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Use of spin-polarized current in spintronics

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Spintronics is a relatively new branch of conventional electronics, where the electron spin (together with the electron charge) is an active element in storing and conveying information [1]. Devices that utilize electron spin may displace or supplement to a large measure traditional electronic devices. More than that, spintronics has real potential for use in new areas of technology, for example, in quantum calculations and quantum data transmission [2].

Nature has supplied us with a natural source of spin-polarized electrons in the form of ferromagnetic metals of the 3d group: Fe, Ni, and Co and their alloys. By now the origin of the ferromagnetic state of these metals has been established with rather great accuracy. For instance, there is no doubt that spontaneous magnetization arises from the part of the electron–electron Coulomb interaction that changes as a result of the permutation of two identical Fermi particles (electrons) and is called the exchange energy E^{exch}. This energy is lowest if the electron spins in the metal are parallel. True, in some cases the energy minimum is realized in a more complicated configuration of spins, for example, in a helical spin-density wave. On the other hand, the kinetic energy of an electron in the metal together with the Pauli exclusion principle tend to disrupt the spin order. Detailed first-principles calculations of the band structure of almost all the metals from the Periodic Table have shown that for 3d-metals (Fe, Ni, and Co) the electron density of states $\rho(\varepsilon_{\text{F}})$ at the Fermi level is high enough for the so-called Stoner criterion $E^{\text{exch}}\rho(\varepsilon_{\text{F}}) > 1$ to be met. It is the emergence of spontaneous magnetization that is ensured by meeting this criterion, i.e., the population of subbands with different directions of spin is nonequivalent and the system acquires spontaneous magnetization. Notice that the main contribution to magnetization is provided by d-symmetry electrons whose density of states at the Fermi level is much higher than that of sp-symmetry electrons.

If, however, we turn to electron transfer phenomena, we are forced to conclude that the main contribution to the current in ferromagnetic metals is provided by the mobile sp-electrons rather than the heavier but strongly magnetized d-electrons. But is the current in a ferromagnetic d-metal spin-polarized? A direct answer to this question was obtained in 1988 as a result of a discovery [3] of what is known as the giant magnetoresistance (GMR) effect. Generally, the magnetoresistance phenomenon, or the change in the electrical resistance of a nonmagnetic or ferromagnetic metal on imposition of an external magnetic field, has been known for a long time. For ordinary samples this change is relatively small, however, amounting up to fractions of a percent for nonmagnetic metals and about 1% for ferromagnetic metals. On the other hand, GMR may be as high as 100% at low temperatures. Let us describe this phenomenon in greater detail.

GMR was first observed in a multilayer thin-film $[\text{Fe/Cr}]_n$ structure, where Fe is a thin (several angstroms) layer of iron, Cr is a layer of chromium, and n is the number of repetitions of such a bilayer. What is important here is that the chromium layer is approximately 12 Å thick. Experiments provided an explanation for this fact — as the chromium layer thickness varies, the mutual orientation of the magnetizations peculiar to the adjacent iron layers changes from parallel to antiparallel, and it becomes almost strictly antiparallel when the Cr layer is 12 Å thick. According to theoretical investigations into this phenomenon, the magnetizations of the adjacent iron layers are coupled by the indirect exchange interaction via the conduction electrons in chromium. This interaction oscillates in space, changing its sign with a period determined by the Fermi-electron momentum in chromium and equal to 12 Å in the case of chromium. Thus, the magnetizations of the adjacent layers proved to be coupled antiferromagnetically (antiparallel) or ferromagnetically (parallel), depending on the thickness of the Cr interlayer. Now, if in the absence of an external magnetic field the magnetizations of the adjacent iron layers are antiparallel, a strong enough magnetic field (about 20 kOe in the case at hand) aligns these magnetizations parallel to each other and to the field direction. Measuring the electrical resistance R of the system with the current flowing in the plane of the layers (CIP) for the parallel (R^{P}) and antiparallel (R^{AP}) magnetization orientations, Schad et al. [4] found that the resistance R changes in such a way that $(R^{\text{AP}} - R^{\text{P}})/R^{P} \approx 1.2$ at 1.5 K for the $[[\text{Fe}(4.5\ \text{Å})/\text{Cr}(12\ \text{Å})]_{50}$ system. An even greater effect has been observed for analogous systems with the current flowing perpendicularly to the plane of the layers. Note that a similar effect has been observed in much weaker external fields (~ 20 Oe) for sandwich structures of the $\text{F}_1|\text{P}|\text{F}_2$ type, where F_1 and F_2 are the thin layers of ferromagnetic metals with different coercitivities (e.g., Permalloy and cobalt), and P is a nonmagnetic metal (e.g., copper). In this case, initially the magnetizations of the ferromagnetic layers are parallel, and an external magnetic field stronger than the smaller coercitive field of one layer (Permalloy) and weaker than the greater coercitive field of the other layer, when applied to the system, reverses the magnetism of the layer with the smaller coercitivity, so that the magnetization of that layer aligns itself antiparallel to the magnetization of the other (ferromagnetic) layer with the greater coercitivity. In other words, we are again in the situation we have just described and, measuring the resistance of the given system, we will again find that the resistance changes significantly when an external magnetic field is applied to the system, but the maximum effect is achieved in the fields of about 20 Oe, which are much weaker than in (Fe/Cr) multilayer structures.

Several researchers have provided theoretical interpretations of the GMR effect. These were based on the quasi-classical approaches using the Boltzmann equation [5–9] or on Kubo's quantum-mechanical formalism [10–12]. In this short report there is no sense discussing the ways in which the basic formulae describing the spin-polarized transport in the above structures were derived. Instead we will examine the GMR effect qualitatively.

As noted earlier, a ferromagnetic metal contains at least two groups of electrons: heavy d-electrons which practically do not participate in electron transport but whose band is

heavily split in spin, and light sp-electrons for which the spin splitting is much weaker than for heavy d-electrons but which are the main charge carriers in electron transport. But even if we assume that the Fermi surfaces of the sp-electrons coincide for different directions of spin (although generally such is not the case), in that event, too, one of the main characteristics determining electron transport, i.e., the electron mean free path, proves to be different for sp-electrons with opposite directions of spin projections. This distinction can be explained by the intense scattering of sp-electrons into the d-band for which the densities of states for 'up' and 'down' spins at the Fermi level differ by a factor of ten. Since for any particle the scattering probability is proportional to the finite density of states into which the particle scatters, the lifetimes τ of the sp-electrons with different spins are also distinct. If we now take the elementary Drude formula for conductivity, viz.

$$\sigma^{\uparrow(\downarrow)} = \frac{ne^2}{m}\tau^{\uparrow(\downarrow)},$$

where e and m are the electron charge and mass, n is the electron number density (number of electrons per unit volume), and $\tau^{\uparrow(\downarrow)}$ is the lifetime of electrons with spin $\uparrow(\downarrow)$, then the conductivities for elements with spins $\uparrow$ and $\downarrow$ may differ by an order of magnitude. Hence, the total current in a ferromagnetic metal proves to be spin-polarized.

We now consider a situation in which the current flows, say, in a multilayer structure described above in the direction perpendicular to the plane of the layers. If the magnetizations of all the ferromagnetic layers are parallel to each other, an electron whose spin is parallel to the magnetization direction and whose lifetime is longer can freely transfer the current from layer to layer, as if the system was short circuited (the electrical resistance of the entire system is small). But if the magnetizations of the adjacent layers are antiparallel, an electron with any direction of spin undergoes strong scattering when traveling from a layer to layer, with the result that the system is not short circuited (the total resistance of the system is large). Just this phenomenon is responsible for the GMR effect. It should be emphasized that the above reasoning has meaning only if the projection of the electron spin is conserved in the process of the electron's movements through the system. If in collisions with impurities, especially in the nonmagnetic interlayer separating the ferromagnetic layers, the projection of the electron spin changes, the GMR effect disappears. For now we note that in the structures exhibiting GMR the thicknesses of all the layers are selected in such a way that they do not exceed the spin-diffusion length, i.e., the mean free path over which all information about the spin of the carrier (electron) is lost. Notice that GMR studies are not purely academic. At present there are commercially available magnetic heads whose operation depends on this effect; they are used for reading superdense information with a density of dozens of gigabits per square inch; there are also pilot samples that allow the user to write and read information with a density several times greater than the values we have just mentioned.

Up to now we have considered spin-polarized transport in heterostructures in which the magnetic electrodes are separated by a thin layer of a nonmagnetic metal. Currently researchers are focused on examining the magnetoresistance in magnetic tunnel structures in which an insulator is the separating layer. Let us now describe this phenomenon in detail.

If the voltage is applied to a sandwich structure of the $F_1|O|F_2$ type, where F_1 and F_2 are two ferromagnetic metals with different coercitivities, and O is an insulator (usually Al_2O_3 oxide) several angstroms thick, a current is brought about in the system. Since this current is caused by quantum tunneling through a barrier, it is extremely weak and falls off exponentially with an increase in the insulator thickness. Now if an external magnetic field transfers the system from a state with parallel orientation of the F_1 and F_2 magnetizations to a state with antiparallel orientation, the current for a fixed drop in voltage across the junction changes (usually decreases), with the relative variation of the electrical resistance reaching $30-50\%$ even at room temperature.

We would like to point out the rapid progress in the last few years in fabricating magnetic tunnel junctions with improved characteristics, namely, with large values of the magnetoresistance and, which is especially important, with smaller values of the resistance-by-area product (the recommended values are $3\ \Omega\,\mu m^2$). Research has also focused on enhancing the stability of the magnetic state of a three-layer sandwich under multiple magnetization reversal of the soft magnetic layer. The stability was achieved by applying a hard magnetic layer on the antiferromagnetic layer of the Pt-Mn, Ir-Mn, Rh-Mn, or Fe-Mn type. In this case, the layer magnetization is rigidly linked to the antiferromagnet by exchange interaction, and this layer proves to be magnetized in one direction even after 10^{10} magnetization reversals of the soft magnetic layer. So much attention is being given to the study and fabrication of new types of magnetoresistive tunnel junctions in view of the problem of creating indestructible, unerasable, and radiation-resistant RAM (or MRAM, magnetic random-access memory), which could replace the common semiconductor RAM.

Thus, let us assume that we have to deal with a tunnel junction consisting of two ferromagnetic electrodes separated by a thin insulating barrier. As noted earlier, in ferromagnetic metals, from which the electrodes are fabricated, spd-electron bands are split due to exchange interaction, with the result that the densities of states for electrons with different spins are distinct. Julliere [13] assumed that the tunneling probability is proportional to the product of the densities of states of the electrons on the right and left electrodes. In this case, the conductivity of a system with parallel orientation of the electrode magnetizations is given by

$$\sigma^{P} = A\left[\rho^{\uparrow}(\varepsilon_F)\rho^{\uparrow}(\varepsilon_F) + \rho^{\downarrow}(\varepsilon_F)\rho^{\downarrow}(\varepsilon_F)\right],$$

while the conductivity of a system with antiparallel orientation of the electrode magnetizations equals

$$\sigma^{AP} = 2A\rho^{\uparrow}(\varepsilon_F)\rho^{\downarrow}(\varepsilon_F),$$

where A is a constant that depends exponentially on the barrier thickness. Then the relative magnetoresistance takes the form

$$\frac{\sigma^{P} - \sigma^{AP}}{\sigma^{P}} = \frac{2P^2}{1+P^2},$$

where

$$P = \frac{\rho^{\uparrow}(\varepsilon_F) - \rho^{\downarrow}(\varepsilon_F)}{\rho^{\uparrow}(\varepsilon_F) + \rho^{\downarrow}(\varepsilon_F)}$$

is the spin polarization of the electrons in the ferromagnetic electrode.

A more accurate quantum-mechanical calculation done by Slonczewski [14] (true, the researcher used the free-electron model allowing for exchange splitting) yielded the same formula for the relative magnetoresistance, in which, however, the expression for the relative spin polarization is more complicated:

$$P = \frac{k_F^{\uparrow} - k_F^{\downarrow}}{k_F^{\uparrow} + k_F^{\downarrow}} \times \frac{\varkappa^2 - k_F^{\uparrow} k_F^{\downarrow}}{\varkappa^2 + k_F^{\uparrow} k_F^{\downarrow}} ,$$

where $k_F^{\uparrow(\downarrow)}$ is the electron wave vector on the Fermi surface for spins $\uparrow(\downarrow)$, and $i\varkappa$ is the imaginary wave vector of an electron inside the barrier (which corresponds to the reciprocal length of an exponential decay of the electron wave function inside the barrier). It is significant that in this theory the magnetoresistance is determined not only by the difference in the densities of states in the ferromagnet for electrons with various directions of spin, but also via $\varkappa$ by the properties of the barrier. This dependence has been corroborated by experiments with the barriers fabricated from dissimilar materials. Another important feature of tunneling is that the major contribution to the tunnel current is provided by sp-electrons rather than by d-electrons which are more heavily split by exchange interaction. This can be explained either by the large mass of d-electrons or by the very weak overlap across the metal/insulator interface of the d-symmetry wave functions in the metal and the sp-symmetry wave functions which are the only wave functions in the insulator. We also note that the magnetoresistance decreases as the quality of the interface declines (i.e., as the surface of the interface becomes rougher) and as the temperature increases. A detailed review of the literature devoted to this problem can be found in Ref. [15]. It is not unreasonable to mention the attempts to use what is known as ferromagnetic semimetals as ferromagnetic electrodes (in such semimetals only one subband with a definite spin is filled, while the other subband with the opposite spin is vacant). Examples of such systems are Heusler alloys (NiMnSb and PtMnSb) and also some oxides (e.g., Fe_3O_4, CrO_2, etc.). So far, however, the experimenters have been unable to achieve 100% polarization of the current.

From what we have discussed and, generally, from experience gained from operating devices that utilize spin-polarized electron transport, we can draw the following conclusion: the current in magnetic heterostructures is, actually, spin-polarized, i.e., it carries not only charge but also spin, and the main obstacles for maintaining this spin-polarized current are the processes that lead to spin flip, i.e., processes that destroy spin coherence.

The conduction electrons lose all memory about their spin orientation as a result of collisions with phonons, other electrons, and impurities. The main interaction that involves a spin-dependent potential is the spin – orbit coupling which is of a relativistic nature. The chief sources of this interaction are the electron – impurity interaction and the interaction of electrons with ions belonging to the basal lattice. The electron interaction with impurities is of a random nature and leads to scattering in which neither the electron momentum nor the electron spin is conserved. The interaction with the ions of the basal lattice is quite different. It is periodic in space and does not lead by itself to any spin relaxation. However, it can result in spin relaxation, when it is accompanied by a mechanism of scattering from impurities or phonons with momentum nonconservation. This mechanism of spin relaxation became known as the Elliott – Yafet mechanism [16].

A typical spin relaxation time T_1 amounts to several nanoseconds (the record time $T_1 \approx 1$ μs was measured in very pure Na at low temperatures). Thus, spin relaxation is an unimaginably drawn-out process as compared to momentum relaxation: the momentum relaxation time τ amounts to several dozen femtoseconds at room temperature. A rough estimate yields $T_1 \approx \tau/b^2$, where $b \approx V_{SO}/\varepsilon_F \ll 1$ (V_{SO} is the average spin – orbit coupling energy, and ε_F is the Fermi energy).

However, in addition to spin-flip scattering, the reason for substantial reduction of the magnetoresistance may be electron scattering by the interface, which is related to the special features of the electronic structure for 3d-ferromagnetic metals. As noted earlier, these metals contain two groups of electrons at the Fermi level: sp-symmetry electrons and d-symmetry electrons, with the density of states for the subband with 'up' spin for sp-electrons exceeding the density of states for the subband with 'down' spin. For the d-electrons, the situation is just the opposite. The tunneling process involves mainly sp-electrons with momentum directed almost perpendicularly to the surface of the interface between the ferromagnetic metal and the insulator. If this surface is rough, the tunneling probability for sp-electrons decreases because of sd-scattering, but at the same time the d-electrons scatter into the sp-band, and this leads to an increase in the tunnel current. This situation has been studied in Ref. [17] where the expressions were derived for the total current with allowance made for scattering from the interface in the case of parallel orientation of the magnetizations of the ferromagnetic electrodes:

$$j^{P} \sim (\rho_s^{\uparrow})^2 + (\rho_s^{\downarrow})^2 + \Gamma^{\uparrow}\rho_d^{\uparrow}\rho_s^{\uparrow} + \Gamma^{\downarrow}\rho_d^{\downarrow}\rho_s^{\downarrow} ,$$

and in the case of antiparallel orientation, one has

$$j^{AP} \sim 2\rho_s^{\uparrow}\rho_s^{\downarrow} + \Gamma^{\uparrow}\rho_d^{\uparrow}\rho_s^{\downarrow} + \Gamma^{\downarrow}\rho_d^{\downarrow}\rho_s^{\uparrow} ,$$

where $\rho_{s(d)}^{\uparrow(\downarrow)}$ is the density of s(d) states of electrons with spins $\uparrow(\downarrow)$, and $\Gamma^{\uparrow(\downarrow)}$ is a dimensionless factor smaller than unity that characterizes the intensity of electron scattering from the interface roughnesses. For an ideal interface, this factor is zero and increases with the scattering amplitude by the interface. This implies that

$$j^{P} - j^{AP} \sim (\rho_s^{\uparrow} - \rho_s^{\downarrow})^2 + (\Gamma^{\uparrow}\rho_d^{\uparrow} - \Gamma^{\downarrow}\rho_d^{\downarrow})(\rho_s^{\uparrow} - \rho_s^{\downarrow}) .$$

The first term on the right-hand side is always positive, while the second is negative (in view of the conditions $\rho_s^{\uparrow} > \rho_s^{\downarrow}$ and $\rho_d^{\uparrow} < \rho_d^{\downarrow}$). Thus, tunneling magnetoresistance decreases as the quality of the interface declines, a fact that has been repeatedly verified in experiments.

Finally, a new way to solve the problem of increasing tunneling magnetoresistance and simultaneously decreasing electrical resistance has been proposed, namely, a system comprised of three barriers which are separated by thin ferromagnetic metallic layers may be used as a tunnel junction. In this case, the motion of electrons in the middle layers is quantized, with the position of the quantum levels depending on the direction of the electron spin. Thus, when the layer magnetizations are parallel, the electron with one direction of its spin tunnels in a resonant manner, but when the magnetizations are antiparallel, the positions of the

resonance levels in the metallic layers do not coincide and the tunnel current has no resonant features. However, for a device of this type to become realizable, the interface between the ferromagnet and the insulator must be nearly ideal, which is practically impossible to achieve with the modern level of technology.

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Circular photogalvanic effect in nanostructures

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1. Introduction. Phenomenological description

During recent years spin-related phenomena in the physics of heterostructures have aroused heightened interest among researchers (e.g., see the review article [1]). The advances in studies of optical orientation in semiconductors [2–4] and spin phenomena in metallic heterostructures [5] form a base for developing such solid-state electronic devices as a spin transistor [6] and a quantum computer [7–9], which both utilize the additional degree of freedom of the electron, viz. its spin. The fabrication of spintronic devices relies on the effects of injection and detection of spin-polarized carriers, on the fact that the spin relaxation times of these carriers in electron transport are long, and on the possibility of controlling the spin polarization by an external electric field [10–13].

One of the most investigated and widespread methods of spin injection consists of using circularly polarized light whose absorption in semiconductors gives rise to spin orientation of the charge carriers [2]. Recently Ganichev et al. [14, 15] discovered that optical orientation in semiconductor heterostructures is accompanied by generation of an electric current. The emergence of such a constant electromotive force, which is induced by light, depends on the sign of circular polarization of the light, is not related to the spatial inhomogeneity of the irradiation or the inhomogeneity of the medium, and has been studied earlier in bulk crystals (see Refs [16–18]), became known as the circular photogalvanic effect (CPGE). Physically this effect consists of transforming the angular momentum of photons into the translational motion of free charge carriers and is described phenomenologically by the following relation

$$j_\lambda = \gamma_{\lambda\mu}\, \mathrm{i}(\mathbf{E}\times\mathbf{E}^*)_\mu\,. \qquad (1)$$

Here, $\mathbf{j}$ is the induced photocurrent density, and $\mathbf{E}$ is the complex-valued amplitude of the electric field of the light wave; for a transverse wave we have the identity $\mathrm{i}(\mathbf{E}\times\mathbf{E}^*) = E_0^2\, P_{\mathrm{circ}}\, \hat{\mathbf{e}}$, where E_0 is the amplitude of $|\mathbf{E}|$, P_{circ} is the degree of circular polarization, and $\hat{\mathbf{e}}$ is the unit vector pointing in the direction of light propagation. According to equation (1), CPGE is allowed in systems without an inversion center, whose point symmetry does not distinguish between the components of polar and axial vectors. It is precisely gyrotropic crystals that possess this property. CPGE was predicted independently in Refs [19, 20] and was first discovered in tellurium [18]. This effect can also manifest itself in two-dimensional (2D) nanostructures [21], which was demonstrated in experiments involving semiconducting quantum wells [14, 15, 22]. Studies of CPGE and its dynamics make it possible to extract information about spin relaxation times in semiconductor nanostructures [23] and the width of the spin splitting which plays an important role in controlling spin processes; they also provide a new instrument for investigating the symmetry of heterostructures and spin injection processes.

More than that, in low-symmetry heterostructures, the nonequilibrium spin orientation leads to appearance of a current irrespective of the way in which such orientation was achieved [21, 24]. Since the operation of the elements of spintronics assumes the presence of strong polarization, it is obvious that this new class of spin-galvanic phenomena must be taken into account in developing electronic devices. The present report discusses the results of a combined theoretical and experimental investigation into the CPGE in quantum wells and the mechanism of this effect in one-dimensional systems, namely, in chiral carbon nanotubes.

2. CPGE in 2D structures with a zinc blende lattice

Bulk semiconductors with a zinc blende lattice are nongyrotropic (the crystal class T_d), so that CPGE is forbidden in them. In heterostructures with quantum wells grown from such semiconductors, the point symmetry is lowered to D_{2d} in a symmetric quantum well with a growth axis [001], to C_{2v} in an asymmetric quantum well or a single heterojunction with a growth axis [001], and to C_s in a 2D structure grown along a low-symmetry axis $[hhl] \neq [001], [111]$. In all three cases the tensor γ in equation (1) comprises nonzero components. In what follows we use Cartesian coordinate axes x, y, and z that are parallel to the crystallographic directions $[1\bar{1}0]$, $[ll(\overline{2h})]$, and $[hhl]$, respectively. Since barriers obstruct the motion of charge carriers along the growth axis, in quantum wells the index λ entering into Eqn (1) runs through the