the Ge$_{1-x}$Sn$_x$ layer are achieved to 6.8% and 87%, respectively, while the Sn precipitation occurs. This result suggests that the Sn precipitation is suppressed by increasing the amount of strain relaxation due to the propagation of misfit dislocations in the case of the lower temperature growth. This Ge$_{1-x}$Sn$_x$ layer has a potential to induce a tensile strain of 0.86% in a Ge layer.

Here, we deduce the reason why such high DSR is achieved by lowering the growth temperature. It is known that the low temperature growth enhances introduction of point defects into the epitaxial layers. There are two types of phenomena of the point defects for dislocation behavior. First, point defects cause climb of dislocations and helps to annihilate the threading dislocation arms. As a result, a new misfit dislocation is created with the fusion of dislocations at the interface and strain relaxation of the epitaxial Ge$_{1-x}$Sn$_x$ layer is effectively enhanced (Fig. 4). Furthermore, the condensation of point defects leads to the formation of prismatic dislocation loops with burgers vector perpendicular to the loop plane inside the layer. These dislocations also reduce the strain in Ge$_{1-x}$Sn$_x$ layer. Because many more point defects are induced in a Ge$_{1-x}$Sn$_x$ layer grown at 150ºC than that grown at 200ºC, a higher DSR of the Ge$_{1-x}$Sn$_x$ layer grown at 150ºC is achieved.

4. SUMMARY

We have investigated the relationship between strain relaxation and the thickness of the Ge$_{1-x}$Sn$_x$ layer. In the sample with a Ge$_{1-x}$Sn$_x$ thickness of 100 nm, higher DSR was realized compared with a thickness of 50 nm. It is considered that the propagation of misfit dislocations at the Ge$_{1-x}$Sn$_x$/Ge interface is promoted by a larger stress from a thicker Ge$_{1-x}$Sn$_x$ layer. We also investigated the impact of low temperature growth of the Ge$_{1-x}$Sn$_x$ layers on strain relaxation and Sn precipitation. Sn contents in Ge$_{1-x}$Sn$_x$ layers grown at 200ºC were not higher than

Fig. 3 The summary of GeSn224 reciprocal lattice points for Ge$_{1-x}$Sn$_x$ layer grown at 200ºC and 150ºC.

Fig. 4 The schematic diagram of the annihilation of threading dislocation arms and the creation of the new misfit dislocation.
5.5% as a result of Sn precipitation after PDA. The critical misfit strain of Sn precipitation is $7.9 \times 10^{-3}$ for the Ge$_{1-x}$Sn$_x$ layer grown at 200°C. On the other hand, in the Ge$_{1-x}$Sn$_x$ layer grown at 150°C, a Sn content and a DSR are achieved to 6.8% and 87%, respectively. We consider that the many more point defects induced by the low temperature growth enhance the propagation of misfit dislocations and a creation of new prismatic-dislocations. As a result, higher DSR was realized and Sn precipitation was suppressed by increasing the amount of strain relaxation.

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References

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