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Experimental Evidence of Low Dislocation Density of SiGe-on-Insulator Substrates Fabricated by Oxidizing SiGe/SOI Structures

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1. Introduction

The enhancement of channel mobility due to application of strain [1] is effective to obtain higher performance MOSFETs without miniaturizing the device size. Recently, we have proposed a new device structure using this strained-Si channel, strained-SOI MOSFETs, which is the combination of strained-Si films with SOI structures. This structure is achieved by growing a strained-Si layer on fully-relaxed SiGe-on-insulator (SGOI) substrates [2]. In order to obtain thin SGOI substrates, we have reported a novel technique, where SiGe epitaxial layers grown on standard SOI substrates are oxidized and, as a result, Ge atoms are condensed into remaining SGOI layers [3]. While this technique has been experimentally confirmed to provide thin SGOI substrates [3] and strained-SOI MOSFETs with high mobility [4], the process condition for minimizing dislocation density of SGOI substrates with keeping full relaxation has not been clarified yet. Also the quantitative evaluation of the low dislocation density has not been reported yet. In this paper, it is demonstrated that fully-relaxed SGOI substrates with low dislocation density of 10^2 cm^{-2} order are successfully fabricated by an appropriate design of SiGe film thickness and oxidation temperature. In addition, the method to count HF defect [5] is applied, for the first time, to SGOI layers, in order to verify the low dislocation density.

2. Application of HF defect counting method to SGOI substrates

A new technique different from conventional TEM and EPD, are needed to evaluate low dislocation density of thin SGOI substrates. It is shown here that HF defect counting is an appropriate method for quantitative evaluation of wide range of dislocation density in SGOI. Fig. 1(a) and (b) show the TEM photographs of a 300nm- thick-SGOI layer with Ge content of 0.1, soaked in HF solution for 30 sec. and 60 sec., respectively. It is confirmed that, after the pinhole in SGOI reaches the buried oxide, HF solution quickly etches it and enlarges the round shape hole up to 20 um diameter, which can be easily observed with optical microscope having low magnification of 10 times. This means that the method can evaluate low dislocation density of as low as 10^2 cm^{-2} or less.

Fig.2 shows the optical microscope image of HF defects in a SGOI layer containing the dislocations of 5 x 10^6 cm^{-2}, which has been evaluated by plan view TEM observation. It is confirmed that the number of HF defects is in good agreement with that in the TEM observation.

3. Fabrication of SGOI substrates

The present fabrication technique of SGOI substrates through oxidation of SiGe/SOI structures is schematically shown in Fig. 3. The previous studies on this process have revealed that (1) when initial SiGe layers are thin, remaining SGOI layers are not relaxed at all for Ge content less than 45% and that (2) when oxidation temperature is not sufficiently high, remaining SGOI includes significant number of dislocations. The insufficient relaxation and the generation of dislocations are attributable to weaker tensile stress coming from thinner initial SiGe films and the gradient of Ge profile due to shorter diffusion length of Ge atoms under lower oxidation temperatures, respectively. In order to realize fully-relaxed SGOI layers without dislocations, thus, it is necessary to grow thick SiGe epitaxial layers, close to the critical thickness, on the SOI substrates because tensile stress coming from the SiGe films becomes higher. Also, oxidation temperature is taken to be as high as 1200 C. Since this high temperature enhances Ge diffusion and provides flat Ge profile, the suppression of dislocation generation is expected. (Table 1)

4. Characterization of fabricated SGOI substrates

Fig. 4 shows the Raman spectroscopy of the sample (a) before and (b) after oxidation at 1200 C. It is found that full relaxation is successfully obtained after Ge condensation by oxidation process, even for the final Ge content less than 20%. This is due to thick SiGe initial layers.

Figs. 5 (a) and (b) show the Ge profiles after the condensation by oxidation at temperature of 1200 C and 1050 C, respectively. It is found that the flat Ge profile is obtained after 1200 C oxidation. On the other hand, the abrupt gradient in the Ge profile appears near the SiGe / oxide interface after 1050 C oxidation, because the flux of Ge atoms pushed out by oxidation is higher than that of Ge diffusion at low oxidation temperatures and, as a result, Ge atoms pile up at the SiGe/oxide interface.

Fig. 6 shows the plan view TEM observation of the sample oxidized at 1050 C. Many dislocations caused by the strong strain due to the abrupt gradient of the Ge profile are observed. In contrast, it is found that SGOI substrates fabricated by oxidation at 1200 C have quite low dislocation density. As seen in Fig. 7(a), no dislocations are observed in the plan view TEM observation for SGOI oxidized at 1200 C., because of the small view area. Thus, the HF defect counting, more suitable for evaluation of low density dislocations, is carried out. As a result, it is demonstrated in Fig. 7(b) that the dislocation density is as low as 2 x 10^2 cm^{-2}. This low value is almost the same as the dislocation density in the initial SOI substrate, indicating that no additional dislocations are generated during the oxidation process. These experimental results clearly show the necessity of high temperature oxidation. On the other hand, many dislocations are observed in a sample with initial SiGe epitaxial layers thicker than the critical thickness, suggesting the importance of the thickness design for initial SiGe/SOI structures to obtain fully-relaxed and dislocation-free SGOI layers.

5. Conclusion

Fully-relaxed SGOI substrates with low dislocation density have been achieved, for the first time, by an appropriate design of the initial SiGe layer thickness and the

SiGe/SOI structures. In addition, the low dislocation density of these SGOI substrates has been verified by the method to count HF defects.

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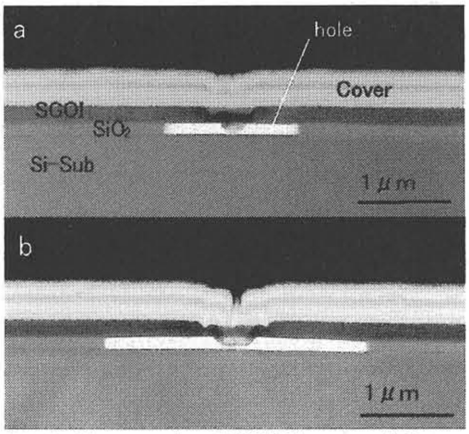

Fig.1: Cross-sectional TEM images of the HF defects formed by (a) 30 sec., and (b) 60sec. soaking

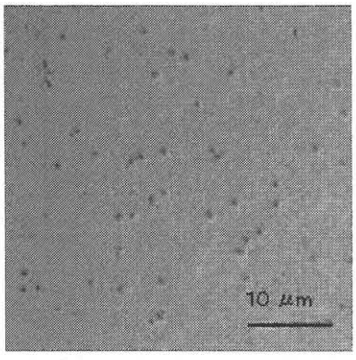

Fig.2: Optical microscope image of HF defects in SGOI layer containing the dislocations of 5×10^6 cm^{-2}.

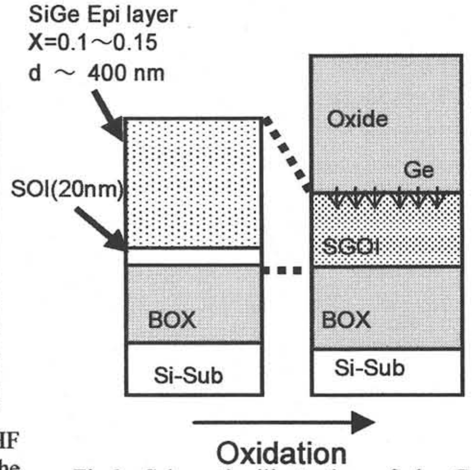

Fig.3: Schematic illustration of the Ge condensation by oxidation.

	Thick SiGe layer	Thin SiGe layer
High Temperature Oxidation	This data	Weaker tensile stress ↓ Insufficient relaxation (ref.3)
Low Temperature Oxidation	Abrupt Ge gradient ↓ Generation of dislocations (ref.6)	

Table 1: Conditions to realize fully-relaxed SGOI layers without dislocations.

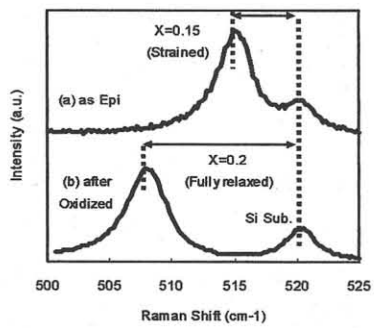

Fig.4: Raman spectroscopy of (a) just after the epitaxial growth of SiGe on the SOI substrate, and (b) after the Ge condensation by oxidation at 1200 C, respectively.

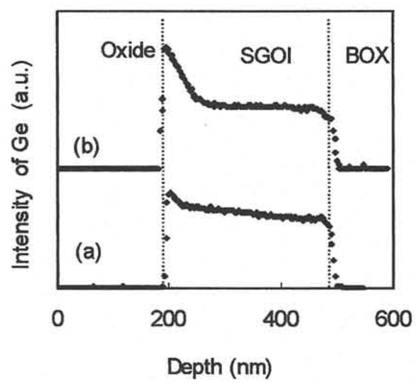

Fig.5: Depth profile of Ge atoms measured by SIMS for the samples after the condensation by oxidation at the temperature of (a) 1200 C and (b) 1050 C, respectively.

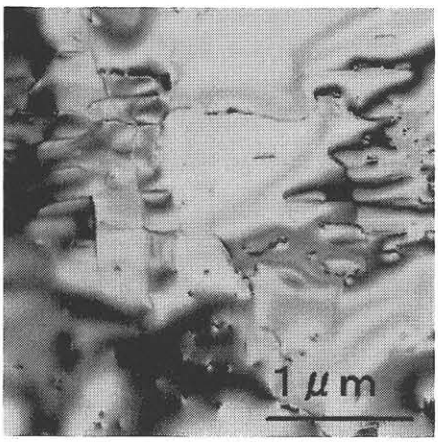

Fig.6: Plan view TEM observation of the sample formed by the Ge condensation at the temperature of 1050 C.

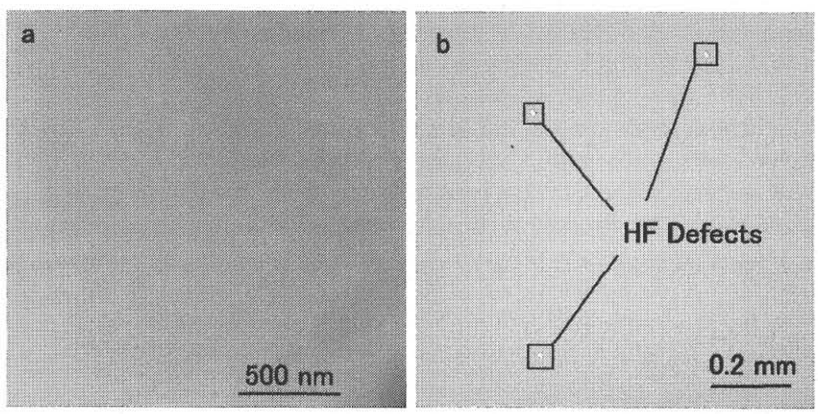

Fig.7: The evaluation of dislocation density for the sample of the Ge condensation by 1200 C oxidation observed by (a) plan view TEM observation, and (b) HF defects observed with low magnification optical microscope.