



Review Article

SPINTRONICS. PROBLEMS AND PROSPECTS OF PRACTICAL APPLICATION

Mykola M. Kpyna

Institute of Magnetism National Academy of Science of Ukraine, Kiev. krupa@imag.kiev.ua

Abstract.

IN the present article we want to describe the main methods and schemes that are used in constructing spintronics elements and devices, and also give a brief analysis of the prospects for their introduction into practice. In our opinion, spintronics devices can replace microelectronic devices in some limited field of technology. First of all, this is the area of registration and processing of small permanent and microwave signals. For such signals, spintronic elements based on metal nanofilms, in comparison with semiconductor elements of microelectronics, have a lower noise level, a high coefficient of thermal stability, and can be used in a higher frequency range. It is most expedient to use the elements of spintronics as high-sensitivity sensors of the magnetic field, in the special devices for recording and storing a data, and for constructing the small-size sources of high-frequency radiation in the gigahertz and terahertz frequency regions.

Keywords: spintronic, magnetic material, spin current spin Hall effect, spin data recording, terahertz radiation.

Introduction

Spintronics is based on the transport processes of spin-polarized current between the elements of electronic devices. The spin current control involves availability of spin current injectors, control apparatuses of electron spin orientation and elements of a spin current filtration. Therefore, the main areas of research in spintronics are the search for new materials with a high degree of spin polarization of the conduction electrons, studies of the laws of spin relaxation in solids and spin-dependent transport in spintronics elements, and the development of methods and schemes for controlling these processes. Unfortunately, in many scientific works, especially in theoretical studies, idealized structures and models are considered without taking into account the influence of technological and constructive factors on the working capacity and the possibility of the practical realization of the investigated elements and devices of spintronics. However, in experimental studies it is necessary to have good repeatability of the measurement results not only on one test sample, but also to obtain these results on many identical samples.

In the series manufacture, even more stringent requirements are imposed on the element or device being manufactured. Such critical requirements are high technical and operational characteristics, as well as manufacturability of production and the possibility of using existing processes and production equipment. Therefore, researchers need to take into account these requirements, and if they do not conduct detailed experimental studies of the influence of these factors on the characteristics of the elements and devices under investigation, then they should conduct at least a comprehensive theoretical analysis of this issue. Such an approach to scientific research will ensure faster and more qualitative introduction of research results into practice.

In this article, we want to describe the main methods and schemes that are used in constructing spintronics elements and devices, and also give a brief analysis of the prospects for their introduction into practice. We hope that our article will be useful not only for researchers but also for the development of new spintronics elements.

History:

Received: June 7, 2017
Accepted: July 17, 2017
First Published:
Collection year: 2017
Confirmation of publication: Published

Identifiers and Pagination:

Year: 2017
Volume: 2
First Page: 1
Last Page: 9
Publisher ID: AdvEngTech.2.1

Corresponding author:

Mykola M. Kpyna, Institute of
Magnetism National Academy of
Science of Ukraine, Kiev.
krupa@imag.kiev.ua

Citation:

Mykola. Spintronics. problems and
prospects of practical application.
Adva Eng Tech. Vol. 2: 2017. p. 1-9

Funding:

The authors received no direct funding for this research.

Competing Interests:

The authors declare no competing interests

Additional information is available at the end of the article.

Spin Current Control

The ideal material for spintronics should have high conductivity and all conduction electrons in it at room temperature should have the same polarization, that is, their spins should be oriented in a direction specified by the magnetic field. Therefore, the search for materials with a high degree of polarization of electrons is one of their priority tasks in spintronics. At room temperatures there is a predominant orientation of electron spins in ferromagnetic metals, magnetic semimetals and magnetic semiconductors [1-6]. For the latter the spin polarization degree at the Fermi surface can reach 100%. Currently, spintronics uses mainly ferromagnetic metals such as Fe, Co and Ni, as well as their alloys. In the ferromagnetic metals at the Fermi level in the magnetization state, a spin (exchange) splitting of the electron band is observed (Figure 1): on a zone with spins directed along the material's magnetization (the lowest band with minimal energy), and on a zone with spins directed against the magnetization of the material (upper zone with higher energy). The splitting Δ represents a ferromagnetic gap in the spectrum of electrons of such a metal. In ferromagnetic 3d-metals (Fe, Co, Ni), as a result of the exchange spreading of the 3d bands, the zone of electrons with spins "up" and "down" are filled in differently and have different density of states $N(E)$ at the Fermi level E_F . In the conductivity of ferromagnetic metals, along with valence electrons (s- and p-type), polarized 3d-electrons (in any case, their significant part) also take part. Therefore, in electronic transport in ferromagnetic metals, in the weak electric fields with a field intensity $E < \Delta/e$, the prevailing direction of the spin polarization of the conduction electrons arises. Polarization is due to an imbalance between electrons with spin "up" and with spin "down". The carrier retains its polarization of the spin until it collides with another magnetic atom or interacts with the lattice due to the spin-orbit coupling.

Ferromagnetic properties also have semiconductors doped with ferromagnetic elements and some semimetals. In ferromagnetic semiconductors and semimetals in the state of magnetization, the exchange splitting Δ is sufficiently large. The upper spin zone in them is practically empty and the electron transport in such materials is almost entirely provided by spin-polarized electrons [2,6] (Figure 1.). Therefore, ferromagnetic semiconductors and ferromagnetic semimetals are a promising material for creating spin injectors in spintronics elements.

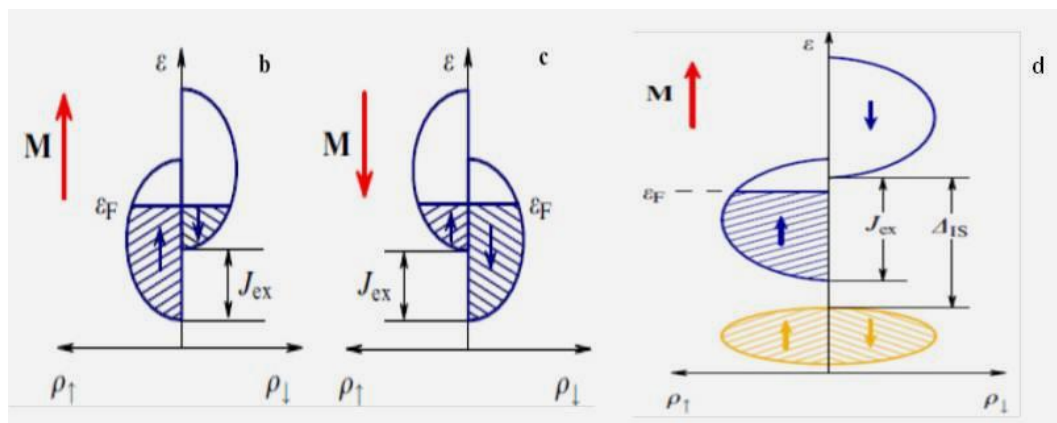


Figure 1. Scheme of the spin-splitting of the band spectrum caused by the exchange interaction J_{ex} , where $\rho_{\uparrow}$ and $\rho_{\downarrow}$ are the densities of electron states with different spin projections ($\uparrow, \downarrow$), $\mathbf{M}$ is the magnetization vector: b and c – ferromagnetic metal, d – magnetic semimetals.

The magnetic properties of ferromagnetic semiconductors are caused by the interaction between

electrons in the *sp*-band of the semiconductor and by electrons on the *d*-shell of the impurity. Such an interaction is one of the forms of the Heisenberg exchange interaction with the Hamiltonian $H = -JsS$, where J is the exchange integral between the spin of the main carriers of the semiconductor (s) and the transition element (S). In particular, the *s*-electron in the conduction band experiences an *s-d* exchange interaction with the energy of the order of one hundred electron-volts $J_{sd} \sim 0.1$ eV. The energy of such an interaction is much weaker for the case of holes in the valence band of a semiconductor. As a result, in the conduction band of the ferromagnetic semiconductors there is the splitting and the value of splitting is proportional to the magnitude of the localized magnetic moment of the ferromagnetic semiconductors.

One of the most important parameters in ferromagnetic semiconductors is the Curie temperature T_c . The value of T_c increases usually with increasing the concentration of doping magnetic atoms. However, the magnetic impurity atoms form inhomogeneous clusters at large concentrations [3, 4]. It is possible to obtain a higher concentration of magnetic impurities in thin semiconductor films, but the value of T_c in such materials is not much higher than room temperature. Another the important parameter of the magnetic semiconductors is the degree of polarization P of the carriers in the conduction band. The value of P increases with the ratio of the band splitting to the Fermi energy. At low temperatures, the value of P can approach $P = 100\%$, but the conductivity of the ferromagnetic semiconductor decreases with decreasing temperature. These features of magnetic semiconductors are their main deficiency when used in spintronics.

More sustained performance has the ferromagnetic semimetals, which include some ferromagnetic oxides and Heusler alloys [2,3,7]. The Heusler ferromagnetic alloys include a combination of three metals and most of them have a sufficiently high Curie temperature and good conductivity. Many semi-Heusler alloys (NiMnSb, PtMnSb) and full-Heusler alloys (Co₂MnSi, Co₂MnGe, Co₂MnSn, Fe₂MnSi) have a high degree of spin polarization of conduction electrons. However, the Heusler ferromagnetic alloys are complex alloys, which complicates the technology of obtaining thin films from these alloys.

The high degree of spin polarization of conduction electrons and the high Curie temperature have ferromagnetic oxides (CrO₂ and Fe₃O₄) [8], manganites (La_{0.7}Sr_{0.3}MnO₃) and double perovskites (Sr₂FeReO₆) [9-11]. However, ferromagnetic oxides have poor conductivity, and chrome dioxide is difficult to obtain due to the complexity of the phase diagram of coexistence. Manganites and double perovskites have quite good conductivity, but their production is a rather complex process.

High degree of spin polarization can be received also in the conducting metals which have the strong spin-orbital interaction. In the heavy metals (for instance Pt, Ta), the spin polarization occurs through the spin-induced transverse deflection (relative to the electric current) and in opposite directions electrons with opposites spin projections, known as the spin-Hall effect [12-15]. In this case, the spin-orbit interaction generates pure spin currents transversally to the input electric current, as it is represented in Figure 2 [15].

In the second type, the spin-orbit interaction generates the spin polarization nearby the interface which is caused by spin splitting of an electron band spectrum (known as the Rashba effect) [16-18]. In real systems, the size of the Rashba spin splitting (Figure 2) [16] depends on the asymmetry of the electronic wave function near heavy nuclei. The size of the spin splitting is highly sensitive to the detailed atomic structure at the interface or surface.

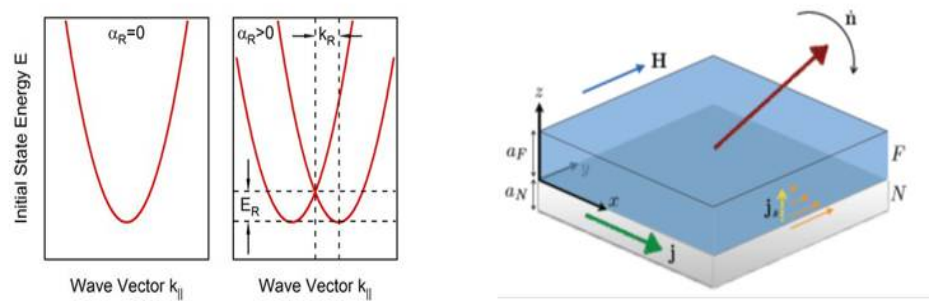


Figure 2. The dispersions of the two-dimensional electron gas previous to (on the left) and after (on the right) action of the Rashba spin-orbit interaction causing the spin-splitting along of planar momentum vector $k_{||}$; α_R is the Rashba parameter, k_R is the offset away from $k_{||} = 0$ of the spectral curves relative to the initial position. The spin Hall effect of the spin-orbit-conversion of the input electric current $\mathbf{j}$ in the transverse spin current $\mathbf{j}_s$ with the spin polarization denoted by arrows along the y axis in the two-layered magnetic nanostructure (on the right). The latter is composed of the bottom layer made of heavy normal metal (N) and the strong spin-orbit interaction and the upper ferromagnetic layer (F). The spin current exerts on the dynamics of magnetization $\mathbf{n}$ of the magnetic layer, $\mathbf{H}$ is external magnetic field.

Obviously, in the production of spintronic elements the problem concerning the adaptation of using materials to existing microelectronic technology arises. The materials of spintronics should not change their properties under the influence of humidity, pressure, temperature and be integrated with modern microelectronics and be "technological", for example, allowing the application of the ohmic contact. The majority of known semimetals are complex compounds, and for their practical use it is necessary to conduct works on working out of manufacturing techniques of thin films.

It is necessary to understand, that the devices of spintronics can replace the similar devices of microelectronics in rather limited areas of technology. First of all, it is the area of registration and processing of small constant and super-high-frequency electromagnetic signals. For such signals elements of spintronics based on metallic nanofilms compared to the semiconductor elements of microelectronics possess a lower degree of noise, high thermal stability factor and can be used in a higher frequency range. The elements of spintronics can compete, in our opinion, with the elements of semiconductor microelectronics in the small-size magnetic field sensors, in the devices of high-speed non-kinematic data recording and the devices for generating the electromagnetic radiation in the gigahertz and terahertz frequency range. Separately, we should note the prospect of using the elements of spintronics in devices of special and military equipment.

The basic material for creation the elements of spintronics are multilayered heterogeneous magnetic nanofilms which are the electrodes in these elements. To control the spin current in the elements of spintronics, it is necessary to change the magnetization direction of the control magnetic electrode. This can be done with the help of a magnetic field of electric current, which flows through the special electrodes. However, such the method is ineffective for creating a sufficiently strong magnetic field in the local nano- and even the microregion. Recently, a number of new methods of controlling the spin current have been proposed. The most interesting and practically perspective methods are: the switching of control nanoelectrode (the free electrode) under the action of the magnetic field of a spin-polarized current injected from the magnetic pinned reference electrode [19-22], the thermomagnetic switching of control nanoelectrode (the weak free electrode) in the multilayers magnetic structure with the temperature-variable interlayer exchange interaction between the magnetic high-coercivity layer (the pinned reference electrode) and magnetic low-coercivity layer (the weak free electrode) [23], the thermomagnetic switching of control nanoelectrode due to the exchange interaction in the antiferromagnetic layer with two magnetic sublattices [24], the switching of the magnetic layer under the action of the magnetic field of spins in the spin Hall effect [12-15] and

the switching of the magnetic layer due to the Rashba effect [17, 18].

The switching of the control nanoelectrode by a spin current occurs due to the injection of spin-polarized electrons into this electrode, which create a control magnetic field (Figure 4). The injected spin-polarized current or the spin current in combination with an *s-d*-exchange interaction can result in the electric-driven magnetization dynamics in the form of the magnetization switching or magnetization precession. With a large value of such the nonequilibrium magnetic field, the control electrode reverses magnetization along the direction of the magnetic field given by the spin current. A great quality of this method is the possibility of locally switch of the conductivity not only in the microstructures but also in the nanostructures with the help of short nanopulses of the electric current. The main shortcoming is the inability to reverse switch in a structure with two magnetic nanolayers when the polarity of the electric pulse is changed. For this, it is necessary to create the magnetic structures with three magnetic nanolayers (Figure 3), which have a different coercive force [21, 22].

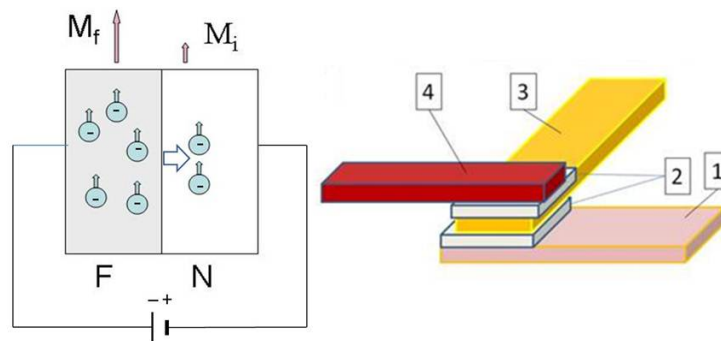


Figure 3. Scheme of generation of nonequilibrium magnetic field in the nonmagnetic nanolayer (N) (at the left) under the injection of the spin-polarized electrons from ferromagnetic nanolayer (F) and the scheme of the rerecording cell (at the right) under the spin current: 1 – ferromagnetic electrode (pinned electrode), with coercive force H_1 ; 2 – barrier nanolayer, 3 – ferromagnetic electrode (free electrode), with coercive force H_3 ; 4 – ferromagnetic electrode (pinned electrode), with coercive force H_4 ($H_4 > H_1 > H_3$).

In the magnetic nanostructures based on the heavy normal metal and magnetic layers the spin current, caused by the spin-Hall effect, enters into the magnetic layer exerting the torque on magnetization and its switching or precession. The features of the mentioned electric-controlled magnetization dynamics are determined by the electron and magnetic structures of the nanolayers and interfaces of the magnetic nanostructures. The mentioned magnetic nanostructures are viable whereas they are characterized by low threshold magnitudes of the input current density required for manipulation by magnetic states at a high thermal stability. Heavy metals with the enough strong spin-orbit coupling can provide a giant spin Hall effect generating spin current intense enough to induce efficient spin-transfer-torque switching of ferromagnets, thereby providing a new approach for controlling magnetic devices that can be superior to existing technologies. In this case, the spin-torque-switching of both out-of-plane and in-plane magnetized layers of can be realized, that permits eliminate the main obstacles currently impeding the development of magnetic memory and non-volatile spin logic technology. The schemes of the corresponding magnetic nanostructure and the magnetic member are depicted in Figure 4 [25].

The switching of the magnetic layer under the action of the magnetic field of the spins produced by the spin-Hall effect has a good prospect of practical use in the elements of spintronics. This method allows one to simply change the direction of the effective magnetic spins, by changing the direction of the electric current, and also to obtain sufficiently strong magnetic fields due to the transmission of a large current. However, it is unlikely to find applications in the manufacture of microchips due to the complexity of the design and manufacturing technology. On the other hand, on the basis of this

effect, good results have already been obtained in the generation of high-frequency electromagnetic radiation due to the oscillation of the magnetic moment in magnetic films [19]. Spin torque oscillator, based on the magnetization precession, has attracted much attention as a future nanocommunication device because it can produce a large emission power ($P > 1 \mu\text{W}$), a high quality factor ($Q > 10^3$), a high oscillation frequency ($F > 1 \text{ GHz}$). In spin Hall oscillators are used generally the magnetic nanolayers from magnetic materials with great values of magnetization and small coercive force that increases magnitude of signal. However in such layers it is difficult to receive rotation of the magnetic moment with the frequency even 1 terahertz. The use of ferrimagnetic layers in the spin Hall's oscillators makes it possible to increase the generation frequency to ten terahertz and maybe up to a hundred terahertz.

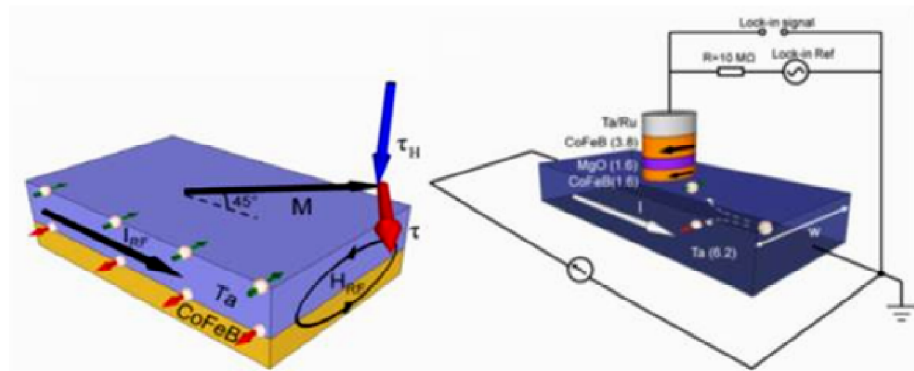


Figure 4. Schematic of the two-layered magnetic nanostructure with the electric-driven magnetization via the effect of the spin Hall generation of the spin current which enters into the magnetic nanolayer. I_{RF} is the electric current vector, red and green arrows denote spin directions, τ_H is the torque on the magnetization due to the Oersted field and the τ_{ST} is the spin-transform-torque from the spin Hall effect (on the left). Schematic of the spin-hall magnetic member with red out based on the tunnel magnetoresistance effect (on the right).

The thermomagnetic switching in a magnetic structure with a temperature-variable interlayer exchange interaction between a magnetic layer with a high coercive force and a magnetic layer with a low coercive force has a weak prospect of the practical use in spintronics not only because it is difficult to localize heating and cooling in the local the micro and nanozone, it is more difficult to realize high-frequency switching back and forth. The switching of the magnetic layer under the action of the Rashba effect can be used in low-power spintronics elements, in which magnetic materials are made of magnetic semiconductors.

The thermomagnetic switching of the antiferromagnetic layer due to the exchange interaction requires a very high rate of heating by ultrashort pulses also requires strict control of the heating temperature. This method is used only for switching of ferrimagnetic films by femtosecond laser pulses and can not be used in spintronics elements.

It is necessary to notice, that passing the spin-polarized current through a row of the regular tunnel structures with two oppositely magnetized layers it is possible to receive effective generation of high-frequency radiation. The analog of such structure is the semiconductor cascade laser. Such sources of the radiation work on the basis of the electron transitions between the spin levels which are split in a magnetic field. The energy of spin splitting in magnetic materials is in area $E = 0,05-0,001 \text{ eV}$, what corresponds to the terahertz area of frequencies of electromagnetic radiation. The population inversion on spin levels can be reached through a pumping of the spin polarized electrons on the top spin-split level.

The device scheme, in which radiation on spin transitions is received, is presented in Figure 5.

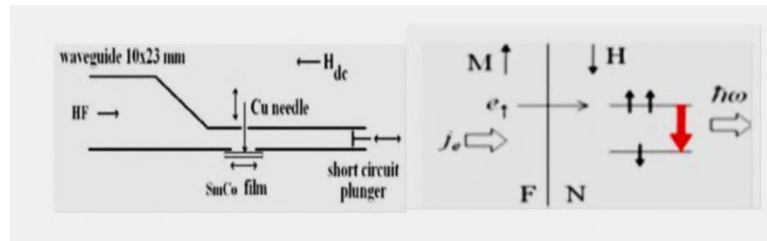


Figure 5. Schematic of the double magnetic structure composed of the needle-like nonmagnetic metallic electrode contacting with the magnetic film. H_{dc} is the external magnetic field determining the spin-splitting and the radiation frequency (upwardly). Schematic of spin-flip transitions accompanied by photon emission (below). Magnetization M and applied field H are antiparallel, majority electrons in the ferromagnetic F are injected into the normal metal N , leading to an inverse population of the Zeeman levels in N . A spontaneous or stimulated spin-flip transition emits a photon with frequency corresponding to the spin-splitting.

Here, point contacts between high anisotropy ferromagnetic SmCo5 and normal metal Cu are used to achieve a strong spin-population inversion in the contact core. Subjected to microwave irradiation in resonance with the Zeeman splitting in Cu, the inverted spin-population relaxes through stimulated spin-flip photon emission, detected as peaks in the point contact resistance. Resonant spin-flip photon absorption is detected as resistance minima, corresponding to sourcing the photon field energy into the electrical circuit. The illustration of the spin-flip photon emission processes, for a majority ferromagnetic injector, such as SmCo5, the electrons injected into the normal metal (N) have their magnetic moment along the magnetization M of the ferromagnetic (F). With the external field applied anti-parallel to M , as in Fig. 3a, the electrons injected into the normal metal populate the high-energy Zeeman level there, which leads to an inverse population of the two spin-split levels. This inverse population is not in equilibrium but maintained by the bias current through the PC. Intrinsic spin relaxation in such weak spin-orbit nonmagnetic metals as Cu is relatively slow, so spin-flip relaxation through emission or absorption of photons can be dominant. [26]

Conclusion

It is clear, that in the ferromagnetic metals the magnitude of terahertz radiation signal should be small however in the semimetals it is possible to expect useful the increase of power of such terahertz signal. The practical realization of the source of the THz radiation based on the viable and technological materials (including magnetic semimetals) and using the effect of the spin-orbit generation of spin current and gaining corresponding prototypes of the mentioned sources of THz radiation have very good perspective.

Conclusion

In conclusion we wish to tell, that scientific analysis and our conclusions resulted in given article are not invariable and unquestionable. The development of technics and technology should and will lead to their change. However, we hope that our analysis corresponds generally level of modern scientific and technological works. We hope also, that our article will be useful to young researchers that it emphasizes importance of the comprehensive approach at studying of any physical phenomenon, and also emphasizes importance of the practical use of the received results.

References

1. Ohno, H.(1998). Making Nonmagnetic Semiconductors Ferromagnetic. *Science*, 281, 951-956.
2. Žutić, I., Fabian. J., Sarma. S. (2004). Spintronics: Fundamentals and applications. *Review of Modern Physics*. 76, 323-413.
3. Cibert, J., Bobo, J., Lüders, U. (2005). Development of new materials for spintronics. *Comptes*

Rendus Physique, 6, 977-996.

4. Al-Nuaimy, E. A., Al Abdulqader, H. (2008). BJT Fabrication Using Excimer Laser Assisted Spin-on Doping Technique. *Journal of Electron Devices*, 6, 197-202.
5. Irkhin, V. Yu., Chioncel, L., Lichtenstein, A. I., Groot, R. A. (2010). Half-metallicity in NiMnSb: A variational cluster approach with ab initio parameters. *Review of Modern Physics*, 81, 315-323.
6. Volkov, N. V. (2012). Spintronics: manganite-based magnetic tunnel structures, *Physics Uspekhi*, 55, 250-259.
7. Feng, L., Ma, L., Zhu, Z. Y., Zhu, W., Liu, E.K. (2010). Ferromagnetic exchange interaction between Co and Mn in the Heusler alloy CuCoMnAl. *Journal of Applied Physics*, 107, 013913-1-013913-5.
8. Gutiérrez-Pérez, R. M., Holguín-Momaca, J. T., Elizalde-Galindo, J. T., Espinosa-Magaña, F., Olive-Méndez, S. F. (2015) Giant magnetization on Mn₃Ga ultra-thin films grown by magnetron sputtering on SiO₂/Si(001). *Journal of Applied Physics*, 117, 123902. doi: [10.1063/1.4916158](https://doi.org/10.1063/1.4916158)
9. Zhang, C., Sun, D., Sheng, C. X., Zhai, Y. X., Mielczarek, K., Zakhidov, A., Vardeny, Z. V. (2015). Magnetic field effects in hybrid perovskite devices. *Nature Physics*, 11, 427-434.
10. Lee, Hong-Sub., Park, Hyung-Ho. (2015). Band Structure Analysis of La_{0.7}Sr_{0.3}MnO₃ Perovskite Manganite. Using a Synchrotron. *Advances in Condensed Matter Physics*, 2015, 746475-746481. doi:10.1155/2015/746475.
11. Lopez, C. A., Viola, M. D., Pedregosa, J. C., Alonso, J. A., Fernandez-Diaz, M. T. (2010). Enhancing Magnetic and Magnetotransport Properties by Topotactic Reduction of the Sr₂Fe_{1.33}Mo_{0.66}O₆ Double Perovskite. *European Journal of Inorganic Chemistry*, 26, 4110-4120.
12. Hoffmann, A. (2013). Spin Hall Effects in Metals. *IEEE Transport Magnetic*, 49, 5172-5193.
13. Tserkovnyak Y., Bender S. A. (2014). Spin Hall phenomenology of magnetic dynamics, *Physic Review*, B90, 014428- 014434.
14. Ebrahim-Zaden, N., Urazhdin, S. (2013). Optimization of Pt based spin-Hall effect spintronic devices. *Applied Physic Letters*, 102, 132402-132411.
15. Cheng, R., Zhu, J.G., Xiao, D. (2016). Dynamic Feedback in Ferromagnet/Spin-Hall Heterostructures. *Physic Review Letters*, 117, 097202-097206.
16. Bychkov Yu. A., Rashba E. I. (1984). Properties of a 2D electron gas with lifted spectral degeneracy. *JETP Letters*, 39, 78-81.
17. Miron, I.M., Gaudin, G., Auffer, S., Rodmacq, D., Schuhl, A., Pizzini, S., Vogel, J., Gambardalla, P. (2010). Current-driven spin torque induced by the Rashba effect in ferromagnetic metal layer. *Nature Materials*, 9, 230-234.
18. Wang, X., Manchon, A. (2012). Diffusive Spin Dynamics in Ferromagnetic Thin Films with a Rashba Interaction. *Physic Review Letters*, 108, 117201-117205.
19. Slonczewski, J.C. (1996). Current-driven excitation of magnetic multilayers. *Journal of Magnetism and Magnetic Materials*, 159, L1-L7.
20. Katine, J., Albert, F., Buhrman, R., Myers, E.B., Ralph, D.C. (2000). Current-Driven Magnetization Reversal and Spin-Wave Excitations in Co/Cu/Co Pillar. *Physic Review Letters*, 84, 3149-3152.
21. Krupa, M. M. (2024). Control Spin Current and data recording on spin storage medium. *SPIN*. 4, 1450006-1-1450006-4. doi: 10.1142/S2010324714500064.
22. Krupa, M. M. (2014). Method of a magnetic recording of the information and a magnetic spin data carrier. *Patent of Ukraine 19 UA 106260*, publication 11.08.2014, bull. №15.
23. Kravets, A.F., Timoshevskii, A.N., Yanchitsky, B. Z., Bergmann, M. A., Buhler, J., Andersson, S., Korenivski, V. (2012). Temperature-controlled interlayer exchange coupling in strong/weak ferromagnetic multilayers: A thermomagnetic Curie switch. *Physic Review B*, 86, 214413-214427.
24. Luqiao Liu L., Pai C. F., Li Y., Tseng H.V., Ralph D. C., Buhrman R. A. (2012). Spin torque

switching with the giant spin Hall effect of tantalum. *Science*, 336, 555-562. doi: 10.1126/science.1218197.

25. Naidyuk Yu.G., Balkashin O.P., Fisun V.V., Yanson I.K., Kadigrobov A., Shekhter R.I., Jonson M., Neu V., Seifert M., Andersson S., Korenivski V. (2012). Stimulated emission and absorption of photons in magnetic point contacts. *New Journal of Physics*, 14, 1-10. doi:10.1088/1367-2630/14/9/093021.
26. Tankhilevich, B. G., Korenblit, Y. (2011). Novel spintronic device: terahertz magnon-photon laser, *Journal of Physics*, . 263,01204-01216/



© 2017 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.

You are free to:

Share — copy and redistribute the material in any medium or format. Adapt — remix, transform, and build upon the material for any purpose, even commercially. The licensor cannot revoke these freedoms as long as you follow the license terms. Under the following terms: Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made. You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use. No additional restrictions. You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits