Magnetoresistance in bilayers of heavy metal and non-collinear antiferromagnet

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We report on magnetoresistance measurements in a heavy metal/ Mn₃Ir multilayers. After a post annealing process, we observed the magnetoresistance associated with the ordered crystalline structure of the Mn₃Ir. 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 $L1_2$-ordered Mn₃Ir, which cannot be accounted for by any conventional magnetoresistance effects.

We formed W 6 nm/Mn₇₅Ir₂₅ 10 nm/MgO 2 nm/W 2 nm and Pt 6 nm/Mn₇₅Ir₂₅ 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°C for 30 min. We separately confirmed that the Mn₃Ir 10 nm layer in both samples possesses an antiferromagnetic order 22). Fig. 1 shows the X-ray diffraction (XRD) of the films before and after the annealing. The films annealing was performed at 220°C for 30 min. We separately confirmed that the Mn₃Ir 10 nm layer in both samples possesses an antiferromagnetic order 22). Fig. 1 shows the X-ray diffraction (XRD) of the films before and after the annealing. The films annealing was performed at 220°C for 30 min. We separately confirmed that the Mn₃Ir 10 nm layer in both samples possesses an antiferromagnetic order 22). Fig. 1 shows the X-ray diffraction (XRD) of the films before and after the annealing. The films annealing was performed at 220°C for 30 min. We separately confirmed that the Mn₃Ir 10 nm layer in both samples possesses an antiferromagnetic order 22). Fig. 1 shows the X-ray diffraction (XRD) of the films before and after the annealing. The films annealing was performed at 220°C for 30 min. We separately confirmed that the Mn₃Ir 10 nm layer in both samples possesses an antiferromagnetic order 22). Fig. 1 shows the X-ray diffraction (XRD) of the films before and after the annealing. The films annealing was performed at 220°C for 30 min. We separately confirmed that the Mn₃Ir 10 nm layer in both samples possesses an antiferromagnetic order 22). Fig. 1 shows the X-ray diffraction (XRD) of the films before and after the annealing. The films annealing was performed at 220°C for 30 min. We separately confirmed that the Mn₃Ir 10 nm layer in both samples possesses an antiferromagnetic order 22).
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-μm-long and 30-μm-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 $R_{xy}$...
$R_{xx}$ resistances were measured with the excitation current of 1 mA ($J \sim 2.1 \times 10^5$ A/cm$^2$) in a rotating magnetic field with a fixed magnitude ($H = 0 \sim 9$ T). The excitation current flows along the $x$-axis. The definition of the rotating angles: $\alpha$, $\beta$, and $\gamma$ are indicated in Figs. 2 (a-c).

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.

4. Discussion

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 Equation (1). $R_{xx}$ is the field independent resistance, and $\Delta R_{AMR}$ and $\Delta R_{SMR}$ are the resistance change due to AMR and SMR, respectively. $m_{n,x}$ and $m_{n,y}$ are respectively a unit vector along the $x$- and $y$-axis of the $n$th magnetic sublattice. Here, we left aside a possible magnetoresistance due to the chiral magnetic structure in absence of 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, $A_{FS}$, $A_{SS}$, $A_{FA}$, 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 6,24,

$$R_{xy} = \sum_n^\infty (\Delta R_{SMR}m_n x m_n y + \Delta R_{AMR}m_n x m_n y + \Delta R_{OHE}m_n z)$$

(2)

where $\Delta R_{OHE}$ is the coefficient for the ordinary Hall effect. The contributions to $\Delta R_{xy}$ by AMR, or planar Hall effect, and SMR are summarized in Table 2 in terms of $\alpha$, $\beta$, 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 $\Delta R_{cal}/R_{xx}$ for a quantitative argument.

According to Table 1, considering both SMR and AMR, the amplitude for the rotation $\alpha$ 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/Mn3Ir 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 $A_F - A_A = -1.54 \times 10^{-5}$ (see Figs. 2 (d)), which are not self-consistent indicate that there are additional magnetoresistances we are missing in our consideration in addition to antiferromagnetic order dominant magnetoresistance. On the other hands, for the Pt/Mn3Ir 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 $\sim 7 \times 10^{-6}$. The results of the Pt/Mn3Ir case is indeed very similar to the previous report which is explained by an uncompensated magnetic moment is induced at Pt/FeMn interface20. In other words, a ferromagnetic order parameter is dominant in this case.

Although Mn3Ir itself is generally robust against 9 T of magnetic field, it is likely that the magnetic moments of Mn3Ir with the Pt and W underlayer can become manipulated by magnetic field after the annealing. In the case of W/Mn3Ir, the

emergences of the magnetoresistance as well as the additional unknown magnetoresistance seem to be associated with the formation of $L1_2$ ordered structure.

| Rotation | $\Delta R_{SMR, M1} / R$ | $\Delta R_{SMR, M2} / R$ | $\Delta R_{AMR, M1} / R$ | $\Delta R_{AMR, M2} / R$ |
|---------|--------------------------|--------------------------|--------------------------|--------------------------|
| $\alpha$ | $A_F \cos^2 \alpha$ | $A_S \sin^2 \alpha$ | $A_F \cos^2 \alpha$ | $A_A \sin^2 \alpha$ |
| $\beta$  | $A_F \sin^2 \beta$ | $A_S \cos^2 \beta$ | 0 | 0 |
| $\gamma$ | 0 | 0 | $A_F \sin^2 \gamma$ | $A_A \cos^2 \gamma$ |

### Table 2 Transverse resistance change due to SMR and AMR

| Rotation | $\Delta R_{SMR, M1} / R$ | $\Delta R_{SMR, M2} / R$ | $\Delta R_{AMR, M1} / R$ | $\Delta R_{AMR, M2} / R$ |
|---------|--------------------------|--------------------------|--------------------------|--------------------------|
| $\alpha$ | $A_F \sin 2\alpha$ | $-A_S \sin 2\alpha$ | $A_F \sin 2\alpha$ | $-A_A \sin 2\alpha$ |
| $\beta$  | $A_F \sin \beta$ | 0 | $A_F \sin \beta$ | 0 |
| $\gamma$ | 0 | 0 | $A_F \cos \beta$ | 0 |

### 5. Conclusion

In summary, the magnetoresistance in the heavy metal/AFM metal multilayers has been studied. Both Pt/Mn3Ir and W/Mn3Ir exhibit appreciable magnetoresistance in a rotating magnetic field with $\sim 9$ 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/Mn3Ir. As this additional magnetoresistance is associated with the formation of $L1_2$-Mn3Ir structure, we speculate that it could be related to the non-collinear antiferromagnetic order.

### Acknowledgements

We thank Prof. Daisuke Kan for helping us with performing the X-ray diffraction measurements. This work was supported by JSPS KAKENHI. Grant Numbers JP15H05702, JP15H05703, JP15H05702, JP26870300, JP17H05181, JP16H04487. We also acknowledge The Cooperative Research Project Program of the Research Institute of Electrical Communication, Tohoku University.

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Received Aug. 13, 2018; Accepted Nov. 19, 2018