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# Anisotropic magnetoresistance in half-metallic $Co_2MnSi$ epitaxial films

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## 1. Introduction

One of the important features in the ferromagnetic materials for spin electronic devices is spin-polarization of density of states (DOS) at Fermi level ($E_F$). Since the DOS contains only one direction of spin-polarized sub-bands at $E_F$, half-metals can result in perfect spin-polarized current and therefore enhance various kinds of spin-dependent transport properties. Generally, when we want to reveal a high spin-polarization in a candidate of half-metallic materials, it is necessary to make a nano-structural vertical or lateral type devices such as CPP-GMR, MTJs and non-local spin-valve device *etc.* by micro-fabrication. Therefore, if the existence of half-metallicity can be investigated by easy and simple measurements on single layer films of the material, it is very convenient to explore a half-metallic material.

The anisotropic magnetoresistance (AMR) effect is a conventional MR effect in ferromagnets, which is a resistance change with a relative angle between current and magnetic field. Basically AMR effect originates from the resistance by the scattering from *s* states to localized *d* states with spin-orbit interaction. Thus, AMR effect contains the information of DOS at the Fermi level. According to Campbell-Fert model [1] and that extended by Tsunoda *et al.* [2], the anisotropic magnetoresistance (AMR) ratio in ideal half-metals is expressed as

$$\frac{\Delta\rho}{\rho}=\frac{-\gamma}{(1-\gamma)+(\rho_{0,\uparrow}/\rho_{sd,\uparrow})} \qquad (1)$$

The constant $\gamma$ is $(3/4)(A/H_{ex})^2$, where $A$ is the spin-orbit coupling constant and $H_{ex}$ is the exchange energy, $\rho_{0,\uparrow}$ is the residual resistivity of conduction electrons with spin↑ in *s*, *p*, and *d* states scattered into their respective states, $\rho_{sd,\uparrow}$ is the resistivity for spin↑ electrons in *s* states scattered into *d* states. Generally $\gamma$ is approximately 0.01; thus theoretically half-metals show a small negative AMR ratio. However, up to now, the understanding of AMR effect in half-metallic materials has not been sufficient yet.

In this study, 50 nm-thick $Co_2MnSi$ (CMS) and $Co_2FeSi$ (CFS) epitaxial films were deposited on (001)-oriented MgO substrate and annealed at different temperatures from 350 to 650 °C. The magnetic and structural properties of the films were investigated by a vibrating samples magnetometer (VSM) and x-ray diffractometer (XRD). Then CMS and CFS films were prepared into wire-shape by photo-lithography and Ar ion milling system. The AMR effect of CMS (CFS) films were detected by PPMS (Physical Property Measurement System) with flowing a current to [110] direction of the CMS (CFS) wires and applying magnetic field of 3 kOe.

## 2. Experimental results and Discussions

The XRD patterns of CMS films are shown in Fig. 1. When the film was annealed at 350 °C, no CMS peaks except for the peaks from MgO substrate were observed. After increasing annealing temperature over 400 °C, (200) and (400) CMS peaks appear, meaning a (100)-preferred orientated growth. The intensity ratio of (200) super-lattice peak to (400) fundamental peak, indicating the degree of B2-ordering, is high even in the sample with 400 °C. Note that, B2-ordering is a sufficient chemical ordering to obtain a half-metallic electric structure in CMS according to the theoretical prediction. [3]

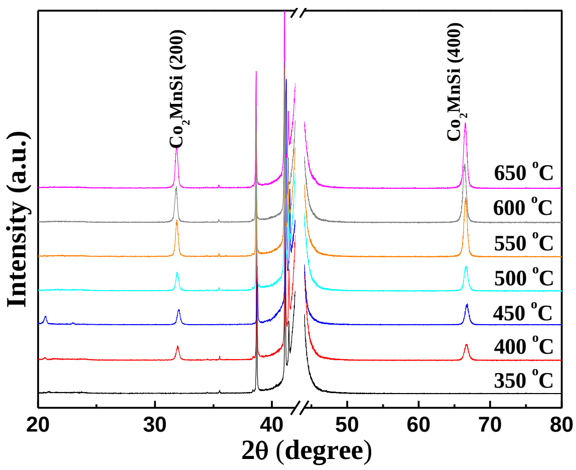


Fig. 1 The XRD patterns of CMS films annealed in vacuum at 350 to 650 °C for 20 minutes.

Figure 2 shows the dependence of relative angle $\theta$ between current and magnetic field directions on the resistance in the CMS film annealed at 400 °C from 0 to 360 °. Clear two fold symmetric curves were observed from 10 to 300 K. As expected from the theoretical prediction, a small negative AMR ratio $(=(R_{//}-R_{\perp})/R_{\perp})$ from -0.167% to -0.137% were observed for whole temperature range.

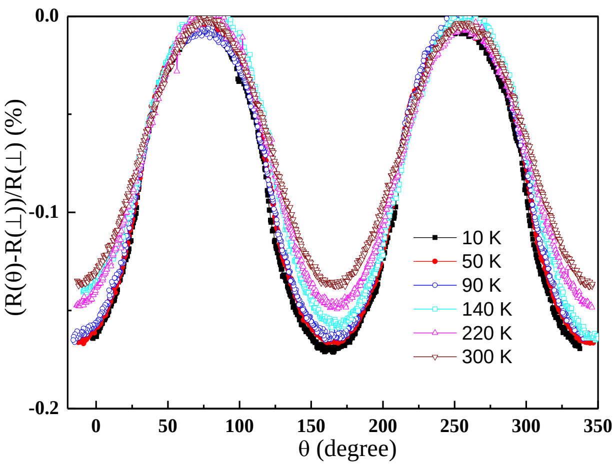


Fig. 2 Resistance changes of CMS films annealed at 400 ℃ as a function of the magnetic field direction against current direction.

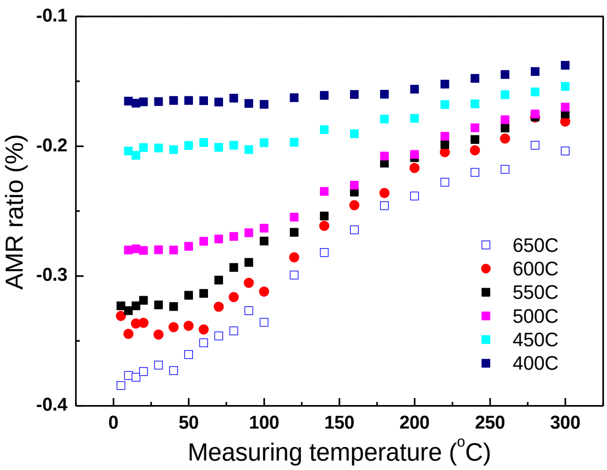


Fig. 3 Change of AMR ratio of CMS films annealed at 400 to 650 °C as a function of the measuring temperature.

The AMR ratio was measured for all CMS films with different annealing temperatures and plotted in Fig. 3 as a function of measurement temperature. All samples annealed above 400°C showed negative AMR ratio, implying a half-metallic nature of these films. The origin of the increasing AMR ratio with increasing annealing temperature is still unclear, but may be related with the reduction of resistivity by annealing because AMR ratio is expressed as $\Delta\rho/\rho$. We also found that the CFS film annealed at 600°C showed a small positive AMR effect (~ +0.2%) although it also has a highly B2-ordered structure. Kubota *et al.* previously studied TMR properties and the magnetic damping parameter in $Co_2(Mn,Fe)Si$. They found that the $E_F$ is across the local *d*-states in minority-spin channel near half-metallic gap edges in CFS, thus CFS showed a small TMR ratio and a large damping parameter. When the local *d*-states appear at $E_F$ in the minority spin-band, a positive AMR ratio is predicted in the case of majority spin conduction in ref. [2].

Observed negative and positive signs of AMR in CMS and CFS, respectively, are consistent with the prediction on the basis of Campbell-Fert model.

## 3. Conclusions

In this study, the AMR effect in CMS and CFS epitaxial films were investigated. Observed sign of AMR ratio, negative in CMS and positive CFS seems to agree with the theoretical prediction. The sign of AMR effect could be one indicator of the half-metallicity.


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