Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 292-293

F-3-4

Strain-Relaxed $Si_{1-x}Ge_x$ and Strained Si Grown by Sputter Epitaxy

Hiroaki Hanafusa[1], Yoshiyuki Suda[1*], Akifumi Kasamatsu[2], Nobumitsu Hirose[2], Takashi Mimura[2], and Toshiaki Matsui[2]

[1] Graduate School of Engineering, Tokyo University of Agriculture and Technology,
2-24-16 Naka-cho, Koganei, Tokyo 184-8588, Japan
Phone/Fax: +81-42-388-7129, *E-mail: sudayos@cc.tuat.ac.jp
[2] National Inst. of Information and Communications Technology,
4-2-1Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan

1. Introduction

We have recently developed a Si/Ge sputter epitaxy method for state-of-the-art $Si/Si_{1-x}Ge_x$ devices [1]. The $Si/Si_{1-x}Ge_x$ layers are currently fabricated by MBE (molecular beam epitaxy) and CVD (chemical vapor deposition). Although a sputter deposition method has merits of high resource usability and high safety deposition process, and large area deposition capability, and thus the method is environmentally light-load method, it is hardly used for $Si/Si_{1-x}Ge_x$ deposition due to difficulty in realization of high crystalline quality.

To overcome this difficulty, we have recently developed a UHV-compatible magnetron sputter epitaxy method with a combination of Ar/H_2 mixture working gas [1]. With this method, we have obtained high quality $Si_{1-x}Ge_x$ epitaxial layers. We have so far reported the fundamental growth characteristics and the strain-relaxation behavior, and its successful applications to n- and p-type resonant tunneling devices (RTDs) [1, 2].

These RTDs are devices where the carriers basically travel in the direction perpendicular to the growth layers. We have further examined the feasibility of application of our sputter epitaxy to high-speed strained-Si devices where electrons travel in the strained-Si layer. As a strain-relaxed buffer, a thick $Si_{1-x}Ge_x$ graded buffer, where the Ge composition, x, is varied by 0.1 μm^{-1}, is commonly used [3]. To save the production energy and time, we have previously proposed a thin double-$Si_{1-x}Ge_x$-layer (DL) buffer [4] and a thin quadruple-$Si_{1-x}Ge_x$-layer (QL) buffer [5].

In this paper, we report the crystallinity and characterization of strained Si on the strain-relaxed QL buffer grown by our new sputter epitaxy, and compare them with those of strained Si on the QL buffer grown by gas-source MBE (GS-MBE).

2. Experimental

Si and $Si_{1-x}Ge_x$ layers were grown on 3-4 Ωcm p-type Si(001) with our sputter epitaxy method [1] and GS-MBE method with Si_2H_6, GeH_4 as Si and Ge source gasses [4, 5]. The sputter and GS-MBE films were grown at substrate temperatures of 500 and 600 °C, respectively.

3. Results and Discussion

3-1. Designs and relaxation mechanisms of thin double- and quadruple-$Si_{1-x}Ge_x$-layer (DL and QL) buffers

The thicknesses of our previously proposed DL and QL buffers (Fig. 1(b), (c)) are about one-fifteenth of that of the graded buffer (Fig. 1(a)). As for the DL buffer [4], the 1st layer is coherently grown. When the 2nd layer is grown, misfit dislocations are generated in the lower interface and the buffer relaxes. The 2nd layer also prevents threading dislocations from being propagated to the 2nd layer. As for the QL buffer [5], misfit dislocations are almost evenly distributed in the lower two interfaces. Due to this distribution, the threading dislocation density on the surface is lower than that of the DL buffer and is ~2 x 10^4 cm^{-2}.

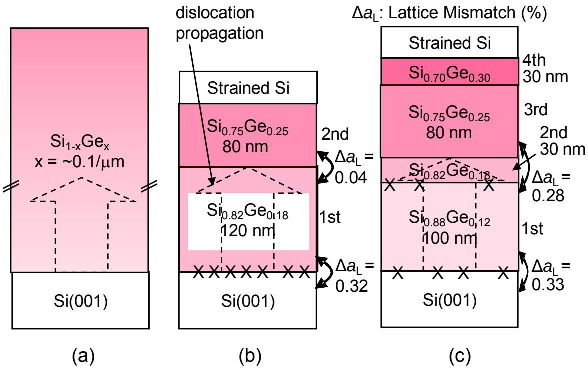

Fig. 1. Strain-relief relaxed buffers: (a) a commonly used thick $Si_{1-x}Ge_x$ graded buffer, our proposed (b) thin double-SiGe-layer buffer [4] and (c) thin quadruple-SiGe-layer buffer [5].

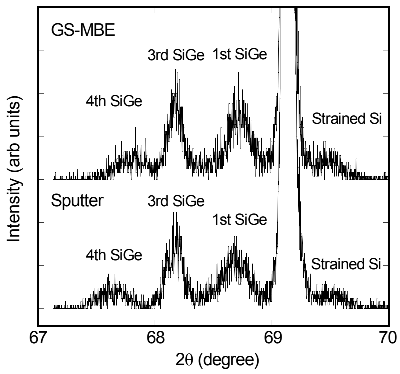

Fig. 2. Typical θ-2 θ XRD patterns obtained from strained Si layers on quadruple-SiGe-layer buffers formed by GS-MBE (upper) and sputter epitaxy (lower).

3-2. Strained Si on the strain-relaxed QL buffer

Typical XRD spectra obtained from strained-Si layers on the QL buffers are compared in Fig. 2. The corresponding relaxation rates and lattice mismatches are summarized in Table 1. The strained-Si layer thickness is 60 nm and each layer thickness of the buffer is the same as that indicated in Fig. 1. The 2nd $Si_{1-x}Ge_x$ layer peaks overlaped the other peaks and were not well separated.

In the sputter case, lattice mismatches between the substrate and the 1st $Si_{1-x}Ge_x$ layer and between the 1st and 3rd $Si_{1-x}Ge_x$ layers were 0.33 and 0.18 %. In the GS-MBE case, the corresponding values were 0.37 and 0.14 %, respectively. In both the sputter and GS-MBE cases, lattice mismatches between the 3rd and 4th $Si_{1-x}Ge_x$ layers were very small (0.08 and 0.004 %, respectively). Thus, the lattice mismatch results indicate that misfit dislocations are mainly distributed in the lower interfaces.

Table 1. Comparison of relaxations and lattice mismatches of strain-relaxed QL buffers grown by the sputter epitaxy and GS-MBE. (*1: based on just the underneath layer, *2: between 1st and 3rd $Si_{1-x}Ge_x$ layers)

GS-MBE

	1st Layer	3rd Layer	4th Layer
composition ratio	0.12	0.24	0.32
relaxation rate (%)	82	56	48
lattice mismatch (%)	0.37*1	0.14*2	0.08*1

Sputter

	1st Layer	3rd Layer	4th Layer
composition ratio	0.13	0.24	0.34
relaxation rate (%)	71	56	39
lattice mismatch (%)	0.33*1	0.18*2	0.004*1

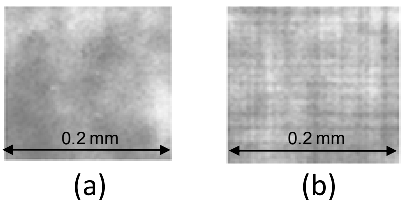

Fig. 3 Scanning white light interferometer images obtained from the surfaces of strained Si layers on quadruple-SiGe-layer buffers formed by (a) sputter epitaxy and (b) GS-MBE.

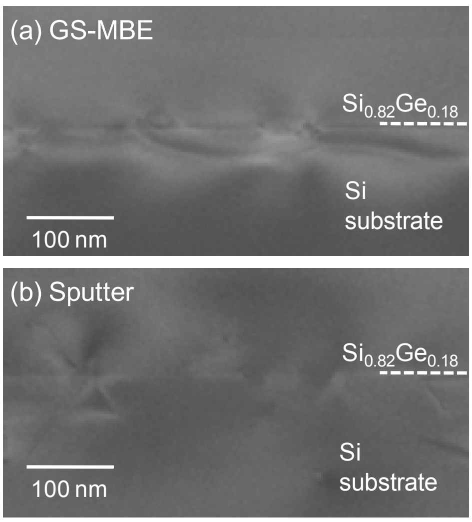

Fig. 4 Typical transmission electron microscope (TEM) images of interfaces between Si substrates and the 1'st $Si_{0.82}Ge_{0.18}$ layers of thin double-SiGe-layer buffers formed by (a) GS-MBE and (b) sputter epitaxy.

The strained-Si peaks are clearly observed in both the XRD curves. The full-width-at-half-maximum (FWHM) values of the 4th $Si_{1-x}Ge_x$ layers and strained-Si layers are almost the same between the sputter and GS-MBE methods. Thus, the XRD measurement results indicate that the relaxation mechanisms and crystallinity are almost the same between the sputter and GS-MBE methods. The strained Si formed by the sputter was strained by 0.31 % and was more strained than that formed by the GS-MBE (0.26 %).

Typical scanning white light interferometer images obtained from the strained Si surfaces are shown in Fig. 3. A cross-hatch undulation pattern was observed on the surface of the sample grown by the GS-MBE. However, it was not observed on the surface of the sample grown by the GS-MBE. Mean square error values for the surface roughness were 0.93 and 1.0 nm for the sputter growth and GS-MBE growth surfaces. Thus, the strained-Si surface formed by the sputter is flatter than that formed by the GS-MBE, which implies that stress distribution on the sputter sample surface is smaller than that on the GS-MBE sample surface.

The same difference in the surface morphology is observed between the DL buffers formed by the sputter and the GS-MBE. Thus, the observed surface morphology may be inherent to the respective growth methods. 60° dislocations in the directions of both the (111) and $(\bar{1}\bar{1}1)$ planes were observed from a typical transmission electron microscope (TEM) image of the DL buffer formed by the sputter (Fig. 4(b)). However, 60° dislocations in nearly one direction were observed from the TEM image of the GS-MBE sample (Fig. 4(a)). The TEM measurements suggest that in the sputter buffer, multi-directional glide dislocation planes cancel out the surface periodic undulation. The difference in the misfit dislocation generation mechanism may results from the difference in the crystal growth mechanism.

4. Conclusions

Strained Si on our previously proposed strain-relaxed thin quadruple-$Si_{1-x}Ge_x$-layer buffer was formed by our new sputter epitaxy method. The buffer relaxation controllability and strained-Si crystallinity obtained with the sputter method are comparable to those with the GS-MBE method. With the sputter method, a flatter strained Si surface without cross-hatch undulation morphology is obtained. The results suggest that our environmentally light-load sputter epitaxy method is effectively applied to new-generation $Si/Si_{1-x}Ge_x$ strained devices.

References

[1] J. Kubota, A. Hashimoto, and Y. Suda, Thin Solid Films **508**, 203 (2006). [2] J. Kubota, A. Hashimoto, and Y. Suda, Ext. Abs. 2005 Int. Conf. on Solid State Devices and Materials (The Japan Society of Applied Physics, Kobe, 2005) pp. 158-159. [3] J. W. P. Hsu, E. A. Fitzgerard, Y. –H. Xie, P. J. Silverman, and M. J. Cardillo, Appl. Phys. Lett. **61**, 1293 (1992). [4] H. Maekawa, Y. Sano, A. Megro, and Y. Suda, Jpn. J. Appl. Phys. Lett. **45**, L1247 (2006). [5] H. Maekawa, Y. Sano, C. Ueno, and Y. Suda, J. Cryst. Growth **301-302**, 1017 (2007).