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# Fabrication of magnetic tunnel junctions with a metastable bcc $Co_3Mn$ disordered alloy as a bottom electrode

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We fabricated MgO barrier magnetic tunnel junctions (MTJs) with a $Co_3Mn$ alloy bottom and FeCoB top electrodes. The (001)-oriented epitaxial films of the metastable bcc $Co_3Mn$ disordered alloys obtained showed saturation magnetization of approximately 1640 emu/cm$^3$. The transmission electron microscopy showed that the MgO barrier was epitaxially grown on the $Co_3Mn$ electrode. Tunnel magnetoresistance of approximately 150% was observed at room temperature after the annealing of MTJs at 350°C, indicating that bcc $Co_3Mn$ alloys have relatively high spin polarization.

The magnetic tunnel junction (MTJ) is a key device for spintronics,[1–3] which has been utilized in various magnetic sensors including the read head of a hard disk drive, magnetoresistive random access memory, and neuromorphic applications.[4–6] One of the issues is to enhance the tunnel magnetoresistance (TMR) effect, i.e., junction resistance change depending on the parallel and antiparallel states of two magnetizations for the junctions. Currently, the MgO barrier and FeCoB alloy electrodes are used as the standard MTJ barrier and magnetic materials,[7–11] which exhibited the record 604% in the TMR ratio at room temperature (RT).[12] Such a high TMR ratio is attributed to the orbital symmetry filtering by the MgO barrier and the highly spin polarized $\Delta_1$ band in FeCo alloys.[13,14] To search for routes to further enhance the TMR ratio, it is curious to investigate various magnetic metals other than FeCo binary systems.

Here, we report the TMR effect observed in MTJs utilizing different types of dis-

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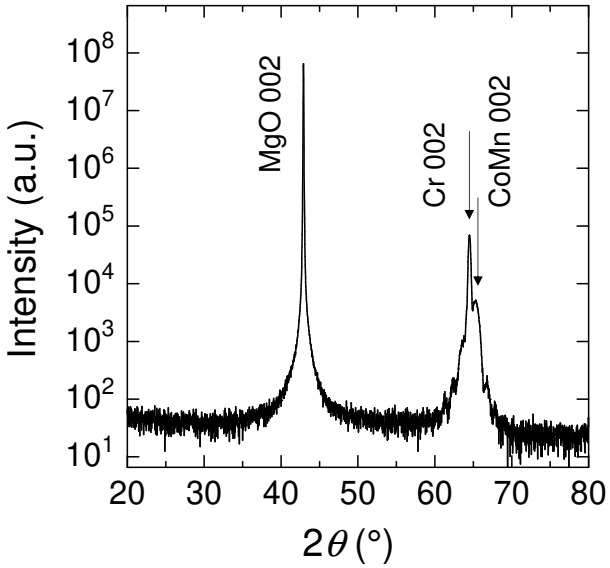


**Fig. 1.** Out-of-plane XRD pattern for $Co_3Mn$ film deposited on (001) Cr-buffered MgO substrate.

ordered bcc CoMn alloy. A bulk Co-rich CoMn binary disordered alloy has a hcp or fcc phase as thermodynamically stable phase.[15–18] The saturation magnetizations and Curie temperatures decrease with increasing Mn concentration, and a magnetic long range order is lost around the Mn concentration of 30–35%.[15–18] In contrast, metastable bcc phase of Co-rich CoMn alloys show the relatively high saturation magnetization at similar Mn composition,[19–21] and a net magnetic moment per atom is in 2.32–2.53 $\mu_B$ at Mn concentration of 24%,[21] being close to that of a bcc Fe. This bcc phase is obtained in thin films grown on (001) GaAs and (001) MgO single crystalline substrates by molecular beam epitaxy (MBE) technique, as reported by a few groups.[19–21] However, there are no reports on MTJs comprised of bcc CoMn alloy electrodes to date.

All samples were deposited on (100) MgO single crystal substrates using a magnetron sputtering technique. The base pressure was $2\times10^{-7}$ Pa. The MTJ staking structure was substrate/ Cr(40)/ $Co_3Mn$(10)/ Mg(0.4)/ MgO(2)/ $Fe_{60}Co_{20}B_{20}$(4.5)/ Ta(3)/ Ru(5) (thickness in nm). All layers were deposited at RT. The composition of $Co_3Mn$ film is $Co_{74}Mn_{26}$ (at.%) determined using inductively-coupled plasma mass spectrometer. We also prepared samples of substrate/ Cr(40)/ $Co_3Mn$(10)/ Mg(0.4)/ MgO(2)/ Ta(2) for structural and magnetization measurements. The crystal structures of the samples were determined using an x-ray diffractometer (XRD) by Cu $K_\alpha$ radiation. Nanostructural analysis of samples was conducted by transmission electron microscopy (TEM). Magnetization measurements were performed using a vibrating sample magnetometer.

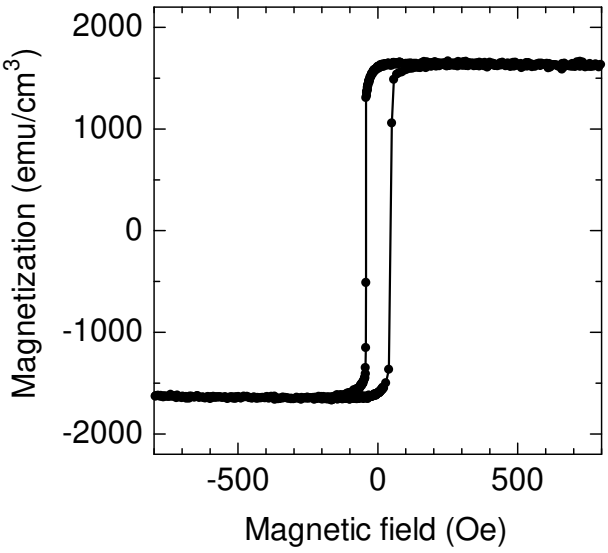


**Fig. 2.** In-plane magnetization hysteresis loop for the $Co_3Mn$ film deposited on (001) Cr buffered MgO substrate.

The microfabrication of the MTJs were performed using a standard ultraviolet photolithography and Ar ion milling. The thirty six junctions with rectangular shapes were obtained on the substrate with the junction areas of 60×15, 40×10, 20×5, 40×2, 15×3, and 20×2 $\mu m^2$. The MTJs were annealed with a vacuum furnace at the temperature range 250–400°C. Magnetoresistance (MR) for the MTJs was measured by a four-probe method using a prober system with a maximum applied field of approximately 1 kOe. All the measurements were performed at RT.

Out-of-plane XRD pattern of the $Co_3Mn$ film is shown in Fig. 1. The 002 peaks from the Cr buffer layer and bcc $Co_3Mn$ were observed, but no other peaks, in particular those from fcc Co-Mn, were detected. The out-of-plane lattice parameter for the $Co_3Mn$ film was evaluated as approximately 0.286 nm, which is close to the lattice constant for the bcc $Co_3Mn$ of 0.285 nm.[19] Thus, it is considered that the (001)-oriented bcc $Co_3Mn$ films were obtained on (001) Cr-buffered MgO substrates.

The in-plane magnetization curve is shown in Fig. 2. The saturation magnetization $M_s$ is approximately 1640 emu/cm$^3$. This value is comparable to that of Co or Fe and is also similar to the magnetic moment value evaluated by x-ray magnetic circular dichroism for bcc $Co_{76}Mn_{24}$ alloy films,[21] rather than that of fcc CoMn alloys with the similar Mn concentration.[16]

The MR curves measured at RT for the 40×2 $\mu m^2$. MTJ annealed at 350°C is shown in Fig. 3(a). The resistance changes depending on the magnetization configuration are

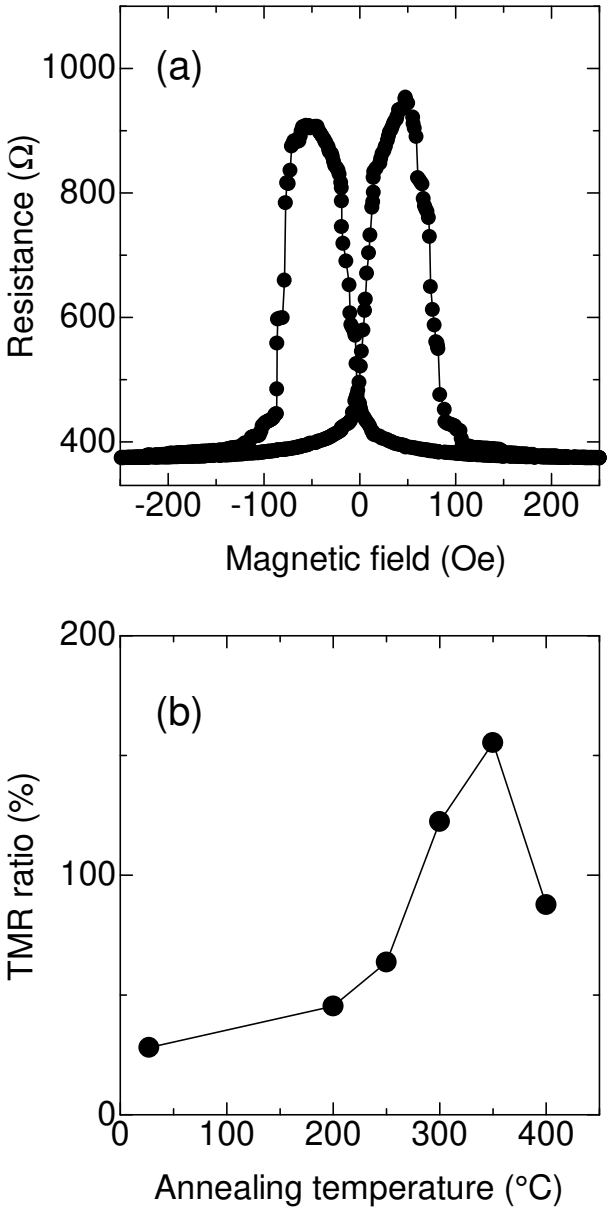


**Fig. 3.** (a) The typical MR curve for MTJs with $Co_3Mn$ film as the bottom electrode. (b) The TMR ratio as a function of the annealing temperature of the MTJ with $Co_3Mn$ film as the bottom electrode.

observed. Note that the MTJ is a pseudo-spin valve type, which means that both magnetic layers were unpinned by the exchange bias[12] and the antiparallel state would not be well defined in this study. Figure 3(b) shows the TMR ratio for this junction as a function of the annealing temperature of the MTJ. The maximum TMR ratio was observed as 155% at the annealing temperature of 350°C in Fig. 3(b) and was 158% for the different MTJ on the same substrate. This value is smaller than the TMR ratio of ∼200% observed at RT in Fe/MgO/Fe fully-epitaxial MTJs fabricated by the MBE

technique.[22)]

Figure 4 shows the cross sectional TEM image for the MTJ sample annealed at 350°C. The MgO barrier is epitaxially grown on the bcc (001) $Co_3Mn$ electrode. Moreover, the coherency of the lattices of $Co_3Mn$, MgO, and almost crystallized FeCoB at the bottom and top interfaces are visible. These observations mean that the coherent tunneling is expected if the bcc $Co_3Mn$ has the $\Delta_1$ band at the Fermi level.

To gain insight into the spin polarization of the bcc $Co_3Mn$ studied here, Julliere's model was used for approximate estimation, which can be expressed as[1)]

$$\text{TMR ratio } (\%) = \frac{2P_1P_2}{1 - P_1P_2} \times 100, \tag{1}$$

where $P_1$ and $P_2$ are the tunneling spin polarization for each magnetic electrode. Since this relation is hold only for an incoherent tunneling, the evaluate spin polarization should be regarded as an effective value in case of the coherent tunneling. To account for the TMR ratio observed in this study using this relation, the tunneling spin polarization for bcc $Co_3Mn$ with MgO barrier should be at least 0.44 at RT if the tunneling spin polarization of FeCoB is 1 . This is relatively higher than the spin polarization of 0.33 evaluated at low temperature in $Co_{73}Mn_{27}$ alloy, which had a low saturation magnetization and was unlikely bcc phase.[23)] A more detailed discussion is beyond the scope of this brief report and will be provided elsewhere.

In summary, we fabricated $Co_3Mn$/MgO/FeCoB MTJs using the sputtering technique. The (001)-oriented metastable bcc $Co_3Mn$ epitaxial films obtained exhibited saturation magnetization of approximately 1640 emu/cm$^3$. The cross-sectional TEM showed that the MgO barrier was epitaxially grown on the $Co_3Mn$ electrode. We observed the TMR ratio of 158% at RT for MTJs annealed at 350°C, indicating that metastable bcc $Co_3Mn$ alloys have relatively high spin polarization.

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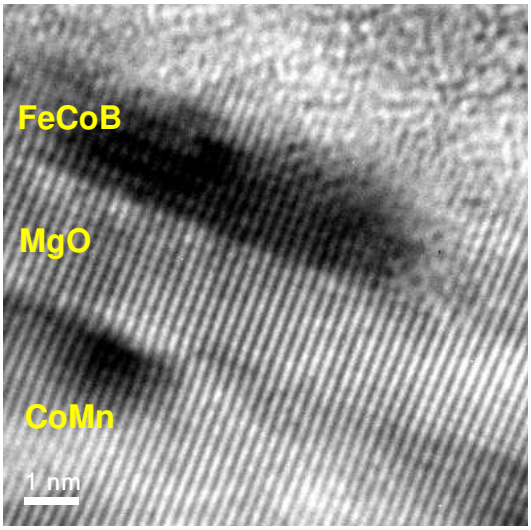


**Fig. 4.** The cross-sectional TEM image for the MTJ sample.

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