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ORIGINAL PAPER

Outline

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This Issue contains a collection of papers that were presented at the International Conference on Nanoscale Magnetism (ICNM-2010) held on September 28–October 2, 2010 in Gebze-Istanbul, Turkey. The scope of the Conference included fundamental magnetic properties on nanometer scale, spin dynamics in nanostructures, spin transport and spintronics, magnetic semiconductors and magnetoelectrics, magnetic measurement techniques, magnetization reversal, magnetotransport properties, magnetic nanoparticles, alloys and compounds, magnetic anisotropy, properties of advanced magnetic nanostructures.

The physics and chemistry of nanoscale systems have advanced rapidly over the last few years. Like in semiconductors, the structure of magnetic materials has been shown to become controllable in very low dimensions. As their dimensions decrease down to nanometer scale, these materials exhibit new and very rich interesting physical properties mainly due to quantum size effects. For instance, magnetic behavior is changed, the magnetization of noble metals is considerably induced, electron interference patterns are observed, oscillatory exchange interactions occur between adjacent layers separated by non-magnetic spacer, magnetoresistivity is enhanced many orders of magnitude, etc. Even the intrinsic physical characteristics of nanostructured materials are observed to change drastically compared to those of their macroscopic counterparts. This means that the intrinsic properties of the materials become extrinsic (size-dependent) as they are tailored in nanometer size. Obviously a particular material in macroscopic scale has a limited number of physical parameters having certain values. However, the same substance shows additional phenomena and most of these parameters can be adjusted by the size in nanoscale, allowing virtually continuous spectra for them. Various combinations of nanostructured elements in a single electronic component further enrich the physics, allowing the devices virtually having any characteristic. These phenomena introduce very good opportunities to the scientists to exploit these new properties to manufacture new and high technological devices, which could not be obtained by using only macroscopic materials.

Magnetic data storage is one of the most promising applications of nanomagnetism. The physical size of the recording bits of hard disk drives is already in the nanometer regime, and continues decreasing due to the ever increasing demand for higher recording densities. Soon the dimension of the recording bit will reach the sub-10-nm regime. At this level, both the writing and reading processes will become extremely challenging, if not impossible. This is because the sensor must be made smaller or at least comparable to the bit size, and at the same time, its sensitivity must be improved continuously so as to compensate for the loss in signal-to-noise ratio due to the decrease in the bit size. The former has to rely heavily on the advance of nanotechnology, and the latter on an emerging field called spintronics. The combination of these two fields has played an important role in advancing the areal density of magnetic recording from a few gigabits/in^2 to the current level of more than 100 Gbits/in^2. In addition to hard disk drives, the developed technologies have also been applied to magnetic random access memories (MRAMs). Further advance in these fields is the key to realizing terabits/in^2 hard disk drives and gigabit nonvolatile memories within this decade.

The spintronics in its broader sense contains all types of electronics that make use of both charges and spins. It is a new and rapidly developing branch of commercial electron-

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ics, which utilizes spin degrees of freedom of the carriers to control an electric current. One may say that spintronics accumulates or synthesizes the frontier knowledge of the physics of spin and magnetism, electronics and optics, putting them together in the nanoscale range and realizing them in new multifunctional devices. The first generation of devices combines standard microelectronics with spin-dependent effects that arise from the interaction between the spin of the carrier and the magnetic properties of the material. Therefore, by controlling the spin alignment one can add an extra parameter to adjust the device characteristics. The magneto-optical effect is another important phenomenon for spin injection, detection and manipulation to bring electron-spin and photon in a single component of an electronic device. The ultimate goal is to use the collaborative effects of the magnetic, electric and optical nature to improve the performance of the devices. The magnetoresistive read heads for the computer hard disk drives give us the first example of successful long-term innovation, which resulted in total re-orientation of the computer hard-disk industry on the magnetoresistive read heads.

These metal-based spintronic devices are based primarily on the spatial modulation of electron spins through using layered structures of magnetic and non-magnetic materials. The lack of capability in charge modulation in these types of structures may eventually limit their ultimate performances in terms of both the magnetoresistance and other functionalities. To address this issue, recently, a great deal of effort has been devoted to the developments of magnetic semiconductors which allow the modulation of both the spins and charges. The advances in this field may eventually lead to spintronic devices with performances superior to their metal-based counterparts. In addition to pure metal-based or semiconductor-based spintronic devices, hybrid devices making use of both technologies also have been explored in recent years.

Although the read sensor for magnetic recording and storage cells for magnetic memory are based on spintronics, the storage of information in disk media is still based on classic physics, and it does not involve spintronics. However, as the bit size continues decreasing, it will approach atomic size in near future. At this stage, a fundamental change in the information storage principle will be required. One of the possible scenarios is to store information in the reciprocal space or energy domain. In this case, the spin of electrons and nuclei instead of the magnetization of magnetic grains will play important role. This is closely related to another emerging field called quantum information storage.

At the present time the small-scale magnetic materials are used both in new recording media and, in particular, in the most critical elements of recording systems, in recording heads. Magnetic layers serving as recording medium in a storage media are becoming increasingly complex with increasing areal density of recording. The size of a single recorded bit in most recent hard disks is now in nanometric scale. Magnetic recording density is increasing close to 100% every year. So, recording technology has already demonstrated recording density over 100 Gbit per square inch at the present time. However, even if all the technological problems could be solved, there is still a theoretical limit for recording density. With decreasing size of recorded bits, these magnetic particles have already been entering the superparamagnetic regime. The thermal agitation energy, kT, becomes comparable to the effective magnetic anisotropy (including the shape anisotropy) energy of a single particle. Then, magnetic moments start to flip within a finite time and therefore the recorded data are partly washed out. The stability of the bit exponentially depends both on the barrier energy (anisotropy energy) and on the particle volume.

The superparamagnetic limit for some typical materials is of the order of 10 nm, which corresponds to a recording density of the order of terabits per square inch. The important parameters are anisotropy, coercivity, size, preferential orientation and the density of magnetic particles. The density can still be improved further by using perpendicular recording. In this case very thin and long enough magnetic wires are ordered perpendicular to the surface of the media. Even individual wire or particle can be used as a bit unit in near future. Production of magnetic fine particles with uniform physical properties can be achieved by some lithography techniques. Dimensions of magnetic components used as sensor and writer elements in recording heads are in nanometric scale and smaller than the limit of optical lithography.

Thus, the sensitivity and the resolution of reading are going to increase drastically as the size of the particles is decreased down to nanometer scale. The sensitivity of magnetoresistive device is defined as relative change of resistivity per oersted. In a recording head, magnetoresistive elements based on GMR or spin tunneling effect are used. By using spin tunneling effect, sensitivity can be an order of magnitude higher compared to conventional magnetoresistive Ni-Fe sensor. High sensitivity has been achieved by GMR materials. In order to enhance the sensitivity further, the current perpendicular to the surface mode is going to be implemented.

Recently magnetic and semiconducting elements are being combined into a chip (MRAM) in order to avoid the mechanical part from our lives (speed of data transfer in hard disks is now close to 1 Gbit/s). Moreover, logic devices based on nanoscale magnetism are under investigation. Magnetic transistors have recently been demonstrated. Basic principles of this device depend on the injection of spin-polarized current between magnetic–nonmagnetic layers. Also, some researchers are trying to use magneto-optic, magneto-elastic, and other material properties to develop novel devices.

The magnetic semiconductors are usually made through adding magnetic impurities to host semiconductors. It is not sufficient, however, that every semiconductor can be made magnetic using this approach because some of them still do not exhibit any magnetic properties even after they are doped with a substantial amount of magnetic impurities. Some of them, although being magnetic, show a very low Curie temperature. However, the situation has changed drastically in recent years due to the intensive efforts made by researchers in this field in many research organizations. Several different types of magnetic semiconductors having a Curie temperature higher than room temperature have already been found. It should be noted, however, that all of these are based on preliminary experimental results; further experiments are required to verify the results. The progress was made not only in materials themselves, but also in the applications of these materials in creating new functional devices such as semiconductor-based magnetic tunnel junctions and spin-injection devices. Although the current technology for a read sensor is based on metallic spintronics, semiconductor-based spintronics has the potential to provide sensors or storage elements with superior performances for next-generation data storage devices.

Evolution beyond passive magnetoelectronic components is envisioned in the next generation of spintronics devices, which should combine memory and logical functions in order to set new standards in future information technology. Recently, there has been growing interest in studying magnetization reversal involving spin transfer from a spin-polarized current injected into the device as an alternative to stray magnetic fields for switching the magnetic configurations in GMR or TMR devices. The required huge current densities hamper the technical realization of this attractive concept. One can use the electric field as alternative means for controlling the magnetic configuration of magnetoresistive systems. So, the quest for higher data density in information storage is motivating investigations into approaches for manipulating magnetization without using magnetic field. This is also evidenced by the recent boom in magnetoelectronics and spintronics, where phenomena such as carrier effects in magnetic semiconductors and high-correlation effects in colossal magnetoresistive compounds are studied for their device potential.

The magnetoelectric effect—the induction of polarization by a magnetic field and of magnetization by an electric field—provides another route for linking magnetic and electric properties. Hence, one expects the direct coupling between the magnetic and dielectric properties and their control by the application of magnetic and/or electric fields. In multiferroic materials, in which ferroelectric and ferromagnetic ordering occurs simultaneously, magnetic domains can be tuned by the application of an external electric field, and likewise electric domains are switched by magnetic field, which is unachievable separately in either ferroelectric or magnetic materials. So, multiferroics, characterized by simultaneous ferroelectric and magnetic ordering, may exhibit a larger magnetoelectricity exhibiting potential in a wide range of applications, including the emerging field of spintronics, data-storage media, and multiple-state memories, information storage, sensors, transducers, actuators, storage devices, etc. Besides application potential, the fundamental physics of multiferroic materials is rich and fascinating. This nontrivial spin-lattice coupling in the magnetoelectrics has been manifested through various forms, such as linear and bilinear magnetoelectric effects, polarization change through field-induced phase transition, magneto-dielectric effect, and dielectric anomalies at magnetic transition temperatures.

Thus, today the role of nanoscale magnetism in human life is more important than ever. The growing need for even higher data-recording densities has driven the size of particles used in recording media down into the nanometer range while the rapidly increasing power of computers has made it feasible to perform simulations of the dynamic properties of realistic model systems of sizes comparable to experimental ones. The quality and the resolution of the devices have been increased in parallel with the developments in scientific research. There is a great expectation in industry that the results of these exciting scientific researches can be exploited in a new generation of high-technology devices. Many of the unique properties of these materials have high potential for technical applications in diverse areas such as information technology, magnetosensors, electronics, data storage, magnetic heads of computer hard disks, single electron devices, microwave electronic devices, etc. In fact, for instance, the GMR materials have already found applications as sensors of low magnetic fields, computer hard disk heads, magnetoresistive RAM chips, etc. Even new terminologies, for example magnetoelectronics, spintronics, spin valve, etc. have recently been introduced to refer to aspects of the field involving magnetic phenomena. Thus this generic nanotechnology will inevitably have great impact on a wide range of industrial sectors and on the everyday lives of humans. In other words, one of the pillars of industry in the 21st century may involve the field of magnetic and electrical nanoscale materials.