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Spintronics/Spintronique

Spin injection into semiconductors: towards a semiconductor-based spintronic device

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Abstract

Spin electronic or *spintronics* is a rapidly growing research field aimed at realizing new high-performance devices that takes advantage of the electron spin as well as of its charge. It is expected that the extension of spintronics to the semiconductors would lead to the development of a new class of functional devices. To do so, the mechanisms at the origin of spin injection and collection with the semiconductors have to be studied first. The aim of this article is to summarize the main results that have been obtained recently in this field. ***To cite this article: A. Bsiesy, C. R. Physique 6 (2005).***

Résumé

Injection du spin dans des semi-conducteurs : vers un composant spintronique basé sur des semi-conducteurs. L'électronique de spin ou la « *spintronique* » est un domaine de recherche qui connaît une forte évolution grâce aux nombreuses applications qui sont soient déjà mises en œuvre dans des composants disponibles sur le marché ou en cours de développement. L'extension de la spintronique aux semiconducteurs présente des perspectives d'applications très prometteuses grâce à la possibilité d'associer spintronique et électronique conventionnelle. Ceci passe par une étude fondamentale des mécanismes d'injection et de collection de spins dans les semi-conducteurs. L'objectif de cet article est de faire le point sur les principaux résultats obtenus dans ce domaine. ***Pour citer cet article : A. Bsiesy, C. R. Physique 6 (2005).***

Keywords: Spintronics; Semiconductors; Spin injection; Spin collection

Mots-clés : Spintronique ; Semi-conducteur ; Injection de spin ; Collection de spin

1. Introduction

The use of electron spin in semiconductors is concentrating important research effort [1] motivated by promising applications of semiconductor-based *spintronic* devices [2]. Indeed, semiconductors can potentially allow the combination of the spin degree of freedom with the classical charge degree of freedom. This may make it possible to realize new functionalities inaccessible thanks to the semiconductors unique features. More precisely, semiconductors are known to have long spin diffusion length compared to transition metals [3,4]. They also allow information exchange between polarized light and spin polarization and can make it possible to take advantage of spin coherence effects related to quantification in quantum wells and dots. The

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spin transistor concept, which utilizes two ferromagnetic layers as a spin injector and a spin analyzer, illustrates well the potential ability of semiconductor-based spintronics to enhance the performances of integrated circuits. For example, a single spin transistor can potentially be used as a non-volatile cell memory where the binary data is stored by the magnetization of one of the ferromagnetic electrodes. This can lead to applications in the areas of ultra-high density storage and non-volatile reconfigurable logic [5,6]. However, the control of spin injection into semiconductors at room temperature has revealed a major obstacle towards the realization of spintronic devices. The aim of this article is to summarize the outcome of some major studies performed in this field in an attempt to underline the research axis that might be followed in pursuing the realization of semiconductor-based spintronic devices.

2. SpinFET concept

Research aimed at developing semiconductor-based spintronic device have been initiated by the spin field effect transistor theoretical concept (spin FET), first proposed by Datta and Das [7]. This concept is based on the possibility of electric control over the electron spin besides the classical electron charge control. The basic idea is to induce a rotation of the electronic spins travelling inside a semiconductor by applying an external voltage. To demonstrate the idea, the authors propose to use a classical HEMT (High Electron Mobility Transistor) structure but having a ferromagnet source and drain electrodes in order to inject polarised electrons and to collect them selectively. The collection selectivity is determined by the angle between of the spins orientation and drain magnetization. Indeed, when the rotated electron spins are anti-aligned to the drain magnetization the drain current is expected to show a minimum value. This effect would lead to a gate voltage-controlled drain current modulation. According to this proposal, the spin rotation control can be obtained via the so-called Rashba spin-orbit coupling taking place at the interface between the 2DEG (two-dimensional electron gas) of the HEMT layer and a potential barrier. Indeed, this structural asymmetry leads to a potential gradient that induces an effective magnetic field at the origin of the spin-orbit interaction.

A number of groups have made inconclusive attempts to demonstrate the Datta and Das spinFET concept [8–11]. Indeed, a very low magnetoresistance of about 0.2% has been obtained, when the source and drain magnetizations orientations were switched from parallel to anti-parallel. The interpretation of such low magnetoresistance levels is complicated by possible contributions of the anisotropic magnetoresistance or Hall effect. The absence of appreciable magnetoresistance signal in the Data and Das spin FET may be attributed to either inefficient spin injection/collection or to important spin dephasing upon diffusion in the semiconductor. However, it was shown that the spin diffusion length can be fairly long in III–V semiconductors, in the order of 100 µm in GaAs [4]. This oriented the research effort on the spin injection issue at the ferromagnet metal/semiconductor hybrid system. Even though enhanced interfacial resistance change of the order of 1% have been observed [12,13] in this system upon reversing magnetisation orientation, some doubt persisted on whether this can evidence spin injection. For example, Hammar et al. [13] have reported the observation of electrical spin injection from permalloy in a two dimensional electron gas (2DEG), by projecting the spin-polarized current in the ferromagnet onto the spin-split density of states at the high mobility 2DEG. The Rashba spin-orbit interaction was used in order to obtain the conduction band spin-splitting that can be reversed by switching the current flow direction in the 2DEG. They have observed a relative change in the interfacial resistance of about 1% that they attributed to spin injection. However, this work has been commented upon and it was suggested that the observed behaviour might be related to a local Hall effect [14].

The first successful spin injection into semiconductors using all-solid structures were obtained with diluted magnetic semiconductors (DMS) as spin injectors towards III–V light emitting diode made of a heterostructure based on gallium arsenide [15,16]. Spin polarization of the injected carriers was determined directly from the polarization of the emitted electroluminescence following radiative recombination with (unpolarized) carriers provided by the substrate. Injected current spin polarization of up to 90% were observed [16]. However, only operations at very low temperatures have been demonstrated since the available DMS become ferromagnetic only at low temperature, e.g., $T_c < 110$ K for (Ga,Mn)As [15,17].

Since room temperature DMS are still to be demonstrated, the metal ferromagnet remains the only credible spin injector candidate for practical semiconductor spintronic device. However, by investigating experimentally and theoretically the spin injection in the metal/semiconductor system and on the basis of earlier studies of spin diffusive transport in the system [18], Schmidt et al. [19] concluded to the impossibility of electrical spin injection into semiconductors using partially-polarized metal ferromagnets. They argued that the origin of this intrinsic obstacle lies in the large conductivity difference between the two materials. Indeed, they showed that the effectiveness of the spin injection across ideal ferromagnetic/non ferromagnetic (FM/NFM) contact depends on the ratio of the conductivities of the FM and NFM electrodes, σ_F and σ_N respectively. When the NFM electrode is a semiconductor, then spin-injection efficiency from a ferromagnet metal will be very low since $\sigma_N \ll \sigma_F$ in this case. In order to overcome this intrinsic problem, Rashba [20] and Fert et al. [21] have simultaneously and independently suggested the use of a tunnel barrier between the ferromagnet and the semiconductor. They argued that since this tunnel barrier supports a difference in electrochemical potential between spin up and spin down bands, it would allow circumventing the constraint of the ferromagnet/semiconductor *mismatched* conductivity. In fact, the necessity to have tunnel barrier for efficient spin injection was first invoked by Prins et al. [22] who studied spin collection efficiency on $Co/Al_2O_3/GaAs$ tunnel junction and on Co/τ-MnAs/AlAs/GaAs junction. It has been found that spin dependent tunnelling current was obtained only in the former structure.

Following the papers of Schmidt et al. [19], Rashba [20] and Fert et al. [21], a number of groups used the ferromagnet/tunnel barrier/semiconductor system and were able to demonstrate efficient spin injection even at room temperature. To do so, a thin dielectric tunnel barrier was inserted between the ferromagnet and the semiconductor. However, efficient spin injection was also reported using tunnelling at the ferromagnet/semiconductor Schottky contacts. In this case, tunnelling takes place across the depleted space charge region at the semiconductor/ferromagnet interface. The following section will summarize the major results obtained in this field.

3. Electrical spin injection investigation by spin-polarized light emitting diodes

The studies on spin injection efficiency were performed by using III–V-based light-emitting diodes in which spin polarized carriers injected from the ferromagnet undergoes radiative recombination. If these carriers retain their spin polarization, the emitted light is circularly polarized. The quantum selection rules which describe the radiative recombination process provide a direct and fundamental link between the circular polarization of the light emitted perpendicularly to the LED surface P_{circ} and the spin polarization of the electrically injected carriers P_{spin} [23]. This direct relation can be illustrated in the case of (Al,Ga)As/GaAs LED, largely used as a spin injection efficiency detector. Fig. 1 represents the radiative recombinations that can take place in a GaAs quantum well according to the electronic radiative transition selection rules.

When the conduction band states are occupied by injected electrons of one spin orientation only, for example by $+1/2$ injected spins, then according to the selection rules for radiative transitions which impose a change in the magnetic quantum number of $\Delta m_j = \pm 1$, only two transitions are possible: one heavy-hole transition (from $+1/2$ to $+3/2$) and one light hole transition (from $+1/2$ to $-1/2$). The heavy-hole transition is circularly polarized in one direction called σ^+ whereas the light-hole transition is circularly polarized in the opposite direction called σ^-. The heavy-hole transition matrix element is a factor of 3 larger than that of the light-hole transition [24], and therefore, the emitted light will be circularly polarized in the σ^+ direction. In the general case where both types of spin are injected the degree of polarization of P_{opt} will be given by:

$$P_{\text{opt}} = \frac{(3n^{\uparrow} + n^{\downarrow}) - (3n^{\downarrow} + n^{\uparrow})}{(3n^{\uparrow} + n^{\downarrow}) + (3n^{\downarrow} + n^{\uparrow})}$$

in which $n^{\uparrow}$ and $n^{\downarrow}$ are the electrons population of $+1/2$ and $-1/2$ levels respectively. This equation connects the circular polarization of the emitted electroluminescence to the injected current polarization degree, i.e., $I_{\text{pol}} = (I^{\uparrow} - I^{\downarrow})/(I^{\uparrow} + I^{\downarrow})$. The spin LED thus provides a *quantitative* and *model independent* measure of electrical spin injection from any given contact.

Table 1 summarizes the major results obtained on the optical investigation of electrical spin injection from metal ferromagnets into semiconductors. For the sake of comparison, results obtained by using magnetic semiconductors as spin injectors are also included in Table 1.

4. Investigation of spin collection

While a number of studies investigated spin-polarized electron injection into semiconductors as has been reported previously in this paper, few efforts concentrated on spin collection. In earlier experiments, spin detection has been investigated only by using spin-polarized scanning tunneling microscopic technique [31,32]. However, a viable spintronic device should be an all-solid one in which spin injection and spin collection are performed electrically. There are mainly two papers on $Py/Al_2O_3/GaAs$

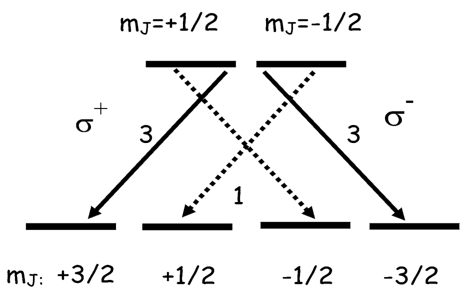

Fig. 1. Allowed conduction band-valence band transitions in GaAs quantum well according to electronic radiative transition selection rules. The transition matrix element of heavy-hole transitions is a factor of three higher than for light-hole transition.

Table 1
Summary of major results on optical investigation of electrical spin injection

Authors	Spin injector	Spin detector	Spin current polarization (%)	Operation temperature (K)
H.J.Zhu et al. (2001) [25]	Fe/GaAs Schottky contact	(In,Ga)As/GaAs	2	300
A.T. Hanbicki et al. (2002) [26]	Fe/AlGaAs Schottky contact	(Al,Ga)As/GaAs	30	240
V.F. Motsnyi et al. (2002) [27]	CoFe/Al_2O_3/AlGaAs MIS diode	(Al,Ga)As/GaAs	9	80
M. Ramsteiner et al. (2002) [28]	MnAs/GaAs Schottky contact	(In,Ga)As/GaAs	6	80
V.F. Motsnyi et al. (2003) [29]	CoFe/Al_2O_3/AlGaAs MIS diode	(Al,Ga)As/GaAs	16	300
A.Kawaharazuka et al. (2004) [30]	Fe_3Si/GaAs Schottky contact	(In,Ga)As/GaAs	10	25
Y. Ohno et al. (1999) [15]	GaMnAs	(In,Ga)As/GaAs	~ 2	6
R. Fiederling et al. (1999) [16]	BeMnZnSe	(Al,Ga)As/GaAs	90	5

[33] or Py/GaAs [34] structures used to investigate spin collection. In both studies, spin-polarized electrons were excited in the GaAs by circularly polarized light and collected by the biased permalloy electrode. An applied external field was used to saturate the permalloy magnetization along the plane normal, parallel to the induced helicity. Spin collection can thus be studied by analyzing the change in the helicity-dependent photocurrent when the magnetization is driven perpendicular to the permalloy plane. Any effect of the helicity asymmetry on the photo-induced current can be attributed to spin-dependent collection without interference with the magnetic circular dichroism effect that can be take place in the ferromagnet layer. Indeed, the permalloy has almost zero magnetic circular dechroism at the vicinity of the GaAs band gap where maximum influence of helicity asymmetry on the photocurrent is expected [33].

In the work reported by Hirohata et al. [34] on permalloy grown on GaAs by molecular beam epitaxy, helicity-dependent photocurrent has been evidenced at room temperature. This result strongly suggests efficient spin-dependent injection from GaAs to permalloy which presumably take place by tunneling across the space charge region at the semiconductor/ferromagnet interface. Helicity-dependent photocurrent asymmetry of up to 20% has thus been observed depending on the orientation of the ferromagnet magnetization with respect to the helicity.

In contrast, Manago et al. [33], who worked on Py/Al_2O_3/GaAs structures, concluded on the absence of helicity effect on the observed photocurrent in spite of high quality dielectric tunnel barriers used in the study. This negative result can be attributed to the existence of surface states at the GaAs/Insulator interface where spin-polarized electrons can be trapped before tunneling through the barrier. If the trapping lifetime is longer than the spin relaxation time, no spin-dependent tunneling should be expected. This interface spin relaxation effect has been thoroughly discussed by Prins et al. [22] and Jansen et al. [35]. These observations indicate the necessity to reduce the density of surface states. Note that in the case of Hirohata et al. [34] interface states do not come into play since tunneling takes place from GaAs bulk state toward the permalloy layer.

5. Outlook

Efficient spin injection and spin collection have been separately demonstrated in structures involving semiconductors at room temperature. Research should now be oriented towards an all-electrical spintronic device able to combine spin injection and detection in a manner similar to the initial Data and Das research. However, in a first stage, it is unnecessary to include spin manipulation by the Rashba effect since performing successful spin injection and collection represents in itself a major challenge. In the absence of the need for spin manipulation, one should think of employing column-IV semiconductors such as silicon and germanium that have weaker spin-orbit interaction and hence higher spin diffusion length, compared to the III–V semiconductors. This would ease some technological constraints since no high electron mobility channel is needed. Besides, successful demonstration of silicon-based spintronic device will more easily pave the way towards its integration in the integrated devices mainstream technology. Research on spin injection and detection in silicon are currently conducted [36]. Given the intense work on spin injection into semiconductors and the recent breakthroughs in this field, there is no doubt that demonstrating semiconductor-based spintronic device is only a matter of time.

References

[1] Special issue: Semiconductor Spintronics, guest Editor Hideo Ohno, Semicond. Sci. Technol. 17 (4) (2002).
[2] 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 (5546) (2001) 1488–1495.
[3] D. Hagele, M. Oestreich, W.W. Ruhle, N. Nestle, K. Eberl, Appl. Phys. Lett. 73 (1998) 1580–1602.
[4] J.M. Kikkawa, D.D. Awschalom, Nature 397 (6715) (1999) 139–141.
[5] S. Sugahara, M. Tanaka, in: Extended Abstracts of the Ninth Symposium on the Physics and Applications of Spin-Related Phenomena in Semiconductors, Tokyo, June 2003, p. 221.
[6] T. Matsuno, S. Sugahara, M. Tanaka, in: Extended Abstracts of the Ninth Symposium on the Physics and Applications of Spin-Related Phenomena in Semiconductors, Tokyo, June 2003, p. 225.
[7] S. Datta, B. Das, Appl. Phys. Lett. 56 (7) (1990) 665.
[8] W.Y. Lee, S. Gardelis, B.C. Choi, Y.B. Xu, C.G. Smith, C.H.W. Barnes, D.A. Ritchie, E.H. Linfield, A.C. Bland, J. Appl. Phys. 85 (1999) 6682.
[9] S. Gardelis, C.G. Smith, C.H.W. Barnes, E.H. Linfield, D.A. Ritchie, Phys. Rev. B 60 (1999) 7764.
[10] A.T. Filip, B.H. Hoving, F.J. Jedema, B.J. van Wees, Phys. Rev. B 62 (15) (2000) 9996.
[11] C.M. Hu, J. Nitta, A. Jensen, J.B. Hansen, H. Takayanagi, Phys. Rev. B 63 (2001) 125333.
[12] Y.Q. Jia, R.C. Shi, S.Y. Chou, IEEE Trans. Magn. 32 (1996) 4707.
[13] P.R. Hammar, B.R. Bennett, M.J. Yang, M. Johnson, Phys. Rev. Lett. 83 (1999) 203.
[14] F.G. Monzon, H.X. Tang, M.L. Roukes, Phys. Rev. Lett. 84 (2000) 5022.
[15] Y. Ohno, D.K. Young, B. Beschoten, F. Matsukura, H. Ohno, D.D. Awschalom, Nature 402 (1999) 790.
[16] R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, L.W. Molenkamp, Nature 402 (1999) 787.
[17] S. Ghosh, P. Bhattacharya, Appl. Phys. Lett. 80 (2002) 658.
[18] P.C. van Son, H. van Kempen, P. Wyder, Phys. Rev. Lett. 58 (1987) 2271.
[19] G. Schmidt, D. Ferrand, L.W. Molenkamp, A.T. Filip, B.J. van Wees, Phys. Rev. B 62 (2000) R4790.
[20] E. Rashba, Phys. Rev. B 62 (2000), 16267(R).
[21] A. Fert, H. Jaffrès, Phys. Rev. B 64 (2001) 184420.
[22] M.W.J. Prins, H. van Kempen, H. van Leuken, R.A. de Groot, W. Van Roy, J. De Boeck, J. Phys.: Condens. Matter 7 (1995) 9449.
[23] F. Meier, B.P. Zachachrenya, Optical Orientation, North-Holland, Amsterdam, 1984.
[24] C. Weisbuch, B. Vinter, Quantum Semiconductor Structures—Fundamentals and Applications, Academic Press, Boston, 1991.
[25] H.J. Zhu, M. Ramsteiner, H. Kostial, M. Wassermeier, H.P. Schönherr, K.H. Ploog, Phys. Rev. Lett. 87 (2001) 016601.
[26] A.T. Hanbicki, B.T. Jonker, G. Itskos, G. Kioseoglou, A. Petrou, Appl. Phys. Lett. 80 (2002) 1240.
[27] V.F. Motsnyi, J. De Boeck, J. Das, W. Van Roy, G. Borghs, E. Goovaerts, V.I. Safarov, Appl. Phys. Lett. 81 (2002) 265.
[28] 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 (2002), 081304(R).
[29] V.F. Motsnyi, P. Van Dorpe, W. Van Roy, E. Goovaerts, V.I. Safarov, G. Borghs, J. De Boeck, Phys. Rev. B 68 (2003) 245319.
[30] A. Kawaharazuka, M. Ramsteiner, J. Herfort, H.-P. Schönherr, H. Kostial, K.H. Ploog, Appl. Phys. Lett. 85 (2004) 3492.
[31] Y. Suzuki, W. Nabhan, R. Shinohara, K. Yamaguchi, T. Katayama, J. Magn. Mater. 198 (1999) 540.
[32] K. Sueoka, K. Mukasa, K. Hayakawa, Jpn. J. Appl. Phys. 32 (1993) 2989, Part 1.
[33] T. Manago, Y. Suzuki, E. Tamura, J. Appl. Phys. 91 (2002) 10130.
[34] A. Hirohata, Y.B. Xu, C.M. Guertler, J.A.C. Bland, S.N. Holmes, Phys. Rev. B 63 (2001) 104425.
[35] R. Jansen, M.W.J. Prins, H. van Kempen, Phys. Rev. B 57 (1998) 4033.
[36] C. Duluard, A. Bsiesy, A. Filipe, A. Francinelli, H. Achard, V.I. Safarov, Mater. Sci. Eng. B (2005), in press.