Magnetoresistance in bilayers of heavy metal and non-collinear antiferromagnet

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We report on magnetoresistance measurements in a heavy metal/ Mn\textsubscript{3}Ir multilayers. After a post annealing process, we observed the magnetoresistance associated with the ordered crystalline structure of the Mn\textsubscript{3}Ir. The resistance change as a function of the strength as well as the direction of the applied field suggests that the magnetoresistance is partially related to a modification of the Néel order by the magnetic field. Our further detailed investigation revealed that there is an additional component of the resistance change, perhaps due to the non-collinear magnetic structure associated with the \textit{L1\textsubscript{2}}-ordered Mn\textsubscript{3}Ir, which cannot be accounted for by any conventional magnetoresistance effects.

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1. Introduction

Antiferromagnetic spintronics is an emerging field which utilizes antiferromagnets (AFMs) as active components in spintronic applications\textsuperscript{1,2).} Compared to ferromagnets (FMs), AFMs have several appealing properties, e.g., zero stray field, robustness against magnetic field perturbations, and ultrafast dynamics, leading to an ultrahigh density memory and ultrafast information processing. However, in other words, the insensitivity to an external magnetic field makes electrical manipulation and detection of the Néel order in AFMs quite challenging. Especially, the difficulty of the electrical detection obstructs experimental advances of antiferromagnetic spintronics as opposed to the ferromagnetic spintronics.

Nevertheless, recent studies have demonstrated the electrical detection of the Néel order in some of the antiferromagnetic materials by the same principle having been used for ferromagnetic materials—i.e. anisotropic magnetoresistance (AMR)\textsuperscript{3) and the spin Hall magnetoresistance (SMR)\textsuperscript{4,5}.} AMR and SMR depend on the square of the spontaneous magnetization, these magnetoresistances in principle appear not only in FMs but also in the AFMs\textsuperscript{6).} These magnetoresistances have been reported in some of the particular collinear AFMs, such as FeRh\textsuperscript{7,8)}, NiO\textsuperscript{9-12), CuMnAs\textsuperscript{13)}, and Mn\textsubscript{3}Au\textsuperscript{14-16),} etc. in which the Néel order control is evidently possible.

More intriguing magnetoresistive effect in AFMs is the giant anomalous Hall effect (AHE) was experimentally reported for a similar material system, i.e. Mn\textsubscript{3}Sn\textsuperscript{18).}

As the electrical detection of the magnetic state in AFMs is one of the indispensable ingredients for advancing the antiferromagnetic spintronics, it is important to further investigate the magnetoresistive effect in various antiferromagnetic multilayer systems. In this work, we examined the magnetoresistance in Pt/Mn\textsubscript{3}Ir and W/Mn\textsubscript{3}Ir bilayers. Mn\textsubscript{3}Ir alloys are one of the most commonly used metallic AFMs in spintronic devices for creating exchange bias\textsuperscript{19,20).} Among various intermetallic alloys of Mn and Ir, \textit{L1\textsubscript{2}}-ordered Mn\textsubscript{3}Ir is of great interest for the abovementioned novel magnetoresistive behavior owing to the non-collinear chiral magnetic structure\textsuperscript{21).}

2. Experimental Procedure

We formed W 6 nm/Mn\textsubscript{75}Ir\textsubscript{25} 10 nm/MgO 2 nm/W 2 nm and Pt 6 nm/Mn\textsubscript{75}Ir\textsubscript{25} 10 nm/MgO 2 nm/W 2 nm on a thermally oxidized Si substrate by magnetron sputtering. The MgO 2 nm/W 2 nm capping layers in both samples are to avoid the sample from oxidation and degradation. The films annealing was performed at 220\textdegree C for 30 min. We separately confirmed that the Mn\textsubscript{3}Ir 10 nm layer in both samples possesses an antiferromagnetic order\textsuperscript{22).} Fig. 1 shows the X-ray diffraction (XRD) of the films before and after the annealing. The films annealing was performed at 220\textdegree C for 30 min. We separately confirmed that the Mn\textsubscript{3}Ir 10 nm layer in both samples possesses an antiferromagnetic order\textsuperscript{22).} Fig. 1 shows the X-ray diffraction (XRD) of the films before and after the annealing. A distinct difference between the W/Mn\textsubscript{3}Ir and the Pt/Mn\textsubscript{3}Ir multilayers can be found in the evolution of the (110) superlattice peak of L\textsubscript{1\textsubscript{2}} Mn\textsubscript{3}Ir\textsuperscript{23) while (220) peak was buried in the intense (400) peak of Si substrate. The L\textsubscript{1\textsubscript{2}} order is developed in W/Mn\textsubscript{3}Ir after annealing while the annealing
annihilates the $L1_2$ order in the Pt/Mn$_3$Ir case, indicating that the crystalline symmetry of the underlayer ($\alpha$ (b.c.c.) or $\beta$ structure for W and f.c.c. for Pt) is important for crystallinity of the Mn$_3$Ir. For electrical measurements, the films were patterned into a 120-$\mu$m-long and 30-$\mu$m-wide Hall bar structure by a conventional photolithography and Ar ion milling process. The electrical measurements were performed using the Physical Property Measurement System (PPMS-9T, Quantum Design). The longitudinal $R_{xx}$ and transverse $R_{xy}$...
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R_{xy} resistances were measured with the excitation current of 1 mA (J ~ 2.1 \times 10^5 A/cm^2) in a rotating magnetic field with a fixed magnitude (H = 0 ~ 9 T). The excitation current flows along x-axis. The definition of the rotating angles: \( \alpha \), \( \beta \), and \( \gamma \) are indicated in Figs. 2 (a-c).

3. Results

Figures 2 (d-g) show the magnetoresistance ratio \( \Delta R_{xx}/R_{xx} \) and \( \Delta R_{xy}/R_{xx} \) as functions of \( \alpha \), \( \beta \), and \( \gamma \) with \( H = 9 \) T before and after annealing. Both W/Mn\(_3\)Ir and Pt/Mn\(_3\)Ir samples did not show any \( \alpha \) dependent magnetoresistive behaviors before annealing (as indicated in gray data points in Figs. 2 (d-g)). Measurements in other angles \( \beta \) and \( \gamma \) are omitted. On the other hand, after annealing, appreciable magnetoresistances were observed but the behaviors with respect to the rotating angles differ for the two samples. The most intriguing and distinct differences can be seen in the resistance variation with respect to the rotating angle \( \alpha \) which are shifted by \( \pi/2 \) between the W/Mn\(_3\)Ir and Pt/Mn\(_3\)Ir samples. Figure 3 shows the field dependence of \( \Delta R_{xx}/R_{xx} \) in the annealed W/Mn\(_3\)Ir(a) and Pt/Mn\(_3\)Ir(b) samples. These \( \Delta R_{xx}/R_{xx} \) are summarized in Fig.3(c).

In order to step into a quantitative argument on these intriguing magnetoresistance behaviors, we firstly consider the change in the longitudinal resistance \( \Delta R_{xx} \) in these multilayer systems. The derivation of the \( R_{xx} \) change due to the SMR and the AMR can start from a detailed quantitative model but will come back to the point in the later argument. Assuming that the external field is large enough to induce the spin-flopping of the AFM and the magnetic anisotropy energy is negligibly small compared to the exchange energy, Equation (1) leads to \( \Delta R_{xx} \) depending on the net magnetization vector \( \mathbf{M}_{\parallel} \) parallel to the external field and \( \mathbf{M}_{\perp} \) perpendicular to the external field, where \( \mathbf{M}_{\parallel} \) is regarded as the ferromagnetic order parameter and \( \mathbf{M}_{\perp} \) maybe regarded as the antiferromagnetic order parameter, or the Néel vector. Table 1 shows the magnetoresistance ratio \( \Delta R_{xx}/R \) considering SMR and AMR for \( \mathbf{M}_{\parallel} \) and \( \mathbf{M}_{\perp} \). One can notice from the list of the magnetoresistances in Table 1 that the contribution of AMR and SMR can be separated out by having the complete data set for \( \alpha \), \( \beta \), and \( \gamma \) rotations. Here, the amplitude of the trigonometric functions, A_{FS}, A_{AS}, A_{FA}, and A_{AA} considers the resistance change due to SMR for \( \mathbf{M}_{\parallel} \), SMR for \( \mathbf{M}_{\perp} \), AMR for \( \mathbf{M}_{\parallel} \), AMR for \( \mathbf{M}_{\perp} \), respectively. We also derive the change in the...
transverse magnetoresistances $\Delta R_{xy}$ in a similar manner starting from the equation \(4,24\),

$$\Delta R_{xy} = \sum_{n} (\Delta R_{SMR} m_{n,x} m_{n,y} + \Delta R_{AMR} m_{n,x} m_{n,y} + \Delta R_{OR} m_{n,z}) \tag{2}$$

where $\Delta R_{OHE}$ is the coefficient for the ordinary Hall effect. The contributions to $\Delta R_{xy}/R_{xx}$ by AMR, or planar Hall effect, and SMR are summarized in Table 2 in terms of $a$, $\beta$, and $\gamma$ rotations. Since the transverse resistance change contains significant amount of the ordinary Hall effect from the Pt layer, which makes the quantitative argument difficult when using $\Delta R_{xy}/R_{xx}$ in the following discussion, we will focus on $\Delta R_{xy}/R_{xx}$ for a quantitative argument.

According to Table 1, considering both SMR and AMR, the amplitude for the rotation $a$ is represented as $(A_F - A_S) - (A_F - A_A)$, the amplitude for the rotation $\beta$ is represented as $A_F - A_S$ and that for the rotation $\gamma$ is represented as $A_F - A_A$. For the W/Mn$_3$Ir case, we find $(A_F - A_S) - (A_F - A_A) = 6.4 \times 10^{-5}$, $A_F - A_S = 8.4 \times 10^{-5}$ and $A_F - A_A = 15.4 \times 10^{-5}$ (see Figs. 2 (d)), which are not self-consistent. Since there are additional magnetoresistances we are missing in our consideration in addition to antiferromagnetic order dominant magnetoresistance. On the other hands, for the Pt/Mn$_3$Ir case, we find $(A_F - A_S) - (A_F - A_A) = 4.5 \times 10^{-5}$, $A_F - A_S = 4.3 \times 10^{-5}$ and $A_F - A_A = 0.9 \times 10^{-5}$ (see Figs. 2 (e)), which are relatively self-consistent within the error factor of $\pm 7 \times 10^{-5}$. The results of the Pt/Mn$_3$Ir case is indeed very similar to the previous report which is explained by an uncompensated magnetic moment is induced at Pt/FeMn interface \(20\). In other words, a ferromagnetic order parameter is dominant in this case.

Although Mn$_3$Ir itself is generally robust against 9 T of magnetic field, it is likely that the magnetic moments of Mn$_3$Ir with the Pt and W underlayer can become manipulated by magnetic field after the annealing. In the case of W/Mn$_3$Ir, the

emergences of the magnetoresistance as well as the additional unknown magnetoresistance seem to be associated with the formation of L1$_2$ ordered structure.

5. Conclusion

In summary, the magnetoresistance in the heavy metal/AFM metal multilayers has been studied. Both Pt/Mn$_3$Ir and W/Mn$_3$Ir exhibit appreciable magnetoresistance in a rotating magnetic field with $\pm 9$ T. Assuming that the AMR and SMR are the relevant magnetoresistive effects in these systems, we found that there is an additional unconventional magnetoresistance contribution in the W/Mn$_3$Ir. As this additional magnetoresistance is associated with the formation of L1$_2$- Mn$_3$Ir structure, we speculate that it could be related to the non-collinear antiferromagnetic order.

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References

22) We did field cooled with an external field of 0.3 T in separate W(6 nm)/Mn3Ir(10 nm)/FeCoB(4 nm) and Pt(6 nm)/Mn3Ir(10 nm)/FeCoB(4 nm) samples to confirm its antiferromagnetic order by observing exchange bias. The magnitude of the exchange bias were estimated from the planar Hall effect by using a fitting function that we reported before in K. Oda, T. Moriyama, M. Kawaguchi, M. Kamiya, K. Tanaka, K.-J. Kim, and T. Ono: Jpn. J. Appl. Phys., 55, 070304 (2016). As a result, exchange bias in the former structure showed 0.0106 T while in latter structure was 0.0416 T.
31) We did field cooled with an external field of 0.3 T in separate W(6 nm)/Mn3Ir(10 nm)/FeCoB(4 nm) and Pt(6 nm)/Mn3Ir(10 nm)/FeCoB(4 nm) samples to confirm its antiferromagnetic order by observing exchange bias. The magnitude of the exchange bias were estimated from the planar Hall effect by using a fitting function that we reported before in K. Oda, T. Moriyama, M. Kawaguchi, M. Kamiya, K. Tanaka, K.-J. Kim, and T. Ono: Jpn. J. Appl. Phys., 55, 070304 (2016). As a result, exchange bias in the former structure showed 0.0106 T while in latter structure was 0.0416 T.

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