Semiconducting nanostructures—materials for spintronics

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Introduction: nanoscience, nanotechnology and spintronics

Nanoscience, the interdisciplinary science that draws on physics, chemistry, biology and computational mathematics, is still in its infancy. Control and manipulation on a nanometric scale allows the fabrication of nanostructures, the properties of which are mainly determined by quantum mechanics and differ considerably from those of the familiar crystalline state. Nanostructures constructed from inorganic solids such as semiconductors have new electronic and optical properties due to their size and quantization effects.[1,2] The quantization effects reflect the fundamental characteristics of structures as soon as their size falls below a certain limit.

An example of the simplest nanostructure is the quantum dot formed as an energy well: a 5–10 nm thick semiconductor is sandwiched between other semiconductors with a wider band gap. Quantum dots have led to important novel technologies for lasers, optical sensors and other electronic devices.

The application of nanolayers to data storage, switching, lighting and other devices, can lead to substantially new hardware, for example energy cells, and eventually to the quantum-based internet.

Nano spintronics, based on magnetic semiconductors, is one of the new and emerging areas of science and engineering in the XXI. century. This is because the creation and development of principally new materials and devices for information technologies, operating with charge and spin degrees of freedom as information carriers, is free from the limitations inherent in metal spintronic devices. Nanoscience and nanotechnology encompasses the development of nano spin electronics or spintronics, spintronics materials production, nano spintronic measuring devices, and associated technologies.

[1] J.J Ramsden. *Nanotechnology Perceptions* **1** (2005) 3.
[2] P.J. Kervalishvili. In: *Proc. Intl Conf. on Materials Testing*. AMA-Nuremberg, 13–15 May 2003, p. 107.

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Spin-polarized transport in semiconductors

Most research in spintronics is concentrated on studying spin-polarized transport in multilayer structures that include alternating layers of ferromagnetic metals and nonmagnetic semiconductors. The central task of such research is the creation of systems with an effective spin injection mechanism for a nonmagnetic semiconductor. There are only a few ferromagnetic materials capable of being reliable and good spin injectors. Magnetic discrete alloys are the most promising. They are multilayer systems composed of submonolayers of a ferromagnetic material in the matrix of a nonmagnetic semiconductor, for example, Mn/GaAs or Mn/GaSb. It is well known that these alloys have high Curie temperatures and sufficiently high spin polarizations. It is also significant that it is possible to control and to manage the ferromagnetic metal-semiconductor boundary surface immediately after the synthesis of these materials.

Recent research has shown that preparation should only be by the methods of MOS hydride epitaxy or laser epitaxy with the use of pulsed annealing of the epitaxial layers. These technologies are rather simple and at the same time allow the layers to be doped.[3]

The possibility to carry electrons with spatially oriented spins (spin transport) from a magnetoactive (ferromagnetic) material in a paramagnetic material has led to one of the most intensively researched areas of solid-state physics. This field of applied research in microelectronics is called “spin electronics engineering” or simply “spintronics”. The significance of spintronics may be judged from the perspective of the development and creation of new types of non-volatile memory with random access (MRAM), quantum single-electron logical structures and ultradense information storage media. Thus, the elementary information storage entity will be represented by an electron spin.[4,5] In this case, probably, the lower size limit of magnetic information recording will be reached.

The realization of spin-polarized current transfer provides new possibilities for solid-state electronics. For instance, there is evidence of spin-polarized luminescence, and for the basis of creating high frequency diodes whose output characteristics may be changed by an external magnetic field.[6,7] Another example is the possibility for the creation of a new generation of narrow-band solid-state devices operating at the millimetre and submillimetre wave ranges, like generators, amplifiers, receivers and filters, all modulated and frequency-tuned by a magnetic field and fully current-controlled.

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[3] A discrete alloy synthesis on the basis of an amorphous silicon hydride (α-Si:H) in combination with ferromagnetic 3D metals (Fe and Co) is planned to be performed at the Kurchatov Institute (Russian Research Centre) in conjunction with the Physics-Technological Institute of the Nizhnii Novgorod State University and the Georgian Technical University in the near future.

[4] D.D. Awschalom, M.E. Flatte and Nitin Samarth. *Scientific American*, June 2002, p. 27.

[5] G.A. Prinz. *Physics Today* **48** (1995) 353.

[6] R. Flederling, M. Kelm, G. Reuscher et al. *Nature* **402** (1999) 787.

[7] Y. Ohno, K.Young, B. Beschoten et al. *Nature* **402** (1999) 790.

The giant magnetoresistance effect (GMR)

The discovery of the giant magnetoresistance effect (GMR) in 1988[8] can undoubtedly be considered as the beginning of the spintronics era. This phenomenon is observed during the study of thin films with alternating layers of ferromagnetic and non-magnetic metals. It is found that, depending on the width of the non-magnetic spacer, there can be a ferromagnetic or antiferromagnetic interaction between the magnetic layers, and the antiferromagnetic state of the magnetic layer can be transformed to a ferromagnetic state by an external magnetic field. The spin-dependent scattering of conduction electrons is minimal, giving a small resistance when the magnetic moments are aligned in parallel, whereas for the antiparallel orientation of magnetic moments the situation is reversed and there is a high resistance. The GMR effect has demonstrated that spin-polarized electrons can carry a magnetic moment through non-magnetic materials while preserving spin coherence, hence the term "spin transport".

The GMR effect was used in a new generation of magnetic field sensors, which appeared as commercial products in 1994, but the present boom in the industry producing information storage devices started later, in 1997, when IBM presented the first hard drives with GMR reading heads. The implementation of this technology has allowed an increase in the density of information storage on magnetic disks, and the size of the market of these reading heads already exceeds 1 milliard US dollars.

Magnetic tunnel junctions (MTJ)

Sensors operating with magnetic tunnel junctions (MTJ) fall into the second class of spintronics devices. Here the ferromagnetic electrodes are divided by a very thin dielectric layer, and electrons tunnel through a nonconducting barrier under the influence of an applied voltage. The tunnelling conductivity depends on the relative orientation of the electrode magnetizations and the tunnel magnetoresistance (TMR). The TMR is small for a parallel alignment of the electrode magnetizations, and high in the opposite case. In contrast with the GMR devices, the electrodes are magnetically independent, and have different critical fields for changing the magnetic moment orientation. The first laboratory samples of (NiFe/Al_2O_3/Co) MTJ structures were demonstrated in 1995,[9] where the TMR effect reached 12% at room temperature.

Some of the largest manufacturers of electronic devices, including IBM, have recently declared the development of new memory devices: the so-called MRAM.[10] They include storage units based on MTJ structures and provide a significant increase in storage density and memory access speed, and enable all data to be saved if the power is disconnected. The first

[8] M. Baibich, J. Broto, A. Fert, F.V. Dau, F. Petroff, P. Etienne, G. Creuzet, A. Freiedrich and J. Chazelas. *Phys. Rev. Lett.* **61** (1988) 2472.
[9] J.S. Moodera, L.R. Kinder, T.M. Wong and R. Meservey. *Phys. Rev. Lett.* **74** (1995) 3273.
[10] S.S. Parkin, K.P. Roche, M.G. Samant, P.M. Rice, R.B. Beyers, R.E. Scheuerlein, E.J. O'Sullivan, S.L. Brown, D.W. Abraham et al. *J. Appl. Phys.* **85** (1999) 5828.

industrial designs of such memory devices appeared in 2003. A disadvantage of these devices is the small scale of integration; hence there is a need for additional controlling circuitry. These limitations may be overcome by the development of semiconducting spintronics, and in particular by the creation of spin transistors. In this case spintronic devices may be multi-functional, able to switch or to detect electrical and optical signals, and also to enhance signals.

For this reason, the third direction of the development of spintronic devices is based on multilayer nanostructures of ferromagnetic semiconductors, which demonstrate properties not available in their metal analogues, such as the ability to control the magnetic state of the material by an electric field,[11] and the giant planar Hall effect, which exceeds by several orders of magnitude the Hall effect in metal ferromagnets. The supergiant TMR effect observed for the first time in epitaxial (Ga,Mn)As/GaAs/(Ga,Mn)As structures[12] is also promising for future applications.

Future trends

Surprisingly, the development of spintronic technology in the XX. century was almost totally independent from semiconductor technology. Naturally, the connexion of these two technologies is extremely necessary for the purpose of combining the well-controlled electronic properties inherent in semiconductors with the additional possibilities of devices in which the spin degree of freedom of the current carriers is used. This represents the essence of semiconducting spintronics, and its central problem, namely the search for an effective way to inject spin into a semiconductor from a spin-polarized reservoir.

There are no effective ways to inject spin-polarized current into non-magnetic semiconductors at present.[13,14] Spin injection from magnetic semiconductors into non-magnetic ones gives good results in a number of cases,[15] but only at low temperatures, far from room temperature.

The so-called magnetic discrete alloys[16,17] are currently the most promising materials for the solution of the spin injection problem. These alloys consist of a periodic system of sub-monolayers of magnetic ions (for example, Mn), placed between semiconducting layers (GaAs, GaSb, InAs), forming a magnetic superlattice. There are randomly distributed Mn ions and 2D magnetic islands of MnAs (or MnSb) as well as manganese-containing layers. These discrete alloys have high Curie temperatures (above 300 K for the GaSb-system), demonstrate an extraordinary Hall effect at high temperatures, and have a relatively high degree of spin polarization. It is possible in such systems to control the quality of the ferromagnetic metal-

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[11] S.A.Wolf et al. *Science* **294** (2001) 1488.
[12] C. Ruster, C. Gould, T. Jungwirth, J. Sinova, G.M. Schott, R. Giraud, K. Brunner, G. Schmidt and L.W. Molenkamp. Cond-mat/0408532 (2004).
[13] M. Ziese and M.J. Thornton, eds. *Spin Electronics*. Heidelberg: Springer-Verlag (2001).
[14] G. Schmidt and L.W. Molenkamp. *Semicond. Sci. Technol.* **17** (2002) 310.
[15] B. Jonker et al. *Phys. Rev.* **B 62** (2000) 8180.
[16] X. Chen et.al. *Appl. Phys. Lett.* **81** (2002) 511.
[17] B.D. McCombe et al. *Physica* **E 16** (2003) 90.

nonmagnetic semiconductor border, to manage the current carrier's concentration and change the type of magnetic ordering. These discrete alloys should be considered as random magnet systems due to the inhomogeneous distribution of the magnetic phase in the submonolayers.

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