From the Editors

This issue of RENSIT journal, 2018, 10 (3) is devoted to spintronics, one of the most rapidly developing areas of science and technology. And although it was not possible to organize a selection of works on the most acute problems of spintronics within a single issue, the editors of the journal believe that a certain slice, reflecting the level and variety of research developed primarily in Russia, is nevertheless marked. The editors hope that further work on the most pressing problems of the development of spintronics will be reflected in the pages of our journal.

SPINTRONICS: PHYSICAL FOUNDATIONS AND DEVICES

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Abstract. **"Spintronics" is one of the most rapidly developing branches of science and technology, which is currently considered as the most promising technology for the further development of the elemental base for information technology. Spintronics includes physical effects caused by the spins of individual electrons and spin-polarized currents flowing in thin magnetic and semiconductor films and heterostructures, and information processing devices based on them. The review provides qualitative estimates demonstrating potential advantages of spintronics in comparison with semiconductor micro- and nanoelectronics. Physical phenomena that form the scientific basis of spintronics, such as domain microstructures, skyrmions, spin waves, spin-polarized current, giant and tunnel magnetoresistance, spin transfer of angular momentum are considered. Prospective spintronics materials, including ferromagnetic metals and semiconductors, semimetal ferromagnetic oxides, Heusler alloys are listed. The possibilities of controlling spin currents using magnetic fields, mechanical deformations in multiferroic structures, and ultrashort optical pulses are shown. The spintronic devices that are under development or already made are described, such as high-sensitivity magnetic field sensors, random access magnetic memory elements, ultra-high frequency nanogenerators, spin diodes and spin transistors, and a spin holographic processor. The final part lists the main research centers for spintronics abroad and in Russia, and provides a list of overview publications on the topic.**

Keywords: **spintronics, magnetic heterostructures, spin-polarized current, spin waves, skyrmion, magnetoresistance, tunnel effect, magnetic field sensors, spin transistor, spin generator, spin processor**

PACS: 67.57.Lm, 72.25.Ba, 75.70.-i, 75.76.+j

Bibliography - 23 references *Received 19 March 2018; accepted 21 May 2018*

RENSIT, 2018, 10(3):343-356 **DOI: 10.17725/rensit.2018.10.343**

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1. INTRODUCTION

The term "spintronics" represents one of the fastest growing direction of science and technology, which, apparently, will make a significant contribution to the development of electronics and information technology in the 21st century. Almost all currently existing electronics is based on the process of electron's charge transfer – electric current. An attempt to use the second fundamental characteristic of an electron, its own magnetic moment – "spin", opens new possibilities to improve performance of existing elecronic devices and create new devices, including the development of high-sensitivity magnetic field sensors, data storage elements with higher recording density and higher operation speed, microwave and terahertz nano-oscillators, new methods of information processing using quantum coherent effects, etc. As many specialists believe, the traditional semiconductor electronics approaches its physical limits in terms of miniaturization and operation speed. This will result in violation of the Moore's law in the near future, which predicts an increase of the computers power by a factor of two every 18 months. Since significant part of the modern economy is based on information technology, the solution of this problem is of specific importance. Currently, the spintronics is considered as the most promising base for further development of the information technology.

In the broad sense, the term "spintronics" include physical effects of magnetic nature, which arise because of magnetic properties of substances and are associated with their own spin and orbital magnetic moments of electrons, as well as their applications in micro- and nano-sizes information processing devices [1-3]. Such phenomena (domains in magnetic films, magnetic resonances, spin waves, magnetoresistance, etc.) are investigated and successfully used in practice for more than 100 years. In a narrow sense, the term "spintronics" includes physical effects which arise due to the spins of individual electrons and spin-polarized currents. Such effects as the spin-dependent transport, tunnel magnetoresistance, excitation of ferromagnetic resonance by a spin- polarized current, etc were discovered in the 1980s. Some of these effects have already found practical application and had a revolutionary impact to the development of information technologies [4-6].

This review provides qualitative estimates which demonstrate potential advantages of spintronics in comparison with traditional electronics, enumerates basic physical phenomena and materials, forming a scientific basis of spintronics, and presents some spintronic devices that have already been fabricated or will be created in the near future.

2. ELECTRONICS AND SPINTRONICS

According to the ideas of modern physics, the behavior of elementary particle "electron" is described by the quantum mechanics. The electron has a mass $m = 9.1{\cdot}10^{-31}$ kg, carries an elementary charge $e = 1.6{\cdot}10^{-19}$ C, has its own mechanical moment $J = h/4\pi$ (where $h = 6.62{\cdot}10^{-34}$ J·is the Planck's constant) and associated magnetic moment $M = \mu_B = 9.27{\cdot}10^{-24}$ J/T (where μ_B is the Bohr's magneton). Besides that, being in a bound state in atom, the electron also has a mechanical and magnetic moments caused by its rotation around the nucleus of the atom. Motion of the electron is described by the quantum mechanics laws, but for qualitative evaluations it can be regarded as a classical particle and the laws of classical nonrelativistic mechanics can be used.

An electron in a quasi-free state, i.e. moving, for example in a semiconductor, possesses a kinetic energy $W_k \sim mv^2/2 \sim kT$, where v is the electron's velocity, $k = 1.38{\cdot}10^{-23}$ J/K is the Boltzmann's constant, T is the temperature in Kelvin. The electron energy at room temperature can be estimated using the approach of the molecular-kinetic theory, as $W_k \sim 1.38{\cdot}10^{-23}{\cdot}300 \sim 4{\cdot}10^{-21}$ J. The speed of the electron of this energy is $v = (2kT/m)^{1/2} \approx 10^5$ m/s, which is much less than the speed of light. The electron covers the distance L ~ 100 nm (the characteristic size of elements in microelectronics) during the time $\tau \sim L/v \sim 10^{-7}/10^{5} \sim 10^{-12}$ seconds.

In digital microelectronics, an electron is used as the carrier of information, i.e. the presence of an electron in a limited region of space corresponds to "1", and its absence corresponds to "0". Therefore on the basis of the above calculation, one can make an optimistic estimate for the minimum energy required for recording one bit of information $W_{min} \approx W_k \sim 10^{-21}$ J. The minimum time which is required for recording or reading this bit of information is ~ 10^{-12} seconds. Modern computers have achieved operation frequency about of 10 GHz, which corresponds to minimum switching time for one element ~10^{-10} sec, that is two orders of magnitude higher, than the estimate gave.

In spintronics, a physical parameter used to record an information, is the magnetic moment of electron μ_B. According to quantum mechanics, an electron placed in external magnetic field B can have a projection of magnetic moment on the magnetic field direction $+\mu_B$ or $-\mu_B$. The positive projection corresponds, for example, to "1", and negative projection corresponds to "0". For estimates let us use classical expression for magnetic moment energy in an external magnetic field $W = -\mu_B B$. By substituting in the formula value of B ~1 T, which is achievable in real conditions, we obtain the energy which is required for recording/reading of one bit of information $W \sim 9.27 \cdot 10^{-24} \cdot 1 \sim 10^{-23}$ J. The time which is required to change projections of magnetic moment of an electron can be estimated using classical approach and considering the motion of magnetic moment in an external magnetic field. This motion is described by the Landau-Lifshitz equation and represents a rotation of magnetic moment around the field direction with the frequency $f = \gamma B$, where $\gamma \approx 3 \cdot 10^{10}$ Hz/T is the gyromagnetic ratio. The period of this rotation at B = 1 T is $1/f \sim 3 \cdot 10^{-11}$ s. Respectively, the rotation of magnetic moment by π must occur in an instant (switching time) of the order of $\tau \sim 10^{-11}$ sec.

It follows from the above estimates, that when magnetic moment (spin) of the electron is used for writing the information, instead of the electron charge, the energy of writing of one bit of information can be reduced from $\sim 4 \cdot 10^{-21}$ J to 10^{-23} J, that is decreased by 2-3 orders of magnitude. The time for one bit recording using the spin memory element in comparable to the time for one bit recording using the charge element. Additional advantage of spintronics, in comparison with electronics, as will be shown shortly, is the possibility of non-volatile memory elements realizing and higher radiation stability of spintronic devices.

The results of experimental investigations carried out during recent years, let to hope that information processing and recording devices based on the spintronics technology will do significantly exceed characteristics of the devices using a charge of electron.

3. PHYSICAL FOUNDATIONS OF SPINTRONICS

3.1. Magnetic structures and spin waves

In many-electron atoms, the magnetic moments of electrons are added up with their orbital moments and form magnetic moment of the atom. In solid states consisting of such atoms, the exchange interaction between electrons leads to the ordering and appearance of spontaneous magnetization of a sample in the absence of external magnetic field. Depending on the nature of the interaction, the magnetic ordering is ferromagnetic or antiferromagnetic. In such magnetically ordered samples, placed in external constant or variable magnetic fields, there are various phenomena that can be used to create information recording and processing devices.

In the 1960s and 1980s, at home and abroad, domain structures in thin ferromagnetic films with different types of magnetic anisotropy were investigated. It was shown that in dielectric

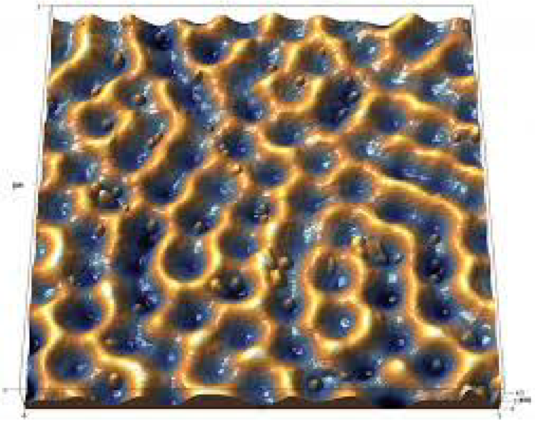

Fig. 1. *Bubble magnetic domains in ferromagnetic film.*

single-crystal films of yttrium iron garnet $Y_3Fe_5O_{12}$ (YIG) substituted with Ga, La, Sr, Sc, and other ions of thickness 1-10 μm and "easy axis" anisotropy, grown by the liquid-phase epitaxy method on dielectric substrates, there can be stable "bubble magnetic domains" (BMD) of micron and submicron sizes (**Fig. 1**). Methods for the bubbles generation and control their motion using pulsed magnetic fields were developed and prototypes of magnetic memory elements were fabricated. However, due to technological difficulties and high cost of garnet films this direction of spintronics has not received further development.

In 1970-2000, much attention in the country and abroad was paid to investigations of spin waves (SW) in single-crystal films of pure YIG and Ga-substituted YIG grown by the liquid-phase epitaxy method on singlecrystal substrates of gallium-gadolinium garnet $Gd_3Ga_5O_{12}$ with different crystallographic orientation (**Fig. 2**). It was shown that YIG is a unique material with extremely low magnetic losses in the microwave range ~0.5-30 GHz. Spin waves in YIG films of thickness 1-20 μm arise due to the long-range dipole-dipole interaction, have the group velocity of v_g ~(1-10)·10^3 m/s, the wavelength of λ ~1-500 μm, the characteristic propagation lengths from hundreds of μm to several cm, and losses of electromagnetic signal to the SW conversion of ~1-10 dB, depending on the wave length. Characteristics of dipole SWs can be easily controlled by means of relatively weak external magnetic fields H ~100-3000 Oe, which gives them significant advantages over, for example, surface acoustic waves. A number of spin- wave devices for microwave signals processing, such as frequency-tunable filters and resonators, low-noise microwave generators signals, controlled phase shifters and microwave delay lines etc have been developed. Some of these spin-wave devices have found applications in special signal processing systems. However, due to high cost of epitaxial films these devices are still not used in commercial scale.

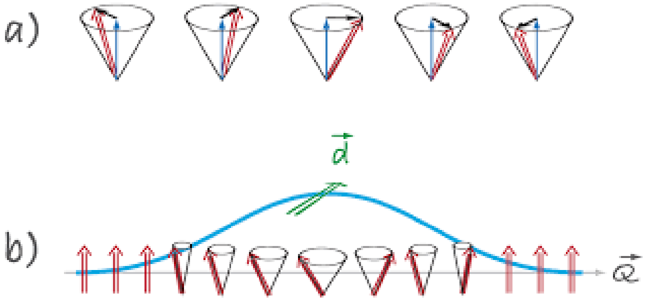

Fig. 2. *Schematic representation of a spin wave. The magnetization rotates around direction of magnetic field*

In recent years, interest to the spin-wave electronics again rose significantly because of achievements in the generation and detection of spin waves in metallic films (permalloy) of submicron and nanometer thickness, which are less expensive than epitaxial garnet films [7]. Spin waves in metal films have a purely exchange nature, their wavelength is a fraction of one microns, and propagation distances reaches units-hundreds of microns. The frequency, wavelength and velocity of exchange SW can be tuned approximately in the same range as for dipole SW, by changing external magnetic field. This opens up possibilities of creation of new controlled spin-wave microwave devices of micron sizes. We emphasize that spin-wave devices realize the basic principle of spintronics – transfer of magnetic moment (spin) without charge transfer. Therefore, characteristics of spin-wave devices may turned out to be better than characteristics of similar semiconductor devices.

Recently, new objects – "skyrmions" in thin ferromagnetic films were discovered, which may be promising for applications in spintronics devices [8]. Skyrmion is a stable two-dimensional topological structure with magnetization distribution in the form of ring with a diameter of ~10-30 nm. The skirmion is formed in a ferromagnetic or antiferromagnetic film 1-100 nm thick due to the competition between exchange interactions between the spins of neighboring atoms and the Dzyaloshinsky-Moriya interaction (**Fig. 3**). Methods for generating and detection of the skyrmions, control of their motion using external magnetic fields are under development now. Usage of skyrmions for information storage, are believed, will allow to increase data storage density and speed of information recording by 1-3 orders, in comparison with existing devices. Studies in this direction are at the stage of physical effects and demonstration of principal possibilities.

3.2. Spin-polarized current

Since the electron has both the "e" charge, its own spin, and its own magnetic moment μ_B, then the electric current ("motion of electrons") transfers not only the charge, but also the spin (i.e., the magnetic moment). For most materials (metals, semiconductors, etc.) the electric current contains a number of electrons with magnetic moment directed along definite direction (for example, the direction of magnetic field) which is equal to a number of electrons whose magnetic moment is directed in the opposite direction. As a result, the total "spin current", i.e. resultant magnetic moment transferred by the electrons is zero. One of the main tasks of spintronics is development of spin current generation methods (or "spin-polarized current") and methods for detection of spin current [9]. As a characteristic of the spin current, is used the "degree of spin polarization of the current" $P = (N_+ - N_-)/(N_+ + N_-)$, where N_+ is the number of electrons with a spin directed along, for example, the field, N_- is the number of electrons with spin directed against the magnetic field. The degree of polarization P = 0 for unpolarized current and P = 1 for completely polarized current.

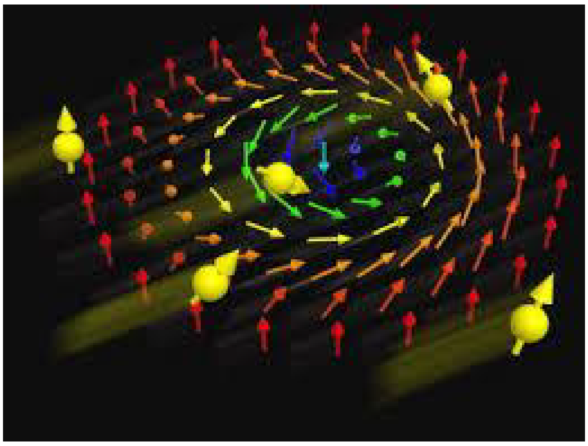

Fig. 3. *Schematic representation of magnetization distribution in skyrmion.*

The main way to obtain the spin-polarized current is the transmission of electric current through a ferromagnet placed in magnetic field (internal magnetic field of an anisotropic ferromagnet) with subsequent injection of this current into a conventional (non-ferromagnetic) metal or semiconductor through the interface (**Fig. 4**). Using such ferromagnetic materials as Fe, Co, Ni allowed to obtain spin currents with polarization of P ~0.1-0.4. When the spin-polarized current enters a conventional conductor, the degree of the current polarization rapidly decreases due to the scattering of electrons by phonons. To date, the relaxation times and the relaxation lengths of the spin-polarized current $\tau > 100$ ns and $l >$ units μm, respectively, are achieved.

For detection of the spin current (i.e., determination of degree of polarization) several methods have been developed.

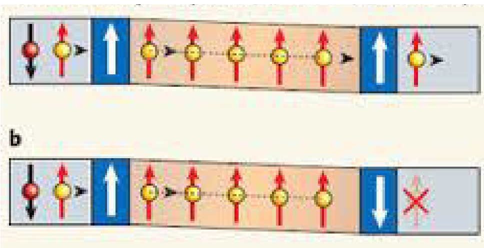

Fig. 4. *Schematic representation of a spin-polarized current in conductor: left - injector, in the center - conductor, right - detector.*

In the *spin-resolving photoemission method* the electrons are emitted from the surface of material and detected in a vacuum using the Moth analyzer which is sensitive to the spin direction. This is the most direct method, but it is limited on energy resolution and depth in within the upper 5-10 Å of the material, which makes the analysis sensitive only to surface states and impurities. *The magnetic tunnel transition method* uses two ferromagnetic layers separated by a thin insulating layer layer, usually Al_2O_3 or $SrTiO_3$, that form a planar tunnel junction. The polarization is obtained by measuring electrical resistance of such a sandwich $MR = 2P^2/(1+P^2)$. The problem is the sensitivity of the MR to the surface state and material of the barrier, because the MR measured is not so much property of a ferromagnet, but property of the entire device. In the *point contact method* the polarization is calculated from the measured magnetoresistance.

Specific properties of the spin-polarized current exhibit in various effects observed in the structures with layers of nanometer thickness.

The first of these effects, known as anisotropic magnetoresistance (AMR), is the change in the resistance of ferromagnetic sample in an external magnetic field. Resistance of the sample depends on the mutual orientation of the current and the direction of the magnetic field. Relative change in resistance of ferromagnetic metals, for example Ni, does not exceed a fraction of a percent.

In 1988, the effect of a *giant magnetoresistance* (GMR) was discovered. The effect manifests in a structure consisting of two layers of ferromagnetic metal (for example, Co) separated by a thin layer of non-ferromagnetic conductor (for example, Cu) (**Fig. 5**). The electric current is passed through the conductor layer in the plane of the structure. Resistance of the structure depends on the mutual direction of magnetizations of ferromagnetic layers. The resistance is small for parallel orientation of magnetizations of the layers, it increases for a counter orientation of the magnetizations. Magnitude of the relative change in resistance can reach ten of percent, which is much larger than the value of ordinary magnetoresistance and justifies the use of the term "giant". The effect arises due to dependence of the electrons scattering efficiency on the spin direction.

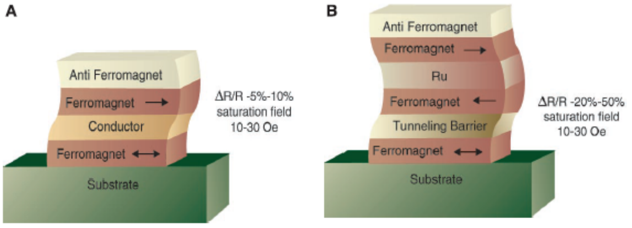

Fig. 5. *Schematic representation of structures: A - with giant magnetoresistance, B - with tunneling magnetoresistance.*

Even greater change in the resistance is observed for *tunnel magnetoresistance* (TMR) effect. The effect is observed in a structure containing two layers of ferromagnetic metal, separated by a dielectric layer with thickness of units of nanometers. The electric current is passed perpendicular to the plane of the structure. Due to the small thickness of the dielectric, the electrons can tunnel through the barrier, creating an electric current. The resistance of the structure is small if the magnetizations of the layers are directed in one direction and increases with the opposite orientation of the magnetizations. The relative change in the tunneling magnetoresistance of a structure can reach hundreds of percent.

The next effect is the *spin momentum transfer* (SMT) [10] reflects the property of polarized electrons to transfer the angular moment (**Fig. 6**). The effect is observed when a spin-polarized current of sufficiently high density is injected into a thin ferromagnetic layer perpendicular to the surface and manifests itself as a change in the magnetization direction of the ferromagnetic layer. This results in an excitation of oscillations of the ferromagnetic layer magnetization with frequencies close to the magnetic resonance frequencies. The phenomenon was first predicted

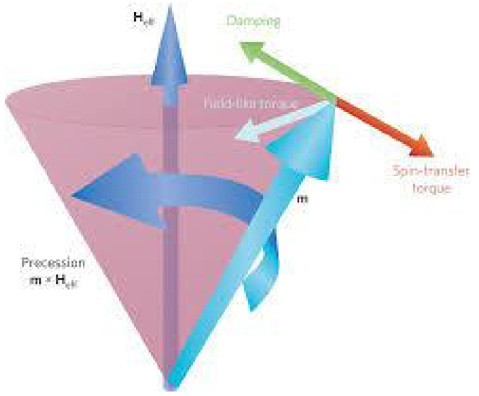

Fig. 6. *Geometry of excitation of magnetization precession when mechanical moment is transmitted by spin current.*

theoretically, and then found experimentally in Co films.

The *spin Hall effect* [11] is an analog of the usual Hall effect for the electron current. The spin Hall effect is observed in the propagation of the electron current in the film of a nonmagnetic conductor in the absence of an external magnetic field. The effect is manifested in the deflection of electrons with different spin directions to opposite sides of the film (**Fig. 7**). The effect arises from the spin-dependent scattering of electrons by impurities. An inverse spin Hall effect was also found in which the spin current leads to a spatial separation of electrons with different spin directions. As a result, an electric voltage is generated between the edges of the film. The effect can be used to detect spin waves.

3.3. Materials of spintronics

A great attention is being paid now to search of new materials that provide effective generation of spin-polarized currents at room temperatures and compatible with well-designed technologies of modern electronics [12-13]. In addition to the basic materials of spintronics - ferromagnetic metals Fe, Co and Ni, perspective are weakly doped ferromagnetic semiconductors, semi-metallic ferromagnetic oxides, Heusler alloys, and some organic materials. Among semiconductors the most interesting materials are groups of A3B5 and A2B6. For example, diluted magnetic semiconductors based on GaAs, in which the individual atoms are random are replaced by magnetic ions Mn^{2+} with a concentration up to 0.07, which have p-type conductivity at room temperatures as well as the semiconductors with a halcogenide structure of the type $Cd_{1-x}Mn_xGeP_2$. Using of semiconductors will significantly accelerate and facilitate the process of the spintronics integration with modern semiconductor technologies. The next materials, which are considered as the most promising for applications in spintronics, are the semimetals such as CrO_2 and oxides of some semiconductors, for example ZnO doped with Co. Semimetals are unusual ferromagnets that have electrons at the Fermi level in a single-spin state: all with spin along the magnetic field, or all with spin against the field. Electrons with opposite-directed spin have gap in the density of states at the Fermi level and therefore do not contribute to the conductivity. The charge carriers in such materials have degree of polarization P = 1. To candidates in semimetals are Fe_3O_4, LaSrMnO and SrFeMoO. Heusler's alloys are a big class of materials that are promising for spintronics. Heusler alloys include, for example, NiMnSb, PtMnSb, CoMnSi, CoMnGe, CoMnSn, and others. Most Heusler alloys are ferromagnets with a Curie temperature of 200 K to 10^3 K. They have a degree of electrons polarization at the Fermi level P ~ 1, which makes them semimetals [14-15].

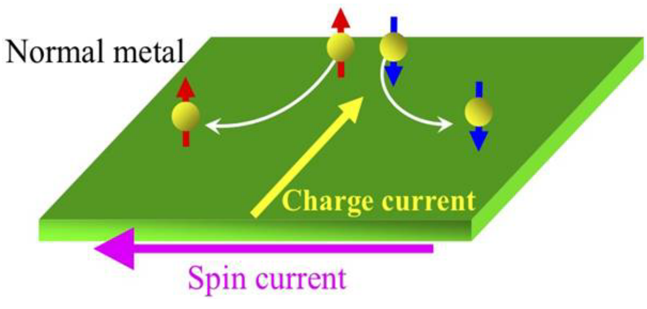

Fig. 7. *The spin Hall effect.*

3.4. Control of effects

There are several approaches to management spin currents and effects used in the spintronics.

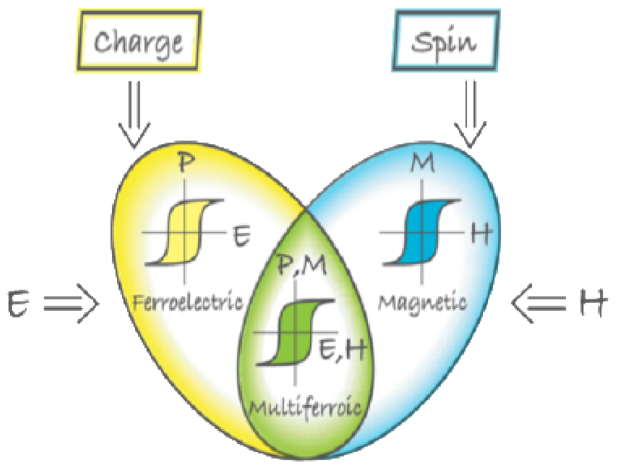

Fig. 8. *Multiferroics are the materials that posses simultaneously ferromagnetic, ferroelectric and ferroelastic properties.*

The main one is the control of the spin-polarized currents by means of a magnetic field, orientation and magnitude of which can easily be changed with external sources, for example, by passing a normal current through the conductors. Amplitude of magnetic fields should be from a fraction of mT to units of T. Such fields are sufficiently easy to implement in a small space using currents or ferromagnets.

The second way is to control the spin currents with the help of multiferroic materials that are simultaneously both ferromagnetic and ferroelectric, such as bismuth ferrite FeBiO$_3$ (**Fig. 8**) [16, 17]. An electric field applied to such material changes its magnetic parameters: saturation magnetization, orientation of the magnetization, magnetic anisotropy field and others. There are dozens of single crystal multiferroics, but only few of them exhibit sufficiently large effects at room temperatures.

Magnetic parameters of many ferromagnetics are strongly dependent on mechanical stresses that can be create artificially with the help of external strains, temperature changes etc. This opens up opportunities, for example, in composite film structures ferromagnet-piezoelectric, manage magnetization of the ferromagnetic layer, by applying an electric voltage to the piezoelectric layer (**Fig. 9**) [18]. Combination of piezoelectric effect and magnetostriction allows, as shown experimentally on structures containing Ni film of nanometer thickness and a piezoelectric with a large piezoelectric modulus (lead zirconate ceramic titanate, crystalline magnesium niobate-titanate lead, lithium niobate, etc.) allows much stronger change the orientation of the magnetization, than in single-phase multiferroic crystals. Interlayer of multiferroics or ferroelectrics are also used as an insulating layer to enhance tunneling magnetoresistance.

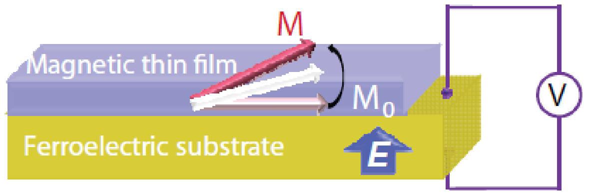

Fig. 9. *Composite ferromagnet- piezoelectric structure in which direction of magnetization is switched by an electric field.*

Finally, in recent years management of spintronic effects has been demonstrated by using ultrashort optical pulses due to inverse Faraday effect (**Fig. 10**) [19]. The effect is as follows: a light pulse with circular polarization of femtosecond duration (~10^{-13} - 10^{-14} s) falls on the surface of a ferromagnetic film and creates a pulsed magnetic field B of up to units of T. This field during the pulse can change the orientation of the ferromagnet magnetization, excite spin waves of microwave or terahertz

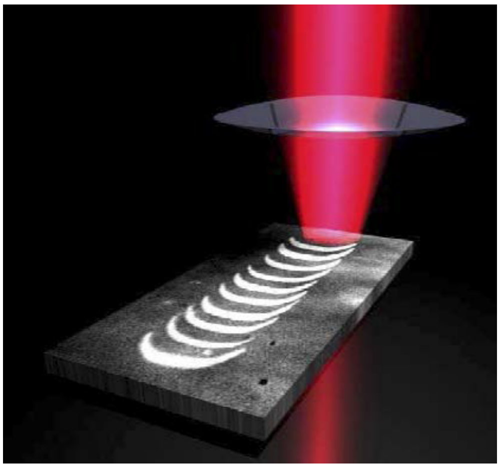

Fig. 10. *Magnetization reversal of a ferromagnetic film with optical pulses.*

frequency bands, change the parameters of the spin-polarized current. It is expected, that control with optical pulses will reduce the switching time of spintronics devices up to ~ 10^{-14} s, which is orders of magnitude shorter than switching times of microelectronic devices.

4. SPINTRONIC DEVICES

By now, several different information processing devices based on the spintronics principles were realized and even more are under development.

The first of them are the magnetic fields sensors [20]. Design of the sensor is shown in Fig. 5. It contains two ferromagnetic layers separated by a layer of non-ferromagnetic metal, most often Cu. A magnetically rigid layer with large anisotropy (as a rule – antiferromagnet) is deposited to one of the ferromagnetic layers. Because of the exchange interface interaction the magnetization of this layer is fixed, while orientation of the second ferromagnetic layer can be changed with the help of a weak external magnetic field H. Change of the layer magnetization orientation due to the GMR effect leads to a change in the resistance of the sensor for a direct current flowing through an average layer. Such sensors allows to register magnetic fields in the range of ~10^{-8}–10^{-2} T for units of nanoseconds. GMR sensors are widely are used to read information recorded on magnetic disks, which led to increase the information capacity and speed of the disks for several orders for the last 20 years. In addition, GMR sensors are widely used in automotive and aviation industry, in security systems, in magnetic defectoscopy, etc. (**Fig. 11**). In 2007, A. Fert and P. Grünberg were awarded the Nobel Prize in physics for these developments.

Fig. 11. *Field sensors based on giant magnetoresistance and their application.*

Almost all leading electronic companies in the world are working on the creation of the STT-MRAM (Spin-Transfer Torque Magnetic Random Excess Memory), the random access memory based on structures with a spin-tunnel effect, which in the coming years can replace both semiconductor memory and normal MRAM memory. The design of the STT-MRAM memory element is shown schematically in **Fig. 12**. Each cell contains a structure with a magnetic tunnel junction that is responsible for storing information, and a transistor, through which addressing is organized. The logical "1" corresponds to the parallel orientation of the magnetizations of the fixed and free magnetic layers, and the logical "0" corresponds to the antiparallel orientation of the magnetizations of the layers.. The recording is carried out by passing a spin-polarized current through the tunnel junction, which changes the orientation of the magnetization of the free magnetic layer. For reading, a weak current is passed through the cell and the state of the cell is determined by its resistance. Using the STT effect, instead of external magnetic fields, to change the state of the cell, made it possible to reduce significantly the recording energy. Advantages of the STT-MRAM memory are higher density

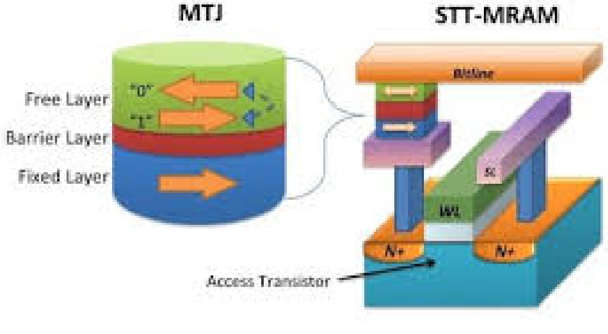

Fig. 12. *Schematic view of the Magnetic Random Access Memory element.*

of information recording and higher speed. It is significant that MRAM is a non-volatile memory, the data in which are stored for unlimited time period without power supply, in contrast to dynamic (DRAM) semiconductor memory.This means that the long process of downloading programs from disks to the computer's memory is excluded, which greatly improves the speed and reduces the power consumption of information systems. According to preliminary estimates, memory based on spintronic technology should also have increased radiation resistance. In 2016, the company Everspin began commercial production of a 40-nanometer STT-MRAM memory with a capacity of 256 Mbit. In Russia, the company "Crocus NanoElectronica" plans to start production of the STT-MRAM memory chips.

A promising area is development of spin nano-generators of microwave range, using effect of ferromagnetic resonance excitation with spin current (**Fig. 13**) [21]. Such generators have dimensions of the order of ~100 nm, consumption power at the level of microwatt, frequency of radiation is in the range from units to tens of GHz, and generate power of tens of *nW*. Research is currently under way on optimization of structures, increase of output power, formation of frequency characteristics of generators. A possibility of creating phased antenna arrays based on such generators has been demonstrated, that will allow to increase their power is 2-3 orders of magnitude. It is proposed to use nano-generators for transmission of information on short distances, for example, inside microprocessors.

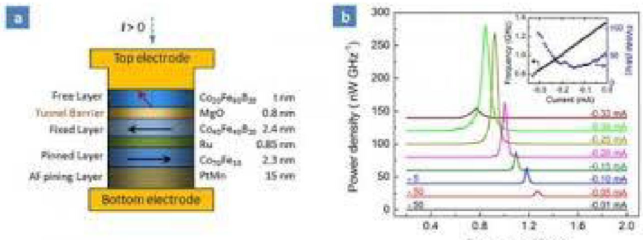

Fig. 13. *Design and frequency spectrum of spin-current microwave oscillator.*

The first step towards creating computers using principles of spintronics, is the development of elements, which are functional analogues of diodes and transistors used in traditional electronics. Respectively, dozens prototypes of spin diodes and spin transistors were proposed and implemented, such as Johnson spin transistor (named for the inventor), a hybrid spin transistor, SPICE-transistor, spin-field-effect transistor and others [2, 22].

As an example, **Fig. 14** shows a schematic view of the spin-field effect transistor. Like the usual transistor, it has source and drain contacts (ferromagnets) and a gate (semiconductor). Spin-polarized carriers leave the source with spins parallel to the magnetization of the ferromagnet and process in motion due to the Rashba effect. In this case, the electrons must move at a rate of 1% of the light speed in vacuum. For sufficient strength of magnetic field (the velocity of electrons in a given case is very important), the spins of the electrons reverse their orientation. As a result, the resistance of the channel increases and the current decreases. By varying potential on the shutter one can change conductivity of the device. This device behaves like a conventional field-effect transistor with the feature that the magnetization of its contacts (and, consequently, its electrical characteristics) is sensitive to external magnetic field.

In addition to traditional approaches, new approaches can be used in spintronics for

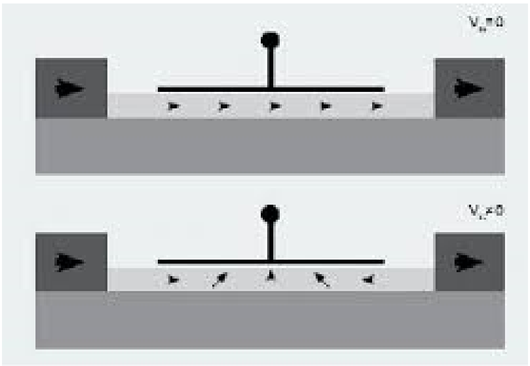

Fig. 14. *Schematic view of the spin-field transistor.*

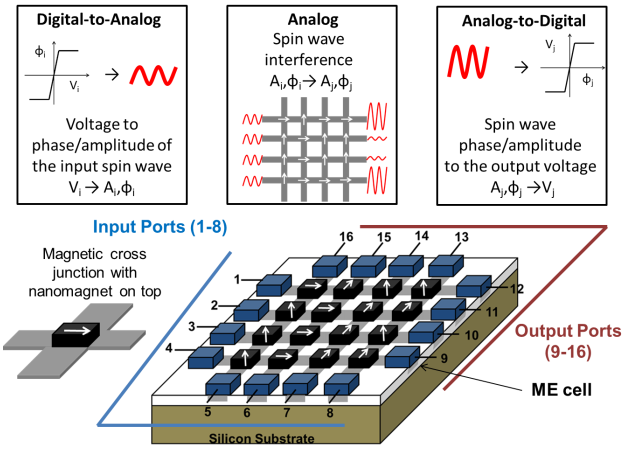

Fig. 15. *Principle of operation and design of the spin holographic processor.*

processing of signals, taking into account specific properties of spin waves [23]. **Fig. 15** shows, as an example, the structure of a spin holographic processor. it uses coherence of spin waves propagating in a thin ferromagnetic film. Input converters (4 + 4) excite in structured film spin waves. Phase and amplitudes of these waves depend on the voltage at the input converter. In the places where the wave beams overlap, the spin current generates a voltage, whose amplitude depends on the phases of the interfering waves. As result, the signals corresponding to certain transformations of the input signals are formed at the outputs. We emphasize that in this device all processing of information occurs on spin waves, in analogy with optical processors. The development of technology is likely to allow processing of big data sets.

Finally, spintronics can become the main base for creating quantum computers working on new principles radically different from currently used. Electron Is a quantum particle with spin which obey the quantum mechanics laws (along with the optical photon). It is the most suitable object for implementation so-called "q-bit". It is believed that the first samples of real quantum computers will appear already within the next ten years.

5. RESEARCH CENTERS ON SPINTRONICS

Fundamental and applied research in the field of spintronics and its applications are currently engaged in dozens of universities and research centers of large electronic firms. Leading role in terms of scientific achievements and volumes of research play organization of the USA [24]. The main customers and sponsors in this area in the US are the Defense agency of perspective research projects (DARPA), the US Department of Defense (DOD), the Naval Research Laboratory (NRL), the National Science Foundation (NSF), such firms as IBM, Honeywell, Motorola, Infineon, Cypress Semiconductor, NEC, Toshiba, Federal Products Inc., Nonvolatile Electronics, and others. Research are conducted, as a rule, in the frames of national programs, such as "Technology Reinvestments Project", "Magnetic Materials and Devices Project", "Spintronics", "SPns IN Semiconductor Project", "Quantum Information Science and Technology" and others.

Below are some of the leading research centers in the field of research and applications of spintronics:

C-SPIN (**Minnesota, USA**) is the Center for spintronics of materials, interfaces and new architecture. Multi-discipline university and industrial research Centre. They develop technologies of spintronic computing devices and memory chips. Located at the State University of Minnesota. The Center is funded by a five-year grant of $28 million from Semiconductor Research Corporation and DARPA.

CSEQuIN is the Center for spin effects and quantum information in nanostructures. It is at the University of Buffalo. Its laboratory of spintronics and semiconductors is financed by DAPRA.

CSQC (**California, USA**) is the Center for spintronics and quantum computers. It is a part of the California Institute of nanosystems at the University of Santa Barbara, USA.

NANOSPIN is the project of the European Commission. It unites 8 academic and industrial partners from 6 EU countries on the basis of interest in spintronic materials and devices.

Spintec is a research laboratory, where they try to transfer the bridge from fundamental research to promising technologies for production of spintronic devices. It is located in Grenoble, under the leadership of the Commissariat for Atomic Energy (CEA) and the National Center of scientific research (CNRS) of France. Main subjects: memory devices, memory chips, MRAM, transfer of spin, semiconductor devices.

In **France**, the universities "Paris-Sud", "Paris-Saclay", "Paris-13", and "Université de Lorraine" deal with both fundamental problems of spintronics and the development of new devices. The research is funded by CNRS and the Commission of Atomic Energy of France.

Oakland University in the United States, where focus on theoretical research into the creation of spintronic generators of microwaves and development of devices. Works are financed by National Science Foundation of the United States, DARPA, and electronic companies.

In Germany, more than 20 scientific groups from various universities are involved in spintronics research. Research is carried out within the framework of two Priority Programs and 9 Special Research Programs

In Japan and China, similar researches in the field of spintronics are conducted in universities and research centers of leading electronic companies.

In Russia, researches on spintronics are carried out by individual scientific groups in institutes of the Russian Academy of Sciences and universities. In particular, in the Institute of Radioengineering and Electronics of RAS, Institute of General Physics of RAS, Institute of General and Inorganic Chemistry of RAS, Institute of Physics of Microstructures of RAS, Institute of Metal Physics of UB RAS, Institute of Physics of SB RAS, in the Russian Technological University, the Sain-Peterburg Electrotechnical University "LETI", Saratov State University, Far Eastern Federal University, Russian Quantum Center, Russian company "Crocus-Nanoelectronics", and a number of other organizations. Unfortunately, the contribution of Russian researchers and developers in the research in this area is still insignificant. It's connected with organizational problems (absence of State programs) and with the absence of a target financing. However, the qualification, experience and existing international contacts allow Russian scientists join to research in the field of spintronics and cut backlog.

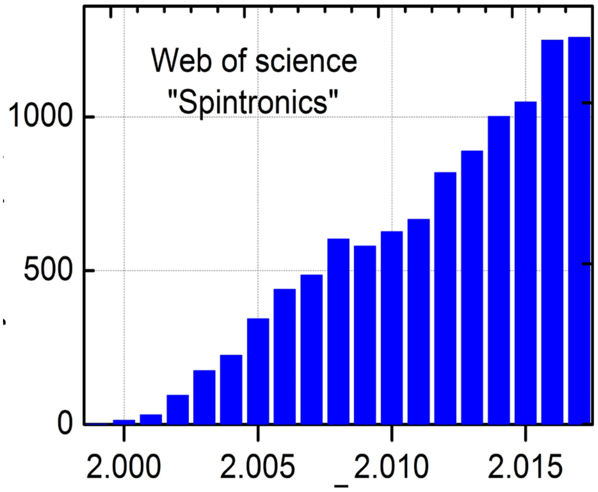

Fig. 16. *Publications on spintronics: on the Y-axis - the number of publications, on the X-axis - the year.*

First publications on spintronics appeared in 1999, now the number of publications is more than 6 thousand and continues to grow. In **Fig. 16** is a graph of annual growth in the number of publications in the leading international journals, built on database Web of Science using keyword "spintronics". According to Web of Science, number of articles count on "spintronics" reaches 9709 and is growing steadily. Annual number of references to articles on the topic "spintronics" in 2016 exceeded 28 thousand, which indicates extraordinary popularity and importance of this direction.

6. CONCLUSION

Brief summary of research and development in the field of spintronics allows us to make the following conclusion:

- Spintronics is the most promising platform for element base of systems for processing and storage of information.
- Spintronics devices allow realize a higher density data storage, will have higher speed of information processing, reduced energy consumption, and higher radiation resistance than existing electronic devices on semiconductors.
- To date, the prototypes of such spintronics devices as highly sensitive magnetic field sensors; non-volatile magnetic random access memory elements; spin-field diodes and transistors; tuned microwave nano-generators, and so on. New principles of information processing based on spintronic technology are under development.
- Leading countries are carrying out intensive research in the area of spintronics in universities and research departments of companies. In the US, investigations are financed by military departments, National Science Foundation, companies IBM, Honeywell, Motorola, Infineon, NEC, Toshiba and others.
- In the US, Europe and Asia (Japan, China) spintronic studies are held as a part of a specially organized programs, executors of which are scientific groups from universities, public and private research organizations.
- In Russia there are several scientific groups in the institutes of the Academy of Sciences and leading universities involved in fundamental research in the area of spintronics. To reduce lag of domestic researchers from Western competitors it is necessary to organize state programs on this direction and increase funding.

ACKNOWLEDGMENTS

The work is supported by the Ministry of Education and Science of the Russian Federation (project 8.1183.2017) and the Russian Foundation for Basic Research (grant 16-29-14017).

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