Spin Hall Effect Measurement Techniques: 
A brief review

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June 19, 2015

Abstract
Spin Hall Effect is relativistic quantum mechanical effect which enables non-magnetic materials show magnetic phenomena without the application of a magnetic field. With spin Hall Effect, one can realize spintronic devices operating purely on electrical and optical means and eliminate the use of ferromagnets which have associated fringe fields. In this review article, we present the experimental developments and current understanding of the Spin Hall Effect Phenomena. We discuss various experiments as well as device structures which employ electrical, optical or both techniques to demonstrate Spin Hall effect. Most of these devices structures are simple and easy to fabricate in modern laboratories.

1 Introduction

The advent of solid state physics into solid state technology has revolutionized the utilitarian aspects of science as well as explore the quantum regimes for fundamental understanding of nature. Transistors made logical and arithmetic operations possible, but the search was for storage devices which hold the information processed. Early inventions of memory storage devices were lead by Magnetic Core memory which consisted of annular rings interlaced by copper wires of diameter of the order of a mm. These rings could be magnetized either in clockwise direction or anti-clockwise direction. Mapping the direction magnetization to 1’s and 0’s memory was stored in these devices. Currently we have reached an era where a palm size device can store information in the order of terrabyte. We can broadly classify the circuits based on their functioning at a given instant of time - circuits that process information and those which store. A device cannot perform both processing and storage simultaneously. In 1980’s Datta and Das thought of a device popularly called as a spin transistor, which could perform both processing and storage simultaneously [1][2][3] opened up a wide range of possibilities towards realizing a
spin transistor. Spintronics devices aim at achieving memory and processing both in the same device, utilizing the information carried by an electron in it’s spin. The challenge until late 19 century was, the limitation on dimension of device that could be fabricated. Control and manipulation of spins requires the electron transport to take place within certain length, over which spin information is sustained (spin diffusion length). With advent of thin film technology we are able to fabricate devices of few atomic layers thick and this makes it possible to experiment on electron transport in low dimensions. We aim this brief review on experimental techniques of spin hall effect to beginners of research in this field and provide detailed qualitative description of the results of various milestone experiments performed so far.

Efficient conversion of spin current into charge current and vice versa are crucial for the working of spintronics based devices. The important aspects for experimental consideration are the efficient injection of spin polarized electrons, transport and detection of the same. Spin injection can be achieved by electronic or optical methods. In optical method, circularly polarized light is used to generate spin polarized electrons in the system. [4, 5, 6] When circularly polarized light excites electrons from valence band to conduction band, the excited electrons are spin polarized. This follows from conservation of total angular momentum [7, 8]. Magneto optic Kerr rotation is used to detect the spin dependent signals [9]. Electronic measurements correspond to measuring either voltage or current. To extract spin dependent signals, the requisites are spin sensitive probes. The obvious choice of material for such a probe is a ferromagnet. The contact electrodes themselves have an Oersted field acting on the electrons in the channel. When a charge current is passed along the length of the sample having significant spin-orbit (SO) coupling coefficient, there is spin separation in direction transverse to the current flow (Fig 1 a). This is called Spin Hall Effect and was proposed by Dyakonov and Perel in 1971. [10]

There are various theoretical models that explain the cause for spin separation - SO coupling, Side Jump mechanism, Skew scattering [11]. In a realistic system we have all the mechanism acting on the electrons. Spin orbit interaction between the injected electrons and a target scatterer are shown in Fig 2 below.

Spin down electrons with momentum $\vec{p}$ are incident on target with spin

![Figure 1: a) Schematic depicting SHE. b) Schematic depicting ISHE.](image-url)
up ($S = 1$). Let us assume the spin orbit potential of the system $V_{so}(r)$ to be negative. For incident electron 1, $\vec{l} = \vec{r} \times \vec{p}$ is into the plain of the page, and therefore $\vec{l} \cdot \vec{S}$ is negative because $l$ and $S$ point in opposite directions. The combination of $V_{so}(r)\vec{l} \cdot \vec{S}$ is positive and hence there is a repulsive force between incident electron and the target. Thus the electron is forced towards the top. For electron 2, $\vec{l}$ points up, $\vec{l} \cdot \vec{S}$ is positive, and the force is attractive; incident electron 2 is pulled towards the target and is also forced to the top. Spin down (up) electrons are therefore preferentially scattered to top (bottom). Thus SO interaction can produce polarized electrons when unpolarized beam of electrons is incident on the target. [12]

![Image](image-url)

Figure 2: Spin down electrons being pushed to top due to spin momentum locking. Spin down (up) electrons approaching the scatterer from top and bottom experience repulsive (attractive) and attractive (repulsive) force respectively.

Therefore, injection of spin up polarized current into such a sample, would divert all spin up electrons towards top edge of the sample (Fig 1 b). A voltmeter between top and bottom edge of the sample will read a non-zero voltage. This is called Inverse Spin Hall Effect (ISHE) where, spin current along the length of the sample gives rise to charge current in a direction transverse to the spin current. The mechanism leading to spin separation in the transverse direction varies between material compositions. One line of argument agrees on spin hall effect to be an intrinsic effect due to spin orbit coupling (SOC) . This is observed in systems like 2DEG with strong rashba SOC co-efficient[13]. The effects due skew scattering is mainly to the asymmetry in the chiral properties of ferromagnets that possess significant spin-orbit coupling[14]. This is an experimental viewpoint of the mechanism. Theoretically, the microscopic analysis is more involved and has been pointed out by Nagoasa. Another mechanism explained so far is the side jump mechanism where the electron moving in the system with wave vector $\vec{k}$ suffers a displacement in transverse
direction to $\vec{k}$. This effect can be distinguished from skew scattering experimentally. Variation of parameters like resistivity are not the same for both mechanisms (Eg: Temperature dependence of spin hall angle, cite seki). The hall resistivity $\rho_H$ varies as $\rho^2$ in the case of side jump mechanism[15]. A broad theoretical description of these mechanism have been well explained in the review by Sinova et.al., [16]. Hirsch proposed a device where injection and detection of spins can both happen in the same device, using the SHE-ISHE. [17]. This was a breakthrough contribution, to use SHE based devices in spintronics. Experimental detection of SHE was first reported by Kato et.al [9], through optical methods. Charge current flows in an unstrained GaAs sample, which has high SO coupling co-efficient. Spin separation that occurs is detected using Kerr microscopy. Regions with oppositely polarized electrons gave kerr rotation spectra in opposite directions which confirmed, the separation of spins in the sample. The accumulation of these spins happened at exactly equal distances from the center. When a perpendicular magnetic field was applied, these signals were destroyed after a certain magnetic field, which further confirmed that the signal was due spin magnetic moment. Wunderlich et al demonstrated a way to quantify spin hall voltage using optical spin injection. 2DEG and 2DHG are created in the at the Al-GaAs/GaAs interface by modulation doping technique. Light of wavelength between 870nm – 930nm is shone on the depletion region. As shown in Fig 3, circularly polarized light in opposite direction, give oppositely spin polarized electrons. Broadly we can classify SHE measurements in three ways as shown in Fig 3. One that uses optical spin injection and, the other two which are purely electrical means of spin injection and detection. In this brief review we summarize the milestone experiments performed in each of these methods, with emphasis on electronic measurements. The device geometry employed for SHE measurements are non-local and in most of the cases very similar. Hence we first present a discussion on experiments in non-local geometry in section II. In section III we describe spin hall effect measurements in detail. The technique of Ferromagnetic Resonance (FMR) is discussed in section IV. Spin Seebeck Effect is the cynosure of spin based devices due to its technological importance. We conclude with the importance of spin seebeck effect and a brief summary of the review.
Spin Hall Effect Measurements

Electronic methods
FMR-STT measurements
FM as spin injector
V
detector electrode
microwave
source
detector
SAMPLE
resonant cavity

Optical methods

Figure 3: Classification based on methods used for SHE experiments

2 Experiments in non-local geometry on spin valves

Electronic detection of spin hall signal corresponds to voltage measurement for current in a certain loop of the device. These are broadly classified into two - local and non-local measurements. Local measurements are the case where the voltage measurement probes lie within spacial regime of the current loop due to the injected electrons. Non-local measurements correspond to the geometry where the voltage measurement is away from the electron loop due to the injected electrons (Fig 4 b). Here the measured voltage is due to the diffusion current and not the drift current driven by the source potential difference. Despite extensive research the cause for SHE is challenging to point out the mechanism that governs this phenomenon. The measurements performed in non-local geometry extracts parameters like spin hall angles, spin orbit co-efficient, spin diffusion length, spin polarization etc. efficiently without any contribution from stray magnetic fields from the electrodes. Hence we first present a detailed report of non-local spin valve experiments to motivate Spin Hall Effect measurements.

Difference between the two kinds of measurement geometries was clearly demonstrated by Jedema et.al [19] (Fig 5). AMR (Anisotropic Magnetoresistance) signatures were seen in negative direction sweep of magnetic field. Non-local measurement showed a lower value for the signal but was devoid of any stray field affects due to the FM electrodes.
Figure 4: a) IV measurement in local geometry. b) Voltage measurement in non-local geometry.

Figure 5: a) Local measurement geometry. b) Non-local geometry measurement geometry. c) Spin valve measurement for local (top curve) and non-local (bottom) measurement configurations. (Reprinted with permission from ref. 15 ©2003 by the American Physical Society.)

Figure 6: a) Spin valve measurement un non-local geometry. Numerically labeled bars the FM electrodes. Current source can be between electrodes 1 and 2 or 1 and 3. Voltage is measured between 4 and 5. b) Spin valve measurement of the sample in fig a. c) Hanle measurement of the sample in Fig a. Data in red shows anti-parallel configuration of electrodes 3 and 4. Data in black corresponds to parallel configuration of the same. d) Spin valve measurement of the sample (right) with Cu as the channel. (Reprinted by permission from Macmillan Publishers Ltd: [Nature] ref. 16 ©2007 and ref. 17 ©2008)
Lou et al. [20] demonstrated spin injection and detection in a FM/semiconductor system as shown in Fig 6 a. The electron channel is n-GaAs. Electrons are injected from the FM electrodes into the n-GaAs through electrode 3. Detection is at the electrodes 4 and 5. Drift current is in the loop between 3 and 1 but the electrons injected at electrode 3 diffuse in all directions. Thus there is a purely diffusive transport of electrons between electrodes 3 and 5. This voltage due to diffusive transport is measured across electrodes 4 and 5. The probes are ferromagnetic and hence spin sensitive. The resistance observed will be high if electrodes 3 and 4 have magnetization aligned in anti-parallel configuration and low resistance in parallel configuration. At sufficiently large magnetic field in the direction parallel to the plane of the channel, both electrodes have magnetization aligned in parallel and hence the resistance is low. As the magnetic field is decreased to zero and then increased in opposite direction, the electrode with lower co-ercivity switches it’s direction where as the other retains it’s initial orientation. Hence the configuration is now anti-parallel leading to high resistance plateau. When magnetic field is sufficiently large the electrodes have again aligned in parallel but in direction opposite to the initial condition. (fig 6 b) Hanle measurements were also performed which showed loss of signal at significant perpendicular magnetic field (Fig 6 c). This indicates that the spin-coherence is lost when a perpendicular magnetic field is applied. Yang et.al. [21] improved upon the work by capping the NiFe electrode by Au, to prevent oxidation of the top layer (Fig 6 e). Spin valve measurements show an increased signal by one order. This is due to clean sample preparation, without breaking vacuum in any step of the device fabrication. The detected signal is of the order of $\mu V$ in case of n-GaAs channel and of the order of $mV$ in case of copper as channel. Thus spin-valves with metal as channel perform with higher sensitivity than those with semiconductors as channel for transport.

Jedema et.al. [22] improved upon the spin dependent resistivity of the de-
vice by introducing a tunnel layer ($Al_2O_3$) in between Co and Al in their spin valve device (Fig 7 a, b). Spin transport was studied as a function of separation between the detector and injector electrodes. The spin signal decays exponentially with increase in this separation, which is given by,

$$ R = V/I = (1/2)P^2(\lambda_{sf}/\sigma_{Al})A\exp(-L/\lambda_{sf}) $$

where, $P$ is the spin polarization, $\lambda_{sf}$ is the spin diffusion length, $L$ is the distance between the two FM electrodes, $\sigma_{Al}$ is the charge conductivity of Al. Fig 7 c shows variation of $\Delta R$ v/s $L$, where, $\Delta R = \Delta V/I$ and $\Delta V$ is the difference between voltages in parallel and anti-parallel aligned magnetization of the FM electrodes. With these experimental results we conclude the section and proceed towards spin hall effect measurement techniques which possess similar device geometry.

3 Spin Hall Effect measurements

Measurements performed by Jedema et.al, were restricted to spin injection and spin detection measurements. Tinkham et.al[23] demonstrated that SHE signals could be extracted using very similar device structures (Fig 9). 50 nm Al layer is deposited on Si/SiO$_2$ substrate using e-beam evaporation techniques. This is oxidized to create $Al_2O_3$. Introducing a tunnel barrier ($Al_2O_3$) increases the spin injection efficiency [25] Two ferromagnetic electrodes are deposited above the oxidized layer. There is also a Al cross bar deposited parallel to the FM electrodes. A non-local measurement made as shown in Fig 9, probes the spin hall voltage. The two FM electrodes are deposited to estimate the spin diffusion length as in the case of Jedema et.al.
Figure 8:  a) Sample configuration and variation of spin hall signal with perpendicular magnetic field. b) Sample configuration and response of inverse spin hall signal with external magnetic field. (Reprinted by permission from Macmillan Publishers Ltd: [Nature] ref. 19 ©2009 , ref. 21 ©2008 )

The novelty of this experiment was measurement of signal across the cross bar of Al. The current path is between the FM and the Al. This causes spin polarized electron injection beneath the FM electrode. Diffusion of electrons along the length of the Al bar constitutes spin current which leads to spin separation in direction transverse to it. A potential difference is created in the transverse direction to spin current due to asymmetry in the number of spin up and spin down electrons being injected into Al. This is the spin hall voltage. To further confirm that the voltage measured is due to spin separation, measurements are made with external magnetic field applied perpendicular to the plane. The spin hall voltage saturates after certain magnetic field which is an indication that the voltage is dependent on the magnetization of the electrode and hence is due to spin hall effect. Analytically the fit to the experimental data was obtained using the equation,

\[ R_{SH} = \frac{1}{2} \Delta R_{SH} \sin \theta, \]

\[ \Delta R_{SH} = \frac{P_{Al}}{t_{Al}} \frac{\sigma_{SH}}{\sigma_{c}} \exp(-L/\lambda_{SF}) \]

Seki et.al.[?] performed SHE measurement with SO coupling material Au, and the FePt FM injector. FePt has the magnetization direction perpendicular to the plane of the sample as shown in figure. Epitaxially grown FePt films have direction of magnetization either up wards or downwards to the plane of the film [26]. As shown in Fig 9 b, spin polarized electrons are injected into the Au through FePt, whose magnetization is perpendicular to the plane. This causes a spin current along the length of Au and hence spin separation in direction perpendicular to the spin current. The device geometry favors measurement of SHE and also Local Hall Effect in the same device. If current
is passed through the FePt and voltage is measured perpendicular to it across Au, this measures Hall voltage. If the current passes as shown in figure from the FePt to the Au and voltage being measured along the Hall Cross at a certain distance from the point of injection, this signal corresponds to ISHE. The magnitude of ISHE signal is of the order of $m\Omega$ which is 10 times larger than those measured previously in non-magnetic metals. The origin of this effect is due to skew scattering. The possibility of contribution from side jump has been eliminated by temperature dependent studies of the ratio between spin hall resistivity and the electrical resistivity. The cause is attributed to the scattering due to impurities rather than intrinsic spin-orbit coupling of the Au. Theoretical explanations also suggest orbital-dependent Kondo effect of Fe in the Au host metal\cite{27}.

Introducing impurities increases the spin hall angle significantly. This has been very well explained by A. Fert and P. M. Levy \cite{28}. The mention of larger spin hall effect signal (15%) due to doping of Pt in Au is noticeable. Other remarkable spin hall effect signal observed are in Iridium oxide (38$\mu\Omega$) \cite{29}, ISHE resistance in Py/Pt/Cu recipes for spin valves, \cite{30}, large spin hall angle (10%) in AuW alloy \cite{31}.
The ways discussed so far were purely electronic means of studying spin transport and SHE in various systems that exhibits SO coupling. We would also like to briefly describe another system, where SHE measurements can be performed. Wunderlich et al. demonstrated SHE based measurements in 2DEG/2DHG. Fig 9 a shows the device structure used for photovoltaic measurement performed. 2DEG-2DHG junction is formed by fabrication as explained in the ref. Circularly polarized light is shone at the interface. Electron-hole pair is created at the interface. The spin hall voltage varies linearly with the degree of polarization. The experiment performed by masking the hall crosses (Fig 9 b) shows that the spin hall voltage is observed only in reverse bias conditions. Under forward bias the electrons and holes travel as directed by the bias current and the spin coherence is lost. But, in reverse bias the
barrier potential drives holes in the 2DHG region and electrons in the 2DEG region and we see spin separation as a result of spin-orbit coupling. Since the shone light is circularly polarized the spin polarized electrons constitutes spin current along the length of the sample due to difference in concentration between the interface and the ends of the sample. SO coupling in the 2DEG channel leads to spin separation in transverse direction and is measured across the hall crosses. Fig 9 c shows spin hall voltage when circularly polarized light is shone on the entire unmasked region. The signal observed is now is lesser in magnitude and is antisymmetric with respect to the bias voltage which only over the n-region.

The same device was demonstrated as a SHE transistor by Wunderlich et.al,[32] (Fig 9 d). Circularly polarized light is shone on the 2DEG and the Spin Hall Voltages are measured across the hall bars as a function of position of the point of injection. This behavior is oscillatory in nature as shown.

![Figure 10: Spin Polarized electrons injected at one end of the sample, dephase as the diffuse to the other end](image)

This is due to spin dephasing that occurs with position of electron injection and detection. As shown in Fig 10, spin polarized electrons are injected at the right end of the sample. The spin of the injected electrons precess about the magnetic field due to SO interaction. The injected electrons precess and also diffuse towards the other end. Thus there is a phase difference between the injected electrons and the ones that have diffused. Depending on the distance of detection from the point of injection there could also be a phase difference of \( \pi \) or more. This leads to inversion in the sign of the spin hall voltage detected and hence the overall oscillatory behavior. Experiment is also performed by grounding the first hall bar, and the signal still persists which indicates that the voltage measured is purely due to spin transfer and not due to charge current. An additional electrode is introduced as gate electrode. Biasing the 2DEG channel would close or open up the channel for electron transport. Thus, gate voltage controlled measurements are made in analogy with transistor.

4 Experiments using Ferromagnetic Resonance

A major challenge is to efficiently inject and detect information carried by spins in spintronics devices. Spin Pumping (SP) and Spin Transfer torque (STT) are the phenomena which help in spin injection and detection. Spin
injection is achieved by magnetization dynamics and detection using Ferromagnetic Resonance (FMR). Magnetization dynamics is achieved when FM is placed in an external magnetic field. The precision (Larmor) frequency can be tuned externally. There are three common ways by which Larmor frequency can be tuned. First is to apply a d.c. bias and vary the magnetic field, second is through a.c. bias across the FM and third is by shining microwave radiation on the FM sample. The magnetization dynamics induced in the FM leads to spin wave excitation in the adjacent non-magnetic normal metal (NM), which is spin pumping. In spin pumping experiments, magnetization dynamics is induced by one of the methods mentioned earlier. Fig 11 a describes spin pumping schematically. Magnetization dynamics of FM leads to spin polarization in the adjacent layers of NM. STT is transfer of spin angular momentum via conduction electrons. A beam of spin polarized electrons can change the direction of magnetization of the FM. Similarly, unpolarized electrons passing through FM achieve spin polarization (Fig 11 b). Conservation of angular momentum is taken care by generation of spin wave excitations in the ferromagnet. Fig 11 c shows a tri-layer of a NM sandwiched between two FMs, where we can see both SP and STT in the same device.

Figure 11: a) Net magnetization in FM leading to spin polarization in adjacent layers of paramagnet. b) Beam of polarized electrons changing the polarization of the FM layer. Unpolarised electrons are polarized after passing through a FM. c) STT and SP seen in the same system - tri-layer of a paramagnet sandwiched between FM layers.

The magnetization dynamics in FM1 induces spin polarization in NM (spin pumping). If these spin polarized electrons pass through FM2, there is transfer of spin angular momentum to the electrons in the FM2. This is STT. If
the thickness of the NM layer is larger than the spin diffusion length, then we can observe only spin pumping but no STT. SP and STT are studied by FMR techniques. In these techniques, Larmor precession in FM is excited either by a d.c. magnetic field or an a.c. bias or microwave radiation. The resonance is achieved by varying one of the remaining two. A typical dispersion curve for a pure FM is shown in Fig 12. For a FM/NM bi-layer sample, the dispersion curves is broadened (shown in dotted lines), when there is spin pumping. There won’t be any broadening in the dispersion curve if there is no spin pumping. For a FM, at resonance we have coherent oscillations of magnetization, and a peak is observed. In case of a FM/NM bi-layer, momentum is transferred from the FM to the adjacent layers of NM giving rise to distribution of oscillations. This is reflected as broadening of dispersion curve. Suppose the system shown in Fig 12c, has the two FM layers identical, there will not be any spectral broadening. Thus we can conclude that STT and SP are reciprocal effects.

![Figure 12: Schematic for FMR spectra for a mono-layer of FM and bi-layer of FM/paramagnet](image)

Tulapurkar et al [33] for the first time demonstrated the detection of spin dependent signals in MTJs using STT. One of the layers is a pinned layer and the other is free. The circuit for the same is shown in Fig 13 a. When an ac bias is applied, spin polarized electrons travel from fixed layer to the free layer during positive half cycle and vice versa during the negative half cycle. When electrons pass from fixed layer to the free layer, there is a STT from these electrons to the electrons in the free layer. During the negative half cycle electrons move from the free layer to the fixed layer, but this does not cause any STT to the electrons in the fixed layer. Thus there is difference in resistance between positive and negative half cycles, which is analogous to a pn junction diode which gives different current in forward and reverse bias configurations.
The motion of the free layer magnetization is governed by the following equation,

\[
\frac{d}{dt} \hat{s}_{\text{free}} = \gamma \hat{s}_{\text{free}} \times H_{\text{eff}} + \alpha \hat{s}_{\text{free}} \times \frac{d}{dt} \hat{s}_{\text{free}} + \gamma \hat{STI} \hat{s}_{\text{free}} \times (\hat{s}_{\text{free}} \times \hat{s}_{\text{pin}}) + \gamma \hat{FTI} \hat{s}_{\text{free}} \times \hat{s}_{\text{pin}}
\]

where, \( \hat{s}_{\text{free}} \) and \( \hat{s}_{\text{pin}} \) are unit vectors along the magnetization of the free layer and pinned layer respectively. \( \gamma \) is the gyrometric ratio, \( \alpha \) is the Gilbert damping parameter, \( I \) is the rf-current. \( H_{\text{eff}} \) is the sum of external field and the demagnetization field. The first term corresponds to precession motion of the magnetic moment about the effective field. In realistic systems there is precession motion damping which finally aligns the magnetic moment along the effective field. The second term represents the damping. The third and the fourth terms also contribute to precession and damping respectively but, the cause in this case is the magnetization of the fixed layer leading to precession and damping of the free layer. \( ST \) and \( FT \) are spin transfer and field like terms per unit current respectively. The torque on the electrons in the free layer can be written in terms of it’s components. One along the direction perpendicular to the plane of the sample, \( \hat{s}_{\text{free}} \times (\hat{s}_{\text{free}} \times \hat{s}_{\text{pin}}) \), one in the plane of the sample \( \hat{s}_{\text{free}} \times \hat{s}_{\text{pin}} \). These two components are attributed to spin-transfer effect and the one due to effective field due to magnetization respectively. Theoretically it has been shown that if the effect is purely due to spin-transfer it shows a single peak, where as a net effective field will show a dispersion as shown in fig 13 b. The resultant is a superposition of both which shows a dispersive behavior with larger ammplitude on positive side due spin-transfer effect.
The experimental observation shows the same (fig 13 c) which is a conclusive proof for spin-transfer effect in the MTJ. Sankey et al \[34\] also have reported a similar measurement with CoFeB as ferromagnet and MgO as insulator. Differential resistance as a function of applied bias has been measured which shows maximum resistance in anti parallel configuration. As expected, there is very low resistance when the layers are aligned parallel and there is no torque (evident from eqn 3). With change in dc bias current direction it is observed that the FMR spectra is exactly opposite in nature which confirms the spin dynamics contribution leading to FMR. FMR spectra can be obtained by another way. The FM sample is placed in magnetic field which gives larmor precession, and also exposed to microwave radiation. The Larmor precession frequency and the microwave radiation frequency match to give FMR. The reflection/absorption intensity is recorded with variation in magnetic field. The curve for reflection intensity with external magnetic field, is similar to that with the electrical voltage measured in the earlier case. This method is widely used to detect ISHE signals in bi-layers of ferromagnet and paramagnet, where microwave radiation excites spin-pumping from FM to the paramagnet.

The concept of SP and STT is applicable in detection of SHE signals. In this section we emphasize on SHE experiments that used microwave radiation for SP. The initial experiments based on these concepts were performed by Saitoh et.al. \[35\] Their sample was a bi-layer of NiFe and Pt, grown by sputtering and thermal vapor deposition techniques. The paramagnet used was Pt which has high spin orbit coupling co-efficient and the FM was NiFe whose magnetization dynamics causes spin pumping. This is evident by the FMR spectra as shown in Fig 14 b. The response for the bi-layer is broadened compared to the response by a single FM layer. At resonance, maximum spin-pumping occurs from ferromagnet into the paramagnet. The schematic, Fig 14 a, shows the sample configuration and measurement geometry. Spin separation is observed in transverse direction to the spin current density $J_s$ and the corresponding voltage is measured using a voltmeter \[36\]. Measurement can be either directly the spin hall voltage or the change in voltage with respect to external magnetic field with varying external magnetic field. The response for both is as shown Fig 14 c,d supported by experimental data.
In the case of measurements for STT diode in the earlier section, we saw that the response can either be purely due to spin transfer which showed a single peak or due to effective field which showed a dispersive behavior. Similarly, in this case of a FM/paramagnet bi-layer the contribution of magnetization of the FM can lead to Anomalous Hall Effect (AHE) signal. We eliminate this possibility by the spectral response. In case of AHE signal the response will be as shown in Fig 14 c,d. Since, AHE signal is proportional to the net magnetization of the sample, this picks up a phase factor of $\pi$ for every half cycle rotation, leading to dispersive behavior. Where as, ISHE signal is purely due magnitude of spin current and shows a single peak.

Spin Transfer Torque based measurements performed on NiFe/Pt bi-layer samples but with frequency dependent a.c. bias measurement geometry were performed by L. Liu et al, (Fig 15)[37]. As seen in Fig 15 a, the sample is a bi-layer of NiFe-Pt which is connected to an ac bias circuit. When charge current passes through the Pt layer, this injects a spin current in transverse direction, into the NiFe. These electrons transfer spin angular momentum to the conduction electrons in NiFe and there is magnetization induced in NiFe. Oscillating current is generated in NiFe. But, the magnetization of NiFe shows differential resistance to spin up and spin down electrons that are injected into it. This oscillation when tuned to the larmor precession frequency gives
resonant peak. As seen in Fig 15 b, this behavior is a Lorentzian for the dc bias voltage which is a result of differential resistance in FM \( v/s \) externally applied magnetic field causing larmor precession. Experiment is also performed for Cu instead of Pt which also shows a spin transfer behavior in FMR spectra but the magnitude is much lesser compared to that of Pt, which attributes to lower spin-orbit coupling strength in of Cu. This can be seen in Fig 15 c.

![Figure 15: a) Sample configuration and Measurement geometry for ISHE signal. b) Schematic for direction of \( J_s, \sigma, J_c \) and hence \( V_{ISHE} \). c) Experimental results for FMR intensity measurement with external magnetic field. (Reprinted with permission from ref.28 ©2011 by the American Physical Society.)](image)

The STT-diode was also extended to make non-local measurements by Lin Xue et.al, [38]. The structure was an MTJ on top of a spin valve. This basically has 3 ferromagnetic layers with a metal in between the first two layers and MgO in between the second two layers. The second FM is a free layer. The direction of magnetization of the free layer is altered due to STT caused by diffusion of spin polarized electrons from the metal layer below. Externally applied microwave frequency causes and oscillatory non-local spin signals in the free layer, and hence the magnetization precesses. The oscillating magnetoresistance of the MTJ is measured as a function of external magnetic field applied, which is experimentally observed to be the dispersion curve for FMR.

5 Conclusive remarks

Spin Hall effect has technological applications solely due to Spin Seebeck Effect (SSE). In this section we briefly highlight the importance of SSE. It has been observed in ferromagnetic metal/insulator/semiconductor systems that
a temperature gradient in certain direction leads to spin separation of electrons. Depending on the system that is used as spin injector, either longitudinal or transverse configuration of seebeck effect measurement can be performed. SSE signal in metal and insulator spin injectors are of the order of $\mu V$. Uchida et.al. performed extensive study of SSE on NiFe/Pt bilayer [39, 40] and on YIG/Pt system [41]. SSE signal was detected only in single crystalline YIG samples where the magnetic ordering is high unlike in polycrystalline YIG. Both transverse and longitudinal configurations were studied and the magnitude of SSE signal was of the same order. Interestingly SSE is also observed when the substrate used is an insulator with high thermal conductivity. Uchida et.al demonstrated phonon-magnon mediated SSE with sapphire as substrate and grew NiFe/Pt on it. This was also observed in semiconductor systems where GaMnAs/Pt bilayer is grown on Si-GaAs as substrate. Measurements were performed on the system with and without electrical discontinuities made on the films. The signals were the same and this proves the effect to be driven by phonons. SSE signal was observed in insulators like Fe$_3$O$_4$ and in La$_2$Fe$_5$O$_{12}$ by [42]. Despite of absence of conduction electrons, temperature gradient creates a spin voltage. A significant change in seebeck co-efficient when the magnetic states change from parallel alignment to anti-parallel alignment is seen in magnetic tunnel junctions [44]. Thus utilization of thermal energy in electronic devices promising revolution in technology with Spin Seebeck Effect being observed in nano scale devices. Long range order of signals over length scales and the device geometry being the similar to those of spin hall effect devices or magnetic tunnel junctions has favors more applications.

We have discussed various ways of measuring the spin hall effect signals. The spin injection efficiency was improved by introducing tunnel barrier between the FM electrode and the channel. This paves way to come up with suitable combination of FM-tunnel barrier-channel, which will have large spin diffusion length and higher sensitivity. Optical methods also have to be concerned about the band gap of the channel and temperature dependence of the same, to excite the electrons in the channel. Optical methods which use unstrained GaAs as channel, show very small kerr rotation angle. The mechanism used to generate spin polarized electrons in optical methods is through circularly polarized light, where as in electronic methods it is direct usage of FM which are source for spin polarized electrons. The ease of measurements favors electronic methods over optical methods. The channel length in both cases is of the order of $\mu m$. Fabrication procedures are relatively simpler in devices that use FMR for SHE measurements. The magnitude of signal detected is of the order of $\mu V$ where as it is 1000 times larger in the case of devices were detection is through FM electrodes. Quantification of various parameters is relatively easily feasible task in case of electronic measurements (Eg.: Spin Hall angle quantification by O. Mosendz et.al., [45]). Recent reports also use tunneling spectroscopy techniques to measure spin hall effect signals [46].

Experiments so far have been able to achieve SHE and ISHE both in the same device which empowers the device applications using spin seebeck ef-
fect. In this review we have summarized various ways of measurements performed so far. Advancement in spin seebeck effect will help future applications in utilizing energy more efficiently for power generation and also help to explore the understanding of fundamental interactions at nano scale.

6 Acknowledgments

Authors thank P N Deepak, Radhika Vathsan, Abhiram Soori for discussions. RSP acknowledges the financial support from the Department of Science and Technology (DST), Government of India through nanomission project (grant No. SR/NM/NS1002/2010). DS thanks Department of Science and Technology, Government of India - INSPIRE for fellowship (No.DST/INSPIRE Fellowship/2013/742).

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