Bolometric detection of ferromagnetic resonance in YIG slab

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The resistance of the Pt bar deposited on the YIG slab was monitored while the magnetic field was ramped through the ferromagnetic resonance with the YIG slab facing a coplanar waveguide resonator excited at 4.3 GHz excitation. The resistance change provides detection of the ferromagnetic resonance with a high signal-to-noise ratio. It is ascribed to a change in the temperature of the Pt bars. The thermal origin of the signal is confirmed by the observation that the signal vanishes when field modulation is applied at frequencies above 6 Hz. The spin pumping effect was vanishingly small, and the anisotropic magnetoresistance of the Pt bar, though quite easily observed, would imply a rectification voltage that is much smaller than the bolometric effect.

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Electrical detection of the ferromagnetic resonance (FMR) based on the spin pumping effect¹⁻⁵ has recently drawn great attention in the field of spintronics. The spin current generated by the FMR is injected through an interface between ferromagnetic material (FM) and normal metal (NM) and, due to the inverse spin Hall effect, a DC response can be detected. The spin pumping innately demands high quality interfaces. Yttrium iron garnet (YIG) with a Pt bar deposited on top of it is one commonly used hybrid structures.⁶⁻⁸ The experimentally detected electrical voltage signal may have other contributions, most notably the spin rectification effect due to the anisotropic magnetoresistance (AMR) of Pt⁹⁻¹¹ and the bolometric effect due to the heat associated with microwave absorption¹². One may distinguish spin pumping and spin rectification effect based on their different angular dependence¹³⁻¹⁶. When a current is applied either through the sample or through the deposited metal bar, the bolometric effect is another possible contribution to the electrical signal. This has already been shown to be a promising applications in THz technology^{17,18}. Gui et al.¹² in their seminal study show a comparison between spin rectification and bolometric effects in Permalloy. However, very few studies on the bolometric effect in YIG/Pt structures can be found¹⁹. In this work, we present experimental results showing a distinct bolometric effect as a viable electrical detection of the FMR in YIG/Pt. A voltage response as large as $40\text{ }\mu\text{V}$ is observed. It is two orders of magnitude larger than what was reported in previous studies¹⁹. We will show that the signal becomes very small when the ferromagnetic film is very thin. By varying the magnetic field modulation frequency, we demonstrate that the bolometric effect is the dominant contribution in our observation and that the response of spin rectification and spin pumping is below $1\text{ }\mu\text{V}$.

Fig. 1 shows a schematic illustration of our sample and the experimental setup. The sample consists of yttrium iron garnet ($10\text{ }\mu\text{m}$) / Pt (10 nm). YIG was grown on a substrate of Gadolinium Gallium Garnet (111) using LPE. Ar^+ plasma cleaning at energies of 50 to 100 eV for 10 min was used to obtain a clean interface before Pt deposition⁶. Afterwards, a Pt strip of $1.5 \times 4\text{ mm}^2$ surface was prepared by sputtering. FMR is excited at frequencies in the range of 4 to 7 GHz using a coplanar waveguide resonator (CPW) and measured via the derivative of microwave power absorption using a small field modulation of 0.3 Oe and lock-in detection. The magnetic field, which is ramped slowly between -2.5 kOe and 2.5 kOe, is applied perpendicular in plane to the Pt strip. All the measurements were performed with a microwave source power of $P_{\text{mw}} = 16\text{ dBm}$. In order to measure the resistance in YIG/Pt,

we used either a nano-voltmeter when there was no field modulation, or a lock-in amplifier when field modulation was applied.

Figure 1. Schematic illustration of the experimental system: FMR signal is excited by CPW.

Our aim was to detect the FMR signal in YIG/Pt electrically. There are three possible mechanisms : the magnetic proximity effect^{20,21}, the bolometric effect and the spin pumping. In order to test the first two, which correspond to resistive measurements, we applied a constant current of 100 μA , 1 mA or 5 mA to the Pt bars. Considering that the maximum current density of Pt to avoid damage to be of about 10^6 A/cm^2 , 30 mA would be the upper limit in our case. We find a significant signal at the resonance field when the applied current is less than 100 μA . An obvious resistance peak appears at 850 Oe (Fig. 2(a)). The signal amplitude can reach as much as 40 μV with an applied current of 5 mA (Fig. 2(b)), which is two orders of magnitude larger than that observed by Hahn et al.¹⁹ using the same DC current.

We find that the detected signal remains of the same sign when the field is reversed (Fig. 2(a)). Spin pumping voltage response would change sign with a reversed field.²² On the contrary, the bolometric effect keeps the same sign at positive and negative field at resonance since it is due to heating resulting from the resonant microwave absorption.

Figure 2. (a) Resistance of YIG/Pt hybrid structure at positive and negative field with 1 mA current, (b) The magnitude of voltage maximum detected on Pt bar with different applied currents of $100 \mu A$, 1 mA and 5 mA at 4.3 GHz.

We confirm that this is the resonance position by the regular detection method, moni-

toring the reflected signal coming back from the resonator (Fig. 3(a)). The resonance field at about 850 Oe for an excitation frequency of 4.3 GHz is what is expected from the Kittel formula²³:

$$\omega = \mu_0 \gamma \sqrt{H_0(H_0 + M_S)} \quad (1)$$

We can distinguish in Fig. 3(a) some small features that correspond to magneto-static modes in this thick YIG slab²⁴.

We tried to detect the FMR by monitoring the voltage across the Pt bar in the absence of applied current. That is, we relied on the Inverse spin Hall effect (ISHE) detection of FMR with the Pt strip²⁵. Measurement of the ISHE signal was performed either using a lock-in amplifier with a field modulation or a DC nanovoltmeter. No signal was detected using either methods. The most likely reason was that in our sample the surface of the YIG slab was too rough. Because the YIG/Pt interface quality is so critical, most of ISHE experiments are performed on YIG thin film with a thickness in the nm scale.

Fig. 3(b) shows three spectra acquired at three excitation frequencies and detected with a current of 1 mA. This detection scheme yields broader and slightly shifted lines than the regular detection method. It can be understood as follow, when the YIG is excited by microwave at resonance, it heats up the YIG and Pt, the thermal relaxation could not follow immediately as magnetodynamics leads to line shifting. Since the synthetic signal includes rectification and bolometric signal. It could be possibly become broader combining rectification signal with the same shape and bolometric signal with line shifting. The same observation was made by Goennenwein et al²⁶ and by Hahn et al¹⁹.

We can account for the order of magnitude of the effect with a one-dimensional model. We consider that the part of the YIG sample that is subjected to the the highest microwave field just above the hot spot of the CPW resonator heats up because it absorbs power (Fig. 5). We note P_Q the power absorbed by unit volume and C the specific heat per unit volume of YIG. Applying the Fourier law $\mathbf{j}_Q = -\kappa \nabla T$ in the heated column of YIG, we arrive at a modified heat equation that includes the heat source P_Q :

$$C \frac{\partial T}{\partial t} = \kappa \nabla^2 T + P_Q \quad (2)$$

where κ is the heat conductivity. We take the boundary condition that the GGG substrate remains at the ambient temperature T_0 . We assume also that there is no heat dissipation

Figure 3. (a) FMR absorption derivative spectra of 10 μm thick YIG films at an excitation frequency of 4.2 GHz (red), 4.3GHz (black) and 4.4GHz (green). (b) Magnetoresistance measurement at excitation frequencies of 4.2 GHz (red), 4.3GHz (black) and 4.4GHz (green) with applied DC current of 1 mA.

at the air interface, $\mathbf{j}_Q(z = d) = 0$, where d is the thickness of the YIG sample. In the

stationary regime, the integration of Eq (2) is straightforward, yielding :

$$T(z) = \frac{-P_Q}{2\kappa} z^2 + \frac{P_Q d}{\kappa} z + T_0 \quad (3)$$

Thus, we find that the temperature at the surface of YIG is given by,

$$T(d) = \frac{P_Q d^2}{2\kappa} + T_0 \quad (4)$$

We estimate the part of the sample that is irradiated by strong microwave signals to have a surface area A of about 1 mm^2 and d in depth. The power P_0 was 16 dBm, and $P_Q = \frac{P_0}{Ad}$. These numerical values imply a temperature rise of 20 mK. The Pt bar had a resistance of about $98 \text{ } \Omega$ and its temperature dependence was about $0.5 \text{ } \Omega/\text{K}$. Thus, this temperature change provokes a resistance change of $0.01 \text{ } \Omega$. As the current used to measure the data of Fig 2(a) was of 1 mA, this implies a voltage change upon resonance of $10 \text{ } \mu\text{V}$.

Therefore, it is resonable to assume that the detected signal arises from the bolometric effect^{27,28} due to the microwave absorption at the resonance, causing a temperature rise of the sample and thereby, changing the resistance of Pt in close contact to it.

Gui et al. confirmed the thermal origin of their signal by using the power modulation. They estimated the resistance change as $\Delta R_T = \frac{P_0 \tau}{C_0} \frac{dR}{dT}$, where P_0 is the absorption MW power, τ is the thermal relaxation time, and C_0 is the absolute heat capacity of YIG/Pt.¹²

Likewise, we characterize the extent to which a resistance change is of thermal origin, using field modulation and measuring the signal dependence on the modulation frequency f_{mod} . The magnitude of the signal at resonance was measured as a function of f_{mod} (Fig. 4). If the modulation period is shorter than τ , the thermal relaxation could not follow, which means ΔR_T is significantly reduced. In other words, ΔR_T is strongly dependent on f_{mod} . Fig. 4 demonstrates how thermal relaxation τ affects the bolometric effect. We deduce from the data the value of τ to be 0.3 s. Since AMR in our sample was $\frac{\Delta R_{\text{AMR}}}{R} = 7 \times 10^{-4}$ which is comparable to the result of Chien et al.²⁰, we ascribe the high frequency limit to spin rectification. It cannot be spin pumping, because the signal we observe is proportional to the current (Fig. 2 (b)).

This time constant can be understood as follows. There is one column of YIG, of depth d and surface area A that is heated up (Fig. 5). This heat is communicated to the whole of the YIG sample by a heat current going through a surface of area S . This heat is driven by a temperature gradient, which is of the order of magnitude of $(T - T_0)/d$. Thus, as a rough

Figure 4. Lock-in detected voltage response as a function of the field modulation frequency up to 40 Hz with the microwave frequency of 4.3 GHz and the DC current of 1 mA. Error bars indicate noise level at each measured spectrum.

estimate, the dynamics of heating is modeled by :

$$C V \frac{\partial T}{\partial t} = -\kappa \frac{T - T_0}{d} S \quad (5)$$

which can be rewritten as

$$\tau \frac{\partial (T - T_0)}{\partial t} = -(T - T_0) \quad (6)$$

with

$$\tau = \frac{C}{\kappa} \frac{V d}{S} \quad (7)$$

Given that S is about 1 mm times the thickness d of YIG, this rough estimate yields a time constant τ of 0.2 s, which is of the right order of magnitude compared to our actual data.

In conclusion, we have studied the resistance change under the microwave irradiation in YIG/Pt. The observed voltage, appearing at the ferromagnetic resonance field, exhibits a dependence on the field modulation frequency which is characteristic of the bolometric

Figure 5. Schematics of the sample (outer frame) and the region (red) of strong microwave irradiation produced by the CPW. Notation : d , thickness of YIG, A , surface area of the region exposed to strong microwave, S , surface area of the section through which heat propagates in YIG, V , volume in which heating occurs.

effect, as it has a time constant characteristic related to heat diffusion in the sample (Eq. 7). The effect scales with the square of the thickness (Eq. 4), hence becomes very small if one were to study FMR in YIG films of only 10 nm in thickness, as in Ref. 19.

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