

Quantitative Analysis of Spin Hall Effect in Nanostructures

N. Gupta¹, K. K. Choudhary² and S. Katiyal³

Submitted in January 2012; Accepted in July 2012

Abstract - Spin transport in nano structured devices depends on interface resistance, electrode resistance, Spin polarization and Spin diffusion length. Spin Hall Effect (SHE), caused by Spin-orbit scattering in nonmagnetic conductors, gives rise to the conversion between Spin and charge currents in a non local device. Recently, SHE has been observed using non local Spin injection in metal-based nanostructured devices, which paves the way for future Spin electronic applications. In present work we have theoretically analyzed the SHE phenomena based on experimental results obtained till date. We have used the Hamiltonian of two dimensional electron systems with Rashba Spin-orbit coupling. We undertake the quantitative analysis of Spin Hall Effect in low dimensional materials using Spin dynamical equations and Spin Hall conductivity.

Index Terms - Spin transport, Spin Hall Effect, nanostructures

PACS: 75.76.+j, 73.43.-f, 73.63.-b.

1. INTRODUCTION

Spin-dependent transport phenomena in nanostructures are of great interest in the potential applications to Spin electronic devices [1]. Recently much attention has been paid to the Spin Hall Effect, which allows the polarization of electron Spins in nanomaterials [2-6]. In the Spin Hall Effect, electrically induced Spin polarization accumulates near the edges of a channel and is zero in its central region. This effect is caused by deflection of carriers, moving along an applied electric field, by extrinsic [3] and/or intrinsic [4] mechanisms. In a non-magnetic homogeneous system, Spin accumulation is not accompanied by a charge voltage, because two Spin Hall currents due to Spin-up and Spin-down electrons cancel each other [2]. The absence of transverse voltage leads to difficulties in probing the Spin Hall Effect: measuring a charge accumulation is much easier than measuring a Spin accumulation.

Recently, the Spin Hall Effect has been observed both optically [5] and electrically [6]. Valenzuel and Tinkham [6] have reported the electrical measurements of the Spin Hall effect in a diffusive metallic conductor, using a ferromagnetic electrode in combination with a tunnel barrier to inject a Spin-polarized

¹Department of Electronics, Shri Vaishnav Institute of Technology and Science, Baroli, Indore -453331, India.

²Department of Physics, Shri Vaishnav Institute of Technology and Science, Baroli, Indore 45331, India.

³School of Electronics, Devi Ahilya University, Khandwa Road Campus, Indore-452001, India.

E-mail: namitg@hotmail.com

current. An induced voltage has observed that results exclusively from the conversion of the injected Spin current into charge imbalance through the Spin Hall Effect. Such a voltage is proportional to the component of the injected Spins that is perpendicular to the plane defined by the Spin current direction and the voltage probes. In a Spin-orbit-coupled system, a non-zero Spin current is predicted in a direction perpendicular to the applied electric field, giving rise to a Spin Hall Effect [7, 8]. Consistent with this effect, electrically induced Spin polarization was recently detected by optical techniques at the edges of a semiconductor channel [9] and in two-dimensional electron gases in semiconductor hetero structures [10, 11].

Efficient Spin injection, Spin accumulation, Spins transfer and Spin detection are key factors in utilizing the Spin degree of freedom as a new functionality in Spin electronic devices. By analyzing the Spin transport in the structure, we obtain the optimal conditions for Spin accumulation and Spin current. The injection of Spin-polarized electrons and the detection of Spin accumulation depend strongly on the nature of the junction interface.

The theoretical studies on quantum Spin Hall Effect in solid systems are mainly included in metallic graphene and semiconductor system with strain gradient sand. However, since the Spin-orbit interaction in graphene is too small, the theoretical proposals in such systems are difficult to be achieved in experiment. Quantum Spin Hall regime is also very difficult to achieve in semiconductor systems with strain gradients, due to the demanding requirement of a large strain gradient with special configuration and a very low electron density with a clean environment. Spintronics in semiconductors is richer scientifically than Spintronics in metals because doping, gating, and hetero junction formation can be used to engineer key material properties and because of the intimate relationship in semiconductors between optical and transport properties. Spin transport in nano structured devices depends on interface resistance, electrode resistance, Spin polarization and Spin diffusion length. Spin Hall Effect (SHE), caused by Spin-orbit scattering in nonmagnetic conductors, gives rise to the conversion between Spin and charge currents in a non local device.

Optical coherent control method provides a remarkable controllability in the dynamics of atomic Spin states. Furthermore, parameters of cold atomic systems, e.g. atomic number, atom-atom interacting strength, can be well controlled in current experiments. This makes it possible to control the atomic Spin propagation through optical methods, and further demonstrate the quantum Spin hall effect (SHE) in neutral atomic system.

Also the quantitative analysis of the Spin Hall Effect can be done by measuring electrically in completely non-magnetic systems and without injection of Spin-polarized electrons. A comparative study of requirement tools showing trends in the use of methodology for gathering, analyzing, specifying and validating the software requirements has been used in [17], which has helped us in theoretically analyzing the Spin Hall Effect in low dimensional materials using Spin dynamical equations and Spin Hall conductivity.

2. RESULTS AND DISCUSSIONS

In high mobility two-dimensional electron systems (2DES) that have substantial Rashba Spin-orbit coupling [12], Spin currents always accompany charge currents. The Hamiltonian of a 2DES with Rashba Spin-orbit coupling is given by

$$H = \frac{P^2}{2m} - \frac{\lambda}{\hbar} \vec{\sigma} \cdot (\hat{z} \times \vec{p}) \tag{1}$$

Where λ is the Rashba coupling constant, $\vec{\sigma}$ refresh the Pauli matrices, m is the electron effective mass, and \hat{z} is the unit vector perpendicular to the 2DES plane. The Rashba coupling strength in a 2DES can be modified by as much as half, by a gate field [13]. The above discussion is valid even when the atomic number, Z , is not equal to one (hydrogen). Recent observations of a Spin-galvanic effect and a Spin-orbit coupling induced metal-insulator transition in these systems [14], illustrate the potential importance of this tunable interaction in semiconductor Spintronics [115].

The dynamics of an electron Spin in the presence of time-dependent Zeeman coupling is described by the Bloch equation:

$$\frac{\hbar d\hat{n}}{dt} = \hat{n} \times \vec{\Delta}(t) + \alpha \frac{\hbar d\hat{n}}{dt} \times \hat{n} \tag{2}$$

Where \hat{n} is direction of the Spin and α is a damping parameter, that we assume is small. For the application we have in mind, the \vec{p} dependent Zeeman coupling term in the Spin Hamiltonian is $-\vec{s} \cdot \vec{\Delta} / \hbar$, where $\vec{\Delta} = 2\lambda / \hbar (\hat{z} \times \vec{p})$. The Spin orbit interaction is a purely relativistic effect, which is derived from the Dirac equation.

The Spin Hall (SH) conductivity σ_{SH} can be given by the following equation [4]:

$$\sigma_{SH} = -\frac{j_{s,y}}{E_x} = \frac{e}{8\pi} \tag{3}$$

Which is independent of both, the Rashba coupling strength and of the 2DES density.

But in homogeneous charge and current densities conditions:-

$$j_{y,\uparrow(\downarrow)} = \sigma_{\uparrow(\downarrow)} E_y + eD\nabla n_{\uparrow(\downarrow)} \pm \gamma I_{x,\uparrow(\downarrow)}$$

Where Spin conductivity is

$$\sigma_{\uparrow(\downarrow)} = en_{\uparrow(\downarrow)}\mu$$

where $\sigma_{\uparrow}(\sigma_{\downarrow})$ is Spin conductivity due to Spin up (\uparrow) and Spin down (\downarrow) electrons respectively and $n_{\uparrow}(n_{\downarrow})$ is electrons density of states for Spin up (\uparrow) and Spin down (\downarrow) alignment.

Current $I_{x,\uparrow(\downarrow)}$, coupled to the electric field E_0 , which is responsible for the Spin hall Effect is

$$I_{x,\uparrow(\downarrow)} = en_{\uparrow(\downarrow)}\mu E_0.$$

Thus,

$$I_{x,\uparrow(\downarrow)} = \sigma_{\uparrow(\downarrow)} E_0$$

Show that Spin conductivity is directly depending upon Electric field and the current I.

$$\sigma_{\uparrow(\downarrow)} = I_{x,\uparrow(\downarrow)} / E_0$$

Which when integrated to get the Hall Voltage, we gives

$$V_H = \alpha_H \omega_N \rho_N j_s$$

Where ω_N is the width of the Spin hall device N

Thus Transverse Hall Voltage as a function of the longitudinal Electric field E_0 is plotted as:-

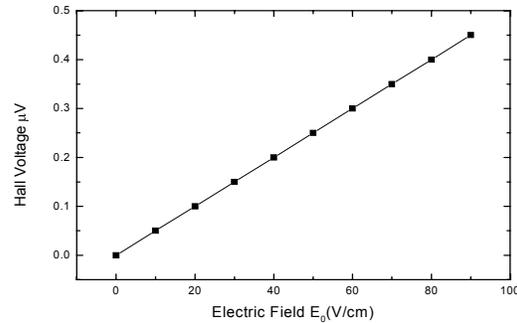


Figure 1: “Traverse Voltage as a function of the longitudinal electric field”

The above result shows an understanding that the average profile curve between the Hall voltage and the longitudinal electric field is normally linear in nature. Certain other Models for the above have also been proposed by the [18], in which novel approaches for developing more efficient relationship model between time and efficiency, have motivated us to model the above work.

In diffusive normal metals, the SHE is known to be induced by the Spin-orbit scattering originating as an extrinsic effect due to impurities or defects [16]. Since the optical detection technique is limited for semiconductor systems, the electrical detection is the only way to access the SHE in diffusive metals. Nonlocal Spin injection in nanostructured devices, provides a new opportunity for observing Spin Hall Effect. If Spin-polarized electrons flow in nonmagnetic electrode, these electrons are deflected by Spin-orbit scattering, to induce Spin and charge Hall currents in the transverse direction and accumulate Spin and charge at the edges.

3. FUTURE SCOPE & CONCLUSION

In nano devices the distribution of the current across the interface depends on the relative magnitude of the interface resistance to the electrode resistance. When the interface resistance is much larger than the electrode resistance as in tunnel junctions, the current distribution is uniform in the

contact area, which validates the assumption of uniform interface current. However, when the interface resistance is comparable to or smaller than the electrode resistance as in metallic contact junctions, the interface current has inhomogeneous distribution with a high current density around a corner of the contact. Using the nonlocal Spin injection, a pure Spin current is created in nonmagnetic conductors, so that we have the opportunity to observe the Spin-current induced SHE in nonmagnetic conductors via the Spin-orbit scattering by nonmagnetic impurities. The observation of the SHE provides direct verification of the existence of Spin current flowing in nonmagnetic conductors. In a reversible way, the electrical current creates the Spin current via the SHE, which provides a Spin-generating source without the need to use ferromagnetic materials. The nonlocal Spin injection also makes it possible to realize a nonlocal Spin manipulation. The advantages of nonlocal lateral structures are flexibility of the layout and the relative ease of fabricating multi terminal devices with different functionalities. The development of nonlocal Spin devices is a new challenge in the research field of Spin electronics.

This result opens up a new possibility to use normal metals with high Spin-orbit coupling as Spin current sources operating at room temperature for the future Spintronic applications.

ACKNOWLEDGMENTS

Financial assistance from M. P. Council of Science and Technology, Bhopal (MP) is gratefully acknowledged.

REFERENCES

- [1]. Saburo Takahashi and Sadamichi Maekawa, *Technol. Adv. Mater.* 9, 014105 (2008).
- [2]. J. Inoue and H. Ohno, *Science* 309, 2004 (2005).
- [3]. J. E. Hirsch, *Phys. Rev. Lett.* 83 1834 (1999).
- [4]. J. Sinova, D. Culcer, Q. Niu, N. A. Sinitsyn, T. Jungwirth and A. H. MacDonald, *Phys. Rev. Lett.* 92, 126603 (2004).
- [5]. J. Wunderlich, B. Kaestner, J. Sinova and T. Jungwirth, *Phys. Rev. Lett.* 94, 047204 (2005).
- [6]. S. O.Valenzuela and M. Tinkham, *Nature* 442, 176 (2006).
- [7]. M. I. Dyakonov, and V. I. Perel, *Phys. Lett. A* 35, 459 (1971).
- [8]. J. E. Hirsch, *Phys. Rev. Lett.* 83, 1834 (1999).
- [9]. Y. K. Kato, R. C. Myers, A. C. Gossard, and D.D. Awschalom, *Science* 306, 1910 (2004).
- [10]. J. Wunderlich, B. Kaestner, J. Sinova, and T. Jungwirth, *Phys. Rev. Lett.* 94, 047204 (2005).
- [11]. V. Sih, R.C. Myers, Y. K. Kato, W. H. Lau, A.C. Gossard, and D. D Awschalom, *Nature Physics* 1, 31 (2005).
- [12]. Y. A. Bychkov and E. I. Rashba, *J. Phys. C* 17, 6039 (1984).
- [13]. J. Nitta, T. Akazaki, H. Takayanagi, and T. Enoki, *Phys. Rev. Lett.* 78, 1335 (1997).
- [14]. T. Koga, J. Nitta, T. Akazaki, and H. Takayanagi, *Phys. Rev. Lett.* 89, 046801 (2002).
- [15]. [J. Inoue, G. E.W. Bauer, and L.W. Molenkamp, *Phys. Rev. B* 67, 033104 (2003).S. Zhang, *Phys. Rev. Lett.* 85, 393 (2000).
- [16]. Mohammad Ubaidullah Bokhari and Shams Tabrez Siddiqui, "A Comparative Study of Software Requirement Tools for Secure Software Development", *BVICAM's International Journal of Information Technology, BIJT*, issue 4, 2010 Vol. 2 No. 2
- [17]. Tamanna Siddiqui, Munior Ahmad Wani and Najeeb Ahmad Khan, "Efficiency Metrics", *BVICAM's International Journal of Information Technology, BIJT* issue 5, 2011 Vol. 3 No. 2.

Continued from page no. 491

- [33]. Iwan Ulrich, "Appearance based obstacle detection with Monocular Color Vision", AAAI National Conference on Artificial Intelligence, Aug. 2000.
- [34]. Nick Pears, Bojian Liang, "Ground Plane Segmentation for Mobile Robot Visual Navigation", in the Proc. of IEEE RSJ international Conference on Intelligent Robots and Systems, Maui, Hawaii, USA, Oct. 29- Nov. 03, 2001.
- [35]. D. Santosh Kumar, C.V.Jawahar, "Robust homography based control for camera positioning in piecewise planar environment", in the Proc. of Indian Conference on Computer Vision, Graphics and Image Processing (IGVGIP), pp. 906-918, 2006.
- [36]. Wenbing Tao, Hai Jin, Yimin Zhang, "Color Image Segmentation based on Mean Shift and Normalized Cuts", IEEE Transactions on Systems, Man, and Cybernetics, Part B, pp. 1382, Oct. 2007.

Continued from page no. 495

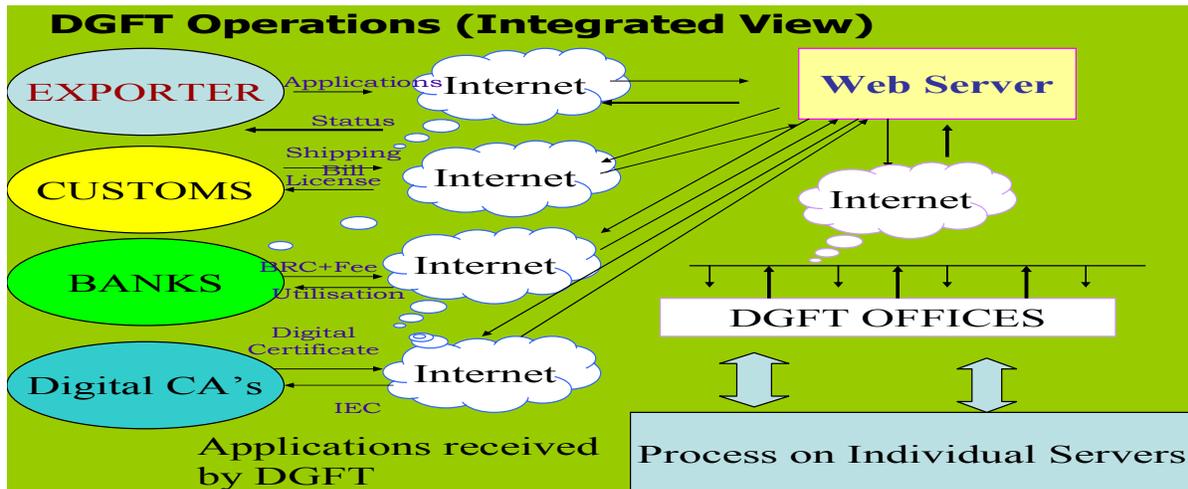


Figure2: "Electronic Data Interchange Flow Chart"