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Defect-Induced Deep Levels in SiGe-on-Insulator Substrate Fabricated Using Ge Condensation Technique

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1. Introduction

Ge-rich SiGe-on-insulator (SGOI) is one of promising materials for mobility enhancement technique because it can provide high hole mobility for SGOI p-channel metal-oxide-semiconductor field-effect-transistor (MOSFET), as well as virtual substrate for strained Si, resulting in high electron mobility for strained Si-on-SGOI n-channel MOSFET. Ge condensation by dry oxidation of SiGe layer on SOI substrate is an attractive method for the fabrication of Ge-rich SGOI or even pure Ge-on-insulator (GOI) [1]. However, defects such as threading dislocations [2], stacking faults (SF) and microtwins [3,4] generate with an increase in Ge fraction (Ge%) owing to the strain relaxation, and a critical problem related to such defect generation is to be unintentionally induced hole concentrations as high as 10^{16}–10^{18} cm^{-3} in SGOI layers after the Ge condensation [3]. Therefore, the origin and nature of defect-induced level in the band gap should be clarified from a viewpoint of defect control. However, it is still open question whether the defect-induced level exists in the band gap or not.

In this work, we measured the drain current (I_D) versus gate voltage (V_G) characteristics under inversion mode operation by using back-gate MOSFET method for SGOI with different Ge%, which was fabricated using Ge condensation. From the threshold voltage (V_T) and the subthreshold swing (S) determined by I_D–V_G characteristics, we evaluated the acceptor concentration (N_A) in SGOI layer. We found that N_A's were much higher than the hole concentration (p) measured by Hall effect for low-Ge% SGOI, while N_A's were almost the same as p for high-Ge% SGOI. Such different behaviors between N_A and p as a function of Ge% can be explained by the model that deep acceptor level (E_{TA}) exists in SGOI and the position of E_{TA} shifts to valence band with the increase in Ge%.

2. Results and discussion

All of SGOI substrates were conveniently fabricated using Ge condensation by the dry oxidation. The SGOI with Ge%>20% was fabricated using 10 nm-thick Si/62 nm $Si_{0.78}Ge_{0.22}$/BOX/Si substrate, which was used in our previous work and the detailed condensation method is given by elsewhere [4]. The SGOI's with Ge% of 10 and 15% were prepared by oxidation of 10 nm-thick Si/160 nm $Si_{0.9}Ge_{0.1}$/70 nm SOI/BOX/Si substrate at 1200 ^{0}C for 1 h and 10 nm-thick Si/70 nm $Si_{0.85}Ge_{0.15}$/BOX/Si substrate at 1000 ^{0}C for 10 min, respectively. After Ge condensation, we fabricated back-gate n-channel MOSFET structure on SGOI substrates, as shown in Fig. 1. For the formation of n^+ source/drain (S/D), we utilized solid state diffusion (SSD) technique. First, 400 nm-thick SiO_2 mask was deposited by plasma sputtering, and windows were opened in S/D areas. Second, a thin film mainly consisting of P_2O_5-doped SiO_2 was spin-coated on the sample surface, and SSD was carried out at 1000 ^{0}C for 10 min in N_2 to form n^+ S/D, of which concentrations were as high as approximately 10^{20} cm^{-3}. Third, after the coating film and top SiO_2 were removed, Al film was then deposited and patterned as S/D electrodes. Fourth, mesa etching was performed for SGOI layer for isolation of the MOSFETs. Finally, In-Ga alloy was rubbed onto back Si to form an ohmic contact.

Figure 2 shows the I_D–V_G characteristics in the linear region of I_D versus drain voltage (V_D) by applying a small V_D of 0.05 V. It is very clear that V_T drastically increased with an increase in Ge%. From the V_T and S determined by I_D–V_G characteristics, we examined N_A for SGOI with different Ge%, as shown in Fig. 3. It can be seen that N_A's are higher than 1×10^{16} cm^{-3} even though low Ge%, and drastically increased with an increase in Ge%.

In order to confirm the high N_A for the case of the low Ge%, we checked the capacitance (C) versus V_G characteristics for SGOI with Ge%=20% by dual-MOS capacitance method [5], showing N_A

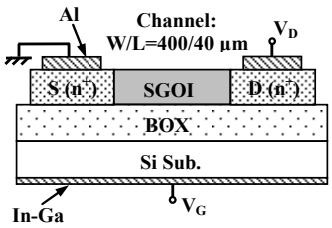

Fig. 1 Back-gate MOSFET structure on SGOI substrates.

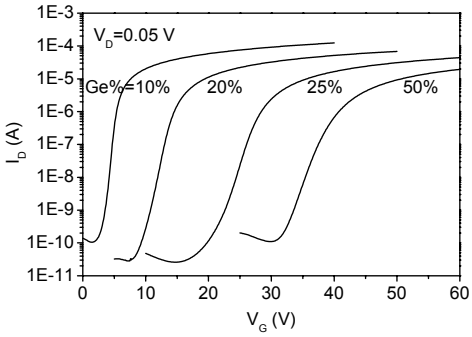

Fig. 2 I_D–V_G characteristics for SGOI with different Ge%.

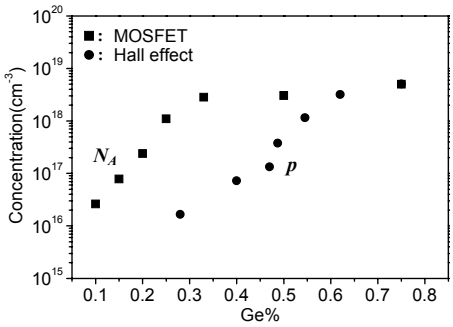

Fig. 3 Dependences of N_A and p on Ge%.

of 1.5×10^{17} cm^{-3}, which is in good agreement with that of 2.4×10^{17} cm^{-3} measured by MOSFET method. Thus, we can verify the validity of N_A measurement using back-gate MOSFET method.

The p's measured by Hall effect were also given in Fig. 3. When Ge%<25%, p's are less than 1×10^{16} cm^{-3} (the detection limit of Hall effect system for the very thin samples used in this work), because they cannot be detected. When Ge%>25%, p also increased with an increase in Ge%. Thus, it can be found that the increasing tendencies of N_A and p are quite different, and N_A's are much higher than p's for low-Ge% SGOI.

The energy bands of SGOI with low and high Ge% are schematically described in Fig. 4. The distinct difference between MOSFET and Hall effect methods is the energy-band bending. For p measurement by Hall effect, there is no energy-band bending. By contrast, N_A measurement by MOSFET was performed under the inversion mode operation, thus energy-band bending is $2\psi_B$ at $V_G=V_T$, where ψ_B is the energy difference between E_i and E_F. (See in Fig.4 for the definition of E_i and E_F.)

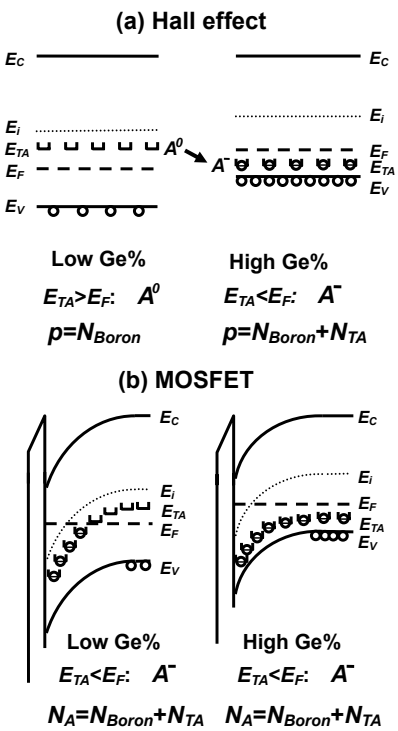

Fig. 4 Schematic diagrams of the energy band of SGOI with different Ge%: (a) Hall effect; (b) MOSFET.

It should be also noted that the initial SGOI showed almost complete lattice relaxation. This means that strain relaxation should occur during the structural change from SiGe-on-SOI to SGOI at the initial stage of Ge condensation, resulting in SF defect generation, which has been clearly observed in photoluminescence measurements [6].

Although the energy level position of SF defect in Si is still not clear, we believe the E_{TA} would be located at upper half of band gap (E_g) [7]. Thus, we speculate that SF defects exist in SGOI layer and induce E_{TA} in the lower half of E_g for the SGOI with Ge% ≥10%, as shown in Fig. 4, where N_{TA} is the concentration of the defect-induced acceptor level.

Since the ratio of ionized N_{TA}^- to neutral N_{TA}^0 is given by $N_{TA}^-/N_{TA}^0=\exp[(E_F-E_{TA})/kT]$, (where the degeneracy factor was ignored), electronic states of E_{TA} should be neutral (A^0) when Ge% is lower than approximately 25%, because E_{TA} is located at upper position than E_F. Therefore, p originates only from the residual boron atoms of approximately 1×10^{15} cm^{-3}, which is lower than the detection limit of Hall effect system and cannot be detected.

With an increase in Ge%, E_g becomes narrow and E_{TA} is close to E_F. Consequently, N_{TA}^- components rapidly increase even for flat band according to the above ionization ratio, thus p's come from the contribution of both the residual boron and N_{TA}^-. When E_{TA} is situated at lower position than E_F for the case of high Ge%, p's are equal to $N_{Boron}+N_{TA}$. The phenomenon of the E_{TA} shift with the increase of Ge% has been demonstrated by DLTS in epitaxial SiGe alloy layer [8,9].

Different from Hall effect measurement, MOSFET measurement is done under the energy-band bending of $2\psi_B$ (Fig. 4b), thus, E_{TA} is always negatively ionized even for the low Ge% case. Therefore, the measured N_A by MOSFET method comes from the contributions of both the residual boron atoms and N_{TA}^- for SGOI with various Ge%.

The difference behavior between N_A and p gives the strong evidence for the existence of acceptor states of defects generated during Ge condensation. Because it is impossible to induce N_A as high as 10^{16}–10^{18} cm^{-3} in SGOI as impurity during Ge condensation [3], the origin of deep E_{TA} should be attributed to the generation of SF defect, as described previously.

3. Conclusion

Unintentional hole generation in SGOI is associated with the SF defects generated by strain relaxation. The defects act as acceptor, of which the level shifts from deep to shallow positions with increasing Ge%. From this model, the different increasing tendency of N_A and p with an increase of Ge% can be well explained. This difference behavior between N_A and p provides an strong evidence for the existence of acceptor states of defects generated at the initial stage of Ge condensation.

Acknowledgements

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