Interface-dependent magnetotransport properties for thin Pt films on ferrimagnetic Y$_3$Fe$_5$O$_{12}$

Y. Shiomi$^1$, T. Ohtani$^1$¢S. Iguchi$^1$, T. Sasaki$^1$, Z. Qiu$^2$, H. Nakayama$^{1,3}$, K. Uchida$^{1,4}$, and E. Saitoh$^{1,2,5,6}$

$^1$Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
$^2$WPI Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
$^3$Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan
$^4$PRESTO, Japan Science and Technology Agency, Saitama 332-0012, Japan
$^5$CREST, Japan Science and Technology Agency, Tokyo 102-0076, Japan
$^6$Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan

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We have studied magnetoresistance and Hall effects for 1.8-nm-thick Pt films grown on a ferrimagnetic insulator Y$_3$Fe$_5$O$_{12}$ in a wide temperature (0.46-300 K) and magnetic-field (−15-15 T) region. In the low-temperature regime where quantum corrections to conductivity are observed, weak antilocalization behavior observed in Pt films is critically suppressed when the film is attached to Y$_3$Fe$_5$O$_{12}$. Hall resistance in the Pt film is also affected by Y$_3$Fe$_5$O$_{12}$, and it exhibits logarithmic temperature dependence in a broad temperature range. The magnetotransport properties in the high-field range are significantly influenced by the interface between Pt and Y$_3$Fe$_5$O$_{12}$.

In the field of spintronics, a pure spin current, which is a flow of spin angular momentum without a net charge current, has attracted a great deal of attention in view of spin-current science and also of practical application$^1$. For study on spin-current phenomena, Pt/Y$_3$Fe$_5$O$_{12}$ (Pt|YIG) bilayers have been used frequently as a typical system. YIG is a ferrimagnetic insulator with a large charge gap (∼2.7 eV) and a high magnetic-transition temperature (∼553 K), which enables spin-current injection free from spin-polarized currents at room temperature. Injected pure spin currents are able to be detected electrically in Pt by means of the inverse spin Hall effect (ISHE) which is the conversion of an injected spin current into a transverse electric current due to the spin-orbit interaction. Since Pt has strong spin-orbit interaction, efficiency of the ISHE is as high as 1-10 percent; hence, Pt has often been used as a spin-current detector. Using Pt|YIG systems, many experiments on spin-current injection and detection have been performed, e.g. spin pumping$^2$ and the spin Seebeck effect$^3$.

Recently, an unconventional magnetoresistance (MR) effect was reported for Pt|YIG structures. Although Pt is a paramagnetic metal, MR in about 10-nm-thick Pt films on YIG reflect the magnetization direction of YIG and anisotropic MR was observed in a low magnetic-field region (≤0.2 T)$^4$$^5$. This anisotropic MR was found to be caused mainly by a spin mixing effect at the interface between Pt and YIG$^6$; concerted actions of the direct and inverse spin Hall effects generate an additional electric current and thus lead to resistance change affected by the magnetization direction in YIG. This magnetoresistance was named the spin-Hall magnetoresistance (SMR)$^6$ and this mechanism has been supported by following reports$^6$$^{13}$.

In the present paper, we discuss interface-dependent magnetotransport properties in Pt|YIG at low temperatures using very thin (∼2 nm) Pt films where the interface effect should be further pronounced owing to the reduced Pt volume. By conducting magnetotransport measurements in a wide temperature (0.46-300 K) and magnetic field (−15-15 T) region, we have shown that MR and Hall effects at high magnetic-fields in Pt|YIG exhibit totally different behavior from those in conventional paramagnetic metals. These unconventional magnetotransport properties are prominent at low temperatures and at high magnetic-fields, which are clearly irrelevant to magnetization change in YIG.

We measure magnetotransport properties of Pt thin films attached to (111) planes of YIG films or paramagnetic Gd$_3$Ga$_5$O$_{12}$ (GGG) substrates. Here, Pt|GGG was used for control experiments, since GGG has the same crystal structure as YIG and is paramagnetic down to 0.46 K. Micrometer-thick YIG films were grown on (111) GGG substrates by liquid phase epitaxy$^{14}$; the magnetization of YIG films is saturated for $\mu_0 H > 0.3$ T in a perpendicular magnetic field [Fig. 1(a)]. Before deposition of Pt, YIG films and GGG substrates were first cleaned in organic solvents inside an ultrasound bath, following surface treatment with H$_2$SO$_4$ and H$_2$O$_2$; this process is important to observe the interface-dependent magnetotransport phenomena in the present work. We then sputtered 1.8-nm-thick Pt thin films with Hall-bar geometry on cleaned YIG or GGG surfaces in Ar pressure of 7.0 mTorr. The magnetotransport measurements were performed as illustrated in Fig. 1(b). The measurements were carried out in superconducting magnets up to ±15 T in the temperature range between 0.46 K and 2 K as well as up to ±9 T in that from 2 K to 300 K.

We show, in Fig. 1(b), the temperature (T) dependence of sheet resistance, $R_{\text{sheet}}$, for Pt|YIG and Pt|GGG. The resistance for both the samples shows metallic T dependence with the residual resistance...
\[ R_{\text{sheet}} \approx 300-500 \, \Omega. \] Different magnitudes of \( R_{\text{sheet}} \) between Pt\|YIG and Pt\|GGG mainly originate from slightly different Pt-thicknesses which are inevitable in our sputtering system. As shown in the inset to Fig. 1(b), \( R_{\text{sheet}} \) shows a minimum around 20 K and then increases with decreasing \( T \) below \( \sim 20 \, K \). This resistance rise is almost proportional to \( \ln T \), indicating manifestation of weak (anti-)localization which is incipient of quantum corrections in disordered conductors.

Figure 1(c) shows magnetic field \( (H) \) dependence of MR for Pt\|YIG and Pt\|GGG at 0.46 K. Here, the magnitude of MR is defined as \( \Delta R/R \equiv (R(H) - R(H = 0))/R(H = 0) \). For Pt\|GGG, positive MR is observed and its magnitude is \( \sim 1 \% \) at 15 T. This positive MR in Pt\|GGG is well explained by weak anti-localization (WAL) which appears in disordered conductors with strong spin-orbit interaction [15,16]. By contrast, Pt thin films on YIG show a totally different MR effect from Pt\|GGG, at 0.46 K. The MR is negative and its magnitude is as small as 0.1\%. This clear difference in MR between Pt\|YIG and Pt\|GGG is not observed at high temperatures; as shown in the inset to Fig. 1(c), at 200 K, while SMR reflecting the magnetization process of YIG is observed for Pt\|YIG in a low-\( H \) region \( (< 0.5 \, T) \), MR effects in a high-\( H \) regime \( (> 0.5 \, T) \) are similar between Pt\|YIG and Pt\|GGG. These results clearly show that in a low-\( T \) range where quantum corrections are observed, unconventional MR shows up in Pt\|YIG at high magnetic-fields where the magnetization of YIG is fully aligned along the \( H \) direction.

In Fig. 2(a), we show MR in Pt\|YIG at various temperatures. At 200 K, positive MR showing quadratic \( H \)-dependence is observed in a high-\( H \) region; this is characteristic of ordinary MR related with Lorentz force [17]. As \( T \) is decreased, MR hardly changes with \( T \) down to 10 K, but, below 10 K, MR in a high-\( H \) region shows a sign change from positive to negative and its magnitude abruptly increases, while SMR observed in a low \( H \) region \( (< 0.5 \, T) \) is almost independent of temperature even in this \( T \) range [see also Figs. 1(c) and 1(a)]. We compare the \( T \) range of MR enhancement and that of weak (anti-)localization regime determined from \( T - R_{\text{sheet}} \) curve, in Figs. 2(a) and (b). As shown in Fig. 2(b), in the weak (anti-)localization regime (highlighted in yellow color in Fig. 3), negative MR at 9 T is enhanced almost in proportion to \( \ln T \), which signals weak localization (WL) behavior [18]. On YIG, WAL in Pt is suppressed and WL appears in spite of the strong spin-orbit interaction in Pt.

In magnetic fields and under strong spin-orbit interaction, the quantum correction to the sheet conductance, \( \Delta \sigma_{\text{sheet}}(H) \equiv 1/R_{\text{sheet}}(H) - 1/R_{\text{sheet}}(H = 0) \), is given
The fitting parameters are shown in Figs. 1(c) and 2(c), respectively. The fitted curves at $|B|$ and $|P|$ respectively. Using eq. (1), we fit MR at 0.46 K for $P$|YIG and at 1 K for $P$|GGG. $R_H$ for $P$|GGG shows linear dependence on $H$; this is the normal Hall effect induced by Lorentz force. In $P$|YIG, by contrast, $R_H$ shows clearly nonlinear $H$-dependence and its magnitude is much larger than that for $P$|GGG; with increasing $H$ from the zero field, $|R_H|$ increases dramatically and becomes almost saturated above 5 T. This dependence of $R_H$ corresponds to neither the applied magnetic field nor the magnetization process in YIG. As shown in Fig. 1(d), the field value ($\sim 5$ T) where $R_H$ becomes almost saturated is much higher than the saturation field of YIG magnetization ($\sim 0.3$ T), which indicates that the internal magnetic field induced by YIG magnetization is not the origin of the nontrivial $H$-dependence of $R_H$.

A plot of Hall resistance ($R_H$) versus $H$ is shown at various temperatures between 0.46 K and 300 K in Fig. 2(b). While $B_{SO}$ is smaller in $P$|YIG, $B_\phi$ is larger in $P$|YIG than $P$|GGG. A possible magnetic scattering mechanism may enhance the effective $B_\phi$ value in $P$|YIG.

Such an interface effect also appears in the Hall effect. Figure 3(d) shows $H$ dependence of Hall resistance, $R_H$, at 0.46 K for $P$|YIG and at 1 K for $P$|GGG. $R_H$ for $P$|GGG shows linear dependence on $H$; this is the normal Hall effect induced by Lorentz force. In $P$|YIG, by contrast, $R_H$ shows clearly nonlinear $H$-dependence and its magnitude is much larger than that for $P$|GGG; with increasing $H$ from the zero field, $|R_H|$ increases dramatically and becomes almost saturated above 5 T. This dependence of $R_H$ corresponds to neither the applied magnetic field nor the magnetization process in YIG. As shown in Fig. 1(d), the field value ($\sim 5$ T) where $R_H$ becomes almost saturated is much higher than the saturation field of YIG magnetization ($\sim 0.3$ T), which indicates that the internal magnetic field induced by YIG magnetization is not the origin of the nontrivial $H$-dependence of $R_H$.

A plot of Hall resistance ($R_H$) versus $H$ is shown at various temperatures between 0.46 K and 300 K in Fig. 2(b). While MR largely changes only at low temperatures below 10 K, $R_H$ depends on $T$ even above 100 K. $R_H$ in $P$|YIG significantly changes with $T$ and even shows a sign change around 60 K. Since the normal Hall effect in paramagnetic metals is independent of $T$ as observed in $P$|GGG (not shown), this sign change suggests the presence of another contribution to the Hall effect other than the normal Hall effect in $P$|YIG: anomalous Hall effect or topological Hall effect.

We found that the Hall coefficient defined as $R_H/(\mu_0 H)$ in a low-$H$ region below 1 T shows logarithmic $T$ dependence in all the $T$ region between 0.46 K and 300 K, as shown in Fig. 2(d). In very recent papers [23, 24], the origin of similar nonlinear Hall resistance in $P$|YIG [23] and $P$|YIG [24] was attributed to the anomalous Hall effect assuming local paramagnetic moments produced near the interface; the $H$ dependence was analyzed with Langevin or Brillouin function. The
observed $\ln T$ dependence is, however, different from the Curie law ($1/T$) expected from the Langevin/Brillouin function in a low-$H$ region, which is the simplest model of localized magnetic moments [23, 24]. Also, similarly to the low-$H$ case, the $T$ dependence of $R_H$ at 9 T is proportional to $\ln T$ in a high-$T$ regime, as shown in Fig. 3(c). With decreasing $T$ below 10 K, however, $R_H$ at 9 T deviates from the $\ln T$ behavior and becomes almost saturated below 2 K, although the weak-(anti) localization does not affect the Hall effect at least in the conventional framework of weak localization. These results suggest that $\ln T$ dependence of $R_H$ is observed in a low-field limit, i.e., $\mu_B B/k_B T \ll 1$; since $T = \mu_B B/k_B \approx 6$ K for $B = 9$ T, $R_H$ measured at 9 T deviates from the $\ln T$ dependence in the low-$T$ range below ~10 K.

At last, anisotropy of MR is shown at 2 K for Pt/YIG and Pt/GGG in Figs. 3(a) and (b), respectively, where $H$ is applied in three different directions for each sample: $H||x$, $H||y$, and $H||z$ [see also Fig. 1(a)]. As shown in Fig. 3(b), in Pt/GGG, MR, i.e., WAL, clearly depends on the $H$ direction: $|\Delta R/R|$ in $H||z$ is larger than that in in-plane $H$ cases ($H||x$ and $H||y$), which is the behavior expected from WAL in nearly two-dimensional electron systems [19, 27, 28]. In contrast, in Pt/YIG, except for SMR contribution affected by magnetization direction in YIG in a low-$H$ region [3], the high-$H$ behavior is almost isotropic with respect to $H$, as shown in symbols in Fig. 3(a). Since anisotropic MR is not observed even at 2 K in our Pt/YIG, the possibility of AMR due to proximity-induced ferromagnetism in Pt [4] is ruled out. Isotropic WL observed in Pt/YIG indicates that three dimensional nature is prominent compared with Pt/GGG owing to the stronger inelastic scattering (the larger $B_\phi$ value) in Pt/YIG than Pt/GGG, since the condition for two dimensionality with respect to WL is that film thickness is much smaller than the dephasing length, $\sqrt{\hbar/(4eB_\phi)}$ [15].

In summary, we have shown unconventional magnetotransport properties which are prominent at low temperatures and at high magnetic-fields for 1.8-nm-thick Pt films in contact with YIG. $T$ dependence and $H$ dependence of Hall resistance are clearly affected by the interface, but not associated with those of YIG magnetization; in fact, Hall resistance shows logarithmic $T$-dependence in a broad $T$-range and nonlinear $H$ dependence at low temperatures. Also, magnetoresistance is influenced by the interface at low temperatures where quantum corrections are important, and WL behavior is observed despite the strong spin-orbit interaction of Pt. Such unconventional characteristics were not observed in Pt/GGG, although the magnitude of field-induced magnetization for GGG is comparable to that for YIG at 2 K.

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