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## Spin Seebeck effect in nanometer-thick YIG micro-fabricated strips

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We have investigated the spin Seebeck effect (SSE) generated by current induced-heating in ultra-thin yttrium iron garnet film (20 nm) covered by an 8 nm thick Pt layer. By passing current in the Pt layer, an out-of-plane temperature gradient is established that, in turn, generates an out-of-equilibrium magnons population. The resulting pure spin current is detected using the inverse spin Hall effect (ISHE) measured in the Pt electrode. A lock-in detection scheme is used to separate the SSE signal from other magneto-galvanic effect. Indeed, the SSE signal is obtained as the second harmonic voltage response, while spin Hall magnetoresistance (SMR) is measured as the first harmonic response to the ac excitation current. Interestingly, the amplitude of the SSE in such thin YIG film is comparable to what has been reported for much thicker films. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). [<http://dx.doi.org/10.1063/1.4976332>]

### I. INTRODUCTION

Caloritronics has become a field of intense interest as it holds promise to advantageously use what is usually considered as wasted thermal energy to create and manipulate spin information.<sup>1</sup> Thermal gradients, through the generation of out-of-equilibrium chemical potential profiles, have the ability to give rise to pure spin currents, which is particularly interesting notably in case of insulating ferromagnets like Yttrium Iron Garnet (YIG).<sup>2</sup> The key phenomenon in caloritronics is the spin Seebeck effect (SSE),<sup>3</sup> and some SSE experiments have been performed on magnetic metallic systems such as Permalloy.<sup>4,5</sup> However, in ferromagnetic metals, there are a number of thermo-electric effects (such as anomalous or planar Nernst effect) that can bring artefacts in the quantitative interpretation of the SSE. By considering an electrical insulator ferromagnet such as the low damping YIG,<sup>6–8</sup> the SSE signal can be more easily detected without any charge induced thermal effects. When combined with a large spin-orbit coupling material such as platinum (Pt), these caloritronic spin currents generated in YIG can be detected by the inverse spin Hall effect (ISHE).<sup>2</sup> We present here, a study of ISHE voltage on a Pt layer deposited on a 20 nm thick YIG film.

In YIG/Pt system, the longitudinal spin Seebeck effect is present when a perpendicular temperature gradient over the interface excites thermal magnons in YIG film. This out-of-equilibrium magnons population then transfers part of its excess angular momentum to the conduction electrons in the Pt layer leading to an ISHE voltage (see Fig. 1(b)). In most of the previous experiments, the driving force for SSE is an external thermal source (Peltier elements or laser spots) to create the temperature gradient over the device.<sup>9–12</sup> Recently, it has been shown by Schreier *et al.*<sup>13</sup> that a SSE voltage can be obtained by simply passing a current in the Pt layer. In this approach, the Joule heating

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in Pt is at the origin of the out-of-plane temperature gradient. However, this experimental procedure has the drawback that the charge current will cause the measurement to be sensitive to magnetoresistance effects such as the spin Hall magnetoresistance (SMR),<sup>14–17</sup> thus making SSE more difficult to detect and to analyze. As all magnetoresistance phenomena in Pt are linear with current, a lock-in detection technique can be used to extract separately the first order ( $\omega$ ) from the second order ( $2\omega$ ) contribution to the voltage. The first order response contains only linear effects like SMR while in the second harmonic, the SSE can be detected. Vliestra *et al.* have first used this approach to extract a clear SSE signal by current induced heating in 200 nm thick YIG films.<sup>18</sup>

In the present work, we aim investigating the SSE in an ultra-thin (20nm) YIG/Pt stripe with an out-of-plane temperature gradient, here the YIG thickness is approximately twice the magnetic exchange length ( $\sim 10$  nm). The induced ISHE voltage is recorded for different in-plane field orientations  $\theta$  and for different amplitudes of the ac-current. Even if the total volume of YIG is very small compared to previous studies, the detected SSE is large enough to allow us to understand the origin of the SSE signal. Moreover, we can in parallel also study the SMR in this YIG/Pt stripe.

## II. EXPERIMENTAL METHODS

The studied sample presented in Fig. 1 consists of a 1  $\mu\text{m}$ -wide stripe based on high quality 20 nm thick YIG film grown by pulsed laser deposition on a (111) gadolinium gallium garnet (GGG) substrate. Previous to the spin Seebeck experiments, the properties of the extended YIG film have been characterized and we found a low Gilbert damping parameter  $\alpha_0 = (4.8 \pm 0.5) \times 10^{-4}$  and a small inhomogeneous contribution to the linewidth,  $\Delta H_0 = (1.9 \pm 0.5)$  Oe (full width at half maximum). More details about the growth and the standard characterization of the structural properties of our YIG films can be found in O. d’Allivy Kelly *et al.*<sup>6</sup> The YIG film is covered by 8 nm of Pt deposited by dc magnetron sputtering with prior *in situ* plasma and the YIG/Pt bilayer is patterned using Ar ion beam etching in a 1  $\mu\text{m}$ -wide stripe. A thick Pt layer is used (few times more than the spin diffusion length of Pt) in order to reliably inject large enough ac-currents. The stripe has a total length of 100  $\mu\text{m}$  and Au (100 nm)/Ti (20 nm) contacts are defined by optical lithography on top of the

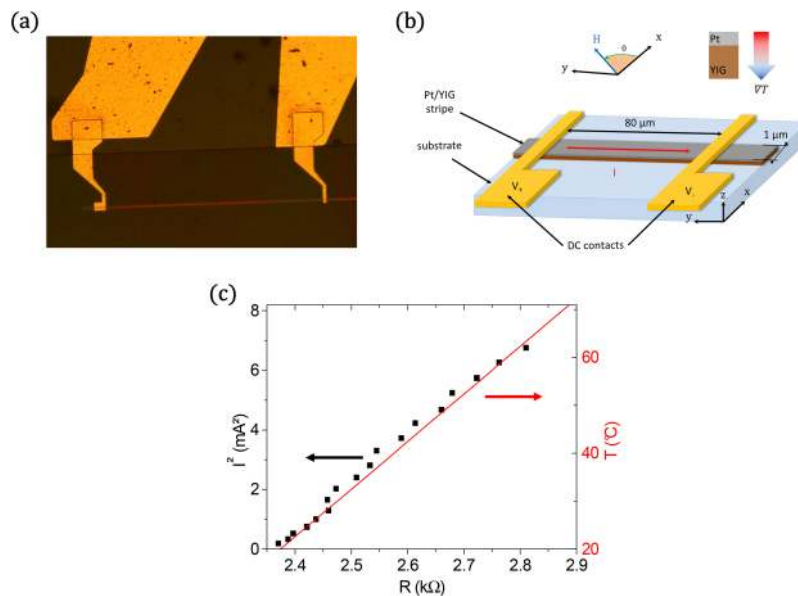


FIG. 1. (a) Optical microscopic image of the studied device. The horizontal line is the YIG (20 nm)/Pt (8 nm) 1  $\mu\text{m}$ -wide stripe. Ti/Au pads are used to electrically contact the device and detect the voltage signal. These are separated by 80  $\mu\text{m}$ . (b) Sketch of the experimental setup. The applied magnetic field angle is referenced to the  $Ox$  axis and given by  $\theta$ . The temperature gradient is perpendicular to the interface. The ISHE signal is detected using the Au contact-leads. (c) Current and temperature dependence with respect to the Pt stripe resistance.

YIG/Pt waveguide to inject and detect the charge current in Pt. The distance between the contacts is of  $80\ \mu\text{m}$ . An optical microscopic image of the device can be seen in Fig. 1(a). This ultra-thin YIG film has allowed observing spin Hall effect torque induced magnetization auto-oscillation evidenced by inductive measurements<sup>19</sup> and micro-focused BLS spectroscopy ( $\mu$ -BLS).<sup>20,21</sup> As enounced before, the SSE originates from current-induced heating of the Pt stripe. The Joule heating scales with  $I^2$  where  $I$  is the rms heating ac current. Using the evolution of the resistivity measured in the Pt layer as a thermometer, we have observed as expected, that the Pt temperature increases quadratically with the applied current (see Fig. 1(c)). As a result, the SSE will appear in the second harmonic response and is detected via the ISHE voltage in the Pt layer. The temperature in the sample obtained for  $I = 2.5\ \text{mA}$  is about  $60\ ^\circ\text{C}$ .

The measurements were performed using a lock-in amplifier with a modulation frequency of  $17\ \text{Hz}$ . We measure separately and simultaneously the first and the second harmonic of the voltage responses. The ac-current is injected in the sample using a voltage source with sinusoidal modulation and the rms current value is recorded continuously. The applied current ranges from  $0.5$  to  $3\ \text{mA}$ . A bridge measurement configuration is used to offset the measured voltage and therefore remove the Ohm's law contribution. An external magnetic field is applied in the film plane with an angle  $\theta$  from the  $Ox$  direction as shown in the inset of Fig. 1(b). All the presented measurements have been carried out at room temperature.

### III. RESULTS AND DISCUSSION

In Fig. 2(a), we show the second harmonic voltage associated to the SSE signal as a function of the angle between the magnetic field and the current ( $\theta$ ) measured for  $I = 2\ \text{mA}$  and  $H = 600\ \text{Oe}$ . The voltage is positive for  $\theta = -180^\circ$  with a maximum value around  $1.5\ \mu\text{V}$  then decreases to reach a minimum at  $0^\circ$  with a minimum value of  $-1.25\ \mu\text{V}$ . Then the amplitude increases again to reach the same value for  $\theta = 180^\circ$ . An offset corresponding to the voltage at  $\theta = 90^\circ$  is applied to the raw data. Using the same technique, the results reported by other groups show similar values for the SSE signal in thin YIG/Pt systems.<sup>13,18</sup>

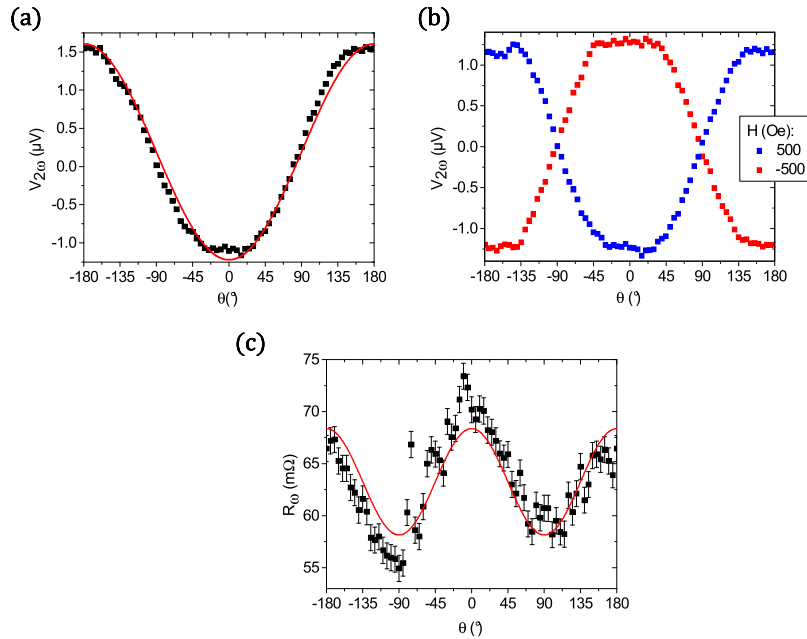


FIG. 2. (a) Room temperature angular dependence of the second harmonic voltage showing the SSE signal for  $I = 2\ \text{mA}$  and  $H = 600\ \text{Oe}$ . The red line is a cosine fit of the data. (b) Room temperature angular dependence of the second harmonic voltage showing the SSE signal for  $I = 2\ \text{mA}$  and two opposite directions of the magnetic field  $H = 500\ \text{Oe}$  and  $H = -500\ \text{Oe}$ . (c) Angular dependence of the first harmonic response corresponding to the SMR signal for  $I = 3\ \text{mA}$  and  $H = 600\ \text{Oe}$ . The red line is a  $\cos^2(\theta)$  fit of the data.

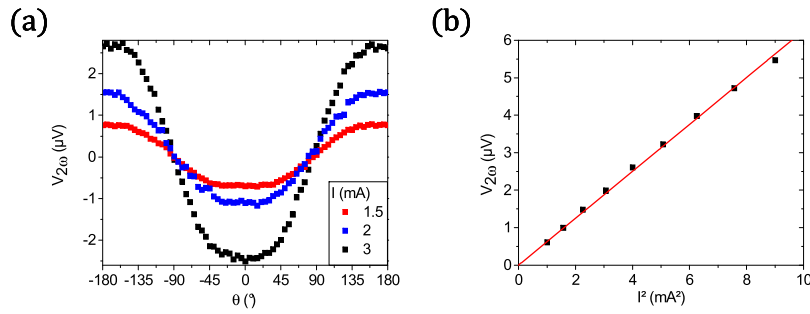


FIG. 3. (a) Current dependence of the second harmonic voltage signal for  $H = 600$  Oe. (b) Linear dependence of the SSE amplitude with  $I^2$  in agreement with the Joule heating origin of the signal.

A first observation is that the SSE signal presents a  $2\pi$  periodicity with a cosine behavior. The continuous line in Fig. 2(a) is a fit to the expected SSE/ISHE angular dependence. The voltage is proportional to the projection of the magnetization on the axis normal to the voltage measurement stripe (i.e. along  $Ox$ ). As expected from the SSE symmetry, the sign of the SSE signal is reversed when the direction of the magnetic field is opposite as shown on Fig. 2(b). As for the first harmonic voltage, we find that the SMR effect is the dominant contribution. Indeed, with the given measurement configuration, it is expected that the SMR effect has a  $\cos^2(\theta)$  angular dependence as confirmed by the experimental measurements shown in Fig. 2(c) (black dots) with a good agreement when compared to  $\cos^2(\theta)$  fit (red line in Fig. 2(c)). Note that the larger noise in the first harmonic compared to the second harmonic voltage is probably due to contact resistances contribution. These two measurements at  $\omega$  and  $2\omega$  unambiguously prove that both SSE and SMR are present in this YIG (20 nm)/Pt (8 nm) system.

In Fig. 3(a), we present the evolution of the second harmonic voltage amplitude for three values of the ac current ( $I = 1.5, 2$  and  $3$  mA). Defining the SSE amplitude as the voltage difference between  $\theta = 0^\circ$  and  $\theta = 180^\circ$ , we find that the SSE voltage scales quadratically with  $I$  as shown on Fig. 3(b). This further confirms that the source of the SSE voltage is the Joule heating of the Pt layer.

We do not observe any abrupt change or criticality on the  $V_{2\omega}$  voltage dependence with current even at  $2.6$  mA which correspond to the threshold current for spin-orbit torques induced magnetization auto-oscillation. This value has been evidenced by  $\mu$ -BLS experiments on the same sample.<sup>20</sup> Even if spin orbit torque is linear with current, above the threshold current, its effect induces non-linear coupling between the thermal magnons and the coherent precession. Such a change can be seen as an effective magnon temperature modification at the interface compared to the phonon temperature. We speculate that consensual theoretical understanding of the SSE origin as an interfacial temperature mismatch between the YIG magnons and the Pt electrons<sup>22</sup> does not grab all the physics in the non-linear excitation regime.

#### IV. CONCLUSION

In summary, we have measured the SSE voltage in an ultra-thin YIG micro-fabricated stripe by current-induced heating. Simultaneously, thanks to a lock-in detection technique, SMR has been recorded separately from the SSE. At high applied magnetic fields, the obtained signal closely follows the behavior expected from the angular dependence of the SSE. The Joule heating origin of the SSE has been proven for this system and no specific signature of the auto-oscillation regime has been observed. Our study shows that the SSE has to be considered in future magnonics devices based on nano-structured ultra-thin YIG films.

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