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Ion Species Dependence of Relaxation Phenomena of Strained SiGe Layers Formed by Ion Implantation Induced Relaxation Technique

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I. Introduction

o realize high speed sub-10nm CMOS, a source heterojunction MOS transistor (SHOT) is a candidate for the high velocity electron injection into the channel from the source, utilizing the excess kinetic energy corresponding to the source-heterojunction band offset [1]. Recently, we have also developed a new abrupt lateral source-heterojunction with relaxed/strained semiconductor layers on a single semiconductor substrate by O^+ ion induced relaxation technique of strained layers [2]-[4], using breaking the bonds of the strained layer/buried oxide layer (BOX) due to the O^+ recoil energy, E_R at the two-layer interface (two-step relaxation model [4]). However, in applying this technique to entire wafer, the O^+ ion induced relaxation technique has the limit to realize both high relaxation rate R and the crystalline quality of the ion implanted semiconductor layers [4].

In this work, we have experimentally studied a new H^+ ion induced relaxation technique of strained SiGe layers on BOX (SGOI) to improve the crystalline quality of the ion implanted layers, using the very steep E_R distribution of H^+ ion. We have experimentally shown that the strained SiGe layers can be also fully relaxed even by the H^+ ion implantation, using Raman spectroscopy. In addition, the crystalline quality of H^+ ion implanted SiGe layers can be improved, compared to that of O^+ ion implanted area.

II. Experimental for H^+ Ion Induced Relaxation Technique

To relax the strained semiconductors on BOX layer without degrading the crystalline quality, the E_R distribution of ions is strongly required to be very steep and low in the surface strained semiconductors, but the E_R value at the strained-layer/BOX interface is higher than the critical E_R value to relax the strained layer [2]-[3]. Fig. 1 shows ion implantation Monte-Carlo simulation (SRIM [5]) results of E_R distribution per one ion with the Si/BOX interface having the E_R peak at various ion species. With decreasing the ion mass, the acceleration energy E_A is needed to decrease, resulting in the very steep E_R distribution in Si layer. Thus, H^+ ion is the best solution. However, high dose D_I of H^+ ions is required to relax the strained layer, because of the very small E_R per one H^+ ion. Fig.2 shows also the simulated critical E_R (E_R per one ion times D_I) distribution to relax the strained Si [2] at various ion species. Compared to other ion species, it is noted that H^+ ions have very steep critical E_R distribution. On the other hand, in usual source/drain n^+ extensions, the E_R distribution due to As^+ ions has the peak value at the Si surface, which causes large damages into the Si layers.

H^+ ion induced relaxation technique was applied to a 20-nm-thick $Si_{0.72}Ge_{0.28}$ with a fully compressive strain of 1.1%, where the acceleration energy E_A=10keV. 25-keV O^+ ion induced relaxation technique was carried out, as a reference [2]. Post annealing process at 950°C for 30min. was carried out to cause the slip at the SiGe/BOX interface [4] as well as to recover the SiGe crystal quality.

To evaluate both the strain and the crystal quality of the ion implanted SiGe layers, we have carried out visual (532 nm) Raman spectroscopy with a laser beam diameter of about 1 μm and have analyzed the Si-Si Raman peaks of the SiGe layers [2].

III. Relaxation of Strained SGOIs due to H^+ Ions

Fig. 3 shows the D_I dependence of the R of SGOIs. SGOIs can be fully relaxed even by H^+ ion. The R at H^+ ions suddenly increases when D_I is higher than the critical H^+ dose D_{IC}, but the D_{IC} of H^+ ion is higher by about 200 times than that of O^+ ion.

Here, Fig.4 shows the R values as a function of the E_R at the SiGe/BOX interface in both ion species. It is obvious that both ion species have almost the same E_R dependence of the R. Namely, the critical E_R value of about 1.5×10^{16}eV/cm^{-2} to relax the strained SiGe layers is independent of the ion species, whereas the critical E_R value depends on the strained layer materials, that is, the bonding energy between the strained-semiconductor/BOX layers [3]. Therefore, we have confirmed that the E_R model for relaxing strained layers is also valid even in the H^+ ion implantation technique. However, when E_R is about 2.5×10^{16}eV/cm^2, the R at H^+ ion is higher than that at O^+ ion. Thus, the critical E_R for H^+ ions to realize the fully relaxed SiGe layer is lower than that for O^+ ions.

IV. Crystal Quality of H^+ Ion Implanted Strained-SiGe Layers

We discuss the crystallization rate R_C determined by the full width at half maximum (FWHM) of the Si-Si Raman peak of the SiGe layers, because the FWHM is an indicator for the crystalline quality. As a result, $R_C=W_{FI}/W_F$, where W_F and W_{FI} are the FWHMs of the Raman peaks of the ion implanted SiGe and the initial SGOIs, respectively [4].

Fig.5 shows FWHM values of the ion implanted strained SiGe layers as a function of the E_R at the SiGe/BOX interface in both ion species. The FWHM values at H^+ ions increase with increasing E_R, which is the same E_R dependence as those at O^+ ions. Namely, the crystal quality of SiGe layers is degraded by increasing E_R.

Here, Fig.6 shows the relationship between the crystallization rate R_C and the R values in both ions, according to Figs. 4 and 5 data. When R<80%, both ions have the universal relationship of $R_C\propto-3.3\times10^{-3}R$. However, when R>80%, the R_C at O^+ ions rapidly degrades. Thus the R_C at H^+ ions is much higher than that of O^+ ions, which is due to the lower E_R values in the SiGe layers, as shown in Fig.2. This is the advantageous characteristics for H^+ ions.

Good crystal quality at H^+ ions is also confirmed by TEM observation of the cross section of the H^+ ion implanted SiGe layers with the R of 55%, as shown in Fig.7. We have observed no dislocations in the TEM image.

Here, Fig. 8(a) and (b) show 2D-mapping data of FWHM values in a 400 μm^2 area at H^+ and O^+ ions, respectively. The average R at H^+ and O^+ ions were 98% and 94%, respectively, and the standard deviation of R in both ions was very small and 0.8%. As discussed in Figs.5-6, the average FWHM value at H^+ ions is much lower than that at O^+ ions. In addition, the standard deviations of FWHM σ_F at H^+ and O^+ ions are 0.1 and 0.4 cm^{-1}, respectively. Thus, the σ_F at H^+ ions can be reduced, compared to that at O^+ ions. This uniformly good crystal quality at H^+ ions is considered to be due to the uniform E_R profile in the wafer plane, as discussed as follows. Average distance D_A between each ion atoms can be expressed by $D_I^{-1/2}$ and thus, the D_A of H^+ and O^+ ions are 0.026 and 0.22 nm, respectively. As a result, the surface density of breaking bonds at the SiGe/BOX interface due to E_R per one H^+ ion is much higher than that per one O^+ ion, whereas the E_R itself per one H^+ ion is much lower than that per one O^+ ion (Fig.1). This is the physical mechanism for higher R_C and uniform FWHM at H^+ ions.

However, in the local area of the SGOI substrates, the uniform and high E_R of H^+ ions cause the SiGe layer splitting away from the BOX layer, as shown in Fig.9, although the SiGe splitting by O^+ ions never occurs. This phenomenon is also due to the hydrogen induced degradation of the BOX layer bonding, as discussed in smart-cut technology [6]. Therefore, it is necessary to optimize both the H^+ ion (E_A and D_I) and the post annealing processes in relaxing the strained layers on the BOX.

VI. Conclusion

We have experimentally studied a new H^+ ion induced relaxation technique of strained SiGe layers on BOX, using the very steep recoil energy E_R distribution of H^+ ion. We have demonstrated that the relaxation rate of strained SiGe layers by the H^+ ions has the same E_R dependence as that by the O^+ ions. Moreover, uniformly higher crystal quality of H^+ ion implanted SiGe layers can be achieved, compared to that of O^+ ion implanted ones, which is due to high surface density of H^+ ions and its lower E_R per one H^+ ion. The H^+ ion induced relaxation technique is very promising for relaxing the strained layer in both the local and entire substrates.

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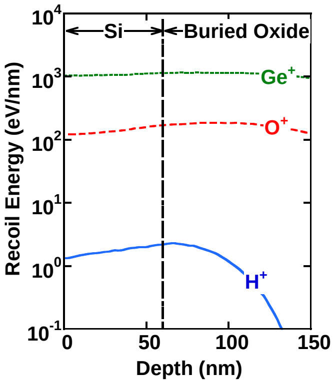


Fig.1 SRIM simulation results of recoil energy E_R distribution per one ion in SOI substrate, where the solid, the dashed, and the dotted lines shows the results of H^+, O^+, and Ge^+ ions, respectively. H^+ ions have very steep E_R distribution, compared to those of other ions.

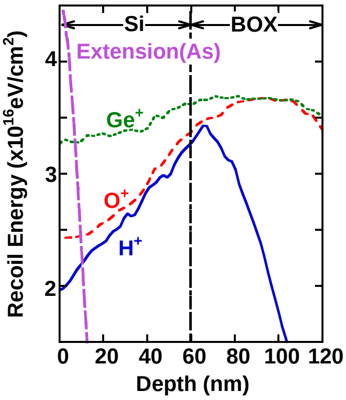


Fig.2 SRIM simulation results of ion type dependence of critical E_R distribution for relaxing strained Si layers. The solid, the dashed, and the dotted lines shows the results of H^+, O^+, and Ge^+ ions, respectively. The dotted and dashed line shows the recoil energy distribution due to As^+ ion for forming source/drain extensions, where the acceleration energy E_A and the dose D_I are 10keV and 1×10^{14}cm^{-2}, respectively. H^+ ions have very steep E_R distribution in the Si layer.

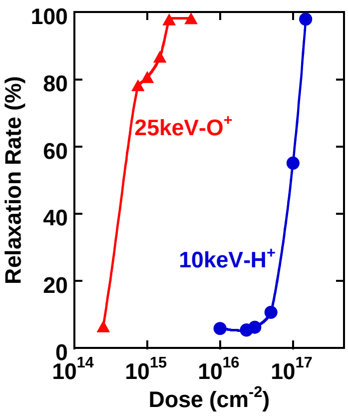


Fig.3 Ion dose dependence of relaxation rate R of strained SiGe layers fabricated by H^+ (circles) and O^+ (triangles) ions, where the SiGe thickness is 20nm, and the E_A of H^+ and O^+ ions are 10 and 25 keV, respectively. Here, $R=(\Delta\omega-\Delta\omega_{SG})/(\Delta\omega_R-\Delta\omega_{SG})$, where $\Delta\omega$, $\Delta\omega_{SG}$, and $\Delta\omega_R$ are the experimental Raman peak shift from the peak of relaxed Si (520cm^{-1}), the Raman shift of the initial SGOIs, and the ideal Raman shift of fully relaxed SGOIs, respectively [2]. Strained SiGe layers can be also relaxed by H^+ ions, but the critical H^+ dose is much higher than the O^+.

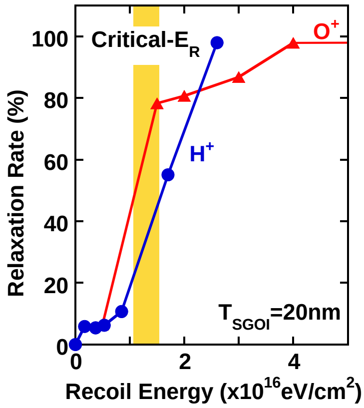


Fig.4 Relaxation rate R of strained SiGe layers vs. E_R value of SRIM results at the SiGe/BOX interface for H^+ (circles) and O^+ (triangles) ions at various D_I, where the E_A of H^+ and O^+ ions are 10 and 25 keV, respectively. The orange region shows the critical E_R for relaxing the strained SiGe layers. Both ions have the universal E_R dependence of R.

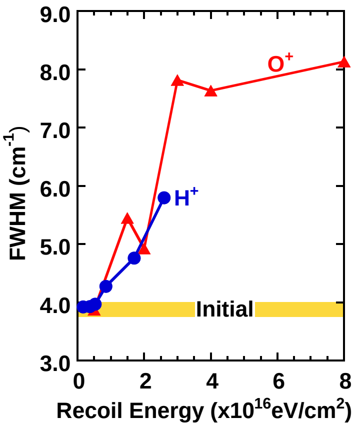


Fig.5 FWHM of Si-Si Raman peak of SiGe layers as a function of E_R value of SRIM results at the SiGe/BOX interface for H^+ (circles) and O^+ (triangles) ions at various D_I, where the E_A of H^+ and O^+ ions are 25 and 10keV, respectively. The orange region shows that the FWHM value of initial SiGe layer before ion implantation process is about 4cm^{-1}. Both ions have the universal E_R dependence of FWHM.

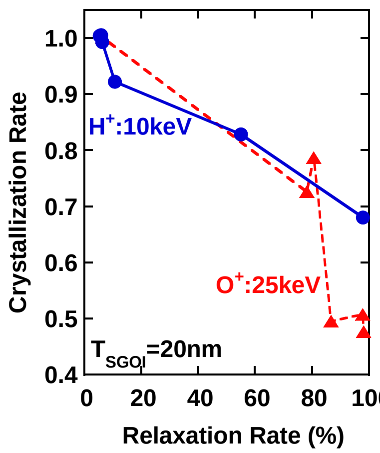


Fig.6 Relationship between crystallization rate R_C and relaxation rate of ion implanted SiGe layers at various D_I, where the E_A of H^+ and O^+ ions are 10 and 25 keV, respectively. In the case of H^+ ions, $R_C\propto-3.3\times10^{-3}R$, and the R_C at is higher than O^+ ions, when R>80%.

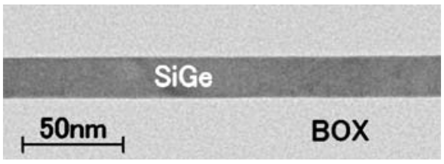
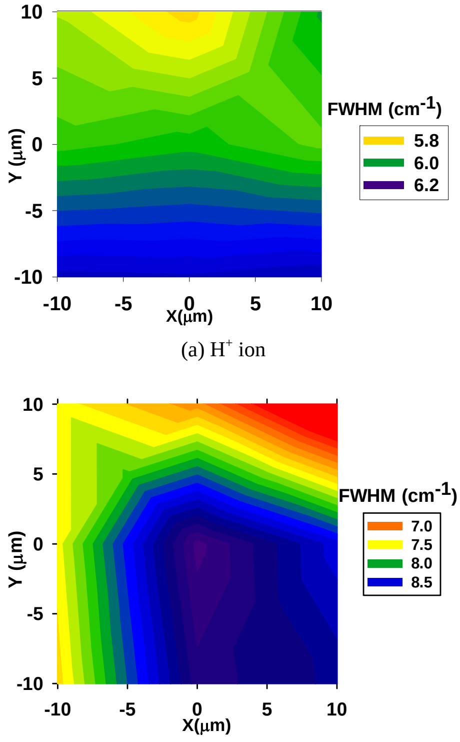


Fig.7 TEM image of cross section of H^+ ion implanted SiGe layer with R of 55%, where E_A =10keV and D_I=1×10^{17}cm^{-2}. We have observed no dislocations.



(a) H^+ ion

(b) O^+ ion

Fig.8 FWHM mapping of (a) H^+ (D_I=1.5 × 10^{17}cm^{-2}) and (b) O^+ (D_I=2 × 10^{15}cm^{-2}) implanted SiGe layers in a 400 μm^2 area. The average R of H^+ ion (98%) is almost the same as that of O^+ ion (94%) and the standard deviation in both ion conditions is about 0.8%. The standard deviation of FWHM of H^+ and O^+ ions are 0.1 and 0.4 cm^{-1}, respectively. Namely, in the only case of H^+ ions, small and uniform FWHM can be achieved.

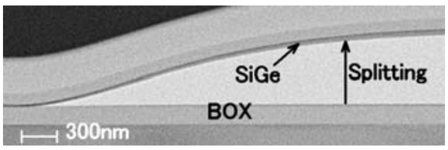


Fig.9 TEM image of cross section of H^+ ion implanted SiGe layer, where E_A =10keV and D_I =1×10^{17}cm^{-2}. The SiGe layer partially splits away from the BOX layer, because the high dose H^+ ions break the SiO_2 bonding in the BOX layer.