International Journal of Nanotechnology and Applications
ISSN 0973-631X Volume 19, Number 1 (2025), pp. 1-9

http://www.ripublication.com

Spin precession mechanism and control of the electron-hole spin exchange coupling: dynamics of the spin physics

M. I. Miah[1, 2]

[1]*Department of Physics, University of Chittagong, Chittagong 4331, Bangladesh.*
[2]*Queensland Micro- and Nano-Technology Centre, Griffith University, Nathan, QLD 4111, Australia.*

Abstract:

The electric-field control of the electron-hole spin exchange coupling in gallium arsenide (GaAs) quantum wells (QWs) is investigated by time-resolved photoluminescence measurements. The circularly polarized light induced spin polarization (P_σ) is studied in dependences of the electric and magnetic field fields. The P_σ is found to decay and oscillate with different frequencies for different strengths of the electric and magnetic fields. However, there is no spin oscillation in the absence of these fields. The spin control strategy and the role of the electric field in the breakage of the exchange coupling between the electron and hole spins are explored. This study, however, demonstrates the control dynamics of the spin physics in QWs.

Keywords: Spin transport; Spin relaxation; Spin current; Semiconductors

1. Introduction

Spintronics or magnetoelectronics is the modern aspect of electronics in which, in addition to the charge of the carriers, the spin is a highly considering factor. This approach to electronics is emerging that is based on the spin sates (up and down spins) of the carriers rather than on carriers (electrons of holes) as in traditional electronics [1-5]. This field was initiated the studies of Baibich et al [6] and Binasch et al [7] who showed that a system of alternating ferromagnetic and nonmagnetic metal interlayers, with appropriate construction and an applied magnetic field, could change an electrical resistance from small (with parallel magnetizations) to large (with antiparallel magnetizations) and the changes could be large enough to be called a giant magnetoresistance (GMR) and to drive a spin-sensitive magnetic device. The GMR effect found its way to computer applications when IBM incorporated a magnetic device known as a ‘spin-valve’ into the read-head of hard disks. It allowed the ‘write/read’ head to be made smaller and the storage density on hard disks to be increased from 10^6 bits/cm^2 in 1988 to more than a thousand times in a decade. This spin technology (the metallic part of spintronics, or metallic sprntronics) was established after the discovery of GMR by Albert Fert and Peter Grünberg (They jointly got the Novel Prize in 2007).

The underlying fundamental physics (so-called spin physics) of such applications is the spin-dependent transport and interactions, and spin-correlated behavior of many- or multi-electron systems. Spintronics is now a multidisciplinary field involving physics, chemistry, materials science and engineering and has widely been studied [2,4,5] in the semiconductor bulks. Semiconductor spintronics has a huge potential of applications and devices, as semiconductors have more flexibility of controlling both charge and spin. From a vast and rapidly increasing literature, we select examples to indicate some recent and relevant interests. However, for the pioneering efforts, we focus on the theoretical prediction [8] and later experimental confirmation [9] that magnetic properties (the arrangement of electron spins and spin-effects) of a reduced dimensional system, such two-dimensional ultra thin films (or wells), one-dimensional wires and zero-dimensional dots, differs from the bulk.

Spin polarization in bulk GaAs and its two-dimensional systems or quantum wells (QWs) has been studied by time-resolved photoluminescence (PL). The PL polarization was used to directly measure the spin relaxation time in the samples [10-13]. Optically detected magnetic resonance in a finite magnetic field was used to study the excitons in type-II GaAs/AlAs QWs, where the spectra were analysed using the spin Hamiltonian for the quasi-two-dimensional indirect excitons [14,15]. Potoexcited carrier transport and excitonic energy in quantum dots (QDs) was studied in Ref. [16]. CdSe/CdS nanostructures were also studied for this purpose [17-18] In the earlier investigation, we studied the excitonic spin dynamics in semiconductor QWs [19,20]. Here, in the present investigation, we study the spin dynamics and electric-field control of the electron-hole spin exchange coupling in gallium arsenide QWs. The spin polarization (P_σ), generated by a circularly polarized light, is studied in dependences of the strength of the electric and magnetic field fields. The P_σ is found to decay and oscillate in electric and magnetic fields. However, in absence of these fields the spin oscillation is not observed. The spin control dynamics and the role of the electric field in the breakage of the exchange coupling between the electron and hole spins are explored. On the basis of the electron-hole coupling the results are discussed.

2. **Experimental**

Samples grown on the *n*-type doped GaAs substrate using the MBE growth technique were GaAs double QWs separated by an 15-nm $Al_{0.3}Ga_{0.7}As$ barrier. For the application of the negative external electric field normal to the heretostructure layers, the top surface of the sample was coated with a semitransparent gold electrode. The magnetic field was applied in the Voigt configuration, i.e. normal to the sample. The sample was mounted in a chip-carrier of the liquid helium temperature-regulated cryostat. We measured PL excited by circularly polarized (using a quarter wave plate) ps pulses of a tunable Ti:sapphire laser with a repetition rate of 76 MHz using a streak camera. According to the spin generation scheme based on optical selection rules, depicted in Fig. 1, transition probability from the heavy-hole (HH) states to the conduction band (CB) is three times larger than from the LH states. As the LH transition generates opposite spins, the optical excitation produces a 3:1 ratio of to spin-up to spin-down CB electrons for a left (right) circularly polarized light $\sigma^-(\sigma^+)$ provided that the photon energy is low enough to avoid exciting carriers from the split-off band. If $N_\uparrow$($N_\downarrow$) is the number of electrons with spin up (down), the degree of spin (P) polarization is calculated from

$$P_\sigma(\vec{r},t) = \frac{N_\uparrow(\vec{r},t) - N_\downarrow(\vec{r},t)}{N_\uparrow(\vec{r},t) + N_\downarrow(\vec{r},t)} \ , \qquad \textbf{(1)}$$

which gives a maximum (3+1)/(3-1)=0.5 or 50% spin polarization P_σ in bulk semiconductors. As in a QW the degeneracy of HH and LH valence bands is removed by the strain, optical excitation of the HH band produces a maximum P_σ= 1. Optical excitation with a σ^+(σ^-) orients spins along the direction parallel (antiparallel) to the direction of the light propagation, i.e. along $-z$ ($+z$) in the Fig. 1. The PL was excited directly to the exciton absorption band and was detected with the small long-wavelength shift to minimize the polarization losses. The PL was measured in the right and left circularly polarizations under the right circularly light excitation in the presence of external bias and magnetic field. The degree of spin polarization P_σ was calculated using the relation

$$P_\sigma(\Delta t) = \frac{I_{\sigma^+}(\Delta t) - I_{\sigma^-}(\Delta t)}{I_{\sigma^+}(\Delta t) + I_{\sigma^-}(\Delta t)} \, , \qquad \textbf{(2)}$$

where $I_{\sigma^+}(I_{\sigma^-})$ is the PL intensity of σ^+ (σ^-) light under the σ^+ light excitation. The P_σ was measured in the presence of the combined electric and magnetic fields and at various field strengths. A schematic representation of the experimental setup is also shown in Fig. 1.

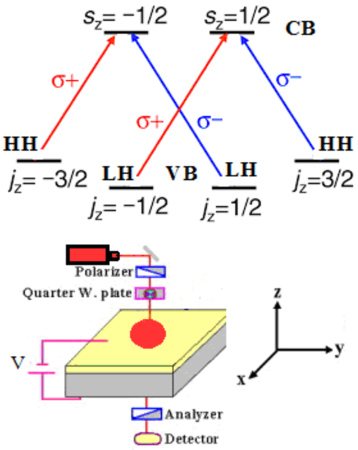

Figure 1: Energy levels of the heavy-hole (HH), light-hole (LH) bands of GaAs and optical transitions between conduction band (CB) and HH and LH valence band (VB). In QW, the degeneracy of HH and LH valence bands is removed by the strain. Optical excitation of the HH band of the QW with a right (left) circularly polarized light σ^+(σ^-) orients spins along the direction parallel (antiparallel) to the direction of the light propagation, i.e. along *-z* (+*z*). A schematic representation of the experimental setup (bottom).

3. **Results and Discussion**

The spin polarization P_σ in $Al_{0.3}Ga_{0.7}As$ QWs was studied in dependence of the strength of the electric and magnetic fields. Figure 2 shows that P_σ decays with the decay constant and spin oscillation frequency in the absence or presence of an electric field, but a magnetic field with strength of 4 T.

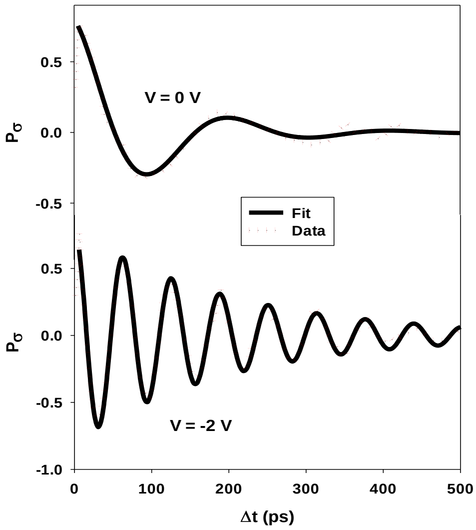

Figure 2: Spin polarization decays with the decay constant and spin oscillation frequency in the absence or presence of an electric field.

In a QW, the degree of spin polarization P_σ permitted by the optical selection rule is 1 or 100%. P_σ is also 1 when only the majority spin-carriers are there ($N_\downarrow = 0$), which is a case in ferromagnetic half metals or Heusler alloys. If the majority and minority spin-carriers are equal ($N_\uparrow = N_\downarrow$), $P_\sigma = 0$ (in e.g. nonmagnetic semiconductors and paramagnetic or normal metals). The case or situation is considered as a system of randomly oriented spins. In a QW, $P_\sigma = \pm 1$ and so the single species ($N_\uparrow / N_\downarrow$) spin polarization P_σ should oscillate between +1 to -1 in the absence of decay [21]. However, $P_\sigma = 1$ or 100% spin polarization has not yet been observed in QWs by any research group, or in any experiment.

As can be seen, in the absence of the electric field P_σ decays rapidly with time. However, in the presence of an applied bias, the electric field reduces the electron-hole exchange coupling by spatially separating the charges, and as a result, the interaction of the hole spin with phonons becomes stronger than the exchange interaction. This leads to breakage of the coupling between the electron and hole spins. In the presence of the electric field, P_σ shows distinct oscillations symmetric with respect to the horizontal axis [22,23]. An analysis of the polarization dynamics in the transverse magnetic field gives an additional evidence for the exchange interaction suppression in an external electric field. In the absence of the bias, there involves only the behavior of the exciton spin as a whole. The magnetic field mixes the excitonic states, and as a result, the right circularly polarized light becomes capable of exciting several states [24,25]. The dynamics of the polarized PL is controlled here by the interference of the states of the exciton fine structure split by the combined action of the magnetic field and exchange coupling governed by the external electric field [26]. For the higher field strengths, the P_σ varies in time in a rather complicated fashion of the PL polarization kinetics, reflecting superposition of the beats at several frequencies. In the presence of the bias, the hole spin rapidly relaxes, and thus the electronic spin freely precesses around the magnetic field orientation. The application of the bias to the samples weakens the exchange interaction between the electron and hole spins. The P_σ also found to decay with the strength of the magnetic field B and with different decay constant and spin oscillation. The spin oscillates with the the Larmor frequency $\omega = g_e \mu_B B / \hbar$, where μ_B is the Bohr magneton, g_e is the electron-g factor and $\hbar = h / 2\pi$ is the reduced Planck constant [27].

The spin oscillation frequency (ω) and the polarization decay (δ) as a function of the strength of the magnetic field were obtained from fittings to the experimental data of the time dependent polarization by the exponentially damping harmonic oscillating function [21]

$$P_\sigma = P_{\sigma 0} \cos \omega t \exp(-t / \delta) . \qquad \textbf{(3)}$$

The obtained results are presented in Figs. 3 and 4. As can be seen, the spin oscillation or precession frequency increases linearly with increasing the strength of the electric field and with magnetic fields, while δ decreases with increasing magnetic field. The linear fits to the data of Fig. 4 gives the transverse electron *g*-factor for the respective electric field. The zero-field, however, corresponds to the HH *g*-factor.

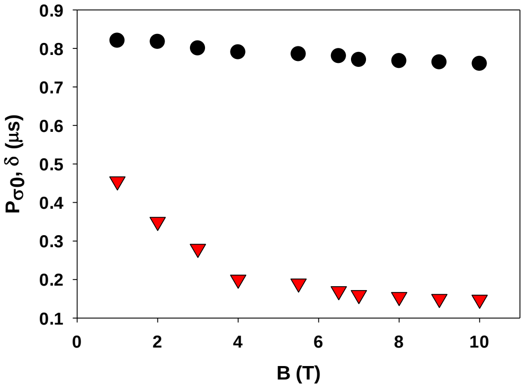

Figure 3: Initial spin polarization (circle) and polarization decay constant (triangle) as a function of the magnetic field.

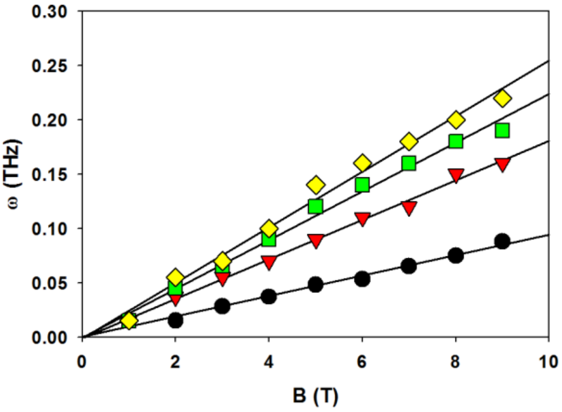

Figure 4: Spin oscillation frequency as a function of magnetic field for different strength of the electric field: 0 V (circle), -1 V (triangle), -2 V (square) and -3 V (diamond).

Figure 3 also shows the magnetic field dependence of the initial polarization, defined as $P_{\sigma 0} = P_{\sigma}$ (Δt=0), where it can be seen that a maximum $P\sigma_0$ of 0.82 is obtained for the low magnetic field and that the initial spin polarization slightly decreases with increasing the strength of the magnetic field. The decrease of polarization with field might be due to the increased spin precession or oscillation frequency of the electrons. The observed polarization decays correspond to the spin dephasing and relaxation in the QWs for the transverse magnetic fields and are due to the bias-induced reduction of the electron–hole exchange coupling, resulting in a stronger interaction of the hole spin with phonons than the electron–hole exchange interaction. Spin polarization with no electric and magnetic fields is shown in Fig. 5. As can be seen, the polarization decays, but there is no spin oscillation (ω =0) in the process. The results agrees well with those obtained in other observations [28,29]. However, the polarization degrades with the time. This might be due to randomization of the initial spin polarization by the Dyakonov-Perel (DP) spin relaxation mechanism [30]. The DP mechanism is due to SO coupling in semiconductors with an effective magnetic field originated from the SO interaction.

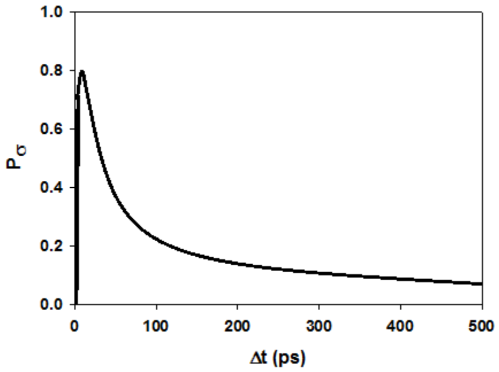

Figure 5: Spin polarization with no electric and magnetic fields. There is a decay of polarization decay, but no oscillation (ω =0) in the process.

4. **Conclusions**

We studied the spin dynamics and electric-field control of the electron-hole spin exchange coupling in gallium arsenide QWs. The optically generated spin polarization was studied in dependences of the strength of the electric and magnetic field fields. The spin polarization was found to decay and oscillate with different frequencies for different electric and magnetic fields. However, the spin oscillation was not observed in the absence of these fields. The spin control dynamics and the role of the electric field in the breakage of the exchange coupling between the electron and hole spins were explored. The results are discussed. This spin control strategy in semiconductor QWs could be useful in spin physics, and spintronic applications and devices.

Conflicts of interest

The author declares no conflicts of interest.

References

[1] G. A. Prinz, Science **282**, 1660 (1998).

[2] M. I. Dyakonov and A. V. Khaetskii, Spin Hall Effect (Spin Physics in Semiconductors, M. I. Dyakonov, Ed., Springer-Verlag, Berlin, 2008).

[3] Spin Electronics, M. Ziese and M. J. Thornton, Eds., Vol. 569, Springer–Verlag, Heidelberg, 2001.

[4] Semiconductor Spintronics and Quantum Computation, D.D. Awschalom, D.Loss, and N. Samarth, Eds., Springer, Berlin, 2002.

[5] M. I. Miah, J. Optoelectron. Adv. Mater. **10**, 2487 (2008).

[6] M. N. Biabich, J. M. Broto, A. Fert, F. Petroff, P. Etienne, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988).

[7] G. Binasch, P. Grunberg, F. Saurenbach, and W. Zinn, Phys. Rev. B. **39**, 4828 (1989).

[8] L. Valenta, Phys. Stat. Solidi **2**, 112 (1962).

[9] A. Fert, G. Guntherodt, B. Heinrich, E. E. Marinero, and M. Maurer, Eds (1991), Magnetic thin films, multilayers and superlattices, Elsevier, North-Holand.

[10] R. J. Seymour and R. R. Alfano, Appl. Phys. Lett. **37**, 231 (1980).

[11] J. Wagner, H. Schneider, D. Richards, A. Fischer, and K. Ploog, Phys. Rev. B **47**, 4786 (1993).

[12] T. Endo, K. Sueoka, and K. Mukasa, Jpn. J. Appl. Phys. **39**, 397 (2000).

[13] H. Gotok, H. Ando, H. Kamada, A. Chavez-Pirson, and J. Temmyo, Appl. Phys. Lett. **72**, 1341 (1998).

[14] S. Cortez, O. Krebs, S. Laurent, M. Senes, X. Marie, P. Voisin, R. Ferreira, O. Bastard, J.-M. Gerard, and T. Amand, Phys. Rev. Lett. **89**, 207401 (2002).

[15] H. W. van Kesteren, E. C. Cosman, W. A. J. A. van der Poel, and C. T. Foxon, Phys. Rev. **B 41**, 5283 (1990).

[16] S. P. Dash, S. Sharma, R. S. Patel, M. P. de Jong, and R. Jansen, Nature **462**, 491 (2009).

[17] F. Feng, L. T. Nguyen, M. Nasilowski, B. Nadal, B. Dubertrel, L. Coolen, and Maitre, Nano Res. **11**, 3593 (2018).

[18] F. Feng, L. T. Nguyen, M. Nasilowski, B. Nadal, B. Dubertrel, A. Maitre, and L. Coolen, ACS Photonics **5**, 1994 (2018).

[19] M. I. Miah, Opt. Photon. Lett. **6**, 1350005 (2013).

[20] M. I. Miah, Optoelectron. Lett. **16**, 0318 (2020).

[21] G. E. Pikus and A. N. Titkov, In Optical Orientation (Modern Problems inCondensed Matter Science, Vol. **8**, North-Holland, Amsterdam, 1984).

[22] E. L. Ivchenko and A. A. Kiselev, Sov. Phys. Semicond. **26**, 827 (1992).

[23] G. Lampel and C. Weisbuch, Solid State Commun. **16**, 877 (1975).

[24] E. O. Kane, J. Phys. Chem. Solids **1**, 249 (1957).

[25] V. K. Kalevich, B. P. Zakharchchenya, K. V. Kavokin, A. V. Petrov, P. Le Jeune, X. Marie, D. Robart, T. Amand, J. Barrau, and M. Brouseau, Phys. Solid State **39**, 681 (1997).

[26] M. I. Miah, Bull. Mater. Sci. **38**, 1329 (2015).

[27] N. G. Khlebtsov, L. A. Trachuk, and A. G. Mel’nikov, Opt. Spectros**. 98**, 77(2005).

[28] E. G. Barbagiovanni, D. J. Lockwood, P. J. Simpson, and L. V. Goncharova, Appl. Phys. Rev. **1**, 011302 (2014).

[29] J. M. Kikkawa, and D. D. Awschalom, Phys. Rev. Lett. **80**, 4313 (1998).

[30] M. I. D’yakonov, and V. I. Perel’, Phys. Lett. A 35, 459 (1971).