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Giant damping enhancement induced by exchange coupling in $Y_3Fe_5O_{12}/Co_2FeAl_{0.5}Si_{0.5}$ bilayers

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A B S T R A C T

Gilbert damping enhancement induced by the spin pumping effect is investigated in $Y_3Fe_5O_{12}$(YIG)/heavy metal bilayers. Because its spin polarization is high and Gilbert damping is low, $Co_2FeAl_{0.5}Si_{0.5}$ (CFAS) is deemed a promising ferromagnetic material in spintronics devices. We studied microwave dynamic magnetizations in YIG/CFAS bilayers combined with ferromagnetic resonance measurement using a vector network analyzer to reveal a 5-fold giant damping enhancement compared with that for the YIG/Pt bilayers. This phenomenon was attributed to both the exchange coupling effect and spin pumping effect. By inserting a 10-nm Cu spacer, direct exchange coupling can be suppressed. A spin mixing conductance $g_{eff}^{\uparrow\downarrow}$ of $7.75 \times 10^{18} m^{-2}$ generated by spin pumping was obtained. The study provides an effective approach to tailor the damping in magnetic thin films.

1. Introduction

With the development of spintronics, magnetoelectronic devices have been widely applied as they are driven by spin currents, which inherently means less Joule heating and significant energy savings. These devices such as magnetic tunnel junctions [1,2], spin torque oscillators [3,4], and spin transistors [5] exploit the spin transport in magnetic heterostructures. Various heterostructures of different constitutions were investigated in succession. For example, spin pumping, SHE (spin Hall effect), and ISHE (inverse spin Hall effect) were assessed in the Permalloy/Pt, ferromagnetic(FM)/normal metal(NM) structure [6–8]. The yttrium iron garnet (YIG) film [9], a magnetic insulator with low Gilbert damping, came next into view. YIG/Pt [10] is an insulator FM/NM bilayer in which only a pure spin current is injected into the NM instead of an extra spin polarized electron current like Py/Pt [11–14]. Recently, spin pumping, spin current, and the ISHE were reported in ferromagnetic metals such as the YIG/Py, a FM/FM metal heterostructure [15–17].

Damping in a magnetic material was used to be achieve energy redistribution and energy transfer [18,19]. Spin pumping as an effective method to generate spin currents at the interface of magnetic heterostructures lead to an additional damping. Significant work has been performed since the early 2000s [20–22]. In the present study, we focused on the high spin polarization and low Gilbert damping of the ferromagnetic Heusler alloy $Co_2FeAl_{0.5}Si_{0.5}$ (CFAS) and investigated the YIG/CFAS (FM/FM semimetal) heterostructures, discovering a huge damping enhancement caused by exchange coupling and spin pumping. Moreover, we separated this additional damping using a Cu spacer and obtained an even larger spin mixing conductance than the conventional YIG/Pt bilayer.

2. Experiment and method

Using liquid phase epitaxy, a single crystal yttrium iron garnet (YIG) sample of 300-nm thickness was grown on a (111) $Gd_3Ga_5O_{12}$ (GGG) substrate. The YIG film was verified by X-ray diffraction; its surface roughness is about 0.2 nm as measured from atomic force microscopy. For the YIG/Pt, YIG/CFAS, and YIG/Cu/CFAS samples, where the Pt, Cu, and CFAS layers were deposited by DC magnetron sputtering at a base vacuum pressure of 3.5×10^{-5} Pa. Fig. 1 shows the magnetic properties of the YIG and CFAS samples used in our work. To reduce the influence of the magnetic properties induced

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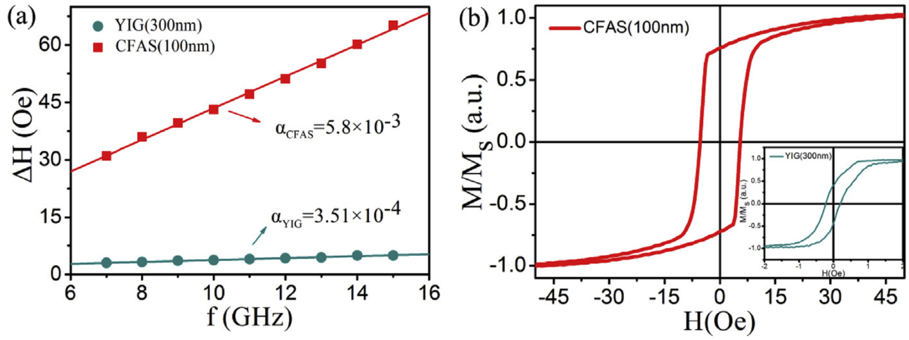

Fig. 1. (a) The FMR linewidth ΔH as a function of microwave frequency for a bare YIG (300 nm) and CFAS (100 nm) samples. (b) Hysteresis loops of YIG (300 nm) and CFAS (100 nm) with the in-plane magnetic field.

by the substrate, the CFAS film was sputtered on a (111) GGG because this substrate matches the lattice constant of YIG very closely. Fig. 1(a) presents the magnetic dynamitic properties extracted from ferromagnetic resonance (FMR) measurements. The FMR linewidth ΔH as a function of microwave frequency was fitted using Eq. (1). The Gilbert damping values are 5.8×10^{-3} and 3.51×10^{-4} for CFAS(100 nm) and YIG(300 nm), respectively. The vibrating sample magnetometer (VSM) also enables the static magnetic properties of the sample to be extracted without an applied magnetic field during the deposition, and therefore the CFAS film retains its isotropic in-plane behavior. The magnetic hysteresis loops [Fig. 1(b)] show that the magnetic contribution from the paramagnetic GGG substrate is removed. $4\pi M_S$ is the saturation magnetization. We obtained a saturation magnetization of 1.76 kG for YIG(300 nm) and 14.45 kG for CFAS(100 nm); the coercivity is 0.21 Oe for YIG(300 nm) and 5.42 Oe for CFAS(100 nm). Its FMR spectrum was measured in a coplanar waveguide (CPW) with an in-plane magnetic field while a rf field h_{rf} was applied perpendicular to it. We obtained the FMR linewidths (ΔH) by fitting the FMR absorption spectrum registered by a vector network analyzer with a Lorentzian fit. The in-plane magnetization hysteresis loops were measured using the VSM. For a more convenient sample testing, the YIG samples or substrates were cut into 5-mm square pieces.

3. Results and discussion

For the FMR set-up [Fig. 2(a)], the applied field is in-plane and parallel to the CPW. The microwaves ranged in frequency from 7 GHz to 15 GHz with a power of 1 mW (0 dBm), well below the threshold for any nonlinear effect. In the course of the FMR measurements, samples were covered on the CPW. For the YIG/CFAS samples, the YIG thickness was 300 nm and the CFAS thickness (d_{CFAS}) ranged from 5 to 50 nm. The FMR absorption spectrum of the YIG/CFAS(50 nm) sample at a microwave frequency of 14 GHz [Fig. 2(b)] shows two separated peaks. The CFAS film had a lower FMR field than YIG because its saturation magnetization (14.45 kG) is large compared with that for YIG (1.76 kG). The FMR linewidth ΔH as a function of microwave frequency [Fig. 2(c)] was obtained for bare YIG, YIG/Pt(20 nm), and YIG/CFAS of various CFAS thickness

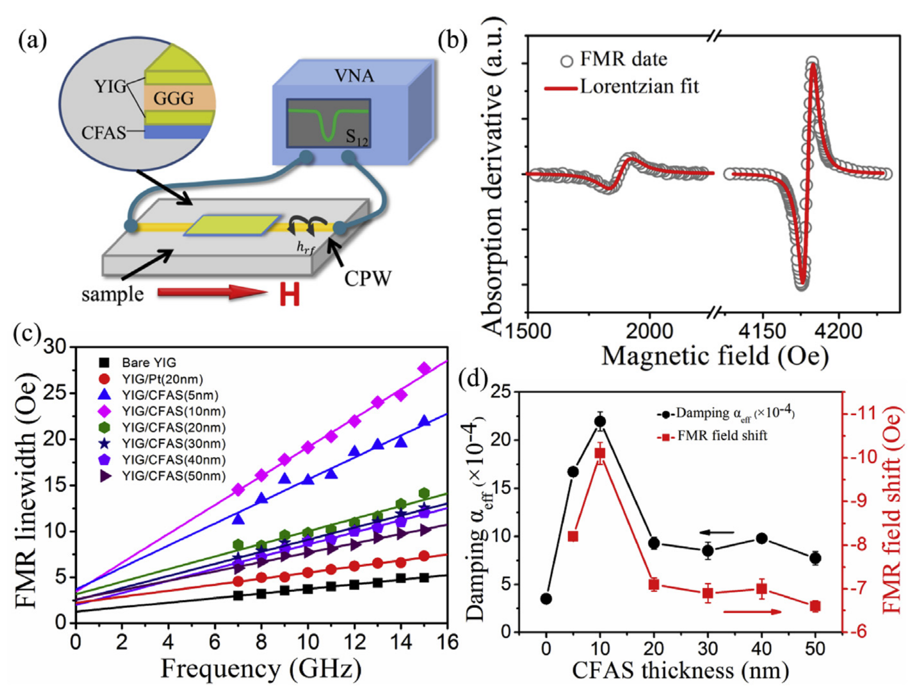

Fig. 2. (a) Schematic diagram of the FMR measurement configuration. (b) FMR profile for a YIG(300 nm)/CFAS(50 nm) sample. (c) FMR linewidth as a function of microwave frequency for several samples. (d) Damping α_{eff} and CFAS layer caused FMR field shift as a function of the CFAS thickness.