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Ferromagnetic Resonance Tunability by Microwave Frequency in Bilayer $Fe_{97}Si_3/Pt$ Thin Film

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Abstract

Microwave induced Spin-Hall Effect (SHE) has been investigated in $Fe_{97}Si_3/Pt$ /Pt bilayer magnetic thin film using ferromagnetic resonance (FMR) technique. Applied microwave signal and in plane DC magnetic field on bilayer developed, a maximum DC voltage of 87.6 μV due to SHE at 0.5 GHz under FMR condition. The magnetic damping (α) and spin Hall angle (θ_{SHA}) for $Fe_{97}Si_3/Pt$ was experimentally evaluated as 0.09 and 0.078 respectively from FMR linewidth. The shift in FMR resonant frequency, shape and broadening of FMR line width with respect to the applied DC magnetic field has been observed.

Keywords

Magnetic damping; Microwave; Spin hall angle; Ferromagnetic resonance; Spin hall effect

Introduction

Spin Hall Effect (SHE) is the generation of a transverse spin current by a charge current, with spin perpendicular to the plane of two currents [1]. It has been experimentally demonstrated that the spin current generated from SHE can tune magnetic switching and relaxation time of magnetization dynamics [2-4]. An electric voltage due to SHE confirms efficient spin-orbit interaction, signifying its potential application in the field of spintronics. Ferromagnetic resonance (FMR) is the absorption of microwave power by a magnetic thin film, measured as a function of the applied sweeping DC magnetic field. Single Microwave frequency based resonant FMR measurement technique to demonstrate SHE in NiFe/Pt, Co/Pt, Pt/Py has been reported by most of the authors [5-6] here we have used microwave device jig as a broadband measurement technique to explore SHE in $Fe_{97}Si_3/Pt$ bilayer thin film [23]. The magnetization dynamics in a thin ferromagnetic layer can be described by a generalized Landau-Lifshitz-Gilbert equation.

The generation and detection of spin currents are of fundamental interest. One efficient way for generating a spin current is SHE due to spin-orbit coupling. The measurements on $Fe_{97}Si_3/Pt$ bilayer thin film were carried out, where microwave signal is applied in the plane of the thin film to excite magnetic precession. The amplitude of the resonant motion is detected from the changing resistance of the film by measuring the DC output voltage due to mixing of the applied microwave current and the changing resistance. We can interpret the output FMR voltage spectra as the injected microwave charge current is converted into spin current, giving rise to an electrical potential difference across the sample. The magnitude, shape and FMR resonance frequency of the output depends upon the magnetic field direction, magnetic anisotropy, magnetic inhomogeneity and quality of thin film used. FMR can be used to characterize bilayer thin films for its resonance frequency, resonance field linewidth, damping constant and spin current density with high sensitivity.

The investigation related to spin orbit torque is due to its application in magnetization switching [7-10], domain-wall motion [11-13], and HF magnetization dynamics [14-16]. The efficiency of spin-charge current conversion can be quantified by spin-Hall angle (SHA), defined as the ratio of two charge conductivities. In principle, the SHA is an intrinsic property of Pt and it should remain constant in various bilayer thin film samples of Pt. Present experimental studies for Pt report wide range of SHA results that vary from 0.011 to 0.100 [15-22]. A DC voltage signal of the order of microvolt has been observed due to spin-orbit interaction in $Fe_{97}Si_3/Pt$ thin film. The magnitude of signal was measured as a function of frequency and power level. All the measurements were carried out at room temperature.

Experimental

The $Fe_{97}Si_3/Pt$ bilayer thin film was deposited on Si (100) substrate using pulse laser deposition technique. The layers thicknesses were controlled during deposition, and the sample was cut in a dimension of 8.0 mm × 5.0 mm. Bilayer thin film comprising 30 nm thick magnetic $Fe_{97}Si_3$ layer and a 40 nm thick Pt layer. A microstrip based non-resonant sample holder named as microwave device jig having Cu electrodes for SHE voltage measurements was designed & developed indigenously in the laboratory [23]. The designed pattern and high bandwidth of the microwave device jig enabled us to carry out sweep measurements with microwave frequency excitation from 0.01 GHz to 10 GHz.

The generation of DC voltage in magnetic hetrostructures under FMR excitation has been reported by various groups (Figure 1) [17-20]. Subsequently, thin film was mounted on a microwave device jig in order to measure DC output voltage [24]. The DC voltage due to SHE using the derived equations [17] constituting FMR spectrum is measured by applying in plane DC magnetic field on the sample. FMR voltage spectra were measured across the film using microwave power signal of 10 mW at the desired frequencies when the external magnetic field (H_{DC}) was applied upto 0.2 T along the bilayer film plane under the controlled environmental condition. In plane static magnetic field (H_{DC}) is applied and DC voltage due to SHE was measured at ends of the Pt layer along the x axis as shown in schematic illustration of thin film Figure 2a. SHE model representation and its magnetization dynamics for $Fe_{97}Si_3/Pt$ bilayer thin film is shown in Figure2b.

Results and Discussion

Characterization of the $Fe_{97}Si_3/Pt$ bilayer thin films has been done using X-ray diffraction (XRD), Scanning Electron Microscope (SEM)

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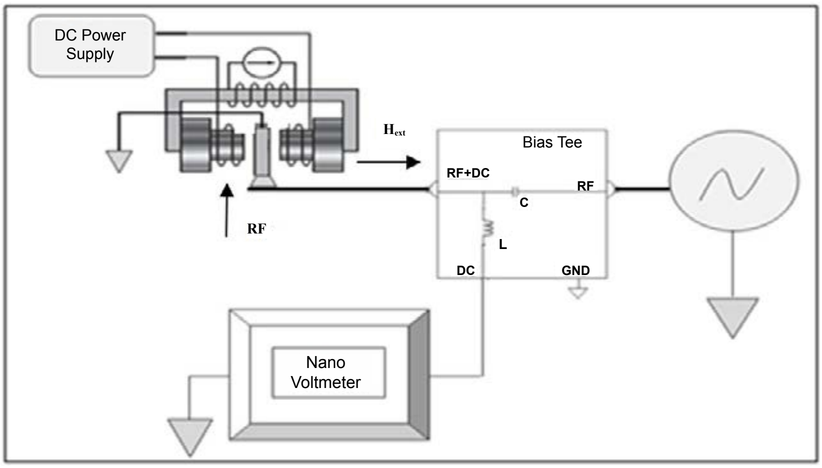


Figure 1: Schematic illustration of Ferromagnetic resonance setup.

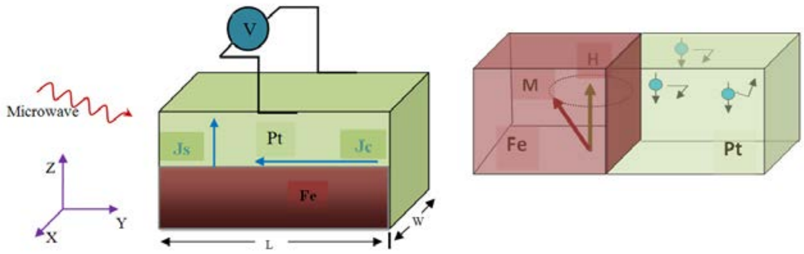
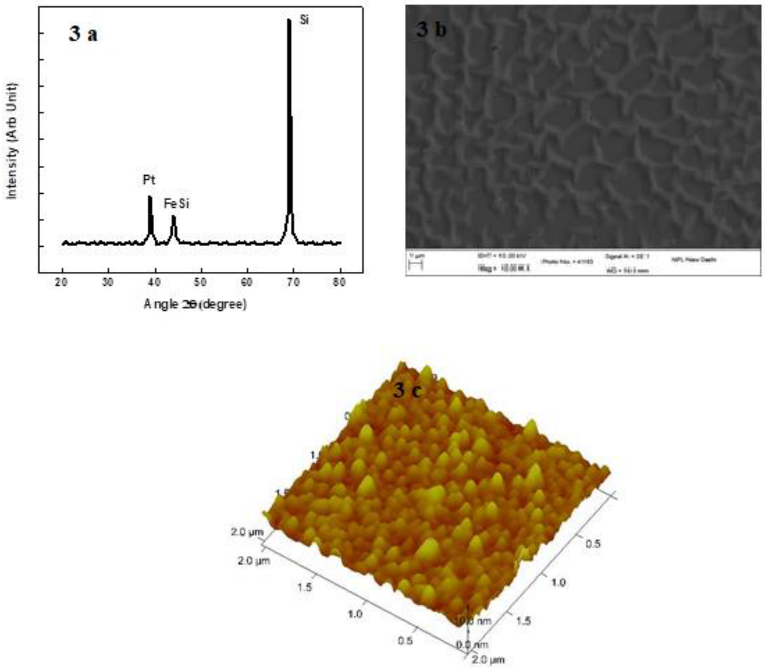


Figure 2(a): Schematic illustration of $Fe_{97}Si_3$/Pt bilayer thin film on Si substrate, **2(b):** SHE model representation of $Fe_{97}Si_3$/Pt thin film.

& atomic force microscopy (AFM). Phase formation of $Fe_{97}Si_3$/Pt thin bilayer film was investigated by X-ray diffraction (XRD) analysis at room temperature, scanned for 2θ from 10° to 80°. The XRD data has been shown in Figure 3(a). Peak corresponds to ~38 degree and ~44 degree is assigned to Pt and $Fe_{97}Si_3$ respectively. The high intensity peak observed at ~69 degree has been assigned to Si (100) substrate. XRD measurement has shown that a bilayer film has a well-defined crystalline structure. The thin film surface morphology was characterized by scanning electron microscope (SEM). The SEM image is shown in Figure3 (b), confirms the quality of thin film. The surface roughness of thin film was analysed by atomic force microscopy (AFM). The AFM image is shown in Figure 3 (c), which shows the value of thin film roughness as 17.43 nm. The saturation magnetization of $Fe_{97}Si_3$/Pt thin film measurements using Vibrating Sample Magnetometer (VSM) at 300 K has been reported earlier [25].

The flow of RF current through a bilayer thin film generates an oscillating transverse spin current in Pt layer, and the resultant transfer of spin angular momentum to the $Fe_{97}Si_3$/Pt layer induces FMR dynamics, which leads to an oscillation of the bilayer resistance. The dc voltage signal developed across the film is due to mixing of microwave power and the oscillating resistance. The injected charge current is converted into spin current, which gives rise to an electrical potential difference across the sample. FMR voltage spectra of $Fe_{97}Si_3$/Pt film at different frequencies has been plotted, which is field derivative of absorbed microwave power in terms of DC voltage with respect to static magnetic field at different frequencies. The comparison plot of microwave induced FMR voltage spectra among different frequencies is shown in Figure 4. The magnitude of SHE voltage generated across bilayer thin film was measured as 87.6 µV at 0.5 GHz for an incident microwave power of 10 mW with respect to sweeping DC magnetic field upto 0.2 T. There is a shift in FMR resonant frequency, decrease in the amplitude of the FMR voltage spectra and broadening of FMR line width with increasing DC magnetic field. It may be due to increase in microwave frequency increases mismatch losses and hence decrease in the injected microwave charge current. The presence of ferromagnetic resonance tunability by microwave frequency in magnetic bilayer thin film is confirmed by reduction in FMR output signal and broadening of FMR line width with respect to the increase in microwave frequency as shown in Figure 4.

The frequency dependence of FMR linewidth for $Fe_{97}Si_3$/Pt bilayer thin film is shown in Figure 5 (a). Maximum DC voltage generated across the film is at resonance condition, which is a combination of symmetric and antisymmetric Lorentzian peaks in SHE voltage. The microwave power linear dependence of SHE voltage at 0.7 GHz is shown in Figure 5 (b). The output DC voltage exhibits linear dependence with increase in microwave power confirms that spin polarization increases with power level. The intensity of a microwave signal absorbed by thin film depends upon the power level. Furthermore, frequency dependence of SHE voltage has been explored with respect to in plane DC magnetic field at 10 mW power level, where SHE voltage decreases with respect to frequency upto 900 MHz and ultimately attained a minimum constant value afterwards. Furthermore, our observed values for output voltage spectra and its shape are in good agreement with reported values [21-28]. However, significant work has been done by several groups to study the parameters associated with thin films of different combinations



Figures 3(a): X-ray diffraction pattern of $Fe_{97}Si_3$/Pt bilayer thin film deposited on Si (100) substrate film, **3(b):** SEM image of $Fe_{97}Si_3$/Pt thin film, **3(c):** Atomic force Microscopy image of $Fe_{97}Si_3$/Pt bilayer thin film.

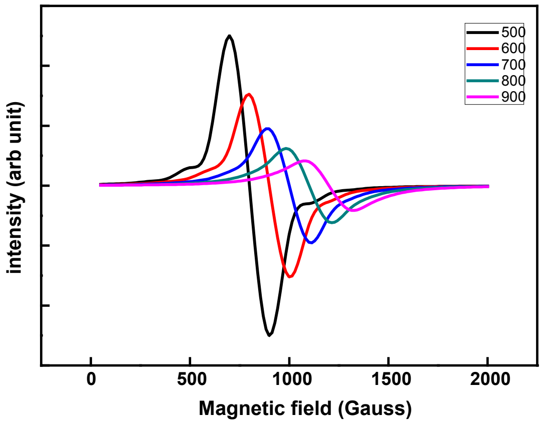


Figure 4: FMR voltage spectra at 10 mW microwave excitation with respect to DC magnetic field at 0.5 GHz, 0.6 GHz, 0.7 GHz, 0.8 GHz and 0.9 GHz respectively.

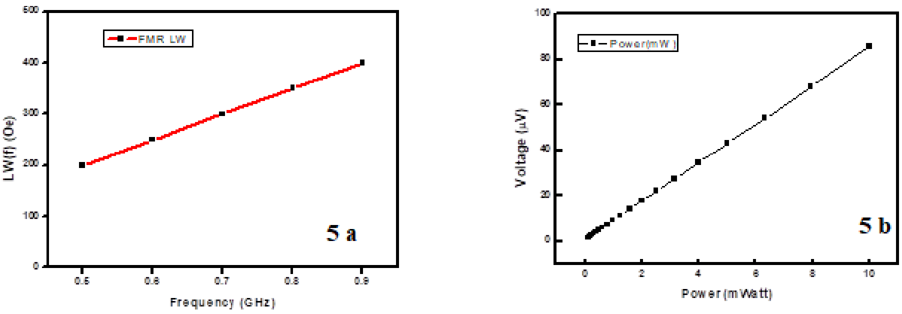


Figure 5(a): Frequency dependence of FMR linewidth for $Fe_{97}Si_3$/Pt bilayer thin film, red line represent a linear fitting curve, **5(b):** SHE voltage as a function of microwave power level at 0.7 GHz.

Magnetic damping of thin film has been determined as α=0.09 from the linear fits to the FMR linewidth data (ΔH) using the relation, $\alpha = (\gamma/2\pi f)\Delta H$ Spin-orbit interactions are the major origins of magnetic damping for FM thin films. Gilbert damping factor (G) of the film is important for achieving high speed magnetization switching, which has been calculated using $G = \alpha\gamma M_s$, where α is damping coefficient, γ is gyromagnetic ratio and M_s is the saturation magnetization of thin film. Value of Gilbert damping factor $G = 2.05 \times 10^8\ s^{-1}$ has been determined. This finding is consistent with the reported value of 'G' as $1.26 \times 10^8\ s^{-1}$ for Fe thin films [29-31]. The FMR linewidth enhancement with frequency indicates that attenuation in magnetic thin film is governed by Gilbert damping determined from the slope of FMR linewidth LW(f) as shown in Figure5. It has been found that the FMR line width increases linearly with frequency with a slope of 500 Oe/GHz.

The efficiency of this inter conversion can be characterized by a parameter called the spin Hall angle (SHA), which is given by the ratio of spin to charge current. Our method, which is fundamentally the same as that reported by Liu et al. is based on the broadband FMR and the spin-torque method. Spin current is generated and injected into adjacent layer affecting the magnetization dynamics of the ferromagnetic layer. The relationship between charge current, j_c injected into Pt layer through SHE and a transverse spin current, j_s is given by equation (1) [32-34].

$$j_c = \theta_{SHE}\left(\frac{2e}{\hbar}\right) j_s \times \sigma \qquad (1)$$

Where, θ_{SHE}, e, ħ and σ are SHA, elementary charge, reduced Plank constant and spin polarization vector of the spin current respectively. Using demagnetization field and magnetic saturation of thin film SHA in Pt has been estimated as 0.078. Our value is in good agreement with the value reported by Xin Fan et al of SHA in Pt as 0.070 and our earlier reported value of SHA in Pt is 0.071 [34]. By measuring magnetic damping in Pt/Py versus current, Ando et al. reported SHA as 0.08 in Pt [10]. The SHA obtained by us is slightly lower than the value reported by Wang et al. [16-24]. This may be due to an additional orbital magnetic moment at interface results in increase of Gilbert damping. The measured values of SHA in Pt by different groups are shown in Table 1. The different experimental studies reported different values of SHA for platinum. SHA measurements vary significantly among various groups due to measurement methods used, fabrication techniques, anisotropic magneto resistance in metallic FM and variation of sample characteristics. Magnetic damping decreases with increase in thickness of FM layer; this effect modifies FMR spectrum such that SHA also increases with the FM layer thickness [28].

Hence, in the case of a bilayer structure, the magnetic properties of FM layer and interface of FM and NM layers plays a crucial role in determining SHA. The microwave frequency induced FMR in $Fe_{97}Si_3$/Pt is an encouraging tool to control, tune and manipulate the magnetic dynamics. For many applications, SHA is also the figure of merit of direct interest as it is an important mechanism to quantify the material characteristics in the field of spintronics.

Table 1: Spin Hall Angle for Platinum having different FM layer thickness.

S.No.	Bilayer thin film	Spin Hall angle (θ_{SHE})	FM Thickness (nm)	Reference
1	YIG/Pt	0.100	20.0	*H.L Wang et al.*, PRL 112, 2014
2	CoFe/Pt	0.085	4.7	*A Ganguly et al.*, APL 104, 2014
3	Py/Pt	0.080	15.0	*L. Liu et al.*, PRL, 106, 2011
4	Pt/Py	0.011	15.0	O. Mosendz et al., Phys. Rev. B, 82, 2010
5	Py/Pt	0.020	10.0	H. Y. Hung et al., JAP, 113, 2013
6	Py/Pt	0.080	10.0	*K. Ando et al*, PRL, 101, 2008
7	Py/Pt	0.013	10.0	*F.D Czeschka et al.*, PRL, 107, 2011

Conclusion

FMR measurements at resonance suggest that the microwave current in the normal metal significantly modifies the excitation of the magnetization and thereby results in experimentally measured spin Hall voltages. It has been observed that FMR voltage spectra of $Fe_{97}Si_3$/ Pt bilayer thin film was maximum at 0.5 GHz and then decreases as we increase the frequency with respect to applied DC magnetic field, which shows that electromotive force tunability is dominated mainly by applied microwave frequency signal. The dependence of FMR in $Fe_{97}Si_3$/Pt on microwave frequency has been studied at room temperature. The FMR resonance position was found to have a linear dependence with frequency at the rate of 500 Oe/GHz. This linear dependence confirmed that the microwave signal absorption and spin current transfer at the bilayer interface was due to uniform FMR precession [35]. In conclusion, we have demonstrated microwave induced SHE in $Fe_{97}Si_3$/Pt bilayer thin film using FMR technique that enables measuring spin Hall voltage across the bilayer thin film. Further studies on ferromagnetic $Fe_{97}Si_3$/Pt thin film are underway, as this being a soft magnetic material provides an interesting possibility for potential spintronic device applications.

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