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Enhancement in tunnel magnetoresistance effect by inserting CoFeB to the tunneling barrier interface in Co_2MnSi/MgO/CoFe magnetic tunnel junctions

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Tunnel magnetoresistance (TMR) effect was investigated in Co_2MnSi/CoFeB(0–2 nm)/MgO/CoFe magnetic tunnel junctions (MTJs). TMR ratio was enhanced by inserting a thin CoFeB layer at the Co_2MnSi/MgO interface. The MTJ with CoFeB thickness of 0.5 nm exhibited the highest TMR ratio. From the conductance-voltage measurements for the fabricated MTJs, we infer that the highly spin polarized electron created in Co_2MnSi can conserve the polarization through the 0.5-nm-thick CoFeB layer. Furthermore, by insertion of the thin CoFeB layer, the temperature dependence of the TMR ratio was improved because of the suppression of the fluctuation of the magnetic moment at the Co_2MnSi/MgO interface. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3156858]

The development of ferromagnetic materials with high spin polarization is the most important subject in the spin-electronics field. Ideal high spin polarization materials are half-metallic ferromagnets with a band gap at the Fermi energy level for one spin band.[1] Experimentally, we have observed large tunnel magnetoresistance (TMR) ratios of up to 159% at 2 K in magnetic tunnel junctions (MTJs) with Co_2MnSi/Al–O/CoFe structure, thus proving the half-metallic property of Co_2MnSi (CMS).[2]

Similarly, a crystalline MgO tunnel barrier producing coherent tunneling through the Δ_1 band of ferromagnetic electrodes is attracting much interest for some spin devices. Ikeda *et al.*[3] showed huge TMR ratios of up to 600% at RT in a CoFeB/MgO/CoFeB MTJ. However, the TMR ratio using a CoFeB electrode and a MgO barrier is coming close to the theoretical limit.[4] Miura *et al.*[5] showed that coherent tunneling through the Δ_1 band of Co_2MnSi Heusler alloy theoretically could also occur in a Co_2MnSi/MgO/Co_2MnSi MTJ. We have demonstrated a giant TMR ratio of 753% at 2 K in MTJs with Co_2MnSi/MgO/CoFe structure in, which the MgO barrier was deposited by electron beam (EB) evaporation system. This result indicates that Heusler alloys as electrodes of MgO-based MTJs have great potential to achieve giant TMR ratio by half-metallicity and coherent tunneling.[6] However, the TMR ratio decreased drastically with increasing temperature. We think that the large temperature dependence originated with the inelastic tunneling process occurred by fluctuation of magnetization at the CMS/MgO interface.[7]

On the other hand, CoFeB/MgO/CoFeB MTJ has very small temperature dependence on spin polarization.[3] This indicates that the fluctuation of magnetization at the CoFeB/MgO interface is relatively small compared to that of CMS/MgO interface. Then, insertion of a very thin CoFeB layer into the CMS/MgO interface can improve temperature dependence of the TMR ratio. In this study, to achieve high TMR ratio at RT, we fabricated MTJs with a structure of Co_2MnSi/CoFeB/MgO/CoFe and investigated their spin-dependent tunneling properties.

The magnetron sputtering technique was used to prepare all thin films. We fabricated MTJs with a structure of MgO(20 nm)/Co_2MnSi(50)/CoFeB(d_{CoFeB})/MgO(2.3)/$Co_{50}Fe_{50}$(5)/IrMn(10)/Ta(5) on single crystalline MgO (001) substrates. A Co–Mn–Si alloy target (Co, 43.7%; Mn, 27.95%; and Si, 28.35%) was used to prepare Co_2MnSi films, and the deposited film composition was Co, 50.1%; Mn, 24.0%; and Si, 25.9% as measured by inductively coupled plasma analysis. The CMS bottom electrode was deposited at RT and annealed at 500 °C to obtain good chemical ordering. The CoFeB modifying layer was deposited from 0.3 to 2.0 nm at RT. The MgO tunneling barrier was formed by rf direct sputtering using a MgO target. The Ar pressure was 0.33 Pa. This Ar pressure was optimized to obtain a highly (001)-oriented MgO layer on the CoFeB thin film. All the MTJs were patterned into a four-terminal structure by photolithography and Ar ion milling. The TMR effect was measured at 310 and 10 K. To improve the crystallinity of the MgO barrier and CoFeB, patterned MTJs were annealed in the range of 300–475 °C for 1 h in high vacuum by applying a magnetic field of 1 T. The differential conductance $G(=dI/dV)$ was measured using a standard ac lock-in technique. A positive bias voltage is defined as electrons tunneling from the bottom CMS/CoFeB to the top CoFe electrode. For comparison, we prepared a MTJ with a structure of MgO (001)-subs./Cr/CoFeB/MgO/CoFe/IrMn/Ta, and measured the TMR effect.

Figure 1 shows the annealing temperature dependence of TMR ratio and the typical MR curves for the Co_2MnSi/CoFeB/MgO/CoFe MTJ with various CoFeB thicknesses, and CMS/MgO/CoFe MTJ. TMR ratio increases with increasing annealing temperature because of crystallization of the CoFeB and the MgO layers, and shows a maximum at 425–450 °C. However, for the MTJ with 2.0-nm-

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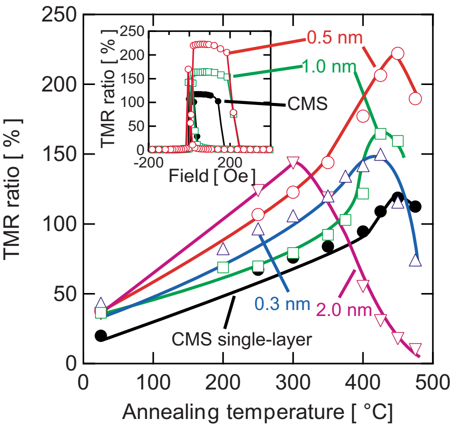

FIG. 1. (Color online) Annealing temperature dependence of TMR ratio.

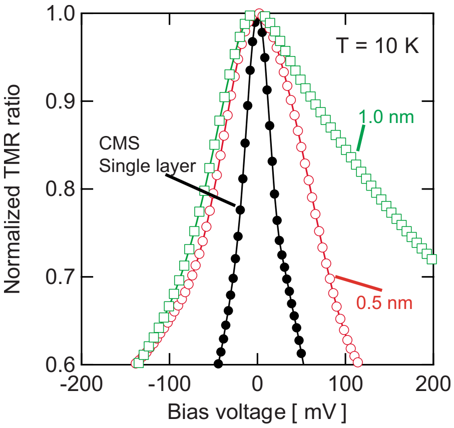

FIG. 3. (Color online) Bias voltage dependence of TMR ratio with various CoFeB thicknesses at 10 K.

thick CoFeB layer, TMR ratio decreased rapidly over 300 °C. We infer that this reduction in TMR is caused by the large amount of boron diffusion in the CMS or MgO layers.

Figure 2(a) shows CoFeB thickness dependence of TMR ratio at 310 and 10 K for the optimized MTJ for each CoFeB thickness. The MTJ with CoFeB thickness of 0.5 nm shows the highest TMR ratio, up to 510% at 10 K and 222% at 310 K. This TMR ratio is larger than those of the CMS/MgO/CoFe MTJ and the CoFeB/MgO/CoFe MTJ. Larger TMR ratio of CMS/MgO/CoFe MTJ than that of CoFeB/MgO/CoFe MTJ at low temperature (LT) indicates that spin polarization of CMS is larger than that of CoFeB. However, TMR ratio of CMS/MgO/CoFe MTJ at RT is smaller than that of CoFeB/MgO/CoFe MTJ. This large temperature dependence of TMR for CMS/MgO/CoFe MTJ is due to inelastic tunneling process, as reported previously.[6]

Figure 2(b) shows the temperature dependence of the TMR ratio (TMR_{RT}/TMR_{LT}) with each CoFeB thickness. TMR_{RT}/TMR_{LT} ratio tends to saturate beyond a thickness of 1.0 nm. This indicates that the temperature dependence of TMR ratio is improved by CoFeB insertion. Figure 3 shows the bias voltage dependence of TMR ratio for various CoFeB thicknesses at 10 K. The CMS/MgO/CoFe MTJ shows a large bias voltage dependence of TMR ratio. On the other hand, the bias voltage dependence of TMR is improved in the MTJs with the CoFeB insertion layer.

Figures 4(a) and 4(b) show bias voltage dependence of conductance (G) measured at 10 K for parallel magnetic configuration. G is normalized by that at zero bias. The MTJs shown in Fig. 4 were annealed at the optimized temperature. For the MTJs with 0.3 and 0.5-nm-thick CoFeB, the conductance curves are similar to the MTJ with CMS single-layer electrode. The shape of the conductance curve reflects the density of states of half-metallic Co_2MnSi, as reported previously.[8,9] On the other hand, for the MTJ with 1.0- and 2.0-nm-thick CoFeB, conductance curves are similar to the MTJ with the CoFeB single-layer electrode.[10] The shape of the conductance curve is characteristic in the MTJs with coherent tunneling through the Δ_1 band of CoFeB.[11] We infer that the highly spin polarized electron in the Co_2MnSi layer can conserve the polarization through the 0.5-nm-thick CoFeB layer.

Figure 5 shows the bias voltage dependence of G measured at 10 K for antiparallel magnetic configuration for the MTJs shown in Fig. 4. G_{AP} for the CMS/MgO/CoFe MTJ increased sharply at low bias voltage. This large zero-bias anomaly of G_{AP} at low bias is caused by the inelastic tunnel-

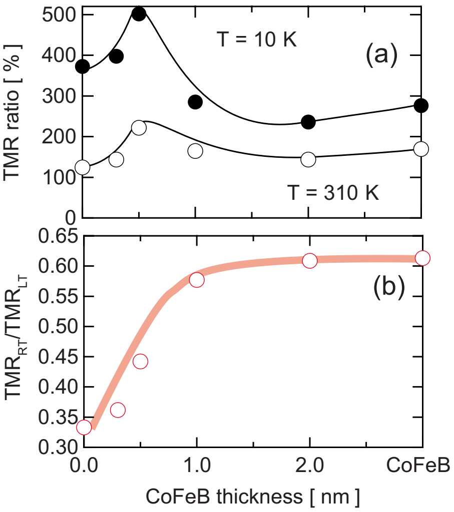

FIG. 2. (Color online) (a) The CoFeB thickness dependence of TMR ratio at 10 and 310 K. (b) The temperature dependence of TMR ratio with each CoFeB thickness.

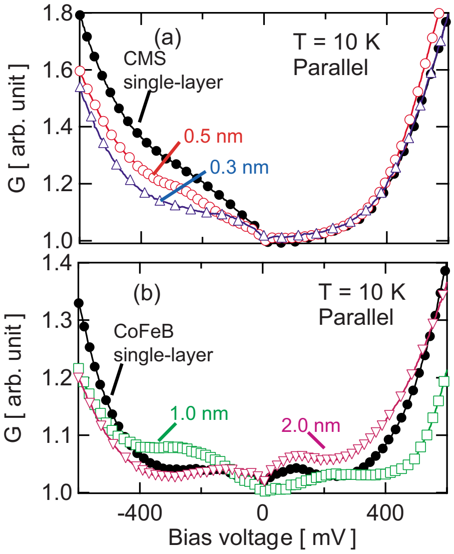

FIG. 4. (Color online) Bias voltage dependence of conductance (G) for parallel magnetic configuration at 10 K.

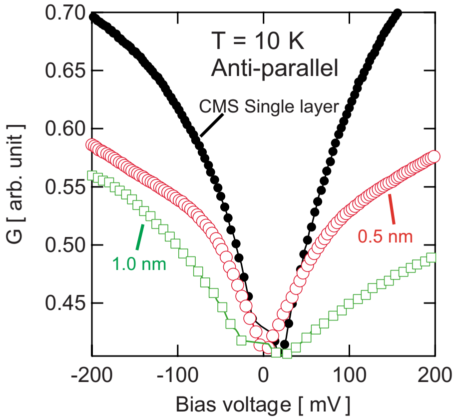

FIG. 5. (Color online) Bias voltage dependence of conductance (G) for antiparallel magnetic configuration at 10 K.

ing processes occurring due to magnetization fluctuation at the CMS/MgO interface. On the other hand, for the MTJs with CoFeB insertion layer, zero-bias anomaly seems to be small compared to G_{AP} of CMS/MgO/CoFe MTJ. This result indicates that the CoFeB insertion layer suppresses fluctuation of magnetization and improves the temperature dependence of TMR ratio.

From the results of G-V measurements, we think that the enhancement in TMR ratio by insertion of CoFeB up to 0.5 nm thickness results from suppression of inelastic tunneling process, and the reduction in TMR ratio by insertion of CoFeB over 0.5nm comes from relatively small spin polarization of CoFeB compared to that of CMS.

In summary, we can improve the TMR ratio by insertion of very thin CoFeB films. From the G-V measurement, we expect that the highly spin polarized electron in the Co_2MnSi layer can conserve the polarization through the 0.5-nm-thick CoFeB layer. Furthermore, the temperature and bias voltage dependence of TMR ratio were improved by inserting CoFeB. These improvements are due to the suppression of the fluctuation of magnetic moment at the CMS/MgO interface.

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