InP(001)基板上に熱処理によって作製した MnP の構造、磁気、電気的物性

Structural, magnetic, and electrical properties of thermally-formed MnP electrodes on InP(001)

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A promising way to realize large spin-dependent characteristics of metal-oxide-semiconductor field-effect transistors (spin MOSFETs) [1] is to fabricate spin MOSFETs with a very short channel length. Recently, III-V-based MOSFETs with very short channel lengths were successfully fabricated by a self-align way [2], in which the most important two processes are i) to form metallic source/drain (S/D) electrodes by annealing of metal/III-V structures and ii) to etch un-reacted (unwanted) metal selectively after annealing. Thus, if ferromagnetic S/D electrodes are formed by these processes, we can fabricate III-V-based spin MOSFETs with a very short channel length.

Here, we report structural, magnetic, and electrical properties of $Mn_{1-x}P_x$ alloy electrodes formed by annealing of Mn/InP(001) structures. To realize spin MOSFETs by a self-align way, following issues were investigated; formation of ferromagnetic MnP with orthorhombic crystalline structure, selective etching of residual Mn and unwanted $Mn_{1-x}P_x$ phases after annealing, and electrical stability of MnP/InP(001) Schottky junctions. We used n-type InP(001) wafers with a donor concentration of 1×10^{17} cm^{-3} as substrates. Under an ultra-high vacuum, 20-nm-thick Mn layers were deposited at room temperature on S-terminated substrates using a Knudsen cell. After exposed to air, the Mn/InP structures were annealed in a N_2 atmosphere at T_A (= 300, 350, 400, and 450°C) for t_A (= 5, 10, 30, and 60 min).

Figure 1 shows X-ray diffraction (XRD) patterns of the samples (T_A = 300, 350, 400, and 450°C, t_A = 60 min) obtained with the θ-2θ method: a ferromagnetic MnP (210) peak is clearly seen for all the samples, whereas a Mn_2P (201) peak is also seen for the samples with T_A = 300 and 350°C. After etching of all the samples with 7% HCl solution, the MnP (210) peak remained unchanged, whereas the unwanted Mn_2P (201) peak vanished. Only the MnP (210) peak was also detected for other HCl-etched samples (T_A = 400°C, t_A = 5, 10, 30 min) (not shown). Figure 2 shows magnetization per unit area (M) versus external magnetic field (H) measured at 10 K for HCl-etched samples (T_A = 400°C, t_A = 5 and 60 min), where the direction of H was parallel to the in-plane [110]InP. The hysteretic loops in Fig. 2 for both the samples indicate ferromagnetic properties, and very similar loops were also obtained for other HCl-etched samples (T_A = 400°C, t_A = 10 and 30 min). Temperature dependence of spontaneous magnetization for all the sample (T_A = 400°C) showed Brillouin function-like shapes with the Curie temperature of ~ 300 K, and clear hysteretic loops were also confirmed at 280 K. Figure 3 shows current density-voltage (J-V) characteristics at room temperature of Schottky junction diodes of the samples (T_A = 400°C, t_A = 5 and 60 min), and the inset shows the cross-sectional device structure and the forward bias geometry. Since the J-V characteristics did not vary in the same sample (T_A = 400°C, t_A = 5, 10, 30, and 60 min), the MnP/InP junctions were found to be electrically stable. Whereas the J-V characteristics were the same for the samples (t_A = 10, 30, and 60 min), J is smaller for the sample (t_A = 5 min). Although further study is needed, the Schottky barrier height seems to be low (~0.3 eV) for electrons in the samples (t_A = 10, 30, and 60 min). In summary, the MnP formed with T_A = 400°C, and t_A (= 10, 30, and 60 min) are promising for the application to InP-based spin MOSFETs with a short channel length.

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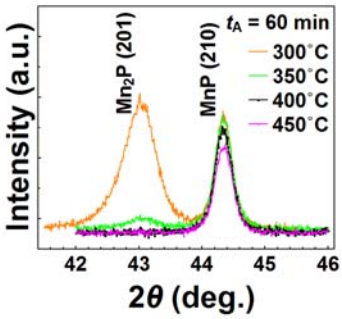

Fig. 1. XRD patterns of annealed Mn/InP(001) with t_A = 60 min and T_A = 300, 350, 400, and 450°C before etching.

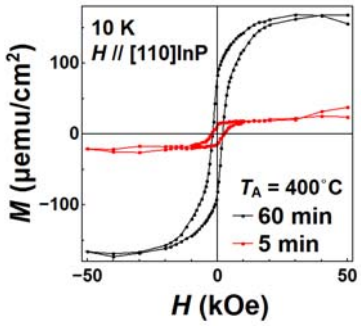

Fig. 2. Magnetic moment per unit area (M) vs. in-plane magnetic field measured at 10 K of the samples formed with T_A = 400°C, t_A = 5 and 60 min, after etching with HCl.

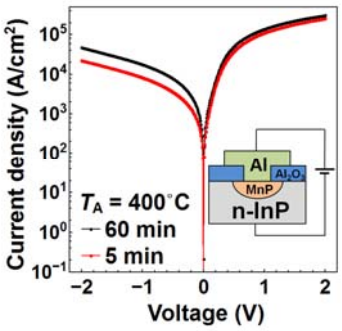

Fig. 3. I-V characteristics of MnP/n-InP diodes in the samples formed with T_A = 400°C, t_A = 5 and 60 min.