Estimation of magnetic domain size in chiral antiferromagnet Mn$_3$Ir by the anomalous Hall measurements

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Chiral antiferromagnets have recently been drawing attention due to their unique magnetic transport properties such as the giant anomalous Hall effect. We previously reported an experimental demonstration of the giant anomalous Hall effect in the chiral antiferromagnet Mn$_3$Ir thin films with quite blunt hysteresis curves suggesting a large distribution of magnetic properties associated with magnetic domains. In this work, we measured the anomalous Hall effect and its hysteresis curve in the Mn$_3$Ir of various device sizes. By comparing the experimental data with our developed statistical model, we characterize a distribution of the magnetic domain size in our Mn$_3$Ir films.

Keywords: anomalous Hall effect, chiral antiferromagnet, Mn$_3$Ir, magnetic domain, thin film, statistical analysis

Chiral antiferromagnets, a new class of non-collinear antiferromagnets, have recently been drawing attention owing to their intriguing transport properties. The non-collinear magnetic structure with broken space inversion symmetry causes a large Berry curvature which gives rise to a giant anomalous Hall effect (AHE)\(^{12,27}\), anomalous Nernst effect (ANE)\(^{3-6}\), and magneto-optical Kerr effect\(^{7-9}\). Chiral antiferromagnets have been investigated in the context of not only the topological physics\(^{10,11}\), but also antiferromagnetic spintronics\(^{22}\) where their small net magnetization\(^1\) and the high-speed magnetic response\(^{13}\) are advantageous for spintronic devices such as spin-torque magnetic memories\(^{14-16}\). Most of these leading-edge researches have been successful with a particular chiral antiferromagnet, D0$_{19}$-ordered Mn$_3$Sn, which is one of the chiral antiferromagnetic compounds Mn$_3$X (X = Sn, Ge, Ga, Ir, Pt, and Rh) family\(^{17-23}\). Mn$_3$Ir which is focused on in this paper is much less investigated although the relatively large anomalous Hall conductivity is predicted among the Mn$_3$X family\(^{22}\).

We previously reported the fabrication of L1$_2$-ordered Mn$_3$Ir thin films and the demonstration of the giant AHE. The AHE hysteresis curves emerge due to the reversal of the magnetic domain associating with the reversal of the small net magnetization\(^{24}\). As L1$_2$-Mn$_3$Ir have a large magnetocrystalline anisotropy due to a large spin-orbit interaction of Ir\(^{20,26}\), the coercive field, or the switching field, is found larger than several Tesla\(^{24}\). Our previously observed hysteresis curves of the anomalous Hall effect were quite blunt with a large switching field, suggesting that the magnetic reversal is not uniform but is driven by magnetic domains. To further explore the potential of the Mn$_3$Ir as a chiral antiferromagnet, it is important to understand the magnetic reversal giving rise to the AHE\(^{27,28}\).

In this work, we investigate the hysteresis curves of the AHE in Mn$_3$Ir to characterize the “magnetic domain” size within which the magnetizations uniformly rotate to give rise to the AHE\(^{28}\). We took a distribution of the hysteresis curves for various sizes of the Hall cross devices which should be significantly affected by the relative size of the magnetic domains to the device size. Assuming there are two key distributions: one is the magnetic domain size distribution and the other is the AHE distribution in each magnetic domain. For instance, in the limit where the magnetic domain is much larger than the device size, the AHE distribution would be averaged out by the many domains and would be smaller. The device size dependence of the distribution was analyzed by a statistical model based on the above assumption to determine the domain size.

Mn$_3$Ir thin films of thickness 20 nm were grown by magnetron sputtering on a thermally oxidized Si substrate at the substrate temperature $T_s = 700$ °C in the Fig. 1. (a) The Hall cross device. $w$ is the channel width of the Hall cross bar. (b) The transverse resistivity $\rho_{xy}$ for the Hall cross area $S_{Hall} = 1 \mu m^2$ as a function of magnetic field.
chamber with the base pressure of 1.5×10^{-5} Pa. The fabrication process is identical to our previous report(24). During the deposition, we rotate the sample holder along its normal axis to ensure a uniform composition and thickness. A plate of arc-melted Mn75%-Ir alloy was used for the sputtering target. SiO_2 of thickness 5 nm was deposited on top of the Mn3Ir film to prevent the oxidation. For the transport measurements, the films were photolithographically patterned into a Hall cross structure with the channel width \( w \) ranging from 1 \( \mu \text{m} \) to 10 \( \mu \text{m} \) (Fig. 1(a)). Hall measurements were carried out at room temperature with an external field applied perpendicular to the sample plane, by using the current-spinning technique to remove any parasitic offset voltage due to geometrical imperfections of the Hall cross structure(30). Any residual offset should be intrinsically linked to the material property in response to the magnetic field.

Figure 1(b) shows transverse resistivity \( \rho_{xy} \) as a function of external field \( H \) of typical Hall cross area \( S_{\text{Hall}} = w^2 \) equal to 1 \( \mu \text{m}^2 \), the Hall cross area which is relevant to the anomalous Hall effect (see Fig. 1 (a)). We measured at least 10 different devices for each Hall cross area \( S_{\text{Hall}} = 1, 4, 9, 25, 49, \) and 100 \( \mu \text{m}^2 \).

Since the hysteresis curves do not saturate with the external magnetic field available in the lab (< 9 Tesla), all the AHE hysteresis curves are considered as a minor loop. Therefore, the coercive field \( H_c \) is not a good physical quantity and does not directly reflect the distribution of the coercive field in each domain \( H_{c,\text{domain}} \). We instead take the maximum \( \rho_{xy} \) for each hysteresis curve to evaluate a distribution of the hysteresis curves, as,

\[
\rho_{\text{max}} = \frac{\rho_{xy}(9T) - \rho_{xy}(-9T)}{2}
\]

The histogram of \( \rho_{\text{max}} \) from which we take the standard deviation is shown in Fig. 2.

We now explain the statistical model to estimate the magnetic domain size from the standard deviation of \( \rho_{\text{max}} \) (Fig. 3). The model is developed based on two critical assumptions: (i) the magnetic domain size has a normal distribution in the blanket film \( H_{c,\text{domain}} \); and (ii) each domain has an expected hysteresis curve with normally populated coercive field \( H_{c,\text{domain}} \). With the assumption (i), we can hypothesize that our Hall cross pattern cut out the magnetic domain(s) on the blanket film having distribution of the domain size. We then simulate the hysteresis curve by calculating the sum of the AHE hysteresis curves arisen by each magnetic domain based on the assumption (ii).

With this framework, the simulation is performed by the following procedure. First, sizes of the magnetic domains \( S_{\text{domain,k}} \) is assumed to be normally populated in the blanket film (Assumption (i)) with the mean size \( S_{\text{domain,mean}} \) and the standard deviation \( S_{\text{domain,dev}} \). We then randomly and repeatedly pick up \( S_{\text{domain,k}} \) from the population until the Hall cross is fully filled, i.e. \( \sum_{k=1}^{n} S_{\text{domain,k}} \geq S_{\text{Hall}} \) where the repetition number \( n \) is the number of magnetic domains occupying the Hall cross. Second, we stochastically assign a hysteresis curve to the magnetic domain(s) from a normally distributed population of the hysteresis curves characterized by coercive field \( H_{c,\text{domain}} \), the mean \( H_{c,\text{mean}} \), and the standard deviation \( H_{c,\text{dev}} \). For convenience, we utilize

\[
\text{Hist}(H (\text{a.u.})) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left( -\frac{(H - \mu)^2}{2\sigma^2} \right)
\]

**Fig. 2.** Histogram of \( \rho_{\text{max}} = \frac{\rho_{xy}(9T) - \rho_{xy}(-9T)}{2} \) for various Hall cross area \( S_{\text{Hall}} \).

**Fig. 3.** The statistical model and procedure for estimating the magnetic domain size from the standard deviation of \( \rho_{\text{max}} \).
Fig. 4. Normalized standard deviation of the simulated results $D_{\text{sim}}$ (solid lines) and the experimental result $D_{\text{obs}}$ (square points) as a function of $S_{\text{Hall}}$. $S_{\text{domain}}$ is set to half of $S_{\text{Hall}}$.

The error function $\text{erf}(H) = \frac{2}{\sqrt{\pi}} \int_0^H e^{-t^2} dt$ to represent the hysteresis curve as,

$$\rho_{xy,\text{domain},k}(H) = \text{erf}\left(N \times (H - H_{c,\text{domain}})\right)$$

where $\rho_{xy,\text{domain},k}(H)$ is a pseudo hysteresis function of the AHE taking values ranging from -1 to 1 which reproduces a half of the AHE hysteresis curve. $N$ is an adjustable coefficient to mimic the hysteresis curve obtained in the experiment. We should note that the use of the error function is not necessary condition but can be any function if it can reasonably mimic the hysteresis curve. Considering that the saturation field of the AHE hysteresis curve is close to 24 T, we set the population of $\rho_{xy,\text{domain},k}(H)$ with $H_{c,\text{mean}} = 12$ T and $H_{c,\text{dev}} = 6$ T. Coefficient $N$ is set to $9.0 \times 10^{-6}$. We do not set any correlation between $\rho_{xy,\text{domain},k}(H)$ and $S_k$. It is worthwhile to note that the function for each $\rho_{xy,\text{domain},k}$ and coefficient $N$ has little influence on the final results, since the aim of this model is to evaluate the distribution depending on relative size of magnetic domains to $S_{\text{Hall}}$. The AHE hysteresis curve of the Hall cross device is the sum of $n$ hysteresis curves with a weight of the size of the magnetic domain as,

$$\rho_{xy,\text{device}}(H) = \sum_{k=1}^n \frac{\rho_{xy,\text{domain},k}(H) \times S_{\text{domain},k}}{\sum_{k=1}^n S_{\text{domain},k}}$$

This procedure is iterated 1000 times to derive a distribution of $\rho_{xy,\text{device}}(9T)$. Since the average value of the measurement results and the simulation value are different, the standard deviation was normalized by dividing by the mean of $\rho_{xy,\text{device}}(9T)$.

Fig. 4 shows normalized standard deviation of simulated results $D_{\text{sim}}$ and experimental results $D_{\text{obs}}$ as a function of $S_{\text{Hall}}$. The solid line shows the $D_{\text{sim}}$, and the square points show the $D_{\text{obs}}$. $D_{\text{obs}}$ is within the range of $D_{\text{sim}}$ curves for $S_{\text{domain}} = 0.01 ~ 4 \mu m^2$, suggesting that the magnetic domains of L12-Mn3Ir could be within the range of 0.01 to 4 $\mu m^2$. The estimated size of the magnetic domain is larger than previous reports and this result suggests that the magnetic domains of Mn3Ir could be observable by commonly used imaging method, e.g. magnetooptical Kerr effect. On the other hand, the general trend of the experimental results deviates so much from the expected $D_{\text{sim}}$ curves. To increase the reliability of this model, we need to increase number of experimental samples. However, the nature of the present measurements which requires 9T magnetic field using the superconducting magnet does not allow to increase the number of samples further due to the time constrain. We emphasize that our model can be more reliably applied to broad range of magnetic materials when sufficient number of samples are taken.

In summary, we explored the Hall cross area dependence of anomalous Hall effect in L12-Mn3Ir. By developing the statistical model, we attempted to estimate the magnetic domain size of the Mn3Ir thin films. Although the detailed analysis revealed that the present number of samples cannot be sufficient to guarantee a good statistical confidence, the data infers that the magnetic domain size can range from 0.01 to 4 $\mu m^2$. The present result is a step forward to elucidate the magnetization process of the chiral antiferromagnets.

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