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Internal electric field influence on tunneling anisotropic magnetoresistance in epitaxial ferromagnet/n-GaAs junctions

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A strong voltage-dependent tunneling anisotropic magnetoresistance (TAMR) effect was observed in a fully epitaxial Co2MnSi/n-GaAs junction and a Co50Fe50/n-GaAs junction. Angular dependence of the TAMR effect showed uniaxial-type anisotropic tunnel resistance between the [110] and [1 1 0] directions in the (001) plane. The voltage at which the TAMR effect was suppressed was close to that at which the differential conductance reached a minimum in both samples, suggesting that the strength and/or the sign of the internal electric field at the Co2MnSi/n-GaAs and Co50Fe50/n-GaAs junctions could be related to the voltage-dependent TAMR effect through spin-orbit interaction. © 2010 American Institute of Physics. [doi:10.1063/1.3456558]

Spin-injection into semiconductors (SCs) has attracted much interest for future-generation spintronic devices, such as spin transistors and spin light-emitting diodes. In these devices, ferromagnet (F)/SC heterojunctions are used to create and detect a spin-polarized state in SCs. Thus, it is important to clarify spin-dependent transport properties of F/SC junctions. Recently, a tunneling anisotropic magnetoresistance (TAMR) effect, in which the tunnel resistance changes depending on the magnetization direction of the F with respect to the crystal axis, was observed in F/SC junctions. Moser et al. observed uniaxial-type anisotropy of the tunnel resistance with respect to the in-plane magnetization due to the TAMR effect in Fe/GaAs/Au vertical junctions. We also observed the TAMR effect in both single Co90Fe10/n-GaAs Schottky junctions and lateral Co50Fe50/n-GaAs/Co50Fe50 junctions consisting of two Co50Fe50/n-GaAs Schottky junctions and found that the TAMR effect possibly affects the transport properties of SC spintronic devices consisting of F/SC heterostructures, such as spin transistors.

One Co-based Heusler alloy, Co2MnSi, is a promising candidate material for the ferromagnetic electrodes of spintronic devices because it is theoretically predicted to be half-metallic and has a high Curie temperature of 985 K. We recently developed fully epitaxial magnetic tunnel junctions (MTJs) with either a Co2MnSi thin film as a lower or upper electrode or Co2MnSi thin films as both lower and upper electrodes, with a MgO barrier in both cases, and demonstrated high tunnel magnetoresistance (TMR) ratios of up to 1135% at 4.2 K and 236% at room temperature (RT), indicating that Co2MnSi has high spin polarization. In order to apply Co2MnSi to a ferromagnetic electrode as an efficient spin injector into SCs, the basic transport properties of Co2MnSi/SC heterojunctions should be clarified. In this study, we investigated the bias-voltage dependence of the TAMR effect in both Co2MnSi/n-GaAs and Co50Fe50/n-GaAs single junctions, and found that the voltage at which the TAMR effect was suppressed was close to that at which the differential conductance reached a minimum in both Co2MnSi/n-GaAs and Co50Fe50/n-GaAs junctions; this suggests that the strength and/or the sign of the internal electric field at the Co2MnSi/n-GaAs and Co50Fe50/n-GaAs junctions possibly affects the voltage-dependent TAMR effect through the spin-orbit interaction (SOI).

Layer structures consisting of (from the substrate side) undoped GaAs (50 nm)/n+-GaAs (Si=2×1016 cm−3, 750 nm)/n−-GaAs (Si=3×1018 cm−3, 30 nm) were grown by molecular beam epitaxy at 580 °C on a GaAs(001) substrate. This layer structure was similar to that described in Ref. 12, where electrical spin injection and detection using an Fe electrode were reported. The n+-GaAs layer was inserted to reduce the Schottky barrier width, so that the tunnel conductance was dominant. The sample was then capped with an arsenic protective layer and transported to an ultrahigh-vacuum magnetron-sputtering chamber with a base pressure of about 6×10−8 Pa. Prior to the growth of the F, the arsenic cap was removed by heating the sample to 400 °C. A 20-nm-thick Co2MnSi film or a 20-nm-thick Co50Fe50 film was grown by magnetron sputtering at RT. The Co2MnSi film was in situ annealed at 350 °C for 15 min. right after the deposition of the Co2MnSi film. The magnetoresistance (MR) and differential conductance (G=dI/dV) of Co2MnSi/n-GaAs junctions were measured at 4.2 K by the conventional four-probe method. The bias-voltage was defined with respect to the n-GaAs.

X-ray pole figure measurements confirmed that both Co50Fe50 and Co2MnSi thin films were epitaxially grown on the GaAs with a cube-on-cube relation. Thus, the crystal axis direction described hereafter is common between Co2MnSi and Co50Fe50 and GaAs, and between Co2MnSi and GaAs. Figure 1 shows a polar plot of the junction resistance at 4.2 K for a Co2MnSi/n-GaAs junction under a magnetic field of H=3000 Oe. A bias voltage of −0.05 V was applied to the Co2MnSi electrode. The polar angle in Fig. 1, which indicates the direction of H with respect to the [1 1 0] direction of the Co2MnSi, corresponds to the direction of the magnetization of the Co2MnSi, because the magnetization was forced to align along the direction of H under the sufficiently large field of 3000 Oe. The figure clearly shows uniaxial-type anisotropic resistance with respect to the in-plane magnetization direction. The resistance value took the maximum when the magnetization was oriented to the [110] or [1 1 0] direc-

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tion and the minimum when the magnetization was oriented to the [110] or [110] direction. We will define $R_{110}$ and $R_{110}$ as the resistance for $M\parallel[110]$ and $M\parallel[110]$. The current-voltage characteristics of the Co$_{2}$MnSi/n-GaAs junctions show that the tunnel resistance for the Schottky barrier formed at the Co$_{2}$MnSi/n-GaAs interface was dominant in the junction resistance compared with that of the Co$_{2}$MnSi electrode or the n-GaAs. Thus, the observed anisotropic resistance was due to the TAMR effect rather than an anisotropic magnetoresistance effect of the Co$_{2}$MnSi electrode or a local Hall effect in the n-GaAs due to a stray field from the Co$_{2}$MnSi electrode. Similar uniaxial-type anisotropy in the tunnel resistance was observed in Co$_{50}$Fe$_{50}$/n-GaAs junctions$^{5}$ and Fe/GaAs/Au junctions.$^{4}$

Figures 2(a) and 2(b) show the bias-voltage dependence of the MR ratio ($r$) for both Co$_{2}$MnSi/n-GaAs and Co$_{50}$Fe$_{50}$/n-GaAs junctions. Here, $r$ is defined by $(R_{110} - R_{110})/R_{110}$. Positive $r$ corresponds to $R_{110} > R_{110}$, and negative $r$ corresponds to $R_{110} < R_{110}$. We obtained $r > 0$ for $V < 0$ V and $r > 0$ for $V > 0$ V for a Co$_{2}$MnSi/n-GaAs junction, and obtained $r > 0$ for $V < +0.2$ V and $r < 0$ for $V > +0.2$ V for a Co$_{50}$Fe$_{50}$/n-GaAs junction. The zero-crossing voltage ($V_0$), where the sign of $r$ changes from positive to negative or vice versa, was approximately 0 V for the Co$_{2}$MnSi/n-GaAs junction and +0.2 V for the Co$_{50}$Fe$_{50}$/n-GaAs junction. These results indicate that both the magnitude and sign of $r$ were dependent on both the bias-voltage and the ferromagnetic electrode material.

Figures 2(c) and 2(d) show the G-V characteristics for Co$_{2}$MnSi/n-GaAs and Co$_{50}$Fe$_{50}$/n-GaAs junctions. We observed almost symmetric G-V characteristics regarding the bias polarity for a Co$_{2}$MnSi/n-GaAs junction and asymmetric G-V characteristics for a Co$_{50}$Fe$_{50}$/n-GaAs junction. Importantly, the voltage for the $G$ minimum ($V_{\text{min}}$) was almost equal to $V_0$ for both samples. This indicates that the strength and/or the sign of the internal electric field at F/n-GaAs junctions possibly relates to the voltage-dependent TAMR effect as will be discussed later.

We will now discuss the origin of the bias-voltage dependence of $r$ shown in Figs. 2(a) and 2(b). The complex bias-voltage dependence of $r$ in terms of its sign and magnitude can be explained in terms of two following features: (a) $|r|$ decreases monotonically with increasing $|V|$ for both polarities of $V$ and (b) $r$ is zero-crossing at $V=V_0$. For the Co$_{50}$Fe$_{50}$/n-GaAs junction, $V_0$ is approximately 0.2 V, so $r$ reached the maximum at $V=0$ V due to (a) and its sign changed at $V=V_0$ (=0.2 V) due to (b). For the Co$_{2}$MnSi/n-GaAs junction, $V_0=0$ V, so features (a) and (b) were competing at $V=0$ V, resulting in $|r|$ reaching the maximum at $V=\pm 60$ mV instead of 0 V. Feature (a) is similar to that observed in the bias-voltage dependence of the TMR ratio of MTJs.$^{13,15}$ and its origin is possibly related to some spin scattering through magnon excitation or caused by magnetic impurities during tunneling or a two-step tunneling process as is the case for MTJs.

We next consider the origin of feature (b). Positive (negative) $r$ means that $R_{110}$ is larger (smaller) than $R_{110}$ from its definition. Recently, a theoretical model based on the combination of Rashba and Dresselhaus SOIs was proposed to explain the origin of the anisotropy of tunnel resistance observed in a Fe/GaAs/Au junction.$^{4,16,17}$ We applied this model to the tunnel resistance of the Co$_{2}$MnSi/n-GaAs and Co$_{50}$Fe$_{50}$/n-GaAs junctions. The Hamiltonian for both the Rashba and Dresselhaus SOIs is given by

$$H_{\text{SO}} = \alpha(\sigma_xk_x - \sigma_yk_y) + \beta(\sigma_xk_x - \sigma_yk_y) \equiv w(k_x,k_y) \cdot \sigma,$$

where $\alpha$ and $\beta$ are the effective Rashba and Dresselhaus parameters; $\sigma=(\sigma_x,\sigma_y,\sigma_z)$ are the Pauli spin matrices; $k_x, k_y$ are the electron wave vector components, and $w=(ak_x + \beta k_y, -ak_y - \beta k_x, 0)$ is the SOI-induced effective magnetic field. Here, the $x$-axis and $y$-axis are, respectively, set to the [100] and [010] direction, and the $z$-axis is set to the tunneling direction. Because of the anisotropy of $w$ in the $k_z=-k_y$, the spin-orbit parameters are modified as

$$\alpha' = \alpha + \beta k_y, \quad \beta' = \beta - \alpha k_y,$$

where $\alpha'$ and $\beta'$ are the modified Rashba and Dresselhaus parameters, respectively.
space, the tunneling probability of an electron depends on its initial spin orientation, resulting in the anisotropy of tunnel resistance between $R_{110}$ and $R_{110}$. The difference between $R_{110}$ and $R_{110}$ is then given by

$$R_{110} - R_{110} = C \alpha \beta,$$

(2)

where $C$ is a proportionality coefficient related to the averaged Fermi wave number. Since $\alpha$ is proportional to the strength of the $z$-component of the electric field at the $F/n$-GaAs interface, the sign as well as its magnitude would be voltage-dependent. Thus, one can explain the sign change in $r$ at $V = V_0$ if $\alpha$ is zero-crossing at $V = V_0$.

Given this model, the internal electric field becomes zero at $V = V_0$ because $\alpha = 0$ at $V = V_0$. This means that the flat-band voltage ($V_{FB}$) is equal to $V_0$. Then, we assumed that the Co$_2$MnSi/n-GaAs junction has a symmetric potential (i.e., $V_{FB} = 0$ V), and that the Co$_5$Fe$_5$0/n-GaAs junction has a trapezoidal potential with $V_{FB} = 0.2$ V, as shown in the insets of Figs. 2(a) and 2(b). Under these assumptions, we discuss the relation between $V_0$ (i.e., $V_{FB}$) and $V_{min}$, which is the voltage at which the differential conductance reaches a minimum. According to Brinkman’s formula, $V_{FB}$ is related to $V_{min}$ as follows:

$$V_{FB} \approx \left( - \frac{2}{3} \ln T \right)^{-1} V_{min},$$

(3)

where $T$ is the tunneling probability of electrons under the flat-band condition. Since $V_{FB} = V_0$, $V_0$ is proportional to $V_{min}$, whose proportionality coefficient (i.e., $[-2/3 \ln T]^{-1}$) is positive. We found experimentally that $V_0$ was almost equal to $V_{min}$ for both Co$_2$MnSi/n-GaAs and Co$_5$Fe$_5$0/n-GaAs junctions, as shown in Figs. 2(a)–2(d). This result is consistent with Eq. (3). Although the tunneling probability $T$ for the Co$_2$MnSi/n-GaAs junction cannot be fitted by Eq. (3), because $V_{min} = 0$, $T$ for the Co$_5$Fe$_5$0/n-GaAs junction was fitted to be approximately 0.2, which is a reasonable value for electrons tunneling through a Schottky barrier. Thus, these experimental findings support the SOI-based model.

Last, we discuss the ferromagnetic materials dependence of the TAMR effect. Table I summarizes the value of $V_0$ and the sign of $dr/dV$ at $V = V_0$ for different systems. The sign of $r$ changed from negative to positive with increasing $V$ (or $dr/dV > 0$) for both the Co$_2$MnSi and Fe electrodes, while it changed from positive to negative for the Co$_5$Fe$_5$0 electrode with increasing $V$. Since the layer structures of the n-GaAs are the same between the Co$_2$MnSi/n-GaAs and the Co$_5$Fe$_5$0/n-GaAs, the difference in the TAMR characteristics between the samples in terms of the sign of $r$ was due to the difference of the ferromagnetic electrode material. If the sign of parameter $C$ in Eq. (2) depends on the ferromagnetic materials, one can explain the ferromagnetic material dependence of the MR ratio. To check the validity of this assumption, however, further theoretical and experimental investigations are necessary.

In summary, we observed the voltage-dependent TAMR effect in both Co$_2$MnSi/n-GaAs and Co$_5$Fe$_5$0/n-GaAs junctions, and found that the sign and/or the sign of the internal electric field at F/n-GaAs junctions are possibly related to the voltage-dependent TAMR effect through the SOI.

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**Table I. Summary of the voltage at which the TAMR effect was suppressed ($V_0$) and the sign of the derivative of the MR ratio at $V = V_0$ for different systems.**

<table>
<thead>
<tr>
<th>System</th>
<th>$V_0$ (mV)</th>
<th>Sign of $dr/dV$ at $V = V_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co$_2$MnSi/n-GaAs</td>
<td>0</td>
<td>Positive</td>
</tr>
<tr>
<td>Co$_5$Fe$_5$0/n-GaAs</td>
<td>200</td>
<td>Negative</td>
</tr>
<tr>
<td>Fe/GaAs/Au</td>
<td>50</td>
<td>Positive</td>
</tr>
</tbody>
</table>

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*Reference 4.
*Reference 5.