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Exchange-biased ferromagnetic electrodes and their application to complementary spin transistors

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Exchange biased $Co_{84}Fe_{16}/Ir_{22}Mn_{78}$ bilayers are designed for controlling the magnetization direction of ferromagnetic source and drain in the spin field effect transistor. Depending on the applied field direction during the sputtering, two different orientations of exchange bias fields, +35.5 mT and −36.3 mT are obtained. Using these $Co_{84}Fe_{16}/Ir_{22}Mn_{78}$ electrodes, two types of spin transistors, which have roles of *n* and *p*-type transistors in the conventional complementary scheme, are implemented. Using the parameters extracted from experimental data, the complementary inverter operation is also presented.

1. Introduction

The spin field effect transistor (spin-FET), proposed by Datta and Das [1], is one of the most attractive concepts for the next generation devices due to low power consumption, high speed, and nonvolatility. The main mechanism of spin-FET is that the spin orientation is modulated by a gate electrode in a semiconductor channel. In this device, the spin-polarized current is injected from a ferromagnetic source and detected by the other ferromagnetic drain. While traveling spin polarized current from the injector to the detector in a semiconductor quantum well, the spin precession angle is decided by Rashba field which is controlled by a gate electric field [1,2].

In the previous research, gate control of spin orientation has been experimentally illustrated in an InAs-based quantum well layer [2]. In order to obtain spin precession, the spin orientation of injected electrons should be perpendicular to the Rashba effective field so the magnetization direction of source and drain should be carefully selected. The previous research showed the spin-FET operation modulated by the gate electric field, but it needs an external magnetic field to set the magnetization of ferromagnetic electrode. In this research, we utilizes an exchange bias field for the source and drain electrodes to remove the applied magnetic field.

2. Device structure and experimental technique

The moving electrons with an electric field produce the Rashba effective magnetic field which is driving force of spin precession in a spin-FET. In our channel, the quantum well is asymmetric, so the intrinsic electric field arises in *z*-direction. Fig. 1(a) shows a cross-sectional view of an InAs quantum well structure grown by molecular beam epitaxy. The InAs active layer is surrounded by $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ double cladding layers. Because the carrier supply layer is located below the active layer, the asymmetry potential gradient is induced along the growth direction, *z*. We confirmed an internal electric field inside the quantum well by performing band calculations as shown in Fig. 1(a) [3]. This electric field results in the strong spin–orbit interaction effect, so-called Rashba effect.

For realizing spin-FET, the prerequisite is that the Rashba effect is modulated by applying a gate electric field as shown in Fig. 1(b) [1,2]. The spins injected by a ferromagnetic source (S) flow along the *x*-axis process around the Rashba magnetic field (B_R) which is induced along the *y*-axis. The channel resistance is determined by the vector alignment between spin orientation of electrons arriving at the ferromagnetic drain (D) and the magnetization direction of the drain. If the alignment of two vectors is parallel (anti-parallel), the channel conductance is high (low). The factors to determine the

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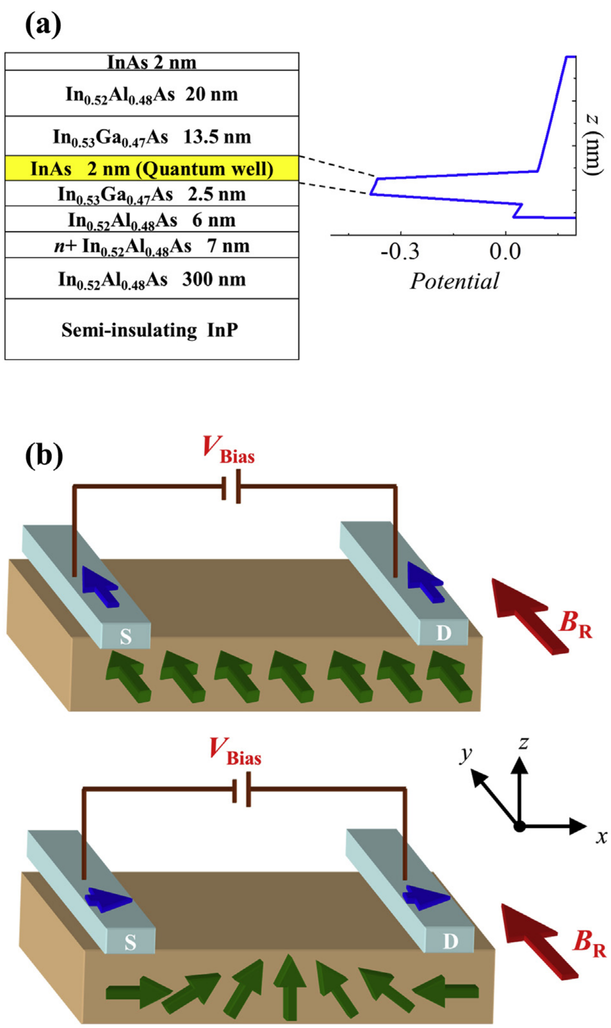

Fig. 1. (a) Cross section of an InAs quantum well channel. Energy diagram shows the asymmetric quantum well which induces an intrinsic electric field and a Rashba effective field. (b) Schematic geometry of spin transistors as a function of the magnetization direction of the ferromagnetic electrodes. The injected spin orientation is parallel (top) or perpendicular (bottom) to the Rashba field.

magnetization direction of the ferromagnetic electrode (FM) are shape and crystalline anisotropies. Considering shape anisotropy, the longer axis of the pattern is easy axis of magnetization. To minimize the channel length, the structure shown in the top of Fig. 1(b) is usually adopted for the lateral spin valve measurement. In this case, the magnetization direction of source and drain is along the y-axis, so spin precession does not occur due to the parallel alignment of FM magnetization and the Rashba field [2]. When, however, the magnetization direction of source and drain is in the x-direction, the injected spins process around the axis of the Rashba field (Fig. 1(b) bottom) [2,4]. Subsequently, control of spin orientation is possible by adjusting the gate electric field.

In order to align the FM along the x-axis, we utilized an exchange bias field of ferromagnet/antiferromagnet bilayer of $Co_{84}Fe_{16}/Ir_{22}Mn_{78}$ [5–9]. The thicknesses of $Co_{84}Fe_{16}$ and $Ir_{22}Mn_{78}$ are 3 nm and 7 nm, respectively. A nonmagnetic Au film of 50 nm is deposited for a capping layer. To obtain the different directions of the exchange bias field, we applied magnetic fields of +20 mT and −20 mT Oe along the x-axis ($B_{sputter,x}$) as shown in Fig. 2(a). The magnetization direction of ferromagnetic $Co_{84}Fe_{16}$ is controlled by the external field direction during the sputtering. The first layer of

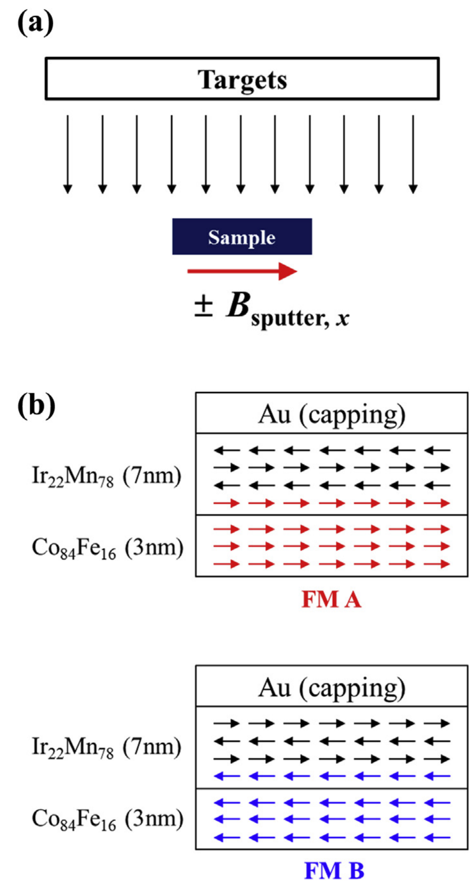

Fig. 2. (a) Fabrication of $Co_{84}Fe_{16}/Ir_{22}Mn_{78}$ bilayers. (b) Magnetization vectors of $Co_{84}Fe_{16}/Ir_{22}Mn_{78}$ bilayers.

$Ir_{22}Mn_{78}$ has the same magnetization direction as $Co_{84}Fe_{16}$ due to the ferromagnetic coupling. Above the second layer the $Ir_{22}Mn_{78}$ has the alternative magnetization direction due to the antiferromagnetic coupling as shown in Fig. 2(b). These antiferromagnetic coupling makes the ferromagnetic layer remain the magnetization direction even without an applied magnetic field. Fig. 2(b) shows magnetization vectors of the bilayers, which expect the FMs A and B have opposite signs of exchange bias fields. The sign control of exchange bias is very useful to fix the magnetization direction even without an applied magnetic field.

3. Results and discussion

The magnetization behaviors of $Co_{84}Fe_{16}/Ir_{22}Mn_{78}$ bilayers were measured using alternating gradient magnetometer (AGM) as shown in Fig. 3. The hysteresis curves are shifted due to the exchange bias whose sign is determined by the orientation of the applied magnetic field during the sputtering ($B_{sputter,x}$). The ferromagnet/anti-ferromagnet bilayers have +35.5 mT and −36.3 mT of exchange bias fields for FMs A and B, respectively, at room temperature. Thus, we can control the orientations of exchange bias as well as magnetization easy axis. Usually, annealing with an external magnetic field is needed for initializing the magnetization of $Co_{84}Fe_{16}$ and $Ir_{22}Mn_{78}$ [5–9], but any heating process is not required in our fabricaton. Thus, our method would exclude the sample damage from the high temperature treatments.

In the field of semiconductor technology, complementary metal oxide semiconductor (CMOS) is the most popular scheme due to the low power logic operation. To implement complementary operation, a p-type and an n-type MOS transistors are currently