Improved tunnel magnetoresistance characteristics of magnetic tunnel junctions with a Heusler alloy thin film of Co$_2$MnGe and a MgO tunnel barrier

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We fabricated magnetic tunnel junctions (MTJs) with a Co-based full-Heusler alloy thin film of Co$_2$MnGe (CMG) and a MgO tunnel barrier. The microfabricated MTJs with a Co-rich CMG film showed relatively high tunnel magnetoresistance ratios of 83% at room temperature and 185% at 4.2 K. These values are much higher than those previously obtained for CMG/MgO MTJs with a Co-deficient CMG film. © 2007 American Institute of Physics.
We observed the surface morphologies of the 45-nm-thick CMG films deposited on MgO buffer layers (10 nm) using atomic force microscopy. The root mean square (rms) values of the surface roughness increased with postdeposition annealing, from a rms roughness of 0.16 nm for the as-deposited film to 0.26 nm for the 600 °C annealed film. The substrate was a MgO (001) single crystal. The arrows indicate streak patterns corresponding to CMG (110) reflection. The streaks of the as-deposited CMG, obtained previously for an as-deposited Co-deficient CMG film annealed at 600 °C after deposition (t_CMG = 2.4 nm). The junction size was 8 × 8 μm². TMR ratios were 83% at RT and 185% at 4.2 K. (b) TMR ratio, as well as RA_P and RA_AP, at V = 5 mV for the same MTJ shown in Fig. 2(a) as a function of temperature from 4.2 K to RT, where RA_AP and RA_P are the respective resistance-area products for the antiparallel and parallel magnetization configurations between the upper and lower electrodes.

Next, we will describe the spin-dependent tunneling characteristics of fabricated epitaxial MTJs. Figure 2(a) shows typical magnetoresistance curves at a bias voltage (V) of 5 mV at RT and 4.2 K for an as-fabricated CMG/MgO/Co_50Fe_50 MTJ, having a 2.4-nm-thick MgO tunnel barrier, where the lower CMG electrode was in situ annealed at 600 °C after deposition. The junction size was 8 × 8 μm². Exchange-biased TMR characteristics were obtained with relatively high TMR ratios of 83% at RT and 185% at 4.2 K. These values are comparable to the TMR ratios of 90% at RT and 192% at 4.2 K previously obtained for CMS/MgO/Co_50Fe_50 MTJs with a Co-rich CMS film, of which the film composition was Co_2Mn_0.8Si_0.2 (Ref. 22); these are significantly enhanced from the lower TMR ratios of 14% at RT and 70% at 7 K previously reported for CMG/MgO/Co_50Fe_50 MTJs with a Co-deficient CMG film, of which the film composition was Co_2Mn_1.05Ge_1.17.18

Figure 2(b) plots the TMR ratio, as well as RA_AP and RA_P, at V = 5 mV for the same MTJ shown in Fig. 2(a) as a function of temperature (T) from 4.2 K to RT. As T decreased from RT to 4.2 K, the TMR ratio increased by a factor of 2.2. If we use parameter γ = α/RT, where α is the TMR ratio, to represent the degree of T dependence of the TMR ratio, γ for CMG/MgO/Co_50Fe_50 MTJs was 2.2. This value is comparable to the previously obtained γ = 2.1 for CMS/MgO/Co_50Fe_50 MTJs (a TMR ratio of 192% at 4.2 K and 90% at RT)23 and significantly lower than γ = 5.0, which was previously obtained for CMG/MgO/Co_50Fe_50 MTJs (a TMR ratio of 70% at 7 K
and 14% at RT).\textsuperscript{17,18} As shown in Fig. 2(b), $RA_{AP}$ also increased with decreasing $T$, while $RA_{AP}$ was almost independent of $T$. These behaviors were similar to those previously observed for CCFA/MgO/Co$_{50}$Fe$_{50}$ MTJs (Ref. 24) and CMS/MgO/Co$_{50}$Fe$_{50}$ MTJs.\textsuperscript{22} These behaviors were also observed for Co$_{50}$Fe$_{50}$/MgO/Co$_{50}$Fe$_{50}$ MTJs.\textsuperscript{25}

Figure 3 plots $RA_{P}$ and the TMR ratio at RT (measured at $V=5$ mV) as a function of $t_{MgO}$ for the fabricated CMG/MgO/Co$_{50}$Fe$_{50}$ MTJs where the CMG lower electrode was in situ annealed at 500 °C after deposition. The junction size was $10 \times 10 \mu m^2$. A clear exponential dependence of $RA_{P}$ on $t_{MgO}$ was observed for the $t_{MgO}$ range of 2.0–2.8 nm, indicating typical tunnel junction behavior. Relatively high TMR ratios from 72% to 88% were obtained at RT for this wide range of $t_{MgO}$ from (2.0–2.8 nm).

We estimated the spin polarization for the CMG electrodes by using Jullière’s model for the TMR ratio:\textsuperscript{26} $TMR = 2P_{1}P_{2}/(1 - P_{1}P_{2})$, where $P_{1}$ and $P_{2}$ are the spin polarizations at the Fermi level ($E_F$) of the ferromagnetic electrodes in MTJs. We first estimated the effective spin polarization for the Co$_{50}$Fe$_{50}$ electrode from the TMR ratio of 146% at 4.2 K (96% at RT) obtained for the identically fabricated epitaxial Co$_{50}$Fe$_{50}$/MgO/Co$_{50}$Fe$_{50}$ MTJs by using Jullière’s model. Thus, the effective spin polarization value obtained for the Co$_{50}$Fe$_{50}$ electrode ($P_{CoFe}$) was 0.65 at 4.2 K (0.57 at RT). Then, we estimated the effective spin polarization of the CMG film ($P_{CMG}$) from the TMR ratio of 185% at 4.2 K (83% at RT) for the epitaxial CMG/MgO/Co$_{50}$Fe$_{50}$ MTJs by using Jullière’s model with $P_{CoFe}$ of 0.65 at 4.2 K (0.57 at RT). The obtained effective spin polarization or tunneling spin polarization values of $P_{CMG}$ were 0.74 at 4.2 K and 0.51 at RT. These $P_{CMG}$ values are comparable to previously obtained values of 0.75 at 4.2 K and 0.54 at RT for the CMS films.\textsuperscript{22}

The enhanced TMR ratios for the CMG/MgO/Co$_{50}$Fe$_{50}$ MTJs fabricated with a Co-rich CMG film demonstrated that the lower TMR ratios observed previously for the CMG/MgO/Co$_{50}$Fe$_{50}$ MTJs with a Co-deficient CMG film\textsuperscript{17,18} were not due to an intrinsic property of the Co-based full-Heusler alloy of Co$_2$MnGe. The improved TMR characteristics in terms of the TMR ratio or the effective spin polarization at $E_F$ are probably related to the improved structural properties of the CMG film in terms of the degree of structural order.

In summary, we fabricated epitaxial MTJs with a Co-based full-Heusler alloy thin film of CMG and a MgO tunnel barrier. The microfabricated MTJs with a Co-rich CMG film demonstrated relatively high tunnel magnetoresistance ratios of 83% at RT and 185% at 4.2 K. These values are much higher than those previously obtained for CMG/MgO/Co$_{50}$Fe$_{50}$ MTJs with a Co-deficient CMG film.

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