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Stress-Relaxation Process during Post-Annealing in SGOI Formed by H^+ Irradiation and Oxidation-Induced Ge Condensation

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1. Introduction

Formation of highly stress-relaxed SiGe buffer layers on insulator (SGOI) is essential to establish the strained-Si CMOS technology. Oxidation-induced Ge condensation method using SiGe/Si on insulator (SOI) structures is a promising technique to realize thin SGOI [1, 2]. However, it was difficult to obtain highly relaxed ultra-thin SGOI by this method. We have proposed the improved method combined with H^+ irradiation, oxidation, and post-annealing; and realized highly stress-relaxed ultra-thin SGOI [3]. In the present paper, stress-relaxation process during post-annealing has been investigated, and the enhanced stress-relaxation is explained on the basis of the local area slipping at SGOI/BOX interfaces.

2. Experimental Procedure

The Si (thickness: 7-30nm)/$Si_{1-x}Ge_x$ (x: 0.07-0.25, thickness: 80-400nm) structures were epitaxially grown on SOI (top Si thickness: 55nm) wafers by chemical vapor deposition at 750°C, and categorized into the samples (A) and (B) as shown in Table I. The samples (B1) were irradiated with H^+ (energy: 8.4keV, dose: 0-5x10^{16}cm^{-2}) and two-step annealed (500°C for 30min and 850°C for 60min) in N_2. The two-step annealing was performed to remove irradiation-induced defects and suppress irradiation-enhanced oxidation [2]. The samples were oxidized (1100-1200°C) to condense Ge fraction to 30%, and post-annealed (1150-1200°C) for 180 min in N_2. The formed SGOI were characterized by Auger electron spectroscopy (AES), Raman spectroscopy, and transmission electron microscopy (TEM).

3. Results and Discussion

Relaxation rates of samples formed by the conventional method are summarized as a function of the SGOI final thickness (d_f) in Fig.1. Completely relaxed SGOI were obtained for thickness above 100 nm. However, the relaxation rate abruptly decreases with decreasing thickness below 50 nm. This is a serious problem for realization of fully depleted strained Si devices.

In order to enhance the relaxation rate in ultra-thin (<50 nm) SGOI layers, we proposed the improved method combined with H^+ irradiation, oxidation (1100°C), and post-annealing (1200°C) [3]. The modification of the SiGe/BOX interface by H^+ irradiation enhanced stress relaxation during oxidation, and additional relaxation was induced without changing Ge fraction by post-annealing.

Post-annealing effects (1150 and 1200°C) on relaxation enhancement of SGOI (thickness: 28 nm) are shown as a function of the dose of H^+ irradiation in Fig.2. Before post-annealing, the high relaxation rate (60%) was obtained only for the sample irradiated with high dose (5x10^{16} cm^{-2}). Although post-annealing at 1150°C did not cause any significant improvement of the relaxation rates, post-annealing at 1200°C increased the relaxation rates. Especially, the increase was remarkable for medium dose (5x10^{15} cm^{-2}).

To clarify such an enhanced relaxation for the medium dose sample, TEM and AFM observations were carried out before and after post-annealing. The results are shown in Figs.3 and 4. For the high dose sample (5x10^{16}cm^{-2}), the threading dislocation density (TDD) is high (1x10^{8}cm^{-2}), which suggests stress-relaxation by defect generation. On the other hand, TDD of the medium dose sample (5x10^{15} cm^{-2}) is almost same as that of no irradiated sample (<10^{6} cm^{-2}), and do not change after post-annealing, which suggests that stress-relaxation was not induced by defect generation. AFM images indicated that the height of cross hatch (h_{ch}) of the medium dose sample increased from 1-2 nm to 5-10 nm after post-annealing, while the cross hatch interval (d_{ch}) did not change. Such a significant increase in h_{ch} was observed only for the medium dose. These suggest that slipping at the SiGe/BOX interface occurred in local areas surrounded by the cross hatches.

Recently, Tezuka et al. [4] fabricated the $Si_{0.85}Ge_{0.15}$ (thickness: 90 nm) mesa on BOX by the oxidation-induced Ge condensation method and investigated the relaxation rate as a function of the radius of the mesa. Their results are shown in Fig.5. For small radius (<5 μm), the stress was relaxed by slipping at the SiGe/BOX interface [4]. The relaxation rate of the SGOI layer formed by the present method (dose: 5x10^{15} cm^{-2}, post-anneal: 1200°C) is also plotted in Fig.5, where the horizontal axis is regarded as the cross hatch interval d_{ch}. Our result shows a good agreement with those of the mesas.

This agreement is considered to support our speculation that slipping in local areas surrounded by cross hatches is the main factor to cause additional stress relaxation during post-annealing. The local areas were constrained at the edges by neighboring local areas, while the mesas in the experiment by Tezuka et al. were free at the edges. It is speculated that SiGe/BOX interfaces weakened by H^+ irradiation resulted in the same results as the mesa experiment.

4. Conclusions

The stress-relaxation during post-annealing in SGOI formed by the H^+ irradiation and Ge condensation method was investigated. For samples irradiated with a medium dose H^+ (5×10^{15} cm^{-2}), the relaxation rate of ultra-thin (~30 nm) SGOI significantly improved (70 %) with keeping a low defect density ($<10^6$ cm^{-2}), however the height of cross hatches increased after post-annealing (1200°C). The high relaxation rate has been explained on the basis of the local area slipping at the SGOI/BOX interface.

		top Si layer	SiGe layer	
			SiGe thick (d_i)	Ge fraction (x_i)
A	1	7 nm	40 nm	7 %
	2		80 nm	
	3		160 nm	
	4		250 nm	
B	1	30 nm	55 nm	15 %
	2			25 %

Table I Sample structures.

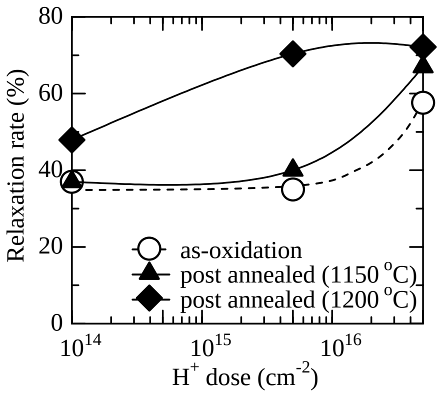

Fig. 2 Dependence of relaxation rate on H^+ dose before and after post-annealing at 1150 °C and 1200 °C.

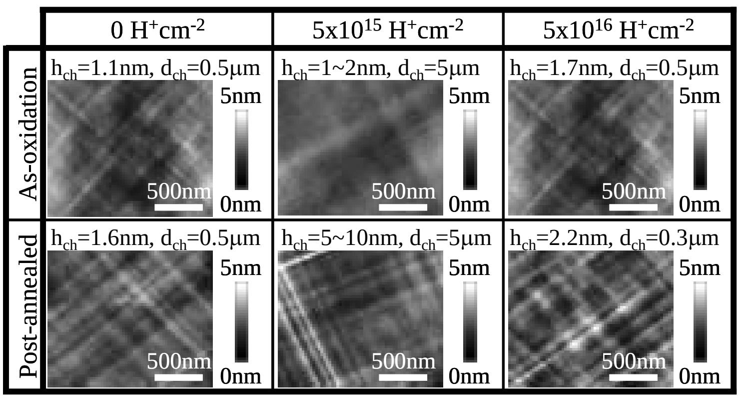

Fig. 4 Change in surface morphology before and after post-annealing (AFM image).

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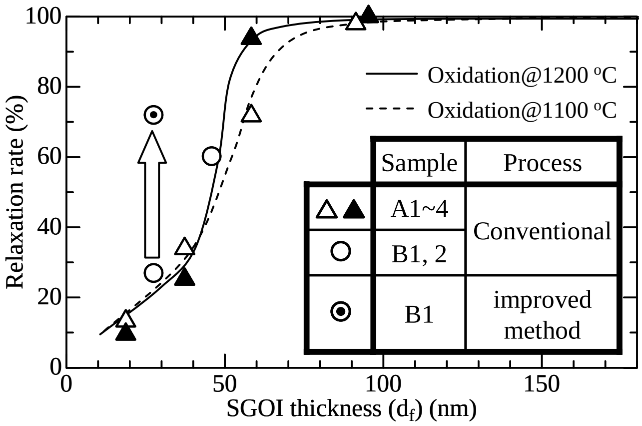

Fig. 1 Dependence of relaxation rate on SGOI thickness. The result obtained by the improved method is also shown by the double circle.

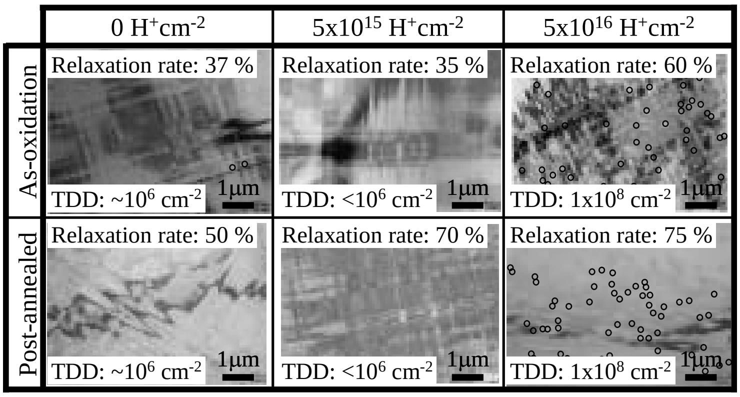

Fig. 3 Evaluation of threading dislocation densities (TDD) before and after post-annealing (Plane-view TEM image).

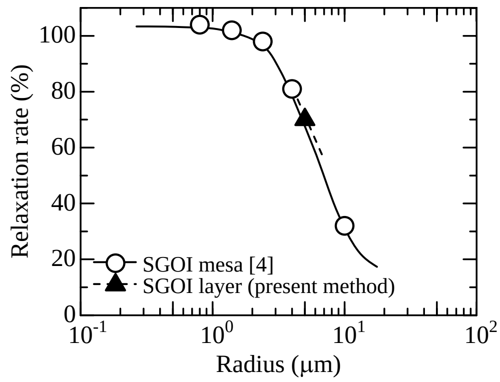

Fig. 5 Relaxation rate of SGOI mesa as a function of the radius [4]. The result of SGOI layer obtained by the present method is also plotted, where the horizontal axis is regarded as the cross hatch interval d_{ch}.