Structural, magnetic, and electrical properties of $Co_2MnSi/MgO/n$-GaAs tunnel junctions

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(Presented on 6 November 2007; received 12 September 2007; accepted 15 October 2007; published online 24 January 2008)

The structural, magnetic, and electrical properties of Co_2MnSi (CMS)/MgO (0–3.0 nm)/n-GaAs tunnel junctions were investigated. CMS films with $L2_1$-ordered structures were grown epitaxially on GaAs. The crystallographic relations were CMS(001)[100]∥GaAs(001)[110] when a thin MgO interlayer was inserted between the CMS and the GaAs, and CMS(001)[110]∥GaAs(001)[110] when the CMS film was directly grown on GaAs without a MgO interlayer. The CMS film without a MgO interlayer showed strong magnetic anisotropy consisting of uniaxial anisotropy with an easy axis of CMS[1−10] (GaAs[1−10]) direction and cubic anisotropy with easy axes of CMS⟨110⟩ directions. The uniaxial anisotropy was weakened in the samples with a MgO interlayer. The magnetization value of the CMS film with a 3.0-nm-thick MgO layer was approximately 820 emu/cm^3 ($3.9\mu_B$/f.u.) at room temperature (RT), a value slightly higher (~7%) than that of the sample without MgO. The resistance value of the CMS/MgO (3.0 nm)/n-GaAs junction was approximately two to three orders of magnitude higher than that of the CMS/n-GaAs junction at RT. The potential height and width of the tunnel barrier in the CMS/MgO/n-GaAs junction were estimated to be 0.6 eV and 3.3 nm, respectively. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2830833]

I. INTRODUCTION

Co-based full-Heusler alloy (Co_2YZ) thin films are one of the promising ferromagnetic materials for spintronic devices because of their intrinsically high spin polarization at room temperature (RT). Relatively high tunnel magnetoresistance (TMR) ratios were recently observed in magnetic tunnel junctions (MTJs) using Co-based full-Heusler alloys such as $Co_2Cr_{0.6}Fe_{0.4}Al$ (CCFA),[1] Co_2MnSi (CMS),[2,3] or $Co_2FeAl_{0.5}Si_{0.5}$.[4] However, in experiments on spin injection into semiconductors, relatively low injection efficiency was achieved.[5,6] One possible reason is the poor interface quality between Heusler materials and semiconductors.[7,8] Recently, relatively high spin injection efficiencies at RT were reported in CoFe/MgO/GaAs [9] and FePt/MgO/GaAs.[10] Insertion of a thin MgO layer between Heusler materials and semiconductors is therefore expected to be a useful approach for achieving high spin injection efficiency.

We recently developed fully epitaxial MTJs with a Co_2YZ thin film and a MgO tunnel barrier,[1,3,11] and demonstrated relatively high TMR ratios of 109% at RT (317% at 4.2 K) for CCFA/MgO/$Co_{50}Fe_{50}$ MTJs,[1] and 90% at RT (192% at 4.2 K) for CMS/MgO/$Co_{50}Fe_{50}$ MTJs.[3] These results indicate that the spin polarization at the Co_2YZ/MgO interface was kept high and that the Co_2YZ/MgO structure is promising as an efficient spin injector into semiconductors. In previous studies, we demonstrated epitaxial growth of CCFA thin films on GaAs with a MgO interlayer.[12,13] The structural and magnetic properties of the CCFA thin films with MgO, however, were degraded compared with those of the CCFA without MgO. In this study, we grew CMS thin films on GaAs with a MgO interlayer, and investigated their structural and magnetic properties. Furthermore, we characterized the electrical properties of the CMS/MgO/n-GaAs tunnel junctions.

II. EXPERIMENTAL PROCEDURES

Layer structures consisting of 400-nm-thick undoped GaAs and 100-nm-thick n-GaAs ($Si=3\times10^{18}$ cm^{-3}) were grown by molecular beam epitaxy at 580 °C on GaAs(001) substrates. Each sample was then capped with an arsenic protective layer and transported in air to an ultrahigh vacuum chamber equipped with magnetron sputtering cathodes and an electron beam (EB) evaporator. Prior to the growth, the arsenic cap was removed by heating the sample to 400 °C. The MgO layer was then grown by EB evaporation, with the thickness (t_{MgO}) ranging from 0.75 to 3.0 nm at 200 °C. Last, a 50-nm-thick CMS film was grown by rf-magnetron sputtering at 200 °C. A sample without a MgO layer (i.e., CMS/n-GaAs) was also fabricated for comparison. The crystalline structures of the fabricated CMS thin films were characterized using x-ray pole figure measurements. Magnetic properties were measured using a superconducting quantum interference device magnetometer. Electrical properties of the CMS/MgO/n-GaAs tunnel junctions were measured at RT and 8 K using the conventional four-probe method.

III. RESULTS AND DISCUSSION

A. Structural properties

Figure 1 shows pole figures of 022 diffraction for the CMS thin films with t_{MgO} of (a) 0 nm and (b) 3.0 nm. The

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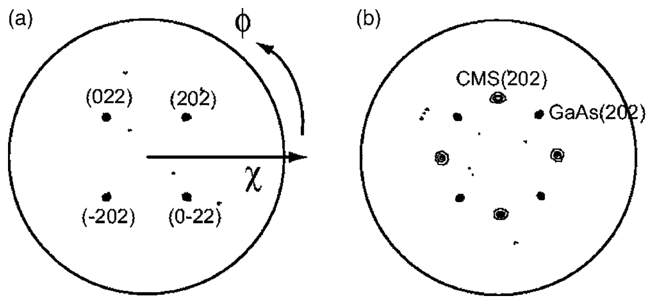

FIG. 1. Pole figure of CMS 022 diffraction in the samples with (a) t_{MgO} =0 nm and (b) t_{MgO}=3.0 nm. In these figures, GaAs 022 peaks are also observed due to a small lattice mismatch.

CMS 022 diffraction peaks showed fourfold symmetry with respect to the sample rotation angle ϕ at a tilt angle χ of 45° in both samples; this was direct evidence of epitaxial growth. Here, we set the GaAs[110] direction to the origin of ϕ. The crystallographic relations were CMS(001)[110]‖GaAs(001)[110] (cube on cube) for the sample without MgO, and CMS(001)[100]‖GaAs(001)[110] (45° rotated) for the samples with a MgO interlayer. Furthermore, CMS 111 diffractions were observed for all the samples with a MgO interlayer, indicating that the CMS films had the $L2_1$-ordered structure. This contrasted with previous results for the CCFA films grown on GaAs with a MgO interlayer, in which the CCFA had $B2$-type and/or $A2$-type structures, both of which are more disordered than the $L2_1$ structure.[12,13]

B. Magnetic properties

Figure 2 shows the magnetic hysteresis curves at RT for the samples with t_{MgO} of (a) 0 nm and (b) 3.0 nm. The magnetic field was applied along the GaAs[110] and [1−10] directions. As shown in Fig. 2(a), the CMS film without a MgO interlayer showed strong magnetic anisotropy. This can be explained by a model in which (i) uniaxial anisotropy imposed by the GaAs symmetry with an easy axis of either the GaAs[110] or [1−10] direction and (ii) cubic anisotropy imposed by the Co_2YZ with easy axes of $Co_2YZ\langle 110\rangle$ are superimposed.[14–16] In our case, the easy axis direction of the uniaxial anisotropy was along the GaAs[1−10] direction. When the MgO interlayer was inserted, the uniaxial anisotropy was weakened [Fig. 2(b)]. For the CCFA films grown on GaAs with a MgO interlayer, however, strong uniaxial anisotropy remained even in the presence of a MgO interlayer.[12,13] The origin of this difference between the CCFA and the CMS, though, is not yet clear.

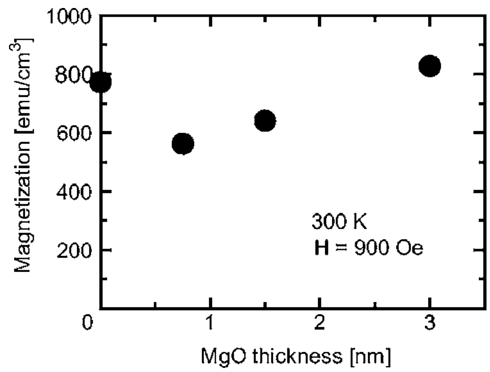

FIG. 3. Magnetization value at RT as a function of t_{MgO}. A magnetic field of 900 Oe was applied along the GaAs[110] direction.

Figure 3 shows the magnetization value (M) at RT as a function of t_{MgO}. The value of M for the sample without MgO was approximately 770 emu/cm^3 (equivalently 3.7μ_B/f.u.) under a magnetic field of 900 Oe. This value corresponds to 74% of the Slater-Pauling value. When a 0.75-nm-thick MgO interlayer was inserted, the M decreased by approximately 29% compared with the sample without MgO. M increased, however, as t_{MgO} increased, and interestingly, M for the sample with t_{MgO}=3.0 nm was slightly larger than that for the sample without MgO. This result also contrasted with those obtained for the CCFA/MgO/GaAs structures in which the value of M for the CCFA film monotonically decreased as t_{MgO} increased.[12,13]

C. Electrical properties

Figure 4(a) shows current (I)-voltage (V) characteristics of the CMS/MgO (3.0 nm)/n-GaAs junction and CMS/n-GaAs junction at RT. The V was defined with respect to the GaAs. The junction resistance of the CMS/MgO/n-GaAs was two to three orders of magnitude higher than that of the CMS/n-GaAs. This indicates that the MgO layer acts as a tunnel barrier. To estimate the tunnel barrier height and width in the CMS/MgO/n-GaAs, we analyzed the I-V characteristics measured at 8 K. Figure 4(b) indicates the I-V and conductance (dI/dV)-V characteristics at 8 K for the CMS/MgO (3.0 nm)/n-GaAs. The conductance took the minimum value at a relatively low bias voltage of +20 mV, indicating that the potential barrier was al-

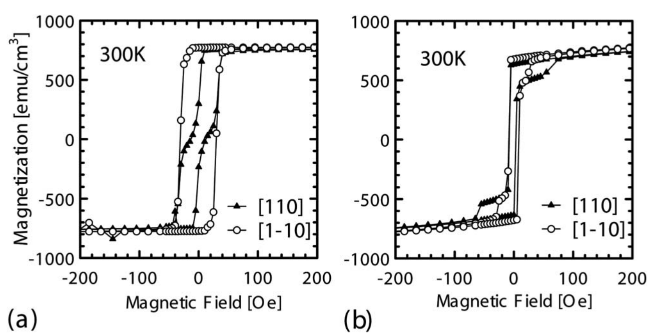

FIG. 2. Magnetic hysteresis curves at RT for the samples with (a) t_{MgO} =0 nm and (b) t_{MgO}=3.0 nm.

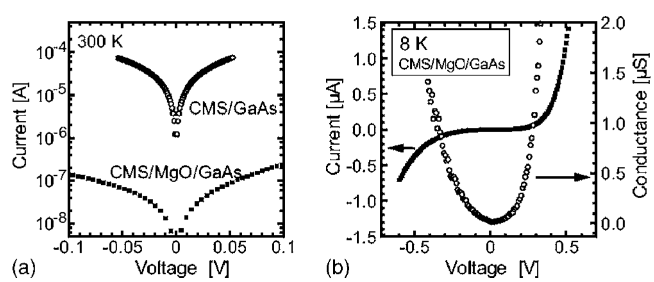

FIG. 4. (a) I-V characteristics at RT for CMS/MgO (3.0 nm)/n-GaAs and CMS/n-GaAs. (b) I-V and G-V characteristics measured at 8 K for CMS/MgO (3.0 nm)/n-GaAs. The junction size was 20×100 μm^2. The bias voltage was defined with respect to n-GaAs.

most symmetric; i.e., the potential barrier height at the CMS/MgO interface (the energy difference between the bottom of the conduction band of the MgO tunnel barrier and the Fermi level of the CMS) was almost equal to that at the *n*-GaAs/MgO interface (the energy difference between the bottom of the conduction band of the MgO tunnel barrier and the Fermi level of the *n*-GaAs). We estimated $m^{*}\varphi$ and d to be 0.6 eV and 3.3 nm, respectively, by fitting the *I-V* curve based on Simmons' formula,[17] where m^{*} is the effective electron mass normalized by the bare electron mass, φ is the averaged potential barrier height, and d is the barrier width. The calculated value of d was close to the nominal thickness of the deposited MgO, indicating that the MgO layer acts effectively as a tunnel barrier.

IV. SUMMARY

We have grown epitaxial CMS thin films with a $L2_1$-ordered structure on GaAs substrates with a MgO interlayer. The magnetization value of the CMS film with a 3.0-nm-thick MgO interlayer was slightly higher than that obtained in the CMS films directly grown on GaAs without a MgO layer. Furthermore, the resistance value of the CMS/MgO (3.0 nm)/*n*-GaAs tunnel junction was approximately two to three orders of magnitude higher than that of the CMS/*n*-GaAs junction. The potential width of the MgO tunnel barrier calculated from Simmons' formula was close to the nominal MgO thickness. These results indicate that the MgO layer acts effectively as a tunnel barrier.

ACKNOWLEDGMENTS

We thank Professor Yasuo Takahashi for allowing us to use a cryogenic probing system for the measurement of *I* – *V* characteristics and for his helpful suggestions. This work was partly supported by a Grant-in-Aid for Scientific Research (B) (No. 18360143), a Grant-in-Aid for Scientific Research on Priority Areas (No. 19048001), a Grant-in-Aid for Scientific Research (C) (No. 19560307), and a Grant-in-Aid for Young Scientists (B) (No. 19760225) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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