14th Czech and Slovak Conference on Magnetism, Košice, Slovakia, July 6–9, 2010

Inverse Spin Hall Effect by Spin-Pumping in $Co_2Cr_{0.4}Fe_{0.6}Al$/Pt Structures

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Inverse spin Hall effect consists in conversion of spin currents into electric currents and has recently been observed using spin-pumping operated by ferromagnetic resonance in permalloy/Pt(Cr) thin film structures. We prepared several $Co_2Cr_{0.4}Fe_{0.6}Al$/Pt thin film structures to observe for the first time inverse spin Hall effect in bilayer structures comprising ferromagnetic half-metallic Heusler alloy. In but a few $Co_2Cr_{0.4}Fe_{0.6}Al$/Pt samples we succeeded in observing inverse spin Hall effect voltage of few microvolts by spin pumping resulting from ferromagnetic resonance. This confirms that spin polarized current can be transferred into Pt layer. Inverse spin Hall effect was 2–3 times larger than that detected in permalloy/Pt bilayer under the same conditions.

PACS numbers: 72.25.Rb, 75.47.−m, 76.50.+g

1. Introduction

Recently electric-field generation due to the inverse spin Hall effect (ISHE) driven by spin-pumping has been detected in ferromagnetic metal(FM)/normal metal(NM) thin film structures [1]. In a series of experiments [1–3] it has been shown that spin current can be converted to charge current in structures consisting of FM $Ni_{81}Fe_{19}$ and NM Pt. In such structures spin-pumping operated by ferromagnetic resonance (FMR) transfers angular momentum from the precessing spins to the conduction electrons [4] that can propagate into Pt as a pure spin current. On the other hand, due to a relatively strong spin–orbit interaction in Pt, the spin current can be converted into a charge current. This process is called the ISHE [1] and has been shown to be an effective tool for detection of spin current. Specifically, it has been shown that under various excitation in a microwave cavity ISHE can be separated from anomalous Hall effect [2] and spin Hall effect can be quantified by integrating bilayer permalloy/Pt structures into coplanar waveguide [5]. In all mentioned experiments with spin-pumping operated by FMR, permalloy has been used as FM layer. Permalloy has spin polarization of 35–40% [6] and, hence, it would be interesting to observe ISHE by spin-pumping in similar structures in which permalloy is replaced by half-metallic ferromagnet with 100% spin polarization; e.g. $Co_2Cr_{0.4}Fe_{0.6}Al$ (CCFA) Heusler alloy (HA). Although in practice 100% polarization is still difficult to achieve, a large magnetoresistance effect in $Co_2Cr_{0.4}Fe_{0.6}Al$ HA [7] suggests that it is one of the most promising spintronic material. In this contribution we report on the results of preliminary experiments carried on $Co_2Cr_{0.4}Fe_{0.6}Al$/Pt structures and compare them with that of permalloy/Pt obtained under the same condition.

2. Experimental details and discussion

Insets in Fig. 1 show schematically the structure of the samples used in present study. Cr or Pt 20 nm thick layer was deposited on Si substrates and then a CCFA or $Ni_{81}Fe_{19}$ (permalloy) 50–100 nm layer was flash evaporated or thermally evaporated at high vacuum, respectively. To achieve a proper ordering of CCFA layers the samples were annealed at high vacuum at 350 °C for 10 min. Two electrodes for voltage measurements were attached to the Pt(Cr) layers (see Fig. 1, inset) in order to measure the voltage changes on sweeping the magnetic field across the ferromagnetic resonance — the ISHE signal. We checked with independent FMR measurements that the effective magnetization of the best ordered CCFA layers was nearly the same as that of the bulk samples (3.6 μ_B per formula unit). We prepared and measured several samples. In some of them the ISHE signal (e.g. the voltage signal taken from two electrodes) was very low and comparable to electronic noise. Here we present the results for two CCFA/Pt samples: A — with 100 nm and B — with 20 nm thick CCFA layers, respectively.

The experiments were carried out in a similar way as in Ref. [1]. The samples were placed in the center of a

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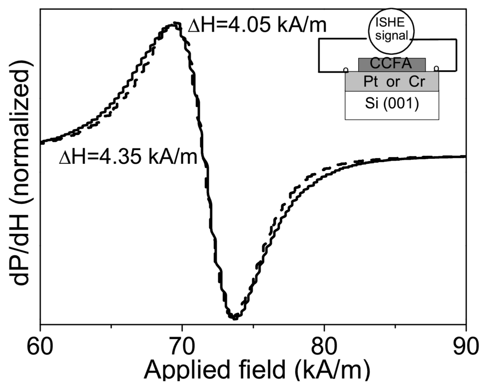

Fig. 1. FMR signal (the first derivative of FMR absorption) $\mathrm{d}P/\mathrm{d}H$ for a CCFA/Pt film (continuous line) with $\Delta H = 4.35$ kA/m and for a CCFA/Cr film (dashed line) with $\Delta H = 4.05$ kA/m. Insets shows schematically structure of the samples together with electrodes used for ISHE signal measurements.

TE 102 microwave cavity (operating at 9.1 GHz) to minimize the effect of microwave electric field component. We estimate the microwave power (which determines the strength of the microwave magnetic component) to less than 50 mW. The microwave magnetic field was applied parallel to the long edge of the samples with the external magnetic field applied in-plane and parallel to the short edge. Therefore the Larmor condition was fulfilled to obtain FMR excitations in the magnetic CCFA layer with the minimized microwave electric component. After the FMR signal had been recorded, the voltage on the electrodes was measured using lock-in amplifier on sweeping the field across the resonance field. Since we used additional modulation of the magnetic field, the first derivative $\mathrm{d}V/\mathrm{d}H$ (it will be referred to as the ISHE signal) was recorded in a similar way as the first derivative of FMR absorption. For sample A we also recorded changes of ISHE signal as a function of temperature.

Figure 1 shows exemplary FMR spectra of CCFA layers in contact with Pt and Cr, respectively. Since Pt exhibits a high spin–orbit coupling, Pt underlayer is frequently used as "spin sink" [1, 4] which results in an increase in precessional damping and, hence, in broadening of the FMR linewidth [4]. Indeed, the linewidth of the CCFA/Pt bilayer is slightly enhanced (of 0.3 kA/m) in comparison with that of the CCFA/Cr bilayer in which lighter element Cr should have lower spin–orbit coupling. A characteristic signature of FMR operating spin-pumping from CCFA to Pt seems to be confirmed. Since the FMR spectra shown in Fig. 1 were taken in the parallel configuration (e.g. with the field applied in-plane) a substantial contribution to the linewidth comes from extrinsic sources such as defects etc. We checked that the linewidth of the spectra taken at the perpendicular configuration (e.g. where two-magnon scattering is not operative) is much lower — of 1.6 kA/m. Therefore we assume it to be of the intrinsic origin. In summary to Fig. 1, we can estimate the additional broadening of 0.3 kA/m of the linewidth to be due to spin-pumping from CCFA into Pt, which is comparable to that already observed in permalloy/Pt structures [5]. Unfortunately the ISHE signal taken from the CCFA/Pt sample was very low and comparable to the electronic noise of ≈ 1 μV.

A clear ISHE signal was observed in but a few CCFA/Pt samples. Figures 2a and b show exemplary field dependences of ISHE signal for sample A and B, respectively. Against a background of noisy ISHE signals there are shown scaled FMR spectra (thick black lines). As can be seen from Fig. 2a smoothed ISHE signal (not shown) reproduces the shape of FMR spectrum quite well despite a substantial noise. This indicates that ISHE signal originates from ferromagnetic resonance pumping. The ISHE signal with the most intensive amplitude I (depicted in Fig. 2a as the peak-to-peak height of ISHE signal) of 3.5–4 μV was recorded in but a few samples. Usually I amounts to ≈ 2 μV on the noisy background of ≈ 1 μV (see Fig. 2b). Nevertheless, even in this case a specific shape of FMR spectrum (due to some magnetic inhomogeneity of CCFA in sample B) is well reproduced.

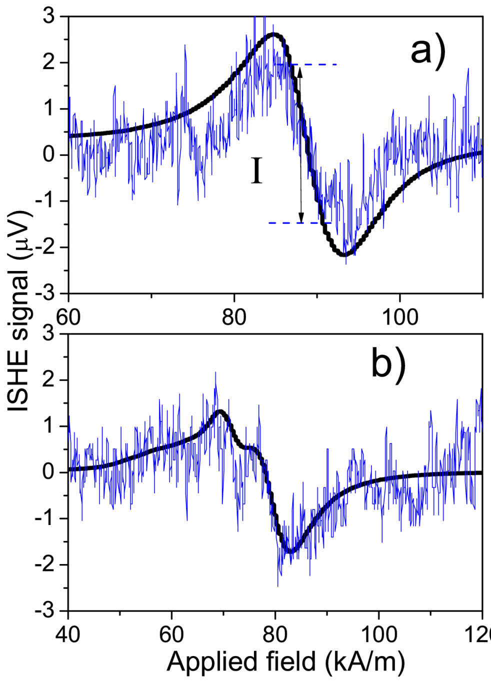

Fig. 2. (a) Field dependence of ISHE signal (blue noisy line) for CCFA/Pt/Cr film A together with a scaled FMR signal (black thick line). (b) Field dependence of ISHE signal for CCFA/Pt inhomogeneous film B (blue noisy line) together with a scaled FMR signal (black thick line). The total amplitude I of ISHE signal is shown.

In order to compare the results obtained for CCFA/Pt samples with those presented in Refs. [1–3] we performed the same measurements of ISHE signal for two samples consisting of permalloy/Pt bilayers. In our experimental setup the ISHE total amplitude amounted only to

$I \approx 2\ \mu$V, so it was comparable to the noise. To sum up the results shown in Fig. 2, it may be concluded that our results suggest that ISHE signal in the CCFA/Pt bilayers is 2–3 times larger than the effect observed in permalloy/Pt structures. This may result from a stronger spin polarization of $Co_2Cr_{0.4}Fe_{0.6}Al$ than that of permalloy [7]. However, it seems that the effect critically depends on a quality of interface between HA and Pt, which is hardly controllable.

For sample A we measured the total amplitude of ISHE signal as a function of temperature. The Curie temperature of CCFA is high, of 800 K [8] and therefore the magnetization fluctuations should not affect the ISHE signal. Indeed, as it is shown in Fig. 3, I is nearly constant in a temperature range of 100–300 K and at the higher temperatures $T > 300$ K it decreases more visibly. In view of Eq. (10) in Ref. [5] quantifying the ISHE signal in a bilayer structure a weak dependence of ISHE amplitude suggests that both the spin mixing conductance and the spin diffusion length in Pt are weakly dependent on temperature in this temperature range.

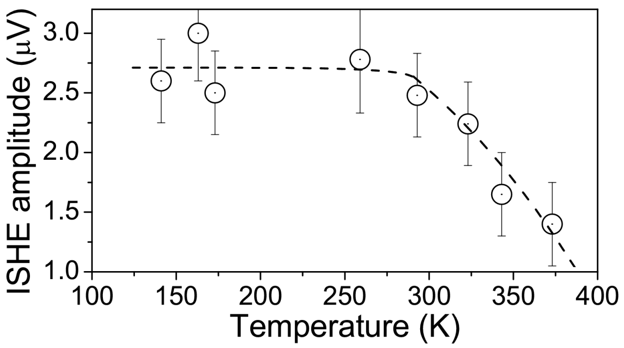

Fig. 3. The total amplitude of ISHE signal (the peak-to-peak height) I versus temperature for a CCFA/Pt/Cr film A.

3. Summary

In summary, we performed similar experiments as presented in Refs. [1–3] on FM/NM bilayers comprising FM half-metallic $Co_2Cr_{0.4}Fe_{0.6}Al$ and NM Pt layers. The observed ISHE signal by FMR spin-pumping was 2–3 times larger than that observed in permalloy/Pt under the same conditions which suggests that CCFA films with a higher spin polarization than permalloy may be more useful for spin-pumping experiments. However, it seems that the effect critically depends on a quality of interface between HA and Pt, which is hardly controllable. ISHE voltage weakly depends on temperature and decreases stronger above 300 K.

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