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Low Temperature Phosphorus Segregation at NiGe/Ge Interface by "Snowplow" Effect

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1. Introduction

Ge-CMOS is one of promising solutions to overcome scaling limit of Si-CMOS, because of its high carrier mobility both of hole and electron. Since Ge-CMOS should be used for further scaled devices, the parasitic resistance, particularly the contact resistance, should be carefully considered. The contact resistance is basically described by the Schottky barrier height (SBH) and the impurity concentration of Ge side at metal/Ge interface. To reduce the contact resistance, decreasing the SBH and/or increasing the impurity concentration are required.

On the other hand, the strong Fermi-level pinning to the valence band edge of Ge at metal/Ge interface has been pointed out[1]. Though it is difficult to shift the SBH at Ge interface by means of conventional surface modulation techniques, we have reported that the SBH was significantly shifted by inserting an ultra-thin insulator between metal and Ge[2], and that metal source/drain Ge n-MOSFETs were well operated[3].

In this paper, we focus on the other part, in which the points are how to introduce higher impurity concentration at metal/Ge interface and how to activate them at low temperatures. We pay attention to the "snowplow" effect, which is well known for the silicide formation in Si process technology[4]. Although, in Ge, the snowplow effects of As, Sb and S through the germanide reaction were reported, the ohmic contact to n-Ge was not obtained[5]. We investigate phosphorus (P), whose diffusion coefficient and solid solubility in Ge are lower and higher than those of As and Sb[6,7], from the viewpoints of the impurity "activation" and "segregation".

2. Experimental Results and Discussion

Ge wafers were cleaned by using methanol, HCl, H_2O_2 +NH_4 and HF, followed by 50-nm-thick Ni film evaporation on Ge by electron beam in an ultra-high vacuum chamber (base pressure ~10^{-8} Pa). The germanide reaction was performed in N_2 in the range from 200 to 500°C. From XRD patterns, well crystallized Ni_5Ge_3 and NiGe films are observed for samples annealed at 200°C and 300-500°C, respectively.

(i) Activation

The impurity activation by the snowplow effect through the germanide reaction was first investigated. Both n-type (Sb; $2x10^{16}$ /cm^3) and p-type (Ga; $3x10^{15}$ /cm^3) Ge (100) substrates were used for $NiGe_x$/Ge diodes. 100-nm-thick field SiO_2 films were deposited on Ge substrate by rf-sputtering and it was etched to form square

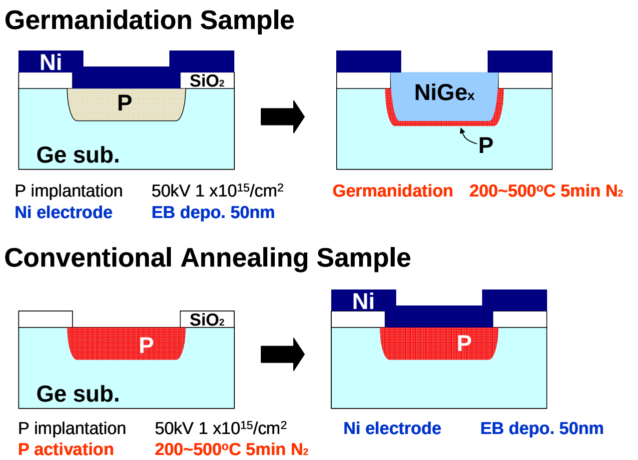

Fig. 1. Schematic diagram of germanidation sample and reference one.

holes (80x80 μm^2) by HF solution. P ions were implanted by 50 kV with the dose of $1x10^{15}$ /cm^2. Ni film was deposited in the UHV chamber, and then Ge substrates were thermally annealed in N_2 ambient. We also fabricated P implanted Ni/Ge diodes as references without germanide reaction. These sample fabrication flow is shown in **Fig. 1**.

I-V characteristics were measured in the range of ±1 V. We confirmed that metal(including germanide)/Ge junctions without P implantation show Schottky characteristic on n-Ge and ohmic one on p-Ge, respectively, due to the strong Fermi level pinning[1]. Namely, Ni-germanidation itself does not modulate I-V characteristics. Typical I-V curves of P-implanted $NiGe_x$/Ge are shown in **Fig. 2**. In $NiGe_x$/n-Ge junction,

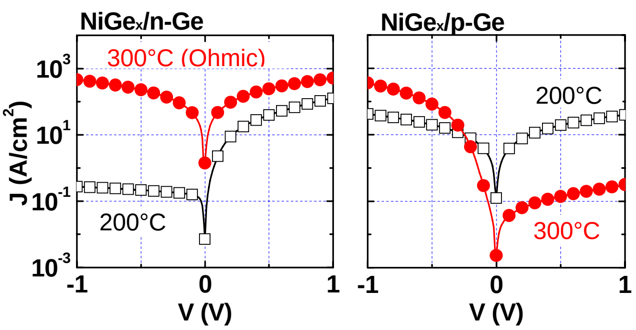

Fig. 2. I-V characteristics of P-implanted NiGe/Ge junction with germanide reaction at 200 and 300°C. Implanted P atoms are highly activated at 300°C through the germanide reaction to form ohmic contact on n-Ge and to form Schottky one on p-Ge.

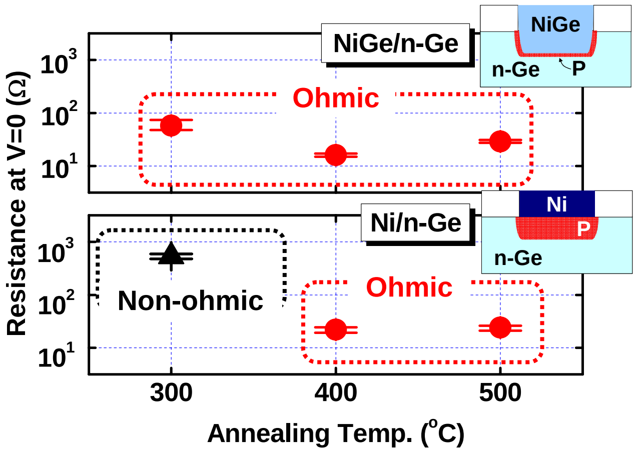

Fig. 3. Resistance of P-implanted NiGe/n-Ge and Ni/n-Ge (reference) diodes at V=0 ($|\partial I/\partial V|_{V=0}$) vs. annealing temperature. At 300°C, ohmic contact is obtained at P-implanted NiGe/n-Ge by germanidation-assisted activation.

the transition from Schottky to ohmic is observed between 200 and 300°C germanidation, while NiGe/p-Ge diode annealed at 300°C clearly shows the transition from ohmic at 200°C to Schottky. From the results on n- and p-Ge substrates in Fig. 2, I-V characteristic change is not attributable to a possible degradation at NiGe/Ge interface, but to the actual activation of P atoms. As shown in **Fig. 3**, the resistance at V=0 for the NiGe/n-Ge sample germanided at 400°C is slightly smaller than that at 300°C, and the resistance of sample germianided at 500°C goes up again. This might be attributed to out-diffusion of P atoms. On the other hand, the Ni/n-Ge sample annealed at 300°C (reference) does not show a linear I-V characteristic due to the insufficient activation of P. Thus, it is concluded that the germanide reaction really lowers the P activation temperature down to 300°C.

(ii) Segregation

Next, the segregation of P by the snowplow effect at NiGe/Ge interface is discussed. The Ni film thickness from 10 to 200 nm was varied so as to change the NiGe/Ge interface depth from 20 to 400 nm for a given implanted profile of P. The definition of the depth in this work and as-implanted profile of P in Ge calculated by SRIM[8] are shown in **Fig. 4(a)** and **(b)**. If NiGe/Ge interface depth is over 200 nm, there should be no impurity atoms at the interface. **Figure 4(c)** shows the NiGe/Ge interface depth dependence of the resistance at V=0 in NiGe/n-Ge junctions annealed at 300 and 500°C. In the NiGe/Ge interface depth of ~50 nm, the ohmic resistance decreases with increasing the Ni film thickness for both samples annealed at 300 and 500°C. In the NiGe/Ge interface depth of 200 and 400 nm, however, the sample annealed at 300°C show ohmic characteristics, while that annealed at 500°C show Schottky behavior. This result directly indicates that P atoms are segregated at the NiGe/Ge interface by the snowplow effect in the germanidation process at 300°C, while they are not at 500°C.

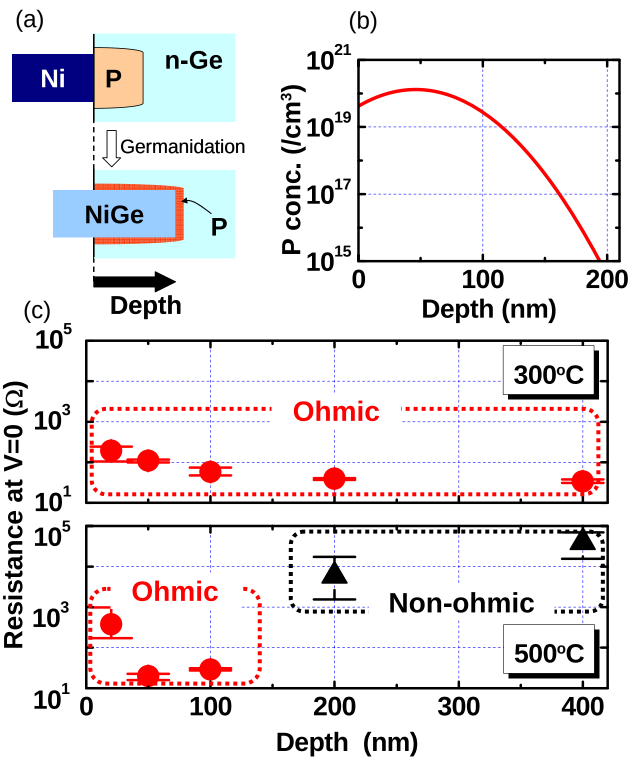

Fig. 4. (a) Definition of "depth". Depth is relative position from initial Ge surface. **(b)** Calculated as-implanted P profile (Voltage: 50 kV, Dose: 1×10^{15} /cm^2). **(c)** Resistance of P-implanted NiGe/n-Ge diodes at V=0 ($|\partial I/\partial V|_{V=0}$) vs. NiGe/Ge interface depth. By 300°C germanidation, ohmic contact was obtained irrespective of Ni thickness. This indicates that lots activated P atoms are segregated to NiGe/Ge interface.

From these results in (i) and (ii), the germanide reaction at Ni/Ge interface around 300°C enables us to segregate and to activate P atoms, and to form a very shallow junction. The germanide reaction around 500°C loses an advantage of the segregation by the snowplow effect.

3. Conclusion

By the snowplow effect through the Ni-germanidation, P atoms can be segregated at NiGe/Ge interface and activated efficiently at 300˚C. This low temperature process surely suppresses the diffusion of P atoms. This result might be a key to form shallow n^+-layer in scaled Ge-CMOS.

Acknowledgement

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