HOKKAIDO UNIVERSITY

Title	Internal electric field influence on tunneling anisotropic magnetoresistance in epitaxial ferromagnet/n-GaAs junctions
Author(s)	Uemura, Tetsuya; Harada, Masanobu; Matsuda, Ken-ichi; Yamamoto, Masafumi
Citation	Applied Physics Letters, 96(25), 252106 https://doi.org/10.1063/1.3456558
Issue Date	2010-06-21
Doc URL	http://hdl.handle.net/2115/43204
Rights	Copyright 2010 American Institute of Physics. This article may be downloaded for personal use only. Any other use requires prior permission of the author and the American Institute of Physics. The following article appeared in Appl. Phys. Lett. 96, 252106 (2010) and may be found at https://dx.doi.org/10.1063/1.3456558
Type	article
File Information	APL96-25_252106.pdf

Instructions for use

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

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

Tetsuya Uemura,[a)] Masanobu Harada, Ken-ichi Matsuda, and Masafumi Yamamoto
Division of Electronics for Informatics, Hokkaido University, Sapporo 060-0814, Japan

(Received 28 April 2010; accepted 2 June 2010; published online 24 June 2010)

A strong voltage-dependent tunneling anisotropic magnetoresistance (TAMR) effect was observed in a fully epitaxial Co_2MnSi/n-GaAs junction and a $Co_{50}Fe_{50}$/n-GaAs junction. Angular dependence of the tunnel resistance showed uniaxial-type anisotropic tunnel resistance between the $[110]$ and $[1\bar{1}0]$ 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 Co_2MnSi/n-GaAs and $Co_{50}Fe_{50}$/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[1,2] and spin light-emitting diodes.[3] 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.[4,5] Moser *et al.*[4] 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 $Co_{50}Fe_{50}$/n-GaAs Schottky junctions and lateral $Co_{50}Fe_{50}$/n-GaAs/$Co_{50}Fe_{50}$ junctions consisting of two $Co_{50}Fe_{50}$/n-GaAs Schottky junctions,[5] 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, Co_2MnSi, 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.[6,7] We recently developed fully epitaxial magnetic tunnel junctions (MTJs) with either a Co_2MnSi thin film as a lower electrode[8] or Co_2MnSi thin films as both lower and upper electrodes,[9–11] 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),[10,11] indicating that Co_2MnSi has high spin polarization. In order to apply Co_2MnSi to a ferromagnetic electrode as an efficient spin injector into SCs, the basic transport properties of Co_2MnSi/SC heterojunctions should be clarified. In this study, we investigated the bias-voltage dependence of the TAMR effect in both Co_2MnSi/n-GaAs and $Co_{50}Fe_{50}$/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 Co_2MnSi/n-GaAs and $Co_{50}Fe_{50}$/n-GaAs junctions; this suggests that the strength and/or the sign of the internal electric field at the Co_2MnSi/n-GaAs and $Co_{50}Fe_{50}$/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 ($Si=2\times10^{16}$ cm^{-3}, 750 nm)/n^+-GaAs ($Si=3\times10^{18}$ 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 conduction 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 Co_2MnSi film or a 20-nm-thick $Co_{50}Fe_{50}$ film was grown by magnetron sputtering at RT. The Co_2MnSi film was *in situ* annealed at 350 °C for 15 min. right after the deposition of the Co_2MnSi film. The magnetoresistance (MR) and differential conductance ($G\equiv dI/dV$) of Co_2MnSi/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 $Co_{50}Fe_{50}$ and Co_2MnSi thin films were epitaxially grown on the GaAs with a cube-on-cube relation. Thus, the crystal axis direction described hereafter is common between $Co_{50}Fe_{50}$ and GaAs, and between Co_2MnSi and GaAs. Figure 1 shows a polar plot of the junction resistance at 4.2 K for a Co_2MnSi/n-GaAs junction under a magnetic field of $H=3000$ Oe. A bias voltage of -0.05 V was applied to the Co_2MnSi electrode. The polar angle in Fig. 1, which indicates the direction of H with respect to the $[110]$ direction of the Co_2MnSi, corresponds to the direction of the magnetization of the Co_2MnSi, 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 $[\bar{1}\bar{1}0]$ direc-

[a)]Electronic mail: uemura@ist.hokudai.ac.jp.

 © 2010 American Institute of Physics

Downloaded 12 Jul 2010 to 133.87.26.199. Redistribution subject to AIP license or copyright; see http://apl.aip.org/apl/copyright.jsp

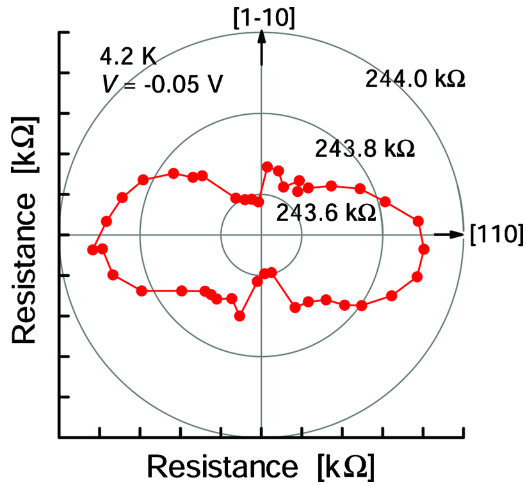

FIG. 1. (Color online) A polar plot of the junction resistance for a Co_2MnSi/n-GaAs junction at 4.2 K under $H=3000$ Oe. The polar angle is defined with respect to the [110] direction of the Co_2MnSi electrode.

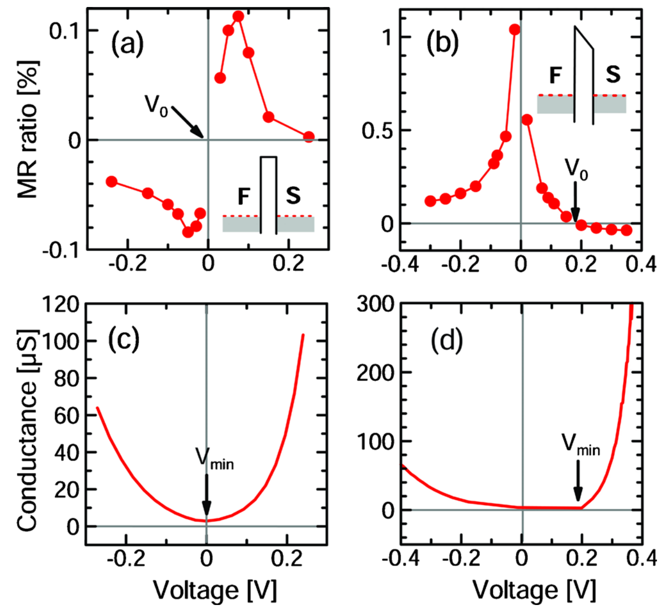

FIG. 2. (Color online) The bias-voltage dependence of (a) MR ratio for Co_2MnSi/n-GaAs, (b) MR ratio for $Co_{50}Fe_{50}$/n-GaAs, (c) differential conductance for Co_2MnSi/n-GaAs, and (d) differential conductance of $Co_{50}Fe_{50}$/n-GaAs. The MR ratio (r) was defined by $(R_{1\bar{1}0}-R_{110})/R_{110}$, where R_{110} and $R_{1\bar{1}0}$ stand for the tunnel resistance when the magnetization of the ferromagnetic electrode orients to the [110] and $[1\bar{1}0]$ directions, respectively. The insets of Figs. 2(a) and 2(b) indicate a sketch of the effective tunnel barrier at the F/n-GaAs junctions when $V=0$.

tion and the minimum when the magnetization was oriented to the $[1\bar{1}0]$ or $[\bar{1}10]$ direction. We will define R_{110} and $R_{1\bar{1}0}$ as the resistance for $M\|[110]$ and $M\|[1\bar{1}0]$, respectively. The current-voltage characteristics of the Co_2MnSi/n-GaAs junctions show that the tunnel resistance for the Schottky barrier formed at the Co_2MnSi/n-GaAs interface was dominant in the junction resistance compared with that of the Co_2MnSi 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_2MnSi electrode or a local Hall effect in the n-GaAs due to a stray field from the Co_2MnSi 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_2MnSi/n-GaAs and $Co_{50}Fe_{50}$/n-GaAs junctions. Here, r is defined by $(R_{1\bar{1}0}-R_{110})/R_{110}$. Positive r corresponds to $R_{1\bar{1}0}>R_{110}$, and negative r corresponds to $R_{1\bar{1}0}<R_{110}$. We obtained $r<0$ for $V<0$ V and $r>0$ for $V>0$ V for a Co_2MnSi/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_2MnSi/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_2MnSi/n-GaAs and $Co_{50}Fe_{50}$/n-GaAs junctions. We observed almost symmetric G-V characteristics regarding the bias polarity for a Co_2MnSi/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_{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 $V\approx 0$ V due to (a) and its sign changed at $V=V_0$ (=+0.2 V) due to (b). For the Co_2MnSi/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 $R_{1\bar{1}0}$ 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_2MnSi/n-GaAs and $Co_{50}Fe_{50}$/n-GaAs junctions. The Hamiltonian for both the Rashba and Dresselhaus SOIs is given by

$$H_{SO}=\alpha(\sigma_x k_y-\sigma_y k_x)+\beta(\sigma_x k_x-\sigma_y k_y)\equiv \boldsymbol{w}(k_x,k_y)\cdot\boldsymbol{\sigma}, \tag{1}$$

where α and β are the effective Rashba and Dresselhaus parameters; $\boldsymbol{\sigma}=(\sigma_x,\sigma_y,\sigma_z)$ are the Pauli spin matrices; k_x, k_y are the electron wave vector components, and $\boldsymbol{w}=(\alpha k_y+\beta_x k_x,-\alpha k_x-\beta k_y,0)$ 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 $\boldsymbol{w}$ in the k_x-k_y

Downloaded 12 Jul 2010 to 133.87.26.199. Redistribution subject to AIP license or copyright; see http://apl.aip.org/apl/copyright.jsp

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.

System	V_0 (mV)	Sign of dr/dt at $V=V_0$
Co_2MnSi/n-GaAs	0	Positive
$Co_{50}Fe_{50}$/n-GaAs [a]	200	Negative
Fe/GaAs/Au [b]	50	Positive

[a]Reference 4.
[b]Reference 5.

space, the tunneling probability of an electron depends on its initial spin orientation, resulting in the anisotropy of tunnel resistance between R_{110} and $R_{1\bar{1}0}$. The difference between R_{110} and $R_{1\bar{1}0}$ is then given by

$$R_{1\bar{1}0} - R_{110} = C\alpha\beta, \tag{2}$$

where C is a proportionality coefficient related to the averaged Fermi wave number.[17] Since α 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 α 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_2MnSi/n-GaAs junction has a symmetric potential (i.e., $V_{FB}=0$ V), and that the $Co_{50}Fe_{50}$/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:[18]

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

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_2MnSi/n-GaAs and $Co_{50}Fe_{50}$/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_2MnSi/n-GaAs junction cannot be fitted by Eq. (3), because $V_{min}=0$, T for the $Co_{50}Fe_{50}$/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_2MnSi and Fe electrodes, while it changed from positive to negative for the $Co_{50}Fe_{50}$ electrode with increasing V. Since the layer structures of the n-GaAs are the same between the Co_2MnSi/n-GaAs and the $Co_{50}Fe_{50}$/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_2MnSi/n-GaAs and $Co_{50}Fe_{50}$/n-GaAs junctions, and found that the strength 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.

This work was partly supported by Grants-in-Aid for Scientific Research (Grant Nos. 20246054 and 21360140), and a Grant-in-Aid for Scientific Research on Priority Area "Creation and control of spin current" (Grant No. 19048001), from the MEXT, Japan.

[1]S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
[2]S. Sugahara and M. Tanaka, Appl. Phys. Lett. **84**, 2307 (2004).
[3]A. T. Hanbicki, O. M. J. van't Erve, R. Magno, G. Kioseoglou, C. H. Li, B. T. Jonker, G. Itskos, R. Mallory, M. Yasar, and A. Petrou, Appl. Phys. Lett. **82**, 4092 (2003).
[4]J. Moser, A. Matos-Abiague, D. Schuh, W. Wegscheider, J. Fabian, and D. Weiss, Phys. Rev. Lett. **99**, 056601 (2007).
[5]T. Uemura, Y. Imai, M. Harada, K.-i. Matsuda, and M. Yamamoto, Appl. Phys. Lett. **94**, 182502 (2009).
[6]S. Ishida, S. Fujii, S. Kashiwagi, and S. Asano, J. Phys. Soc. Jpn. **64**, 2152 (1995).
[7]P. J. Webster, J. Phys. Chem. Solids **32**, 1221 (1971).
[8]T. Ishikawa, T. Marukame, H. Kijima, K.-i. Matsuda, T. Uemura, and M. Yamamoto, Appl. Phys. Lett. **89**, 192505 (2006).
[9]T. Ishikawa, S. Hakamata, K.-i. Matsuda, T. Uemura, and M. Yamamoto, J. Appl. Phys. **103**, 07A919 (2008).
[10]T. Ishikawa, H.-x. Liu, T. Taira, K.-i. Matsuda, T. Uemura, and M. Yamamoto, Appl. Phys. Lett. **95**, 232512 (2009).
[11]M. Yamamoto, T. Ishikawa, T. Taira, G.-f. Li, K.-i. Matsuda, and T. Uemura, J. Phys.: Condens. Matter **22**, 164212 (2010).
[12]X. Lou, C. Adelmann, S. A. Crooker, E. S. Garlid, J. Zhang, K. S. M. Reddy, S. D. Flexner, C. J. Palmstrøm, and P. A. Crowell, Nat. Phys. **3**, 197 (2007).
[13]J. Inoue, J. Phys. D: Appl. Phys. **31**, 643 (1998).
[14]S. Zhang, P. M. Levy, A. C. Marley, and S. S. P. Parkin, Phys. Rev. Lett. **79**, 3744 (1997).
[15]J. Zhang and R. M. White, J. Appl. Phys. **83**, 6512 (1998).
[16]J. Fabian, A. Matos-Abiague, C. Ertler, P. Stano, and I. Žutić, Acta Phys. Slov. **57**, 565 (2007).
[17]A. Matos-Abiague and J. Fabian, Phys. Rev. B **79**, 155303 (2009).
[18]W. F. Brinkman, R. C. Dynes, and J. M. Rowell, J. Appl. Phys. **41**, 1915 (1970).

Downloaded 12 Jul 2010 to 133.87.26.199. Redistribution subject to AIP license or copyright; see http://apl.aip.org/apl/copyright.jsp