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Temperature Dependence of Spin-dependent Tunneling Conductance of Magnetic Tunnel Junctions with Highly Spin-polarized Electrodes

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Abstract

We experimentally investigated the temperature (*T*) dependence of tunneling conductance *G* for the parallel (P) and antiparallel (AP) configurations, G_P and G_{AP}, of Co_2MnSi-based and $Co_2(Mn,Fe)Si$-based magnetic tunnel junctions (MTJs) both exhibiting giant tunneling magnetoresistance (TMR) ratios. We found that G_P of MTJs, which showed a lower TMR ratio, increased with increasing *T* from 4.2 K to 290 K while G_P of MTJs, which showed a higher TMR ratio, decreased with increasing *T* from 4.2 K to a certain temperature T_2. We showed that these *T* dependence could be consistently explained by the change in the dominant tunneling process that determines the *T* dependence of G_P.

1. Introduction

A highly efficient spin source is essential for spintronic devices. We showed that controlling defects through the film composition is critical to retain the half-metallicity of ternary Heusler alloy Co_2MnSi (CMS) and quaternary alloy $Co_2(Mn,Fe)Si$ (CMFS) [1−3]. As a result, we demonstrated giant TMR ratios for CMS/MgO/CMS MTJs (CMS MTJs) and CMFS/MgO/CMFS MTJs (CMFS MTJs) CMFS of up to 2610% at 4.2 K and 429% at 290 K [1,3]. To fully exploit the half-metallic character of CMS and CMFS for spintronic devices, the key factors that determine the temperature (*T*) dependence of the device characteristics have to be understood. The purpose of the present study is to clarify the key mechanisms that determine the temperature dependence of the spin-dependent tunneling conductances *G*(= I/V) for P and AP, G_P and G_{AP}, in particular, G_P of CMS and CMFS MTJs both featuring giant TMR ratios. To do this, we experimentally investigated how the *T* dependence of G_P and G_{AP} varied with the degree of the half-metallicity of CMS and CMFS electrodes that were varied through the film composition of the electrodes.

2. Experimental methods

The preparation of fully epitaxial CMS MTJs with various values of α in $Co_2Mn_\alpha Si$ electrodes and CMFS MTJs with various values of α' and β' in $Co_2Mn_{\alpha'}Fe_{\beta'}Si$ electrodes has been described elsewhere [1,3]. The tunneling conductances G_P and G_{AP} were measured by a dc four-probe method at temperatures from 4.2 to 290 K at a small bias voltage of 2 mV. The TMR ratio was defined as TMR = $(G_P-G_{AP})/G_{AP}$.

3. Results and discussion

Figure 1 shows the T dependence of G_P of three kinds of epitaxial MgO-based MTJs; a CMS MTJ and a CMFS MTJ both showing high TMR ratios of 2011% at 4.2 K (329% at 290 K) and 2500% at 4.2 K (429% at 290 K), respectively, and an identically prepared $Co_{50}Fe_{50}$ (CoFe)/MgO/CoFe MTJ (CoFe MTJ) showing a relatively low TMR ratio of 382% at 4.2 K (258% at 290 K). Contrasting dependences were observed: G_P of the CoFe MTJ that showed a lower TMR ratio increased with increasing *T*, in particular, for $T >$ 100K. On the other hand, G_P of the CMS MTJ and CMFS MTJ that showed giant TMR ratios decreased with increasing *T* in a *T* range from T_1 (~25 K) to T_2 (~220 K). Then it increased for $T > T_2$. This result suggested the correlation between the *T* dependence of G_P and the spin polarization at the Fermi level, SP. To clarify the possible origin of the contrasting *T* dependence of G_P, we systematically investigated the *T* dependence of G_P of a series of CMS MTJs with various Mn compositions α in $Co_2Mn_\alpha Si_\beta$ (β = 0.84) electrodes. It has been demonstrated that the TMR ratio increased with increasing α from a Mn-deficient composition ($\alpha < 2-\beta$) to a Mn-rich composition ($\alpha > 2-\beta$) [1−3]. Figure 2 shows the *T* dependence of the normalized G_P, $G_{N,P}$, as a function of *T* from 4.2 K to 290 K for CMS MTJs with various α values in $Co_2Mn_\alpha Si_{0.84}$ electrodes (α = 0.73, 1.24, and 1.30), where G_P was normalized by its value at 4.2 K. It was observed that the maximum decrease in $G_{N,P}$, defined by $\Delta = (1-G_{N,P}(\text{minimum}))$, increased with an increase in the TMR ratio at 4.2 K [Fig. 3]. Along with the increase in Δ, the characteristic temperature, T_2, increased, i.e., the *T* region in which $G_{N,P}$ decreased with increasing *T* extended.

We now discuss the possible origin of the contrasting behaviors of the *T* dependence of G_P of MTJs featuring a various range of the TMR ratio at 4.2 K. We take into consideration two tunneling processes that influence the *T* dependence of the spin-dependent tunneling conductance proposed by Zhang et al. [4] and Shang et al. [5]. In the former model, a spin-flip, inelastic tunneling process via a thermally excited magnon is taken into account (the Zhang's term) [4]. In this model, however, SP is assumed to be fixed against T. In the latter model, only spin-conserved elastic tunneling process is taken into account but the T dependence of SP as for the magnetization is introduced (the Shang's term). Note that the contribution to G_P from the Zhang's term is positive and decreases with increasing SP while the contribution from the Shang's term to G_P is negative. Thus, it is reasonable to ascribe the increase in G_P for MTJs showing lower TMR ratios to the Zhang's term and ascribe the decrease in G_P for a T range from $T_1 < T < T_2$ for MTJs showing higher TMR ratios to the Shang's model because of the relative decrease in the contribution from the Zhang's term. Given these consideration, we fitted the T dependence of G_P of MTJs showing high TMR ratios by taking into account both the Shang's term responsible for the decrease in G_P for $T_1 < T < T_2$ and the Zhang's term responsible for the increase in G_P for $T > T_2$. We confirmed that the thus fitted curve well reproduced the $G_P(T)$ for a CMS MTJ showing a giant TMR ratio [Fig. 4].

4. Conclusion

We showed that the T dependence of the tunneling conductance for P of MTJs with highly spin-polarized electrodes can be explained by the competition between a spin-flip tunneling process via a magnon and a spin-conserved tunneling under the T-dependent spin polarization. These findings advance the understanding of the mechanism of spin-dependent tunneling in spintronic devices with half-metallic electrodes.

References

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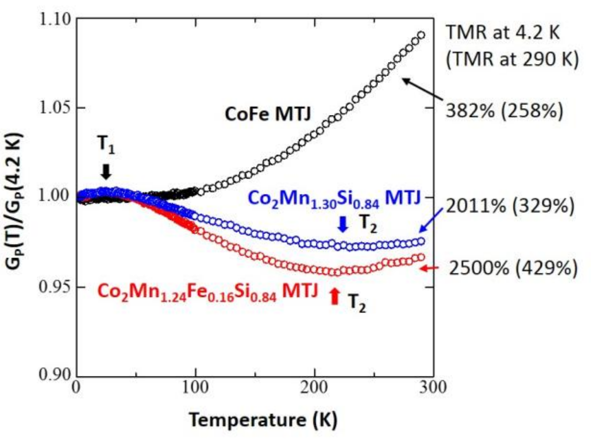

Fig. 1. Typical T dependence of the normalized tunneling conductance for P of three kinds of MgO-based MTJs having a wide range of the TMR ratio at 4.2 K and 290 K.

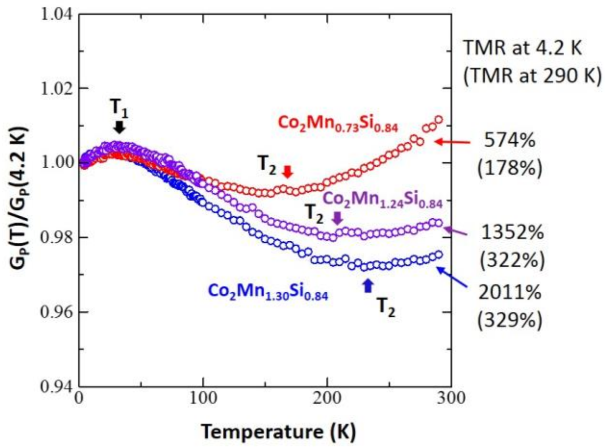

Fig. 2. T dependence of normalized tunneling conductance for P of CMS MTJs with various Mn compositions α in $Co_2Mn_\alpha Si_{0.84}$ electrodes (α = 0.73, 1.24, and 1.30).

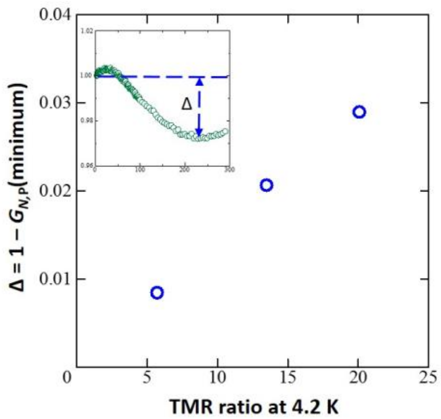

Fig. 3. Maximum decrease in the normalized tunneling conductance for P, $G_{N,P}$, defined by $\Delta = (1-G_{N,P}(\text{minimum}))$, for CMS MTJs shown in Fig. 2 as a function of the TMR ratio at 4.2 K.

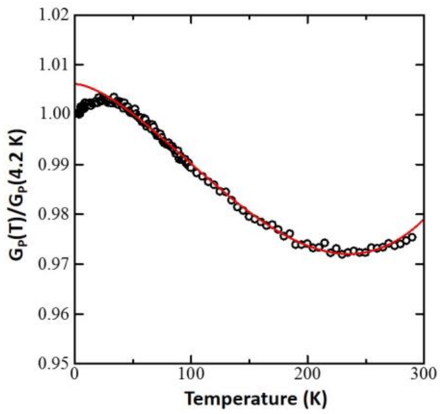

Fig. 4. Experimental (open circles) and fitted (line) curve for a $Co_2Mn_{1.30}Si_{0.84}$ MTJ showing giant TMR ratios of 2011% at 4.2 K and 329% at 290 K.