Spin Injection at the Magnetic Insulator (YIG)/Normal Metal (Au) Interfaces

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Spin injection across the ferrimagnetic insulator (YIG)/normal metal (Au) interface was studied by ferromagnetic resonance. The spin mixing conductance was determined by comparing the Gilbert damping in bare YIG films with those covered by a Au/Fe/Au structure. The Fe layer in Au/Fe/Au acted as a spin sink as displayed by an increased Gilbert damping parameter $\alpha$ compared to that in the bare YIG. In particular, for the 9.0 nm YIG/2.0 nm Au/4.3 nm Fe/6.1 nm Au structure, the YIG and Fe films were coupled by an interlayer exchange coupling, and the exchange coupled YIG exhibited an increased Gilbert damping compared to the bare YIG. This relationship between static and dynamic coupling provides direct evidence for spin pumping. The transfer of spin momentum across the YIG interface is surprisingly efficient with the spin mixing conductance $g_{11} \approx 1.2 \times 10^{14}$ cm$^{-2}$.

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Giant magneto resistance and spin transfer torque devices [1] are based on spin-polarized electron currents. In these devices, the spin and electron transport are not separated and therefore are affected by typical limitations of electronic circuits: circuit capacitance, heat generation, and electron migration. Recently, attention has turned to developing ideas and systems where spin transfer torque can be achieved by pure spin currents. A newly emerging field called spin caloritronics [2] addresses the generation of a spin current by a thermal gradient. In his pioneering work, Slonczewski has shown that a higher efficiency in spin transfer torque devices can be achieved by using spin transport driven by thermal gradients in magnetic insulator/normal metal structures [3]. Magnetic insulators, yttrium iron garnets (YIG), in particular, have very low magnetic losses, and by heat gradient one can create a large number of low loss magnons, allowing one to generate an appreciable pure spin current.

In order to pursue this approach, one has to establish the effectiveness of spin momentum transfer across a magnetic insulator (MI)/normal metal (NM) layer interface. Xiao et al. faced a similar situation in the theoretical treatment of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2]. They have shown that the transfer of spin momentum is governed by the real part of the spin Seebeck effect [2].
Spin pumping and interface damping.—The pumped magnetic current across the FM1/NM interface is given (see [4,5]) in a system with electron diffuse interface scattering by
\[ I_{sp} = -\frac{g\mu_B}{4\pi} \text{Re}(2g_{II}^r) \left( \frac{\partial u}{\partial t} \right), \tag{3} \]
where \( u \) is the unit vector in the instantaneous direction of the magnetic moment, \( g \) is the Landé factor in FM1, and \( \mu_B \) is the Bohr magneton. For small precessional angles of the magnetic moment in FM1, the pumped magnetic moment is almost entirely transverse to the static magnetic moment, and the FM2 layer in FM1/NM/FM2 will act as a perfect sink [10]. In YIG/Au/Fc/Au magnetic double layer structures, the ferromagnetic resonance (FMR) fields corresponding to the YIG and Fe films are separated by several kOe, therefore, the YIG and Fe films are not involved at the same time in interchanging spin currents. When the Au films covering YIG are much thinner than the spin diffusion length in Au (35 nm [6]), one can in a very good approximation neglect the loss of accumulated spin momentum in the Au layer. The spin current generated at the YIG/Au interface leads to an increased Gilbert damping in YIG and in this approximation is given by
\[ \alpha_{sp} = \frac{g\mu_B}{4\pi M_s} \left( \frac{1}{d} \right), \tag{4} \]
where \( 4\pi M_s \) is the saturation induction and \( d \) is the thickness of the YIG film.

Sample preparation and FMR measurements.—YIG \( \text{Y}_{3}\text{Fe}_2(\text{FeO}_4)_3 \) films with thicknesses of 5 and 9 nm grown on (111) \( \text{Gd}_3\text{Ga}_5\text{O}_{12} \) substrates were prepared by pulsed laser deposition. The deposition was performed in high purity oxygen for 9 min with the substrate at 790°C and the oxygen pressure held at 0.1 torr. Right after the deposition, the YIG films were annealed at the same temperature and oxygen pressure for 10 min. The thickness of the YIG films was determined by low angle x-ray diffraction. The YIG films were characterized by x-ray photoelectron spectroscopy. The Au and Fe films were deposited by molecular beam epitaxy at pressures in the low 10^{-10} torr at room temperature.

In the presented studies, the sample S1 is 9 YIG/2 Au/4.3 Fe/6.1 Au and S2 is 9 YIG/6.1 Au/4.3 Fe/6.1 Au, with the numbers indicating film thickness in nanometers. The x-ray photoelectron spectroscopy spectra indicated Fe was deficient at the YIG surface. The atomic ratio Fe/Y for both samples was 0.55, while, according to the chemical formula, it is expected to be 1.7.

The atomic ratio O/Y was found to be 4 and 6 for S1 and S2, respectively. The expected ratio by the chemical formula is 4. This indicates that the oxygen concentration in S2 was higher than that in S1. The difference in chemical composition at the YIG surface compared to its bulk is caused by the surface chemistry during pulsed laser deposition, and it is similar to thick YIG films. Cleaning of the YIG surface by a hydrogen atom gun led to splitting and broadening of the FMR lines and therefore was not used. The Au and Fe films were polycrystalline.

FMR measurements were carried out at 10, 14, 24, and 36 GHz by using an Anritsu microwave generator with a static magnetic field along the film surface. Samples inserted in microwave cavity were 3 \times 4 mm². The microwave power was adjusted for a small precessional angle. Bare YIG films, by eye inspection, exhibited only one resonance peak corresponding to a homogeneous distribution of the rf magnetization across the YIG film, the \( k = 0 \) magnon mode. However, in order to fit these apparently single FMR peaks, one needs to take the superposition of up to three closely separated Lorentzian lines; see Fig. 1. This indicates that the films consisted of up to three regions having slightly different saturation magnetizations. The intrinsic FMR linewidth \( \Delta H \) (half width at half maximum) in the YIG films was linearly dependent on the microwave angular frequency \( \omega (= 2\pi f) \) but exhibited an appreciable zero frequency offset; see Fig. 2. The linear slope is consistent with Gilbert damping:
\[ \Delta H = \alpha \frac{\omega}{\gamma}, \tag{5} \]
where \( \gamma \) is the absolute value of the gyromagnetic ratio and \( \alpha \) is the Gilbert damping parameter. The zero frequency offset is caused by long range magnetic inhomogeneities.

In the bare YIG films, the Gilbert damping parameter was small: \( \alpha \approx 0.0006 \). The zero frequency offset did not

FIG. 1 (color online). The field derivative of the FMR signal as a function of the external field. (a) \( f = 23.988 \text{ GHz, bare YIG} \) 9 nm. The FMR line required 3 Lorentzian absorption lines with the following parameters: \( H_{\text{res,1}} = 7.556 \text{ kOe, } \Delta H_1 = 9.7 \text{ Oe, and } RA_1 = 60\% \); \( H_{\text{res,2}} = 7.551 \text{ kOe, } \Delta H_2 = 7.7 \text{ Oe, and } RA_2 = 31\% \); and \( H_{\text{res,2}} = 7.563 \text{ kOe, } \Delta H_2 = 7.2 \text{ Oe, and } RA_3 = 9\% \). (b) \( f = 23.9751 \text{ GHz, YIG/2.0 Au/4.3 Fe/6.1 Au} \). The three peaks in the bare sample became well split due to ferromagnetic coupling between the YIG and Fe layers. \( H_{\text{res,1}} = 7.380 \text{ kOe, } \Delta H_1 = 31.3 \text{ Oe, and } RA_1 = 49\% \); \( H_{\text{res,2}} = 7.468 \text{ kOe, } \Delta H_2 = 50.6 \text{ Oe, and } RA_1 = 40\% \); and \( H_{\text{res,3}} = 7.552 \text{ kOe, } \Delta H_3 = 6.3 \text{ Oe, and } RA_3 = 11\% \). RA represents the relative area of the sample with the corresponding FMR parameters. Notice that the FMR lines for the areas (1) and (2) are shifted towards lower magnetic fields and the line (3) is unshifted from the FMR field of the bare YIG film. The areas (1) and (2) are coupled by ferromagnetic interlayer exchange coupling to the Fe layer.
Results and discussion.—The saturation induction was determined by SQUID magnetometry, and it was found to be 1.31 kG. The lower value compared to the bulk was accompanied by long range magnetic inhomogeneities [11]; see Fig. 2. The FMR line position and $\Delta H(f)$ did not change by depositing a thin Au film over YIG.

Important results, shown in Figs. 1 and 2, were obtained with the Fermi spanning $k$ wave vectors [13] and decreases with the thickness of the NM spacer layer. This picture remains valid for polycrystalline layers, where the overall coupling strength and oscillatory period are averaged over the orientation of crystalline grains. Because of interface roughness, this coupling quickly approaches zero and is usually zero for the Au spacer thickness above 3 nm [14]. The spin pumping contribution creates an accumulated spin density at the YIG/Au interface, and its transport across the Au spacer is governed by spin diffusion equations. The accumulated spin density decreases with an increasing distance from the YIG/Au interface due to the loss of spin momentum by a spin flip relaxation mechanism. The length scale of penetration of the accumulated spin density from the YIG/Au interface is given by the spin diffusion length, which in Au spacers was found to be of 35 nm; see [10]. For a Au thickness significantly less

| Magnetic properties | $g_{||} \ [10^{14} \text{ cm}^{-2}]$ | $4\pi M_{\text{eff}} \ [\text{kOe}]$ | $g$ factor | $\alpha \ [10^{-3}]$ | $J_{\text{ex}} \ [\text{erg/cm}^2]$ |
|--------------------|----------------------------------|-------------------------------|------------|----------------|------------------|
| S1 (upper solid line in Fig. 2) | 1.2 | 1.885 | 2.027 | 2.21 | 0.15 |
| S1 (lower solid line in Fig. 2) | 1.1 | 1.885 | 2.027 | 1.62 | 0.08 |
| S2 (squares in Fig. 3) | 1.3 | 1.966 | 2.02 | 2.40 | 0 |
| Bare YIG for S2 (circles in Fig. 3) | N/A | 1.966 | 2.02 | 0.71 | N/A |

FIG. 2. FMR linewidth $\Delta H(f)$ as a function of microwave frequency for sample S1: 9.0 YIG/2.0 Au/4.3 Fe/6.1 Au and the bare corresponding YIG film. The solid square and circle points correspond to the areas (2) and (1) in Fig. 1 which are coupled by ferromagnetic exchange coupling to the Fe layer. The solid lines correspond to S1. The dashed lines correspond to the bare YIG sample. The sample area (3) was not exchange coupled to the Fe film and showed no change in $\Delta H(f)$ compared to that in the bare YIG. The increase in zero frequency offset in $\Delta H_{1,2}(f = 0)$ for the exchange-coupled areas compared to the bare YIG is caused by an inhomogeneous distribution of the interlayer exchange coupling.
spin pumping conductance which is \(\sim 11\%\) of that observed in the metallic interface of Fe/Au. The strength of the spin mixing conductance was found somewhat homogeneous across the YIG surface. This inhomogeneity is not surprising considering that the thin YIG film surface chemistry deviates from that of the bulk. A large spin mixing conductance can provide an effective source of pure spin currents for spintronics circuits. YIG films over a micrometer in thickness exhibit very narrow FMR line-widths and can be then brought to a large angle of precession with a moderate microwave power. This can provide large dc spin currents. For an angle of precession in an extreme limit of \(\pi/2\) (achievable in lateral nanostructures where magnon-magnon scattering can be suppressed by the selection rules), the dc magnetic moment current density can reach values of \(1 \times 10^{24} \mu_B/cm^2 s\) at 10 GHz. This shows that a large number of magnons can be generated by either microwave power or thermal gradients, allowing one to design spintronics devices based on these novel magnetic insulator/normal metal interfaces.

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