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Resistivity dependence of the spin mixing conductance and the anisotropic magnetoresistance in permalloy

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A B S T R A C T

Microwave spin pumping at ferromagnetic resonance from ferromagnetic films into nonmagnetic films is an efficient method to realize spin injection. The spin injection efficiency is proportional to the spin mixing conductance and can be detected by measuring voltages converted from spin current via the inverse spin Hall effect. In this work, we modified the properties of the ferromagnetic layer by thermal annealing. The results show that the crystal quality of the ferromagnetic films, as well as the magnetic properties has been greatly modified while the spin mixing conductance is insensitive to it. The work represent an incentive to work on engineering the spin Hall angle of the nonmagnetic layer to improve the spin Hall effect or the inverse spin Hall effect.

1. Introduction

There are several ways to inject spin currents from magnetically ordered materials to nonmagnetic materials by using polarized light, electron tunneling effects as well as heat gradient, etc. A recent review of these topics can be found in Refs. [1–3] and works cited therein. It was recently proposed that the spin can be pumped by microwave irradiation from the ferromagnetic (FM) materials to adjacent nonmagnetic (NM) metal materials [4,5]. This is an important breakthrough in this field, because the spins can be effectively injected from FM to NM metals in this way. DC voltages were generated in the NM metal due to the inverse spin Hall effect (ISHE), which follows the line shape of the ferromagnetic resonance (FMR) spectra. The spin current is converted to the charge current via the ISHE due to the spin-dependent scattering. Soon after, it was realized that in FM/NM bilayers, voltages at FMR have contributions not only from the ISHE, but also from the spin rectification effect (SRE) [6]. The SRE, according to the generalized Ohm's law, originates from the AMR effects, anomalous Hall effect and the phase differences between the RF magnetization and its current. The voltages are determined by three main processes: The magnetic moment is driven to process around certain effective field (H) by the microwave field. When the frequency (f_r) of the microwave magnetic field satisfies the condition that $f_r = \gamma H$, where γ is the gyromagnetic factor, FMR is achieved. The spin is generated (pumped out) from the ferromagnetic materials. Within the linear regime, the pumped spin current is proportional to the power of the microwave (P). The spins then diffuse through the interface, i.e. from FM to adjacent NM materials, which is characterized by a phenomenological parameter g_{mix} with $j_s = \frac{g_{mix}}{2\pi}P$. The diffused spin current (j_s) is then converted to electronic current (j_c) and the efficiency is expressed $\vec{j}_c = \frac{2e}{\hbar}\theta_{SH}\vec{j}_s \times \vec{\sigma}$, where θ_{SH} is the spin Hall angle, $\hbar$ is the Planck constant and e is the electron charge.

Annealing is a widely used technique to reduce defects and improve the crystalline in materials. In permalloy (Py, $Ni_{80}Fe_{20}$), annealing was report to be crucial to improve the anisotropic magnetoresistance (AMR) effect [7,8]. It was found that proper thermal treatment of the sample can release stress, promote crystal growth and reduce defects in the films [9,10]. It will also play its role in the SRE by changing the AMR effects. However, its influence to the spin-current conversion efficiency and, therefore, to the inverse spin Hall effects was less well studied. The process is sensitively dependent on the FM/NM interfaces, and crystalline quality of NM and FM layers. In this work, we perform a combination study of AMR effect, SRE and ISHE in Ta/Py/SiO_2(substrate) double layers with samples under different heat treatment. The results show that the heat treatment will influence the film magnetic performances, while the conversion efficiency of the microwave energy to electric voltages is insensitive to it within the accuracy of the present

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measurements.

2. Experimental details

The films were deposited by RF magnetron sputtering vacuum coating system at room temperature on SiO_2/Si substrates with dimensions of $5 \times 10 \times 0.5$ mm [3]. The base pressure is 4.5×10^{-5} Pa and the working gas is Ar with purity of 5 N kept at 0.2 Pa. The target Py and Ta purity is 4 N and the film deposition rates are 6 nm/min and 12 nm/min, respectively. Seven NiFe (20 nm)/Ta (10 nm) and NiFe (20 nm) samples were prepared. After deposition, the annealing was carried out in-situ from 100 °C to 400 °C for 3.5 h.

The AMR is measured by the standard four-probe methods with source meter (KEITHLEY 2400). The magnetic field is applied in the film plane parallel and perpendicular to the long edge of the samples. The microwave related property measurement was performed by our shorted microstrip fixture which can work up to 8 GHz. We obtained the photonic voltage by lock-in techniques (SR830, Standford Research System) with microwave source provided by Rohde & Schwarz (SMB 100 A). At certain fixed microwave frequency, we swept the static magnetic field so that FMR was achieved. Separation of the SRE and ISHE signals was performed by the methods proposed by Zhang et al. [11] In order to put the samples at the same positions in the fixture and minimize the differences of the microwave field before and after sample flipping during measurements, we covered the samples with SiO_2/Si substrate of the same dimensions as the substrate.

3. Results and discussions

3.1. The AMR effect after annealing

The AMR of the Py monolayer and Py/Ta layer after annealing are shown in Fig. 1. In the bilayers, annealing gradually improves the AMR ratios from 0.5 to 1.0. Not only the absolute values of AMR is increased, but also the sensitivity of the AMR to the magnetic field is increased. It can be seen from the narrowed curves and reduced the full width at half maximum of the curves from 6 Oe to 4 Oe, which is because of the reduced coercivity of the films under annealing. The AMR in monolayer is higher than the double layers when annealed at the same temperature due to the shunt effect of the conducting Ta layer in the bilayers. The sheet resistance of Ta is about 68 $\Omega/_\square$, which is stable on annealing at the temperatures we used. Annealing reduces the resistivity of the films with only moderately improved ΔR. This can be confirmed by plotting the AMR with respect to resistivity ρ as shown in Fig. 2, where AMR is the ratio of ΔR to R. The reduction of the resistivity of NiFe film with the increase of the annealing temperature can be understood by increment of the grain size, and thus the grain boundary scattering can be reduced [10,12,13].

3.2. The magnetic parameters from SRE measurements

Typical photonic voltages obtained in Py and Py/Ta films are shown in Fig. 3. In Py monolayer, we have a combination of symmetric (V_L) and antisymmetric (V_D) Lorentzian contributions to the total voltage due to the SRE effects (seeing Fig. 3 (a)). As developed by Hu et al., [6] the SRE is another way to characterize magnetic films under microwaves magnetic field. In Ta/Py bilayers, the photonic voltage has additional contributions from ISHE due to the spins diffused into the Ta layer. The ISHE and SRE signals can be well separated by taking into account the symmetry of the two effects as shown in our previous work [11]. The voltages measured before and after sample flipping are shown in Fig. 3(b), together with the separated contributions of SRE and ISHE curves.

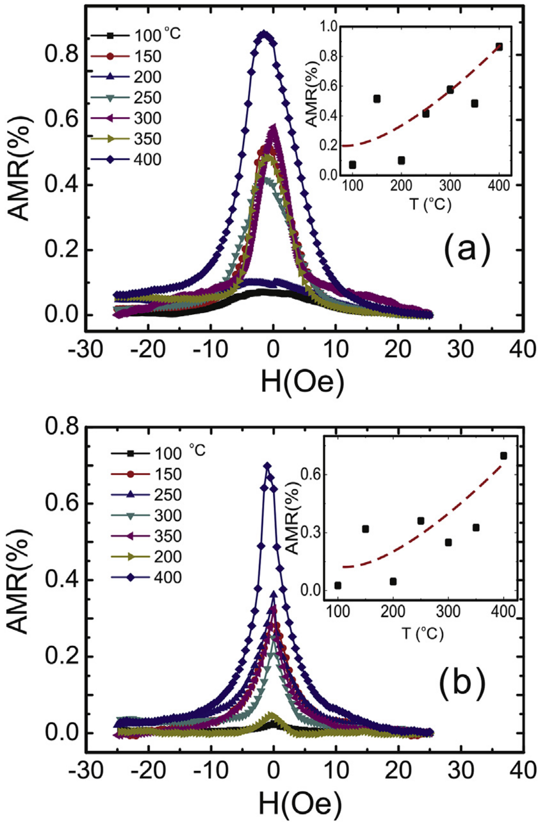

Fig. 1. AMR of samples annealed at temperatures from 100 °C upto 400 °C: (a) NiFe and (b) NiFe/Ta. The insets are the AMR vs. annealing temperatures with dashed curves to guide eyes. For clearness of the figure, only the values from $+H$ to $-H$ are shown. The data from $-H$ to $+H$ can be well reproduced by mirroring the data with respect to $H = 0$.

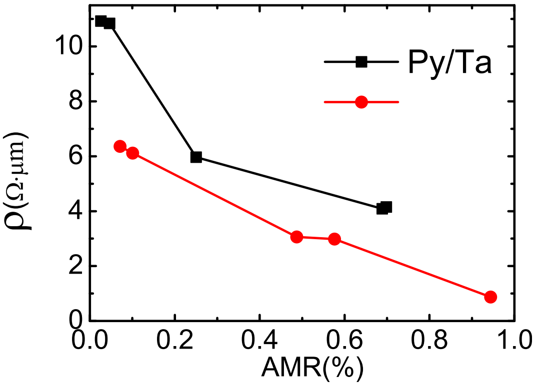

Fig. 2. AMR vs. resistivity of samples annealed at temperatures from 100 °C upto 400 °C.

From the SRE curve peaks, the resonance magnetic field (H_r) at the different resonant frequency (f) can be obtained in the samples. The H_r increases with the applied microwave frequencies as plotted in Fig. 4, which can be fitted to the Kittel's formula

$$f_r = \frac{\gamma}{2\pi}\sqrt{(H_r + H_k)\left(H_r + H_k + 4\pi M_{eff}\right)}, \qquad (1)$$

where $4\pi M_{eff}$ is the effective saturation magnetization and H_k is