Inverse Spin Hall effect in ferromagnetic nanomagnet. Dependencies on magnetic field, current and current polarity

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The measured Hall angle in a ferromagnetic nanomagnet shows a substantial non-linear dependence on an external magnetic field, which cannot be explained by adopted mechanisms of the Ordinary and Anomalous (AHE) Hall effects implying a linear plus constant dependence on the external magnetic field. We suggest that there is an additional non-linear contribution from the Inverse Spin Hall effect (ISHE). The significant contribution of ISHE in a ferromagnet is supported by perfect agreement of experiment with a phenomenological theory of ISHE. We observed different dependencies of AHE and ISHE on current suggesting their different thermal dependencies. We also observe dependence of the Hall angle of the current polarity which is due to the Spin Hall effect.

I. INTRODUCTION

The Hall effect (HE) is a generation of an electric current perpendicularly to the bias current, which flows along an applied electric field. The measure of the HE is the Hall angle \( \alpha _{\text{HE}} = \sigma _{xy}/\sigma _{xx} \), which is defined as the ratio of non-diagonal \( \sigma _{xy} \) and diagonal \( \sigma _{xx} \) conductivities. There are several contributions to the Hall effect in a ferromagnetic metal. The first considered mechanism of HE is the Ordinary Hall effect (OHE), which is created by the Lorentz force and linearly proportional to the external magnetic field \( \sim \alpha _{\text{OHE}} H \), where \( \alpha _{\text{OHE}} \) is the OHE coefficient\textsuperscript{3}. Another contribution is the Anomalous Hall effect (AHE). The AHE occurs due to the scattering of carriers on the aligned local magnetic moments in a ferromagnet and its contribution is proportional to the total spin of localized d-electrons\textsuperscript{4}. The AHE contribution is independent on external magnetic field \( H \) provided the local magnetic moments are field-independent. This is the case when temperature is not in close vicinity of Curie temperature \( T_c \) (\( T/H_c < 0.99 \)) and at a moderate magnetic field (H<1T). The joint contribution of the OHE and AHE to the Hall angle is the sum of the field-independent AHE \( \sim \alpha _{\text{AHE}} \) and the linear OHE \( \sim \alpha _{\text{OHE}} H \), which is the prototypical case encountered in plenty of magnetic compounds\textsuperscript{4}.

The observed nonlinear dependence of HE on the external magnetic field suggests that either the AHE and OHE dependencies are non-linear or there is an additional contribution to the HE. As has been shown in Ref. \textsuperscript{15}, the non-linear AHE and OHE contributions can be excluded in our specimens and the only candidate left is the Inverse Spin Hall effect (ISHE), which describes the fact that an electrical current is created perpendicularly to a flow of spin-polarized conduction electron\textsuperscript{2,15}.

The existence of the ISHE in a non-magnetic material has been verified experimentally\textsuperscript{2,11}. In equilibrium the electron gas is not spin-polarized in a non-magnetic material and there is no ISHE contribution. However, when the spin polarization is externally created, the ISHE contribution can be detected and identified. In experiments of Refs. \textsuperscript{10} and \textsuperscript{11}, the conduction electrons were spin-polarized due to alignment of their spins along an external magnetic field. Their HE contribution was measured by a resonance technique. In experiment of Ref. \textsuperscript{9} the spin polarization in a paramagnetic AlGaAs/GaAs heterojunction was created by circularly-polarized light. The dependence of the measured Hall angle on the degree of circular polarization and therefore on the spin polarization was clearly detected\textsuperscript{5}, confirming the existence of the ISHE contribution.

The possibility of the ISHE contribution in a ferromagnetic metal was addressed experimentally only recently\textsuperscript{3} A measurement of the ISHE contribution in a ferromagnetic metal is more difficult, because the electron gas is spin-polarized even in an equilibrium and, therefore, the ISHE contribution exists even in equilibrium. As a result, ISHE can not be pinned down by inducing of spin polarization of otherwise unpolarized electron gas. A possible way to detect the ISHE in a ferromagnetic metal is an modulation of the number of spin-polarized electron by an external magnetic field\textsuperscript{10,15}. The nature of the ISHE must inevitably lead to a change of the Hall angle in the external magnetic field. Similar method of identification of the ISHE contribution from a modulation of the spin polarization by an external magnetic field has been used in experiments of Refs. \textsuperscript{10} and \textsuperscript{11}. The severe caveat of such approach lies in the fact that the average local magnetic moment can be field-dependent as well, which also leads to a field dependence of HE. Therefore, it seems that one cannot pin down the ISHE if there is a suspicion that any substantial realignment of localized moments can occur like, e.g., in a paramagnet\textsuperscript{2}.

Eventually, the idea of detecting the ISHE by a dependence of HE on the external magnetic field can be accessible in a ferromagnet if, and only if the local magnetic moments are appreciably independent on the external magnetic field. Then, a nanomagnet made of a ferromagnetic metal with the perpendicular magnetic anisotropy (PMA\textsuperscript{15}) is just hunted unique object required for such a measurement. In such nanomagnet, the magnetic moments are firmly aligned perpendicularly to the film surface due to the strong PMA effect. The nano-size of the nanomagnet ensures a one-domain state, in which all localized moments are aligned in one direction. As a result,
the AHE contribution becomes essentially independent on external magnetic field and the joint contribution of the OHE and AHE is strictly a sum of field independent AHE $\alpha_{\text{AHE}}$ and linear OHE $\sim \alpha_{\text{OHE}}H$ terms.

In this study we perform field dependent measurements of the HE angle in a FeB nanomagnet with a strong PMA effect. We develop a phenomenological theory of the ISHE dependence on the external magnetic field $H$ which is in perfect agreement with the experimental dependence of the Hall angle on external magnetic field. We also measure the dependence of the HE on the magnitude and direction of the bias current and conclude that the observed current direction asymmetry provides an additional argument in favor of the importance of the ISHE in ferromagnetic metals.

II. EXPERIMENT AND PHENOMENOLOGICAL THEORY OF ISHE IN A FERROMAGNETIC NANOMAGNET

The Hall angle is measured in 1.1-nm-thick FeB grown on SiO$_2$/Ta(2.5nm) and covered by MgO using a Hall-bar setup. The width and length of nanomagnet are 800 and 1000 nm, correspondingly. Details of fabrication and measurement are described Ref. [3].

We present the Hall angle $\alpha_{\text{HE}}$ as a sum of three terms

$$\alpha_{\text{HE}}(H) = \alpha_{\text{OHE}}H + \alpha_{\text{AHE}} + \alpha_{\text{ISHE}}P_S(H),$$

where coefficients $\alpha_{\text{AHE, OHE, ISHE}}$ are field- independent and the function $P_S(H)$ is defined as the spin polarization of the conduction electrons in the external field $H$. We show in Fig. 1 how $\alpha_{\text{HE}}(H)$ can be divided into three contributions.

The ISHE originates from the spin-dependent scatterings of the conduction electrons when the amount of spin-polarised conduction electrons scattered into the left/ right directions are different due to the Spin-Orbit Interaction. As a result, the ISHE contribution is linearly proportional to the number of spin-polarized electrons and therefore to the spin polarization

$$P_S(H) = n_{\text{SP}} / (n_{\text{SP}} + n_{\text{SU}})$$

in the external magnetic field $H$. This fact can be understood as follows. All conduction electrons $n_{\text{SP}} + n_{\text{SU}}$ in Eq. (2), which participate in charge transport, are divided into the group of the spin-unpolarized electrons $n_{\text{SU}}$ and the group of the spin-polarized electrons $n_{\text{SP}}$. All electrons $n_{\text{SP}} + n_{\text{SU}}$ contribute to the diagonal component $\sigma_{xy}$ of the conductivity whereas only the spin-polarized ones $n_{\text{SP}}$ participate in $\sigma_{xy}$. Since the Hall angle is a ratio of the non-diagonal $\sigma_{xy}$ and diagonal $\sigma_{xx}$ conductivities, ISHE contribution to the Hall angle is proportional to the spin polarization $P_S(H)$.

The conversion rate between spin-polarised $n_{\text{SP}}$ and spin unpolarised $n_{\text{SU}}$ electrons can be calculated as [4][16]

$$\frac{\partial n_{\text{SP}}}{\partial t} = \left[ \frac{n_{\text{SU}}}{\tau_M} \right] - \frac{n_{\text{SP}}}{\tau_{\text{rel}}} + \frac{n_{\text{SU}}}{\tau_H},$$

where $1/\tau_M$ and $1/\tau_H$ are the rates of spin-pumping processes $n_{\text{SU}} \rightarrow n_{\text{SP}}$ whereas the rate $1/\tau_{\text{rel}}$ describes the spin-relaxation $n_{\text{SP}} \rightarrow n_{\text{SU}}$ into spin unpolarized states. The spin pumping rate $1/\tau_M$ is set by spin-dependent scattering on the aligned magnetic moments $M$ and $1/\tau_H$ describes the rate of the spin-polarization processes caused by external magnetic field. The expression for spin polarization $P_S(H)$ follows from Eqs. (2-3) and balance condition $\partial n_{\text{SP}} / \partial t = 0$,

$$P_S(H) = \frac{P_S(0) + (H/H_S)}{1 + (H/H_S)},$$

where the spin-polarization in the absence of the external magnetic filed is $P_S(0) = \tau_{\text{rel}} / (\tau_{\text{rel}} + \tau_M)$ and $H_S$ is the scaling relaxation magnetic field $H_S = 1/(\epsilon \cdot \tau_{\text{rel}})$, which is determined by the relation between the spin-depolarization relaxation rate $1/\tau_{\text{rel}}$ and magnetic field alignment rate per field unit $\epsilon$[13].

It was shown[3] that the experimental variation of $\alpha(H)$ vs $H$ can be perfectly described in terms of the relation
dependent on five fit parameters, namely $\alpha_{\text{OHE}}, \alpha_{\text{AHE}}, \alpha_{\text{ISHE}}, H_S$, and $P_S(0)$. Therefore, we can conclude on the essential role of the ISHE in HE in ferromagnets and consider the summary in Fig. 1 as an illustration of the structure of the HE in ferromagnets.

III. CURRENT DEPENDENCE OF THE HALL EFFECT

Figure 2a,b shows the Hall angle $\alpha_{\text{HE}}^{(l)}$ and its first derivative measured at a different current density $l$. The dependence of the Hall angle $\alpha_{\text{HE}}^{(l)}$ on current is clear and substantial. In contrast, the current dependency of its first derivative is weak. It indicates a substantial current dependency of AHE, but a weak dependency of ISHE on current. This fact can be understood as follows. The AHE is independent of $H$ and it contributes only to $\alpha_{\text{HE}}^{(l)}$ but not to $d\alpha_{\text{HE}}^{(l)}/dH$. In contrast, the non-linear
ISHE contributes to both. The change of $\alpha^{(l)}_{\text{HE}}$ without corresponding change of $d\alpha^{(l)}_{\text{HE}} / dH$ can occurs only due to a change of AHE.

As was shown in Ref. [5], there are several parameter sets which represent exactly identical function $\alpha^{(l)}_{\text{HE}}(H)$ of Eq. (1). In a general case, it prevents an unambiguous separation of the AHE and ISHE contributions from a fitting of data of Fig. 2a,b. However, the case becomes simpler when only AHE, but not ISHE depends on an external parameter. In this case, the current dependency of AHE can be found by the following method. Since the AHE contribution is independent of H, the Hall angle at different current density can be expressed as

$$\alpha^{(l)}_{\text{HE}}(H) = \alpha^{(H=-5mA/\mu m^2)}_{\text{HE}}(H) + \Delta\alpha^{(l)}_{\text{HE}}$$

where $\Delta\alpha^{(l)}_{\text{HE}}$ is independent of H and represents a change of the AHE contribution with current. The value of $\Delta\alpha^{(l)}_{\text{HE}}$ is calculated by minimizing a mean square difference between curves of Fig. 2a. Figure 2 shows the result of the minimization. All curves perfectly coincide with each other.

Figure 3a shows current-dependent change of AHE $\alpha^{(l)}_{\text{HE}}$. The curve has a parabolic shape, which implies that the AHE change is caused by the Joule-Lenz heating of the nanomagnet proportional to the square of current density $I$. Indeed, the nanomagnet heating up to $80^\circ\text{C}$ at $I = 90\text{mA}/\mu \text{m}^2$ was confirmed from the measured change of nanomagnet resistance. At this current density, the change of AHE is about 5 percent. The exactly same percentage of change for magnetization is predicted from the Curie-Weiss law for the corresponding temperature change and known FeB Curie temperature $T_c \approx 900 \pm 100$K. Since AHE is linearly proportional to the total spin $S_d$ of localized d- electrons, the temperature dependence of $S_d$ is perfectly described by the Curie-Weiss law in the studied temperature range.

Figure 2b shows that the ISHE, in contrast to the AHE, is not reduced for the similar 5 percent under the heating and therefore its temperature dependence does not follow the Curie-Weiss law. Indeed, the ISHE is proportional to the total spin $S_{\text{con}}$ of conduction electrons and therefore to the spin polarization which, in turn, is a function of the spin pumping and the spin relaxation (See Eqs. (21,23)) and therefore the ISHE temperature dependence is defined by the temperature dependencies of the spin pumping and relaxation rates, but not by the Curie-Weiss law.

Another interesting observed feature is the dependence of the Hall angle on the polarity of current. The parabola of Fig. 3a is not symmetric with respect to a reversal of current polarity. The polarity-dependent AHE contribution $\delta\alpha^{(l)}_{\text{HE}}$ describes a change of the Hall angle under the same current of different polarity and is calculated as

$$\delta\alpha^{(l)}_{\text{HE}} = \left(\Delta\alpha^{(l)}_{\text{HE}} - \Delta\alpha^{(-l)}_{\text{HE}}\right) / 2$$

Figure 3b shows dependence $\delta\alpha^{(l)}_{\text{HE}}$ on the current density $I$. Note, the data at a negative and positive current are independent measurements taken at the same parameters. The dependence of $\delta\alpha^{(l)}_{\text{HE}}$ on current is linear with a negative slope at $I<40 \text{mA}/\mu \text{m}^2$ and is saturated at a larger current density.

At first sight, the magnetic and transport properties of the nanomagnet have to be fully symmetric with respect to current reversal. The only possible asymmetry can follow from the Spin Hall effect (SHE) because reversal of the current leads to asymmetric spin accumulations on the different sides of wire. Then, polarities of the accumulated spins are opposite at the opposite sides of wire and the spin direction is reversed when the current polarity is reversed. Strong change of AHE points out to substantial interaction between spins of localized and conduction electrons in the vicinity of interface. Distribution is different on different interfaces and, hence, this interaction substantially depends on the properties of the interface. Since the studied nanomagnet has different materials FeB/Ta and FeB/MgO at opposite interfaces, the spin interaction should depend on the polarity of spins generated by SHE and therefore the current polarity. The above explains the reason why the total spins of localized electrons depends on the flow direction of conduction electrons.
IV. CONCLUSIONS

Our study provides strong arguments in favor of the importance of the inverse spin Hall effect in ferromagnetic metals. This conclusion is based on the measurements of the external magnetic field and current dependencies of the Hall angle in metallic ferromagnetic samples. Adopted mechanisms of ordinary and anomalous Hall effects imply a linear plus constant dependence on the external magnetic field whereas our measurements show essentially nonlinear behavior. We exclude a lot of possible contributions which are not relevant in our nano-sized samples with perpendicular magnetic anisotropy and find that only inverse spin Hall effect can explain the experimental dependence of the Hall effect on the external magnetic field. We have found that near the room temperature the temperature dependence of the total spin of localized d-electrons follows the Curie-Weiss law. However, temperature dependence of the total spin of conduction electrons is different and does not follow this law. We also observe dependence of the Hall angle of the current polarity. The dependence is due to the Spin Hall effect and the spin interaction of localized and conduction electrons at interfaces.

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