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Reduction of NiGe/*n*Ge Schottky Barrier Height by S and P Co-introduction for Metal Source/Drain in Ge *n*MOSFETs

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I. Introduction

The segregation of impurities at the NiGe/*n*Ge interface has received much attention as a way of reducing the Schottky barrier height (SBH), leading to low contact resistance (R_C) for metal source/drain (S/D) Ge *n*MOSFETs. In S-segregated NiGe/*n*Ge [1], a low SBH value of 0.15 eV was estimated by Arrhenius plots, and in P-segregated NiGe/*n*Ge [2], the *J-V* characteristics showed ohmic ones. To realize Ge *n*MOSFETs, even lower SBH values, zero or effectively minus, are desirable. We have investigated S and P co-introduced NiGe/Ge (SP-NiGe/Ge), and found that P was less prone than S to segregation around the interface, that S and P independently acted as dopants in NiGe/Ge, and that the co-introduction of S and P could reduce the R_C [3]; however, it has not been clarified how SBH values were modulated. It is important to evaluate the SBH values to realize even lower ones. Therefore, in this study, we further investigated S-and/or P-introduced NiGe/*n*Ge, and estimated the SBH values to pursue lower R_C.

II. Experimental

NiGe/Ge diodes were fabricated as follows (the experimental procedure was the same as previously reported [3]): Into Sb (Ga)-doped *n* (*p*)-type Ge(100) substrates (0.05-0.25 Ωcm) with and without SiO_2 isolation, S (5×10^{14} cm^{-2}) or P (1×10^{15} cm^{-2}) or both ions (the same doses as in the only S and only P cases) were implanted at the acceleration energy of 10 keV. Ni films (~15 nm) were deposited on the substrates by sputtering. Then, RTA for Ni germanidation was performed at 250, 350, or 450^{o}C in N_2 for 1 min. Unreacted Ni on NiGe was removed by HCl solution. On the back surface of the substrates, Al layers were formed by thermal evaporation to reduce the back R_C. For comparison, NiGe/Ge diodes without S or P introduction were also fabricated at each annealing temperature (*T*) as references. *J-V* characteristics at a wide range of *T* (11.0-413 K) were measured for the NiGe/Ge diodes. The profiles of impurity concentration and carrier concentration were examined by SIMS and spreading resistance probe (SRP), respectively. The positions of NiGe/Ge interfaces were defined as the half maximum intensities of Ni peaks in SIMS profiles. Although the conditions in this study were almost the same as those in a previous study [3], we fully re-fabricated the NiGe/Ge using different annealing apparatus to realize lower R_C for NiGe/*n*Ge.

III. Results and Discussion

First, we examined the electron concentration profiles for the S-and/or P-implanted *n*Ge to confirm whether those impurities were electrically activated at the same temperature as germanidation. Note that P in Ge behaves as a single donor (E_D=E_C-0.012 eV [4]), whereas S in Ge behaves as a double donor (E_D=E_C-0.28, E_C-0.59 eV [5]). SRP profiles revealed that electrons were generated in P-implanted *n*Ge and in S and P co-implanted *n*Ge in this experiment (Fig. 1). Interestingly, electron concentrations were higher in the SP co-implanted *n*Ge than in the P-implanted *n*Ge, though no electron increase in S-implanted *n*Ge was observed.

Under the same annealing condition as for Ge, we fabricated NiGe/Ge. It was revealed that the SIMS profiles in SP-NiGe/Ge were similar to those in the mixture of S-NiGe/Ge and P-NiGe/Ge (Fig. 2), which reproduced our previous results [3]. Although the dose of P was higher than that of S, the concentration of P around the NiGe/Ge interface was lower than that of S. This implies that P is less prone than S to segregation around the interface. It is worth noting that the absence of P segregation has no relation to ion implantation damage of the Ge substrate before germanidation. We confirmed no segregation of P even in NiGe/n^+Ge that was well annealed at 600^{o}C for 30 min in N_2 for recovery of the damage after P ion (1×10^{15} cm^{-2}) implantation (data not shown).

Next, we investigated *J-V* characteristics at 300 K for those NiGe/Ge diodes (Fig. 3) analyzed for the profiles (Fig. 2). Reverse current (J_R) for the NiGe/*n*Ge diode [=|*J*(*V*<0)|] increased more than that for the reference NiGe/*n*Ge diode, i.e., changing the characteristics from rectifying toward ohmic [Fig. 3(a)]. J_R in P- and SP-NiGe/*n*Ge diodes was higher than that in the S-NiGe/*n*Ge diode, and showed ohmic characteristics. On the contrary, J_R for the P- and SP-NiGe/*p*Ge diodes [=|*J*(*V*>0)|] decreased more than those for the reference and S-NiGe/*p*Ge diodes, i.e., changing the characteristics from ohmic to rectifying [Fig. 3(b)]. Besides, it is clear that the SP-NiGe/*p*Ge diode was more effective in reducing J_R than the P-NiGe/*p*Ge diode. J_R for the diodes in this work was suppressed more than about 10-fold compared with our previous work [3], and the optimum *T* of germanidation for low R_C for NiGe/*n*Ge and high R_C for NiGe/*p*Ge diodes was 250^{o}C.

Although the J_R for the NiGe/*n*Ge diodes showed ohmic characteristics, the SBH values cannot be estimated from them because substrate-limited currents were dominant at 300 K. Therefore, we measured the *J-V* characteristics over a wide range of *T* (11.0-413 K) to estimate the SBH values. The |*J*| for the reference NiGe/*n*Ge diode decreased with decreasing *T* from 413 K, indicating that Schottky current was dominant, and remained almost unchanged below ~33 K, indicating that tunneling current was dominant (the region where |*J*|~10^{-10} A/cm^2 is the lower limit of measurement) [Fig. 4(a)]. Although showing asymmetric and rectifying |*J*| similar to the reference, the S-NiGe/*n*Ge diodes showed higher |*J*| than the reference at the same *T* [Fig. 4(b)]. On the other hand, the P-NiGe/*n*Ge diodes showed a nearly linear relation between *J* and *V*, and the *J* decreased with decreasing *T* [Fig. 4(c)]. *J-V* characteristics for the SP-NiGe/*n*Ge diodes also showed a similar linear relationship to the P-NiGe/*n*Ge diodes, though the *T* dependences were slightly different [Fig. 4(d)].

The SBH values can be estimated by the relationship Log[|*J*|/T^2]-1/*T*, based on the equation for Schottky current: $J=A^*T^2\exp(-q\Phi/kT)[\exp(qV/kT)-1]$ (1), where A^* is the Richardson constant for *n*Ge(100) and is ~143 A/cm^2/K^2 [6], and Φ is SBH. If the conduction mechanism obeys the Schottky theory, the data for the diodes at a certain *V* should be distributed almost on straight lines with negative slope.

Figure 5 shows the relationship for the reference NiGe/*n*Ge and S-NiGe/*n*Ge diodes, where the data for each one were fitted by the least squares method. Each of the data was apparently distributed almost on a line with a negative slope and slightly depended on *V*. Figure 6 shows the effective SBH values as a function of *V*, which were derived from fitted slopes in the relationship at the measured *V*. The effective SBH values were higher at negative voltages, the behaviors of which were reasonable taking Eq. (1) into account. The SBH value for the reference diode was estimated to be ~0.65 eV. Note that the value is slightly overestimated, because the SBH value has probably a similar dependence on *T* to the band-gap of Ge, although SBH is assumed to be independent of *T* in Eq. (1). Nonetheless, the value for the S-NiGe/*n*Ge diode was as low as ~0.32 eV at most. Thus, S-introduction is effective for reducing the SBH value compared to the reference. The formation of a S-Ge dipole layer at the NiGe/*n*Ge interface or the decrease of interface trap density is a possible mechanism for the SBH reduction [1]. In addition, we suppose the possibility that another mechanism also has acted at the same time, because the value estimated by only slope is lower than that by Eq. (1) at each *T* (e.g., ~0.41 eV at 300 K). If S atoms exist in the *n*Ge as well as at the NiGe/*n*Ge interface, the current through the S donor levels in Ge [5] may be dominant, resulting in lower effective SBH values.

Similarly, we examined the relationships for P- and SP-NiGe/*n*Ge diodes (Fig. 7). In contrast to the reference and S-NiGe/*n*Ge diodes, the data for both P- and SP-NiGe/*n*Ge diodes showed lines with positive slope, indicating that they obeyed not the Schottky mechanism but a different mechanism, which is probably mainly substrate-limited current. The data at the lowest *T* (~11.0 K) were below the line for SBH of 0.01 eV. Assuming that Schottky current satisfies Eq. (1), the SBH values for P- and SP-NiGe/*n*Ge diodes are estimated to be <0.01 eV. Thus, it was clarified that P- and SP-NiGe/*n*Ge could greatly reduce the SBH values. Taking account of leakage current, i.e., J_R in the NiGe/*p*Ge diode, the co-introduction of S and P is more applicable to metal S/D in Ge *n*MOSFETs.

IV. Summary

S-, P-, and SP-NiGe/Ge diodes were investigated structurally and electronically to reduce NiGe/*n*Ge SBH, leading to low R_C. We found that P was less prone than S to segregation around the NiGe/Ge interface. S-, P- and SP-introduction into the NiGe/*n*Ge interface modulated the characteristics from rectifying toward ohmic. The SBH values were estimated by *J-V* measurements over the wide range of temperature (11.0-423 K), and whereas that for S-NiGe/*n*Ge was ~0.32 eV, those for P- and SP-NiGe/*n*Ge were as low as <0.01 eV. Correspondingly, P- and SP-introduction into NiGe/*p*Ge modulated the characteristics from ohmic to rectifying, and the reverse current was suppressed more for the SP-NiGe/*p*Ge diode than for the P-NiGe/*p*Ge diode. In conclusion, S and P co-introduction is effective for the metal S/D in Ge *n*MOSFETs.

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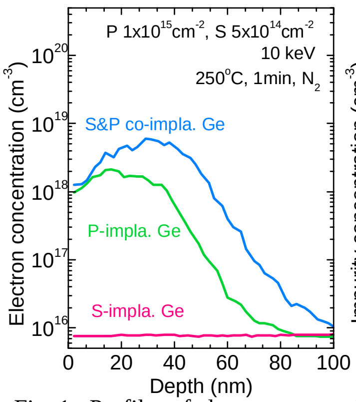

Fig. 1: Profiles of electron concentrations in S-implanted, P-implanted, and S and P co-implanted Ge. RTA was performed at 250°C in N_2 for 1 min.

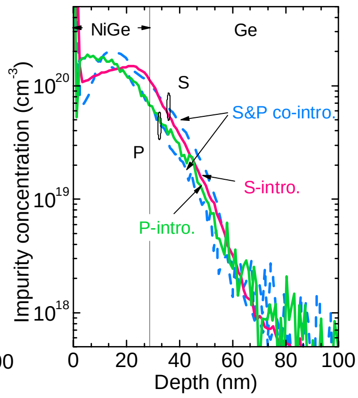

Fig. 2: Profiles of impurity concentrations in S-introduced, P-introduced, and S and P co-introduced NiGe/Ge. Germanidation temperature was the same as Ge in Fig. 1.

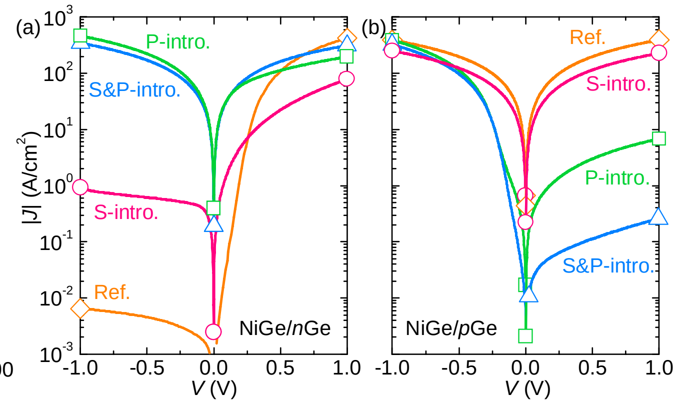

Fig. 3: *J-V* characteristics of (a) NiGe/*n*Ge and (b) NiGe/*p*Ge diodes into which S, P or both S and P were introduced. *J–V* characteristics of NiGe/Ge diodes without S or P (Ref.) are also shown as references. Diodes are the same ones analyzed for profiles in Fig. 2.

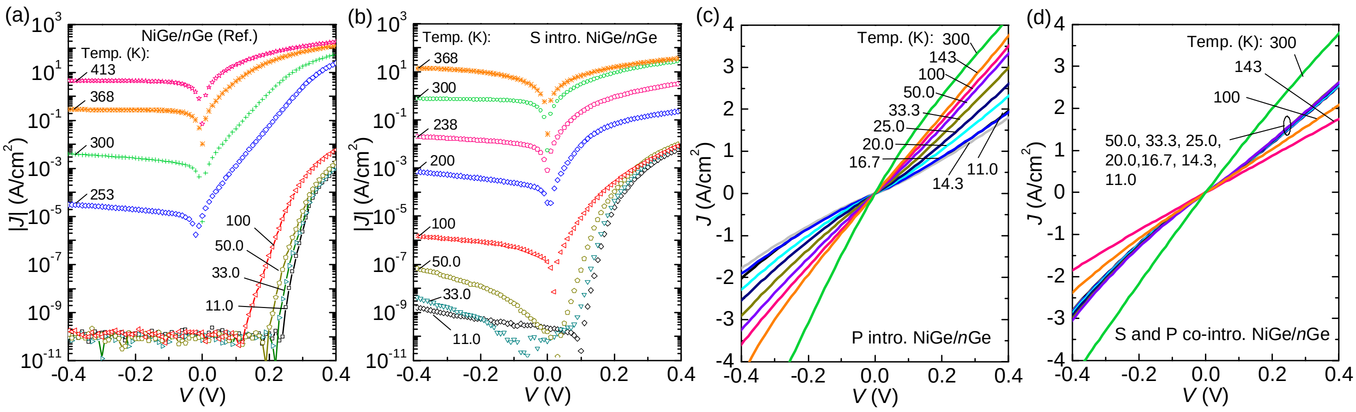

Fig. 4: *J-V* characteristics at different temperatures (11.0-413 K) for (a) reference, (b) S-introduced, (c) P-introduced, and (d) S and P co-introduced NiGe/*n*Ge diodes.

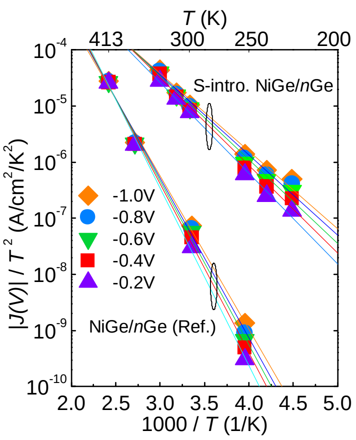

Fig. 5: Log[$|J(V)|/T^2$]-1/T relation for reference and S-introduced NiGe/*n*Ge at measured voltages. Temperatures were 223-413 K. Lines were fitted by the least square method.

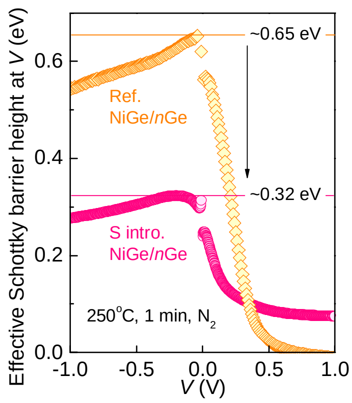

Fig. 6: Effective SBH values as a function of V for reference and S-introduced NiGe/*n*Ge, each of which was derived from fitted slopes in the Log($|J(V)|/T^2$)-1/T relation at measured voltages (Fig. 5).

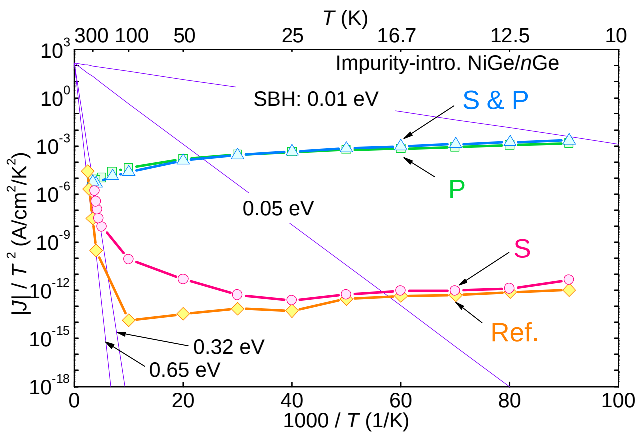

Fig. 7: Relationship Log($|J|/T^2$)-1/T for reference, S-introduced, P-introduced, and S and P co-introduced NiGe/*n*Ge diodes. Temperatures were 11.0-413 K. Straight lines indicate calculated ideal Schottky currents. The region where $|J|/T^2 \sim < 10^{-10}$ A/cm²/K² is the lower limit of measurement.