JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 10, No. 10, October 2008, p. 2487 - 2493

Review Paper

Semiconductor spintronics and its requirements

M. IDRISH MIAH[a,b]
[a]*Nanoscale Science and Technology Centre, Griffith University, Nathan, Brisbane, QLD 4111, Australia*
[b]*Department of Physics, University of Chittagong, Chittagong, Chittagong – 4331, Bangladesh.*

Requirements of the injection and detection of spin current in a semiconductor are crucial for semiconductor spintronic devices. By reviewing the potentials and the recent success and understanding, we demonstrate the techniques for the injection and detection of spin current in a semiconductor. However, as a particular emphasis is given for the electrical detection, the spin-dependent Hall effects are discussed in more details. The major obstacles and challenges in the development of such devices are also pointed out.

(Received December 4, 2007; accepted August 14, 2008)

Keywords: Spintronics, Semiconductor, Spin-dependent hall effects

1. Introduction

Conventional electronic devices rely on the electric charge of electrons, which allows the control of the current flow by electric fields; the spin (self-rotation – rotation of the electron on its axis) of the electron is ignored. However, researchers [1-15] now realize that the spin of the electrons can create a current called “spin current”, like the movement of electrons forming a charge current. The idea of using the spin of the electron in electronic devices has gained a lot of attention since the discovery of long spin lifetimes in semiconductor structures in 1997 by Kikkawa and co-workers [16], leading to the appearance of the field “spintronics”, based on the control and manipulation of electron spin instead of, or in addition to, its charge. (“Spintronics” was coined by S. A. Wolf in 1996 and appeared in scientific journals from 1999). It is generally expected that addition of a spin degree of freedom in information processing will extend the functionality of conventional devices and allow development of novel electronic devices (spintronic devices), which can hold promise of, e.g. reduced power consumption, faster operation and smaller size. Recent interest has been motivated by successful examples of metallic spintronic devices, such as ferromagnetic metal-based reading heads for hard disc drives and magnetic random access memory [17,18]. These first metallic spintronic devices, discovered in 1986, were sandwiched structures consisting of alternating ferromagnetic and nonmagnetic metal layers whose electric resistance depends strongly on the external magnetic field. Depending on the relative orientation of the magnetizations in the magnetic layers, the device conductance changes from large (parallel magnetizations) to small (antiparallel magnetizations). This change in resistance is called the giant magnetoresistance, a quantum mechanical effect in layered magnetic thin-film structures. In comparison with metal-based spintronics, utilization of semiconductors promises more versatile design due to the ability to adjust potential variation and spin polarization in the device by, e.g. external voltage and device structure.

The first semiconductor spintronic device was suggested by Datta and Das in 1990 [19], where they proposed an electronic analogue of an electro-optical modulator, that was later termed “spin field effect transistor (SPINFET)”, in a two-dimensional electron gas contacted with two ferromagnetic electrodes: one as a source for the injection of spin-polarized electrons and the other as an analyser for electron-spin polarization. The Datta-Das SPINFET device relies on the basic concept of modulating the transistor’s source-to-drain current by varying the Rashba interaction in the channel with a gate voltage. Although the proposal given by Datta and Das has been believed since then to be the most promising, it has recently been criticised by, e.g. Bandyopadhyay and Cahay [20]. They showed that in terms of common performance metrics, e.g. power dissipation, transconductance, unity gain frequency, etc., the performance projections for a Datta-Das SPINFET are below those for a conventional silicon or GaAs field-effect transistor. Although different types of semiconductor devices have recently been proposed [20-29], the actual advantages of these devices as compared to the conventional electronic devices have not been clearly established. One of the major hurdles in the development of semiconductor spintronic devices has been the problem of efficiently injecting spin-polarized carriers into a semiconductor (such that they can be transported reliably, i.e. without spin flipping or spin relaxation over reasonable distances) and then detecting them (since information is carried by the electron spin). Much effort [30-43] has thus been made towards understanding generation/ injection and detection of spin-polarized carriers or spin current in semiconductors.

In this paper, we first demonstrate the spin polarized charge current and the spin current in relation to the current in a conventional electric circuit. As the essential requirements for spintronic devices, the methods for the injection and detection of spin current in a semiconductor have been discussed. By reviewing the potentials and present success and understanding, the major barriers and challenges in the development of such devices have also been identified.

2. Spin current and charge current

In a conventional electric circuit the number of spin-up ($N_\uparrow$) and spin-down ($N_\downarrow$) electrons are the same and both species (↑,↓) of electrons move in the same direction under an external electric field (Fig. 1(a)). The total spin current $\vec{j}_s \equiv \vec{j}_\uparrow - \vec{j}_\downarrow$ is therefore zero and only the charge current $\vec{j} = \vec{j}_\uparrow + \vec{j}_\downarrow$, where $\vec{j}_\uparrow$ and $\vec{j}_\downarrow$ are the currents due to $N_\uparrow$ electrons and $N_\downarrow$ electrons respectively, is relevant. When a system, however, includes a circularly polarized optical pulse excitation or a ferromagnetic coupling (or under an external magnetic field), electron spins can be polarized so that the total spins of the system is nonzero (Fig. 1(b)). The corresponding charge current is then spin-polarized, i.e. $\vec{j}_\uparrow \neq \vec{j}_\downarrow$, although both (majority and minority spin) species of electrons move in the same direction, which gives a nonzero total spin current. As the spin current is produced by the motion of spin polarized electrons, it is typically associated with the spin-polarized charge current. A spin current without charge current (often called "pure spin current") can be obtained if one can create an ideal situation where $N_\uparrow$ electrons move to one direction while an equal number of $N_\downarrow$ electrons move to the opposite direction (Fig. 1(c)). Then the total charge current is identically zero ($\vec{j}_\uparrow + \vec{j}_\downarrow = 0$) and only a net spin current exists.

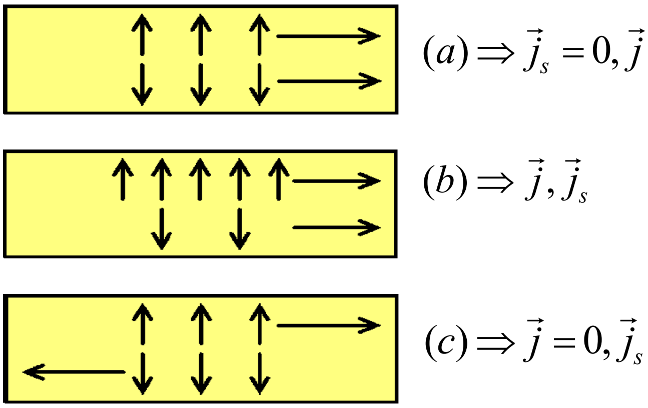

Fig. 1. Schematic representations for (a) the charge current with zero spin current (conventional electric circuit), (b) the charge current with a nonzero spin current (spin polarized charge current) and (c) the spin current with zero charge current (pure spin current).

3. Injection of spin current

Generation of spin polarization usually means creating a nonequilibrium spin population. This has been obtained mostly by ferromagnetic contacts [7,31,32,44-46]. Several attempts, for example, using ferromagnetic contacts to Si or InAs-based quantum wells (2DEG structures) have resulted in modest spin injection effects measured at 1% or even below (e.g. [44-46]). Such small effects make it difficult to either unambiguously confirm spin injection or successfully implement new device concepts. Spin flip scattering at the interface between the magnetic contact and semiconductor host appears to be the limiting factor (or due to the "conductivity mismatch", or more precisely, a mismatch between effective resistances in the metal and in the semiconductor), but very little is known about such interfacial contributions. However, generation of spin-polarized carrier populations can also be achieved by optical techniques, in which circularly polarized photons transfer their angular momenta to electrons [5,14,30,36,37].

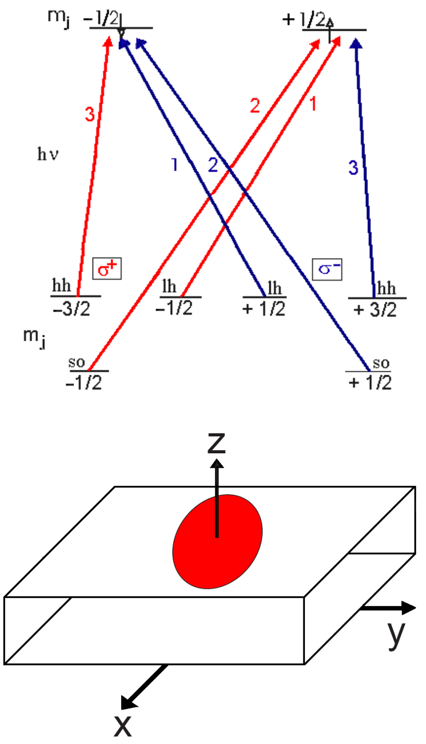

Fig. 2. Optical spin current injection ($E_g < h\nu < E_g + \Delta$). (Top) Optical selection rules for the transitions from the heavy-hole (hh) and light-hole (lh) valence bands to conduction band. The allowed transitions for σ^+ are shown by the red (blue) lines, where σ^+ (σ^-) for right (left) circularly polarized light. The numbers near the lines represent the relative transition probabilities. (Bottom) A schema showing the spin injection location and areas and the direction of spin injection for σ^- beam. For a σ^- beam excitation, $\vec{j}_\uparrow > \vec{j}_\downarrow$ or $N_\uparrow$ (along $\hat{z}$) $> N_\downarrow$ (along $-\hat{z}$), so spins are injected along $\hat{z}$ and vice versa for σ^+. The optical techniques provide control over the optical pulse duration and in locations and areas dictated by the pulse focal spot (the round red area).

It has been known [47] for nearly four decades that a spin polarized carrier population can be produced by the absorption of a monochromatic, circularly polarized light beam with photon energy above the direct band gap in a bulk semiconductor, such as GaAs. The production of a carrier population with a net spin by direct absorption of circularly polarized light is a consequence of the optical selection rules ($\triangle m_j = \pm 1$ for $\sigma^{\pm}$, where σ^{+} (σ^{-}) for right (left) circularly polarized light) for the heavy-hole (*hh*) and light-hole (*lh*) valence to conduction band transitions (Fig. 2 top). Since hole spin polarization in bulk semiconductors is known to relax in ≤100 fs, on a longer time scale one typically obtains only the electron spin polarization [26].

For a $\sigma^{\pm}$ light direct transitions from the *hh* valence band produce electrons with the opposite spin from those from the *lh* band. However, the *hh* transition in unstrained bulk GaAs is three times stronger than the *lh* band transition, leading to a 3:1 ratio of $N_{\downarrow}$ to $N_{\uparrow}$ ($N_{\uparrow}$ to $N_{\downarrow}$) conduction band electrons for σ^{+} (σ^{-}). Consequently, optical excitation with σ^{+} (σ^{-}) injects spins along the direction parallel (antiparallel) to the direction of the light propagation, i.e. along $-z$ (z) in Fig. 2 bottom, and produces an initial population of spin polarization electrons with polarization $p_0 = 50\%$ [$p = (N_{\uparrow} - N_{\downarrow})/(N_{\uparrow} + N_{\downarrow}) = \pm 0.5$ for $\sigma^{\mp}$], provided that the photon energy is in the range $E_g < h\nu < E_g + \triangle$ (where E_g is the energy gap and $\triangle$ is the spin-orbit (SO) splitting), i.e. low enough to avoid exciting carriers from the split-off band to the conduction band. Although the maximum optical spin polarization for an unstrained bulk sample is expected to be 50% in theory, the maximum is experimentally observed to be ~ 40% [47]. The reason is that in bulk samples there are usually some background unpolarized (not photo-excited) electrons. If there is a background density of unpolarized electrons N_u in the sample, the polarization would be $p_0 = 0.5/(1+N_u/N_0)$ for an optically generated electron density $N_0 = N_{\downarrow}(0) + N_{\uparrow}(0)$. Furthermore, if the degeneracy of the *hh* and *lh* valence bands is removed, for example, by quantum confinement or strain (e.g. in quantum wells) and if only the *hh* band is excited, 100% (theoretically) spin-polarized populations can be generated. A spin-polarized carrier population produced in this way will be distributed symmetrically in ***k***-space in materials with zinc-blende symmetry and consequently, there can be no net electrical current without a bias or an external electric field, even though each individual carrier may be generated initially with a large momentum when the material is excited well above the band gap. Such symmetric populations have been the subject of the work on optically generated spin polarized carries in semiconductors [5,30,43]. However, optically generated spin-polarized carrier populations have recently been dragged by an external electric field to create a spin-polarized current or spin current [1,13,14]. Although the optical spin current injection has been found to be efficient and is under well-control, the electrical spin injection is advantageous at least for some devices and needs to be established.

4. Detection of spin current

The detection of spin current in semiconductors has previously been obtained mainly through optical methods, specifically, from measurements of the differential transmission using pump-probe techniques with the same and oppositely circularly polarized pulses, or from optical Kerr rotation microscopy or from photoluminescence measurements with varying degrees of success [4,5,8,9,31,33]. However, an electrical means of detecting spin current (possibly, without magnetic field or magnetic material) is very desirable for fully exploring the possibility of utilizing spin degree of freedom and spintronic device applications.

The spin-dependent Hall effects (SDHEs), namely, the anomalous Hall effect (AHE) and the spin Hall effect (SHE) (bearing the name of Edwin H. Hall) have recently been proposed [34,35] to be useful tools for electrically detecting spin currents in paramagnetic materials or semiconductors. It was predicted that a Hall voltage, proportional to the spin current, can be generated in the material when a spin current is injected into it. It was also shown that the spin current (or the Hall voltage) has two current contributions: (i) the drift current and (ii) the diffusion current and that a way to increase the spin current (or the SDHE) for a given electric field (E) would be to use the semiconductor degenerate regime by, for example, lowering the temperature. We focus here on the SDHEs. Before going into detail of the SDHEs, it would be advantageous to discuss first the ordinary Hall effect (OHE) because the SDHEs are conceptually similar to the OHE. In the OHE, the Lorentz force (F) due to the magnetic field deflects like-charge carriers and results in transverse Hall voltage (voltage that arises from the deflected motion of charged carriers, i.e. electrons and/or holes – the absence of electrons, in solids under an external electric field and a magnetic field) due to the charge imbalance but no spin accumulation on the transverse boundaries of the sample (Fig. 3(a)).

The AHE, observed by Edwin Hall in ferromagnetic metals since only 1 year after his discovery of the OHE in 1879 [48,49], is the result of spin-dependent deflection of carrier (spin-polarized) motion, which produces a Hall voltage proportional to the spin polarization i.e. the magnetization and spin accumulation at the transverse boundaries. In the AHE, the SO coupling force (F_{SO}) deflects like-spin carriers, which causes spin imbalance as well as charge imbalance and results in Hall voltage and spin accumulation (Fig. 3(b)). Although AHE in magnetic materials has been observed for a long time, AHE has attracted recently much attention because of its close theoretical connection to the SHE and because of the rapidly growing interest in spin-dependent transport phenomena or spin transport in general [50]. In addition, AHE has been used in demonstrating the existence of a ferromagnetic state in several semimagnetic (diluted magnetic) semiconductors while searching for materials for possible applications in spintronics [51].

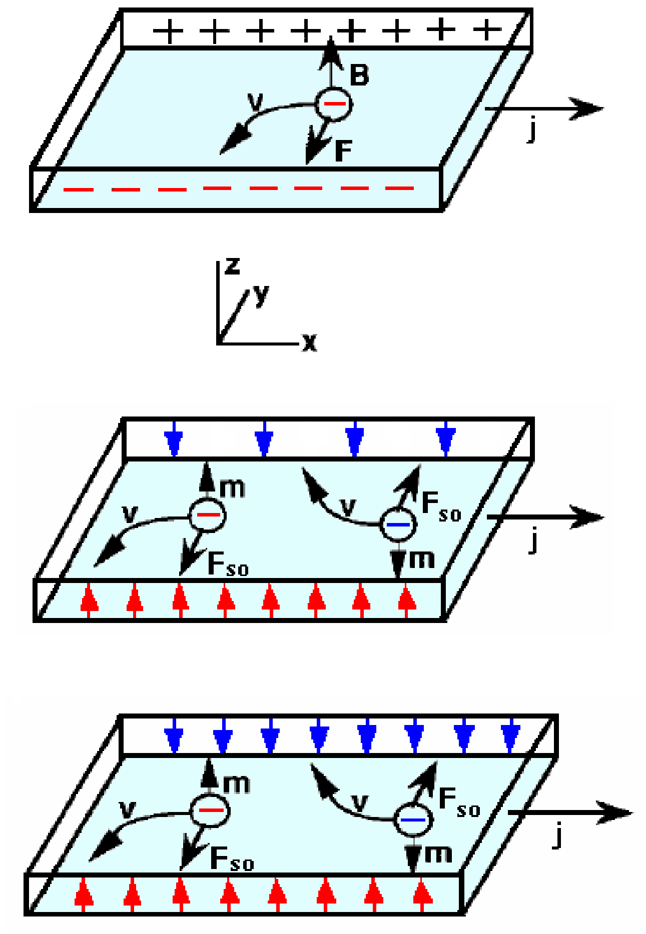

Fig. 3. (a) Hall effect (Hall voltage but no spin accumulation), (b) anomalous Hall effect (Hall voltage as well as spin accumulation) and (c) spin Hall effect (no Hall voltage but spin accumulation). In the anomalous Hall effect and spin Hall effect, carriers with same charge but opposite spin are deflected by the spin-orbit coupling to opposite sides.

The Hall resistivity (ρ_H) of ferromagnetic or magnetic materials can be expressed [52] as a sum of two terms: $\rho_H = R_{OH}B + \mu_0 R_{AH} m$, where is $R_{0\mathrm{H}} = (en_\mathrm{s})^{-1}$ is the ordinary Hall coefficient, μ_0 the permeability of the free space and R_AH the anomalous Hall coefficient. The first term (the ordinary Hall resistivity, $\rho_{0\mathrm{H}} = R_{0\mathrm{H}}B$) is due to the Lorentz force acting on the charge carriers and is present in nonmagnetic materials as well and is proportional to the magnetic field B, and inversely proportional to the charge per carrier (e) and the sheet density of carriers (n_s). The second term is the anomalous contribution and is a characteristic of the magnetic state of the material and is proportional to the magnetization m. The charge current in ferromagnets is dependent on spin (which can be either "up", ↑ or "down", ↓), and assuming Mott's two-carrier approximation [53,54], one can relate $j_{\uparrow(\downarrow)}$ to the spin-dependent resistivity $\rho_{\uparrow(\downarrow)}$ through the expression $j_{\uparrow(\downarrow)} = E/\rho_{\uparrow(\downarrow)}$, where $\rho_{\uparrow(\downarrow)}$ is the resistivity for carriers with spin ↑(↓). The spin dependence of $\rho_{\uparrow(\downarrow)}$ may be caused by spin-dependent electronic states or by spin-dependent scattering attributable to impurities or imperfections and phonons in materials. These effects manifest themselves in the Hall voltage via the SO interaction that couples spin with the orbital motion of carriers. Historically, these effects were though to results from an intrinsic effective magnetic field $B_\mathrm{eff}(\boldsymbol{k})$ in the momentum space due to the phase (curvature) called the Berry phase (curvature) acquired by the moving electron [55]. When scattering is spin-dependent, ↑ and ↓ spin electrons are scattered into opposite directions, resulting in spin ↑ and ↓ charge Hall currents along the direction perpendicular to E.

While the OHE results from the F, AHE is due to the SO coupling in the present of spin polarization. In a ferromagnetic metal, the presence of the spontaneous m leads to AHE. For a nonmagnetic semiconductor, there is no spontaneous m, so one needs to apply a magnetic field to polarize the carriers, and the effect consists of two contributions: the ordinary one (OHE) and an anomalous (AHE), as in ferromagnetic or magnetic materials. The SDHE (AHE) observed in n-doped InSb and Ge has been separated from the much larger OHE by using a spin-resonance method [56]. If one, however, can inject a spin current into a semiconductor such that it can be sustained on the required length (or time) scale, one could observe AHE. In the presence of injected spin currents, the nonmagnetic semiconductor could behave more like a ferromagnet as far as (or as long as) the transport is concerned. The SO coupling in a nonmagnetic semiconductor produces left-right asymmetric scattering of the carriers for a fixed spin orientation. The spin-up electrons, for example, tend to be scattered to the right more than to the left via skew scattering and side jump defined below. If the longitudinal current is spin-polarized, e.g. current carriers contain more spin-up electrons than spin-down electrons, there would be more electrons scattered to the right than to the left. This leads to both spin and charge accumulations in the transverse direction of the sample. The anomalous Hall voltage is precisely the measure of this net charge accumulation and is proportional to the spin current in nonmagnetic semiconductors.

Very recently, AHE has been observed in a nonmagnetic semiconductor device, fabricated on Si-doped GaAs, without magnetic field but only in the presence of circularly polarized light [13,14]. It was claimed that the device detects photo-generated spin current electrically via the measurements of the AHE in semiconductors. As the experiment was performed without magnetic field or ferromagnetic coupling, the device measured the pure anomalous Hall current ($\rho_H = \mu_0 R_{AH} m$), i.e. without any contribution from the ordinary Hall current ($R_{0\mathrm{H}}B$=0). It was found that the anomalous Hall voltage remains almost constant in electric fields within the moderate range, indicating that the electron spin preserves during drift transport in GaAs in moderate electric fields, which is very important for implementing spin-sensitive new device ideas. However, it was also found that a high field completely destroys the electron spin polarization due to an increase of the D'yakonov–Perel' (DP) [57-59] spin precession frequency of the hot electrons, suggesting that high field transport conditions might not be suitable for spintronic technology with GaAs. Since electron spins in the spin-based devices can be subject to highly nonthermal transport conditions including drift fields within a moderate range for high-speed transfer of spin information, the findings resulting from the investigation might have potential applications in spintronics. A theoretical investigation to analyse the SO mechanism responsible for the optically spin-induced AHE has also been reported [41]. In the calculation, the spatial wave functions of the spin-selective states (delocalized spin states originating from the Si-donors in gallium arsenide) were calculated using pseudopotential [60,61] in dependences on Si density and applied electric field in presence of a circularly polarized pump including anharmonic electron-phonon interactions [40].

In the SHE, the F_{SO} deflects like-spin carriers, as in the AHE, which causes only the spin imbalance and results in no Hall voltage but spin accumulation on the transverse boundaries (Fig. 3(c)). A transverse (along $\hat{y}$) z-polarized spin current following in response to an applied (along $\hat{x}$) electric field, $j^{z}_{s,y} = E / \rho_{sH}$, is referred to as the SHE and ρ_{sH} is called spin Hall resistivity. For nonmagnetic materials, although the two charge Hall currents (the Hall currents for $j_{\uparrow}$ and $j_{\downarrow}$) cancel and no Hall voltage develops, spin-dependent scattering still produces the up and down spin currents that flow in the opposite directions (the same case as is shown in Fig. 1(c)) as long as the SO interaction is nonvanishing, resulting in spin polarization of opposite signs at the boundaries even in the absence of applied magnetic fields. This effect allows for the generation, detection and control of spin current by purely electrical means, which is a great advantage when operating electronic devices. After its first prediction in 1971 by M. I. Dyakonov and V. I. Perel' [57-59] this effect has been quite rarely mentioned in literature during almost 30 years, while at the beginning of the new millennium a worldwide-band of interest to it emerged. The SHE for p-type semiconductors has been predicted by Murakami and co-workers [62]. They showed that $B_{\mathrm{eff}}(\boldsymbol{k})$ originated from the Berry phase makes ↑ and ↓ spin electrons drift toward opposite directions and leads to SHE. Sinova et al. [63] predicted a universal (independent of the strength of the SO scattering) spin Hall conductivity $\sigma_{sH} = 1/\rho_{sH} = e/(8\pi)$ for a two-dimensional electron gas with a Rashba SO interaction produced by the asymmetry of the potential. The SHE has found its experimental proof only recently (in 2004) by Kato and co-workers [9] after its theoretical rediscovery by Hirsch [35]. They spatially resolved the Kerr rotation of the reflected light from n-doped GaAs and InGaAs and found accumulation of opposite spins at the sample boundaries. Although they observed the SHE in semiconductors optically using Kerr rotation microscopy, an electrical means of detecting the effect still remains a challenge due to the difficulties associated with the absence of the Hall voltage in the SHE.

Although the mechanism of SDHEs been a subject of controversy, it is now generally accepted that SDHEs consist of the contribution due to an asymmetric "skew scattering" [64] of charge carriers, the contribution due to a "side jump" [65] that the charge carriers undergo at each scattering event (charge carrier changes its trajectory because of a lateral displacement) and the contribution not related to scattering, i.e. the intrinsic contribution, arising as a result of the band structure [66]. It means the evaluation of the intrinsic contribution does not require knowledge of the disorder or impurity present in the system. It should mention here that there are discrepancies in predictions and in size of the contributions among the theoretical research groups [10,11,64-66]. The observed SDHEs originated from the scattering mechanisms described are likely to be extrinsic. This is in contrast to the intrinsic SDHE, proposed initially (for AHE) by Karplus and Luttinger [67] and predicted recently by others [68-70], which is entirely due to coupling terms in the single particle spin-orbit Hamiltonian and independent of any scattering process, which means there may exist an intrinsic SDHE arising as a result of the band structure even in the absence of scattering.

As the SDHEs have great importance in spintronics, in particular, for the generation, control and detection of spin current in semiconductors, a clear understanding the nature of the SDHEs is now the emerging issue for experimentalists as well as theorists. More sophisticated experiments toward all-electrical spintronic devices (similar to the SPINFET) using controllable parameters, such as device structure or gate voltage, able to combine spin injection and detection are needed. Such device and control strategies for realizing new high-performance devices taking advantage of the electron spin as well as of its charge might open the way to establish the semiconductor systems for spintronics in the near future.

5. Conclusions

Starting from a demonstration of the spin current in relation to the conventional charge current, we reviewed the recent success and understanding on the injection and detection of spin current in a semiconductor. The SDHEs in relation to the techniques of the generation, control and electrical detection of spin current were discussed. The major hurdles and challenges in the development of semiconductor spintronic devices and possible topics on further directions were also discussed.

References

[1] J. Kikkawa, D.D. Awschalom, Nature **397**, 139 (1999).

[2] S. D. Sarma, Am. Sci. **89**, 516 (2001).
[3] S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnar, M. L. Roukes, A. Y. Chtchelkanova, D. M. Treger, Science **294**, 1488 (2001).
[4] S. D. Sarma, R. de Sousa, X.Hu, and B.Koiller, Solid State Commun. **133**, 737 (2005)
[5] D. D. Awschalom, D. Loss, and N. Samarth, Eds., Semiconductor Spintronics and Quantum Computation (Springer, Berlin, 2002).
[6] S. D. Sarma, J. Fabian, X. Hu, I. Žutić, Solid State Communic. **119**, 207, 2001. Phys. Rev. B. **62**, 8180 (2000).
[7] H. - A. Engel, P. Recher, and D. Loss, Solid State Commun. 119, 229 (2001).
[8] I. Žutić, J. Fabian, and S. D. Sarma, Rev. Mod. Phys. **76**, 323 (2004).
[9] Y. K. Kato, R. C. Myers, A. C. Gossard, D. D. Awschalom, Science **306**, 1910 (2004).
[10] H.–A. Engel, B.I. Halperin, and E.I. Rashba, Phys. Rev. Lett. **95**, 166605 (2005).
[11] W.- K. Tse, D. S. Sarma, Phys. Rev. Lett. **96**, 056601 (2006).
[12] Y. Kato, R.C. Myers, A.C. Gossard, D.D. Awschalom, Nature, **427**, 50 (2004).
[13] M. I. Miah, Mater. Lett. **60**, 2863 (2006)
[14] M. I. Miah, J. Phys. D: Appl. Phys. **40**, 1659 (2007).
[15] M. I. Miah, J. Phys. D: Appl. Phys. (press).
[16] J. M. Kikkawa, I. P. Smorchkova, N. Samarth, D.D. Awschalom, Science **277**, 1284 (1997).
[17] G. Prinz, Phys. Today 48, 58 (1995).
[18] P. P. Freitas, S. Cardos, R. Sousa, W. Ku, R. Ferreira, V. Chu, J. P. Conde, IEEE Transac. Magn. **36**, 2796, (2000).
[19] S. Datta, B. Das, Appl. Phys. Lett. **56**, 665 (1990).
[20] S. Bandyopadhyay, M. Cahay, Appl. Phys. Lett. **85**, 1433 (2004).
[21] B. Wang, J. Wang, H. Guo, Phys. Rev. B **67**, 092408 (2003).
[22] S. Zhang, J. Appl. Phys. 89, 7564 (2001).
[23] V. V. Osipov, A. Bratkovsky, Appl. Phys. Lett. 84, 2118 (2004).
[24] A. Bratkovsky, V. V. Osipov, Phys. Rev. Lett. 92, 098302 (2004).
[25] M. I. Miah, E. M. Gray, Solid State Sci. (press).
[26] I. Žutić, J. Fabian, S. D. Sarma, Phys. Rev. Lett. 88, 066603 (2002).
[27] Z. G. Yu, M. E. Flatté, Phys. Rev. B **66**, 201202 (2002).
[28] Y. V. Pershin, V. Privman, Phys. Rev. Lett. **90**, 256602 (2003).
[29] Y. V. Pershin, Phys. Rev. B **68**, 233309 (2003).
[30] R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, L. W. Molenkamp, Nature **402**, 787 (1999).
[31] M. Oestreich, J. Hübner, D. Hägele, P. J. Klar, W. Heimbrodt, W. W. Rühle, D. E. Ashenford, and B. Lunn, Appl. Phys. Lett. **74**, 1251 (1999).
[32] M. Ramsteiner, H. Y. Hao, A. Kawaharazuka, H. J. Zhu, M. Kästner, R. Hey, L. Däweritz, H. T. Grahn, K. H. Ploog, Phys. Rev. B **66**, 081304-1 (2002).
[33] B. T. Jonker, Y. D. Park, B. R. Bennet, H. D. Cheong, G. Kioseoglou, A. Petrou, Phys. Rev B **62**, 8180 (2000).
[34] S. Zhang, Phys. Rev. Lett. **85**, 393 (2000).
[35] J. E. Hirsch, Phys. Rev. Lett. **83**, 1834 (1999).
[36] Y. K. Kato, R. C. Myers, A. C. Gossard, and D. D. Awschalom, Phys. Rev. Lett. **93**, 176601 (2004).
[37] H. Sanada, I. Arata, Y. Ohno, Z. Chen, K. Kayanuma, Y. Oka, F. Matsukura, H. Ohno, Appl. Phys. Lett. **81**, 2788 (2002).
[38] J. M. Kikkawa, D.D. Awschalom, Phys. Rev. Lett. **80**, 4313 (1998).
[39] J. A. C. Bland, A. Hirohata, X. Yong-Bing, C. M. Guertler, S. N. Holmes, IEEE Transac. Magnet. **36**, 2827 (2000).
[40] M. I. Miah, Opt. Mater. **29**, 845 (2007).
[41] M. I. Miah, I. V. Kityk, E. M. Gray, Acta Mater. 55, 6392 (2007).
[42] H. Dery, L. J. Sham. Phys. Rev. Lett. 98, 046602 (2007).
[43] O. D. D. Couto, Jr., F. Iikawa, J. Rudolph, R. Hey, P. V. Santos, Phys. Rev. Lett. **98**, 036603 (2007).
[44] Y. Q. Jia, R. C. Shi, and S. Y. Chou,, IEEE Trans. Magn. **32**, 4707 (1996).
[45] P. R. Hammer, B. R. Bennett, M. J. Yang, and M. Johnson, Phys. Rev. Lett. 83, 203 (1999).
[46] S. Gardelis, C. G. Smith, C. H. W. Barnes, E. H. Linfield, D. A. Ritchie, Phys. Rev. B **60**, 7764 (1999).
[47] D. T. Pierce, F. Meier, Phys. Rev. B. **13**, 5484, 1976.
[48] E. H. Hall, Am. J. Math. **2**, 287 (1879).
[49] E. H. Hall, Philos. Mag. 12, 157 (1881).
[50] A. Gerber, A. Milner, M. Karpovsky, B. Lemke, H. – U. Habermeier, J. Tuaillon-Combes, M. Négrier, O. Boisron, P. Mélinon, **A**. Perez , J. Magn. Magn. Mater. **242**, 90, (2002).
[51] F. Matsukura, H. Ohno, T. Dietl, in Handbook on Magnetic Materials, K. H. J. Buschow, Eds. (Elsevier Science, Amsterdam, 2003).
[52] C. L. Chien, and C. R. Westgate, Eds., The Hall Effect and Its Applications (Plenum, New York, 1980).
[53] N. F. Mott, Proc. R. Soc. London Ser. A **153**, 699 (1936).
[54] N. F. Mott, Proc. R. Soc. London Ser. A **156**, 368 (1936).
[55] M. V. Berry, Proc. Roy. Soc. A **392**, 45 (1984).
[56] J. - N. Chazalviel, Phys. Rev. B **11**, 3918 (1975).
[57] M. I. D'yakonov, V. I. Perel', Zh. Eksp. Teor. Fiz. **60**, 1954 (1971).
[58] M. I. D'yakonov, V. I. Perel', Phys. Lett. A **35**, 459 (1971).
[59] G. E. Pikus, A. N. Titkov, in Optical Orientation, Modern Problems in Condensed Matter Science, Vol. 8 (edited by F. Meier and B. P. Zakharchenya, North-Holland, Amsterdam, 1984).
[60] G. B. Bachelet, D. R. Hamann, and M. Schluter, Phys. Rev. B **26**, 4199 (1982).

[61] I. V. Kityk, and B. Andriyewskii, Phys. Status Solidi. V **188B**, 711 (1995).
[62] S. Murakami, N. Nagaosa, and S.-C. Zhang, Phys. Rev. Lett. **93**, 156804 (2004).
[63] J. Sinova, D. Culcer, Q. Niu, N. A. Sinitsyn, T. Jungwirth, A. H. MacDonald, Phys. Rev. Lett. **92**, 126603 (2004).
[64] J. - N. Chazalviel, I. Solomon, Phys. Rev. Lett. **29**, 1676 (1972).
[65] L. Berger, Phys. Rev. B **5**, 1862 (1972).
[66] N. A. Sinitsyn, A. H. MacDonald, T. Jungwirth, V. K. Dugaev, J. Sinova, Preprint cond-mat/0608682 (2006).
[67] R. Karplus, J. M. Luttinger, Phys. Rev. **95**, 1154 (1954).
[68] S. Murakami, N. Nagaosa, S.-C. Zhang, Science **301**, 1348 (2003).
[69] R. Mathieu, A. Asamitsu, H. Yamada, K. S. Takahashi, M. Kawasaki, Z. Fang, N. Nagaosa, Y. Tokura, Phys. Rev. Lett. **93**, 016602 (2004).
[70] S. Onoda, N. Sugimoto, N. Nagaosa, Phys. Rev. Lett. **97**, 126602 (2006).

---

[*] Corresponding author: m.miah@griffith.edu.au