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Microwave device jig characterization for ferromagnetic resonance induced spin Hall effect measurement in bilayer thin films

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Microwave device jig for evaluating magnetic thin films consists of two symmetrical radial copper pad sections each having panel mounted *RF* connector. A non resonant measurement method for obtaining spin Hall voltage across magnetic thin films using ferromagnetic resonance was developed, based on electrical impedance of thin film and copper pads of the microwave device jig both in contact with each other. A geometry is introduced, which provides good impedance match characteristics and is optimised for maximum power transmission. It also gives the flexibility in measurements for any orientation of thin film with respect to applied magnetic field. In this geometry, a quantitative study of the microwave device jig has been done by measuring spin Hall voltages in the frequency range 0.1-10 GHz for bilayer thin films. The experimentally recorded voltages can be fully ascribed to SHE detection due to microwave induced FMR.

Keywords: Microwave magnetics, Spin Hall effect, Ferromagnetic resonance

1 Introduction

Spin Hall effect (SHE) aims to explore the role of electron spin in building the next generation electronic devices. Using electron spin rather than electron charge may allow faster, lower energy cost devices. The SHE originally presented by Dyakonov and Perel[1], can be described as an accumulation of spin generated by an electric current at the edges of a non magnetic metal. Ferromagnetic resonance is the most widely used technique for characterizing thin films[2] and a pure source of spin currents for spintronic applications[3,4]. Spin electronics does not just exploit electric charge of electrons but also their spin, which leads to development of new approaches for industrial applications. The research work in this area of spintronics has been focused on thin film characterization and phenomenon that will make it possible to control both spin orientation and spin flow. It is very important and will have major impact in understanding fundamental research as well as modern spin based technological applications. A discrepancy in SHE measurement result clearly shows that accurate measurements, understanding and analysis are essential in the area of spintronics.

The use of microwave device jig is experimentally demonstrated based on non resonant method with an optimized geometry to detect spin Hall voltage due to microwave induced FMR in a magnetic hetrostructures. An alternate microwave device jig is a cavity based resonant method where sample is placed in a resonant waveguide cavity[12-15]. The limitation for the cavity based device is that it is dependent on frequency. The study of SHE has been further extended as a function of orientation of thin film with respect to applied magnetic field, frequency and microwave power using specially designed microwave device jig. A geometry is introduced, which provides good impedance match characteristics and is optimised for maximum power transmission. A vector network analyzer (VNA) is used for evaluating the S parameters of microwave device jig using calibration kit. A vector network analyzer is a swept frequency reflectometer system used to measure the magnitude and phase angle of reflection and transmission coefficients for one port or two port network (S-parameters). The signal transmitted through or reflected from the unknown device is compared in amplitude and phase with a reference signal. The reflection coefficient ($|S_{11}|$ or $|S_{22}|$) in general ($|S_{nn}|$) of a device is measured in terms of return loss ($RL = -20 \log(1/|S_{nn}|)$) against a zero dB return loss standard.

This method allows us to tune the magnetization dynamics regardless of film size by applying microwave current directly to the magnetic layer.

Studies of the resonance frequencies, amplitudes, line widths, and line shapes as a function of microwave power, frequency and magnetic field shall provide detailed additional information about the exchange, damping and spin transfer torques that govern dynamics in magnetic hetrostructures[5-7].

2 Microwave Device Jig: Design and Fabrication

Spin current related phenomenon is an important aspect of modern magnetism, like spin currents which is nothing but a flow of angular momentum without a charge current and it can propagate in magnetic hetrostructures. Using microwave device jig along with its assembly, spin-Hall effect was studied in magnetic thin films to control both spin orientation and spin flow. Microwave device jig for evaluating magnetic thin films consists of two symmetrical radial copper pad sections designed and fabricated on a double sided teflon laminated copper foil plated board. These double sided teflon laminated copper foil plated board with the following specifications : teflon thickness 1.6 mm, copper thickness 35 μm both sides, teflon dielectric constant 2.55, *RF* connector SMA panel mount has been used for fabricating the microwave device jig. This is a high quality laminate with controlled dielectric constant. The layout details of microwave device jig are shown in Fig. 1. A non-resonant measurement method for obtaining spin Hall voltage across magnetic thin films using FMR was developed based on electrical impedance of thin film and copper pads of the microwave device jig both in contact with each other. In this geometry, a quantitative study of the microwave device jig has been done by measuring spin Hall voltages in the frequency range 0.1-10 GHz for bilayer thin films. The microwave device jig has a mounting section on which a thin film sample is mounted and a *RF* connector section which connects the device to an external microwave source using panel mount *RF* connectors.

The microwave device jig is designed using radial fan type structure in the form of microstrip conductor, a teflon substrate, a ground plane and coaxial *RF* connectors as shown in Fig. 2. In this method, a bilayer thin film is in contact with the radial microstrip conductor; propagating high frequency EM wave hence, the electric field generated has the maximum interaction with the sample. The microwave device jig is designed in such away to have a good impedance match with the 50 ohm microwave source and optimised for maximum power transmission. A radial stub is used as good impedance matching device in the form of a microstrip line[8]. It is used in many microwave circuits for impedance matching or as an *RF* ground. As known radial stub has three characteristic parameters: the radius R_L, angle α and the inner radius R_i. The theoretically characteristic impedance Z_o of the microwave device jig is calculated[8] using the Eq. (1):

$$Z_0(R_1) = \frac{120\pi}{\sqrt{\varepsilon_r}}[J_0^2(K_{R1}) + N_0^2(K_{R1})]^{1/2} \times [J_1^2(K_{R1}) + N_1^2(K_{R1})]^{-1/2} \quad \ldots(1)$$

$$K = 2\pi\frac{\sqrt{\varepsilon_r}}{\lambda_0} \quad \ldots(2)$$

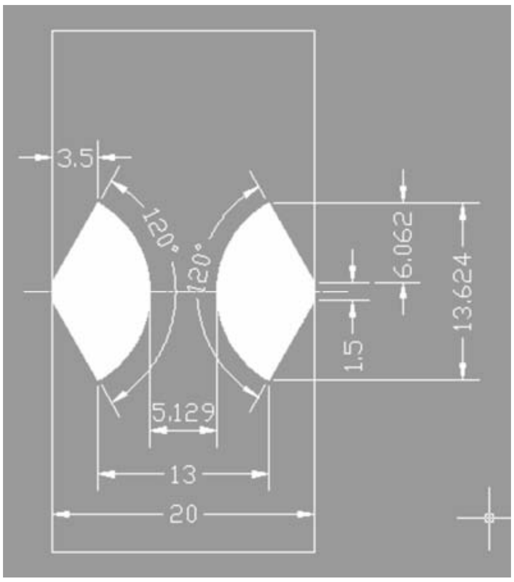

Fig. 1 — Layout details of a microwave device jig

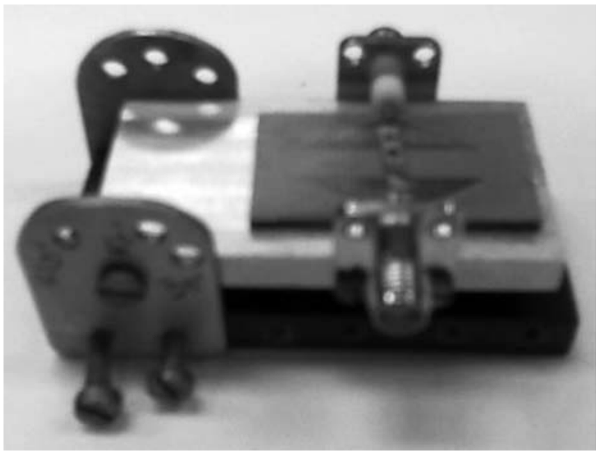

Fig. 2 — Microwave device jig assembly

J_n is the Bessel function of the first kind of order n and N_n is the Bessel function of the second kind of order n. Finally, k is the wave number, λ_o the wavelength and ε_r is the dielectric constant. In our case, the radius R_L=7.5 mm, angle α=120°and the inner radius R_i=2.0 mm. Dielectric constant of teflon used is 2.55 with an operating frequency of 1 GHz. Using Eqs (1 and 2), along with the tables of Bessel's function, we get the characteristic impedance Z_o as 52.13 ohm.

The assembly is designed and developed indigenously in our central workshop. The non magnetic material has been used with all the screw alignment for having different orientations. It also gives the flexibility in measurements for any orientation of thin film with respect to applied magnetic field as shown in Fig. 2.

The layout of microwave device jig was simulated using SONNET as an electromagnetic simulator to analyze its *RF* characteristics. The schematic of the microwave device jig under EM simulation is shown in Fig. 3. Sonnet as a 3D planar high frequency electromagnetic simulation software is used to analyze the designs in the complete frequency range. It provides a full-wave EM solution for planar structure having benefit of fast and efficient. The Sonnet develops precise *RF* models (S-, Y-, Z-parameters or extracted SPICE model) for planar circuits. It requires a physical description of your circuit (arbitrary layout and material properties for metal and dielectrics) and employs a rigorous Method-of-Moments EM analysis based on Maxwell's equations that include all parasitic, cross-coupling, enclosure. Sonnet maintains a single, dedicated focus on providing the most accurate and reliable high frequency planar EM software. The simulated input impedance in terms of return loss for the fabricated microwave device jig using vector network analyzer (VNA) is shown in Fig. 4. The microwave device jig was fabricated based on the optimum simulation

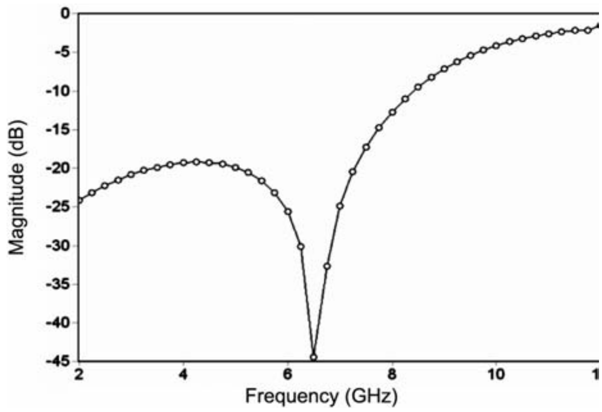

Fig. 3 — Schematic: Microwave device jig for EM simulation using SONNET

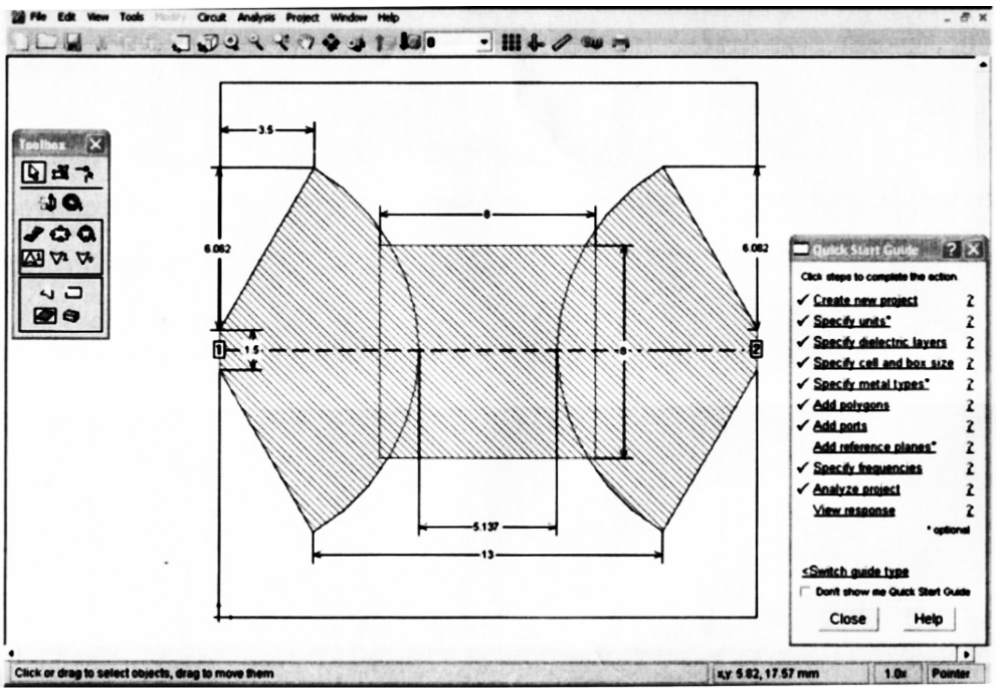

Fig. 4 — Simulation result (S11 in dB) using SONNET

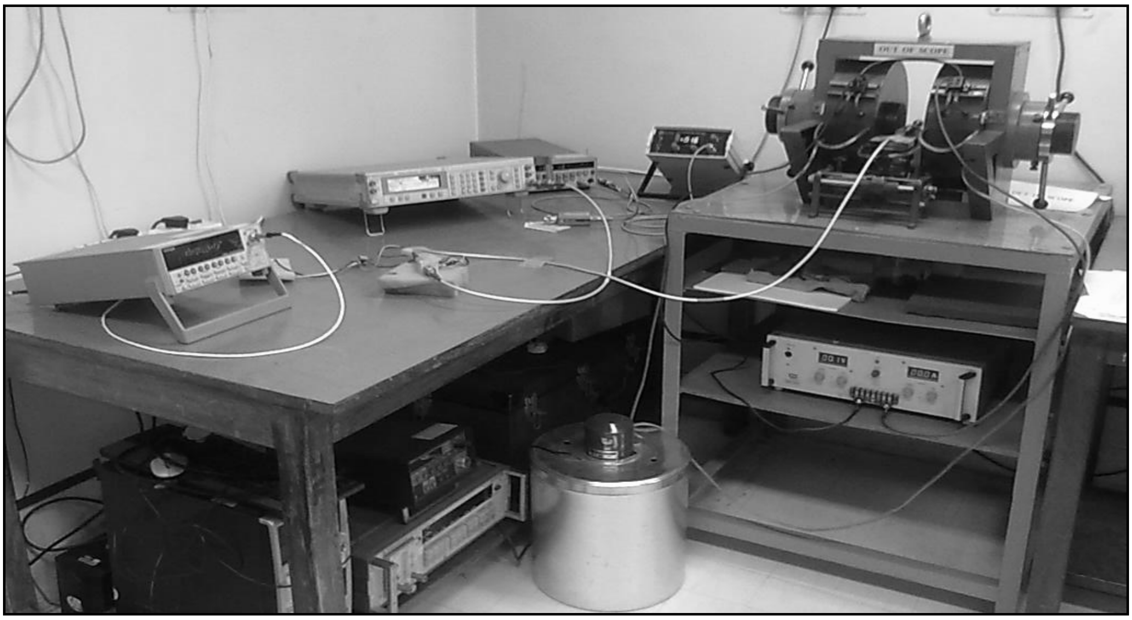

Fig. 5 — FMR measurement set-up

results and used for electrical characterization of magnetic thin film hetrostructures[9-11]. The simulated layout pattern was fabricated on the substrate using lithography.

3 Results

Ferromagnetic resonance is the absorption of microwave power by a magnetic film, measured as a function of applied sweeping *dc* magnetic field. The FMR measurement system is composed of a microwave device jig along with its assembly, an electromagnet, a *dc* power supply, a network analyzer, *RF* source and bias tee as shown in Fig. 5. Thin film samples are characterized using microwave device jig, which have electrodes having a gap of 5 mm for the contact. In this broadband experiment, a sweeping magnetic field is applied in film plane and microwave power from the synthesized signal generator varied up to 20 dBm (100 mW). A *dc* voltage signal is generated across the sample from the interaction of microwave power and oscillating resistance[12-15]. With the help of the microwave device jig and FMR measurement set-up, one can perform SHE measurements either in the direction of applied microwave signal or in the direction perpendicular to the applied signal. Using microwave device jig, bilayer thin film is in contact with the radial microstrip conductor of the device; propagating high frequency EM wave hence, the electric field

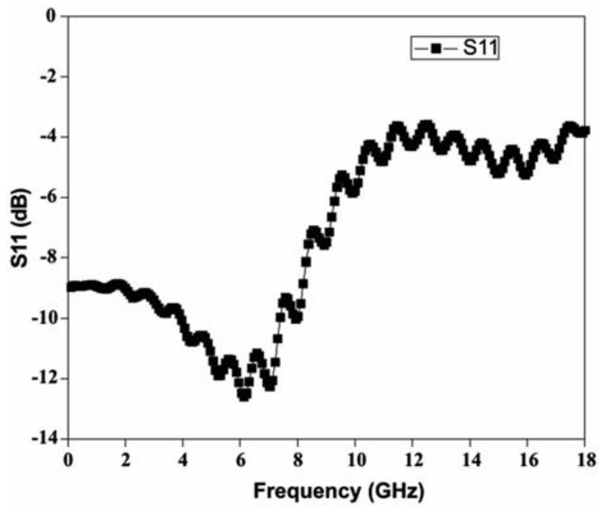

Fig. 6 — Measurement results of microwave device jig on VNA

generated has the maximum interaction with the thin film sample. We can also have the flexibility of measurements in any orientation of thin film with respect to the applied magnetic field. All measurements are performed at room temperature[16-21].

Vector network analyzer is used for impedance measurements that is calibrated and connected to one port of the sample holder as the other end is shorted to *RF* ground. VNA excites the port of the microwave device jig and measures the reflected power due to the impedance mismatch at thin film interface to calculate

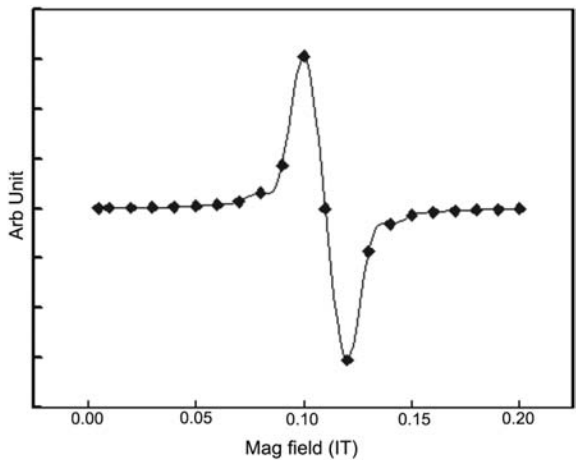

Fig. 7 — FMR Plot for a bilayer thin film

the return loss in dB. The measured return loss of the microwave device jig is shown in Fig. 6. FMR technique is implemented based on impedance of the magnetic film in contact with electrical conductors pad. An alternate method is a resonant method where sample is placed in a resonant waveguide cavity[13-16]. Although it is a good method for FMR measurements but the major disadvantage of this method is that one can perform the experiment at a single resonant frequency, where as in non-resonant method one can sweep the entire frequency range. The spin Hall voltage for a bilayer thin film was evaluated by the proposed method[4]. The FMR voltage spectra has been measured at the applied microwave frequencies and plotted as shown in Fig. 7.

4 Discussion

The simulated return loss and measured return loss in broadband frequency are different, which is a characteristic for the impedance mismatch. The measured values are low as compared to simulated results because of losses involved in microwave measurements. In simulation, software assumes perfect match between the film and layout, but in practical situation the match depends upon the geometrical dimensions of thin film. Though, the measured values are low as compared to the simulated results but both have identical pattern in the frequency range 0.1-10 GHz. Furthermore, the differences between measured and the simulated input impedance values may be because the magnetic film was driven by the high frequency current, and hence, high frequency losses are involved. The measured input impedance shows a good impedance match up to 9.0 GHz as return loss (S_{11}) greater than-10.0 dB with an uncertainty of ± 0.07 dB is a good practical realization[22-27].Spin electronics does not just exploit electric charge of electrons but also their spin, and should therefore, lead to development of new approaches for industrial applications. It is very important and will have major impact in understanding fundamental research as well as for modern spin based technological applications.

5 Conclusions

A non-resonant method has been successfully implemented for detecting spin Hall voltage using FMR technique. In this method of measurement, spin current generated due to spin-Hall effect in non-magnetic thin film is injected into the adjacent ferromagnetic thin film to study the voltage developed across the film. It is demonstrated microwave device jig geometry, its design, simulation and measurement results in terms of return loss, which allows broadband detection of spin Hall effect. The design of microwave device jig and its assembly gives the flexibility of measurements in any orientation of thin film with respect to the applied magnetic field. Electromagnetic simulator SONNET has been used to optimize *RF* layout of the microwave device jig for good impedance match, having maximum electric field interaction with the sample. An alternate method is a cavity based resonant method, though it is a good one for FMR measurements but its drawback is frequency limitation, where as in non-resonant method one can sweep the entire frequency range. The experimental investigation of in-plane *dc* voltage signal generated in bilayer thin film under the microwave excitation and sweeping magnetic field have been shown and discussed.

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