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Novel Source Heterojunction Structures with Relaxed-/Strained-Layers for Quasi-Ballistic CMOS Transistors using Ion Implantation Induced Relaxation Technique of Strained-Substrates

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I. Introduction

We have developed high performance source heterojunction MOS transistors (SHOTs) for quasi-ballistic electron transport and experimentally demonstrated high velocity electron injection into channels, utilizing the excess kinetic energy corresponding to the conduction band offset ΔE_C at the source-relaxed-SiGe/channel-strained-Si heterojunction edge [1-3]. However, the SiGe/strained-Si hetero structures can be used only for n-MOS, and another source hetero structure is needed to realize p-channel SHOTs [2]. Moreover, the Ge atom diffusion into the channel from the source SiGe layer leads to leakage currents generated at the source heterojunction [1], and in addition, it is very difficult to fabricate an abrupt heterejunction, resulting in the reduction of SHOT performance. In order to overcome the above problems, new source heterojunction structures for CMOS-SHOTs based on a single semiconductor are strongly needed [1-2].

In this work, we have experimentally studied novel source heterostructures with lateral relaxed-/strained-semiconductor layers on a single semiconductor, that is source-Si/channel-strained-Si for n-MOS and source-SiGe/channel-strained-SiGe for p-MOS [2], by developing a simple process for local relaxing strained-Si-on-insulator (SSOI) and SiGe-on-insulator (SGOI) substrates due to recoil energy of O^+ ion implantation. We have successfully relaxed both SSOI and SGOI substrates without poly-crystallizing the substrates.

II. Novel Source Heterojunction Structures for CMOS

Fig. 1 shows the usual SHOT structures with source-SiGe/channel-strained-Si layers. Using the conduction band offset at the source edge ΔE_C, an ideal velocity enhancement Δv of the injected electrons can be expressed by $\Delta v=(2\Delta E_C/m_T^*)^{1/2}$, where m_T^* is the transverse effective mass of inversion electrons of the channel. Therefore, higher ΔE_C and lower m_T^* are needed to increase Δv in SHOTs. Moreover, in order to overcome the several problems in the usual SHOTs, as mentioned in Sec.I, Table-1 shows novel source heterostructures for CMOS-SHOTs, using SSOIs for n-MOS and SGOIs for p-MOS, because it is possible to fabricate an abrupt source-heterojunction on a single semiconductor layer, and lower m_T^* of both electrons and holes can be realized in the strained-channel layers.

As shown in Figs.2 and 3, local relaxed-source layers can be simply fabricated by local slip of the strained-layers at the buried oxide interface due to O^+ ion (neutral impurity in Si) implantation recoil energy E_R to strained-substrates/buried-oxide interface. Therefore, the O^+ ion implantation process should be obeyed by the condition that $E_E+E_R>E_B$, where E_E and E_B are elastic energy of strained-substrates and bonding energy between strained-layer and buried-oxide (BOX), respectively. As a result, the conduction band offset ΔE_C between relaxed-/strained-Si layers and the valence band offset ΔE_V between relaxed-/strained-SiGe layers can be achieved, as shown in Figs.2 and 3. Thus, the band offset induces high velocity injection of both electrons and holes. Moreover, ΔE_C and ΔE_V can be expressed, as follows [4].

$$\Delta E_C[\text{meV}] \approx 134\Delta\varepsilon;\ \Delta E_V[\text{meV}] \approx 0.77x\cdot r \quad (1)$$

where $\Delta\varepsilon$ is the strain shift (%) of strained-Si layers and r is the relaxation rate (%) of strained-$Si_{1-x}Ge_x$ layers realized by local O^+ ion implantation. Here, E_R in the strained-layers should be as small as possible to reduce defect generation in the strained-layer due to ion implantation damage. Therefore, we have designed the O^+ ion implantation conditions of the dose D_O and the acceleration energy E_A, using SRIM simulation [5].

Fig.4 shows the SRIM simulation results of depth profile of E_R per one O^+ ion E_{R0} and O^+ density in 60nm SSOIs. We successfully optimize the O^+ ion implantation conditions that the E_{R0} has a peak value at around the strained-Si/BOX interface (the depth of around $0.6R_P$ (projected range of O^+ ion)) and rapidly deceases in the strained-Si layer. Here, $E_R= D_O E_{R0}$.

In this experiment, we have carried out furnace annealing for 30min. at 950°C after O^+ ion implantation into large area (1cm^2) of strained-substrates with 15nm-thick surface oxide. Initial conditions of strained-substrates are as follows: 60nm SSOIs have tensile strain of 0.7%, and 20nm SGOIs with Ge content of 28% are fully compressive-strained.

III. Relaxation of SSOIs and SGOIs by O^+ Ion Implantation

Fig.5 (a) and (b) show Raman spectroscopy of SSOIs before and after O^+ ion implantation, respectively, where $D_O=2\times10^{15}\text{cm}^{-2}$ and E_A=60keV. It is clear that the Raman shift peak of strained-Si shifts toward the relaxed-Si peak of 520cm^{-1} after O^+ ion implantation and the strained-Si is partially relaxed.

The D_O dependence of the Raman shift $\Delta\omega$ in SSOIs and SGOIs from the relaxed-Si peak are shown in Fig.6, where E_A for SSOIs and SGOIs are 60keV and 25keV, respectively. The upper axis shows the E_R at the BOX interface simulated by SRIM. When the D_O becomes higher than the critical dose D_{CR}, the relaxation rate of both SSOIs and SGOIs drastically increases. Moreover, Figs.7 show D_O dependence of TEM photos of the cross section of SSOIs. At low D_O, SSOIs indicate good quality, whereas SSOI layers are poly-crystallized at high D_O. Half width ω_{HD} of Raman peak of SSOIs and SGOIs, which is a barometer of the quality of strained-layers, is shown in Fig.8. The ω_{HD} of both SSOIs and SGOIs still remains smaller at $D_O\le D_{CR}$. However, the ω_{HD} rapidly increases, when the strained-substrates are poly-crystallized at high D_O. Moreover, TEM observation shows that the minimum dislocation density of around 10^7cm^{-2} in relaxed-SSOIs can be achieved, which is possible to be reduced. Thus, we have demonstrated the relaxation technique of SSOIs and SGOIs without poly-crystallizing the substrates, by optimizing the O^+ ion implantation conditions.

According to Fig.6 data and Eq.(1), the E_R dependence of ΔE_C in SSOIs and ΔE_V in SGOIs can be estimated in various O^+ ion implantation conditions, as shown in Fig.9. We have obtained universal relationship between $\Delta E_C/\Delta E_V$ and E_R, and the critical E_R, E_{RC} for relaxing both SSOIs and SGOIs really exists at around $2\times10^{16}\text{eV/cm}^2$, which is much higher than E_B of bonding wafers ($\sim2\times10^{15}\text{eV/cm}^2$) [6]. In this study, the ΔE_C and ΔE_V values at the optimized O^+ ion implantation condition of E_{RC} amount to about 70meV and 160meV, respectively.

IV. Simulation of SHOT Performance at Sub-10nm Regime

Considering the tunnel effects of electrons at the energy spike of the source heterojunction in SHOTs, we have simulated the SHOT performance at sub-10nm regime. Fig.10 shows ΔE_C dependence of the maximum transconductance G_M enhancement of SHOTs, against G_M of SOIs, G_0, where effective channel length is 7nm. The G_M enhancement rapidly increases with increasing ΔE_C, and amounts to over 1.1 even at small ΔE_C of around 200meV.

V. Conclusion

We have studied a novel source relaxed-/strained-layers heterojunction structures for quasi-ballistic CMOS, by controlling the strain in SSOIs for n-MOS and SGOIs for p-MOS. Using O^+ ion implantation recoils energy to BOX interface, we have successfully relaxed both SSOI and SGOI substrates without poly-crystallizing the substrates. As a result, the source band offset ΔE_C and ΔE_V can be controlled by O^+ ion implantation conditions. According to simulation results, G_M enhancement of sub-10nm SHOTs can be realized even at small ΔE_C. Therefore, SHOT structures with the novel source heterojunction are very promising for future quasi-ballistic CMOS devices.

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Device	Source	Channel
n-MOS	Si	Tensile Strained-Si
p-MOS	SiGe	Compressive Strained-SiGe

Table 1 Source/channel heterostructures for n- and p-MOS in this study.

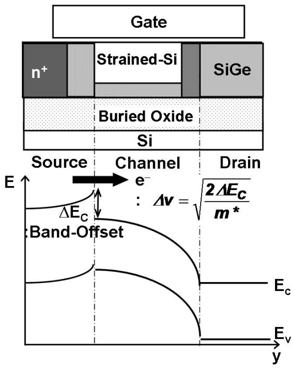


Fig.1 Schematic n-channel SHOT structures, using a usual source relaxed-SiGe/strained-Si heterojunction.

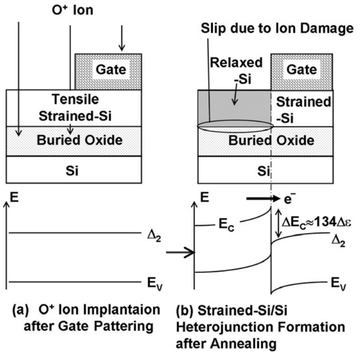


Fig.2 New n-channel SHOT structures with source relaxed-Si/tensile-strained-Si heterojunction, using source O$^+$ ion implantation. Δ_2 is the energy level of 2-fold valley.

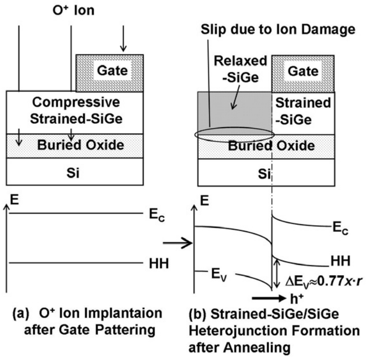


Fig.3 New p-channel SHOT structures with source relaxed-SiGe/compressive-strained-SiGe heterojunction, using source O$^+$ ion implantation. HH is the energy level of heavy hole band.

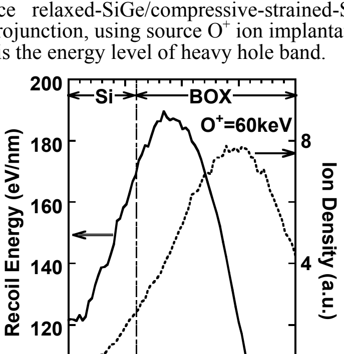


Fig.4 SRIM simulation results of recoil energy (solid lines) due to one O$^+$ ion and O$^+$ ion density profile (dashed lines) in SSOI (60nm) substrates, where E_A=60keV.

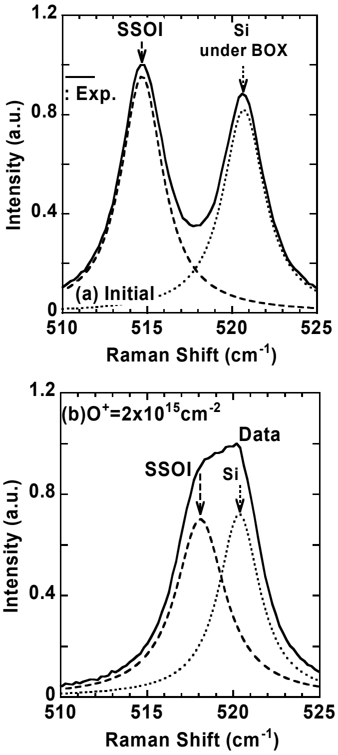


Fig.5 Raman shift data (solid lines) of (a) before and (b) after O$^+$ ion implantation, where T_{SSOI}=60nm, D_O=2×10^{15}cm^{-2} and E_A=60keV. The dashed and the dotted lines indicate fitting curves of SSOI and Si under BOX peaks, respectively.

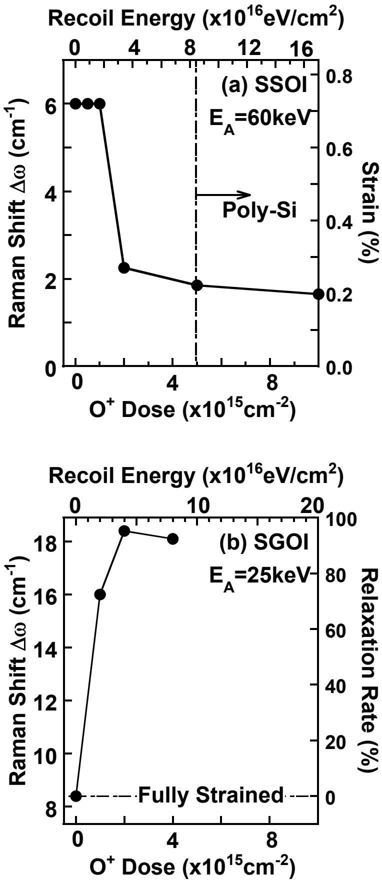
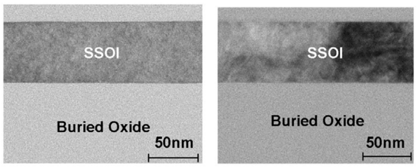


Fig.6 Raman shift and strain/relaxation-rate value of (a) SSOI and (b) SGOI versus O$^+$ ion dose. (a) T_{SSOI}=60nm and E_A=60keV, (b) T_{SGOI}=20nm and E_A=25keV. The upper axis indicates simulated recoil energy per 0.1nm thickness at the BOX interface.



(a) 2x10^{15}cm^{-2} (b) 5x10^{15}cm^{-2}

Fig.7 TEM photos of cross section of SSOIs after O$^+$ ion implantation, where O$^+$ dose of (a) 2×10^{15}cm^{-2} and (b) 5×10^{15}cm^{-2}.

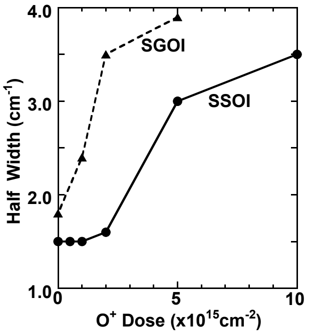


Fig.8 Half width of SSOI (circles) and SGOI Raman peaks (triangles) versus O$^+$ ion dose, where the process conditions are the same as in Fig.6.

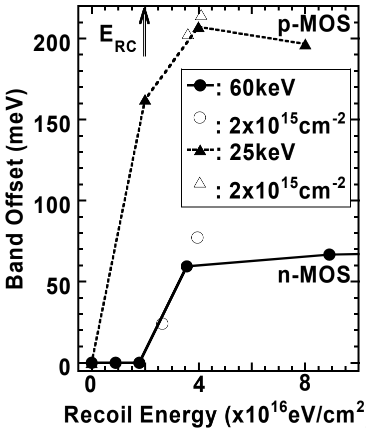


Fig.9 Conduction (circles) and valence band (triangles) offset values determined by Raman shift data and Eq.(1) as a function of simulated recoil energy per 0.1nm thickness at the BOX interface due to O$^+$ ion in various ion doses and ion energies. Closed and open characters show results at fixed ion energy and fixed ion dose conditions, respectively. E_{RC} (~2×10^{16}eV/cm^2) indicates the critical recoil energy for relaxing SSOIs and SGOIs.

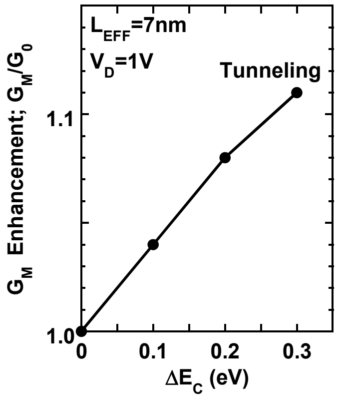


Fig.10 Simulated enhancement of maximum G_M value of SHOTs G_M/G_0 as a function of ΔE_C, where G_0 shows the maximum G_M value at ΔE_C of 0eV, L_{EFF}=7nm and V_D=1V, considering tunneling effects of electrons at the energy spike of the source heterojunction.