УДК 681.382

G. Mladenov, DSc.[1], E. Koleva, PhD.[1], V. Spivak, PhD.[2], A. Bogdan[2], S. Zelensky[2]

Prospects of spin transport electronics

This review provides basic information on spintronics. Briefly described the effects on which the development of spintronic nanoscale devices are based: giant magneto-resistance, spin-dependent tunnelling effect, transport of spin-polarized current, the creation of spin-polarized current torque for a magnetic switch and the motion of the magnetization of magnetic domains. As a example of successive applications spin-dependent devices are given parameters of magnetic memories based on use of spintronics components. It is shown that such memory is competitive to nowadays standard memories (at 90 nm) and has the potential for future development (for example, reducing the critical size to 32 nm).

В обзоре приведены основные сведения о спинтронике. Коротко описаны эффекты, на которых базируется развития спинтронных наноразмерных приборов: гигантское магнетосопротивление, спин-зависимый туннельный эффект, транспорт спин-поляризованного тока, создание спин-поляризованным током крутящего момента для магнитного переключения намагничивания и движения магнитных областей. Как пример успешного применения спинтронных приборов приведены параметры магнитной памяти со спинтронными компонентами. Показано, что такая память конкурентоспособна (при 90 нм) при реализации современных запоминающих устройств и имеет потенциал для будущего развития (при уменьшении размеров до 32 нм).

Keywords: *spintronics, magneto-resistance, spin-polarized current, magnetic memories*

Introduction

The success of microelectronic technologies allow to achieve high processing speeds and volumes of information preservation. But the physical and technological limitations associated with a decrease in the size, growth, density and dissipated energy consumption, will require the development of new ideas. *Spintronics* (sometimes called magneto-electronics), which is based on the quantum spin states of electrons and its transfer, is a good source of ideas for the growth of the degree of integration and reduced power consumption of integrated circuits [1-3]. Spintronic components – sensitive magnetic field sensors, which include reading heads of magnetic disk storage – have already taken a worthy place among the nanoscale electronic components of up-to-date storage devices. A nascent technology and spintronic devices clearly occupy an important place among the technologies and devices of this century.

1. Physical basis of spintronics

Electron spin represents a quantum property of electrons (together with its mass and elementary charge). This internal angular momentum has two orientations and amplitudes of $\pm(\hbar/2)$. In a magnetic field, depending on whether the electron spin parallel or antiparallel, the electron has a different energy. Spin and an associated magnetic moment of atoms in ferromagnetic materials plays an important role in understanding of magnetic properties. For nonmagnetic materials, however, it is only the quantum-mechanical parameters. The electron spin plays a minimal role in conventional electronics, which considers the charge transfer by electrons, but does not account for the spin [1]. In conventional electronic devices spin orientation is random. It is known that the spin in ferromagnetic is ordered in one direction. In the 80 years of the last century (after the discovery of giant magneto-resistance effect [4,5]) empirically showed that the current passing of the ferromagnetic in the normal metal preserves the spin ordering of the moving electrons at distances greater than atomic dimensions and interatomic distances. It turns out that a nanoscale film can be transported spin ordering and associated magnetisation.

Spin polarization in nonmagnetic materials can be achieved, or through the Zeeman effect in strong magnetic field at low temperatures, or through non-equilibrium method (excitation of electrons outside the energy impact). In the latter case, the nonequilibrium polarization decays in time with a characteristic "spin lifetime". In metals, it is short (about less than 1 ns), but for semiconductors it can be very long (microseconds at low temperatures). In cases of isolated electrons in local traps impurities (about defects), the spin lifetime reaches a millisecond.

Spin-polarized current is the main phenomena considered in spintronic devices. In the magnetized metal it takes as a result of an unbalanced spin density of two species of free flow of electrons (at the Fermi level under the influence of the magnetic field of the sample). It can also flow through multilayer sandwich structure: two or more films of ferromagnetic separated by a nonmagnetic material (due to the effect of giant magneto-resistance), or even through nanofilms from insulator (the effect of tunnelling spin current). Interesting physical processes occur in the interfaces of the ferromagnetic / semiconductor and ferromagnetic / superconductor and on the borders of the sample through which the spin-polarized current flows, generated by an electric field.

It is possible to create a *spin wave*, which represents a wave-like change in the direction of the spins in a certain set of neighbouring electrons. This is another area where spintronic devices are based on the absence of charge transfer minimizes dissipation of energy as a result of electron scattering from atomic particles. It shall be noted that all the abilities to move the spin back without the electronic charge transfer are very attractive because of the possibility of minimizing energy consumption.

The injector of spin-polarized current – is the main component of spintronic device. This may be of the conductive magnetic layer of a conductor or semiconductor, which has a magnetized state of spontaneous spin ordering of electrons. In a sample of the ferromagnetic semiconductor spin polarization reaches 100%, while in metals - 10%. In addition, imposed stringent and conflicting requirements to the material injector. Electrons with polarized spins can be injected into a semiconductor at room temperature. Using an injector from a ferromagnetic metal with a sufficiently-high Curie temperature - it is realistic, but unresolved problem. Difficulties in constructing a metal-semiconductor device associated with the incompatibility of the electronic structure of metals and semiconductors, as well as phenomena at the interface. There are difficulties in establishing a device with the operational semiconductor part, through which will be transported and detected spin-polarized current. Because of lower efficiency and the above-mentioned problems, the use of a semiconductor heterostructure containing a semi-conducting ferromagnetic, is more likely. Therefore, is actively searching for a ferromagnetic semiconductor with high Curie point.

The second approach is to work with a hybrid structure with a well-studied and a suitable transition between magnetic metals and semiconductors. There is necessary a consistent spin density during magnetization and the possibility of electron transfer. *Spin coherence* of the spin-polarized current in semiconductors is preserved for a relatively long time. Such a design for a sufficiently effective injection looks realistic for practical applications.

Spin orientation of the electron is preserved much longer (order of nanoseconds) compared with the moment of the electron motion (femtoseconds). Therefore, spintronic devices are suitable for dynamic memory. Packages of spin-polarized electrons will save and transfer the information in the computer systems of the future.

When spin-polarized current is transported, nonmagnetic metal films do not strengthen it, while the semiconductor can strengthen. Therefore, they are multifunctional. The traditional material of the microelectronics - silicon has a weak spin-orbit scattering. It has no piezoelectric properties, which is an advantage in spintronics, but problems arise at the boundary with the ferromagnetic injector (obtained by the Schottky barrier). Adding additional nanooxyde film to get a tunnel barrier and make the flow of spin-polarized current [6] proved promising, and the tunnelling magneto-resistant effect finds new applications. It is important to study the role of doping silicon for spintronic applications. It is known that lattice defects affect the magnetic properties of silicon. Now it is important to find the role of magnetic ions and other acceptors and donors for the magnetic properties of the material.

The next element of spintronic devices – is an effective *filter of spin-polarized current*. It must selectively ignore the electrons of one spin orientation.

And finally – the creation and application of the element, detecting spin-polarized current reached it. After passing through the medium transporting spin-polarized current should be recorded, thanks to the sensitivity of the detection medium to the spin of electrons come.

The manipulation of electron spin during transportation between the injector and the detector is performed by an external magnetic field or the effective spin-orbit interaction. The electric field acts on the electron charge and the magnetic field on the spin. At the semiconductor environment the orbital motion of electrons and electron spin are coupled. This relationship is a manifestation of special relativity. Electric field for a moving electron is transformed into a magnetic field that interacts with the electron spin and eliminates the degeneration of the spin state up or down. Effective field-orbital field called Dresselhaus and Rashba fields, depending on a creation of volume or inverse structure of the asymmetry.

In cases of magnetisation or precession of the spin Hall effect in metals and semiconductors it is necessary a coherence of the electron spin. It may be noted that the length of spin coherence in semiconductors is much larger than in metals. Therefore, the forecasts are more promising for use in semiconductor devices based on these phenomena.

Spin transportation or undulating changes can be used for processing or preservation of information, for generating coherent electromagnetic radiation with a frequency control of an external magnetic field. It is expected the creation of combined devices (logic, memory, and sensors) using spintronic devices.

In an external magnetic field it is possible, using Zeeman method, the split into two energy subband. Zeeman effect was found in 1896 for a beam of Na atoms with a split of the atomic spectra of the magnetic field. When the semiconductor is injected by spin-polarized current it becomes possible the management transitions at the upper and lower levels, creating a population inversion and consequently leads to the generation of coherent electromagnetic radiation, controlled by an external magnetic field.

Other quantum effects occur in Josephson junctions with an insulating ferromagnetic, where tunnelling is controlled via an external magnetic field.

Recognition (or filtering) the spins of passing electrons can be done if between injector and transport medium spintronic device, as well as between the transport and recording layers are deposited from the filters of the magnetic layers. Depending on the match or mismatch of these filters with the direction of the spins of electrons, the electrons pass through or stop. Based on this method of operation (transmission or stop the spin-polarized current), these devices called *spin valves*.

Fig. 1 shows the structure of the sandwich of two magnetic layers and one nonmagnetic with a thickness of about 1 nm between them. Ferromagnetic layers 1 and 3 are magnetized and nonmagnetic layer 2 between them serves to limit the magnetic interaction between ferromagnetic layers.

Figure 2 shows the spin-valve of a multilayer sandwich nanofilms of ferromagnetic and nonmagnetic material.

Studies have shown that in the absence of an external magnetic field, depending on the match or mismatch of the magnetization of films 1 and 3, the resistance of the sandwich shown in Fig. 1 can be large or small. The observed effect was named the *giant magneto-resistance*, and the structure in Fig. 1, which is associated with one of its manifestations - *the spin valve*.

The resistance of a multilayer sample is associated with the scattering of electrons. If the ferromagnetic layers are magnetized in opposite directions, one of them scatter electrons with spin up (a symbol of one spin state) and the other - the spin-down (the second symbol of a possible state of the electron spin) and, in general resistance of the spin valve with antiparallel ferromagnetic layers is large. If the ferromagnetic films are magnetized in the same direction, regardless of the precise direction, then one type of electrons with certain spin is not dissipated and therefore the electrical resistance of the spin valve is small, and thus through the valve flows higher current.

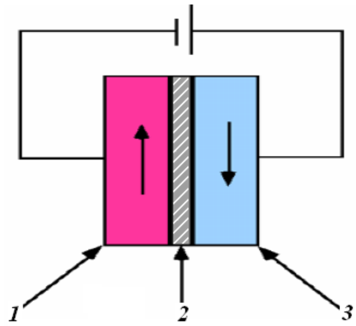

Fig. 1. The operating principle of the spin valve

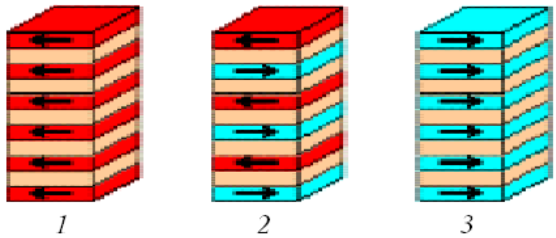

Fig. 2. Multilayer spin valves made of ferromagnetic and nonmagnetic films: 1,3 – ferromagnetic nanofilms magnetized parallel, 2 – antiparallel magnetization

For the discovery of the giant magneto-resistance two groups of researchers were awarded the Nobel Prize in Physics in 2007. Peter Grunberg from the Research Center in Jülich (Germany), and Albert Fer whose group has worked with periodically repeated films of Fe and Cr, at the University of Paris-Sud (France) – they independently discovered the effect in 1984 and 1987. This effect [4,5] has made a revolution in the field of magnetic memory and led to the study of many new phenomena and generate ideas to create a fundamentally new devices.

If instead of a nonmagnetic separation layer we (position 2 in Fig. 1) place of alluvial insulator, you get a phenomenon known as tunnelling magneto-resistance effect. Instead, the nonmagnetic metal layer can be a semiconductor or superconducting layer.

The potential use has a magnetic switching induced by the electron current, the conduction between the localized magnetic states [7,8]. The understanding of transmitted spin torque in a variety of structures is important when designing magnetically logic. In addition to the magnetic switching between equilibrium states of a current-induced torsional stress, which can switch the magnetic configuration between the stationary or equilibrium states. Necessary to study the spin-current dynamics of individual domains and dynamics of domain walls in multidomain systems, magnetic materials, where you can observe the rotation of the magnetic moment. The ability to switch the charge current without applying an external magnetic field is of great importance for the development of memory devices. In addition, the spin-polarized current induces a magnetic switch configurations, it can induce a steady-state precession vibrations in nanocolumns that can be used as a source of generating microwaves.

GMR effect describes the change in electrical resistance when the magnetic configuration of a multilayer filter (spin valve) varies from parallel to antiparallel (or vice versa). The effect of current induced magnetic switching (CIMS) changes by current the state of magnetic multilayer systems or nanocolumns. There exist an inverse CIMS, which holds the reorientation of magnetic moments induced by spin-polarized current. Using the fact that the charge current is associated with the spin-polarized current, a magnetic inhomogenity leads to spin exchange between the conduction electrons and local magnetic moments. Spin transfer is equivalent to the twisting force that causes the magnetic switch.

2. Examples of different types of memory devices with spintronic components

In the early 90's in magnetic storage devices have been introduced reading heads using the magnetoresistance of the magnetic field. This helped to increase the density of magnetic recording. This was followed by rapid development of the reading heads of magnetic memory based on the principle of the GMR effect (1997), in which much larger changes in conductivity are observed for small changes in the external magnetic field. Followed by a more rapid increase in the density of recorded information.

The next step in the development of memory was the use of spin-dependent tunnelling devices (SDTD). In them between two ferromagnetic layers, instead of the nonmagnetic nanofilms, nanofilm of insulating material is applied. Tunnelling current is flowing through them when ferromagnetic layers are magnetized in one direction and that the difference in the resistance of a coordinated and uncoordinated magnetization of spin-dependent tunnelling device much more than the GMR. Recently, such a device was designed to create the first magneto-resistance random access memory (MRAM as in Table 1). In this memory the size of memory cells are reduced to 60 nm or more.

The next innovation – the use of the spin moment transfer. This capability (inverse CIMS) has been predicted theoretically in 1996 and consists in the fact that the transfer of angular moment of spin-polarized current can create a moment acting on the magnetisation of the magnetic layer magnetized in a direction not parallel. This effect, called spin-torque moment, discovered experimentally in 2000 [6]. In the conventional memory magnetic field generated by current reverses magnetisation second magnetized layer (effect CIMS). In memory, built on the principle of spin torque, it makes the spin-polarized current. In this case, the switching is robust to interference, and the memory needs smaller current for dubbing. Predictive parameters of this type of memories are given in Table 1 as SPT MRAM.

Table 1. Parameters of new types of memories with spintronics components

	MRAM	SPT MRAM	SPT MRAM
Critical dimension comp. [nm]	90	90	32
Node dimension [µm2]	0,25	0,12	0,01
Density of inform. [Mb/cm2]	256	512	5000
Reading time [ns]	10	10	1
Programming time [ns]	5-20	10	1
Prog.energy/bit [pJ]	120	0,4	0,02

Spintronic memory compete with flash-electronic, even when using 90-nm lithography.

Another approach is the use of spin-polarized current is used in developed by IBM memory type "treadmill" [2].

Conclusions

Spintronics nowadays is at an early stage of development but has great potential for the creating of new electronic nanodevices.
Magnetic sensors, reading heads based on on the GMR effect are produced in large volumes and take their place in the modern information systems, demonstrating the potential of spintronic devices. The following devices of spintronics, which accelerate technical progress – is a spin-dependent tunnelling devices and appliances based on the effect of spin transfer. Next will be implemented opto-spintronic devices, spin-wave devices, spintronic devices for information processing and integrated spintronic systems.

References

1. *M. Zieze*, M.J. Thornton(eds), Spin Electronics,Springer-Verlag, Berlin,2001
2. *Г.М. Младенов,* В.М. Спивак, Е.Г. Колева, А.В. Богдан, Наноэлектроника: 1 книга, Введение в наноэлектронные технологии, Киев-София, Аверс,2010
3. *Г.М. Младенов,* Е.Г. Колева, В.М. Спивак, А.В. Богдан, Функциональные микроэлектронные компоненты с использованием квантового эффекта спинового состояния электронов и их переноса, Международная научно-техническая конференция: "Автоматизация: проблемы, идеи, решения 2010", Севастопольскии НТУ, Севастополь, 6-9 сентября 2010г.
4. *M.N. Baibich,* J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, J. Chazelas, Phys.Rev.Lett. 61, 2472 (1988)
5. *G. Binash,* P. Grünberg, F. Saurenbach, W. Zinn, Phys.Rev. B 39, 4828 (1988)
6. *D.A. Thompson,* J.S. Best, IBMRes. Development, 44, 2000, 311-322
7. *Slonczewski J.C.,* J. Magn. Magn. Mater. 159, L1 (1996)
   8. *J. Barnaś*, A. Fert, M. Gmitra, I. Weymann, and V.K. Dugaev, Phys. Rev. B 72, 24426 (2005)

[1] *Institute of Electronics, Academy of Sciences of Bulgaria*
[2] *National technical university of Ukraine «Kyiv Polytechnic Institute »*