Improved tunnel magnetoresistance characteristics of magnetic tunnel junctions with a Heusler alloy thin film of Co_2MnGe and a MgO tunnel barrier

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We fabricated magnetic tunnel junctions (MTJs) with a Co-based full-Heusler alloy thin film of Co_2MnGe (CMG) and a MgO tunnel barrier. The microfabricated MTJs with a Co-rich CMG film showed relatively high tunnel magnetoresistance ratios of 83% at room temperature and 185% at 4.2 K. These values are much higher than those previously obtained for CMG/MgO MTJs with a Co-deficient CMG film. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2713209]

Cobalt-based full-Heusler alloy (Co_2YZ) thin films have recently attracted much interest as highly promising ferromagnetic electrodes for spintronic devices.[1–7] This is because of the half-metallic ferromagnetic nature[8] theoretically predicted for some of these alloys[9,10] and because of their high Curie temperatures, which are well above room temperature (RT).[11,12] Relatively high tunnel magnetoresistance (TMR) ratios have been demonstrated at RT for magnetic tunnel junctions (MTJs) with a Co_2YZ thin film.[13–23] We developed fully epitaxial MTJs with a Co_2YZ thin film and a MgO tunnel barrier,[16–19,22–24] and showed a relatively high TMR ratio of 109% at RT (317% at 4.2 K) for $Co_2Cr_{0.6}Fe_{0.4}Al/MgO/Co_{50}Fe_{50}$ MTJs,[23] and a TMR ratio of 90% at RT (192% at 4.2 K) for Co_2MnSi (CMS)$/MgO/Co_{50}Fe_{50}$ MTJs (CMS-MTJs).[22] Compared with these MTJs, previously reported fully epitaxial Co_2MnGe (CMG)$/MgO/Co_{50}Fe_{50}$ MTJs (CMG-MTJs) showed a much lower TMR ratio of 14% at RT (70% at 7 K).[17,18] The CMG film used in the previous study was a Co-deficient CMG film (the film composition was $Co_2Mn_{1.05}Ge_{1.17}$),[17,18] while the CMS film used in the previous study was a Co-rich CMS film (the film composition was $Co_2Mn_{0.84}Si_{0.80}$).[22] Hereafter, we refer to this Co-deficient CMG film as the CMG_d film. Our purpose in the present study was to improve the TMR characteristics of CMG-MTJs. For this purpose, we fabricated CMG-MTJs with a Co-rich CMG film and investigated their TMR characteristics.

We fabricated epitaxial MTJs that consisted of a CMG thin film and a wedge-shaped MgO tunnel barrier. The composition of the CMG film used in this study was determined to be $Co_2Mn_{0.74}Ge_{0.43}$ (Co-rich CMG), with an accuracy of 2%–3% for each element, through inductively coupled plasma analysis. This Co-rich film composition was obtained by using a sputtering target with a composition of $Co_{2.0}Mn_{1.0}Ge_{1.0}$. Hereafter, we refer to this Co-rich CMG film as the CMG_r film. The fabricated epitaxial MTJ layer structure (from the substrate side) consisted of a MgO buffer layer (10 nm), a CMG lower electrode (50 nm), a MgO tunnel barrier (1.6–2.8 nm), a $Co_{50}Fe_{50}$ upper electrode (3 nm), a layer of Ru (0.8 nm), a layer of $Co_{90}Fe_{10}$ (2 nm), a layer of IrMn (10 nm), and a Ru cap (5 nm); this structure was grown on a MgO(001) substrate. Each layer in the MTJ layer structure was successively deposited in an ultrahigh vacuum chamber (with a base pressure of around 6×10^{-8} Pa) through the combined use of magnetron sputtering and electron beam (EB) evaporation. The CMG layer was deposited at RT using magnetron sputtering and subsequently annealed *in situ* at 500–600 °C for 15 min. The MgO tunnel barrier was deposited by EB evaporation at RT. The pressure during the deposition of the MgO tunnel barrier was around 6×10^{-7} Pa. The nominal thickness of the MgO tunnel barrier (t_{MgO}) was varied from 1.6 to 2.8 nm on each 20×20 mm^2 substrate by using a linearly moving shutter during fabrication. All the layers in the MTJ layer structure were deposited with a magnetic field applied. We fabricated MTJs with the layer structure described above by using photolithography and Ar ion milling. The fabricated junction sizes were from 8×8 to 10×10 μm^2. The magnetoresistance was measured with a magnetic field applied along the [110] axis of the Co_2YZ at temperatures from 4.2 K to RT using a dc four-probe method. We defined the TMR ratio as $(RA_{AP}-RA_P)/RA_P$, where RA_{AP} and RA_P are the respective resistance-area products for the antiparallel and parallel magnetization configurations between the upper and lower electrodes. As shown below, as-fabricated (i.e., not *ex situ* annealed) MTJs showed exchange-biased TMR characteristics. Transport properties of as-fabricated MTJs are described below.

X-ray pole figure scans of a CMG_r film deposited at RT and subsequently annealed at 600 °C showed fourfold symmetry of the CMG (111) peaks at $\chi=54.7°$, which gives direct evidence that the 600 °C annealed film is epitaxial and crystallized in the $L2_1$ structure. Because the φ values for the CMG (111) peaks were shifted by 45° with respect to those of the MgO (111) peaks, the crystallographic relationship was CMG (001)[100] ∥ MgO (001)[110] on a 45° in-plane rotation. These structural properties are similar to those previously observed for the CMG_d films.[6,17]

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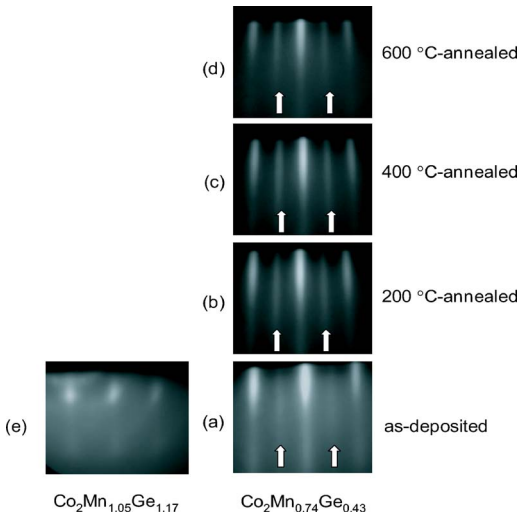

FIG. 1. [(a)–(d)] RHEED patterns, along the azimuth of $[100]_{MgO}$ corresponding to $[110]_{CMG}$, obtained *in situ* for a Co-rich Co_2MnGe (CMG) film during fabrication. The CMG film was deposited at RT on a MgO buffer layer (10 nm) and subsequently *in situ* annealed step by step at 200–600 °C. The substrate was a MgO (001) single crystal. The arrows indicate streak patterns corresponding to CMG (11^*) reflection. (e) A RHEED pattern for comparison, along the azimuth of $[100]_{MgO}$ corresponding to $[110]_{CMG}$, obtained previously for an as-deposited Co-deficient CMG film during fabrication (Ref. 17). Streak patterns corresponding to the CMG (11^*) reflection were not observed.

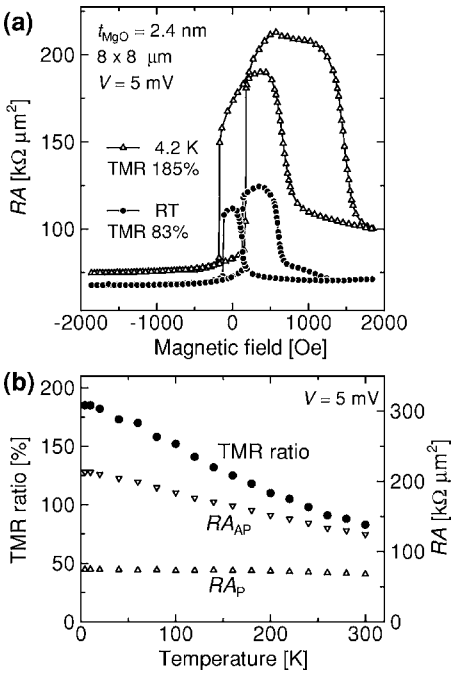

FIG. 2. (a) Typical magnetoresistance curves at a bias voltage (V) of 5 mV at RT and 4.2 K for a fabricated Co_2MnGe (CMG)/MgO/$Co_{50}Fe_{50}$ MTJ with a Co-rich CMG film where the CMG lower electrode was *in situ* annealed at 600 °C after deposition (t_{MgO}=2.4 nm). The junction size was 8×8 μm^2. TMR ratios were 83% at RT and 185% at 4.2 K. (b) TMR ratio, as well as RA_{AP} and RA_P, at V=5 mV for the same MTJ shown in Fig. 2(a) as a function of temperature from 4.2 K to RT, where RA_{AP} and RA_P are the respective resistance-area products for the antiparallel and parallel magnetization configurations between the upper and lower electrodes.

We observed the surface morphologies of the 45-nm-thick CMG_r films deposited on MgO buffer layers (10 nm) using atomic force microscopy. The root mean square (rms) values of the surface roughness increased with postdeposition annealing, from a rms roughness of 0.16 nm for the as-deposited film to 0.41 nm for the 600 °C annealed film. This dependence on postdeposition annealing temperature was in contrast to that previously observed for the CMG_d film, i.e., the rms values of the surface roughness decreased with postdeposition annealing, from a rms value of roughness of 0.40 nm for the as-deposited film to 0.26 nm for the 600 °C annealed film.[6,17]

Figure 1 shows reflection high-energy electron diffraction (RHEED) patterns, along the azimuth of $[100]_{MgO}$ corresponding to $[110]_{CMG}$, observed *in situ* for a CMG_r film deposited at RT on a MgO buffer layer (10 nm) and subsequently annealed *in situ* step by step at 200–600 °C; Fig. 1(e) shows a RHEED pattern obtained previously for an as-deposited CMG_d film for comparison. We did not observe the streak pattern corresponding to the (11^*) reflection for the as-deposited CMG_d film as shown in Fig. 1(e), although we observed streaks corresponding to the (11^*) reflection for the CMG_d film annealed at 600 °C. It is notable that we see streak patterns that correspond to the (11^*) reflection even for the as-deposited CMG_r film [Fig. 1(a)]. The streaks that correspond to the (11^*) reflection for the CMG_r film annealed at 200–600 °C [Figs. 1(b)–1(d)] became sharper and more distinct than those of the as-deposited film [Fig. 1(a)]. The streaks of the (11^*) reflection for the as-deposited film indicate the existence of the $L2_1$ structure even in the as-deposited CMG_r films, which means that the structural properties of the CMG_r films were better than those of the CMG_d films with respect to the degree of structural order.

Next, we will describe the spin-dependent tunneling characteristics of fabricated epitaxial MTJs. Figure 2(a) shows typical magnetoresistance curves at a bias voltage (V) of 5 mV at RT and 4.2 K for an as-fabricated CMG_r/MgO/$Co_{50}Fe_{50}$ MTJ, having a 2.4-nm-thick MgO tunnel barrier, where the lower CMG electrode was *in situ* annealed at 600 °C after deposition. The junction size was 8×8 μm^2. Exchange-biased TMR characteristics were obtained with relatively high TMR ratios of 83% at RT and 185% at 4.2 K. These values are comparable to the TMR ratios of 90% at RT and 192% at 4.2 K previously obtained for CMS/MgO/$Co_{50}Fe_{50}$ MTJs with a Co-rich CMS film, of which the film composition was $Co_2Mn_{0.84}Si_{0.80}$ (Ref. 22); these are significantly enhanced from the lower TMR ratios of 14% at RT and 70% at 7 K previously obtained for CMG/MgO/$Co_{50}Fe_{50}$ MTJs with a Co-deficient CMG film, of which the film composition was $Co_2Mn_{1.05}Ge_{1.17}$.[17,18]

Figure 2(b) plots the TMR ratio, as well as RA_{AP} and RA_P, at V=5 mV for the same MTJ shown in Fig. 2(a) as a function of temperature (T) from 4.2 K to RT. As T decreased from RT to 4.2 K, the TMR ratio increased by a factor of 2.2. If we use parameter $\gamma=\alpha(4.2\ \mathrm{K})/\alpha(\mathrm{RT})$, where α is the TMR ratio, to represent the degree of T dependence of the TMR ratio, γ for CMG_r/MgO/$Co_{50}Fe_{50}$ MTJs was 2.2. This value is comparable to the previously obtained γ =2.1 for CMS/MgO/$Co_{50}Fe_{50}$ MTJs (a TMR ratio of 192% at 4.2 K and 90% at RT)[22] and significantly lower than γ =5.0, which was previously obtained for CMG_d/MgO/$Co_{50}Fe_{50}$ MTJs (a TMR ratio of 70% at 7 K

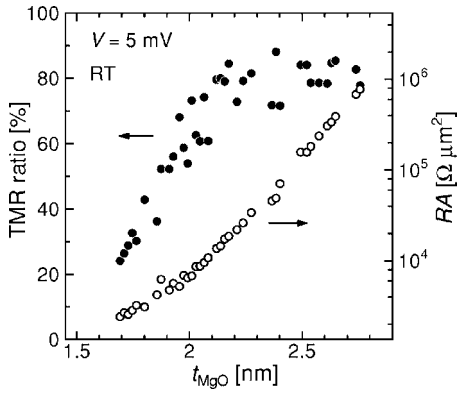

FIG. 3. RA_P and TMR ratio at RT (measured at $V=5$ mV) as a function of MgO tunnel barrier thickness t_{MgO} for fabricated Co_2MnGe (CMG)/MgO/$Co_{50}Fe_{50}$ MTJs with a Co-rich CMG film where the CMG lower electrode was *in situ* annealed at 500 °C after deposition. RA_P represents the resistance-area product *RA* for the parallel magnetization configuration. The junction size was 10×10 μm^2. The scale of the vertical axis for RA_P is logarithmic.

and 14% at RT).[17,18] As shown in Fig. 2(b), RA_{AP} also increased with decreasing *T*, while RA_P was almost independent of *T*. These behaviors were similar to those previously observed for CCFA/MgO/$Co_{50}Fe_{50}$ MTJs (Ref. 24) and CMS/MgO/$Co_{50}Fe_{50}$ MTJs.[22] These behaviors were also observed for $Co_{70}Fe_{30}$/MgO/$Co_{84}Fe_{16}$ MTJs.[25]

Figure 3 plots RA_P and the TMR ratio at RT (measured at $V=5$ mV) as a function of t_{MgO} for the fabricated CMG_r/MgO/$Co_{50}Fe_{50}$ MTJs where the CMG lower electrode was *in situ* annealed at 500 °C after deposition. The junction size was 10×10 μm^2. A clear exponential dependence of R_{AP} on t_{MgO} was observed for the t_{MgO} range of 2.0–2.8 nm, indicating typical tunnel junction behavior. Relatively high TMR ratios from 72% to 88% were obtained at RT for this wide range of t_{MgO} from (2.0–2.8 nm).

We estimated the spin polarization for the CMG_r electrodes by using Jullière's model for the TMR ratio;[26] TMR $=2P_1P_2/(1-P_1P_2)$, where P_1 and P_2 are the spin polarizations at the Fermi level (E_F) of the ferromagnetic electrodes in MTJs. We first estimated the effective spin polarization for the $Co_{50}Fe_{50}$ electrode from the TMR ratio of 146% at 4.2 K (96% at RT) obtained for the identically fabricated epitaxial $Co_{50}Fe_{50}$/MgO/$Co_{50}Fe_{50}$ MTJs by using Jullière's model. Thus, the effective spin polarization value obtained for the $Co_{50}Fe_{50}$ electrode (P_{CoFe}) was 0.65 at 4.2 K (0.57 at RT). Then, we estimated the effective spin polarization of the CMG film (P_{CMG}) from the TMR ratio of 185% at 4.2 K (83% at RT) for the epitaxial CMG_r/MgO/$Co_{50}Fe_{50}$ MTJs by using Jullière's model with P_{CoFe} of 0.65 at 4.2 K (0.57 at RT). The obtained effective spin polarization or tunneling spin polarization values of P_{CMG} were 0.74 at 4.2 K and 0.51 at RT. These P_{CMG} values are comparable to previously obtained values of 0.75 at 4.2 K and 0.54 at RT for the CMS films.[22]

The enhanced TMR ratios for the CMG/MgO/$Co_{50}Fe_{50}$ MTJs fabricated with a Co-rich CMG film demonstrated that the lower TMR ratios observed previously for the CMG/MgO/$Co_{50}Fe_{50}$ MTJs with a Co-deficient CMG film[17,18] were not due to an intrinsic property of the Co-based full-Heusler alloy of Co_2MnGe. The improved TMR characteristics in terms of the TMR ratio or the effective spin polarization at E_F are probably related to the improved structural properties of the CMG film in terms of the degree of structural order.

In summary, we fabricated epitaxial MTJs with a Co-based full-Heusler alloy thin film of CMG and a MgO tunnel barrier. The microfabricated MTJs with a Co-rich CMG film demonstrated relatively high tunnel magnetoresistance ratios of 83% at RT and 185% at 4.2 K. These values are much higher than those previously obtained for CMG/MgO/$Co_{50}Fe_{50}$ MTJs with a Co-deficient CMG film.

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