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Scaling of Anomalous Hall Effects in Facing-Target Reactively Sputtered Fe₄N Films

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ABSTRACT

Anomalous Hall effect (AHE) in the reactively sputtered epitaxial and polycrystalline γ′-Fe₄N films is investigated systematically. The Hall resistivity is positive in the entire temperature range. The magnetization, carrier density and grain boundaries scattering have a major impact on the AHE scaling law. The scaling exponent \( \gamma \) in the conventional scaling of \( \rho_{\text{Ah}} \propto \rho_{xx}^\gamma \) is larger than 2 in both the epitaxial and polycrystalline γ′-Fe₄N films. Although \( \gamma > 2 \) has been found in heterogeneous systems due to the effects of the surface and interface scattering on AHE, \( \gamma > 2 \) is not expected in homogenous epitaxial systems. We demonstrated that \( \gamma > 2 \) results from residual resistivity (\( \rho_{xx0} \)) in γ′-Fe₄N films. Furthermore, the side-jump and intrinsic mechanisms are dominant in both epitaxial and polycrystalline samples according to the proper scaling relation.
Introduction

With the rapid development of spintronics, the iron nitrides have attracted considerable interest due to its potential applications in the spintronic devices.\textsuperscript{1–7} Among them, $\gamma'$-Fe\textsubscript{4}N has been paid much attention as a ferromagnetic electrode. Highly enhanced negative spin polarization of transport electrons in $\gamma'$-Fe\textsubscript{4}N has been theoretically predicted.\textsuperscript{8} The spin polarization of $\gamma'$-Fe\textsubscript{4}N(100) lattice measured by point-contact Andreev reflection is 60\%.\textsuperscript{9} The $\gamma'$-Fe\textsubscript{4}N Curie temperature of 767 K makes it a suitable material for practical applications. Recently, the current-induced magnetization switching was reported in the magnetic tunnel junctions (MTJ) with the $\gamma'$-Fe\textsubscript{4}N free layer.\textsuperscript{10} The structure, magnetic properties and tunnel magnetoresistance of the MTJ based on $\gamma'$-Fe\textsubscript{4}N electrode were also investigated.\textsuperscript{2,3,11,12} Negative anisotropic magnetoresistance (AMR) has been observed in the epitaxial $\gamma'$-Fe\textsubscript{4}N films due to the spin-down conduction electrons.\textsuperscript{13–15} Meanwhile, a rectangular-like AMR was reported in epitaxial $\gamma'$-Fe\textsubscript{4}N/CoN bilayers.\textsuperscript{16} Up to now, no papers reported the anomalous Hall effect (AHE) of $\gamma'$-Fe\textsubscript{4}N films.

The AHE in ferromagnetic materials has received intense renewed attention in recent years due to its intrinsic physics related to asymmetric scattering of spin-polarized electrons and technical applications.\textsuperscript{17} The Hall resistivity ($\rho_{xy}$)
follows the phenomenological equation

\[ \rho_{xy} = R_0 B + 4\pi R_s M \]  

(1)

where the first term is the ordinary Hall resistivity from the Lorentz force and the second one is the anomalous Hall resistivity (\(\rho_{\text{AH}}\)) that is proportional to the out-of-plane magnetization of the ferromagnetic film.18 In order to identify the AHE mechanisms, the scaling law between \(\rho_{\text{AH}}\) and \(\rho_{xx}\) is usually given as\(^19\)

\[ \rho_{\text{AH}} \propto \rho_{xx}^\gamma. \]  

(2)

Skew scattering mechanism leads to \(\gamma = 1\),\(^20\) while both scattering-dependent side jump and scattering-independent intrinsic mechanisms yield \(\gamma = 2\).\(^{21-23}\) The intermediate values \(1 < \gamma < 2\) accepted as a superposition of these mechanisms. In the recent theoretical investigation on AHE,\(^{24}\) the scaling law of the AHE is expected to depend on the longitudinal resistivity (\(\rho_{xx}\)) of the ferromagnetic materials. The magnitude of \(\rho_{xx}\) of the \(\gamma'\)-Fe\(_4\)N film is about \(10^3\) \(\mu\Omega\) cm at room temperature, which lies in the middle region between the Fe (10 \(\mu\Omega\) cm) and Fe\(_3\)O\(_4\) (10\(^4\) \(\mu\Omega\) cm) films. The AHE of Fe and Fe\(_3\)O\(_4\) films has been investigated in details, which is in good agreement with the unified theory of the AHE.\(^{25,26}\) However, the origin of AHE in...
$\gamma'$-Fe$_4$N films has remained confusing. The clarification of the AHE in $\gamma'$-Fe$_4$N films is of fundamental importance for better understanding of AHE.

In this paper, the AHE scaling in the epitaxial and polycrystalline $\gamma'$-Fe$_4$N films fabricated by reactive facing-target sputtering is investigated in details. We study the effect of magnetization, carrier density and grain boundaries scattering on the AHE scaling in $\gamma'$-Fe$_4$N films. The scaling exponent $\gamma > 2$ has been found in both the epitaxial and polycrystalline $\gamma'$-Fe$_4$N films by the conventional scaling of $\rho_{AHE} \propto \rho_{xx}^{\gamma}$, which can be attributed to the residual resistivity ($\rho_{xx0}$). The different contributions to AHE in $\gamma'$-Fe$_4$N films are also investigated.

**Experimental section**

$\gamma'$-Fe$_4$N films with different thicknesses $t$ were fabricated on glasses, natural oxidized Si, and MgO(100) wafers by a DC reactive facing-target sputtering method from a pair of pure Fe (99.99%) targets. The sputtering pressure was kept at 1.0 Pa with an Ar (99.999%) and N$_2$ (99.999%) gas mixture. The Ar and N$_2$ gas flow rates were fixed at 100 and 20 sccm, respectively. The substrate temperature was set at 450 °C. The film thickness was determined using a Dektak 6M surface profiler and confirmed by the transmission electron microscopy (TEM). The deposition rate was 0.08 nm/sec. The structure was analyzed by X-ray diffraction (XRD) with Cu $K_a$.
radiation (wavelength 1.5406 Å) and high-resolution TEM (HRTEM). The magnetic properties were measured by a Quantum Design superconducting quantum interference device (SQUID). Hall bars were fabricated by using the shadow masks that have five terminals, which can be used to measure transverse and longitudinal resistances simultaneously. The width of the films in the Hall bar geometry is 0.3 mm. Hall loops were measured with a Quantum Design physical property measurement system (PPMS-9) under a magnetic up to 5 T applied perpendicular to the film plane in the temperature range of 5–350 K. The Hall resistivity $\rho_{xy}$ was calculated from $V_{xy}t/I$, where $V_{xy}$ was the transverse voltage, $t$ was the film thickness, and $I$ was the applied DC current. For excluding the contact resistance, the real Hall resistivity was obtained by subtracting the Hall resistivity measured at the negative magnetic fields from that measured at the positive magnetic fields, then divided by 2 because the magnetoresistance is an even function of magnetic field.

**Results and discussion**

Fig. 1(a) shows the $\theta$-2$\theta$ XRD pattern of the polycrystalline $\gamma'$-Fe$_4$N films on natural oxidized Si wafer. The diffraction peaks located at 33.2° and 69.3° are from Si(200) and (400) lattices. Two strong peaks situated at 41.2° and 47.8° come from the $\gamma'$-Fe$_4$N(111) and (200). A weak peak located at 84.5° is attributed to
$\gamma'$-Fe$_4$N(311). The XRD results of the film on Si suggest that the film is composed of single phase $\gamma'$-Fe$_4$N, and no other phases of iron nitrides appear. Fig. 1(b) shows the XRD $\theta$-2$\theta$ patterns of the $\gamma'$-Fe$_4$N film on MgO(100). It is clear that only the peaks from $\gamma'$-Fe$_4$N(100) and (200) appear, and no other peaks from $\gamma'$-Fe$_4$N are observed, suggesting that the films grow with a preferred (100) orientation. In order to confirm that the preferred oriented films are epitaxial, X-ray $\phi$ scan was performed. For the (100)-oriented films, X-rays were collected at $2\theta=41.22^\circ$, $\alpha=5.26^\circ$, where no peaks from MgO appear, and only a peak from $\gamma'$-Fe$_4$N(111) is detected. In the left inset of Fig. 1(b), it is clear that for the (100)-oriented film, 4-fold symmetric peaks with identical intervals appear. The above X-ray $\theta$-2$\theta$ and $\phi$ scan suggest that the $\gamma'$-Fe$_4$N films on MgO(100) substrate are epitaxial and cubic. In order to further confirm the epitaxial growth of $\gamma'$-Fe$_4$N films, X-ray pole figure of $\gamma'$-Fe$_4$N films on MgO(100) substrate is recorded. In the right inset of Fig. 1(b), the relevant strong diffraction peaks indicate that all the films are epitaxial.

In order to observe the growth mechanism of the reactively sputtered polycrystalline $\gamma'$-Fe$_4$N films, the cross-section SEM image of the films on Si is given in Fig. 2(a). In Fig. 2(a), Fe$_4$N grains grow with a columnar structure, which is similar to the growth manner of Fe$_3$O$_4$ grains using reactive sputtering.$^{27}$ In Fig. 2(b), it is clear that the disordered grain boundaries exist between the grains. Meanwhile, the density of the grain boundaries increases with the decrease of film thickness.$^7$
Fig. 2(c) shows the TEM images of $\gamma'$-Fe$_4$N films on MgO(100). It is clear that the film thickness is about 90 nm with a shape interface. The high-resolution TEM image at the $\gamma'$-Fe$_4$N/MgO(100) interface in Fig. 2(d) shows the epitaxial growth of the film, further confirming the X-ray $\theta$-2$\theta$, $\varphi$ scans and pole figure results.

Fig. 3(a) shows the $\rho_{xx}$–$T$ curves of the epitaxial $\gamma'$-Fe$_4$N films with different $t$. It is clear that the $\rho_{xx}$ of the epitaxial $\gamma'$-Fe$_4$N films increases with the increase of temperature, showing a metallic conductance. The inset of Fig. 3(a) shows the $\rho_{xx}$–$t$ curves at 350 K. The $\rho_{xx}$ decreases with the increase of $t$, which is ascribed to the enhanced surface scattering due to the decreased $t$. Meanwhile, $\rho_{xx}$ of epitaxial $\gamma'$-Fe$_4$N films is smaller than that of polycrystalline ones because of the enhanced grain boundary scattering in the latter, as shown in the inset of Fig. 3(b). For both the epitaxial and polycrystalline films, the decrease ratio of the $\rho_{xx}$ with the decreased temperature increases as $t$ increases, implying that the electron scattering increases with the decreased $t$. This phenomenon can be ascribed to the enhanced surface scattering for the epitaxial films and the increased surface and grain boundaries scattering for the polycrystalline ones as the grain size decreases with the decrease of $t$. Generally, at $T \geq \theta_D$, ($\theta_D$ is the Debye temperature) temperature-dependent $\rho_{xx}$ from the electron–electron scattering follows $\rho_{ph}(T) \propto T$, and at $T \leq \theta_D$, the $\rho_{xx}$ can be written as $\rho_{ph}(T) \propto T^5$. The electron–electron interaction is prominent at the low-temperature region where the electron–phonon scattering is
frozen out and the $\rho_{xx}$ follows the $\rho_{ee}(T) \propto T^2$ law. The contribution to $\rho_{xx}$ from the disordered localized magnetic moment is important in the entire temperature range and can be given as $\rho_{in}(T) \propto T^2$ for the ferromagnetic coupling, $T^6$ and $T^4$ for the antiferromagnetic coupling. In this case, the experimental data of both the epitaxial and polycrystalline films satisfies the $T^2$ law at the low temperatures, which suggests that the $\rho_{xx}$ mainly comes from the thermal disordering of the localized ferromagnetic moments and/or electron–electron interaction. In the high-temperature range, the $\rho_{xx}$—$T$ curves satisfy the $T^n$ relation, where $n$ is smaller than 1. This relation suggests that $\rho_{xx}$ should be from the electron–phonon scattering and the slope of $\rho_{xx}$—$T$ curve decreases with the increased temperature because if $T^n$ ($n>1$) phase is in $\rho_{xx}$—$T$ curves at high temperatures, the slope of $\rho_{xx}$—$T$ curves should increase with temperature, so only $T$ phase can be considered in the $\rho_{xx}$—$T$ curves.

Fig. 4 shows the $\rho_{xy}$—$H$ of the epitaxial and polycrystalline $\gamma'$-Fe$_4$N films with different $t$. The $\rho_{AH}$ can be extracted from the Hall loops by extrapolating the high-field data from positive field to zero field. Both the polycrystalline and epitaxial $\gamma'$-Fe$_4$N films show the positive $\rho_{xy}$ at positive magnetic field in the entire range of $t$ in contrast to the negative $\rho_{xy}$ in Fe$_3$O$_4$.\textsuperscript{26} In the temperature range from 5 to 350 K, $\rho_{AH}$ increases with the increase of temperature. It should be mentioned that the $\rho_{AH}(T)$ show a strong dependence on temperature for both epitaxial and polycrystalline in contrast to Fe samples.\textsuperscript{25} The value of room temperature $\rho_{AH}$
increases from 14.15 µΩ cm for \( t = 100 \) nm up to 18.20 µΩ cm for \( t = 18 \) nm in epitaxial \( \gamma' \)-Fe\(_4\)N films. The thicker the films are, the smaller \( \rho_{\text{AH}} \) is. Meanwhile, at the same temperature, \( \rho_{\text{AH}} \) in epitaxial films is larger than that polycrystalline ones.

Since AHE may originate from either intrinsic or extrinsic mechanisms characterized by different exponential factors \( \gamma \) in the scaling relationship of \( \rho_{\text{AH}} \propto \rho_{xx}^{\gamma} \), it is informative to examine the relation between the \( \rho_{\text{AH}} \) and \( \rho_{xx} \) for determining the exponential factor \( \gamma \). Fig. 5(a) shows the scaling relation of the epitaxial \( \gamma' \)-Fe\(_4\)N films with different \( t \) in a log-log scale. The \( \rho_{\text{AH}} \) versus \( \rho_{xx} \) curves can be fitted by a straight line with a slope of \( \gamma = 2.28 \) below 125 K. However, the \( \rho_{\text{AH}} \) deviates from the linear \( \rho_{xx} \) dependence at high temperatures. In fact, varying temperature inevitably changes saturation magnetization \( M_s \) in samples. The \( M_s \) of \( \gamma' \)-Fe\(_4\)N films varies significantly with temperature, and satisfies the modified Bloch’s spin wave theory.\(^7\) The insert of Fig. 5(b) shows the temperature-dependent normalized magnetization. The normalized magnetization \( m \) defined by

\[
m(T) = M_s(T)/M_s(5 \text{ K})
\]  

In Fig. 5(b), we plot the \( \rho_{\text{AH}}/m \) versus \( \rho_{xx} \) curves in a log-log scale. We can see that all data have collapsed along a straight line with \( \gamma = 2.25 \). Therefore, the nonlinear scaling relation of the epitaxial \( \gamma' \)-Fe\(_4\)N films at high temperatures results from the
temperature-dependent magnetization.

In order to clarify whether the AHE current in γ'-Fe₄N films is dissipationless, it is necessary to factor out the carrier density \( n \). Based on the simple theoretical model proposed by Noziéres and Lewiner, AHE current can be expressed as

\[
J_{\text{AH}} = 2ne^2\lambda E \times S
\]  

(4)

where \( \lambda \) is the enhanced spin-orbit parameter, \( e \) is the electronic charge, \( E \) is the crossed electric fields, \( S \) is the electron spin, the electron carrier density \( n \) was calculated using the formula \( n = -1/R_0e \), where \( R_0 \) is the ordinary Hall coefficient. Fig. 5(c) shows the \( \rho_{\text{AH}}/n - \rho_{xx} \) curves in a log-log scale for all the epitaxial γ'-Fe₄N films at 5 K. By fitting the data with a straight line, we obtain a slope of \( \beta = 2.41 \). Conventionally, the quadratic dependence of \( \rho_{\text{AH}}/n \) on \( \rho_{xx} \) was considered as the dissipationless nature of AHE current. The slope of \( \beta = 2.41 \) in the epitaxial γ'-Fe₄N films indicates that the AHE conductivity is scattering-dependent.

In order to clarify the effect of the grain boundaries scattering on the scaling law, we perform the measurements on the polycrystalline films fabricated at the same conditions. Fig. 5(d) shows the scaling law of the polycrystalline γ'-Fe₄N films with different \( t \). The \( \rho_{\text{AH}}/\rho_{xx} \) curves revealed significant influence of film thickness in contrast to epitaxial samples, which can be attributed to the different grain
boundaries varying with the film thickness. The scaling exponents $\gamma = 2.10, 2.75, 2.56, 1.95$ below 125 K show a downward trend with increasing $t$. However, no linear relation can be observed in the high-temperature region. After considering the effect of magnetization, the $\rho_{AH}/m - \rho_{xx}$ curves can be linearly fitted in the entire temperature regions, and is also thickness-dependent, as shown in Fig. 5(e). Fig. 5(f) shows the scaling relation of $\rho_{AH}/n \propto \rho_{xx}^\beta$ of the polycrystalline $\gamma'$-Fe$_4$N films at 5 K. By fitting the data using a straight line, we obtain the slope of $\beta = 2.61$, suggesting that a scattering-dependent AHE conductivity in the polycrystalline $\gamma'$-Fe$_4$N films.

We now focus on the scaling exponent $\gamma > 2$ in $\gamma'$-Fe$_4$N films. The scaling exponent $\gamma > 2$ was usually observed in heterogeneous ferromagnetic systems, e.g., $\gamma = 3.7$ in the Co-Ag granular films, $\gamma = 2.6$ in the Fe/Cr multilayers, $\gamma = 5.7$ in the Co/Pd multilayers. The spin-dependent interfacial and surface scattering on AHE were considered to account for $\gamma > 2$ in the ferromagnetic heterogeneous systems. In Fig. 6, we plot the $\rho_{AH}/\rho_{xx}$ curves of both the epitaxial and polycrystalline $\gamma'$-Fe$_4$N films with various thicknesses below 125 K, where the influence of the temperature dependence of the magnetization on $\rho_{AH}$ is negligible. One can find that the scaling exponents of most samples are larger than 2. Although $\gamma > 2$ in the polycrystalline $\gamma'$-Fe$_4$N films can be attributed to grain boundaries scattering on AHE, $\gamma > 2$ is not expected in the homogenous epitaxial $\gamma'$-Fe$_4$N films. It should be noted that the unconventional scaling exponents $\gamma > 2$ in the epitaxial $\gamma'$-Fe$_4$N films are
thickness-independent, suggesting that the surface scattering contribution to the scaling of the AHE is insignificant. Recent studies on AHE in Fe and Co films have demonstrated a proper scaling of \( \rho_{AH} = a' \rho_{xx0} + b \rho_{xx}^2 \). The proper scaling relation excluded the contribution of phonons to skew scattering and showed that the extrinsic contributions to AHE are only related to impurity or defects scattering. In contrast, the skew scattering contributions from phonons and impurity or defects in the conventional scaling of \( \rho_{AH} \propto \rho_{xx}^{\gamma} \) are treated on an equal basis. The neglect of the differences between phonon and impurity or defects contributions to AHE transport data maybe result in the unconventional scaling exponent \( \gamma > 2 \) in \( \gamma' \)-Fe\(_4\)N films. Based on this consideration, we propose a new scaling of

\[
\rho_{AH} = c' \rho_{xx0} + b \rho_{xx}^\alpha,
\]

which separates out the temperature-independent residual resistivity \( (\rho_{xx0}) \) from the different contributions to the measured AHE transport data. As shown in Fig. 7, the data fits quite well with the new scaling for both the epitaxial and polycrystalline \( \gamma' \)-Fe\(_4\)N films, which provides convincing evidence that the contributions from phonon and impurity or defects to AHE are distinctly different. The obtained new scaling exponents \( \alpha \) are between 1 and 2 as shown in Fig. 7. The fitting results strongly suggest that the \( \rho_{xx0} \) in \( \gamma' \)-Fe\(_4\)N films leads to the unconventional scaling
The new scaling of $\rho_{\text{AH}} = c \rho_{xx0} + b \rho_{xx}^\gamma$ has the same form as the proper scaling of $\rho_{\text{AH}} = a \rho_{xx0} + b \rho_{xx}^2$. We also consider that the temperature-dependent scattering leads to intrinsic mechanism.\textsuperscript{34-36} The $\rho_{xx0}$ were separated from various contributions to AHE in both new scaling and proper scaling relation. The scaling exponent $\alpha$ in the new scaling relation is a fitting result from the measured AHE transport data, while the scaling exponent in the proper scaling relation is a constant=2 representing the intrinsic contribution to AHE. The novel of the new scaling relation is that the scaling exponent $\alpha$ from the fitting result can give a direct evidence that the large scaling exponent $\gamma>2$ in the conventional scaling of $\rho_{\text{AH}} \propto \rho_{xx}^\gamma$ is closely related to the $\rho_{xx0}$. It should be mentioned that $\alpha=1.92, 1.96, 2.01$ and $1.94$ found in epitaxial samples with $t=40, 60, 80$ and $100$ nm are nearly to 2, which indicates the same physics as the proper scaling relation. Unluckily, $\alpha<2$ has been found in other samples, especially for polycrystalline ones. This is an imperfect result that the temperature-dependent scaling exponent corresponding to the intrinsic contribution to AHE are not a constant=2. At the present, we suggest that the deviation of the scaling exponent $\alpha$ from the constant=2 may be due to the thermal disorder from a relatively small skew scattering contribution.\textsuperscript{37} However, comprehensive understanding of the phenomenon need to more efforts from both experimental and theoretical studies.
At last, we plot $\rho_{xx}^2 \rho_{AH}$ curves of both epitaxial and polycrystalline samples according to the proper scaling relation as shown in Fig. 8. It is clear that the proper scaling relation also shows an excellent agreement with the experiment data. The intrinsic contribution $b$ from temperature-dependent scattering to AHE obtained by the proper scaling relation is plotted in Fig. 9(a). The intrinsic contribution is 276 and 196 S/cm for epitaxial and polycrystalline samples respectively. The large intrinsic contribution in epitaxial sample can be attributed to its homogenous structure.\textsuperscript{19} In order to clarify the effect of impurities scattering on AHE, Fig. 9(b) and (c) shows the $\rho_{AH} \rho_{xx}$ curves at 5 K with different $t$ for both the epitaxial and polycrystalline samples respectively. By fitting the data to a straight line, we obtained the slope value $\gamma=2.01$ for epitaxial samples and $\gamma=1.87$ for polycrystalline samples indicating the less contribution from skew-scattering to AHE. Therefore, we suggest that the side-jump and intrinsic mechanisms are dominant in both epitaxial and polycrystalline samples.

**Conclusion**

In conclusion, the scaling of AHE in the epitaxial and polycrystalline $\gamma'$-Fe$_4$N films is investigated systematically. The $\rho_{xy}$ is positive in the whole temperature range. The deviation of the scaling relation in high temperature region is due to the
magnetization that varies with temperature significantly. The scaling relation in the polycrystalline $\gamma'$-Fe$_4$N films shows a strongly dependence on film thickness, which can be attributed to different grain boundaries scattering in various films. The normalized anomalous Hall conductivity by carrier density is not a constant, indicating that the anomalous Hall conductivity is scattering-dependent in $\gamma'$-Fe$_4$N films. The scaling exponent $\gamma$ is larger than 2 in both epitaxial and polycrystalline $\gamma'$-Fe$_4$N films by the conventional scaling of $\rho_{\text{AH}} \propto \rho_{xx}^\gamma$, which can be attributed to the $\rho_{xx0}$. The mechanisms of AHE in $\gamma'$-Fe$_4$N are mainly from side-jump and intrinsic contributions.

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Figure captions

Fig. 1. The $\theta$-2$\theta$ XRD patterns of (a) the polycrystalline $\gamma'$-Fe$_4$N films on natural oxidized Si substrate and (b) the epitaxial $\gamma'$-Fe$_4$N film on MgO(100). The insets of Fig. 1(b) give X-ray $\phi$ scan and pole figure of $\gamma'$-Fe$_4$N films on MgO(100).

Fig. 2. (a) The cross-section SEM image of the polycrystalline $\gamma'$-Fe$_4$N film on Si substrates, (b) planar-view TEM image of the polycrystalline $\gamma'$-Fe$_4$N film, (c) cross-sectional TEM image of $\gamma'$-Fe$_4$N films on MgO(100), (d) the high-resolution TEM image at the $\gamma'$-Fe$_4$N/MgO(100) interface.

Fig. 3. The temperature-dependent $\rho_{xx}$ of (a) the epitaxial $\gamma'$-Fe$_4$N films and (b) the polycrystalline $\gamma'$-Fe$_4$N films with different $t$. The insets give the relevant film-thickness dependent $\rho_{xx}$ measured at 350 K.

Fig. 4. The $\rho_{xy}$-$H$ curves of the epitaxial and polycrystalline $\gamma'$-Fe$_4$N films measured at different temperature, (a) $t$=18 nm epitaxial film, (b) $t$=18 nm polycrystalline film, (c) $t$=100 nm epitaxial film, and (d) $t$=100 nm polycrystalline film.
Fig. 5. The scaling relation of the epitaxial and polycrystalline $\gamma'$-Fe$_4$N films with different $t$, (a) $\rho_{AH}\rho_{xx}$ curves for epitaxial films, (b) $\rho_{AH}/m-\rho_{xx}$ curves for epitaxial films, (c) $\rho_{AH}/n-\rho_{xx}$ curves for epitaxial films, (d) $\rho_{AH}-\rho_{xx}$ curves for polycrystalline films, (e) $\rho_{AH}/m-\rho_{xx}$ curves for polycrystalline films, (f) $\rho_{AH}/n-\rho_{xx}$ curves for polycrystalline films. The insert of Fig. 5(b) shows the temperature-dependent $m$ of $\gamma'$-Fe$_4$N films.

Fig. 6. The $\rho_{AH}\rho_{xx}$ curves below 125 K with different $t$ in log-log scale for both epitaxial and polycrystalline $\gamma'$-Fe$_4$N films, (a) $t=18$ nm, (b) $t=26$ nm, (c) $t=40$ nm, (d) $t=60$ nm, (e) $t=80$ nm, (f) $t=100$ nm. The red and black line is a linear fit of the data.

Fig. 7. The $\rho_{AH}-\rho_{xx}$ curves below 125 K with different $t$ for both epitaxial and polycrystalline $\gamma'$-Fe$_4$N films, (a) $t=18$ nm, (b) $t=26$ nm, (c) $t=40$ nm, (d) $t=60$ nm, (e) $t=80$ nm, (f) $t=100$ nm. The red and black line is fitting result with a new scaling of $\rho_{AH} = c'\rho_{xx0} + b\rho_{xx}^\alpha$.

Fig. 8. The $\rho_{AH}-\rho_{xx}^2$ curves below 125 K with different $t$ for both epitaxial and polycrystalline $\gamma'$-Fe$_4$N films, (a) $t=18$ nm, (b) $t=26$ nm, (c) $t=40$ nm, (d) $t=60$ nm.
nm, (e) $t=80$ nm, (f) $t=100$ nm. The red and black line is a linear fit of the data.

**Fig. 9.** (a) The $t$ dependence of the intrinsic contribution $b$ to AHE obtained by the proper scaling relation for both epitaxial and polycrystalline samples. The $\rho_{AH}\rho_{xx}$ curves at 5 K with different $t$ for (b) epitaxial films, (c) polycrystalline films.
Fig. 1, Y. Zhang, et al.
Fig. 2, Y. Zhang, et al.
Fig. 3, Y. Zhang, et al.

(a) Epitaxial

(b) Polycrystalline

$\rho_{xx}(T)/\rho_{xx}(350 \text{ K})$

$T (K)$

$\rho_{xx}$ ($\mu\Omega \text{ cm}$)

Thickness (nm)
Fig. 4, Y. Zhang, et al.

![Graphs showing the change in conductivity with magnetic field strength](image-url)
Fig. 5, Y. Zhang, et al.

(a) Epitaxial

(b) Polycrystalline

(c) (d) (e) (f)
Fig. 6, Y. Zhang, et al.

(a) Epitaxial slope=2.02 ρ_{AH} (µΩ cm)
18 nm
(b) Polycrystalline slope=2.75 100 150 200 250 300

(c) Epitaxial slope=2.63 ρ_{AH} (µΩ cm)
40 nm
(d) Polycrystalline slope=2.56 50 100 150 200

(e) Epitaxial slope=2.16 ρ_{AH} (µΩ cm)
80 nm
(f) Polycrystalline slope=1.94 50 100 150 200
Fig. 7. Y. Zhang, et al.

(a) $\alpha = 1.86$, 18 nm

(b) $\alpha = 1.77$, 26 nm

(c) $\alpha = 1.92$, 40 nm

(d) $\alpha = 1.83$, 60 nm

(e) $\alpha = 2.01$, 80 nm

(f) $\alpha = 1.94$, 100 nm
Fig. 8, Y. Zhang, et al.
Fig. 9, Y. Zhang, et al.

(a) Epitaxial and Polycrystalline

(b) Epitaxial

slope = 2.01

(c) Polycrystalline

slope = 1.87