Magnetic Nanostructures: from fundamental studies to technical applications

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Abstract

Magnetic nanostructured materials produced in the present are reviewed. Some of their technical applications are presented.

I. Introduction

The place of scientific research in economical and social life is of great importance. The generated knowledges and their interactions with industry contributed essentially to the evolution of the human society. Since our summer school is mainly connected with the field of magnetism, the evolution of the research in this field and the connection with nanomaterials seem to be useful to be remembered. The development of the knowledge in the field of magnetism may be divided in seven periods [1]: (1) ancient (-1000 ÷ 1500), (2) early (1500 ÷ 1820), electromagnetic (1820 ÷ 1900), understanding (1900 ÷ 1935), high frequency (1935 ÷ 1960), applications (1960 ÷1995) and spin electronics (1995 ÷ present). Atomic scale magnetic phenomena were discovered in the first half of the last century, but only in recent decades it became clear that solid-state magnetism is, to a large extent, a nanostructural phenomena. A naturally occurring biomagnetic phenomenon is magnetite nanoparticles precipitated in bacteria, mollusks and contain chains of 40-100 nm particles used for vertical orientation [2, 3]. Similar magnetite particles have been found in the brains of bees or pigeons and may serve as field sensors for migration [4].

The recent improvement of magnetic materials knowledge is connected to their nanostructuring. The artificial nanostructuring create completely new materials and technologies. The progressing miniaturization in computer technology is based mainly on nanostructured media for ultra-high density magnetic recording [5]. Related to the above is the spin electronics [9, 10] and various types of nanostructures such as multilayers and nanojunctions. Another area is constituted by magnetoresistive sensors based on magnetoresistance effect in metallic thin films [11, 12], granular systems [5, 13] and magnetic oxides[10, 14, 15]. The nanoparticles can be used also in medicine [16], microelectromechanical systems, various nanodevices as nanoscale magnetic-force nanotips [17, 18] or permanent magnets [19].

Magnetic recording technology has an excellent future growth potential. The requirements connected with a reduction in the peripheral device size and power consumption while maintaining an exponential increase in storage capacity is strongly related to the development of nanomaterials. The various types of storage in relation capacity-average access time is given in Fig.1a and in Fig.1b a hierarchy based on access time and cost per bit is shown [20]. Although the access rate in semiconductor memories is fast and capacity is high, this type of memory is still very expensive and in addition the memory is volatile. The disk drives offer longer access time but they are cheaper and are used in standard PC and laptop applications. The magnetic memories are also nonvolatile. Magneto-optical memories now grow as importance since of their good average access time and low price.

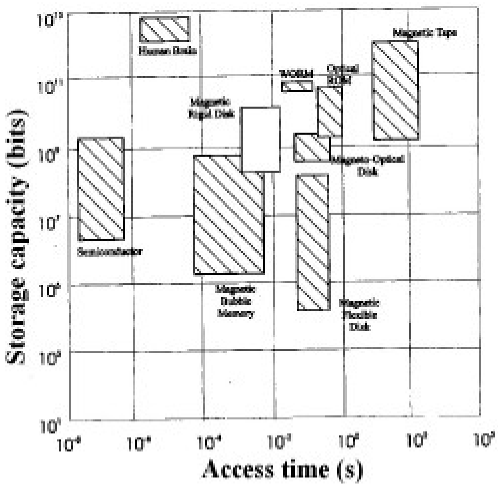

Fig 1a

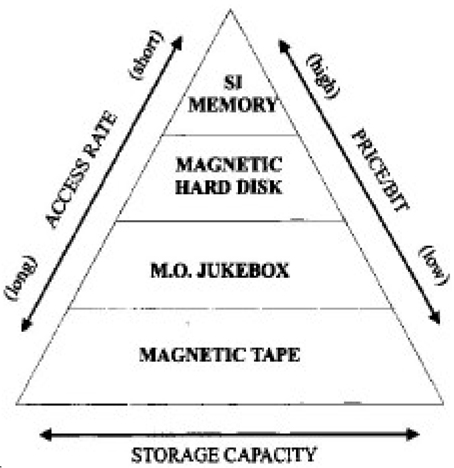

Fig 1b

II. Nanostructure materials

The magnetic nanostructured materials may be characterized by diversity of geometries. Various types of small magnetic particles exist in nature or were artificially manufactured. A somewhat arbitrary division may be as: (1) particle and cluster, (2) thin films and multilayers, (3) particle arrays, (4) nanowires, (5) nanocomposites. Typical nanostructured geometries are shown in Fig.2 [3]. There are: chain of fine particles (a), striped nanowires (b), cylindrical nanowires (c), nanojunctions (d), vicinal surface step (e), nanodots (f), antidots (g) and particulate medium (h). The elongated single domain (ESD) particles are commonly used for magnetic recording. In addition, small particles can be used to produce ferrofluids. In this case typical dimensions of particles are 10 nm and are realized from Fe_3O_4, $BaFe_{12}O_{19}$, Fe, Ni etc. The nanoparticles may be also arranged in both free- and embedded clusters. Twodimensional arrays of nanoparticles are useful in advanced recording media. The dots disposed on a thin film are of submicron dimensions and are made from 3d series transition metals or 3d magnetic alloys. The geometry of dot arrays may be square, hexagonal or to form other structures as corrals [3]. The antidots nanostructures are constituted as holes in the film [21, 22] and through potential applications are: magnetic recording, sensors, mechanical devices, spin electronics. The magnetic thin films and multilayers can be considered as nanostructures [23]. Since of their use in magnetic recording devices, the thin films were largely studied.

Magnetic nanowires have potential applications in advanced nanotechnology including patterned magnetic media, magnetic devices and as materials for microwave applications. Thin film nanowires- Fig.2b. - may be obtained by depositing magnetic materials on vicinal surfaces. They can be produced with thickness down to one or two monolayers. By electrodeposition may be also obtained a regular wire arrays [24]. Cylindrical nanowires may be obtained be deposition into molecular sieve [25, 26]. By electrodeposition into porous anodic alumina was possible to produce Fe, Co and Ni wires with diameter d = 4 - 200 nm and length $l \cong 1$ μm [24, 27]. Typically, the nanowires form nearly hexagonal columnar arrays with centre to centre spacing of ≅ 50 nm [28]. These systems are of great interest for magnetic recording media [29].

III. Magnetic nanomaterials in data storage applications

Nanomagnetic systems are an important part of today's technology and have potential applications in future new devices. The applications of nanomaterials as patterned media for hard disks, miniature magnetic sensors using GMR effect and magnetic memory cells which are being developed for fast and dense solid state memory will be outlined. The areal density of magnetic recording has been increased over the past few years at 60 % per annum due to concurrent optimization of successive generations of thin film heads, miniaturization of the planar write head and improvement of Co-based in-plane thin film media. The hard disks having a greater storage density have been developed. However, the effects associated with the finite grain size of magnetic alloys used for storage, limit the miniaturization [7]. As a result a new type of storage media has been proposed made from a closely-packed array of nanomagnets patterned onto a hard disk [30]. A conventional hard disk is constituted by a thin film of granular Co-alloys. The thin films are constituted from exchange decoupled grains, each grain reversing individually their magnetization. Intergranular exchange coupling is suppressed by adding a non-magnetic element (particularly Cr) which segregates at the grain boundaries. In order to increase the storage capacity, it is necessary to reduce the size of the grains and to ensure a minimum number of grains per bit, to limit statistical noise. It was suggested that for obtaining low particle noise contribution, about 1000 grains are needed in one bit cell. For example a bit cell in the Co-based medium used for the IBM (0.184 Gbit cm^{-2}) consists of about 1900 grains with a grain size of about 20 nm [20]. Thus, for a 1.5 $Gbitcm^{-2}$ thin film medium, a grain size of about 10 nm is necessary. In this case there will be about 600 grains in a 1 bit area. The reduction of the size of grain is limited to $\cong$ 10 nm, since the grains having smaller dimensions are superparamagnetic. Smaller grains can only be used if their switching field is increased. This may be possible by increasing the coercivity of Co alloys, up to 0.28 MAm^{-1}, by incorporating Ta, Pt [31]. Coercivities up to 0.8 MAm^{-1} would be possible by using permanent magnet materials (Nd-Fe-B, Sm-Co). In this case the grain size can be reduced up to 2.5 nm but in this case it is not possible to use write heads, available today, in which the write fields are limited to maximum 0.4 MAm^{-1}.

As mentioned already, higher storage densities, in the range (16 – 80) $Gbitcm^{-1}$, could be reached by using patterned media. The collection of exchange coupled grains in this case is replaced by an array of nanomagnet bits (10 – 20 nm sizes) physically isolated from their neighbours and able to be switched “independently”. The bit could be oriented either in the plane of disk or perpendicular to it. In Fig. 3 there are plotted three types of patterned media [7] with bars in the plane of the disk (a), perpendicular pillars (b) and cones (c). The perpendicular configuration leads to a more dense packing, but in-plane configuration allows a more conventional reading and writing technology to be used. Nanomagnet bars of Co film with dimensions 40x25x200 (nm), in plane, have a storage density of 4 $Gbitcm^{-2}$ [7]. The average switching field is $\cong$ 0.1 MAm^{-1}. We note that the packing density is limited by the magnetostatic interactions between elements.

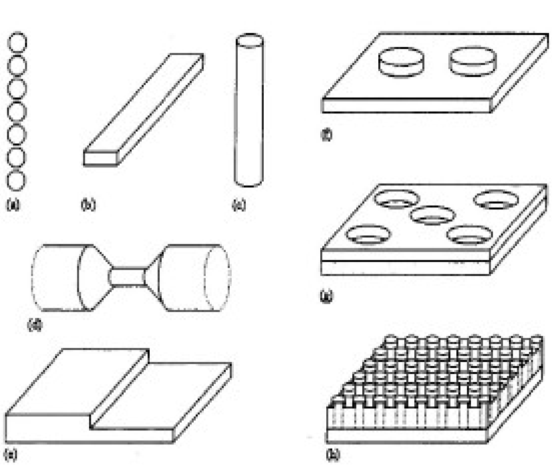

Fig 2

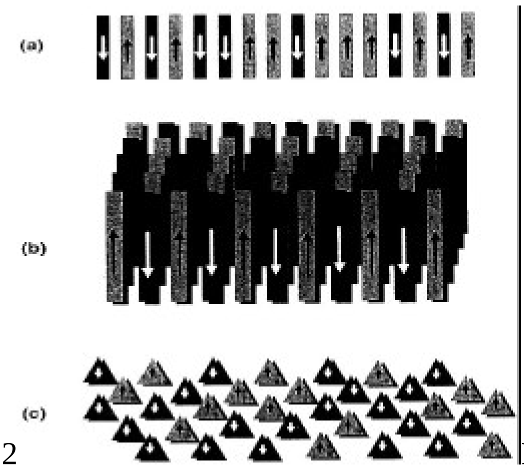

Fig 3

IV. Giant magnetoresistance sensors

Magnetic memory elements are being developed as a new type of non-volatile random access memory (RAM) [32, 33]. As mentioned before, in certain applications magnetic RAM could replace silicon devices based on CMOS technology, particularly where the resistance to radiation is important. The operation of magnetic memory cells is based on the giant magnetoresistance effect (GMR) in spin valves or spin tunnel junction structures and special properties of nanomagnets as storage elements for binary data.

Giant magnetoresistance was first discovered in Fe-Cr superlattices with the non-magnetic Cr layers less than 2nm thick, separating slightly thicker Fe layers [34]. The origin of the GMR effect is the difference in scattering of electrons of opposite spins (up or down) as they pass through a ferromagnetic materials. The GMR sensor could consist of two magnetic layers which have their magnetizations oriented parallel or antiparallel to each other. When the two layers are magnetized antiparallel, the spin-up and spin-down electrons will be scattered equally. When the layers are magnetized parallel, the spin-dependent scattering results in a lower resistivity for one type of electrons and a higher resistivity for the other type – Fig. 4 [7]. The lowering resistivity for one type, result in a lower resistance for the structure, as a whole device. Thus, when the direction of magnetization direction is changed, multilayers structures, spin valves and spin tunnel junctions can be used as sensors. This involves that they must be patterned into micron or sub-micron sized elements.

Multilayers comprising of alternating series of magnetic - non-magnetic bilayers can produce large $\Delta R/R$ values, but requires a field of the order 10-40 kAm^{-1} to reverse the antiparallel coupling of layers and to saturate them in the low resistance state. Thus, the multilayers cannot be used as detectors of small fields. A more sensitive response is possible by using a spin valve structure [35]. The spin valves have two soft magnetic layers (Ni-Fe) separated by a metallic spacer layer (Cu). The GMR effect is generated by having a “pinned” layer held rigidly to a fixed magnetization direction and a layer in which the magnetization is free to rotate relative to the pinned layer when a field is applied. Thus, high resistance (antiparallel) and low resistance (parallel) states can be achieved. Spin tunnel junctions have two magnetic electrodes separated by an insulating tunnel barrier made from aluminium oxide [36]. Unlike in spin valves, the current flows through the junction perpendicular to the layers – Fig. 5 [7]. This increases the effect of spin dependent scattering on the electrons passing through the structure and leads to higher $\Delta R/R$ values than in spin valves.

The interesting physical properties of magnetic nanostructures materials as well as their characterization will be largely presented in the following lectures. The analyze methods will be also described. In addition come of their technical applications will be outlined.

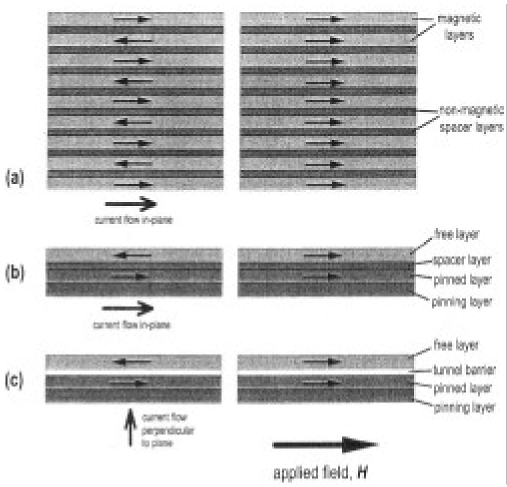

Fig 4

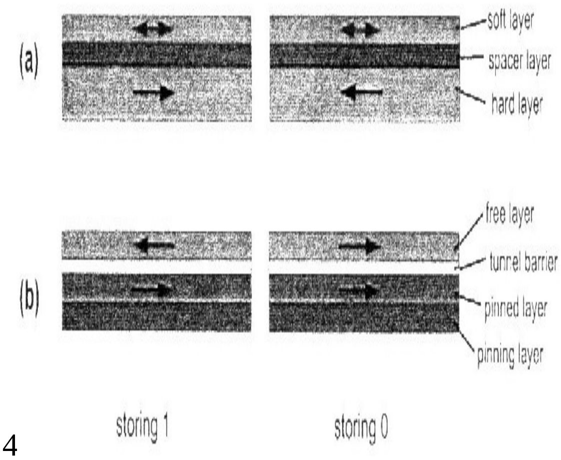

Fig 5

References

[1] J. M. D. Coey, J. Magn. Magn. Mat. **226**, 2107 (2001).
[2] D. Craik, *Magnetism, Principle and Applications*, New york, Willey, 1995.
[3] R. Skomski, J. Phys. Condens. Matter **15**, R841 (2003).
[4] D. J. Dunlap, Rep. Progr. Phys. **53**, 707 (1990).
[5] J. Q. Xiao, J. S. Jiang, C. L. Chien, Phys. Rev. Lett. **68**, 3749 (1992).
[6] R. L. Comstock, *Introduction to Magnetism and Magnetic Recording*, New York, Willey, 1999.
[7] K. Kirk, Contemp. Phys. **41**, 61 (2000).
[8] D. J. Sellmyer, M. Zheng, M. Skomski, J. Phys.: Condens. Matter. **13**, 483 (2001)
[9] M. Ziese, M. J. Thornton (eds.), *Spin Electronics*, Springer Verlag, Berlin, 2001.
[10] J. M. D. Coey, M. Viret, S. von Molnar, Adv. Phys. **48**, 167 (1999).
[11] P. Grünberg et al, Phys. Rev. Lett. **57**, 2442 (1986).
[12] S. S. P. Parkin, Phys. Rev. Lett. **67**, 3598 (1991).
[13] I. E. Berkovitz et al, Phys. Rev. Lett. **68**, 3745 (1992).
[14] E. Burzo, *Perovskites*, Landolt Bornstein Handbuck, vol. III-27f1, Springer Verlag, 1996.
[15] M. M. Salamon and M. Jaime, Rev. Mod. Phys. **73**, 583 (2001).
[16] D. J. Craik, R.S.Tebble, Rep. Progr. Phys. **24**, 116 (1961)
[17] S. H. Liou, Y. D. Yao, J. Magn. Magn. Mat. **190**, 130 (1998).
[18] L. Folks et al., Appl. Phys. Lett. **76**, 909 (2000).
[19] E. Burzo, Rep. Progr. Phys. 61, 1099 (1998)
[20] J. C. Lodder, in *Handbook of Magnetic Materials*, vol. 11, North Holland, 1998, p. 291.
[21] M. Tornow et al, Phys. Rev. Lett. **77**, 147 (1996).
[22] R. P. Cowbun, A. O. Adeyeye, J. A. C. Bland, Appl. Phys. Lett. 70, 2309 (1997).
[23] J. Sauder, Rep. Progr. Phys. **62**, 809 (1999).
[24] F. Y. Li, R. M. Metzger, J. Appl. Phys. **81** 3806 (1997).

[25] B. Roxlo et al, Science **235**, 1692 (1987).
[26] G. A. Ozin, Adv. Mater. **4**, 612 (1992).
[27] G. Zangari, D. N. Lambelth, IEEE Trans. Magn. **33**, 3010 (1997).
[28] O. Jessensky, F. Müller, U. Gösele, J. Electrochem. Soc. **145**, 3735 (1998).
[29] M. Shiraki et al, IEEE Trans. Magn. **21**, 1465 (1985).
[30] S. Y. Chou et al, J. Apl. Phys. **76**, 6673 (1994).
[31] P. J. Grundy, J. Phys. D.: Appl. Phys. **31**, 2975 (1998).
[32] S. S. P. Parkin et al. J. Appl. Phys. **85**, 5828 (1999).
[33] S. Tehrani et al, J. Appl. Phys. **85**, 5822 (1999).
[34] M. N. Baibich et al, Phys. Rev. Lett. **61**, 2472 (1999).
[35] B. Dieny et al, J. Appl. Phys. **69**, 4774 (1991).
[36] J. J. Moodera et al, Phys. Rev. Lett. **74**, 3273 (1995).