Influence of interface termination layer on temperature dependence of tunneling magnetoresistance of Co$_2$MnSi/MgO-based magnetic tunnel junctions

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We have recently demonstrated giant tunneling magnetoresistance (TMR) ratios ($\beta$) of up to 1995% at 4.2 K and up to 354% at 290 K for epitaxial Co$_2$MnSi (CMS)/MgO/CMS magnetic tunnel junctions (MTJs). If we use parameter $\gamma = \beta (4.2 \text{ K})/\beta (290 \text{ K})$ to represent the degree of temperature ($T$) dependence of $\beta$, $\gamma$ for the CMS MTJs that showed a high $\beta$ of 1910% at 4.2 K was 5.4, resulting in a lower $\beta$ of 354% at 290 K than the 604% at RT for a CoFeB/MgO/CoFeB MTJ that exhibited a much lower $\beta$ of 1144% at 5 K ($\gamma = 1.9$). The purpose of the present study was to investigate the possible origin of the strong $T$ dependence of $\beta$ of CMS/MgO-based MTJs. In this study, we prepared epitaxial MTJs having a CMS electrode in combination with a Co$_9$Fe$_{50}$ (CoFe) electrode and a MgO barrier and prepared three kinds of MTJ layer structures on MgO(001) substrates: (1) MTJ-1: (from the lower side) CoFe/MgO/CMS (3 nm), (2) MTJ-2: CoFe-buffer/CMS (3 nm)/MgO/CoFe (3 nm), and (3) MTJ-3: CoFe/MgO/ultrathin CoFe inserted layer (1.1 nm)/CMS (3 nm). We used Mn-rich CMS electrodes$^{3,4}$ having a film composition of Co$_{3}$Mn$_{13}$Si$_{10}$ for MTJ-1 and a film composition of Co$_{2}$Mn$_{13}$Si$_{10}$ for MTJ-2 and MTJ-3.

Figure 1 shows $\beta$ as a function of $T$ from 4.2 K to 290 K for these three kinds of MTJs. We first compare the $T$ dependence of $\beta$ for MTJ-1 and MTJ-2. It has been experimentally shown that harmful Co$_{3}$Mn antisites are strongly suppressed for Mn-rich CMS electrodes,$^{3,4}$ suggesting that the bare tunneling spin polarizations that are determined by the majority- and minority-spin density of states at the Fermi level are close for the Mn-rich CMS electrodes having the almost identical film compositions used in this study. Then, the higher $\beta$ value at 4.2 K for MTJ-1 than MTJ-2 has been attributed to the enhanced coherent tunneling contribution arising from the larger misfit dislocation spacing for MTJ-1. According to the theory by Zhang et al.$^5$, if the bare tunneling spin polarizations and the properties of thermally excited magnons are close for MTJ-1 and MTJ-2, $\gamma$ should be close. Note that, however, MTJ-1 showed much stronger $T$ dependence of $\beta$ ($\gamma = 3.3$) than MTJ-2 ($\gamma = 2.6$), resulting in a slightly lower $\beta$ of 311% at 290 K for MTJ-1 than the 340% for MTJ-2 although the latter exhibited a markedly lower $\beta$ at 4.2 K.

To clarify the origin of the difference in the $T$ dependence of $\beta$, we investigated the interface structure of these MTJs by high-resolution Z-contrast scanning transmission electron microscopy. We found that the termination layer at the CMS/MgO interface for MTJ-2 mainly consisted of MnMn/O termination layer$^6$ which has been theoretically predicted to be thermodynamically unstable.$^7$ On the other hand, we found that the termination layer for MTJ-1 consisted of coexisting MnMn/O and CoCo/O terminations with one monolayer steps probably caused by the very flat interface in MTJ-1. Given the observation of CoCo/O terminations coexisted with MnMn/O terminations, we attribute the stronger $T$ dependence of $\beta$ to the theoretically predicted strong spin fluctuation of Co atoms in the Co plane of CMS in the interfacial region with a MgO barrier.$^8$

To further evidence this understanding, we prepared MTJ-3 in which an ultrathin CoFe layer (1.1 nm) was inserted between the MgO barrier and the upper CMS electrode. Most importantly, the $T$ dependence of $\beta$ was significantly weakened ($\gamma = 2.5$). This resulted in a much higher $\beta$ of 448% at 290 K. The markedly enhanced $\beta$ at RT for MTJ-3 can be explained by the elimination of the CMS/MgO interface, including in particular, the CoCo/O termination, observed in MTJ-1.


Fig. 1. TMR ratios as a function of $T$ from 4.2 K to 290 K for a CoFe/MgO/CMS (MTJ-1), a CoFe-buffered CMS/MgO/CoFe (MTJ-2) and a CoFe/MgO/CoFe (1.1 nm)/CMS (MTJ-3). For comparison, TMR ratios as a function of $T$ for an identically fabricated CoFe/MgO/CoFe are plotted.