SPIN-POLARIZED ELECTRONS IN THE ELECTRONICS OF THE FUTURE
(A review)

V.G. DOROGAN, F.V. MOTSNYI

V.Lashkaryov Institute of Semiconductor Physics, Nat. Acad. Sci. of Ukraine
(45, Nauky Ave., Kyiv 03028, Ukraine; e-mail: fv_motsnyi@isp.kiev.ua)

UDC 621.38

An attempt to analyze experimental and theoretical achievements in a new area of science, spintronics, has been made. Such issues as the optical alignment of spins, spin relaxation, the Hanle effect, the phenomena of giant and tunnel magnetoresistance, the spin injection problem, spin-polarized transport, devices on the basis of spin-polarized electrons, the basics of quantum computers, and perspective materials for spintronics have been considered.

Introduction

The discovery of the transistor effect by J. Bardeen, V. Brattain, and V. Shockley in the middle of the 20-th century caused a revolution in electronics and gave a push to the rapid development of microelectronics. Owing to sound achievements in this area of science and technique, a personal computer became nowadays a reliable assistant to the man in different spheres of his activity. It is practically indispensable in the functioning of modern scientific and educational institutions, industrial enterprises and design offices, various establishments and bureaus.

The rapid development of mobile communication, computer networks, and multimedia requires the enhancement of the data access rate, acceleration of information accumulation, and solutions of involved multipurpose problems. Semiconductor integrated circuits serve as the basis for the data processing and their short-term storage, whereas magnetic materials are used for the long-term storage of large arrays of information. While the information in integrated circuits is transferred by the electron charge, it is accumulated in magnetic devices due to the electron spin. Both the charge and spin of an electron have been used till now independently, separately, although their combination, as will be shown below, can considerably expand the functionalities of electronic devices. The opportunity for an electron to be in two spin states ("spin-up" or "spin-down") and a small time of the electron transition between them allow these states to be considered as 1 or 0 in the binary logic [1]. The science that is based on the application of the electron spin is called spintronics and has been developing extremely rapidly for last years [2,3]. This is confirmed by numerous publications of theoretical and applied character, as well as by materials of the conference on spintronics in Boston, USA (2002).

In order to deal with spin-polarized electrons, i.e. electrons with identically oriented spins, in a device, they must first be injected into a working space or created directly there in some way. Aligned carriers are usually injected into a semiconductor from ferromagnetic metals or alloys. Such experiments play an important role in the creation of devices, but more interesting and more promising are the methods which allow electron spins in solids to be aligned using external magnetic and electric fields or circularly polarized light. The development of information technologies on the basis of the electron spin may lead in the future to the creation of quantum computers [4–6].

In this review, we attempt to analyze the results of experimental and theoretical researches concerning spin-polarized electrons in semiconductors and to comprehend their possible practical implications and perspectives.

1. Optical Alignment of Spins

1.1. Generation and Relaxation of Spin-polarized Current Carriers

The phenomenon of optical alignment of spins of free electrons in semiconductors was discovered by G. Lampel [7] and R. Parsons [8] in 1968—1969 and explained theoretically by M.I. Dyakonov and V.I. Perel in 1971 [9]. It comprises the creation of a prevailing spin orientation for current carriers in a solid at illuminating the latter by circularly polarized light and is a direct consequence of the law of conservation of angular momentum. Because the electric field of a light wave affects immediately the electron orbital motion rather than its spin, the spin orientation of electrons is governed exclusively through the spin-orbit coupling. Spins are oriented along the light propagation direction at the left polarization of the light and in the reverse direction at the right one. Therefore, the phenomenon of optical alignment is possible only if there exists a sufficient spin-orbit coupling in materials.

The process of optical alignment includes two stages. In the first stage, spin-polarized current carriers are generated, and, in the second one, their spins relax during their lifetimes. The measure of optical alignment is a degree of current carrier polarization, which is defined by the ratio of the difference between the concentrations of electrons (holes) with the spins directed in parallel or antiparallel to the light propagation direction to their total concentration. The main physical effects, which manifest themselves at the optical alignment, and their theoretical and experimental aspects were considered in F. Mayer and B.P. Zakharchenya's monograph [10].

If spins are oriented optically, the photoexcited current carriers "live" during some time interval τ before recombination. Within this interval, the spin alignment of carriers decreases owing to different relaxation processes. If the spin alignment has not disappeared completely by the moment of recombination, the recombination radiation will be circularly polarized in part.

The spin relaxation of thermalized electrons is characterized by a time τ_s. Provided a stationary excitation and $\tau_s \gg \tau$, the average value of the total spin $\mathbf{S}$ of thermalized electrons is equal to the average total spin $\mathbf{S}_0$ of photoexcited electrons at the moment of creation. If $\tau_s \ll \tau$, the spin orientation of an electron is completely lost during its lifetime. In the general case, the amplitudes of $\mathbf{S}$ and $\mathbf{S}_0$ are connected by the formula [10]

$$S = \frac{S_0}{1 + \tau/\tau_s}. \tag{1}$$

If electron spins are optically aligned, the following three main mechanisms of spin relaxation can take place: (i) the Elliot—Yafet [11, 12], (ii) the Dyakonov—Perel [9, 13], and (iii) the Bir—Aronov—Pikus [14] ones. The first mechanism is connected to the spin flip of electrons, when they are being scattered by acoustic and optical phonons or by impurities, which occurs simultaneously with the variation of the momentum due to the mixing of the wave functions of electrons with opposite spins. The second mechanism is caused by the spin splitting of the conduction band in crystals without the center of inversion. The third one is caused by the exchange interaction of electrons and holes. It should be noted that, in experiments dealing with the optical alignment of minority current carriers, the relaxation according to the Bir—Aronov—Pikus mechanism prevails [10] because of the fact that, to ensure a high quantum yield of radiative recombination in a substance, it is necessary to provide a high concentration of the majority current carriers.

The reduction of τ_s is possible, as well, both due to the absorption of the recombination radiation by a crystal, which is accompanied by the generation of a new pair of current carriers and the following reradiation, and owing to the superfine interaction of electron magnetic moments with the spins of nuclei of the lattice [10]. Experimentally, τ_s has been determined mainly in gallium arsenide and GaAs-based heterostructures. For example, τ_s = 30 ns for free electrons in n-GaAs at helium temperatures and at $N_D - N_A \sim 10^{13}$ cm^{-3} [15], 42 ns at $N_D - N_A \sim 10^{15}$ cm^{-3} [16], and about 100 ns at $N_D \sim 10^{16}$ cm^{-3} [17], while for electrons localized at shallow donors, $\tau_s = 290 \pm 30$ ns at $N_D - N_A \approx 10^{14}$ cm^{-3} [15]. On the other hand, τ_s = 20 ns for free electrons in double heterostructures δ-doped by acceptors [18], whereas τ_s = 1 ns for holes in the donor-doped GaAs/Al$_x$Ga$_{1-x}$As heterostructures with quantum wells [19].

1.2. Hanle Effect

Provided that electron spins are optically aligned in a magnetic field, the so-called Hanle effect, i.e. the depolarization of photoluminescence (PL) by a magnetic field directed normally to the light propagation direction, takes place [10, 20]. R. Parsons was the first to observe this effect in semiconductors [8]. The Hanle effect is based on the fact that the spins of photoexcited electrons precess with the Larmor frequency $\Omega = \mu_{\rm B} g B/\hbar$ in the magnetic field $\mathbf{B}$ (here, $\mu_{\rm B}$ is the Bohr magneton, g is the g-factor, and $\hbar$ is Planck's constant divided by 2π) around the direction of the magnetic field. If the magnetic field is perpendicular to the exciting light beam ($\mathbf{B} \perp \mathbf{S}_0$), the spin projection onto the direction of this beam will periodically change with the frequency Ω. For convenience, we introduce a new quantity, the spin lifetime constant T_s:

$$\frac{1}{T_s} = \frac{1}{\tau_s} + \frac{1}{\tau}, \tag{2}$$

where τ_s is the time of spin relaxation and τ is the lifetime of an electron. This expression reflects two reasons of why the average spin of the electron disappears: recombination and spin relaxation. If the electron spin executes a great number of precession oscillations around the direction of the magnetic field $\mathbf{B}$ during the time T_s, then, under stationary conditions, the projection of the average spin onto the initial direction $\mathbf{S}_0$ will be small. It is this projection that defines a degree of the circular polarization of luminescence.

After the time interval t following the excitation, the electron spin projection will be equal to

$$S_z^* = S_0 \cos(\Omega t) \exp(-t/\tau_s). \tag{3}$$

Having averaged this expression over the electron lifetime distribution $W(t) = \tau^{-1} \exp(-t/\tau)$ for thermalized electrons under ambient conditions, we find the average projection of electron spins

$$S_z = \frac{S_0}{\tau} \int\limits_0^{\infty} \exp(-\frac{t}{T_s}) \cos(\Omega t) dt. \tag{4}$$

This formula gives the expression for the form of a Hanle curve [10]

$$S_z(B) = \frac{S_z(0)}{1 + (\Omega T_s)^2}, \tag{5}$$

where

$$S_z(0) = \frac{S_0}{1 + \tau/\tau_s}. \tag{6}$$

We point out that formulae (5) and (6) serve as a basis for the determination of the time constants τ and τ_s in the method of optical alignment. Really, the degree of PL circular polarization ρ is defined in terms of the intensities I_+ and I_- of the left- and right-polarized radiations, respectively, by the ratio

$$\rho = \frac{I_+ - I_-}{I_+ + I_-} \tag{7}$$

and is numerically equal to the projection of the average spin of electrons onto the direction of observation

$$\rho = -\mathbf{S}\mathbf{n}_1. \tag{8}$$

Here, $\mathbf{n}_1$ is the unit vector along the direction of PL monitoring. The "minus" sign means that the angular momenta of photon circulations are oriented oppositely to the direction of the average spin of electrons. Knowing the degree of PL circular polarization (7) in the zero field, the halfwidth $B_{1/2} = \hbar/g\mu_{\rm B}T_s$ of the magnetic depolarization curve (the Hanle curve), the g-factor, and using also relations (5) and (6), the time constants τ and τ_s for electrons can be readily obtained.

Thus, the degree of circular polarization of the recombination radiation serves as a convenient and sensitive indicator of both the spin state of current carriers and its changes under the influence of external factors and relaxation processes which govern the kinetics of nonequilibrium current carriers.

The Hanle effect is not only of independent academic interest [21] but has wide practical application [22–34]. In addition, it underlies a series of sensitive experimental methods, which are applied to study quantum-dimensional semiconductor systems [35], superconducting materials [36], and ferromagnetic films in ferromagnet/semiconductor structures [37].

2. Spin Electronics

Spintronics, or spin-dependent electronics, covers a wide set of devices, where the electron spin is used to modify their electric properties. In a broad sense, the term *spintronics* can be applied to all devices, where the electron spin is used, including those which are based on metal, semiconductor, hybrid (metal/semiconductor), organic, and other electronic elements, although some experts draw a boundary between them and passive magnetoelectronic devices, referring the latter to *magnetoelectronics*. But, taking into account the technological state and economic aspects of modern micro- and nanoelectronics, it becomes quite clear that it is the researches and developments in the area of *semiconductor spintronics* that have got the broadest distribution. Therefore, the word *spintronics* is used the most frequently to refer to the branch of semiconductor nanoelectronics that is connected to the implication of spin phenomena for electronic devices.

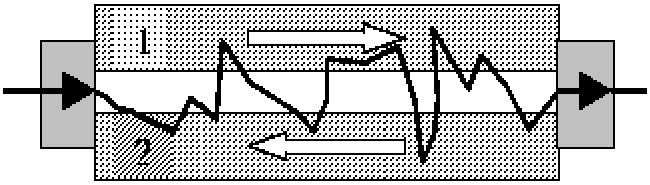

Fig. 1. Scheme of the spin-valve structure. The resistance of the system is minimal, if magnetizations of ferromagnetic layers *1* and *2* are parallel, and maximal, if they are antiparallel

The tunnel magnetoresistance (TMR) [38, 39] and giant magnetoresistance (GMR) [40] phenomena, which have been discovered when the magnetic materials were attempted as components of electronic devices together with traditional materials, became the basis of passive magnetoelectronic devices. It was the TMR and GMR phenomena that started the development of spin electronics ideas.

2.1. Magnetoresistance and Semiconductor Elements

The phenomenon of resistance variation in materials under the action of an external magnetic field became attractive in the construction of electronic devices and resulted in intensive scientific searches and practical developments in this area.

The GMR effect was discovered in the late 1980s [40, 41]. The researches of magnetoresistance in thin magnetic multilayer structures, where the current ran along the layers [the current-in-plane (CIP) geometry], revealed a huge change of resistance if the magnetization of the layers became antiparallel. Later on, the same effect was observed for another, the current-perpendicular-to-plane (CPP) geometry of the device, where the current ran normally to the layers [42]. The fundamental physical phenomenon, which underlies such a huge variation of resistance, is the so-called *spin-valve effect.* In the simplest case, a spin valve consists of two metal ferromagnetic layers separated by a nonmagnetic conducting one.

The principle of operation of a spin valve was described in the pioneer works of G. Prinz [2, 43]. The schematic cross-section of a spin valve (in the CIP geometry) normally to the layer plane is shown in Fig. 1. One of the ferromagnetic films, e.g., the first, is a soft magnetic material and the other a hard magnetic material. With the help of a comparatively weak external magnetic field, it is possible to change the direction of the magnetic moment of the first film, whereas the magnetization of the second film remains intact. In such a way, one can control the resistance of the device.

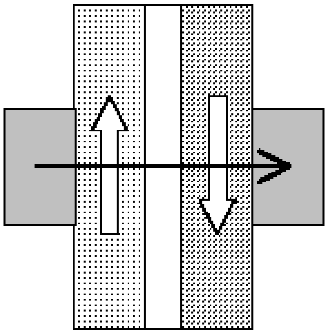

Fig. 2. The magnetic tunnel junction consists of two ferromagnetic films separated by an insulating barrier. The current experiences a large resistance, if the magnetic moments are antiparallel, and a small one, if they are parallel

There is no principal physical difference between the CPP and CIP geometries. The only distinction is that in the CPP geometry, electrons move across heterolayers, thus traversing all the layer interfaces, whereas in the CIP geometry, they move along the layers and, as a consequence, not every electron will traverse all the layer interfaces. As a result, devices with the CPP geometry will be more sensitive to a magnetic field than those with the CIP geometry. However, the latter devices are considerably easier in practical realization because of a very small resistance of the CPP ones.

The TMR phenomenon is similar to the GMR one [2,3,44]. But here, two ferromagnetic films are separated by a thin, no more than 4 nm in thickness, dielectric layer (Fig. 2). The functioning of a TMR junction is based on the quantum-mechanical phenomenon of spin-dependent tunneling of electrons from one ferromagnetic layer into the other through an insulating barrier. Such a system is extremely sensitive to structural imperfections of the insulating layer and to the quality of the interfaces between the insulator and the ferromagnetic layers. Therefore, for manufacturing such a tunnel junction, rather rigid requirements concerning its quality must be fulfilled.

Both those phenomena (GMR and TMR) are characterized by the relative variation of resistance $\Delta R/R$. If $\Delta R/R$ is about 100%, such a structure can be used for designing a specific device [45].

Thus, the two states of the device conductivity, with large and small resistances, can be called the logic states "1" and "0"; the device itself can be used as an element of the magnetic random access memory (MRAM) [2,3].

Practical realization has already led to a significant economic benefit. On the basis of spin valves, there were created sensitive sensors of a magnetic field [46] and heads for reading information from magnetic hard disks [47]. It is also known that the GMR and TMR phenomena are used in the elements of nonvolatile random-access memory of computers [48,49].

The mechanisms of magnetoresistance emergence in thin-film multilayer structures were considered in [50,51]. The magnetic properties of a wide class of other materials and mechanisms, which explain the emergence of the GMR phenomenon in them, were analyzed in [52–54]. The GMR phenomenon was also revealed in the magnetic semiconductor $HgCr_2Se_4$ [55,56], in sulfides $Fe_xMn_{1-x}S$ and $Cr_xMn_{1-x}S$ [57]. Unfortunately, the known mechanisms of magnetoresistance do not describe this phenomenon quantitatively and do not indicate the ways for a further creation of new magnetic materials with large values of the GMR effect.

Under the action of an external magnetic field, semiconductors can change their electrical and optical properties. The magnetic field can either shift the energy levels of the band structure or influence directly current carriers. Therefore, the external magnetic field is widely used in basic researches of semiconductors and quantum-dimensional structures. However, the application of magnetic fields in microelectronic elements is still rather insignificant, because the creation of magnetic fields of required values in tiny devices faces some difficulties. In particular, this matter is supposed to be resolved with the help of depositing a thin magnetic film or a sandwich structure onto a semiconductor surface [45]. In so doing, a ferromagnet may be either in a direct contact with a semiconductor or separated from it by an insulating layer.

2.2. Problems of Spin Injection

In order to create effective spintronic elements, three following problems are to be solved: injection, control, and detection of current carriers' spins. In the ideal case, all spins should be oriented identically (the 100%-polarized state). However, actually, a portion of spins occupies the "majority" states and the other portion the "minority" ones. The degree of spin polarization is defined in terms of the spin-up, $n_\uparrow$, and spin-down, $n_\downarrow$, electron concentrations by the ratio

$$P = (n_\uparrow - n_\downarrow)/(n_\uparrow + n_\downarrow). \tag{9}$$

The first thing to occur in this situation is to inject electrically spin-polarized electrons from a ferromagnetic metal into a semiconductor. The device based on the principle of electron spin injection (an electronic analogue of the electrooptical modulator) was proposed by S. Datta and B. Das [58]. The typical geometry of such a device with two ferromagnetic contacts and a two-dimensional (2D) electron gas between them was analyzed by G. Schmidt, D. Ferrand, and L.W. Molenkamp [59]. They showed that, in the diffusive transport mode, the degree of spin polarization of the injected current is expected to be smaller than 0.1%. The authors of [60] verified this conclusion of the theory by injecting electron spins from a ferromagnet into a semiconductor through an ohmic contact. The injection of electron spins was established in this case to be insignificant indeed. In addition, it was found that a mismatch between the conductances of the ferromagnet and the semiconductor confines the electron spin injection in principle.

To overcome the indicated obstacle, E.I. Rashba [61] suggested to insert an insulating tunnel barrier between the ferromagnet and the semiconductor and obtained expressions for the resistances of the junctions FM–T–S and FM–T–S–T–FM (FM stands for a ferromagnet, T for a tunnel contact, and S for a semiconductor), the spin injection coefficient, the spin-valve effect, and the spin electromotive force (EMF), caused by the gradient of spin orientation under the condition when the diffusion coefficients of "spin-up" and "spin-down" electrons are different (an analogue of the Dember EMF). He also showed that the tunnel junction can ensure a significant increase of spin polarization of electrically injected currents from a ferromagnetic metal into a semiconductor. The eligibility of such an approach was confirmed experimentally by V.F. Motsnyi, J. De Boeck, J. Das, et al. [34]. When investigating the circularly polarized PL of the CoFe/AlO_x/(Al,Ga)As/GaAs structure at 80 K, they found that the degree of polarization of injected electron spins was 9%.

The injection of electron spins through the interface between a ferromagnet and a paramagnetic metal was studied theoretically and experimentally in the classical works of M. Johnson and R.H. Silsbee [62,63]. Having used the Hanle effect, they unequivocally identified the signal connected with spin and, as a consequence, offered a new non-resonant method of measuring the times of spin relaxation of conduction electrons. As a result, the authors' hypothesis about charge-spin coupling at the ferromagnet–paramagnet interface was confirmed.

In order to increase the tunnel magnetoresistance and simultaneously decrease the ohmic resistance of the whole structure, the authors of [64] suggested to use the system with three barriers and thin ferromagnetic metal layers between them, where the electron motion was quantized and the arrangement of the quantum levels was determined by a direction of the electron spin. As a result, electrons with either spin direction tunneled in resonance, provided that the layers were magnetized in parallel, whereas at the antiparallel magnetization of the layers, the arrangements of the resonance levels in the metal layers did not coincide and, as a consequence, the tunnel current had no more resonant character. Such a device can be realized only in the case of the almost perfect interface between a ferromagnet and an insulator.

The spin-dependent resonant tunneling of electrons through asymmetric double barriers made up of nonmagnetic III—V semiconductors was considered theoretically by E.A. de Andrada e Silva and G.C. La Rocca [65] in the framework of the envelope function approximation and the Kane model for the bulk. The spin polarization was expected to exceed 50%.

The tunneling of spin-polarized electrons from a Ni tip of a scanning tunnel microscope onto the GaAs(110) plane was discussed in [66]. The registration of spin polarization in the semiconductor was carried out by measuring the circular polarization of PL. The degree of the spin polarization of tunnel electrons was found to be $P = -31\%$. The sign "minus" testified to that the main contribution into the tunnel current was made by spin-down electrons. A possibility to monitor spin-polarized electrons on the GaAs(110) surface by means of a scanning tunnel microscope was also reported in [67]. The model of spin-polarized transport for a photoexcited tunnel junction "ferromagnet–semiconductor" as well as the data of experimental researches of the spin-polarized tunneling between a GaAs tip of a scanning tunnel microscope and a Pt/Co multilayer structure was considered in [68]. The surface spin lifetime was found to exceed 0.4 ns.

The alignment of electron spins and their registration in II—VI semiconductors were carried out by optical methods in [69]. Spin-polarized electrons were excited by pump pulses of a circularly polarized light incident normally on the sample surface. An external magnetic field made the electron spins precess (the Hanle effect). A probe pulse of linearly polarized light struck the surface at a small angle to the normal and, after being reflected, its polarization plane was rotated at a certain angle (the Kerr effect). The time-resolved Kerr reflection in a 2D-electron gas provided the direct measurement of the precession of electron spins and their relaxation within the temperature range of 4—300 K. The electron spin polarization was shown to survive up to room temperature for several nanoseconds.

In the early theoretical works of F.T. Vasko and N.A. Prima [70, 71] and the following works of L.I. Magarill et al. [72, 73], a possibility to align the spins of 2D electrons by an electric field directed along the layer was considered in the framework of the Rashba Hamiltonian. The spin-orbit coupling ensures the influence of the electric field on electron spins. For this effect to exist, a nonequivalence of the $\mathbf{n}$ and $-\mathbf{n}$ directions, where $\mathbf{n}$ is a normal to the surface, is needed, i.e. we deal with the so-called oriented surface. The physical realization of the oriented surface is a 2D electron system with different top and bottom boundaries, e.g., a heterojunction or an inversion channel. The theoretical researches resulted in the prediction that the spins of 2D electrons can be aligned with the help of an electric field.

A few theoretical developments of spin current sources (spin batteries) have been published recently [74–76], where the generation of a mere spin current without a charge current was reported. The essence of the idea is that in the case where the equal numbers of spin-up and spin-down electrons move in opposite directions, the total charge current $I_e = e(I^*_\uparrow + I^*_\downarrow)$ disappears, but a definite spin current $I_s = \hbar/2(I^*_\uparrow - I^*_\downarrow)$ appears; here, $I^*_\uparrow$ and $I^*_\downarrow$ are the currents brought about by spin-up and spin-down electrons, respectively. All these concepts of spin batteries suppose the presence of an external alternating magnetic field, which makes their practical realization more complicated. In [77], a model of the spin battery based on double lateral quantum dots was proposed, where a constant magnetic field is used and the spin current is governed by a number of gates.

Thus, the considered optical and electric methods of injection of spin-polarized electrons into semiconductor materials have inherent advantages and shortcomings. The development of relatively simple and cheap methods of electron spin injection at room temperature belongs to the tasks of prime importance, whose solution would stimulate their broad application to semiconductor production.

2.3. Spin-polarized Transport

Spin-polarized transport can arise in any solid where the imbalance of spin populations at the Fermi level takes place. Such spin imbalance is typical of ferromagnetic metals (Fe, Co, Ni, and alloys on their basis), because the spin-up and spin-down electron states are shifted

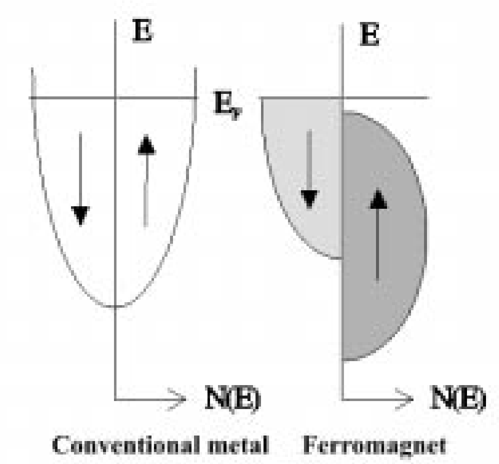

Fig. 3. Schematic diagrams of the electron density of states for a conventional metal and a ferromagnet. The spin-up electron states in a ferromagnet are filled completely. E is the electron energy, E_{F} is the Fermi level, and $N(E)$ is the electron density of states

in energy with respect to each other. This shift will lead to the different fillings of the bands and, as a consequence, to the total imbalanced magnetic moment. Since the populations of spin-up and spin-down electrons at the Fermi level are different in ferromagnetic metals, this leads, in turn, to a partial spin polarization of the current. The degree of current polarization is easy to estimate making use of the simple relation [10]

$$P = (I^*_\uparrow - I^*_\downarrow)/(I^*_\uparrow + I^*_\downarrow). \tag{10}$$

The most striking spin effects can be observed for completely spin-polarized currents. Therefore, the searches for materials and systems which are able to conduct such currents are challenging. In Fig. 3, the idealized densities of states for a conventional conductor and for a ferromagnet, which is capable to conduct the 100%-spin-polarized current, are compared.

During the last decade, extended experimental and theoretical researches of the spin transport of current carriers have been in progress. For example, V.I. Sugakov and S.Ya. Yatskevich [78] studied theoretically electron tunneling through a double-barrier heterojunction with Mn magnetic impurities in the parallel electric and magnetic fields, where the Mn atoms are either in the well (the system CdZnTe/$\mathrm{Cd_{0.8}Mn_{0.2}Te}$/ZnCdTe, the well width a = 80 Å, the barrier width b = 55 Å) or in the barriers (the system ZnSe/$\mathrm{Zn_{0.85}Mn_{0.15}Se}$/ZnSe, a = 60 or 70 Å, b = 55 Å). It was shown that, in a magnetic field, owing to the exchange interaction of current carriers' spins with magnetic impurities, there is a splitting of the levels in the well between the barriers. As a result, the fine structure of peaks should be observed on current-voltage characteristics, with different peaks corresponding to currents with different spin alignments. Therefore, such a phenomenon can be used for current carrier spin polarization.

M. Johnson [79] studied the transport of spin-polarized electrons in gold films by injecting current carriers at the given geometries of experiment. The nonequilibrium density of electron spins in such films was established to exceed both the known and predicted theoretically values. A.Majumdar [80] considered theoretically the same issue for a 2D electron gas in a spatially modulated magnetic field. Provided that electron energies are small, the interaction of spins of such a gas with a magnetic field was shown to reduce substantially the probability of the spin-up electron tunneling through magnetic barriers and to increase it for spin-down electrons. Therefore, these magnetic barriers distinguish between spin states of electrons and can be used as spin filters.

Transport properties of the magnetic semiconductor (Ga,Mn)As and the emergence of ferromagnetism in it were described in [81]. It was shown that the *p-d* exchange between the hole and Mn spins resulted in ferromagnetism of such layers.

The features of the kinetic phenomena in parallel low-dimensional layers separated by tunnel-transparent barriers were studied theoretically by F.T. Vasko and O.E. Raichev [82]. New effects were predicted: a Coulomb nonlinearity in the coherent dynamics, interference oscillations of the current in magnetic tunneling, a bistable response of the systems with independent contacts to layers. The spin injection into ballistic layers and the modulation of resistance in a spin-polarized field-effect transistor were investigated in [83,84], whereas tunnel spectroscopy of spin-split states in quantum wells in [85].

The spin-dependent phenomena of transfer and recombination in semiconductors and semiconductor structures were analyzed by O.V. Tretyak and co-authors in [86–88].

2.4. Devices on the Basis of Spin-polarized Electrons

The foundation of modern microelectronics is composed of semiconductor diodes and transistors. It is clear that the corresponding devices should be in the basis of spin electronics as well. The application of electron spins in electronic devices was considered in the thorough review of J. De Boeck [89].

The concept of spin-polarized field-effect transistor was proposed by S. Datta and B. Das [58]. The cross-section of such a transistor is shown schematically in Fig. 4. A layer of a 2D electron gas is formed by a heterojunction between InAlAs and InGaAs, which ensures the channel with high electron mobility and without spin-flip scattering. Spin-polarized electrons are injected and registered by ferromagnetic metal contacts. During the motion of electrons towards the collector, their spins are precessing, due to the Rashba effect, around the pseudo-magnetic field $\mathbf{B} = \alpha(\mathbf{k} \times \mathbf{z})$, where $\mathbf{k}$ is the wave vector of electrons and $\mathbf{z}$ is a unit vector directed normally to the surface. The parameter of the spin-orbit coupling (the Rashba parameter) is defined by the relation [90]

$$\alpha = 2a_{46}E_z/\hbar g, \tag{11}$$

where E_z stands for an electric field perpendicular to the 2D channel and a_{46} is the quantity connected to the band structure. The Rashba effect [91] arises when the speeds of current carriers in the device are about 10^6 m/s or more, i.e. when a relativistic approximation may be used. The behavior of such electrons in the 2D channel of a field-effect transistor will be as if the electric field applied to the gate had a magnetic component. Depending on its orientation, this field will cause either the splitting of spin-up and spin-down electron bands or the electron spin precession. Therefore, having created a Schottky gate on the surface of the device, it is possible to increase or reduce the internal effective electric field by applying an external voltage V_g normally to the stream of 2D electrons, thus changing the precession of electron spins. In such a way, one can control the orientation of electron spins with respect to the magnetization vector in the other contact and to modulate the current which runs through the device. Unfortunately, the idea of the spin-polarized field-effect transistor has not been realized yet, although many researchers attempted to overcome obstacles in developing such a device [92, 93].

The spin-polarized injection current emitter (SPICE) transistor on the hybrid basis (semiconductor/ferromagnet) was developed and fabricated by J.F. Gregg et al. [94]. This device operates similarly to a conventional transistor but its electric parameters are controllable by an external magnetic field. Between the base and the collector of the transistor, there is a ferromagnetic material with small coercivity, and that with a large coercivity is between the base and the emitter. The hard magnetic layer functions as a spin polarizer of the current, which is injected from the emitter into the base. These electrons diffuse through the base area and are attracted to the back-biased collector barrier. The number of electrons that reach the collector depends on the magnetization direction in the soft magnetic analyzing layer, which acts as a spin-dependent filter. Therefore, the current through the collector can be controlled by an external magnetic field.

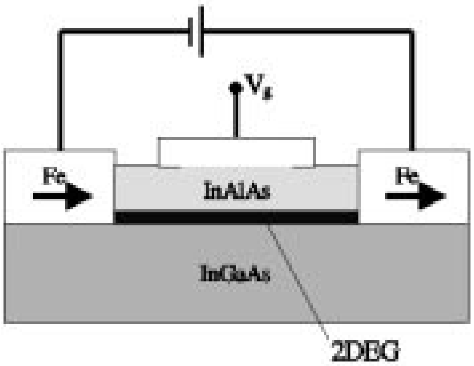

Fig. 4. Scheme of spin-polarized field-effect transistor. V_g is the gate voltage and 2DEG is a two-dimensional electron gas

The early prototypes of the SPICE transistor had weak spin dependence brought about by the scattering at interfaces and by difficulties connected to the spin injection between materials, the conductivities of which differ very much [95]. In addition, the silicides of transition metals arose at the interfaces between silicon and a ferromagnet, which resulted in the degradation of devices. Those shortcomings have been removed partially by introducing additional thin tunnel barrier layers between the emitter and the base and, in some cases, between the base and the collector as well.

Another (hybrid) type of the transistor, which is based on the spin-valve effect and can be used as a magnetic field sensor, was fabricated and investigated by D.J. Monsma et al. [96–98]. The structure of such a transistor is represented schematically in Fig. 5. The base of this transistor is a GMR structure composed of the layer series Pt–Co–Cu–Co and sandwiched between two n-Si(100) plates of the emitter and the collector. At the interfaces between the semiconductor and the metal, the Schottky barriers with typical heights of 0.6–0.7 eV are formed. The reverse bias is applied to the collector's Schottky barrier and the forward bias to the emitter's one. Electrons are accelerated in the emitter and injected into the base with an energy of about 1 eV higher than the Fermi level in the emitter (hot electrons). The

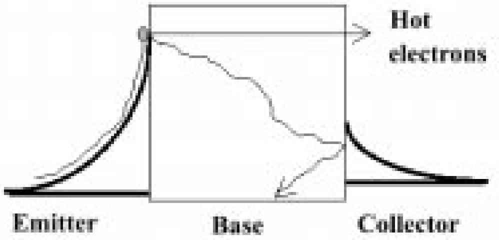

Fig. 5. Schematic diagram of the energy band structure of the spin-valve transistor

probability for electrons to reach the collector is limited by different scattering processes in the GMR structure, which effectively cool down injected electrons. Only ballistic electrons will pass the base and reach the collector. If the emitter current amounts to 100 mA, the typical values of the collector current will be smaller than 1 μA. Therefore, the current in the collector will be 10^5 times smaller. Nevertheless, the magnetic sensitivity of the collector current is rather significant: the variation of magnetoresistance is 400% at 77 K.

The role of thermal scattering in the magnetotransport of hot electrons was studied in [99] using a spin-valve transistor with the $Ni_{80}Fe_{20}/Au/Co$ base. The thermal spin waves were found to produce the quasielastic spin-flip scattering of hot electrons, resulting in the mixing of both spin channels.

In the creation of quantum computers, useful may turn out the so-called single-electron transistors (SETs). Let us consider the principles which underlie the creation of a spin SET. The electrostatic energy of a charged capacitor is equal to $\frac{1}{2}\frac{Q^2}{C}$. If the capacity C is small enough, this energy can compete with the energy of a thermal quantum kT, even if the charge Q is equal to the electron charge ($Q = e$). Small metal spheres or islands (quantum dots) with the physical dimensions of the nanometer scale possess the capacities that do satisfy the conditions indicated above. If such a metal island is produced in a structure between two spatially separated electrodes (the electron source and the electron sink), it is possible to obtain a SET [100, 101], through which only a single electron is able to pass at the same time. The third electrode (the gate), which is capacitively coupled to the metal island, is fed by a pulsed voltage in order to draw every electron across the island. During the functioning of such a device, there is a competition between three energy components, namely, the electrostatic energy of the island which contains only a single electron; the energy of the thermal quantum kT; and the energy eV_b, which is acquired by an electron after passing the potential difference V_b between electrodes. The first electron coming from the source charges the island to the potential e/C. This potential is sufficient to prevent other electrons from further transitions onto the island until the first electron passes to the sink due to a negative voltage pulse at the gate, thus releasing the place for the next electron. It is typical that a fourth energy component, the difference of electrochemical potentials for spin-up and spin-down electrons, which is related to the spin alignment, can be added to this process. In practice, it is attainable by manufacturing either both electrodes and the island, or only electrodes, or only islands from ferromagnetic materials [102, 103].

A completely metallic type of the device (the bipolar spin switch) was proposed by M. Johnson [104] on the basis of a thin-film sandwich structure FM–PM–FM (PM stands for a paramagnetic metal). A bilayer (FM–PM) embodiment of this device was presented by him in [105].

The influence of the spin phenomena on the functioning of optical devices is also reported. In [106], for example, the matter concerns the laser emission from a superlattice structure, the active part of which consists of 25 quantum wells, each of the composition $Cd_{0.81}Mn_{0.19}Te$ and 125 Å in width, which are separated by 24 barriers, each of the composition $Cd_{0.64}Mn_{0.36}Te$ and 40 Å in width. The frequency of this emission can be varied by applying an external magnetic field. The specimens were cooled down to the temperature of 1.9 K and optically pumped with a Nd:YAG laser. The spectral peak of the stimulated emission shifts towards long waves with increase in the magnetic field at the rate $dE/dB \approx 3.4$ meV/T. This dependence is linear up to 10 T.

2.5. Quantum Computers

Modern computers operate exclusively according to the laws of classical physics. However, if computer bits were diminished to nuclear sizes, one could not help to do without a quantum description of bit states and the dynamics. The combination of quantum mechanics and computers results in the new direction, quantum computers [4]. The idea of a quantum computer is simple, contrary to its practical realization. In a conventional computer, all the bits always have a certain definite state at any moment, e.g., 011100101. In a quantum computer, the bit state can be described by a wave function, which may look as follows:

$$\Psi = a|011100101\ldots\rangle + b|111010001\ldots\rangle + \ldots \qquad (12)$$

The coefficients $a, b, \ldots$ are complex numbers, and the probability that the computer is in the state 011100101... is equal to $|a|^2$, that it is in the state 111010001... to $|b|^2$, and so on. Moreover, these coefficients can describe the interference among different states of the computer, which may turn out very useful for computations.

One of the tasks the semiconductor spintronics is faced with is a realization of quantum information processing in semiconductor devices, taking advantage of long-term spin coherence of electron and nuclear spins. The application of semiconductors is very convenient for creating quantum computers, because, on the one hand, the technologies of manufacturing semiconductor integrated circuits are well developed, and, on the other hand, various parameters in those materials are readily controllable with the help of external factors, such as light, electric or magnetic field, pressure, and all that.

A few models of quantum computers, which use single-electron spin states in quantum dots as quantum bits (qubits), are known [107–109]. Such models possess two levels and a relatively long time of spin coherence. Quantum bits can be distinguished by shifting the resonance frequency of the electron energy level with the help of an external local magnetic field or a voltage applied to an additionally created gate contact (see the description of a spin SET in Sec. 2.).

The realization of quantum computations is also possible making use of nuclear spins [110]. The most widespread isotope of silicon, Si^{28}, has no nuclear spin. Therefore, nuclei with non-compensated spins, purposely introduced into silicon, will have long times of spin relaxation. In particular, B.H. Kane suggested a model of the quantum computer, which uses the silicon-based MIS (metal–insulator–semiconductor) structure, where P^{31} atoms with the nuclear spin 1/2 are embedded into silicon [111]. Here, the nuclear spin of P^{31} plays a role of the qubit. In order to manipulate the chosen nuclear spin, a voltage is applied to the gate electrode placed above a single or between two neighbor P^{31} atoms. In such a way, the superfine interaction, which is determined by the overlapping of electron wave functions and nuclear spins, is monitored and, a shift of the nuclear magnetic resonance frequency is obtained.

Thus, for the quantum computer based on nuclear spins to be embodied, the isotopic purity of a semiconductor crystal is of special importance.

3. Perspective Materials for Spintronics

It is ferromagnetic metals and alloys that are usually used as spin injectors, which has both advantages and shortcomings. It would be desirable that magnetic semiconductors compatible with existing ones be used for those purposes. Therefore, an important task of technology is the creation of high-quality semiconductor magnetic materials. Let us consider shortly some of them.

Diluted magnetic semiconductors are compounds where a portion of nonmagnetic semiconductor atoms are replaced by atoms of a magnetic material [112]. The primary goal upon the creation of such semiconductors is to obtain the temperatures of the transition into the ferromagnetic state close to room one.

No more than 15—20 years ago, II—VI semiconductors [(Cd,Mn)Te, (Zn,Mn)Se, (Cd,Mn)Se, and (Cd,Mn)S], where the high densities of magnetic atoms could be obtained, were among the basic objects of investigations in this area [113–116]. Now, they are used as the basis for creating quantum-dimensional structures. However, it is difficult to control the type of conductivity in such semiconductors and quantum-dimensional structures by their doping. At the same time, it is noteworthy that the antiferromagnetic exchange interaction between Mn spins dominates over the ferromagnetic one in II—VI semiconductors. However, it has not been until recently that the ferromagnetic transition has been registered in II—VI diluted magnetic *p*-semiconductors at temperatures below 4 K [117, 118].

A similar problem is also important for III—V semiconductors doped by manganese atoms. Provided the holes are absent, the magnetic interaction between Mn atoms in both the (In,Mn)As of the *n*-type [119] and the completely compensated (Ga,Mn)As is antiferromagnetic [120]. Therefore, the ferromagnetic interaction between Mn spins is connected to the availability of holes in a semiconductor crystal.

The temperature dependence of the magnetic susceptibility above the transition temperature, in accordance with the model [121], which is based on the mean-field theory, is described by the Curie-Weiss law. As an effective magnetic field, which affects the system of current carriers, the *sp-d* interaction is adopted. In the presence of holes and spontaneous magnetization, the spin splitting emerges in the valence band and, as a consequence, the energy of the system of carriers decreases. At the same time, the spontaneous magnetization of carriers increases the free energy of localized magnetic spins. As the temperature becomes lower, the free energy diminishes, and, after reaching a definite temperature, the gains and losses of the energy come into balance. This very temperature is T_c, according to the mean-field theory [121]. The described phenomenon is known as Zener ferromagnetism [122].

In diluted magnetic n-semiconductors, the emergence of ferromagnetism is hindered due to much smaller values of the s-d interaction [123]. Therefore, in order to rise T_c above room temperature, one must increase the concentrations of magnetic atoms, x, and holes, p.

In III—V semiconductors, the equilibrium solubility of magnetic impurities is low. Therefore, it is practically impossible to obtain materials with a high concentration of magnetic impurities under standard conditions of crystal growing. H. Munekata et al. [124] succeeded in the nonequilibrium growing of such crystals, using low-temperature molecular-beam epitaxy (LT-MBE) with the deposition temperature of approximately 250°C, and carried out the epitaxial growing of the alloy of AlAs with Mn on the GaAs substrate. The authors of [125, 126] obtained the diluted magnetic semiconductors (Ga,Mn)As and studied magnetotransport, magnetization, and electroluminescence spectra in them. It should be noted that the highest temperature T_c of the ferromagnetic transition in (Ga,Mn)As is 110 K for the manganese concentration $x = 0.053$ [81].

On the other hand, a possibility of growing (Ga,Mn)As by the LT-MBE method on the GaAs substrate evidences for its compatibility with quantum structures GaAs/(Al,Ga)As and is therefore an indisputable fact in favor of the future aspects of (Ga,Mn)As in spintronics. The values of T_c in the wide band gap semiconductors GaN and ZnO [127] are also expected to exceed room temperature, provided that the concentrations of magnetic atoms and holes in them should reach the corresponding values in (Ga,Mn)As.

More exotic semiconductor magnetic materials are also under examination for different tasks of magnetoelectronics: $LaMnO_3$, $La_{1-x}Ca_xMnO_3$ [52, 53], $HgCr_2Se_4$ [55, 56], $Fe_xMn_{1-x}S$, $Cr_xMn_{1-x}S$ [57], as well as $Ca_{1-x}La_xB_6$, whose Curie temperature reaches almost 900 K at $x = 0.01$ [128, 129]. Useful for spintronics may turn out strongly anisotropic layered semiconductors with magnetic impurities [130–134].

Not beyond the mainstream of spintronics are also such fashionable materials as carbon nanotubes [135]. In [136], e.g., the spin-valve effect in the system of two ferromagnetic contacts connected by a carbon nanotube 40 nm in diameter was investigated. The mean free path of electrons in such nanotubes before spin-flip scattering was found to be surprisingly large (130 nm).

Thus, carbon nanotubes may occupy a proper place in spintronic instrument-making industry in the future.

Conclusions

Semiconductor spin electronics (spintronics) is an object of purposeful comprehensive studies in two following directions: (i) semiconductor magnetoelectronics, which already has oustanding application achievements in the industry of reading information from hard disks and, in the nearest years to come, promises a breakthrough in the industry of MRAM for computers; and (ii) semiconductor quantum spintronics, the sound theoretical achievements and significant practical results of which are well-known, but more than one year is still needed for the ideas of quantum computer to be realized.

The advantage of spintronics over usual electronics is a significant reduction of energy consumption owing to the use of magnetic fields for controlling the electric processes in devices, as well as a capability to store information in a MRAM after switching-off.

The reduction of electronic component dimensions to a nanometer scale results in that the quantum-mechanics laws have the leading hand in the functioning of such devices. Since spintronics uses the essentially quantum-mechanical property of electrons, their spin, it discovers therefore new opportunities for the creation of quantum information technologies. In particular, the spin single-electron transistors (spin SETs) are very promising functional elements for the creation of quantum computers.

The well-known difficulties in spintronics are caused by the absence of base materials, which would perfectly correspond to two main requirements of spintronics, namely, (i) the Curie temperature of such materials, below which they are ferromagnets, must be equal to or exceed the room one and (ii) those materials must be compatible with the semiconductors that are used for manufacturing microelectronic components, mainly the silicon-based ones. We note that the greatest progress in spintronics was achieved when exactly the gallium compounds (Ga,Mn)As and (Ga,Mn)N were in use. These diluted magnetic semiconductors have the Curie temperature T_c of about 150–200 K, although their structural perfection and compatibility with silicon do not yet satisfy the requirements mentioned above.

In the near future, new magnetic materials on the basis of Si-containing semiconductor compounds may appear, which will enable the spintronic and classical semiconductor elements to be united symbiotically in a single integrated circuit on the same silicon crystal, as well as on the basis of layered semiconductors, carbon nanotubes, etc.

To summarize, spintronics belongs to the new priority directions of science development. It poses the challenging problems, the solutions of which will allow the unforeseen summits in the electronics of the future to be conquered.

1. *Sham L.J.*// Science.— 1997.— **277**.— P. 1258—1259.
2. *Prinz G.A.*// Ibid.— 1998.— **282**.— P. 1660—1663.
3. *De Boeck J., Motsnyi V., Zhiyu L. et al.* // Frontiers of Multifunctional Nanosystems / Ed. by E. Buzaneva, P. Scharff.— Dordrecht: Kluwer, 2002.— P. 453—476.
4. *Divincenzo D.P.*// Science.— 1995.— **270**.— P. 255—261.
5. *Gershenfeld N.A., Chuang I.L.*// Ibid.— 1997.— **275**.— P. 350—356.
6. *Cowburn R.P., Welland M.E.*// Ibid.— 2000.— **287**.— P. 1466—1468.
7. *Lampel G.*// Phys. Rev. Lett.— 1968.— **20**, N10.— P. 491—493.
8. *Parsons R.R.*// Ibid.— 1969.— **23**, N20.— P. 1152—1154.
9. *Dyakonov M.I., Perel' V.I.*// Zh. Eksp. Teor. Fiz.— 1971.— **60**, N5.— P. 1954—1965.
10. *Optical Orientation* / Ed. by F. Mayer, B.P. Zakharchenya. — Leningrad: Nauka, 1989 (in Russian).
11. *Elliot P.J.*// Phys. Rev.— 1954.— **96**.— P. 266.
12. *Yafet Y.*// Sol. Stat. Phys.— 1963.— **14**.— P. 1.
13. *Dyakonov M.I., Perel' V.I.*// Fiz. Tverd. Tela.— 1971.— **13**, N12.— P. 3581—3585.
14. *Bir G.L., Aronov A.G., Pikus G.E.*// Zh. Eksp. Teor. Fiz.— 1975.— **69**, N10.— P. 1382—1397.
15. *Dzhioev R.I., Zakharchenya B.P., Korenev V.L. et al.*// Pis'ma Zh. Eksp. Teor. Fiz.— 2001.— **74**, N3.— P. 200—203.
16. *Dzhioev R.I., Zakharchenya B.P., Korenev V.L., Stepanova M.N.*// Fiz. Tverd. Tela.— 1997.—**39**, N11.— P. 1975—1979.
17. *Kikkawa J.M., Awschalom D.D.*// Phys. Rev. Lett.— 1998.— **80**, N19.— P. 4313—4316.
18. *Wagner J., Schneider H., Richards D. et al.*// Phys. Rev. B.— 1993.— **47**, N8.— P. 4786—4789.
19. *Roussingol Ph., Rolland P., Ferreira R. et al.*// Ibid.— 1992.— **46**, N11.— P. 7292—7295.
20. *Novikov L.N., Skrotskii G.V., Solomakho G.I.*// Usp. Fiz. Nauk.— 1974.— **113**, N4.— P. 597—625.
21. *Dzhioev R.I., Zakharchenya B.P., Ichkitidze R.R. et al.*// Fiz. Tverd. Tela.— 1993.— **35**, N10.— P. 2821—2828.
22. *Kop'ev P.S., Mirlin D.N., Polyakov D.G. et al.*// Fiz. Tekhn. Polupr.— 1990.— **24**, N7.— P. 1200—1208.
23. *Merkulov I.A., Perel' V.I., Portnoy M.E.*// Zh. Eksp. Teor. Fiz.— 1991.— **99**, N4.— P. 1202—1214.
24. *Mirlin D.N., Perel' V.I.*// Semicond. Sci. and Technol.— 1992.— **7**.— P. 1221—1229.
25. *Mirlin D.N., Sapega V.F., Sirenko A.A. et al.*// Fiz. Tekhn. Polupr.— 1993.— **27**, N6.— P. 990—995.
26. *Sapega V.F., Perel' V.I., Mirlin D.N. et al.*// Ibid.— 1999.— **33**, N6.— P. 738—741.
27. *Akimov I.A., Mirlin D.N., Perel' V.I., Sapega V.F.*// Ibid.— 2001.— **35**, N6.— P. 758—765.
28. *Bulgakov E.N., Sadreev A.F.*// Pis'ma Zh. Eksp. Teor. Fiz.— 2001.— **73**, N10.— P. 573—577.
29. *Pierce D.T., Meier F.*// Phys. Rev. B.— 1976.— **13**, N 12.— P. 5484—5499.
30. *Gupta J.A., Awschalom D.D., Peng X., Alivisatos A.P.*// Ibid.— 1999.— **59**, N16.— P. R10421—R10424.
31. *Dzhioev R.I., Zakharchenya B.P., Kavokin K.V., Pak P.E.*// Fiz. Tverd. Tela.— 1994.— **36**, N9.—P. 2752—2762.
32. *Hägele D., Ostreich M., Rühle W.W. et al.*// Appl. Phys. Lett.— 1998.— **73**, N11.— P. 1580—1582.
33. *Zhu H.J., Ramsteiner M., Kostial H. et al.*// Phys. Rev. Lett.— 2001.— **87**, N1.— P. 016601-1—016601-4.
34. *Motsnyi V.F., De Boeck J., Das J. et al.*// Appl. Phys. Lett.— 2002.— **81**, N2.— P. 265—267.
35. *Dzhioev R.I., Zakharchenya B.P., Korenev V.L. et al.*// Fiz. Tverd. Tela.— 1998.— **40**, N9.— P. 1745—1752.
36. *Zakharchenya B.P., Tkachuk M.N., Fleishner V.G.*// Ibid.— 1989.— **31**, N8.— P. 208—211.
37. *Dzhioev R.I., Zakharchenya B.P., Korenev V.L.*// Ibid.— 1995.— **37**, N11.— P. 3510—3522.
38. *Moodera J.S., Kinder L.R., Wong T.M., Meservey R.*// Phys. Rev. Lett.— 1995.— **74**, N16.— P. 3273—3276.
39. *Julliere M.*// Phys. Lett. A.— 1975.— **54**.— P. 225.
40. *Baibich M.N., Broto J.M., Fert A. et al.*// Phys. Rev. Lett.— 1998.— **61**, N21.— P. 2472—2475.
41. *Binasch G., Grunberg G., Saurenbach F., Zinn W.*// Phys. Rev. B.— 1989.— **39**.— P. 4828.
42. *Gijs M.A.M., Lenczowski S.K.J., Giesberg J.B.*// Phys. Rev. Lett.— 1993.— **70**.— P. 3343.
43. *Prinz G.A.*// Physics Today.— 1995.— **48**, N4.— P. 58—63.
44. *Vedyayev A., Bagrets D., Bagrets A., Dieny B.*// Phys. Rev. B.— 2001.— **63**, N6.— P. 064429-1—064429-13.
45. *Prinz G.A.*// Science.— 1990.— **250**.— P. 1092—1097.
46. *Freitas P.P., Leal J.L., Melo L.V. et al.*// Appl. Phys. Lett.— 1994.— **65**.— P. 493.
47. *Tsang C., Tsann R.R., Speriosu D.E. et al.*// IEEE Trans. Magn.— 1994.— **30**.— P. 3801.
48. *Dax M.*// Semicond. Intern.— 1997.— **20**.— P. 84.
49. *Koch R.H., Grinstein G., Keefe G.A. et al.*// Phys. Rev. Lett.— 2000.— **84**.— P. 5419.
50. *Parkin S.S.P.*// Ibid.— 1993.— **71**, N10.— P. 1641—1644.
51. *Johnson M.*// Phys. Rev. Lett.— 1991.— **67**, N25.— P. 3594—3597.
52. *Nagaev E.L.*// Usp. Fiz. Nauk.— 1995.— **165**, N5.— P. 529—554.

53. *Nagaev E.L.//* Ibid.— 1996.— **166**, N8.— P. 833—858.

54. *Nagaev E.L.//* Fiz. Tverd. Tela.— 1998.— **40**, N11.— P. 2069—2073.

55. *Solin N.I., Chebotaev N.M.//* Ibid.— 1997.— **39**, N 5.— P. 848—852.

56. *Solin N.I., Naumov S.V.//* Pis'ma Zh. Eksp. Teor. Fiz.— 2000.— **72**, N12.— P. 885—890.

57. *Petrakovskiy G.A., Ryabinkina L.I., Abramova G.M. et al.//* Ibid.— N2.— P. 99—102.

58. *Datta S., Das B.//* Appl. Phys. Lett.— 1990.— **57**, N 7.— P. 665—667.

59. *Schmidt G., Ferrand D., Molenkamp L.W. et al.//* Phys. Rev. B.— 2000.— **62**, N8.— P. R4790—R4793.

60. *Filip A.T., Hoving B.H., Jedema F.J. et al.//* Ibid.— N15.— P. 9996—9999.

61. *Rashba E.I.//* Ibid.— N24.— P. R16267—R16270.

62. *Johnson M., Silsbee R.H.//* Ibid.— 1988.— **37**, N10.— P. 5312—5325.

63. *Johnson M., Silsbee R.H.//* Ibid.— P. 5326—5335.

64. *Vedyaev A.V.//* Usp. Fiz. Nauk.— 2002.— **172**, N 12.— P. 1458—1461.

65. *de Andrada e Silva E.A., La Rocca G.C.//* Phys. Rev. B.— 1999.— **59**, N24.— P. R15583—R15585.

66. *Alvarado S.F., Renaud Ph.//* Phys. Rev. Lett.— 1992.— **68**, N9.— P. 1387—1390.

67. *Molotkov S.N.//* Pis'ma Zh. Eksp. Teor. Fiz.— 1992.— **55**, N3.— P. 180—184.

68. *Prins M.W.J., Jansen R., van Kempen H.//* Phys. Rev. B.— 1996.— **53**, N12.— P. 8105—8113.

69. *Kikkawa J.M., Smorchkova I.P., Samarth N., Awschalom D.D.//* Science.— 1997.— **277**.— P. 1284—1287.

70. *Vasko F.T. //* JETP Lett.— 1979.— **30**.— P. 541—544.

71. *Vasko F.T., Prima N.A. //* Sov. Phys. Solid State.— 1979.— **21**.— P. 994—996.

72. *Magarill L.I., Entin M.V.//* Pis'ma Zh. Eksp. Teor. Fiz.— 2000.— **72**, N3.— P. 195—200.

73. *Magarill L.I., Chaplik A.B., Entin M.V.//* Fiz. Tekhn. Polupr.— 2001.— **35**, N9.— P. 1128—1134.

74. *Brataas A., Tserkovnyak Y., Bawer G.E.W., Halperin B.//* Phys. Rev. B.— 2002.— **66**.— P. 060404.

75. *Wang B., Wang J., Guo H.//* Ibid.— 2003.— **67**.— P. 092408.

76. *Sun Q.-F., Guo H., Wang J.//* Phys. Rev. Lett.— 2003.— **90**.— P. 25830.

77. *Long W., Sun. Q.-F., Guo H., Wang J.//* Appl. Phys. Lett.— 2003.— **83**, N7.— P. 1397—1399.

78. *Sugakov V.Ya., Yatskevich S.Ya.//* Pis'ma v ZhTF.— 1992.— **5**.— P. 15.

79. *Johnson M.//* Phys. Rev. Lett.— 1993.— **70**, N14.— P. 2142—2145.

80. *Majumdar A.//* Phys. Rev. B.— 1996.— **54**, N17.— P. 11911—11913.

81. *Matsukura F., Ohno H., Shen A., Sugawara Y.//* Phys. Rev. B.— 1998.— **57**, N4.—P. R2037—R2040.

82. *Raichev O.E.*Transport Phenomena in Low-Dimensional Electron Systems with Tunnel Interaction: Thesis for Doctorate degree in Physics and Mathematics.— Kyiv, 1998 (in Ukrainian).

83. *Raichev O.E., Vasko F.T. //* Phys. Rev. B.— 2004.— **70**, N7.— P. 075311.

84. *Raichev O.E., Debray P.//* Ibid.— 2002.— **65**, N8.— P. 085319-1—085319-9.

85. *Raichev O.E., Debray P.//* Ibid.— 2003.— **67**, N15.— P. 155304-1—155304-8.

86. *Tretyak O.V.* Studies of Spin-Dependent Transfer and Recombination Phenomena in Semiconductors and Semiconductor Structures: Thesis for Doctorate degree in Physics and Mathematics.— Kyiv, 1985 (in Russian).

87. *Barabanov A.V., Tretyak O.V., L'vov V.A.//* Phys. Rev. B.— 1996.— **54**.— P. 2571.

88. *Barabanov A.V.* Quantum-Mechanical Theory of Spin-Dependent Recombination in Semiconductors: Thesis for Ph.D. degree in Physics and Mathematics.— Kyiv, 1999 (in Ukrainian).

89. *De Boeck J.//* Science.— 1998.— **281**.— P. 357—359.

90. Spin Electronics / Ed. by M.J. Thornton, M.Ziese.— Berlin: Springer, 2001.

91. *Bychkov Y.A., Rashba E.I.//* J. Phys. C.— 1984.— **17**.— P. 6039.

92. *Cabbibo A., Childress J.R., Pearton S.J. et al.//* J. Vac. Sci. Technol. A.— 1997.— **15**.— P. 1215.

93. *Cartoixa X., Ting D.Z.-Y., Chang Y.-C.//* Appl. Phys. Lett.— 2003.— **83**, N7.— P. 1462—1464.

94. *Gregg J.F., Allen W., Viart N. et al.//* J. Magn. Magn. Mater.— 1997.— **175**.— P. 1.

95. *Loraine D.R., Pugh D.I., Jenniches H. et al.//* J. Appl. Phys.— 2000.— **87**.— P. 5161.

96. *Monsma D.J., Lodder J.C., Popma J.A., Dieny B.//* Phys. Rev. Lett.— 1995.— **74**.— P. 5260.

97. *Monsma D.J., Vlutters R., Lodder J.C.//* Science.— 1998.— **281**.— P. 407—409.

98. *Lodder J.C., Monsma D.J., Vlutters R., Shimatsu T.//* J. Magn. Magn. Mater.— 1999.— **198**.— P. 119.

99. *Jansen R., Anil Kumar P.S., van't Erve O.M.J et al.//* Phys. Rev. Lett.— 2000.— **85**, N15.— P. 3277—3280.

100. *Amman M., Mullen K., Ben-Jacob E.//* J. Appl. Phys.— 1989.— **65**.— P. 339.

101. *Altimeyer S., Spangenberg B., Kurz H.//* Appl. Phys. Lett.— 1995.— **67**.— P. 569.

102. *Barnas J., Fert A.//* Europhys. Lett.— 1998.— **80**.— P. 1058.

103. *Majumdar K., Hershenfield S.//* Phys. Rev. B.— 1998.— **57**.— P. 11521.

104. *Johnson M.//* Science.— 1993.— **260**.— P. 320—323.

105. *Johnson M.//* Appl. Phys. Lett.— 1993.— **63**, N10.— P. 1435—1437.

106. *Isaacs E.D., Heiman D., Zayhowski J.J. et al.//* Ibid.— 1986.— **48**, N4.— P. 275—277.

107. *Loss D., DiVincenzo D.P.*// Phys. Rev. A.— 1998.— **57**.— P. 120.
108. *Imamoglu A., Awschalom B.D., Burkard G. et al.*// Phys. Rev. Lett.— 1999.— **83**.— P. 4204.
109. *Sasakura H., Muto S., Oshima T.*// Physica E.— 2001.— **10**.— P. 458.
110. *Valiev K.A., Kokin A.A.*// Priroda.— N12.— P. 28—36.
111. *Kane B.H.*// Nature.— 1998.— **393**.— P. 133.
112. *Ohno H.*// Science.— 1998.— **281**.— P. 951—956.
113. *Semiconductors* and Semimetals.— Vol.25: Diluted Magnetic Semiconductors / Ed. by J.K. Furdyna, J. Kossut.— New York: Academic Press, 1988.
114. *Ryabchenko S.M., Semenov Yu.G.*// Zh. Eksp. Teor. Fiz.— 1983.— **84**, N4.— P. 1419—1431.
115. *Ryabchenko S.M., Semenov Yu.G.*// Fiz. Tverd. Tela.— 1984.— **26**, N11.— P. 3347—3354.
116. *Ryabchenko S.M., Semenov Yu.G.* Radiospectroscopy of Solids.— Kyiv: Naukova Dumka, 1992 (in Russian).
117. *Ferrand D., Cibert J., Bourgognon C. et al.*// J. Cryst. Growth.— 2000.— **214—215**.— P. 387—390.
118. *Haury A., Wasiela A., Arnoult A. et al.*// Phys. Rev. Lett.— 1997.— **79**, N3.— P. 511—514.
119. *Von Molnár S., Munekata H., Ohno H., Chang L.L.*// J. Magn. Magn. Mater.— 1991.— **93**.— P. 356.
120. *Satoh Y., Inoue N., Nishikawa Y., Yoshino J.*// Proc. 3rd Symposium on Physics and Application of Spin—Related Phenomena in Semiconductors, 1997, Sendai, Japan.— P. 23—25.
121. *Dietl T., Ohno H., Matsukura F. et al.*// Science.— 2000.— **287**.— P. 1019.
122. *Zener C.*// Phys. Rev.— 1950.— **81**.— P. 440.
123. *Ohno H., Matsukura F., Ohno Y.*// JSAP Internat.— 2002.— N 5.— P. 4—14.
124. *Munekata H., Ohno H., von Molnár S. et al.*// Phys. Rev. Lett.— 1989.— **63**.— P. 1849.
125. *Van Esch A., De Boeck J., Van Bockstal L. et al.*// J. Phys.: Condens. Matter.— 1997.— **9**.— P. L361—L367.
126. *Ohno Y., Arata I., Matsukura F. et al.*//Appl. Surf. Sci.— 2000.— **159—160**.— P. 308—312.
127. *Fukumura T., Jin Zh., Kawasaki M. et al.*// Appl. Phys. Lett .— 2001.— **78**, N7.— P. 958—960.
128. *Ott H.R., Gavilano J.L., Ambrosini B. et al.*// Physica B.— 2000.— **281—282**.— P. 423.
129. *Tromp H.J., van Gelderen P., Kelly P.J. et al.*// Phys. Rev. Lett.— 2001.— **87**, N1.— P. 016401-1—016401-4.
130. *Motsnyi F.V., Ishchenko S.S., Okulov S.S., Bletskan D.I.*// Fiz. Tekhn. Polupr.— 1977.— **11**, N6.— P. 1043—1048.
131. *Lisitsa M.P, Motsnyi F.V., Sergeev S.O.*// Zh. Prikl. Spektr.— 1988.— **49**, N4.— P. 630—635.
132. *Gnatenko Yu.P., Zhirko Yu.I., Kovalyuk Z.D.*// Phys. status solidi (b).— 1990.— **161**.— P. 419—426.
133. *Gnatenko Yu.P., Zhirko Yu.I., Kovalyuk Z.D.*// Ibid.— P. 427—434.
134. *Dorogan V.G., Zhydkov V.O., Motsnyi F.V.*// Semicond. Phys., Quant. Electr. & Optoelectr.— 2002.— **5**, N4.— P. 417—419.
135. *Terranova M.L., Orlanducci S., Fazi E. et al.* // Chem. Phys. Lett.— 2003.— **381**.— P. 86—93.
136. *Alphenaar B.W., Tsukagoshi K., Ago H.*// Physica E.— 2000.— **6**.— P. 848.

Received 04.02.04.
Translated from Ukrainian by O.I.Voitenko

СПІН-ПОЛЯРИЗОВАНІ ЕЛЕКТРОНИ В ЕЛЕКТРОНІЦІ МАЙБУТНЬОГО

(Огляд)

В.Г. Дороганъ, Ф.В. Моцний

Резюме

В огляді зроблено спробу проаналізувати експериментальні та теоретичні досягнення в новій області науки — спінтроніці. Розглянуто явище оптичної орієнтації спінів, спінову релаксацію, ефект Ханле, явища гігантського і тунельного магнітоопорів, проблеми інжекції спінів, спін-поляризований транспорт, прилади на базі спін-поляризованих електронів, основи квантових комп'ютерів, перспективні матеріали для спінтроніки.