Influence of GaAs surface structure on tunneling anisotropic magnetoresistance and magnetocrystalline anisotropy in epitaxial $Co_{50}Fe_{50}$/n-GaAs junctions

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An epitaxial $Co_{50}Fe_{50}$ layer was grown on As-terminated or Ga-terminated GaAs, and the influence of the termination species on both uniaxial-type tunneling anisotropic magnetoresistance (TAMR) characteristics and magnetocrystalline anisotropy was investigated. The magnetocrystalline anisotropy induced in the $Co_{50}Fe_{50}$ thin film was strongly dependent on the termination species of the GaAs surface, while the TAMR characteristics were almost unchanged. These experimental findings suggest that the TAMR effect is due to the anisotropy of electronic structure rather than the structural anisotropy. © *2011 American Institute of Physics*. [doi:10.1063/1.3561759]

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 the spin-dependent transport properties of F/SC junctions. We recently observed a tunneling anisotropic magnetoresistance (TAMR) effect in both $Co_{50}Fe_{50}$(CoFe)/n-GaAs and Co_2MnSi/n-GaAs Schottky tunnel junctions.[4,5] The TAMR effect modulates the tunnel resistance depending on the absolute direction of the magnetization with respect to the crystal axes of the F. Since the TAMR occurs even for a single F/SC junction and produces a spin-valvelike magnetoresistance, it may affect the electrical detection of spin injection using F/SC heterojunctions. Thus, the origin of the TAMR effect and its influence on spin injection properties should be clarified.

The TAMR effect was first observed in a (Ga,Mn)As/AlO_x/Au tunnel junction,[6] and it has since been observed in several systems,[4–12] such as a CoFe/MgO/CoFe magnetic tunnel junction (MTJ),[9] a (Co/Pt)/AlO_x/Pt tunnel junction,[10] and a Fe/GaAs/Au tunnel junction.[11] The origin of the TAMR, however, differs depending on the system. The TAMR effect produced in a (Ga,Mn)As tunnel junction has been attributed to the anisotropic density-of-states for tunneling electrons due to spin-orbit interactions (SOIs).[6] It was shown by first-principles calculations that the TAMR in an Fe/MgO/Fe MTJ is produced by a shift in the resonant surface states of an Fe energy band due to Rashba-SOI as the Fe magnetization rotates.[13] Moser *et al.*[11] observed uniaxial-type TAMR in a Fe/GaAs/Au tunnel junction, in which the tunnel resistance has 180°-symmetry for the angle of magnetization with respect to the GaAs [110] direction. Our results for CoFe/n-GaAs (Ref. 4) and Co_2MnSi/n-GaAs (Ref. 5) junctions are qualitatively similar to that for Fe/GaAs/Au.[11] Two possible origins for the uniaxial-type TAMR characteristics have been proposed:[14] (a) combination of Rashba-type and Dresselhaus-type SOIs and (b) uniaxial-type-strain-induced SOI. If the latter effect is the dominant origin of the TAMR, the TAMR and magnetocrystalline anisotropy should be correlated since the strain induces magnetocrystalline anisotropy. The strain-induced SOI model was initially introduced to explain the TAMR in a (Ga,Mn)As/AlO_x/Au tunnel junction,[6] and correlation between the TAMR and magnetocrystalline anisotropy was experimentally demonstrated in a (Ga,Mn)As/ZnSe/(Ga,Mn)As MTJ.[8] Although we also observed both uniaxial-type TAMR and uniaxial-type magnetocrystalline anisotropy in CoFe/n-GaAs and Co_2MnSi/n-GaAs Schottky tunnel junctions,[4,5,15,16] the correlation between them was unclear. The purpose of this study is to clarify the correlation between the TAMR characteristics and magnetocrystalline anisotropy observed in a CoFe/n-GaAs Schottky junction. For that purpose we fabricated an epitaxial CoFe layer on As-terminated or Ga-terminated GaAs, and investigated the influence of the termination species on both TAMR characteristics and magnetocrystalline anisotropy.

Layer structures consisting of (from the substrate side) undoped GaAs (50 nm)/n^--GaAs (Si=2×10^{16} cm^{-3}, 750 nm)/n^+-GaAs (Si=3×10^{18} cm^{-3}, 30 nm) were grown by molecular beam epitaxy at 580 °C on a GaAs(001) substrate. The n^+-GaAs layer was inserted to reduce the Schottky barrier width so that the tunnel conduction would be 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 CoFe growth, the GaAs substrates were heated to obtain two kinds of surface reconstruction superstructures. As the substrate temperature increased, the arsenic coverage at the top of the (001) GaAs surface decreased, and surface reconstruction structures changed from c(4×4) to As-stabilized (2×4) and Ga-stabilized (4×2) structures. The formation of As-stabilized (2×4) or Ga-stabilized (4×2) structure was confirmed by reflection high energy electron diffraction. Subsequently, a 20-nm-thick CoFe film was grown by magnetron sputtering at room temperature on either the As-stabilized surface (sample-A) or the Ga-stabilized surface (sample-B). The magnetocrystalline anisotropy of the CoFe thin film was investigated using a superconducting quantum interference device magnetometer

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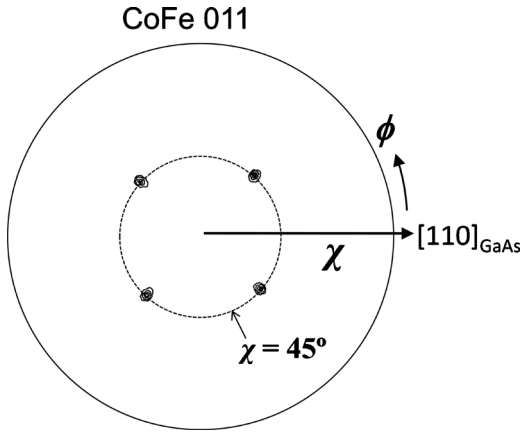

FIG. 1. X-ray pole figure of CoFe 011 diffraction for sample-A.

at 10 K. The TAMR characteristics of CoFe/n-GaAs Schottky junctions were measured at 4.2 K by the conventional four-probe method.

Figure 1 shows a pole figure of CoFe 011 diffraction for sample-A. The diffraction peaks showed fourfold symmetry with respect to the sample rotation angle, ϕ, at a tilt angle, χ, of 45°. Here, we set the GaAs[110] direction to the origin of ϕ. We also obtained a similar result for sample-B (not shown). These results indicate that the CoFe thin film was epitaxially grown on the GaAs with a cube-on-cube relation for both sample-A and sample-B. Thus, the crystal axis direction described hereafter is common between CoFe and GaAs. Figure 2 shows the magnetic hysteresis curves of epitaxial CoFe films grown (a) on the As-stabilized GaAs surface (sample-A) and (b) on the Ga-stabilized GaAs surface (sample-B). A magnetic field was applied along the [110] and $[1\bar{1}0]$ directions. A saturation magnetization of approximately 1500 emu/cm^3 was obtained, a value comparable to that typically reported for the bulk sample. The CoFe films showed strong magnetic anisotropy for both samples. In addition to the cubic anisotropy imposed by the crystal symmetry of CoFe with easy axes of both [110] and $[1\bar{1}0]$, uniaxial anisotropy with an easy axis of either the [110] or $[1\bar{1}0]$ direction was observed because of structural and/or electronic asymmetry of the CoFe/GaAs interface between [110] and $[1\bar{1}0]$, as discussed later. The magnetocrystalline energy of the CoFe thin film is given by

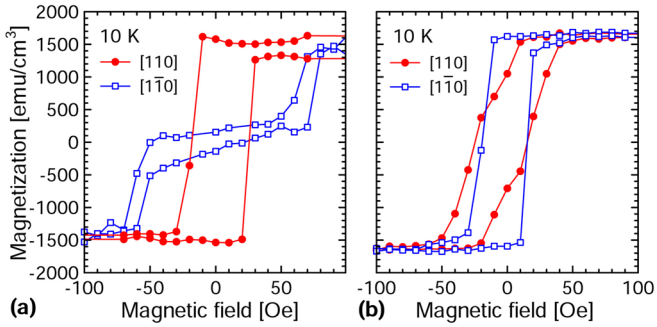

FIG. 2. (Color online) Magnetic hysteresis curves of epitaxial CoFe films grown (a) on the As-stabilized GaAs surface (sample-A) and (b) on the Ga-stabilized GaAs surface (sample-B). A magnetic field was applied along the [110] and $[1\bar{1}0]$ directions.

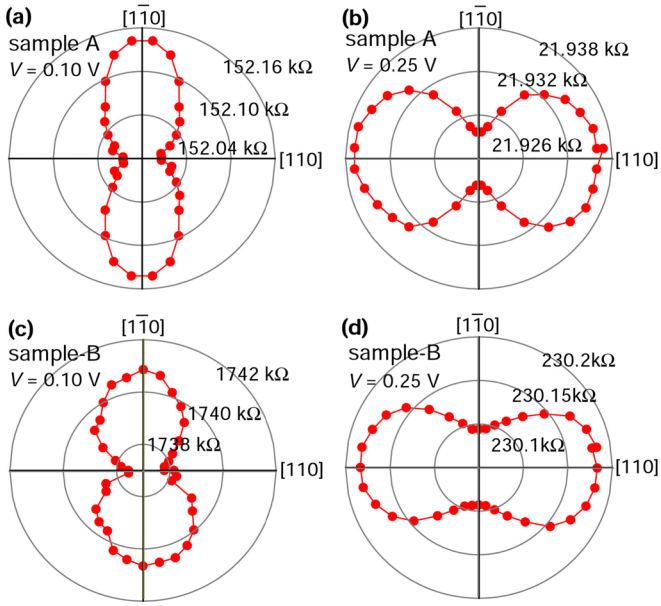

FIG. 3. (Color online) Polar plots of the tunnel resistance of a CoFe/n-GaAs Schottky junction with the As-stabilized n-GaAs surface (sample-A) biased at (a) 0.10 V and (b) 0.25 V, and with the Ga-stabilized n-GaAs surface (sample-B) biased at (c) 0.10 V and (d) 0.25 V. The bias voltage was defined with respect to the n-GaAs. The polar angle indicates the direction of magnetization with respect to the [110] direction.

$$E(\theta) = K_u \sin^2\theta + K_1/4 \sin^2 2\theta, \quad (1)$$

where θ is the angle of the magnetization (M) direction of CoFe with respect to the [110] direction, and K_1 and K_u are cubic and uniaxial anisotropy constants, respectively. The sign of K_u was positive (negative) for sample-A (B) because the easy axis direction for sample-A (B) was [110] ($[1\bar{1}0]$). The fact that the sign of K_u changed between sample-A and sample-B indicates that the origin of the uniaxial anisotropy induced in the CoFe thin film was due to the difference of the surface reconstruction superstructures of GaAs. Such structural anisotropy could induce uniaxial-type strain with different directions between sample-A and sample-B.

Figure 3 shows polar plots of the tunnel resistance of a CoFe/n-GaAs Schottky junction with the As-stabilized n-GaAs surface (sample-A) biased at (a) 0.10 V and (b) 0.25 V, and with the Ga-stabilized n-GaAs surface (sample-B) biased at (c) 0.10 V and (d) 0.25 V. The bias voltage (V) was defined with respect to the n-GaAs. The polar angle indicates the direction of an applied magnetic field of 1000 Oe, where the magnetization was forced to align along the magnetic field, with respect to the [110] direction. The tunnel resistance showed uniaxial-type anisotropy with respect to θ, and is approximately given by

$$R(\theta) = (R_{1\bar{1}0} - R_{110})\sin^2\theta + R_{110} \equiv R_u \sin^2\theta + R_{110}, \quad (2)$$

where R_{110} and $R_{1\bar{1}0}$ are the tunnel resistance for $M \| [110]$ and $M \| [1\bar{1}0]$, respectively, and $R_u \equiv R_{1\bar{1}0} - R_{110}$. The sign of R_u was positive at V=0.10 V and negative at V=0.25 V for both samples. Similar uniaxial-type anisotropy in the tunnel resistance has been observed in Fe/GaAs/Au junctions[12] and Co_2MnSi/n-GaAs junctions.[5] Figure 4 shows the bias-voltage dependence of R_u for CoFe/n-GaAs Schottky junctions with the As-stabilized n-GaAs surface (sample-A) and with the Ga-stabilized n-GaAs surface (sample-B). R_u was

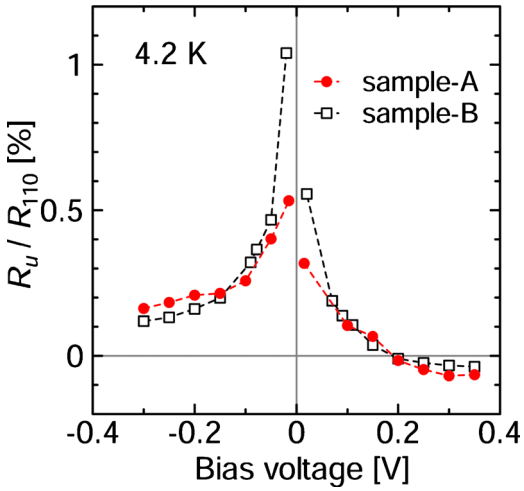

FIG. 4. (Color online) Bias-voltage dependence of the normalized R_u, defined by $(R_{1\bar{1}0}-R_{110})/R_{110}$, of CoFe/n-GaAs Schottky junctions with the As-stabilized n-GaAs surface and with the Ga-stabilized n-GaAs surface (sample-B), where R_{110} and $R_{1\bar{1}0}$ stand for the tunnel resistance when the magnetization of the CoFe electrode orients to the [110] and $[1\bar{1}0]$ directions, respectively.

obtained by measuring R_{110} and $R_{1\bar{1}0}$ at each bias voltage, and it was normalized by R_{110}. The figure clearly shows that the sign of R_u is strongly dependent on the bias-voltage, and that it changed at $V \approx 0.16$ V; however, it was insensitive to any difference in the GaAs surface's superstructure. This contrasted with the magnetocrystalline anisotropy result.

We will discuss the origin of the uniaxial-type TAMR effect. Matos-Abiague *et al.*[14] proposed a theoretical model to explain the uniaxial-type TAMR characteristics: (a) combination of both Rashba-type and Dresselhaus-type SOIs and (b) uniaxial-type-strain-induced SOI. In both cases, the Hamiltonian of SOIs for tunneling electrons has the same form, given by

$$H_{SO1} = \alpha(\sigma_x k_y - \sigma_y k_x) + \beta(\sigma_x k_x - \sigma_y k_y), \tag{3}$$

for Rashba and Dresselhaus-type SOIs, and by

$$H_{SO2} = \eta(\sigma_x k_y - \sigma_y k_x) + \mu(\sigma_x k_x - \sigma_y k_y), \tag{4}$$

for uniaxial-type-strain-induced SOIs. Here, α and β are the effective Rashba and Dresselhaus parameters, η and μ are effective strain tensor components under uniaxial-type strain with respect to the [110] or $[1\bar{1}0]$ direction, σ_x, σ_y, σ_z are the Pauli spin matrices, and k_x, k_y are the electron wave vector components. The x-axis and y-axis are set to the [100] and [010] direction, respectively, and the z-axis is set to the tunneling direction. These SOIs produce anisotropic SOI fields, resulting in a uniaxial-type TAMR, and R_u is proportional to $\alpha \cdot \beta$ or $\eta \cdot \mu$.

The result shown in Fig. 2 that the sign of K_u changed depending on the surface reconstruction superstructures of GaAs indicates that the sign of $\eta \cdot \mu$ changed between sample-A and sample-B. The sign of R_u, however, was insensitive to the surface reconstruction superstructures, as shown in Fig. 4. This result indicates that R_u is dominantly proportional to $\alpha \cdot \beta$ instead of $\eta \cdot \mu$. This model also explains the bias-voltage dependence of R_u. The strain tensor components, in general, are almost constant against the bias-voltage. Thus, if R_u is proportional to $\eta \cdot \mu$, the strong bias-voltage dependence of R_u shown in Fig. 4 cannot be explained. On the other hand, the sign and magnitude of α would be voltage-dependent, since α is proportional to the strength of the z-component of the electric field at the F/n-GaAs interface. Thus, one can qualitatively explain the bias-voltage dependence of R_u, if R_u is assumed to be proportional to $\alpha \cdot \beta$.

In summary, we found there is no direct correlation between magnetocrystalline anisotropy and TAMR in a CoFe/n-GaAs Schottky junction, and that the uniaxial-type magnetocrystalline anisotropy induced in a CoFe thin film grown on GaAs is attributable to the uniaxial-type strain between CoFe and GaAs, while the uniaxial-type TAMR mainly originates from the combination of Rashba-type and Dresselhaus-type SOIs.

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