Inverse Spin Hall Effect in Ni$_{81}$Fe$_{19}$ / Normal Metal Bilayers

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Spin pumping in ferromagnets provides a source of pure spin currents. Via the inverse spin Hall effect a spin current is converted into a charge current and a corresponding detectable DC-voltage. The ratio of injected spin current to resulting charge current is given by the spin Hall angle. However, the number of experiments more or less equals the number of different values for spin Hall angles, even for the most studied normal metal platinum. This publication provides a full study of inverse spin Hall effect and anisotropic magnetoresistance for different Ni$_{81}$Fe$_{19}$(Py) / normal metal bilayers using a coplanar waveguide structure. Angle and frequency dependent measurements strongly suggest that spin pumping and inverse spin Hall effect can be used to quantify spin Hall angles only if certain conditions are met. Ruling out the anisotropic magnetoresistance as a parasitic voltage generating effect measurements of the inverse spin Hall effect in Py/Pt and Py/Au yield spin Hall angles of 0.09 and 0.008 respectively. Furthermore, DC-voltages at ferromagnetic resonance for Py/Pt are studied as a function of temperature and the results are compared to theoretical models.

In 2002 Tserkovnyak, Brataas and Bauer [1, 2] proposed the spin pumping mechanism to inject a pure spin current from a ferromagnet into an adjacent normal metal which can act as a spin sink. This effect can be evidenced in linewidth broadening of ferromagnetic resonance (FMR) curves [3, 5]. The inverse spin Hall effect (ISHE) offers the possibility to detect pure spin currents generated by spin pumping electrically [3]. In materials with reasonably large spin orbit coupling ISHE converts a pure spin current into a detectable charge current [7–9]. The efficiency of this conversion process can be quantified by the spin Hall angle $\alpha_{SH}$. A number of materials have been investigated with respect to the spin Hall angle in mostly two experimental configurations: non local lateral spin valves (NLSV) and dynamic spin injection related to ferromagnetic resonance (spin pumping). The first materials examined in the NLSV geometry were Al ($\alpha_{SH} = 0.0001 - 0.0003$) [10], Pt ($\alpha_{SH} = 0.0037$) [11] and Au ($\alpha_{SH} = 0.11$) [12]. Experiments using ISHE in combination with spin pumping reported values of $\alpha_{SH} = 0.08$ [13], $\alpha_{SH} = 0.013$ [14, 15], $\alpha_{SH} = 0.012$ [16] for Pt and $\alpha_{SH} = 0.0067$ [14, 15] for Au. Using the related method of spin transfer torque FMR Liu et al. reported a value of $\alpha_{SH} = 0.07$ [17] for Pt. Thus depending on the experimental method used, the reported values for $\alpha_{SH}$ vary by more than an order of magnitude even for the same material.

The large scatter in the values of the spin Hall angles may be caused by the number of parameters used for the interpretation of the experimental data and is discussed at length in [18]. Moreover, details of the experimental configuration used to detect pure spin currents have to be considered carefully, since in particular when detecting ISHE in combination with spin pumping, parasitic signals that are often indistinguishable from ISHE may arise. It is hence important to carefully address these issues in parallel while searching for new materials featuring large spin Hall angles [19, 21].

In this letter the angular, material, and temperature dependence of ISHE due to spin pumping is measured. We demonstrate that for a particular excitation geometry an unambiguous separation of signals arising from the anisotropic magneto-resistance (AMR) and ISHE is possible. Microwave frequency as well as temperature dependent measurements of ISHE, for different Py/normal metal bilayer systems are performed. We demonstrate that the amplitude of ISHE depends linearly on the microwave frequency, as predicted. Furthermore the temperature dependence of the ISHE related DC-voltage generated in Py/Pt at FMR allows the determination of the effective spin diffusion length of Pt as a function of temperature.

The samples consist of ferromagnet/normal metal bilayers (Permalloy (Py)/Pt, Py/Au) deposited on GaAs(001) substrates. The layers are structured into wires using electron beam lithography (EBL) and sputter deposition of the single layers in ultra high vacuum. The thickness of the individual layers is 12 nm. The bilayers are integrated into a coplanar waveguide (CPW) structure which is used to create a well defined microwave excitation field. The CPW consists of a 50 µm wide signal line and a 30 µm wide gap corresponding to an impedance of 50 Ω in the GHz frequency range. The metallic bilayer wires are 5 µm wide and 350 µm long and placed either on top of the signal line (in-plane excitation) or in the gap between signal line and ground planes (out-of-plane excitation). Electrical isolation between CPW and metallic bilayer is ensured by a 50 nm thick Al$_2$O$_3$ layer. The samples are placed in an external magnetic field which is rotatable in the film plane. Sketches of the samples corresponding to the different excitation field geometries are shown in Fig. 1(a) and (b).

Spin current injection from a ferromagnet into an adjacent normal metal layer due to spin pumping is derived theoretically in [1] and [2]. It is convenient to consider the precession of the magnetization, which in the static case is saturated in the film plane, and the related injected spin current in a coordinate system ($x', y', z'$), where $x'$ always points along the direction of the dynamic magnetization, $y'$ is always in the magnetic film plane, and $z'$ points out-of-plane [22]. To describe
the direction of a static magnetic field $H$ relative to the bilayer wire a second static coordinate system $(x, y, z)$ is defined, as shown in Fig. 1. Again $x$ and $y$ lie in-plane and $z$ points out-of-plane. The direction of the spin current is along $z'$ and its polarization along $x'$. In this case ISHE will generate a charge current along the $y'$-direction according to $J_C y' = \alpha_{SH} \frac{2e}{h} J_S(z) z' \times x'$ and its magnitude is given by [13]:

$$J_C = \alpha_{SH} \frac{2e}{h} J_S(0) \frac{\lambda_{sd}}{t_{nm}} \tanh \left( \frac{t_{nm}}{2\lambda_{sd}} \right),$$

where $\lambda_{sd}$ is the spin diffusion length and $t_{nm}$ the thickness of the normal metal layer. $J_S(0)$ is the injected spin current density at the ferromagnet/normal metal interface. The voltage probes with a separation $l$ given by the length of the Py/normal metal bilayer are placed along a fixed direction, e.g., $y$, see Fig. 1. The voltage due to ISHE is given by projecting $J_C y'$ onto $\hat{y}$, integrating over $l$, and scaling by the inverse conductivity of the bilayer $1/\sigma$. The voltage due to spin pumping and ISHE for the out-of-plane $(V_{OOP})$ excitation field is then given by:

$$V_{OOP} = \alpha_{SH} \frac{8\pi}{\sigma} \frac{\lambda_{sd}}{M_S^2} \frac{e}{t_{nm}}$$

$$g_{12} \frac{1}{\tilde{\chi}_{yz}^2} \frac{3(\chi_{xx}^\text{res}) \chi_{yy}^\text{res} \tanh \left( \frac{t_{nm}}{2\lambda_{sd}} \right)}{\tanh \left( \frac{t_{nm}}{2\lambda_{sd}} \right)}$$

$$\times \left( \frac{(\Delta H)^2}{(H - H_{\text{FMR}})^2 + (\Delta H)^2} \cos(\phi_H) \right)$$

$$+ \frac{\Delta H (H - H_{\text{FMR}}) \sin(\phi_H)}{(H - H_{\text{FMR}})^2 + (\Delta H)^2} \sin(2\phi_H),$$

where $H_{\text{FMR}}$ and $\Delta H$ are FMR field and linewidth, $\chi_{xx}^\text{res}$ and $\chi_{yz}^\text{res}$ are the in- and out-of-plane rf-susceptibilities and $\phi_H$ is the angle between $x$ and the applied magnetic field $H$, see Fig. 1. Eq. (2) is derived in an analogous manner as described in [13], but using out-of-plane excitation and the applicable entries of the magnetic susceptibility tensor. Also AMR can generate a dc-voltage signal at FMR by mixing the time dependent resistivity (AMR and precessing magnetization) with a capacitively or inductively coupled microwave current $I$ in the bilayer. The line shape of the signal depends on the magnitude of the phase angle $\phi_B$ between precessing magnetization and rf-current in the bilayer. Due AMR the resistance of the bilayer changes with the orientation of the magnetization with respect to the current: $R_A = R_B - R_A$. For out-of-plane excitation the generated voltage due to the AMR-effect can be described by the following formula [13] [16]:

$$V_{\text{OOP}} = \frac{\alpha_{AMR} \chi_{yz}^\text{res}}{M_S}$$

$$\times \left( \frac{(\Delta H)^2 \cos(\phi_B)}{(H - H_{\text{FMR}})^2 + (\Delta H)^2} \right)$$

$$+ \frac{\Delta H (H - H_{\text{FMR}}) \sin(\phi_B)}{(H - H_{\text{FMR}})^2 + (\Delta H)^2} \sin(2\phi_B),$$

First the study of a Py/Pt bilayer located on top of the...
due to geometric reasons and can be well described by a \( \sin(\phi_H) \sin(2\phi_H) \) dependence \[^13\]. As suggested in \[^13\] the phase angle \( \phi_1 \) is not necessarily equal to 90° at FMR. Therefore, the amplitude of the symmetric part of the voltage arises in general from a sum of signals originating from ISHE and AMR. It is thus not possible to uniquely separate signals arising from ISHE from signals caused by AMR using in-plane magnetic field excitation. However, from Eq. (2) it becomes clear that by placing a bilayer in the gap between signal and ground line of a CPW, see the sketch in Fig. 1(b), and measuring at \( \phi_H = 0° \) only ISHE contributes to the voltage signal. The angular dependence of the amplitudes of symmetric and antisymmetric part of the voltage in Fig. 1(b) shows, that the symmetric part is generally a mixture of ISHE and AMR-effect related signals. The amplitude of the antisymmetric part vanishes when \( \phi_1 \) is an integer multiple of 180°. At these angles the voltage signal is purely symmetric and can only be caused by ISHE. The asymmetry of the data presented in Fig. 1(b) with respect to \( \phi_H = 180° \) is most likely caused by the phase angle \( \phi_1 \). The data shown in Fig. 1(b) are consistent with \( \phi_1 = 40° \) for \( \phi_H = 0° - 180° \). The angular plot of Fig. 1(b) suggests, that the phase \( \phi_1 \) between capacitively coupled current and precessing magnetization is not constant, but shifts across \( \phi_H = 180° \) to a corresponding value of \( \phi_1 = 80° \). This is also reflected in the fact that the amplitude of the symmetric voltage part for \( \phi_H = 0° - 180° \) is larger than for \( \phi_H = 180° - 360° \). The phase difference for \( \phi_1 \) corresponds to an excitation field angle of 20° relative to the normal of the bilayer \[^22\].

![Graph](image-url)

**FIG. 2.** Voltage signals at FMR (at 12 GHz) for Py/Pt and Py/Au at small angles around \( \phi_H = 0° \), panel a) and c) respectively. Normalizing with respect to frequency dependent parameters (microwave power, susceptibility and ellipticity) the amplitude of the signal exhibits a linear frequency dependence at \( \phi_H = 0° \) for both Py/Pt and Py/Au, panel b) and d) respectively.

for Pt and Au can be calculated according to the following formula which is the result of solving Eq. (2) for \( \alpha_{SH} \) at FMR.

\[
\alpha_{SH} = \frac{V^{OPT}}{8\pi c \lambda_{sd} g_{\parallel} \omega_{h} \cos(\pi/2)} \frac{\sigma_{nm}}{M_{S}^{2}} \left( \tanh \left( \frac{t_{nm}}{2\lambda_{sd}} \right) \right). \tag{4}
\]

where \( g_{\parallel} \) is the spin mixing conductance. This parameter describes how much spin current is generated by spin pumping and enters the normal metal \[^2\]. For Pt a \( g_{\parallel} \) value of 2.5 \( \times 10^{15} \) cm\(^{-2}\) is determined by measuring the line broadening due to the presence of a Pt cover layer which is in agreement with presented data in \[^2\] and \[^9\]. For Au a value of 1.2 \( \times 10^{15} \) cm\(^{-2}\) is used \[^22\]. The out-of-plane excitation field was determined to be 0.24 mT at 100 mW using electromagnetic simulations of the CPW structure. Furthermore the spin diffusion length enters Eq. (4). For this parameter recent spin pumping experiments suggest a value of 1.4 nm \[^17\], \[^18\] for Pt. For Au a spin diffusion length of 35 nm was measured in \[^24\]. Taking into account all data shown in Fig. 2 and \( \lambda_{sd} = 1.4 \) nm a spin Hall angle of \( \alpha_{SH} \) of 0.09 \( \pm 0.02 \) is obtained for Pt. Similarly using \( \lambda_{sd} = 35 \) nm a value of 0.008 \( \pm 0.001 \) is deduced for Au.

In order to demonstrate the different physical origin of the signals that are obtained at \( \phi_H = 0° \) (ISHE) and \( \phi_H = 45° \) (AMR+ISHE) the temperature dependence of the voltage signals was measured for a Py/Pt bilayer. The results are displayed in Fig. 3. In Fig. 3(a) the
In conclusion, we show that it is not possible to reliably measure ISHE separately from the parasitic AMR for in-plane excitation of the magnetization vector in a Py/normal metal bilayer using a coplanar waveguide experiment. Only out-of-plane excitation and only at certain angles of the polarization of the injected spin current with respect to the voltage probes an unambiguous study of ISHE is possible. Using this geometry spin Hall angles can be quantified reliably using parameters inferred from spin pumping measurements. Temperature dependent measurements underpin the anisotropic magnetoresistive nature of parasitic voltage signals. Moreover, it strongly suggests, that the origin of the signals changes from a mixture of signals arising from ISHE and AMR-effect to a signal originating from ISHE only at appropriate angles. Moreover, the temperature dependent spin diffusion length of Pt has been determined using the inverse spin Hall effect.

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