Temperature dependence of spin-dependent tunneling conductance for the parallel configuration of Co$_2$MnSi MTJs with high spin polarization

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A highly efficient spin source is essential for spintronic devices. We recently showed that controlling defects through the film composition is critical to retain the half-metallicity of ternary Heusler alloy Co$_2$MnSi (CMS) and quaternary alloy Co$_4$(Mn,Fe)Si (CMFS) [1–3]. As a result, we demonstrated a giant TMR ratio of up to 2610% at 4.2 K (429% at 290 K) for CMS/MgO/CMS MTJs (CMS MTJs) and CMFS MTJs [1,3]. The purpose of the present study was to clarify the key mechanisms that determine the temperature dependence of the spin-dependent tunneling conductance $G (= I/V)$, in particular, for the parallel configuration (P), $G_P$ of CMS MTJs.

The preparation of fully epitaxial CMS MTJs with various values of $\alpha$ in Co$_2$Mn$_{1-x}$Si$_x$ electrodes has been described elsewhere [1]. $G_P$ was 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 $\text{TMR} = (G_P - G_N)/G_N$.

Figure 1 plots the $T$ dependence of the normalized $G_P$ of CoFe-buffered CMS MTJs with various Mn compositions $\alpha$ in Co$_2$Mn$_{1-x}$Si$_x$ electrodes. The TMR ratios at 4.2 K of these MTJs significantly increased with increasing $\alpha$ from 574% for Mn-deficient $\alpha = 0.73$ to 2011% for $\alpha = 1.30$ [3]. $G_P$ of these MTJs decreased with increasing $T$ in a $T$ range from $T_1$ (~25 K) to $T_2$ (~220 K). Then, it increased for $T > T_2$. Furthermore, the degree of the decrease in the normalized $G_P$ at $T_2$ became larger for the MTJ that showed the larger TMR at 4.2 K. In contrast, the normalized $G_P$ of a CoFe/MgO/CoFe MTJ (CoFe MTJ) that showed a lower TMR of 382% at 4.2 K (258% at 290 K) slightly increased with increasing $T$ from 4.2 K to around 100 K and then increased with $T$ from around 100 K to 290 K. The $T$ dependence of $G_P$ of the CoFe MTJ can be explained by the Zhang’s model in which a spin-flip, inelastic tunneling process via thermally excited magnon is taken into account [4]. Note that the Zhang’s term provides an increase in $G_P$ and $G_N$ with increasing $T$.

To understand the $T$ dependence of $G_P$ of CMS MTJs with $\alpha$ from 0.73 to 1.30 that showed high TMR ratios ranging from 574% to 2011%, we take into consideration two tunneling processes; one is the Zhang’s term [4] and another is the Shang’s term [5]. In the latter term, only spin-conserved elastic tunneling process is taken into account but the $T$ dependence of spin polarization (SP) is introduced. Given this understanding, the $G_P(T)$ for the CMS MTJs were fitted with the conductance at $T = 0$, and the additional terms from the Shang’s process and the Zhang’s process. This analysis is reasonable because the contribution to $G_P$ from the Zhang’s term decreases for MTJs with higher SP, resulting in a relative increase in the contribution of the Shang’s term to $G_P(T)$ for MTJs with higher SP. These fittings for the CMS MTJs well reproduced the experimental $G_P(T)$ with reasonable values of the parameters involved in the fitting. In conclusion, it was clarified that the characteristic $T$ dependence of CMS MTJs showing giant TMR ratios is highly influenced by the half-metallicity of the CMS electrodes.

References