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Platinum thickness dependence of the inverse spin-Hall voltage from spin pumping in a hybrid yttrium iron garnet/platinum system

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We show the experimental observation of the platinum thickness dependence in a hybrid yttrium iron garnet/platinum system of the inverse spin-Hall effect from spin pumping, over a large frequency range and for different radio-frequency powers. From the measurement of the voltage at the resonant condition and the resistance of the normal metal layer, a strong enhancement of the ratio of these quantities has been observed, which is not in agreement with previous studies on the NiFe/platinum system. The origin of this behaviour cannot be fully explained by the spin transport model that we have used and is therefore still unclear. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4754837]

Recently, in the field of spintronics, spin transfer torque and spin pumping phenomena in a hybrid ferrimagnetic insulator (yttrium iron garnet: YIG)/normal metal (platinum: Pt) system have been demonstrated.[1] Since this observation, the actuation, detection, and control of the magnetization and spin currents in such systems have attracted much attention from both theoretical and experimental point of view.

Spin pumping in a ferromagnetic/normal metal system has been intensively studied as a function of the stoichiometric ratio between nickel and iron atoms,[2] the spin current detector material,[3] and the ferromagnet dimensions.[4,5] Only a few research groups[6–8] have investigated experimentally and theoretically the dc voltage generation (induced by the inverse spin-Hall effect (ISHE)) in a NiFe/Pt system as a function of the thickness of the spin current detector and the ferromagnetic material, at a fixed microwave frequency. To date, no systematic studies of the spin/charge current (charge/spin) conversion in a YIG/Pt system have been presented as a function of the Pt thickness.

In this paper, we show the experimental observation of the Pt thickness dependence in a hybrid YIG/Pt system of the ISHE from spin pumping, actuated at the resonant condition by using a microstrip line in reflection over a large frequency range and for different radio-frequency (rf) powers.

The used insulating material consists of a single-crystal (111) $Y_3Fe_5O_{12}$ (YIG) film grown on a (111) $Gd_3Ga_5O_{12}$ (GGG) substrate by liquid-phase-epitaxy (LPE). We have prepared nine samples with different thicknesses of Pt (1.5, 6.0, 9.0, 11.5, 16, 22.5, 33, 62, and 115 nm) deposited by dc sputtering. Fig. 1(a) shows a schematic of the samples. The Pt layer ($800 \times 1750 \, \mu m$) has been patterned by electron beam lithography (EBL). Ti/Au electrodes of $30 \, \mu m$ width and $100 \, nm$ thick have been grown on top of the Pt detector. The size of the YIG for each sample is $3000 \times 1500 \, \mu m$ with a thickness of $200 \, nm$, which is very small for this kind of fabrication process (LPE). Fig. 1(b) shows the magnetic field dependence of the dc voltage in a YIG/Pt system with a Pt thickness of 11.5 nm for a rf power fixed at 10 mW at 1 GHz.

At the resonant condition (H_{res}), a spin current (j_s) is pumped into the Pt layer and converted in a dc voltage due to the ISHE.

The reversal of the sign of V_{ISHE}, by reversing the magnetic field, shows that the signal is not produced by a possible thermoelectric effect induced by the ferromagnetic resonance absorption. Fig. 1(c) presents the magnetic field dependence of the dc voltage for different thicknesses of Pt measured at 1 GHz and 10 mW. As expected, the maximum value of the dc voltage (ΔV) is reduced by increasing the Pt thickness. No significant changes of the shape of the dc voltage spectrum have been observed as a function of Pt thickness (also not at 3 and 6 GHz).

For each thickness of Pt, we have analysed the dependence of the dc voltage induced by the ISHE as a function of the microwave power [0.25–70 mW], the frequency [0.1–7 GHz], and the in-plane static magnetic field (H) at room temperature.

The frequency dependence of ΔV measured at 10 mW for a Pt thickness of 11.5 nm is presented in Fig. 2(a). The theoretical expression (red dashed line) extracted from Ref. 1 cannot reproduce the measured ΔV at low frequency. In Ref. 1, the frequency dependence of ΔV is defined by the magnetization precession angle, which is proportional to the ratio of the rf microwave field and the linewidth of the uniform mode. In other words, the spin current at the YIG/Pt interface is only defined by the damping parameter, α, assuming that no spin waves are created.[9–11] The enhancement of ΔV at low frequency has been observed for all different thicknesses of Pt. As reported previously in Refs. 9, 12, and 13, this behaviour has been attributed to the presence of non-linear phenomena which are easily actuated for low rf power due to the very low damping of YIG. The dc voltage induced by spin pumping at the YIG/Pt interface is insensitive to the spin wave wavelength, which means that ΔV is not only defined by the uniform mode (long wavelength) but also from secondary spin wave modes which present short wavelengths.
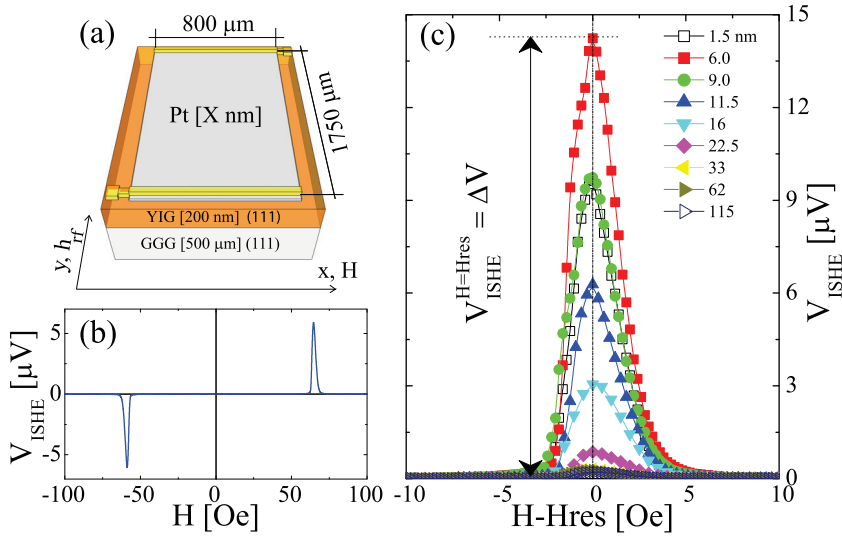
FIG. 1. (a) Schematics of the used sample for the inverse spin-Hall voltage detection. The magnetic field H is applied in the plane of the sample along the $\pm x$ direction with $H \perp h_{rf}$, where h_{rf} is the microwave field applied by a microstrip. (b) Measured voltage (V_{ISHE}) as a function of the magnetic field at 1 GHz and 10 mW for a Pt thickness of 11.5 nm. (c) Magnetic field dependence of the dc voltage for different thicknesses of Pt, measured at 1 GHz and 10 mW.

For each sample, we have extracted ΔV as a function of frequency and rf power. A summary of the rf power dependence of ΔV at 1, 3, and 6 GHz is presented in Figs. 2(b)–2(d), respectively. Each curve presents a different thickness of Pt, grown on top of the YIG sample. By decreasing the Pt
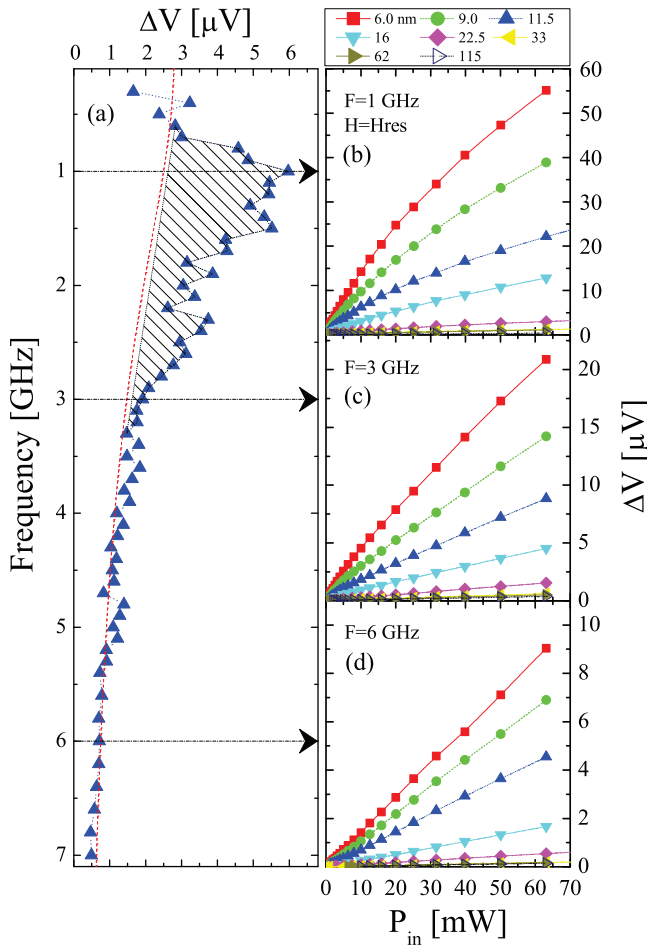

FIG. 2. (a) Frequency dependence of the dc voltage (ΔV) at the resonant condition (see definition in Fig. 1(c)) measured at 10 mW for a YIG/Pt system in which the Pt thickness is equal to 11.5 nm. The red dashed line corresponds to the theoretical expression extracted from Ref. 1. (b), (c), and (d) present the rf power dependence of ΔV at 1, 3, and 6 GHz, respectively, for different thicknesses of Pt. A strong non-linear behaviour can be observed at 1 GHz.

thickness from 115 nm to 6 nm, we are able to detect dc voltages up to 55, 21, and 9 μV at 1, 3, and 6 GHz, respectively, for a rf power of 63 mW. The strong enhancement of ΔV for the thin layer of Pt (a factor of 70 between 6.0 and 115 nm of Pt) permits also to perform measurements at low rf power, lower than 250 μW (not shown).

In order trying to describe the Pt thickness dependence of ΔV, observed in Figs. 2(b)–2(d), we have derived the following expression. The general equation of the spin accumulation in the Pt layer is written as $\mu = a.e^{-z/\lambda} + b.e^{z/\lambda}$. From the boundary conditions, at $z = 0$ nm and $z = t_{Pt}$, where t_{Pt} is the Pt thickness of the spin current detector, one can write

$$
\begin{aligned}
(a) \quad & \frac{d\mu}{dz}\Big|_{z=t_{Pt}} = 0 = -a \cdot e^{-t_{Pt}/\lambda} + b \cdot e^{t_{Pt}/\lambda} \\
(b) \quad & b = a \cdot e^{-2t_{Pt}/\lambda} \\
(c) \quad & \mu(z=0) = \mu_0 = a(1 + e^{-2t_{Pt}/\lambda}),
\end{aligned}
\tag{1}
$$

where λ and μ_0 correspond to the spin diffusion length of Pt and to the spin accumulation at the YIG/Pt interface, respectively. Therefore μ can be written as

$$
\mu = \frac{\mu_0}{(1 + e^{-2t_{Pt}/\lambda})}[e^{-z/\lambda} + e^{-2t_{Pt}/\lambda}.e^{z/\lambda}].
\tag{2}
$$

The spin current, j_s, is written as

$$
\begin{aligned}
j_s &= -\sigma \cdot \frac{d\mu}{dz} \\
j_s &= \frac{\mu_0}{(1 + e^{-2t_{Pt}/\lambda})} \cdot \frac{\sigma}{\lambda} [e^{-z/\lambda} - e^{-2t_{Pt}/\lambda}.e^{z/\lambda}],
\end{aligned}
\tag{3}
$$

where σ corresponds to the electrical conductivity of the Pt layer. From the definition of the spin current at the interface j_s^0 at $z = 0$, the spin conductance of the Pt can be expressed as

$$
g_{Pt} = \frac{j_s^0}{\mu_0} = \frac{\sigma}{\lambda} \cdot \frac{1 - e^{-2t_{Pt}/\lambda}}{1 + e^{-2t_{Pt}/\lambda}},
\tag{4}
$$

with $\mu_0 \propto \frac{g_{\uparrow\downarrow}}{g_{\uparrow\downarrow} + g_{Pt}}$, where $g_{\uparrow\downarrow}$ corresponds to the spin mixing conductance of the YIG/Pt interface. The spin current at the

YIG/Pt interface is then given by the equation: $j_s^0 \propto \frac{g_{\uparrow\downarrow} \cdot g_{Pt}}{g_{\uparrow\downarrow} + g_{Pt}}$. From the equation of the spatially averaged spin current, given $\langle j_s \rangle = \frac{1}{t_{Pt}} \cdot \int_0^{t_{Pt}} j_s(z)dz$, and the expression of the ISHE conversion of a spin current into a charge current, $\langle j_c \rangle = \left[\frac{2e}{\hbar}\right]\Theta_{SH} \cdot \langle j_s \rangle$, the dc voltage can be expressed as

$$V_{ISHE} = \frac{1}{t_{Pt}}\left[\frac{2e}{\hbar}\right]L\Theta_{SH} \cdot \mu_0 \cdot \frac{(1 - e^{-t_{Pt}/\lambda})^2}{1 + e^{-2t_{Pt}/\lambda}}, \quad (5)$$

where Θ_{SH} and L denote the spin-Hall angle and the length (along y) of the Pt layer, respectively. Therefore, by combining Eqs. (4) and (5), the Pt thickness dependence of V_{ISHE} can be written as

$$V_{ISHE} \propto \frac{1}{t_{Pt}} \cdot \frac{g_{\uparrow\downarrow}}{g_{\uparrow\downarrow} + \frac{\sigma}{\lambda} \cdot \frac{1 - e^{-2t_{Pt}/\lambda}}{1 + e^{-2t_{Pt}/\lambda}}} \cdot \frac{(1 - e^{-t_{Pt}/\lambda})^2}{1 + e^{-2t_{Pt}/\lambda}}. \quad (6)$$

Here, we assume that the spin-Hall effect arises from extrinsic effects (scattering processes are dominant), and therefore Θ_{SH} should be independent of the Pt thickness.[14]

Fig. 3(a) presents ΔV as a function of the Pt thickness, t_{Pt}, at 3 GHz, for different rf powers (1, 10, 20, and 50 mW). The general trend of ΔV is the same for the different rf powers and a maximum of ΔV between $t_{Pt} = 1.5$ and $t_{Pt} = 6.0$ nm has been observed (also at 1 and 6 GHz). Concerning the spin diffusion length, many values are reported, varying between 1.4 ± 0.4 (Ref. 14) and 10 ± 2 nm.[15] In order to reproduce the strong dependence of ΔV for thinner layers of Pt, the best value obtained for the spin diffusion length of Pt has been found to be $\lambda = 3.0 \pm 0.5$ nm, which is in good agreement with the value reported by Azevedo et al.[6] For this value of λ and from the Pt thickness dependence of σ, the spin conductance of the Pt (g_{Pt}) can be calculated by using Eq. (4). g_{Pt} varies between 8.5×10^{13} and $6.2 \times 10^{14}\,\Omega^{-1}\mathrm{m}^{-2}$ at $t_{pt} = 1.5$ and 11.5 nm, respectively, and it is constant for thicker layers of Pt, around $9.5 \times 10^{14}\,\Omega^{-1}\mathrm{m}^{-2}$. The inset of Fig. 3(a) presents the experimental dependence of ΔV at 3 GHz and 10 mW as a function of the Pt thickness including the theoretical dependencies from Eq. (6) for two extreme limits: when $g_{\uparrow\downarrow}$ is much lower (solid line) and much higher (dotted line) than g_{Pt}. As observed in the inset of Fig. 3(a), the spin mixing conductance should be lower than g_{Pt} in order to reproduce partially the observed behaviour.

The electrical conductivity of the Pt layers (see Fig. 3(b)) presents a strong Pt thickness dependence. σ has been calculated from the measured resistance (R) and from the sample dimensions (the thickness of the Pt has been measured by atomic force microscopy). σ increases from $1.1 \times 10^6\,\Omega^{-1}\mathrm{m}^{-1}$ (at 1.5 nm) to $2.9 \times 10^6\,\Omega^{-1}\mathrm{m}^{-1}$ (at 33 nm). σ presents a constant value from 33 to 115 nm ($\sim 2.9 \times 10^6\,\Omega^{-1}\mathrm{m}^{-1}$). Mosendz et al.[15] and Jungfleisch et al.[16] reported similar values of σ for a Pt thickness of 15 and 10 nm, respectively, as shown in Fig. 3(b).

Another interesting feature of this study is presented in Fig. 3(c). This figure presents the dependence of $\Delta V/R$ as a function of the Pt thickness for different frequencies (1, 3, and 6 GHz) and rf powers (1, 10, 20, and 50 mW). The trend of these curves does not follow the behaviour observed in a NiFe/Pt system.[6,7] One would expect a constant value of
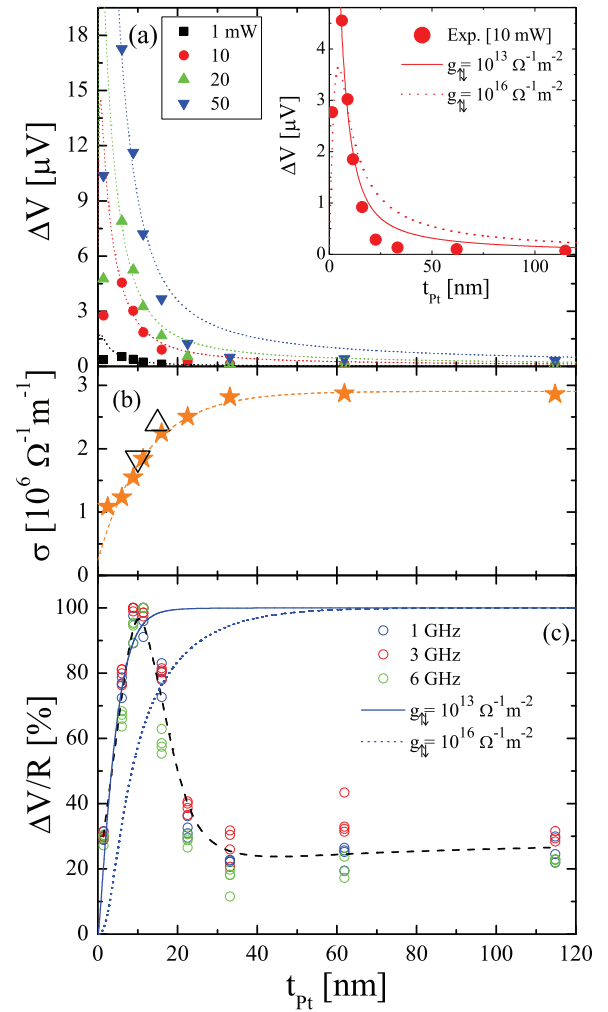

FIG. 3. (a) Pt thickness dependence of ΔV measured at 3 GHz. The rf power has been fixed at 1, 10, 20, and 50 mW. For each rf power, the dotted line shows the theoretical evolution of ΔV as a function of the Pt thickness, as given by Eq. (6) when $g_{\uparrow\downarrow} \ll g_{Pt}$. The inset shows the dependence of ΔV as a function of the Pt thickness. The dots correspond to the experimental data at 3 GHz for a rf power of 10 mW. The solid line and the dotted line correspond to the theoretical dependencies from Eq. (6) of ΔV when $g_{\uparrow\downarrow}$ is lower and higher than g_{Pt}, respectively. (b) The dependence of the electrical conductivity (σ) of the normal metal is plotted as a function of the Pt thickness. The symbols $\triangle$ and ∇ correspond to the magnitude of σ extracted from Refs. 15 and 16, respectively. (c) Pt thickness dependence of $\Delta V/R$ for different frequencies (1, 3, and 6 GHz) and rf powers (1, 10, 20, and 50 mW). The black dashed line corresponds to the average of the experimental data. The blue solid line and the blue dotted line correspond to the theoretical dependence of $\Delta V/R$ when $g_{\uparrow\downarrow} \ll g_{Pt}$ and $g_{\uparrow\downarrow} \gg g_{Pt}$, respectively.

$\Delta V/R$ for a Pt thickness higher than the spin diffusion length. Contrary to Refs. 6 and 7, a maximum around 10 nm followed by a strong decrease until 20 nm of Pt has been observed. Values of $\Delta V/R$ are constant between 33 and 115 nm and the difference between the constant value of $\Delta V/R$ and the maximum is around 70%. The solid line and the dotted line correspond to the theoretical dependence of $\Delta V/R$ when $g_{\uparrow\downarrow}$ is lower and higher than g_{Pt}, respectively. Two points should be made regarding these dependencies. First, when $g_{\uparrow\downarrow} \gg g_{Pt}$, the Pt thickness dependence of $\Delta V/R$ presents, for small thicknesses, a quadratic evolution and therefore cannot reach the experimental values. Second, when $g_{\uparrow\downarrow} \ll g_{Pt}$, the linear dependence of $\Delta V/R$ between 0 and 10 nm of Pt permits to reproduce partially the experimental behaviour. This shows that $g_{\uparrow\downarrow}$ should be lower than

g_{Pt}, which is in agreement with the results published by Kaji-wara *et al.*[1] and Vilela-Leão *et al.*[17] They have found in Ref. 1 that the spin mixing conductance at the YIG [1.3 μm]/Pt [10 nm] interface is around $10^{12}\Omega^{-1}m^{-2}$, which is two orders of magnitude smaller than the computed value for a YIG/Ag system.[18]

In conclusion, we have shown the experimental observation of the Pt thickness dependence in a hybrid YIG [200 nm]/Pt [1.5-115 nm] system of the ISHE from spin pumping, actuated at the resonant condition over a large frequency range and for different rf powers. A strong enhancement of the ratio $\Delta V/R$ has been observed for several frequencies and rf powers, which is different from previous studies on the NiFe/Pt system. The observed dependence of $\Delta V/R$ as a function of the Pt thickness in our system is still unclear and cannot be fully reproduced by our spin transport model.

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