I-2-02
Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp605-606

Current-in-plane spin-valve magnetoresistance in ferromagnetic semiconductor (Ga,Fe)Sb heterostructures with high Curie temperature

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Abstract

We demonstrate spin-valve magnetoresistance (MR) with a current-in-plane (CIP) configuration in (Ga,Fe)Sb / InAs (thickness t_{InAs} nm) / (Ga,Fe)Sb trilayer heterostructures, where (Ga,Fe)Sb is a ferromagnetic semiconductor (FMS) with high Curie temperature (T_C). An MR curve with an open minor loop is clearly observed at 3.7 K in a sample with t_{InAs} = 3 nm, which originates from the parallel – antiparallel magnetization switching of the (Ga,Fe)Sb layers and spin-dependent scattering at the (Ga,Fe)Sb / InAs interfaces. The MR ratio increases (from 0.03 to 1.6 %) with decreasing t_{InAs} (from 9 to 3 nm) due to the enhancement of the interface scattering. This is the first demonstration of the spin-valve effect in Fe-doped FMS heterostructures, paving the way for device applications of these high T_C FMSs.

1. Introduction

Ferromagnetic semiconductors (FMSs) which show both ferromagnetic and semiconducting characteristics are promising materials for future spintronics applications. To realize practical devices, both p-type and n-type FMSs with high Curie temperature (T_C > 300 K) are required, but (Ga,Mn)As and (In,Mn)As, which have been vigorously studied, show only p-type with $T_C \simeq$ 200 K [1]. On the other hand, we have successfully grown Fe-doped FMSs; p-type (Ga,Fe)Sb with $T_C \simeq$ 340 K [2] and n-type (In,Fe)Sb with $T_C \simeq$ 335 K [3], which are promising for devices operating at room temperature. One of the important steps towards practical applications is to realize spin-valve effects in heterostructures containing Fe-doped FMSs.

2. Experiments and Results

In this work, we demonstrate the spin-valve effect with a current-in-plane (CIP) configuration using high-T_C Fe-doped FMS (Ga,Fe)Sb heterostructures with $T_C \simeq$ 260 K. The detailed structure consists of ($Ga_{0.75}$,$Fe_{0.25}$)Sb (40 nm) / InAs (thickness t_{InAs} = 0, 3, 6, 9 nm for sample A, B, C, D, respectively) / ($Ga_{0.8}$,$Fe_{0.2}$)Sb (40 nm) grown by low temperature molecular beam epitaxy (LT-MBE). The small lattice mismatch (~0.1%) between InAs and (Ga,Fe)Sb enables epitaxial growth of high-quality heterostructures, which is confirmed from the streaky patterns of *in situ* reflection high-energy electron diffraction (RHEED) [Fig 1(a)-(c)]. Furthermore, InAs / (Ga,Fe)Sb is a type-III heterostructure, i.e., the conduction band bottom of InAs is lower than the valence band top of (Ga,Fe)Sb at the interface [Fig. 1(d)]. This staggered band profile allows large penetration of the electron wavefunction in InAs into the (Ga,Fe)Sb side, leading to a strong interfacial magnetic proximity effect (MPE) [4].

The samples are patterned into Hall bar devices with a size of $100 \times 400\ \mu m^2$ using standard photolithography and Ar ion milling. Magneto-transport measurements are performed by a four-point-probe method, with a current flown in the film plane and a magnetic field $\boldsymbol{H}$ applied perpendicular to the film plane [Fig. 1(e)]. In these structures, the current is expected to flow mainly in InAs because the Fermi level is pinned in the band-gap of (Ga,Fe)Sb layers due to the formation of Fe-related impurity band, as shown in Fig. 1(d) [5].

Fig. 2(a) shows magnetoresistance (MR) curves of all the samples measured at 3.7 K. The MR ratio is defined as $(R - R_{min})/R_{min}$, where R_{min} is the minimum value of the resistance R. A spin-valve-like MR, which is dominant at low magnetic field, is superimposed with a background MR, which almost linearly depends on the magnetic field and has a positive or negative slope depending on t_{InAs}. For sample B (t_{InAs} = 3 nm), only the spin-valve-like MR is observed. The positive and negative background MRs are attributed to the proximity MR due to the MPE reported in (Ga,Fe)Sb / InAs bilayer [4] and to the enhanced orbital MR in magnetic columnar systems due to the Fe fluctuation in heavily Fe-doped (Ga,Fe)Sb [6], respectively.

To estimate the spin-valve MR signal, we define the spin-valve MR ratio $MR_{SV} \equiv (R_{max} - R_{min})/R_{min}$ where R_{max} (R_{min}) represents the maximum (minimum) value of R after excluding the background MR. The MR_{SV} due to the spin-valve effect becomes larger (from 0.03 to 1.6%) with decreasing t_{InAs} (from 9 to 3 nm), as shown in Fig. 2(b). The increase of MR_{SV} clearly reflects the enhancement of the spin-dependent interface scattering with decreasing the thickness of the conducting InAs layer. MR_{SV} of sample B reaches 1.6%, which is an order of magnitude larger than the previous studies of spin-valve MR with a CIP configuration based on (Ga,Mn)As [7].

We show in the upper panel of Fig. 2(c) detailed results of major loop and minor loop measurements of the spin-valve MR_{SV} in sample B (t_{InAs} = 3 nm) at 3.7 K. A clear spin-valve effect with an MR ratio of ~ 1.6% with an open minor loop is observed, which indicate that the parallel (P) and antiparallel (AP) magnetization configurations of the top and bottom (Ga,Fe)Sb can be stably established. The coercive forces of the magnetization characteristics obtained with Anomalous Hall effect (AHE) and superconducting quantum interference device (SQUID) magnetometry coincide with the peaks of the MR, which supports our conclusion that the MR_{SV} results from the P-AP magnetization switching of the (Ga,Fe)Sb layers. The realization of resistance change in the P and AP configurations is an important milestone for non-volatile spin-device applications of (Ga,Fe)Sb.

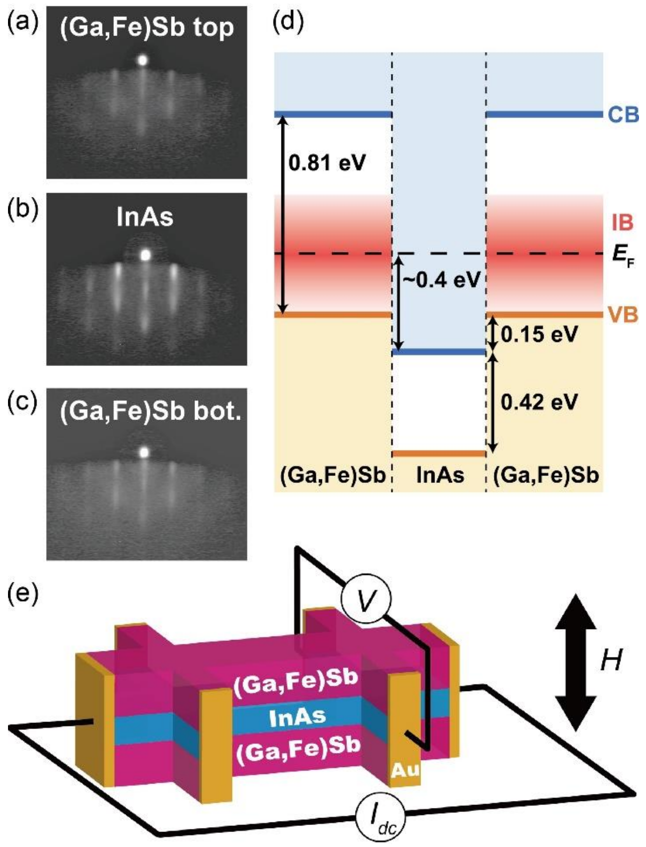

Fig. 1 (a)-(c) Reflection high-energy electron diffraction (RHEED) patterns taken along the $[\bar{1}10]$ azimuth during the MBE growth of sample C (t_{InAs} = 6 nm). (d) Schematic band alignment of the (Ga,Fe)Sb / InAs / (Ga,Fe)Sb heterostructures. CB, IB, VB denote the conduction band, Fe-related impurity band, and valence band. The impurity band lies in the bandgap of the heavily Fe-doped (Ga,Fe)Sb, as shown by the gradient-red color. The Fermi level E_F is pinned at 0.5 – 0.6 eV below the conduction band bottom of the (Ga,Fe)Sb. (e) Schematic device structure and measurement configuration of the Hall bar devices with a size of $100 \times 400\ \mu m^2$.

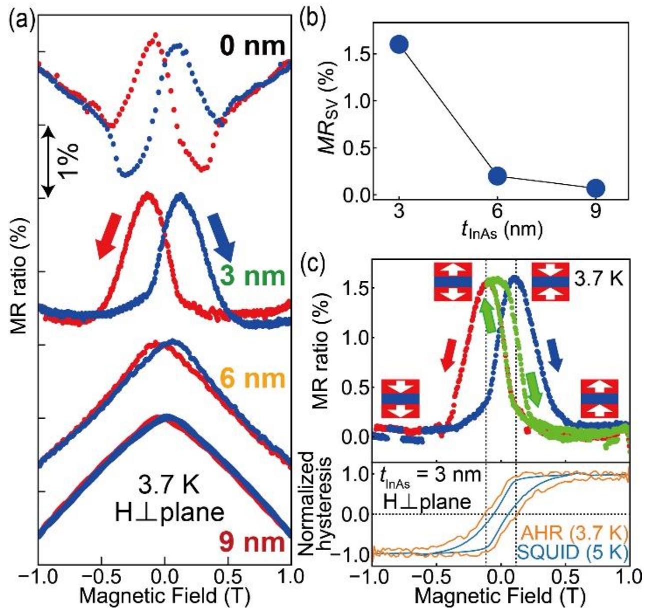

Fig. 2. (a) MR curves of samples A – D (t_{InAs} = 0, 3, 6, 9 nm) measured at 3.7 K with a magnetic field ***H*** applied perpendicular to the film plane. The red and blue curves are the major loops with magnetic-field sweeping directions of + to – and – to +, respectively. (b) Dependence of MR_{SV} on t_{InAs}. (c) Detailed results of major loop and minor loop (green curve) measurements of the spin-valve MR_{SV} (upper panel) and the corresponding magnetization hysteresis (lower panel) in sample B (t_{InAs} = 3 nm) at 3.7 K.

3. Conclusions

We have demonstrated a clear MR (~1.6%) due to the spin-valve effect in trilayer heterostructures containing high-T_C FMS (Ga,Fe)Sb. From the major loop and minor loop MRs, we concluded the origin of the observed MRs is the spin-valve effect that originates from the spin-dependent scattering at the (Ga,Fe)Sb/InAs interfaces. The MR ratio increases (from 0.03 to 1.6%) with decreasing t_{InAs} (from 9 to 3 nm). The demonstration of the spin-valve effect in Fe-doped FMSs in this work is the first important step towards device applications of the high-T_C FMS.

Acknowledgements

This work was supported by JSPS KAKENHI (Grant Nos. 16H02095, 17H04922, 18H05345, and 19K21961), CREST (No. JPMJCR1777) and PRESTO (No. JPMJPR19LB) Programs of JST. Part of this work was carried out under the support of Spintronics Research Network of Japan (Spin-RNJ).

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