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Temperature dependence of spin-dependent tunneling resistances of MgO-buffered $Co_2MnSi/MgO/Co_2MnSi$ magnetic tunnel junctions

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1. Introduction

A heterostructure consisting of a potentially half-metallic Heusler alloy electrode[1] and a MgO barrier is highly advantageous as a spin source for magnetic tunnel junctions and for spin injection into semiconductors. This is because that the heterostructucture benefits not only from the high spin polarizations due to the half-metallic nature but also from the contribution of coherent tunneling of electrons in specific Bloch states to the enhancement of the tunneling spin polarization.[2] Co_2MnSi is one of the most considerably investigated ferromagnetic electrode materials amongst Co-based Heusler alloys. This is because of its theoretically predicted half-metallic nature[1] and because of its high Curie temperature of 985 K. Furthermore, it has been theoretically predicted that coherent tunneling through the Δ_1 band of Co_2MnSi is dominant in an MTJ with Co_2MnSi electrodes and a MgO barrier.[3]

We have recently investigated the effect of defects possibly associated with nonstoichiometry in Co_2MnSi thin films on spin-dependent tunneling characteristics and have found that fully epitaxial $Co_2MnSi/MgO/Co_2MnSi$ MTJs (CMS MTJs) with Mn-rich Co_2MnSi electrodes grown on a MgO-buffered MgO(001) substrate exhibited high tunnel magnetoresistance (TMR) ratios of 1135% at 4.2 K and 236% at 290 K, exceeding those of MTJs with Co_2MnSi electrodes having an almost stoichiometric composition.[4] The observed higher TMR ratio for MTJs with Mn-rich Co_2MnSi electrodes was explained by suppressed Co_{Mn} antisites,[5] which caused a reduced density of minority-spin in-gap states around the Fermi level (E_F). Our purpose of the present study was to clarify how the half-metallicity was influenced by Mn composition α in $Co_2Mn_\alpha Si$ electrodes through investigating the temperature (T) dependence of the spin-dependent tunneling resistances for the parallel (P) and antiparallel (AP) magnetization configurations, R_P and R_{AP}, of MgO-buffered CMS MTJs with various Mn compositions in CMS electrodes. We found that the T dependence of R_P showed characteristic behaviors strongly related to the change in the spin-dependent electronic structure with Mn composition α, although the T dependence of R_{AP} determined the overall T dependence of the TMR ratio.

2. Experimental methods

The preparation of fully epitaxial CMS MTJs on MgO-buffered MgO(001) substrates with various values of α has been reported in Ref. 4. Briefly, the fabricated MTJ layer structure was as follows: (from the substrate side) MgO buffer (10 nm)/CMS lower electrode (30 nm)/MgO barrier (2.0–3.0 nm)/CMS upper electrode (3–5 nm)/Ru (0.8 nm)/$Co_{90}Fe_{10}$ (2 nm)/IrMn (10 nm)/Ru cap (5 nm), grown on a MgO(001) single-crystal substrate. Each layer was successively deposited in an ultrahigh vacuum chamber (base pressure of ~6×10^{-8} Pa). The CMS electrodes were deposited by co-sputtering from a nearly stoichiometric CMS target and a Mn target to systematically vary the Mn composition in CMS. The film compositions of the CMS electrodes were determined to be $Co_2Mn_\alpha Si_\gamma$ ($\gamma = 1.0 \pm 0.06$) by inductively coupled plasma optical emission spectroscopy with an accuracy of 2% for Co or Mn and 5% for Si. Hereafter, we denote $Co_2Mn_\alpha Si_\gamma$ ($\gamma = 1.0 \pm 0.06$) by $Co_2Mn_\alpha Si$ using the mean value of 1.0 for Si composition γ. The tunneling resistances R_P and R_{AP} were measured by a dc four-probe method at temperatures from 4.2 K to 290 K. The TMR ratio is defined as TMR $= (R_{AP}–R_P)/R_P$.

3. Experimental results and discussion

Figure 1 plots the T dependence of the TMR ratios of three CMS MTJs with various α values ranging from Mn-deficient $\alpha = 0.79$ to Mn-rich $\alpha = 1.29$: MTJ-1 with $\alpha = 0.79$, MTJ-2 with $\alpha = 1.0$, and MTJ-3 with $\alpha = 1.29$. The TMR ratios at both 4.2 K and 290 K increased with increasing α from 355% at 4.2 K (97% at 290 K) for $\alpha = 0.79$ to 1035% at 4.2 K (200% at 290 K) for $\alpha = 1.29$. Note that the normalized TMR ratios (the TMR ratio was normalized by its value at 290 K) of CMS MTJs with a higher TMR ratio at 4.2 K showed stronger T dependence (not shown), i.e., the relative decrease in the TMR ratio with increasing T up to 290 K is larger for CMS MTJs with a higher TMR ratio at 4.2 K. Figures 2 and 3 show the T dependence of the normalized R_{AP} (R_{AP} was normalized by its value at 290 K) and the normalized R_P (R_P was normalized by its value at 4.2 K) of these three MTJs. In contrast to very small relative changes in R_P with increasing T for all these MTJs (up to 6% change in the T range from 4.2 K to 290 K for MTJ-1 and almost within 1% for MTJ-2 and MTJ-3), the R_{AP} decreased significantly with increasing T: its relative change was two orders of magnitude larger than that of R_P. Because of the considerably stronger T dependence of R_{AP} than that of R_P, the T dependence of the normalized TMR ratio was almost determined by that of R_{AP} (the normalized T dependence of the TMR ratio of each MTJ was in good agreement with that of the respective normalized R_{AP} (not shown)). Interestingly, the T dependence of the normalized R_P of MTJ-2 (α = 1.0) and MTJ-3 (α = 1.29) featuring higher TMR ratios at 4.2 K and 290 K showed qualitatively different behavior compared with that of MTJ-1 (α = 0.79) featuring a lower TMR ratio. R_P of MTJ-1 was almost independent of T up to a characteristic temperature T_2 of about 100 K and decreased as T increased for $T > T_2$. On the other hand, R_P of MTJ-3 (MTJ-2) increased as T increased for the T range from T_1 of about 40 K (40 K) to T_2 of about 190 K (180 K).

The decrease in R_P as T increased for $T > T_2$ for MTJ-1 can be explained by a model by Zhang *et al.*[6] in which magnon assisted tunneling is introduced under the assumption of T independent spin polarization (model-1). On the other hand, a model proposed by Shang *et al.*[7] in which the spin polarization decreases as T increases via thermal excitation of spin waves at finite temperatures (model-2) cannot explain the decrease in R_P as T increased.

The clear increase in R_P of MTJ-3 and MTJ-2 for $T_1 < T < T_2$ can be ascribed to the decrease in the spin polarization arising from thermal spin fluctuations.[7,8] This means the influence of the decrease in the spin polarization arising from thermal spin fluctuation became dominant for determining the T dependence of R_P compared with the influence of the Zhang's mechanism[6] which increases not only the tunneling conductance for the antiparallel configuration but also that for the parallel configuration. The increase in R_P of MTJ-3 and MTJ-2 for $T_1 < T < T_2$ also indicates the decrease in the residual minority-spin in-gap states around E_F, resulting in the decreased contribution to the enhancement of tunneling conductance from the Zhang's mechanism. This picture that MTJ-3 (α = 1.29) and MTJ-2 (α = 1.0) features the decreased minority-spin in-gap states at E_F compared with MTJ-1 (α = 0.79) is consistent with the understanding that the higher TMR ratio observed for CMS MTJs with Mn-rich CMS electrodes can be attributed to suppressed minority-spin in-gap states around E_F for Mn-rich Co_2MnSi electrodes.[5]

4. Conclusion

In summary, we found that fully epitaxial $Co_2MnSi/MgO/Co_2MnSi$ MTJs on MgO-buffered MgO(001) substrates with Mn-rich Co_2MnSi electrodes and resulting high TMR ratios showed characteristic T dependence of the tunneling resistance for the parallel magnetization configuration which can be ascribed to reduced minority-spin in-gap states. Our finding suggest the importance of the T dependence of R_P to understand the key of the spin-dependent tunneling mechanism in MTJs with electrodes having high spin polarizations and the spin-dependent electronic structures.

References

1. S. Ishida *et al.*, J. Phys. Soc. Japan **64** (1995) 2152.
2. W. H. Butler *et al.*, Phys. Rev. B **63** (2001) 054416.
3. Y. Miura *et al.*, J. Phys.: Condens. Matter **19** (2007) 365228.
4. T. Ishikawa *et al.*, Appl. Phys. Lett. **95** (2009) 232512.
5. M. Yamamoto *et al.*, J. Phys: Condens. Matter. **22** (2010) 164212.
6. S. Zhang *et al.*, Phys. Rev. Lett. **79** (1997) 19.
7. C. H. Shang *et al.*, Phys. Rev. B **58** (1998) R2917 .
8. Y. Miura *et al.*, Phys. Rev. B **83** (2011) 214411.

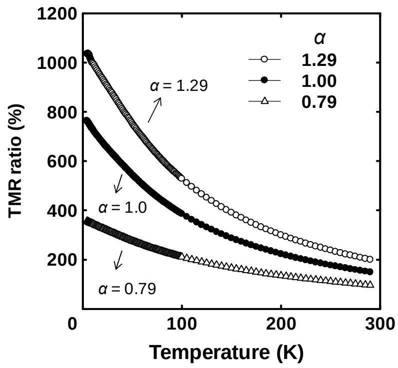

FIG. 1. Temperature dependence of the TMR ratios of $Co_2Mn_\alpha Si/MgO/Co_2Mn_\alpha Si$ MTJs (CMS MTJs) on MgO-buffered MgO(001) substrates with α = 0.79 (MTJ-1), 1.0 (MTJ-2), and 1.29 (MTJ-3) in $Co_2Mn_\alpha Si$ electrodes.

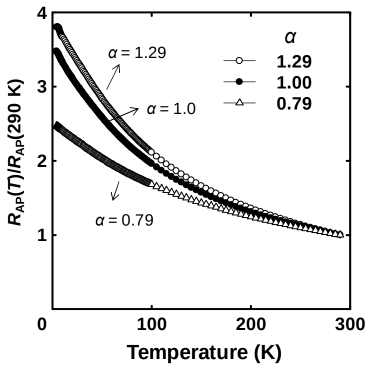

FIG. 2. Normalized T dependence of R_{AP} (R_{AP} was normalized by its value at 290 K) of CMS MTJs with α =0.79 (MTJ-1), 1.0 (MTJ-2), and 1.29 (MTJ-3) in $Co_2Mn_\alpha Si$ electrodes.

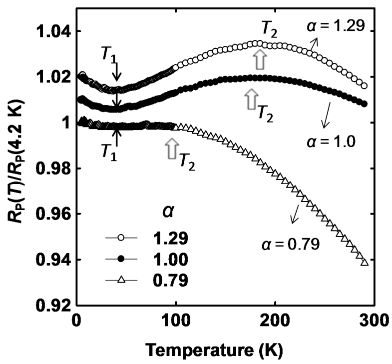

FIG. 3. Normalized T dependence of R_P (R_P was normalized by its value at 4.2 K) of CMS MTJs with α = 0.79 (MTJ-1), 1.0 (MTJ-2), and 1.29 (MTJ-3). The second and third curves from the bottom have respective offsets of 0.01 and 0.02.