Experimental techniques (P473)

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Report

Measurement techniques for Spin Hall effect

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Contents

Abstract

The spin Hall effect is a relativistic spin–orbit coupling phenomenon that can be used to electrically generate or detect spin currents in non-magnetic systems. The spin Hall device studies are placed in a broader context of the field of spin injection, manipulation, and detection in non-magnetic conductors [1]. In this report various techniques for measuring SHE have been shown, some are fully electronic based and some are opto-electronic based.

1 Introduction

The spintronics word comes from the combination of spins with electronics, and when these are thought as together we can say that the fundamental particles in electronics are electrons and when considered with their spins it nicely defines the word spintronics.

The Spin hall effect (SHE) sounds familiar to the ordinary hall effect (HE), where the incoming fundamental charge carriers experience Lorentz force in the presence of magnetic field and thus get accumulated along one of the lateral surfaces and cause an potential difference across the opposite sides of the lateral surface. Fig.1 demonstrates the ordinary hall effect (HE).

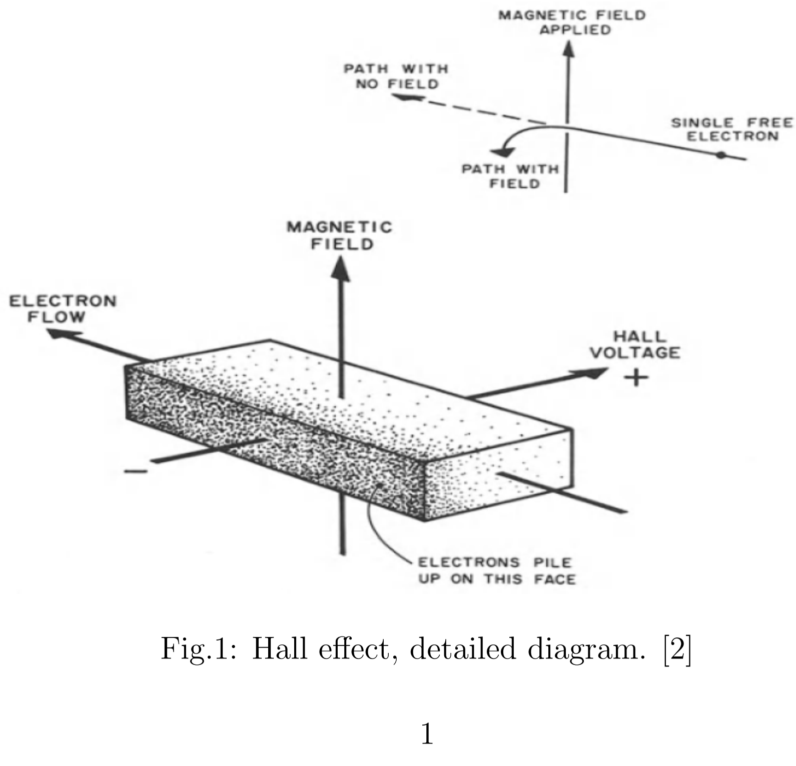

Fig.1: Hall effect, detailed diagram. [2]

In Spin hall effect (SHE), the fundamental charge carriers i.e. electrons get separated along the lateral surface such that on one side of the surface we have pure spin current of a particular spin (up spin or down spin) and the other lateral surface we have a pure spin current of opposite spin (opposite spin w.r.t the spin current in 1st lateral surface); one point must be clear that the spin hall effect (SHE) do not require any magnetic field, instead the separation of spin occurs due to the spin-orbit coupling (SOC). Spin-orbit coupling (SOC) is discussed in section 2.1.2

2 Physics behind the field

2.1 Spin Hall Effect (SHE)

In SHE we generally deal with the materials which are non-magnetic or with weak magnetic properties, in SHE there is no requirement of external magnetic field, where in case of ordinary HE external magnetic field was a must. For the materials to be non=magnetic or weakly magnetic, materials like ferromagnetic and paramagnetic can also be used when using above the Curie temperature.

When current flows through a non-magnetic sample the flowing electrons from one end to the other end of the sample get scattered such that the electrons of opposite spins get accumulated on the opposite lateral surfaces and thus forming a pure spin current along the side, this phenomenon occurs due to the interaction process known as spin-orbit coupling.

2.1.1 Spin currents

A pure spin current can be defined as the flow of electrons of spin " moving in one direction and electrons of the opposite spin i.e. electrons moving along the opposite direction. This results in no net charge current (since rate of movement of electrons in opposing directions is the same) and a net flow of angular momentum.[3]

Fig.2 shows the different spin currents, where 2(d) relates to our discussion above, that pure spins have no charge current and only have a spin current.

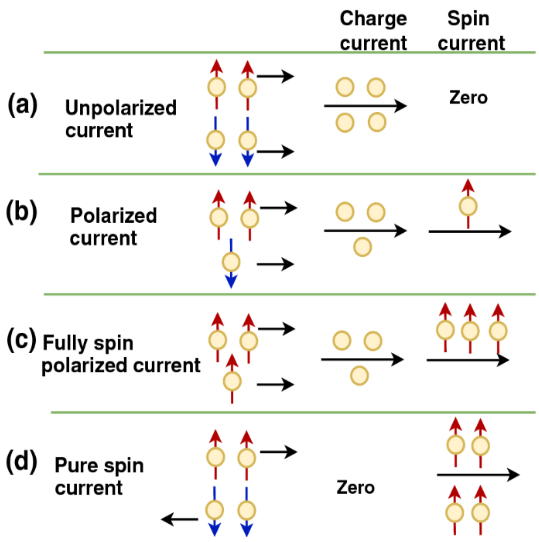

Fig.2: Different spin currents[4]

2.1.2 Spin-orbit coupling

Spin orbit coupling refers to the interaction between the spin angular momentum of electron and the orbital angular momentum of the atom.

The orbital angular momentum of an atom is given as:

$$\boldsymbol{L} = mr \times v \tag{1}$$

and the angular momentum is related to the magnetic field B by:

$$\boldsymbol{B} = \frac{\mu_0 Ze\boldsymbol{L}}{4\pi m_e r^3} \tag{2}$$

The spin-orbit Hamiltonian is given by:

$$H_{LS} = \frac{\mathrm{Ze}^2}{8\pi\epsilon_o c^2 m_e^2 r^3}\vec{L}\cdot\vec{S} \tag{3}$$

where Z is the atomic number, e is the electric charge, ϵ_o is the permittivity of free space, c is the speed of light, m_e is the mass of the electron, r is the distance from the nucleus to the electron, $\vec{L}$ is the orbital angular momentum and $\vec{s}$ is the spin.

Spin orbit coupling strength with atomic number:

From the eq. (3) we can see that spin-orbit coupling is directly proportional to the atomic no. of the element.

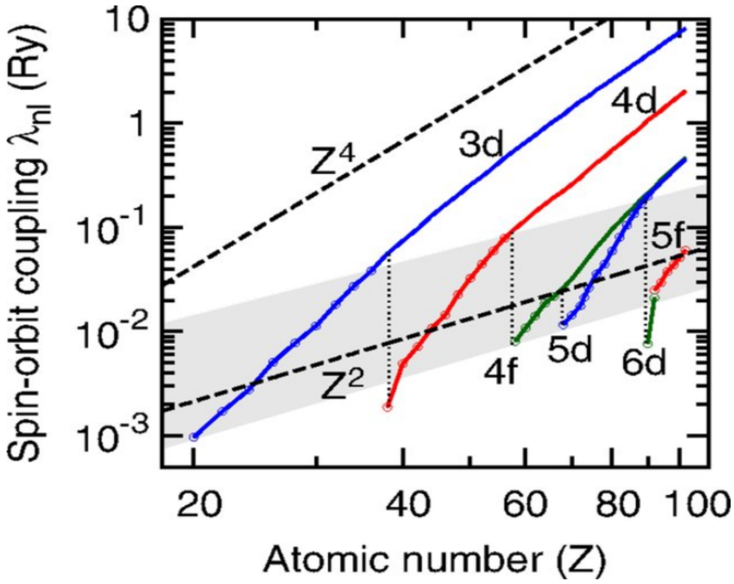

Fig.3: Dependence of the spin-orbit coupling strength nl for atoms as a function of the atomic number Z. The calculated results of Herman and Skillman using the Hartree-Fock method (colored lines) are compared to the hydrogenic Z4 dependence[5]

Some of the elements with high spin-orbit coupling and preferred for SHE are: Bi, Nb, Pd, Pd,etc.

2.2 Inverse spin hall effect (ISHE)

In contrast to SHE, the inverse Hall effect is essentially the same but SHE in reverse. When a pure spin current is injected into a material with high SOC (with no charge current), the same scattering mechanisms3 as the SHE, allow the spin-polarized electrons to preferentially scatter into opposite directions, leading to a charge imbalance across the edges of the material, thus resulting in a potential difference across the edges (in a transverse fashion)
The spin $\uparrow$ electrons scatter along one direction and the spin $\downarrow$ electrons scatter along another direction. The surprising aspect about this, is that both the directions are the same! This leads to a pure charge current.

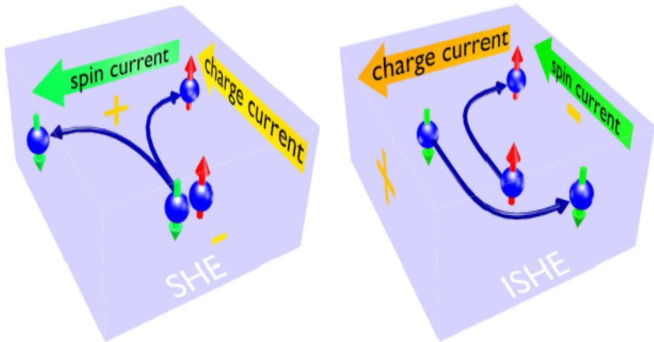

Fig.4: Comparison between SHE and ISHE [6]

3 Various techniques to measure SHE

Theorists Dyakonov and Perel proposed that an unpolarized electrical current should lead to a transverse spin current in systems with the relativistic spin–orbit coupling. In their picture, spin–orbit coupling enters SHE via the Mott scattering of electrons on unpolarized impurities, which results in spatial separation of electrons with opposite spins. The effect has a Hall symmetry, because the polarization axis of the spins is perpendicular to the plane of the transverse spin current and the driving longitudinal electrical current [1].

Hirsch proposal

He proposed a device in which a spin current is generated by SHE in one part and injected into another part where it is detected by the inverse spin Hall effect (ISHE). In ISHE, the spin current generates a transverse current of charge and when accumulated at the edges of the sample the charge can be detected electrically.

3.1 Kerr microscopy method

The intrinsic SHE proposals focused on semiconductors and suggested that the optical activity of these materials be utilized for detecting SHE. In particular, the circularly polarized electro-luminescence was suggested and the magneto-optical Kerr effect in other references[7][8]. These methods were used in the first measurements of the SHE phenomenon.

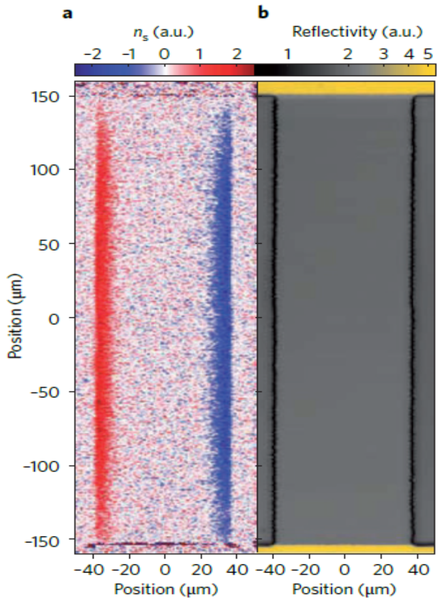

Fig.5: **Observation of SHE by the magneto-optical Kerr microscope.** a,b, Two-dimensional images of spin polarization density ns (a) and reflectivity (b), for the unstrained GaAs sample measured at temperature 30 K and applied driving electric field 10 mV m1. Arbitrary units are used for ns as the measured Kerr rotation signal is not calibrated to the corrresponding spin density for this measurement[1]

A two-colour optical excitation technique with perpendicular linear polarizations of the incident laser beams was used to detect ISHE in a semiconductor. The spin-current source produced by laser excitation is transferred, owing to ISHE, into a transverse electrical current, resulting in a spatially dependent charge accumulation that was detected by the optical transmission signal of a probe laser beam[1].

3.2 Semiconductor approach based on the absorption of circularly polarized light.

The roots of this technique can be traced back to experiments in which a circularly polarized beam at the normal incidence to the surface of a bulk semiconductor was used to excite spin-polarized photo-electrons. These electrons diffuse in the vertical direction from the surface and after aligning their spins along an axis parallel to the surface by an applied magnetic field (by Hanle precession), an electrical voltage was detected in the transverse in-plane direction.

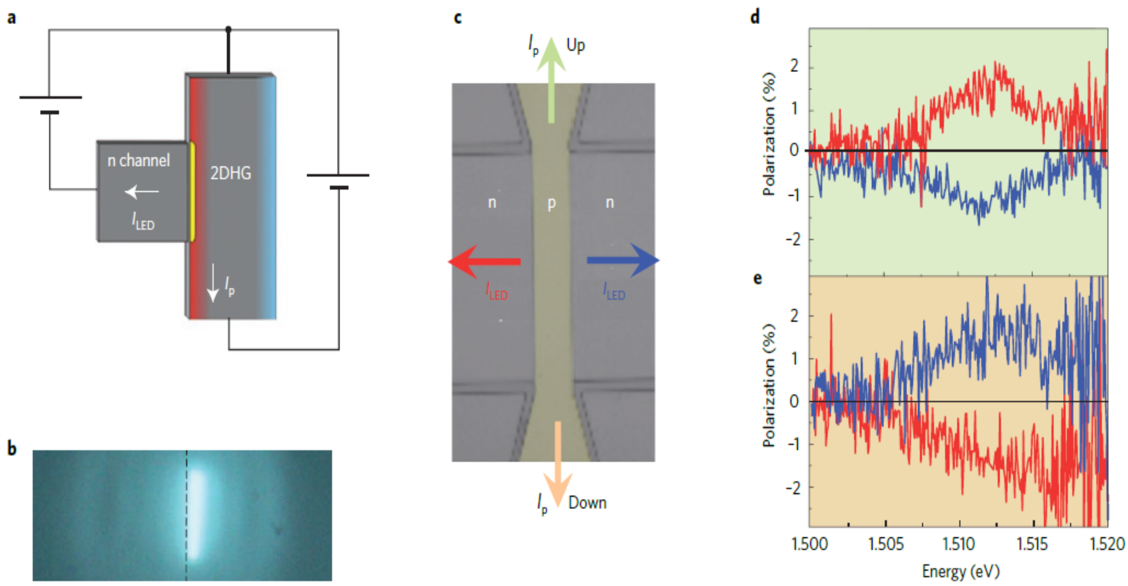

Fig.5: **Observation of SHE by the circularly polarized electroluminescence of coplanar p–n diodes. a,** Schematic of the lateral p–n junction with the channel current Ip and the diode current ILED for detecting spin accumulation. b, Light emission from the p–n junction recorded by a charged-coupled device camera. The black dashed line shows the position of the p–n junction. c, Electron microscope image of the microdevice with symmetrically placed p–n diodes at both edges of the 2D hole gas channel. d,e, Emitted light polarization of recombined light in the p–n junction for the channel and diode current flow indicated by arrows in (c).[1]

Recently, a coplanar p–n diode is used , but now operated as a photo-cell, has allowed the optical spin generation and electrical spin detection regions of the semiconductor to be separated. The inverse spin Hall effect induced by the pure spin-current was eventually observed in these devices by draining the p–n junction electrical current before the Hall cross. The work showed that iSHE can be combined with spin-precession phenomena in electrically controllable Rashba and Dresselhaus spin–orbit fields[1].

3.3 Electrical spin injection technique

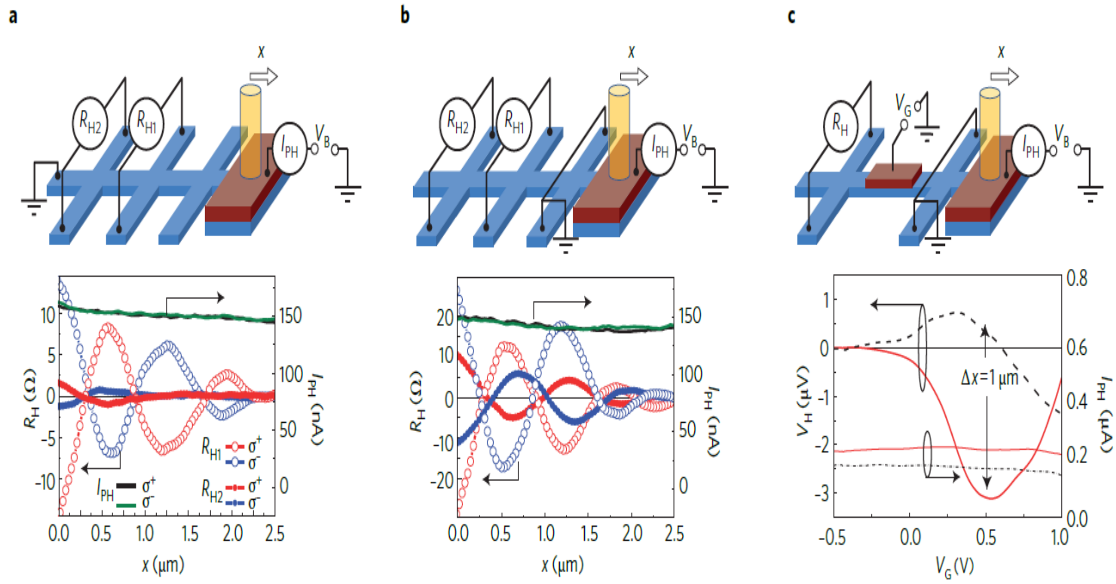

Fig.6: **iSHE-based transistor. a** , Schematic of the spin-injection Hall effect measurement set-up with optically injected spin-polarized electrical current propagating through the Hall bar and corresponding experimental Hall effect signals at crosses H1 and H2. The Hall resistances, RH = VH/IPH, where VH is the Hall voltage and IPH is the photocurrent for the two opposite helicities of the incident light are plotted as a function of the focused light spot position, that is, of the position of the injection point. VB is the p–n junction bias voltage, + and are the helicity of the polarized light. IPH is independent of the helicity of the incident light and varies only weakly with the light spot position. b, Same as (a) for iSHE in which the electrical current is closed before the first detecting Hall cross H1. c, Schematic of the spin Hall transistor and experimental Hall signals as a function of the gate voltage (VG) at a Hall cross placed behind the gate electrode for two light spot positions with a relative shift of 1 m. The red and dashed black lines correspond to measurements with the relative shift of the laser spot of 1 m.[1]

3.4 Other methods

These are the few methods which are also widely used for measuring spin hall effect.

- Tetrahertz emission spectroscopy: The terahertz emission is driven with ultrashort laser pulses from a Ti:sapphire oscillator with a pulse duration of 10 fs, a central wavelength of 800 nm, a repetition rate of 80 MHz, and a pulse energy of about 1 nJ. The terahertz transient is measured via electro-optic sampling in a 1-mm-thick ZnTe(110) crystal with a weak copropagating 10-fs near-infrared probe pulse from the same laser[9].

- VNA FMR : A static magnetic field H is applied along the bilayer normal. FMR is excited by our passing a microwave current of fixed frequency through the CPW while sweeping the magnitude of H. At each value of H, the complex valued microwave transmission S21(H) through the CPW is recorded with the VNA[9].

- Harmonic Hall: For determination of the spin Hall angle, the films are patterned into fourfold rotationally symmetric Hall crosses with conductor width $w = 16\mu$m and length $l = 48\mu$m by optical lithography. Harmonic-Hall-voltage measurements are performed in a dual Halbach cylinder array with a rotating magnetic field up to 1.0 T (MultiMag, Magnetic Solutions Ltd.). An alternating-current density with an rms value of $j_{\rm rms} = 2\times10^{10}$ A m^{-2} ($I_{\rm rms} = 1.92$ mA) and frequency $\omega/2\pi = 3219$ Hz is injected into the Hall crosses, and the in-phase first harmonic and out-of-phase second harmonic Hall voltages are recorded simultaneously on in-plane field rotation with a Zurich Instruments MFLI multi-demodulator lock-in amplifier.

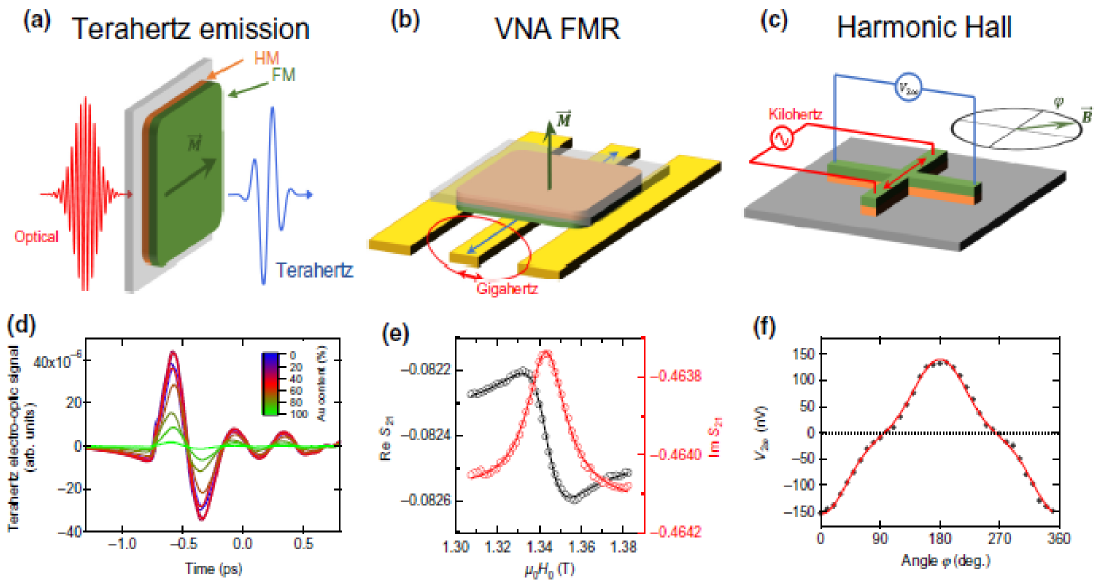

Fig.7: Overview of three different techniques to determine the spin Hall angle of a material as described in the main text. The top row shows schematics of the techniques (not to scale), while the bottom row shows typical raw data. (a),(d) Terahertz emission spectroscopy: an optical laser pulse generates an ultrafast heat pulse in the films. Because of the spin-dependent Seebeck effect, a spin current flows from the FM layer into the HM layer. The inverse spin Hall effect converts the spin current into a charge pulse, which emits terahertz radiation. (b),(e) VNA FMR: a gigahertz current in the coplanar waveguide excites the ferromagnetic resonance in the FM layer. Spin pumping drives a spin current into the HM layer, where it is converted into an oscillating charge current. Its magnetic field couples into the waveguide and can be detected in the complex-valued waveguide transmission signal S21. (c),(f) Harmonic Hall measurements: a kilohertz charge current drives an oscillating spin current from the HM layer into the FM layer. The associated spin-orbit torque drives an oscillating deflection of the magnetization out of the film plane. The associated oscillating anomalous Hall voltage is detected as a second-harmonic transverse voltage in the Hall cross[9]

4 Discussion and Conclusion

Experiments in spin Hall devices performed so far have established the basic physics of SHE and ISHE, showed that the intrinsic and extrinsic mechanisms can contribute to the phenomenon, and that SHE and ISHE are universal to metal and semiconductor systems (3D and 2D) with spin–orbit coupling. As the strength of the spin–orbit coupling increases, the spin current that arises from SHE increases. At the same time, however, the spin lifetime decreases. Finding the optimal compromise between these two counteracting effects of the spin–orbit coupling remains an important open problem in the field.
The utility of SHE and ISHE as an electrical spin injector and detector in non-magnetic systems can allow a variety of new spintronic functionalities to be explored.

New approach :

One of the recently proposed areas is opto-spintronics. For some cases ISHE acts as a direct electrical detection tool for the polarization of light, and because of the universality of the spin Hall phenomenon, the approach can be implemented in semiconductors active over a wide range of wavelengths. Further detailed studies will be done on this later.

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