Available at: http://publications.ictp.it IC/2010/033

United Nations Educational, Scientific and Cultural Organization
and
International Atomic Energy Agency

THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

# EFFICIENT SPIN INJECTION INTO SEMICONDUCTOR

M.A.I. Nahid[1]
*Department of Applied Physics and Electronic Engineering, Rajshahi University, Rajshahi 6205, Bangladesh*
and
*The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy.*

## Abstract

Spintronic research has made tremendous progress nowadays for making future devices obtain extra advantages of low power, and faster and higher scalability compared to present electronic devices. A spintronic device is based on the transport of an electron's spin instead of charge. Efficient spin injection is one of the very important requirements for future spintronic devices. However, the effective spin injection is an exceedingly difficult task. In this paper, the importance of spin injection, basics of spin current and the essential requirements of spin injection are illustrated. The experimental technique of electrical spin injection into semiconductor is also discussed based on the experimental experience. The electrical spin injection can easily be implemented for spin injection into any semiconductor.

MIRAMARE – TRIESTE
June 2010

[1] Junior Associate of ICTP. mainahid@gmail.com

## Introduction

Recently, spintronics has become an exciting and rapidly expanding research field in condensed matter physics [1-5]. The technology roadmaps of various developed countries predict that future devices would be spintronic devices due to the superiority compared to present electronic devices. Thus, it becomes the very hot research field. It is an advanced discipline of microelectronics. The control and manipulation of electron spin is central to spintronics which aims to represent digital information using spin orientation rather than electron charge [3-5]. Such spin based technologies have a profound impact on making devices because of extra degrees of freedom which can give extra functionality and new capabilities. Future anticipated devices based on electron spin will have faster switching time and lower power consumption. Till now, all currently available spin-based devices are memory device and sensor [6]. However, progress is going on for spin-based transistor for making novel reconfigurable logic circuits [7]. Meanwhile, it provides important research subjects in the field of condensed matter physics. In order to fabricate spin-based devices, it is necessary to combine the magnetic and semiconductor technology. Although it is difficult, there is good progress in semiconductor based spintronics. The key things for further development are efficient spin injection, transportation and detection. The question is how can the spin current can be generated and injected into semiconductor efficiently. Although researchers in developed countries have made tremendous progress in this field, very few researchers in developing countries are aware of this field. In this paper, the basics of spin current, requirements of efficient spin injection are reviewed. The problems and perils of spin injection and experimental techniques for spin injection are also illustrated.

## Basics of spin current

In addition to mass and elementary charge, electron has intrinsic angular momentum called spin angular momentum. The spin angular momentum of the electron is the basis of spintronics. Each electron spin has two arbitrary orientations, generally called spin-up and spin-down. Depending on the spin orientation, the electron has different energies in the presence of a magnetic field. In a conventional electronic circuit, the electron spin of charge carriers are random and the current does not exhibit spin properties. Directional or coherent motion of spins can transport or carry information. Therefore, spin current varies from the charge current in two different ways; it is time invariant and it is associated with the angular momentum, that is, a vector quantity [8,9]. This feature allows transporting quantum information. It is noted that the spin angular momentum unlike charge is not conserved in the electric circuit. The conduction can be thought of as taking place in two independent parallel channels for spin-up and spin-down electrons, as proposed by Mott, the two-current-model for conduction in metals [10]. If $I_{\uparrow}$ is the current due to spin-up electrons and $I_{\downarrow}$ is the current due to a simple way, we can define the spin current as the difference between the flows of spin-up and spin-down electrons, $I_S = I_{\uparrow} - I_{\downarrow}$ while the charge current is the sum of the spin-up and spin-down electrons, $I_C = I_{\uparrow} + I_{\downarrow}$. Therefore, if the spin-up electrons flow in one direction and the equal number of spin-down electrons flow in the opposite direction charge current, $I_C = 0$ while $I_S \neq 0$. Thus, pure spin current can flow without charge current. The important thing is how to create and detect the spin currents. One way to generate and detect spin current, which is known as the non-local technique [11-13], is illustrated in fig. 1. When the charge current flows from the ferromagnetic electrode into non-magnetic metal, the spin-polarized electrons diffuse into the metal on either side of the contact. Thus, it injects non equilibrium spins in the non-magnetic metal which results spin dependent potential as the up-spin and down-spin electrons have a different chemical potential. Depending on the ferromagnetic electrodes parallel and anti-parallel configuration, this potential can be detected by placing the ferromagnetic electrode outside the path of the charge current. It works as a lateral spin valve. Seeing that the spin diffusion length is in short length scale (few hundred nanometers), the detection electrode should be placed within that distance from the injection electrode.

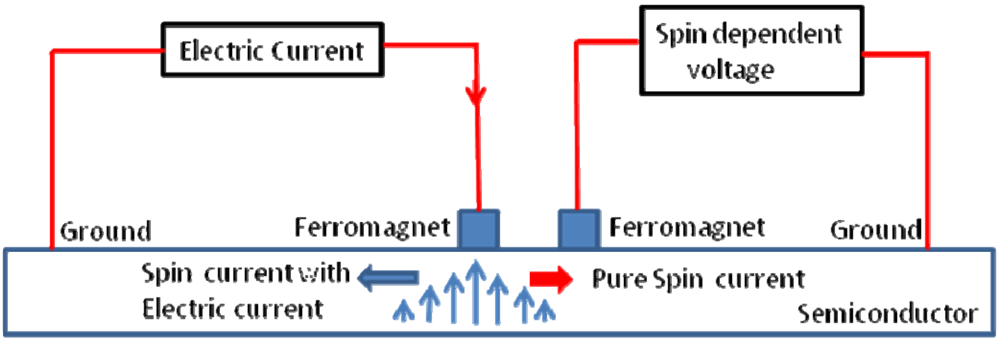


Fig. 1: A schematic diagram for electrical spin injection and detection technique.

**Essential requirements for spin injection**

In order to obtain efficient spin injection from ferromagnetic materials into semiconductor, there are several things that need to be considered. One of them is the proper choice of materials for spin injection. The preliminary focus is on the successful generation of spin current. In order to achieve this, ferromagnetic materials should exhibit high spin polarization. Transition metals such as Fe, Co, Ni etc., exhibit spin polarization below 50% [14]. Till now, there are some reports of spin injection using these materials. Half-metals are good candidates because they exhibit high spin polarization. Heusler alloys such as $Co_2MnSi$, $Co_2FeSi$ and $CrO_2$ etc. are reported to exhibit very high spin polarization [15-18]. Therefore, the spin injection using these materials is very promising for spin injection. When ferromagnetic materials are fabricated on semiconductor, generally diffusion or chemical reaction occur in the interface, which is detrimental for spin injection [19]. Therefore, non diffusive barriers are required for spin injection. One of the choices is using a thin insulating tunnel barrier. MgO, $Al_2O_3$, etc. are the common materials used for barriers. The insertion of these barriers increases the resistance-area product [20]. The resistance-area product should be kept low in order to observe the magneto-resistance effect. Thus, the thin barrier is required. The spin tunneling resistance can also be controlled by choosing a low work function ferromagnetic [21] and by controlling the doping of the semiconductor. The spin injection is also possible if ferromagnetic materials are epitaxial grown on semiconductor with high quality interface without reaction or diffusion. In this case, the Schottky barrier will form and the conductivity mismatch would not be a problem. As the spin transport is an essential part for spin propagation, the desired semiconductor for spin injection is to have long transport length and enhanced lifetime of the spins. Si is a notable superior semiconductor because of its low spin-orbit

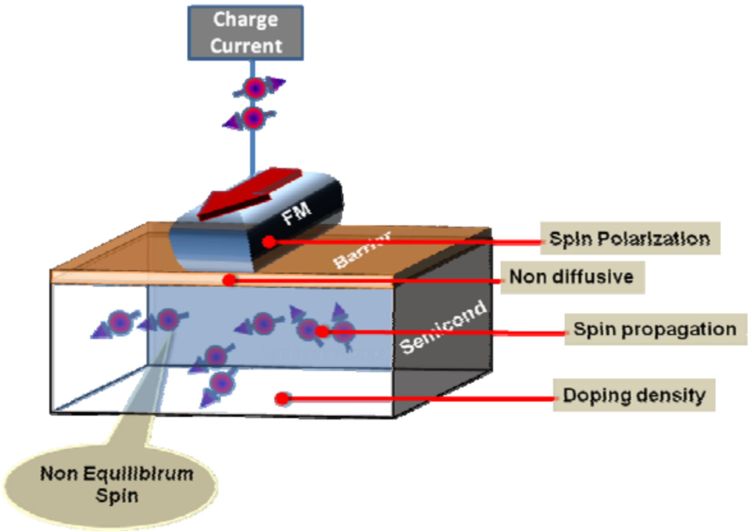


Fig. 2: The requirements for effective spin injection from ferromagnetic materials into semiconductor.

coupling and lattice inversion symmetry [5, 22]. Only problem of Si is that it is reactive. It is reported that there is strong reaction between $Co_2MnSi$ thin films grown on Si which makes a magnetic dead layer at the interface [23]. Another important thing for spin injection into semiconductor is the doping concentration of semiconductor. It is theoretically shown that the spin diffusion length decreases with the doping density [24]. Still there are not so many experiments that report the spin diffusion as a function of doping concentration. Spin propagation direction is another important factor for spin transport. It is not known yet which crystallographic direction is better for spin propagation.

**Problems and perils of spin injection:** In the early days, the spin injection into semiconductor was reported problematic due to the impedance mismatch between ferromagnetic metals and semiconductor [25]. Later on, this problem was be circumvented by the insertion of tunnel barrier [26, 27]. However, the problem is the diffusion or chemical reaction between ferromagnetic materials and semiconductors which makes a magnetic dead layer at the interface, which is detrimental for spin injection. Therefore, insulating barrier is better to use not only for conductivity mismatch but also for stopping diffusion. Spin detection is a very difficult task because the spin decays after short distance at room temperature. The high quality interface and good spin transport by choosing the appropriate material is needed for spin injection at room temperature.

**Experimental methods**

The spin current can be controlled by a physical signal (magnetic, electrical and optical, etc.). On the contrary, the physical signal can control the spin current [8]. The easiest way of spin injection is electrical injection and electrical detection technique. The semiconductor substrates should be properly cleaned by diluted HF acid, Semico clean solution and deionized water. After fabricating the ferromagnetic films on semiconductor substrate, the first step is to make the pattern. As the spin diffusion length is in very short length scale, the detector electrode should be placed very close to the injector electrode. Therefore, the e-beam lithography is suggested better to make the pattern. One of the patterns showing the contacts is illustrated in fig. 3. Two contacts are used for spin injection and the other two are for spin detection. The two contacts are far away so that it works as a ground. The other two electrodes are closely spaced less than 1μm distance away. The shape of these two electrodes should be different so that they have the difference coercivity and switches at different fields. After making a pattern, the Ar milling is to be carried out. The insulating $SiO_2$ is then deposited in order to separate the contact from the semiconductor. After that, the lift-off of the resistance should be made properly. In order to deposit top electrode, preferably photolithography is done to make the pattern of top electrode. The reactive ion etching is then used to obtain the clean surface. Finally top electrode for example Ta/Cu/Ta is to be deposited. After the lift-off of the resistance, the sample is ready for the non-local measurement. The basic principle for non- local measurements

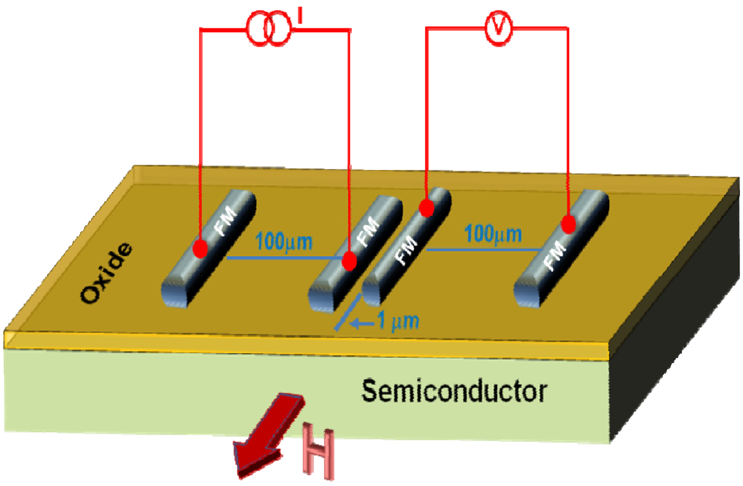


Fig. 3: A schematic diagram of non local measurement system for spin injection.

is applying the dc current and measuring the dc voltage by sweeping the magnetic field, H, from positive to the negative direction. The spin dependent voltage will be seen as a lateral spin valve.

The ac lock technique is a better choice for the non-local measurements in order to avoid the noise. In this case, the low frequency signal with dc offset is to be used and the detection will be done by the ac lock technique.

**Acknowledgments.** This paper was written within the framework of the Associateship Scheme of the Abdus Salam International Centre for Theoretical Physics, Trieste, Italy. The author greatly acknowledges the Ando Lab and Global Center of Excellence (GCOE) project of Tohoku University, Japan, for supporting this research and for discussions.

## References

[1] A. Fert, “The present and the future of spintronics”, *Thin Solid Films* **517**, 2 (2008).

[2] S.A. Wolf et al., “Spintronics: A spin-based electronics vision for the future”, *Science* **294**, 1488 (2001).

[3] S.D. Bader and S. Parkin, “Spintronics”, *Annu. Rev. Condens. Matter Phys.* **1** 3.1 (2010).

[4] J.F. Gregg, I. Petej, E. Jouguelet and C. Dennis, “Spin electronics - a review”, *J. Phys. D: Appl. Phys.* **35**, R121 (2002).

[5] I. Zutic, J. Fabian and C.D. Sarma, “Spintronics: fundamentals and applications”, *Rev. Mod. Phys.* **76**, 323 (2004).

[6] P. Sharma, “How to create a spin current”, *Science* **307**, 531 (2005).

[7] Tanaka, “Spintronics: recent progress and tomorrow’s challenges”, *J. Crystal Growth* **278**, 25 (2005).

[8] K. Takanashi, “Generation and control of spin current in magnetic nanostructures”, *AAPPS Bulletin* **18**, 47 (2008).

[9] B.K. Nikoli´c, L.P. Zˆarbo, and S. Souma, “The Oxford Handbook on Nanoscience and Technology: Frontiers and Advances," *Oxford University Press*, (2010) pp. 814.

[10] N.F. Mott, “The electrical conductivity of transition metals,” *Proc. R. Soc. London, Ser. A* **153**, 699 (1936).

[11] M. Johnson and R.H. Silsbee, “Interfacial charge-spin coupling: Injection and detection of spin magnetization in metals”, *Phys. Rev. Lett.* **55**, 1790 (1985).

[12] F.J. Jedema, A.T. Filip, and B.J. van Wees, “Electrical spin injection and accumulation at room temperature in an all-metal mesoscopic spin valve”, *Nature* **410**, 345 (2001).

[13] X. Lou et al., “Electrical detection of spin transport in lateral ferromagnet–semiconductor devices”, *Nat. Phys.* **3**, 197 (2007).

[14] P.M. Tedrow and R. Meservey, “Spin polarization of electrons tunneling from films of Fe, Co, Ni, and Gd”, *Phys. Rev. B* **7**, 318 (1973).

[15] Y. Sakuraba, J. Nakata, M. Oogane, H. Kubota, Y. Ando, A. Sakuma and T. Miyazaki, “Extremely large spin polarization in $Co_2MnSi$ based magnetic tunnel junctions”, *Jpn. J. Appl. Phys.* **44**, L1100 (2005).

[16] Y. Sakuraba, T. Miyakoshi, M. Oogane, Y. Ando, A. Sakuma and T. Miyazaki, *Appl. Phys. Lett.* **89**, 052508 (2006).

[17] S.J. Hashemifar, P. Kratzer and M. Scheffler, "Preserving the half-metallicity at the Heusler alloy $Co_2$MnSi(001) surface: a density functional theory study", *Phys. Rev. Lett.* **94**, 096402 (2005).

[18] K.A. Yates, "The spin polarization of $CrO_2$ revisited", *Appl. Phys. Lett.* **91**, 172504 (2007).

[19] M.A.I. Nahid, M. Oogane, H. Naganuma and Y. Ando, "Structural and magnetic properties of $Co_2$MnSi Heusler alloy thin films on Si", *Jpn. J. Appl. Phys.* **48**, 083002 (2009).

[20] M.A.I. Nahid, M. Oogane, H. Naganuma and Y. Ando, "The effect of MgO barrier on the structural and magnetic properties of $Co_2$MnSi films on n-Si(100) substrates", *J. Appl. Phys.* **106**, 103907 (2009).

[21] B.-C. Min, K. Motohashi, C. Lodder and R. Jansen, "Tunable spin-tunnel contacts to silicon using low-work-function ferromagnets" , *Nat. Mater.* **5**, 817 (2006).

[22] I. Zutic´, J. Fabian, and S.C. Erwin, "Spin injection and detection in silicon", Phy. Rev. Lett. **97**, 026602 (2006).

[23] M. Hashimoto, J. Herfort, T. Trampert, H.-P. Schonherr and K. H. Ploog, *J. Phys. D: Appl. Phys.* **40**, 1631 (2007).

[24] Y.B. Xu and S.M. Thompson, "Spintronic Materials and Technology", *New York: CRC Press* (2007) pp. 252.

[25] G. Schmidt, D. Ferrand, L.W. Molenkamp, A.T. Filip and B.J. van Wees, "Fundamental obstacle for electrical spin injection from a ferromagnetic metal into a diffusive semiconductor", *Phys. Rev. B* **62**, R4790 (2000).

[26] E.I. Rashba, "Theory of electrical spin injection: Tunnel contacts as a solution of the conductivity mismatch problem", *Phys. Rev. B* **62**, R16267 (2000).

[27] A. Fert and H. Jaffres, "Conditions for efficient spin injection from a ferromagnetic metal into a semiconductor", *Phys. Rev. B* **64**, 184420 (2001).