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# Spintronics in semiconductors

Z. WILAMOWSKI*, A. M. WERPACHOWSKA

Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668 Warsaw, Poland

In the last years, spin effects in semiconductors have been of great interest not only in the context of solid state physics, but also for their potential use in technology. In this paper, we give a short review of spintronic materials, in which electron spin is exploited as an additional degree of freedom. Afterwards, we discuss the properties of classic, non-magnetic semiconductors, where efforts are put into enriching traditional semiconductor technology by engaging the electrical effects of spin effects. Various phenomena and scientific state of the art is highlighted.

Key words: *spintronics, semiconductor; spin-orbit coupling; spin current*

## 1. Introduction

Next to the electron charge, the electron spin corresponds to an additional degree of freedom, which could be used for information storage and processing. To control electron and spin states, one has to measure different physical quantities. Electrical properties are characterized by electrical conductivity, carrier mobility, voltage profile and electrical current, while spin properties are characterized by magnetization, magnetic resonance frequencies, and spin relaxation rates. There are also different tools that can be used to manipulate electron charge and spin states. Electronic devices are controlled predominantly by applying voltages, while to manipulate a spin state one has to use magnetic field. In contrast to voltages, magnetic field cannot be applied locally. For these reasons, spintronics needs sophisticated solutions for the various classes of spintronic materials. In this paper, we discuss the properties of novel spintronic materials and classic, non-magnetic semiconductors, and the possibility of their use in electronic devices.

## 2. Magnetic materials

Ferromagnetic metals owe their great career as spintronic materials to the spin effects they display. The most popular in practical applications are giant magnetoresis-

*Corresponding author, e-mail: wilamz@ifpan.edu.pl

tance and tunnel magnetoresistance in devices built of ferromagnetic metals. The resistance of layered structures depends on the mutual orientations of magnetization in neighbouring layers. Such elements are already commonly applied as reader heads for magnetic memories. The weak spot of ferromagnetic metals is that it is hard to modify their properties with applied electric field.

The possibility of changing physical properties with the applied electric field is the feature of semiconducting materials. Materials of the greatest interest to technology are diluted magnetic semiconductors (DMS). To make a typical DMS, such as (Cd,Mn)Te, we need to substitute a part of the diamagnetic atoms in a classic semiconductor with atoms of a transition metal [1]. Such a highly diluted material is paramagnetic. In the absence of external field, DMS acts like a semiconductor. The application of external field results in a strong spin splitting of the conduction and valence bands. The origin of spin splitting is the exchange coupling sp–d between delocalised carriers and core spins.

The most characteristic feature of DMS is a giant spin splitting, which increases the spin polarization of carriers (usually present in small numbers). It is easy to achieve 100% polarization in laboratory conditions. Since the onset of spintronics, there have been attempts to use this property of DMS to build spintronic elements. The first idea was to build a giant magnetoresistance (GMR) structure. Attempts to build a hybrid ferromagnetic metal–semiconductor–ferromagnetic metal structure failed, due to the fact that small semiconductor conductance suppresses the spin current [2], but enhances spin accumulation.

Efforts to inject spins from semi-magnetic semiconductors, however, were much more successful. As Fiederling at al. [3] have shown, the injection efficiency from DMS to GaAs is near 100%. Spin polarization was estimated from the circular polarization ratio of GaAs. It is also possible to build spin transistors [4] based on DMS.

Increasing carrier concentration in DMS may lead to the appearance of ferromagnetic phase. Given sufficiently large band filling, not only do local spins cause the spin polarization of carriers, but conversely, the polarized carrier band may, through the same p–d exchange, cause the polarization of local spins. Munekata and Ohno [5–8] gave the first evidence of ferromagnetism in (In,Mn)As and (Ga,Mn)As materials. The first theoretical description is attributed to Dietl [6].

(Ga,Mn)As is a canonical semiconductor. The critical temperature of currently manufactured layers exceeds 170 K, and the alloy retains all semiconducting properties. The electrical control of ferromagnetism is possible. In particular, the critical temperature can be changed by applying electric field [6, 7]. (Ga,Mn)As is also a very good source of polarized electrons, which allows spins to be injected into normal semiconductors [8]. Due to spontaneous magnetization in ferromagnets, it is not necessary to apply external magnetic field in order to achieve a stream of spin-polarized carriers. Structures similar to the GMR structures built on (Ga,Mn)As show very large magnetoresistance [9] and tunnel anisotropic magnetoresistance [10]. In the tunnelling transport regime, magnetoresitance exceeds 2000%. Yamanouchi et al. demonstrated that current controls domain wall motion [11]. Astakhov et al. [12] demonstrated spin switching between two metastable magnetization states in materials that possess uniaxial anisotropy. It may be induced not only by applying magnetic field, but also by a laser pulse [13, 14].

## 3. Spin in classic semiconductors

In non-magnetic metals and semiconductors, magnetism plays a secondary role. Due to the Pauli principle, the equal filling of up and down spin subbands leads to the cancellation of magnetic momenta. In external magnetic field, a weak carrier magnetization appears, but the Pauli susceptibility is very low. In most metals and semiconductors, the dependence of electrical properties on spin properties is negligible. The connection between electrical and magnetic properties is visible only in exceptional cases. One of them is the dependence of the resistance of two-dimensional electron gas on its spin polarization. The only mechanism linking electrical and magnetic properties is the existence of spin-orbit coupling, which leads to a band spin splitting.

The zero field splitting of spin subbands occurs only in semiconductor structures with sufficiently low symmetry. In general, there is a distinction between the Dresselhaus field [15] and the Rashba field [16, 17]. Spin splitting is equivalent to an effective spin-orbit field. The Dresselhaus field is the consequence of the lack of crystal inversion symmetry. It occurs, e.g. in zinc blend structures, i.e. in all II–VI and III–V semiconductor compounds, but it is forbidden by symmetry conditions in bulk silicon. The Bychkov–Rashba field is the consequence of the lack of mirror symmetry in 2D structures. It also occurs in silicon 2D structures. The direction of the spin-orbit field, $H_{so}$, is perpendicular to the carrier **k**-vector. In the case of the Bychkov–Rashba field, it is oriented in-plane. Generally, the inversion of the **k**-vector leads to the inversion of $H_{so}$. As a consequence, in thermal equilibrium the sum of all spin-orbit fields acting on a carrier system vanishes. It follows that most spintronic effects (dependent on both magnetic and electrical properties) vanish in thermal equilibrium. Therefore, we need to search for phenomena engaging both spin and electron properties only in systems in thermodynamic non-equilibrium. Below we shall review the class of spin effects induced by electron current, namely spin Hall, spin manipulation by electrical current, and the class of spin photovoltaic effects.

When electric current is applied and the Fermi sphere is moved from the centre, the total spin-orbit (SO) field acting on the ensemble of electron spins is not zero anymore. Electron spins begin a precession and the tendency to create additional spin polarization appears. Both effects are diminished by spin relaxation. When the frequency of the RF current is much higher than the spin relaxation rate, however, spin polarization is not affected by electric current and the effective RF magnetic field is the main consequence of the current. As has been demonstrated by Wilamowski and Jantsch [18], such an SO field can play the role of a microwave magnetic field, leading to an additional resonance absorption. As a consequence, three different ESR signals are observed in a 2D electron gas: classic absorption caused by the magnetic component of the microwave field, the SO field caused by electric current, and an additional, so-called polarization signal, resulting from the change in electrical conductivity under resonance conditions. This effect reflects the dependence of the conductivity of high-mobility 2D electrons on spin polarization and allows for electrical measurements of spin structure.

When a DC or low frequency current is applied to a semiconducting layered structure, two additional processes have to be considered: the possible precession of spin polarization around the total magnetic field, including the effective SO field, and spin relaxation leading to an additional spin polarization caused by the SO field. The interference of these effect leads to the spin Hall effect [19–22]. Spin accumulation at the edges of non-magnetic semiconducting samples has been demonstrated experimentally [19, 20]. The effect can also occur in the absence of any external magnetic field, reflecting its intrinsic character and indicating that the SO field is responsible for the effect.

Since in a 2D electron gas the SO field is oriented only in-plane, the resulting magnetization is oriented the same way. Moreover, the spin polarizations of individual electrons are parallel to individual SO fields. Thus, such a SO field does not cause any precession that would lead to a perpendicular component of carrier magnetization, which seems to be a necessary condition for the Hall effect. For these reasons, modelling of spin Hall effect requires the simultaneous discussion of momentum scattering, which allows the SO field and spin directions to be tilted, and of spin precession and relaxation, which could lead to a perpendicular component of carrier magnetization [21, 22].

It is well known that circularly polarized light, due to spin dependent transition probabilities, causes the spin polarization of excitons and carrier spins. The occurrence of spin polarization means that up and down spin sub-bands are differently occupied. Consequently, the Fermi **k**-vectors for up and down spins are different. For symmetry reasons, however, spin polarization not only does not lead to any macroscopic current, but to symmetry changes when external magnetic field is additionally applied. As has been shown by Ganichev et al. [23, 24], sample illumination leads to an electric current. Such a spin galvanic effect (the Hanle effect) is ruled by a velocity and spin-dependent momentum relaxation and by the precession of magnetization in an external magnetic field. The complex direction dependence of the Dresselhaus SO field results in a complex dependence of the spin galvanic effect on the direction of light illumination, and of the magnetic field on crystallographic directions [24].

Also, the reversed galvanic effect has been observed. In this case, the electric current causes non-equilibrium spin polarization. The idea of such an effect was proposed by Edelstein 15 years ago [25]. Experimental evidence was presented in 2004 by Silov et al. [26], who showed that for the proper experimental geometry the electric current results in circular photoluminescence. Kato el al. [27] also established current-induced spin polarization predictions by measuring Faraday rotation.

## 4. Summary

To summarise, the present fast development of spintronics shows that spintronic elements can be built of not only magnetic materials such as ferromagnetic metals or ferromagnetic semiconductors. A wide spectrum of spintronic effects can also be found in classic, non-magnetic semiconductors.

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## References

[1] FURDYNA J.K., J. Appl. Phys., 64 (1988), R29.
[2] SCHMIDT G., RICHTER G., GRABS P., GOULD C., FERRAND D., MOLENKAMP L.W., Phys. Rev. Lett., 87 (2001), 227203.
[3] FIEDERLING R., KEIM M., REUSCHER R., OSSAU W., SCHMIDT G., WAAG A., MOLENKAMP L.W., cond-mat/0302477 (2003).
[4] ZUTIC I., FABIAN J., DAS SARMA S., Rev. Mod. Phys., 76 (2004), 323.
[5] MUNEKATA H., OHNO H., VON MOLNAR S., SEGMÜLLER A., CHANG L.L., ESAKI L., Phys. Rev. Lett., 63 (1989), 1849.
[6] DIETL T., OHNO H., MATSUKURA F., Phys. Rev. B, 63 (2001), 195205.
[7] OHNO H., CHIBA D., MATSUKURA F., OMIYA T., ABE E., DIETL T., OHNO Y., OHTANI N., Nature, 408 (2000), 994.
[8] OHNO Y., YOUNG D.K., BESCHOTEN B., MATSUKURA F., OHNO H., AWSCHALOM D.D., Nature, 402 (1999), 790.
[9] RÜSTER C., BORZENKO T., GOULD C., SCHMIDT G., MOLANKAMP L.W., LIU X., WOJTOWICZ T.J., FURDYNA J.K., YU Z.G., FLATTÉ M.E., Phys. Rev. Lett., 91 (2003), 216602.
[10] GOULD C., RÜSTER C., JUNGWIRTH T., GIRGIS E., SCHOTT G.M., GIRRAUD R., BRUNNER K., SCHMIDT G., MOLENKAMP L.W., Phys. Rev. Lett., 93 (2004), 117203.
[11] YAMANOUCHI M., CHIBA D., MATSUKURA F., OHNO H., Nature, 428 (2004), 539.
[12] ASTAKHOV G.V., KIMEL A.V., SCHOTT G.M., TSVETKOV A.A., KIRILYUK A., YAKOVLEV D.R., KARCZEWSKI G., OSSAU W., SCHMIDT G., MOLENKAMP L.W., RASING TH., Appl. Phys. Lett., 86 (2005), 152506.
[13] TANG H.X., KAWAKAMI R.K., AWSCHALOM D.D., ROUKES M.L., Phys. Rev. Lett., 90 (2003), 107201.
[14] WELP U., VLASKO-VLASOW V.K., LIU X., FURDYNA J.K., WOJTOWICZ T., Phys. Rev. Lett., 90 (2003), 167206.
[15] DRESSELHAUS G., Phys. Rev., 100 (1955), 580.
[16] RASHBA E.I., Fiz. Tverd. Tela (Leningrad) 2 (1969), 1224 (Sov. Phys. Solid State, 2 (1960), 1109).
[17] BYCHKOV YU.L., RASHBA E.I., J. Phys. C, 17 (1984), 6039.
[18] WILAMOWSKI Z., JANTSCH W., Phys. Rev. B, 69 (2004), 035328.
[19] NIKOLIC B.K., SOUMA S., ZARBO L.P., SINOVA J., cond-mat/0412595 (2004).
[20] KATO Y.K., MYERS R.C., GOSSARD A.C., AWSCHASLOM D.D., Science, 306 (2004), 1910.
[21] SINOVA J., CULCER D., NIU Q., SINITSYN N.A., JUNGWIRTH T., MACDONALD A.H., Phys. Rev. Lett., 92 (2004), 126603.
[22] HANKIEWICZ E.M., MOLENKAMP L.W., JUNGWIRTH T., SINOVA J., Phys. Rev. B, 70 (2004), 241301 R.
[23] GANICHEV S.D., IVCHENKO E.L., BEL'KOV V.V., TARASENKO S.A., SELLINGER M., WEISS D., WEGSCHEIDER W., PRETTL W., Nature, 417 (2002), 153.

[24] GANICHEV S.D., BEL'KOV V.V., GOLUB L.E., IVCHENKO E.L., SCHNEIDER P., GIGLBERGER S., EROMS J., DE BOECK J., BORGHS G., WEGSCHEIDER W., WEISS D., PRETTL W.. Phys. Rev. Lett., 92 (2004), 256601.
[25] EDELSTEIN V.M., Sol. State. Comm., 73 (1990), 233.
[26] SILOV A.YU., BLIANOV P.A., WOLTER J.H., HEY R., PLOG K.H., AVIERKIEV N.S., Appl. Phys. Lett., 85 (2004), 5929.
[27] KATO Y., MYERS R.C., MYERS A.C., GOSSRD A.C., AWSCHALOM D.D., Phys. Rev. Lett., 93 (2004), 176601.

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