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High Hole-Mobility Ge p-MOSFET with HfGe Schottky Source/Drain

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1. Introduction

By virtue of its high intrinsic carrier mobility, Ge is of great interest as a candidate channel material for future CMOS devices. To translate this potential into scaled CMOS devices, an ultra-shallow source/drain (S/D) junction with very low sheet and contact resistances should be achieved. However, it is difficult to satisfy these requirements using conventional doped S/D because of the low solubility limits and large diffusion coefficients of dopants in Ge [1]. Furthermore, since Ge-CMOS should be integrated on a Si platform for practical use [2], a simple structure and low-temperature processing are essential for Ge MOSFET fabrication. A solution to solve these problems is Schottky S/D MOSFET, which is an attractive candidate for future CMOS devices. To embody high-performance Schottky Ge-CMOS, metal/Ge contacts with both low electron barrier height (Φ_{BN}) and low hole barrier height (Φ_{BP}) are needed for n- and p-MOSFETs, respectively.

Schottky p-MOSFET has been demonstrated using the NiGe/Ge contact, the Φ_{BP} of which is 0.16 eV [3]. However, theoretical studies have shown that the Φ_{BP} should be less than 0.1 eV in order for Schottky p-MOSFETs to outperform doped S/D devices [4]. Thus, the Φ_{BP} is still high for the injection of holes from the source to the inverted channel. We searched for a low-Φ_{BP} material and found a HfGe/Ge contact as a candidate for the S/D in the Schottky p-MOSFET.

In this paper, we present electrical properties of the HfGe/Ge contact with low Φ_{BP} and show the device performance of Schottky p-MOSFET using HfGe as S/D. The device performance is comparable to that of p-MOSFET with doped p^+ S/D.

2. Experimental

The substrates were p-type (100) Ge with a resistivity of 0.2 Ωcm, and n-type (100) Ge with a resistivity of 0.3 Ωcm. A HfGe/Ge contact was fabricated using following process: After chemical cleaning and photoresist patterning, a Hf film was deposited using rf sputtering, followed by TaN deposition using rf sputtering to prevent the oxidation of the film during subsequent annealing. Then, Al film was deposited using thermal evaporation and the Al/TaN/Hf layers were patterned using a lift-off technique. After the patterning, postmetallization annealing (PMA) was carried out at a temperature (T_{PMA}) in the range of 300-500 °C in N_2 for 30 min.

We fabricated Schottky MOSFET using the gate-last process. Figure 1 shows the detailed process flow and a schematic cross-sectional view of Schottky p-MOSFET. After the HfGe/Ge S/D fabrication, a GeO_2 interlayer with a thickness of 2.5 nm and a SiO_2 layer with a thickness of 50 nm were formed as a gate insulator by plasma oxidation and the subsequent sputtering using an ECR system [5]. Next, postdeposition annealing (PDA) was carried out. Al gate electrode was formed by vacuum evaporation and patterned by wet etching. Then, contact holes for S/D were opened, and Al electrodes were formed as S/D contacts using a lift-off process. Finally, Al-PMA for gate electrode was carried out at 400 °C for 30 min, leading to a drastic decrease in interface state density (D_{it}) in the lower half of the bandgap (E_g) of Ge [6].

3. Result and discussion

Figure 2 shows cross-sectional TEM image and EDX result for HfGe/Ge contact. It was found that the reaction layer between Hf and Ge was more than 10 nm thick even though there was no PMA. Thus, it is concluded that the HfGe/Ge contact is formed during the Hf sputter deposition. Figure 3 shows the *J-V* characteristic of the HfGe/n-Ge contact with T_{PMA} = 500°C, showing excellent rectifying behavior with a low junction leakage current. From the forward *J-V* characteristic at 300 K, the Φ_{BN} was obtained as 0.60 eV. The HfGe/p-Ge contact showed Ohmic behavior even at 100 K, suggesting that the HfGe/Ge contact exhibits very low Φ_{BP}. The Φ_{BN} and ideality factor (n) of HfGe/n-Ge Schottky contacts with various PMAs are listed in Table 1, which suggests that a HfGe/Ge contact has good thermal stability in the T_{PMA} range less than 500 °C. The Φ_{BP} of HfGe/Ge is estimated as 0.06 eV at 300 K, assuming the relation of $\Phi_{BN} + \Phi_{BP} = E_g$ (0.66 eV) [1]. This electrical performance is comparable to that of PtGe [7]. Also, this low Φ_{BP} contact is useful as S/D in Schottky p-MOSFET.

Figure 4 shows the source current (I_S) and drain current (I_D) versus drain voltage (V_D) characteristics for the fabricated Schottky MOSFET, indicating that channel conductions are well controlled by the gate voltage (V_G). Furthermore, the differences between I_D and I_S are relatively small, which means that substrate currents (I_{sub}) are considerably small thanks to high barriers for substrate majority carriers. Figure 5 shows the I_S versus V_G characteristics with V_D of 0.01 and 1 V for both MOSFETs. Figure 6 shows field-effect hole mobility (μ_h) as function of V_G. The peak μ_h was 336 cm^2/Vs, which is almost the same as our previous result (370 cm^2/Vs) from p-MOSFET with p^+ S/D [5].

This high μ_h should come from an extremely low Φ_{BP} and a thick HfGe layer (~10 nm), which are suitable for hole injection from the source to the inverted channel.

4. Conclusions

We found that the Φ_{BN} of HfGe/Ge is 0.60 eV, which is available to S/D in Schottky p-MOSFET. We fabricated the MOSFET and demonstrated quite normal device operation. The peak hole mobility was as high as that of conventional doped S/D p-MOSFET, which comes from the extremely low Φ_{BP} and thick HfGe layer.

Acknowledgements

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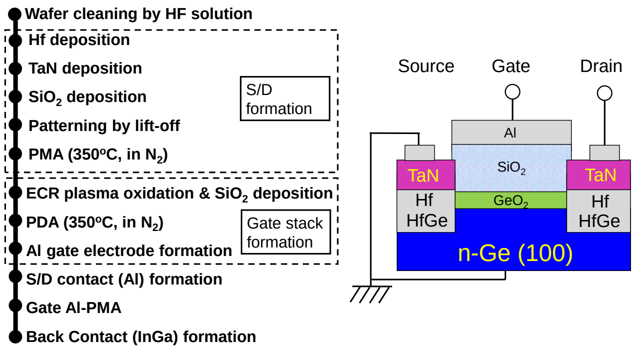

Fig. 1 Process flow and schematic cross sectional view of the Schottky p-MOSFET.

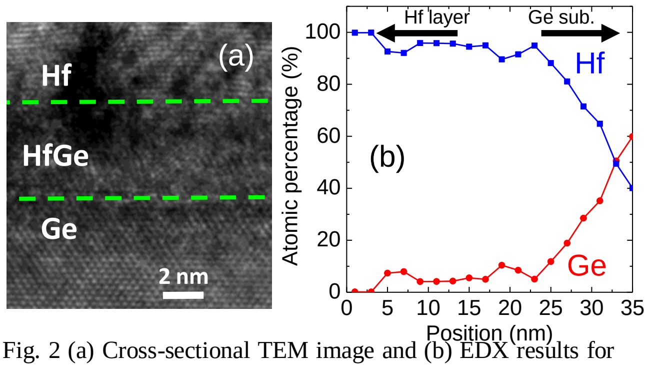

Fig. 2 (a) Cross-sectional TEM image and (b) EDX results for HfGe/Ge contact. This sample was not done any annealing.

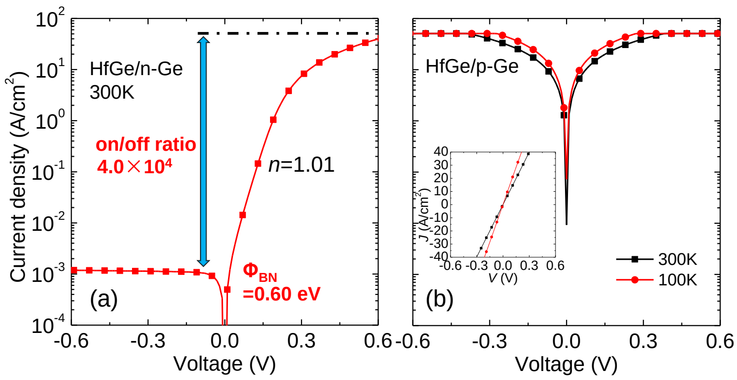

Fig. 3 *J-V* characteristics of (a) HfGe/n-Ge and (b) HfGe/p-Ge contacts. The T_{PMA} for both samples was 500°C.

Table 1 Φ_{BN} and n values for HfGe/n-Ge contacts treated at various T_{PMA}s. The contact showed good thermal stability in the T_{PMA} range below 500 °C.

T_{PMA}	Φ_{BN}	n
300 ºC	0.609 eV	1.008
400 ºC	0.606 eV	1.011
500 ºC	0.599 eV	1.013

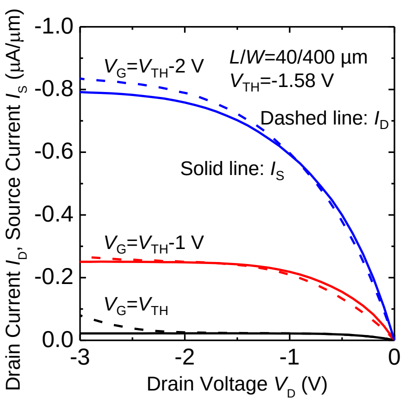

Fig. 4 I_D-V_D characteristics of fabricated Schottky p-MOSFET. The MOSFET works successfully thanks to low Φ_{BP}.

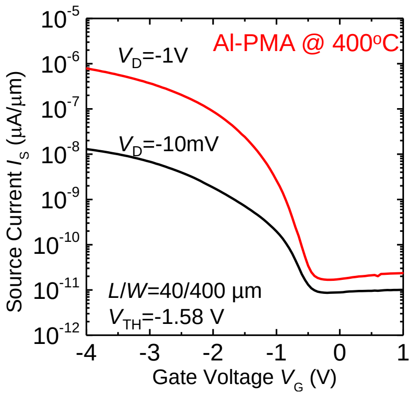

Fig. 5 I_S-V_G characteristics of fabricated Schottky p-MOSFET.

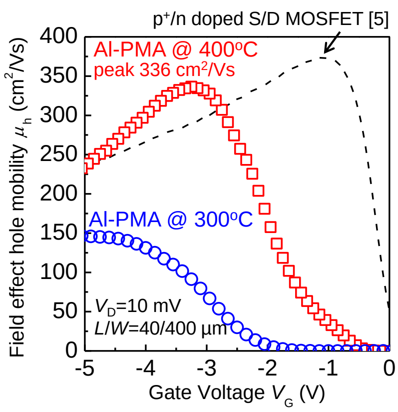

Fig. 6 Field effect mobility vs gate voltage for Ge Schottky p-MOSFET. Al-PMA at 400 °C is effective for the mobility enhancement [6]. The mobility is similar to our previous result from MOSFET with p^+ S/D (dashed line) [5].