RELAXED SIGE-ON-INSULATOR SUBSTRATES THROUGH IMPLANTING OXYGEN INTO PSEUDOMORPHIC SIGE/HETEROSTRUCTURE

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Abstract. SIGE-on-insulator (SGOI) attracts great interest due to its potential for realizing strained Si with in-plane tensile strain. In this paper, 115 nm pseudomorphic SiGe film was grown directly on Si substrate without any buffer layer. A good SGOI structure was formed through implanting low dose (\(\times 10^{12} \text{cm}^{-2}\)) of oxygen ions into the interface of SiGe and its two-step annealing process. Our results demonstrate that, by introducing an annealing process at a moderate temperature of 600°C, Ge loss during the following high temperature annealing at 1300°C, which is necessary for the formation of bridged oxide layer (BOX) can be greatly reduced.

INTRODUCTION

SGE-on-insulator (SGOI) attracts great interest due to its potential for realizing strained Si with in-plane tensile strain, which results in enhanced carrier mobility [1], SiDMOX (2,3), ion-cut (or commercially Smart-cut) [4] and REEOI (5), have been explored to form SGOI noret structures. However, they are yet far from massive industrial applications. Two main reasons are cost and performance. Both SGOI growth and SiDMOX/ion-cut/REEOI process require strict technologies and thus are costly. Therefore simplifying the fabricating processes for SGOI structures to lower the cost is quite necessary. On the other hand, SGOI performance should be further improved.

Among the three fabrication methods, SiDMOX is competing for SGOI fabrication. Nevertheless, most of previous studies use SiGe materials with a thick SiGe buffer and result in SiGe/SGO2D/SiGe/SiGe structure. This thick buffer is important in suppressing Ge loss during high temperature annealing [6]. However, besides high cost, the buffer causes some problems. Using the buffer layer, the implanted oxygen locates in the SiGe layer, Ge has to be rejected from the oxygen-rich region to form SiGe buried layer. For a high Ge composition, this is even not feasible at all. So there is an upper Ge limit (about 17%) for SiGe SiDMOX. The previous work successfully resulting in SGOI adopted SiGe with a Ge concentration of 10% as the SiDMOX target. Meanwhile, the thick buffer brings a dilemma on choosing the annealing temperature. The decreasing melting point of SiGe with increasing Ge concentration induces lowering annealing...
temperature, whereas the formation of mixed silicon dioxide layer requires higher temperature.

In this paper, we present our work through implanting low dose of oxygen ions into pseudomorphic SiGe grown directly on Si substrates. By introducing a two-step heat treatment process, the formed SiGe structure has good properties including decreased Ge lost in the SiGe layer.

EXPERIMENT

A Si$_x$Ge$_{1-x}$ layer was grown on a p-type Czochralski grown 4" (100) Si substrate without buffer layer using ultra-high vacuum chemical vapor deposition (UHV-CVD) at 500°C with Si$Cl_4$ and GeH$_4$ as the precursors of Si and Ge respectively. After that, a pure Si cap layer with a thickness of 3μm was grown on the SiGe surface. This cap layer will be annealed during subsequent treatment. The SiGe thickness and Ge concentration was extracted by XRFS rocking curve combined with simul-fit, which are 115nm and x=14% respectively.

3x10$^{13}$ cm$^{-2}$ oxygen ions were implanted into the sample at an energy of 60keV. The projected range of the C$^+$ ion is near the interface of SiGe/Si substrate. The substrate temperature was kept at 550°C during the C$^+$ implantation. In order to avoid channeling effects, a deliberate misalignment of the wafer normal of 7° was used during implantation. After ion implantation, the samples have undergone annealing in a furnace at moderate temperatures under N$_2$ with 1% O$_2$ at 900°C for 6 hours or 900°C for 5 hours or at 1350°C with an atmosphere of flowing N$_2$ plus 3% O$_2$. Three typical treatments conditions were applied. The first is a single-step at moderate annealing temperature of 800°C (sample 1b) or 900°C (sample 2). The second annealing procedure is a typical one-step at 900°C for 5 hours (sample 3), usually employed in SIMOX technology. The third annealing procedure is the combination of a moderate temperature annealing (800°C or 900°C) and a high temperature annealing (1350°C for 2 hours). Sample 4 was annealed at 900°C followed by 1350°C while sample 5 was annealed at 900°C and 1350°C.

Various techniques including Rutherford back-scattering spectroscopy (RBS), Auger electron spectroscopy (AES) and X-ray diffraction (XRD) were employed to characterize the samples. The four-crystal X-ray reflection rocking curves (RCR) were obtained at a Philips X'pert equipped with a two-crystal four-reflection Ge (220) diffractometer. Cu Kα radiation with a wavelength of 0.15406nm and Rhodium (lI) reflection, were used in all the experiments. An x-ray scan was performed on the working plane (004).

RESULTS AND DISCUSSION

Fig. 1 exhibits the RBS random spectra acquired from samples (a-d) after different heat treatment. The spectrum of C$^+$ as-implanted sample (not shown here) has no obvious difference with the 800°C as-annealed sample. The oxygen signals and Ge signals from samples with different annealing processes are accepted and shown in Figs. 1b and 1c. From Fig. 1b it can be found that samples annealed at 800°C and 900°C are almost the same except that the Ge signal peak of the 900°C annealed 2 sample

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becomes a little wider (Fig. 1c). Signals from channel >550 are Ge signals, among which the peak at 750-790 corresponds to Ge in the SiGe layer while the weak Ge signal in channel 550-720 from the 1350°C annealed is due to Ge diffusion into the Si substrate through the implantation-induced oxygen-rich layer. No Ge signal was detected in sample 3 and 4, suggesting that Ge diffusion into the bulk through the oxygen-rich layer is not obvious at temperature lower than 900°C. The Si signal platform at channel between 500 to 540 in #1 and #2 comes from Si in the surface SiGe layer and Si signal drop in channel 470-500 originates from Si in the oxygen-rich layer. Fig. 1b shows there is one weak and wide (distributed in channel 280-320) O signal peak in sample #1 or #2. This peak attributes to the O in the implantation layer. This result suggests that the implanted O ions distribute in a wide range near the projected range after the implantation and treatment at temperatures below 900°C can not cause the implanted oxygen to co-intercalate.

Figure 1. Rutherford backscattering spectrometry of samples with different heat treatment.

The RBS results after the 1350 °C are quite different with that of the moderate temperature annealed samples. Fig. 1 shows that the Ge signal peaks of samples 3, 4, 4I and 58 become weak and narrower and lower after 1350°C annealing, resulting from decreased SiGe thickness induced by surface oxidation and Ge diffusion. This is reasonable since the Ge diffusion coefficient increases by almost ten times for every 100°C increase in the temperature range of 800°C-1000°C, and its value at 800°C is small enough. On the other hand, the intensity of the Ge signals decreases due to Ge penetration through the burn-out oxide before the establishment of a barrier to Ge diffusion. Ge signals were detected in the channel range of 550-720, indicating Ge diffusion into the Si substrate after the 1350°C annealing. However, comparing the Ge

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signals of Si 2p and Ge 3d, it is very difficult to distinguish the two peaks on SiO2. The sample shows weakest Ge peak, and thus the lowest Ge content in the SiGe layer. While the 800°C × 30min annealed sample has the highest remnant Ge content, the 900°C × 1350°C annealed sample has a second strong signal peak. The highest Ge signal yield of sample #4 (yields=900) is more than one times larger than that of sample #3 (yields=420). These results demonstrate that the annealing step at a suitable moderate temperature can be greatly beneficial to the strengthening of the barrier of the buried oxide against Ge diffusion. Therefore, it is possible to depress Ge diffusion into the Si substrate by optimizing the post-implantation heat treatment processing. The still decreased Ge content can be retrieved even further raised through the internal-thermal-oxidation (ITOx) technology [7], or by controlled surface dry oxidation [8].

Si signals in channel 490–540 of sample #3, #4 and #5 also exhibit a great difference with that of sample #1 and #2 (Fig.1a). Si signal moved from 540 to 525 due to surface oxidation after the 1350°C and signal yields increased because of Si loss. This is in agreement with the Ge signals observed in Fig.1c. In addition, a Si signal valley formed into channel 500, corresponding to the formation of BOX layer. Two O signal peaks were detected in all the 1350°C annealed samples of #3, #4 and #5 as shown in Fig.1b. These signals attribute to O in the formed BOX (near channel 500) and surface thermal oxide layer (near channel 330) respectively. It is very obvious that O signal in the BOX layer of sample #3, #4 and #5 became rather narrower and stronger compared with sample #1 and #2, demonstrating that the implanted low dose O agglomerate into a rather narrow band at the projected range to form the BOX layer. Nored that the O signal yield of BOX is the same as that in the surface thermal oxide layer, suggesting the BOX is of good stoichiometric SiO2.

![Graph of sample #4 with two-step annealing (800°C and 1350°C)](image)

**Figure 2.** The profile of sample #4 with the two-step annealing (800°C and 1350°C), determined by AES.

Fig. 2 depicts the elemental depth profile acquired by AES of sample #4. A good SiO2/SiGe/SiO2/SiO2/Si structure is revealed. The surface oxide which is about 48 nm originates from oxidation during 1350°C annealing, indicating that the former surface Si cap layer has been completely oxidized and a part of SiGe has been consumed. The
Figure 5. Rocking curves of samples #3, #4 and #5 with different annealing.

Figure 4. SEM image of a Si sputtering induced pit of sample #6 with the two-step annealing (600°C > 1350°C).

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Swain relaxation is an important issue for SOGI substrates. Fig. 3 gives the rocking curve of the sample annealed at 800°C ± 150°C. The well-defined diffraction peak from SiGe layer can be observed, suggesting that the implantation damage in SiGe layer has been recovered. Combining the diffraction peak location and the Ge content determined by AES results, we can derive that the SOGI film is fully relaxed. For comparison, Fig. 3 also gives the rocking curve of samples annealed at 1250°C and 900°C<150°C. So we can conclude, from Ge signals in RBS and rocking curves, that the annealing step at a moderate temperature (<800°C) is somewhat important for depressing Ge loss and also the recovery of implantation damage.

Fig. 4 shows a SEM image of a pit, which was induced by Ar sputtering while performing AES measurements, on the sample surface with the two-step annealing (800°C ± 150°C). It is clear from this picture that the interfaces are very flat, confirming the good structure of the obtained SOGI substrates.

CONCLUSION

In conclusion, we have fabricated relaxed SOGI structures starting from a thin pseudomorphic SiGe material without a buffer layer utilizing a modified SIMOX process. The annealing step at a low temperature (<800°C) is beneficial for the suppression of Ge penetration, damage recovery in SiGe, and SOGI fabrication.

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