Characteristic temperature dependence of spin-dependent tunneling conductance of MTJs with highly spin-polarized electrodes

Bing Hu, Kidist Moges, Yusuke Honda, Tetsuya Uemura, and Masafumi Yamamoto
Hokkaido University

Half-metallic ferromagnets are one of the most suitable spin-source materials for spintronic devices because of their complete spin polarization at the Fermi level (E_F). We recently demonstrated that controlling defects through the film composition is critical to retaining 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 magnetic tunnel jucntions (CMS MTJs) and CMFS/MgO/CMFS MTJs (CMFS MTJs) of up to 2610% at 4.2 K and 429% at 290 K [1,3]. The purpose of the present study was to clarify the key mechanisms that determine the temperature (T) dependence of the spin-dependent tunneling conductances G (= I/V) for the parallel (P) and antiparallel (AP), G_P and G_{AP}, in particular, G_P of MTJs with highly spin-polarized electrodes. 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.

The preparation of fully epitaxial CMS MTJs (CMFS MTJs) with various values of α (α' and β') in $Co_2Mn_\alpha Si$ ($Co_2(Mn_{\alpha'}Fe_{\beta'})Si$) 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 K to 290 K at a bias voltage of 2 mV.

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 and an identically prepared $Co_{50}Fe_{50}$ (CoFe)/MgO/CoFe MTJ (CoFe MTJ) showing a relatively low TMR. Contrasting dependences were observed: G_P of the CoFe MTJ increased with increasing T, in particular, for $T > 100$ K, while G_P of the CMS MTJ and CMFS MTJ decreased with increasing T from T_1 (~25 K) to T_2 (~220 K) and then increased for $T > T_2$. This result suggests the correlation between the T dependence of G_P and the spin polarization at E_F.

The possible origin of the contrasting behaviors of the T dependence of G_P of MTJs featuring a wide range of the TMR ratio at 4.2 K can be explained by the competition between two factors involved in the tunneling mechanisms: One is a spin-flip tunneling process via a thermally excited magnon (Zhang's term) [4], which increases G_P with increasing T, and another is a spin-conserved tunneling process but under the decrease in the tunneling spin polarization, which decreases G_P with increasing T due to a spin-wave excitation (Shang's term) [5]. Note that the contribution to G_P from the Zhang's term decreased with increasing spin polarization. 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 two factors: Shang's term responsible for the decrease in G_P for $T_1 < T < T_2$ while the Zhang's term responsible for the increase in G_P for $T > T_2$ (Fig. 2). We confirmed that the thus fitted curve well reproduced the $G_P(T)$ for a CMS MTJ showing a giant TMR ratio.

[1] H.-x. Liu et al., Appl. Phys. Lett. **101**, 132418 (2012). [2] G. -f. Li et al., PRB **89**, 014428 (2014). [3] H. -x. Liu et al., J. Phys. D: Appl. Phys. **48**, 164001 (2015). [4] S. Zhang et al., PRL **79**, 19 (1997). [5] C. H. Shang et al., PRB **58**, 2917(R) (1988).

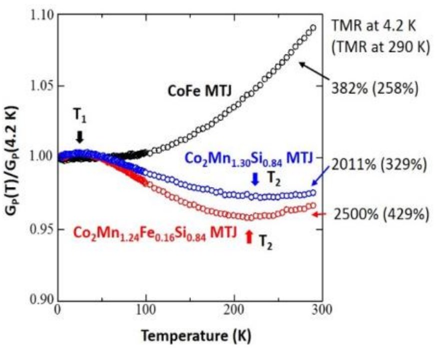

Fig 1. Typical T dependence of the normalized tunneling conductance for P of three kinds of MgO-based MTJs having a wide range of TMR ratio at 4.2 K and 290 K.

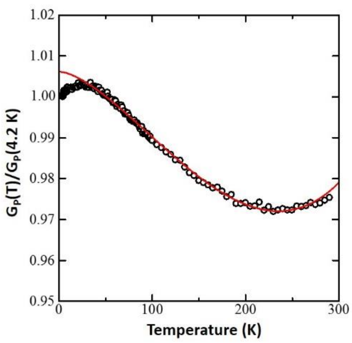

Fig 2. Experimental (open circles) and fitted (line) curve for a $Co_2Mn_{1.30}Si_{0.84}$ MTJ showing giant TMR ratios of 2011% at 4.2 K and 329% at 290 K.