Chapter

Intriguing Properties and Applications of Functional Magnetic Materials

Sabah M. Abdelbasir and Ahmed Esmail Shalan

Abstract

Functional magnetic materials, also called the smart materials of the future, are a group of materials having important and interesting physical properties, which can be affected when an external magnetic field is applied. They are intriguing models that have a strong impact on improving different technologies. Their magnetic response to an external magnetic field can be represented as paramagnetic, diamagnetic, ferromagnetic, or antiferromagnetic. Compared with bulk materials, they show uncommon magnetic behavior as a result of their surface/interface effects, electronic charge transfer, and magnetic interactions. They can be used in different vital applications like data storage systems, refrigeration, magnetic recording, and medical studies. In this chapter, essential attractive magnetic properties that are relevant to different applications will be explained.

Keywords: functional materials, magnetic nanoparticles, magnetic field, physical properties, applications

1. Introduction

1.1 Magnetic materials

Magnetic materials play a crucial role in the progress of industrial development and scientific growth. They are constantly used in power generation and transmission, electronic devices, analog and digital data storage, medical devices, magnetic therapy and drug delivery, sensors and scientific equipment, etc. Functional magnetic materials are materials with unique physical properties, which can be affected when subjected to an applied excitement such as magnetic field. They are considered as the smart materials of the future. A material can be applied in magnetic refrigerators when a change in the entropy across its magnetic ordering temperature occurs. This functionality of a magnetic material has huge possibility to be used as an alternative cooling technology and it is based on magnetocaloric effect (MCE), which is reversible temperature change in a magnetic material when a variable magnetic field is applied. This functionality additionally offers the prospect of a compact, highly efficient, and environment-friendly alternative to the most commonly used vapor-compression-based freezing system. The main challenges are the availability of high magnetocaloric materials in large quantities exhibiting large MCE at room temperature in a reasonable magnetic field as well as low hysteretic losses.

Magnetic nanoparticles have been the focus of research because of their interesting properties, which doubtless may see use in data storage and processing, spintronics, catalysis, drug delivery, magnetic resonance imaging (MRI), environmental studies, etc. These materials show uncommon magnetic behavior compared with bulk materials, principally because of their surface/interface effects, electronic charge transfer, and magnetic interactions. The local magnetic properties with the size scale of nanometers play the key role in the microstructure-magnetic properties interplay in permanent magnets as **Figure 1** illustrates. The typical phenomena related to nanoscale structures are the increased relevance of surface effects, defects, and the existence of new phases. Therefore, these phenomena can be utilized in developing new magnetic nanoparticles.

1.1.1 Hard magnetic materials

Several permanent magnet materials were discovered within the past century. Techniques to effectively manufacture these magnets have been shown [2]. Device designs using such magnets in different active and inactive applications have been fruitfully exploited. The energy product of permanent magnets has been improved, commencing from ≈1 MGOe for steels, increasing to ≈3 MGOe for hexagonal ferrites, and finally peaking at ≈56 MGOe for neodymium-iron boron magnets during the previous few years. With this, almost 90% of the limit for the energy density, $(BH)_{max}$, (based on the Nd_2Fe_{14} B phase) can be attained in commercially produced sintered Nd-Fe-B grades. The historic development, spanning about 100 years, of such permanent magnets is shown in **Figure 2**.

However, the search for novel hard magnetic compounds with higher remnant magnetization has, to some extent, settled and no more breakthrough is noticeable. On the other side, only a modest number of ternary and quaternary systems have been explored as yet. The approach of nanocomposites is currently the most actively chased as well as exchange-coupled with a soft magnetic phase, which has

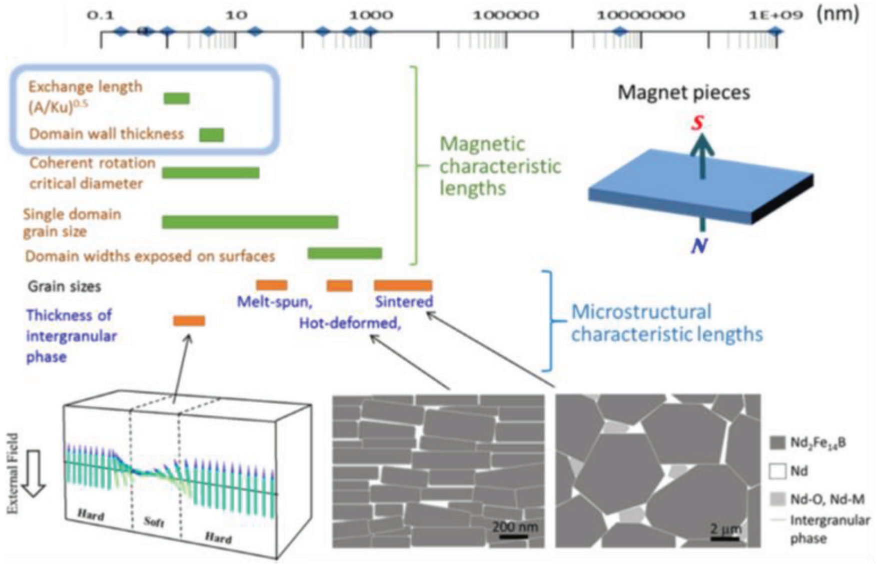

Figure 1.
Magnetic characteristic lengths and illustration of typical microstructures in permanent magnets [1]. Reproducibility with permission from IOP publisher.

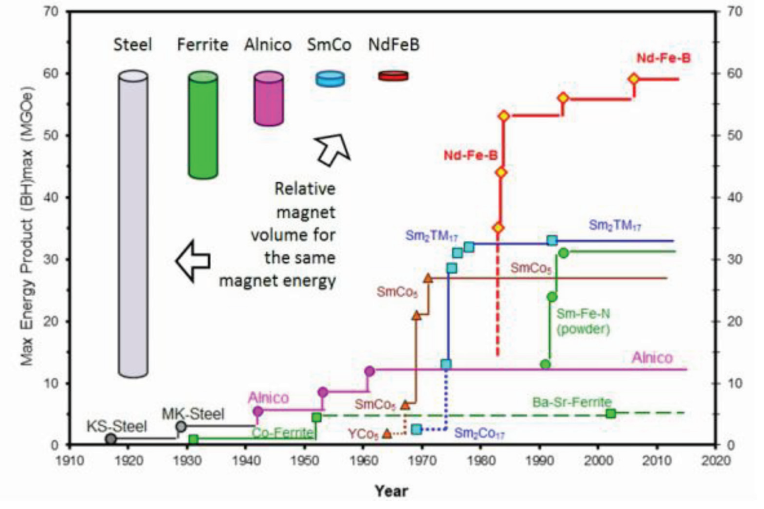

Figure 2.
Development in the energy density $(BH)_{max}$ at room temperature of hard magnetic materials in the twentieth century and presentation of different types of materials with comparable energy density. Reproduced with permission from [3].

an intrinsic upper limit of $\mu_0 M_s$ = 2.43 T for an $Fe_{65}Co_{35}$ alloy, where μ_0 is the permeability of free space and M_s is the saturation magnetization.

Lately, there is a much-energized interest in various types of high-performance permanent magnets based on rare-earth intermetallic compounds. This is led by, for instance, the rising need for energy-efficient technologies in which these magnets often play a vital role. The need for enlarged energy densities at different operating temperatures is the main motive for the development of the rare-earth permanent magnets (RPMs). Most importantly, this comprises less Dy-containing Nd_2Fe_{14} B-type magnets with much improved temperature stability for electromotor applications at around 450 K [4], Pr_2Fe_{14} B-type magnets for applications at 77 K together with high-Curie temperature (Tc) superconductors, [5] and a new generation of SmCo 2:17-type magnets which are applied at temperatures above 670 K [6, 7]. It also includes magnetic-power microelectromechanical systems (MEMSs) [8–11], for example, a high-speed permanent magnetic generator that requires textured, thick RPM films [12]. Currently, importance of research is on how to control the structure of grain boundary phases to understand the relevant coercivity mechanisms and the related elementary magnetization processes. The next class of permanent magnets could be rough-surfaced nanocomposites. This would include controlling the fabrication of privately mixed multiphase and well-directed nanoscale magnets, which cannot be done by conventional techniques.

1.1.2 Soft magnetic materials

The most characterizing properties of soft magnetic materials are the easy magnetization reversal accompanied with a small area of the hysteresis loop and a low coercivity (He). Quite similar to hard magnetic materials, essential magnetic properties and microstructure are to be optimized to obtain soft magnetic materials. However, a very low magnetocrystalline anisotropy and weak to almost zero interaction between magnetic domain walls and grain boundaries are required, which is the opposite of the favorable conditions for permanent magnets. Soft magnetic materials are very significant for the subjects of power electrical applications such as generators, distribution transformers, and a broad assortment of motors as well as in electronics where a mass of inductive components is required as shown in the road map of ultra-low-loss nanocrystalline alloy as shown in **Figure 3** [13]. The widely used soft magnetic materials are low-carbon steel and non-oriented silicon iron. They account for about 80% by weight, and approximately 55% by value of all soft magnetic materials, followed by grain/oriented silicon iron (17/13%), ferrite cores (1.5/7.5%), nickel- and cobalt-iron alloys (0.5/4.5%), and special materials and offices such as metal powder cores (2/8%). Soft magnetic materials are materials easily magnetized and demagnetized. They typically have intrinsic coercivity less than 1000 A m^{-1} and they are used to enhance and/or channel the flux created by an electric current. The main parameter for soft magnetic materials is the relative permeability (μr, where $\mu_r = B/\mu_o H$), which measures the material response to the applied magnetic field. The other important parameters are the coercivity, the saturation magnetization, and the electrical conductivity. The applications for soft magnetic materials are divided into two main categories: AC and DC. In DC applications, the material is magnetized in order to carry out an operation and then demagnetized at the end of the operation, for example, an electromagnet on a lift at a scrap yard will be switched on to attract the scrap steel and then switched off to drop the steel.

For DC applications, the main regard for material selection is very likely to be the permeability. Where the material is used to produce a magnetic field or to create a force, the saturation magnetization may also be important. For AC applications, the important thought is how much energy is lost in the system as the material is cycled around its hysteresis loop. The energy loss can arise from three different sources: (1) hysteresis loss, which is related to the area contained within the hysteresis loop; (2) eddy current loss, related to the generation of electric currents in the magnetic material and the interrelated resistive losses; and (3) irregular loss, related to the movement of domain walls within the material.

Soft magnetic alloys have competed a key role in power generation and conversion for the electrical grid. The necessity for efficient generation, transmission, and distribution of electric power is ever growing; but, at the same time, the annual electric losses are overtaking annual increases in electricity consumption. In the USA, electricity is regenerated to high-voltage AC current at voltages between 138 and 765 kV and transmitted to substations close to its end-use location. The voltage is then turned down to lower values (between 13 kV and 120 V) for distribution to

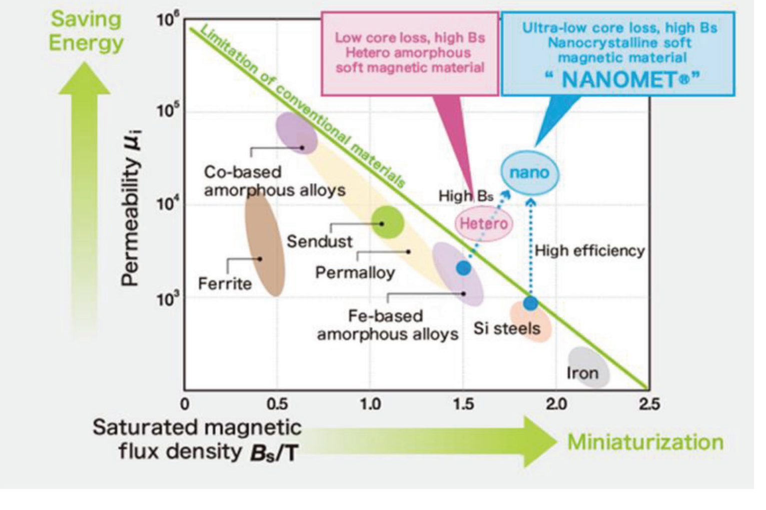

Figure 3.
Development road map of ultralow-loss nanocrystalline alloy. Reproduced with permission from [13].

different consumers. These generation, transmission, and distribution systems are aging, inept, and imperfect to meet the future energy needs of the USA without important changes in operation and infrastructure. For these reasons, advanced electric storage systems, smart controls, and power electronics for AC-DC conversion are technologies that are being supported to reform the desired way.

2. Magnetocaloric materials

Modern society depends on readily available refrigeration for preserving food and providing comfortable living places. Ordinary refrigerators use ozone for reducing harmful chemicals such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), and ammonia (NH_3) in a vapor compression cycle to supply cooling. Ordinary refrigerators tend to be unwieldy, hefty, and lack energy efficiency despite they have met the cooling needs. Recently, an alternate refrigeration method using magnetocaloric effect (MCE) has been investigated as a way to deal with the defects of vapor-compression refrigeration.

Magnetic refrigeration has three outstanding advantages when compared to gas compressing refrigeration. First, it involves no harmful gasses; second, it can be compactly built as its main working material is a solid; and third, magnetic refrigerators are almost noiseless. Also, the cooling efficiency while operating with gadolinium can reach 60% of the theoretical efficiency limit [14] compared to only about 45% in the best gas-compressing refrigerators. While commercial refrigerators of this kind are still in the development stages, research efforts to develop new materials with improved MCE are targeted on maximizing the cooling capability and energy efficiency of this newborn technology. In this part, the different materials are compared, focusing on transition metal-containing compounds. When a material is subjected to an applied magnetic field, its magnetic order changes, leading to subsequent change of the entropy related to the magnetic degrees of freedom (magnetic entropy, S_m). Under adiabatic conditions, ΔS_m must be covered by an equal, opposite change in the entropy associated with the lattice, resulting in a change in the temperature of the material. This temperature change, ΔT_{ad}, is usually called the MCE. It is correlated to the magnetic properties of the material through the thermodynamic Maxwell relation

$$\left(\frac{\partial s}{\partial B}\right)_T = \left(\frac{\partial M}{\partial T}\right)_B \tag{1}$$

From magnetization measurements taken at different temperature periods, ΔS_m can be calculated as illustrated in Refs. [15, 16]. For materials showing a first-order phase transition with large hysteresis, these magnetization measurements should be performed cautiously so as not to overestimate values of the entropy change [17]. Otherwise, the magnetic entropy change can be acquired straight from a calorimetric measurement of the field dependence of the high temperature capacity, c, and then integrating. It has been validated that the values of ΔS_m (T, B) derived from the magnetization measurement concur with the values from calorimetric measurement [18]. Numerical integration of the adiabatic temperature change, [ΔT_{ad} (T, B)], can then be done using the experimentally or theoretically predicted magnetization and heat content values. Clearly, the MCE will be large when $\left(\frac{\partial M}{\partial T}\right)_B$ is large and c (T,B) is small at the same temperature conditions. As effects at high temperatures are concerned, the heat capacity on the order of Dulong-Petit law is c = 3 NR, where N is the number of atoms and R is the molar gas constant. Consequently, we should focus on finding a big change in magnetization at the

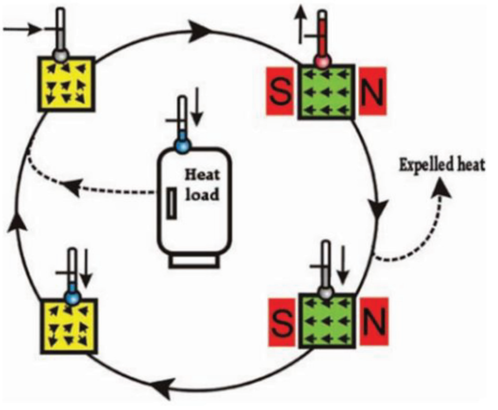

Figure 4.
Schematic representation of a magnetic refrigeration cycle that transports heat from the heat load to the ambient environment. Yellow and green boxes depict materials in low and high magnetic fields, respectively. Reproduced with permission [20]. Copyright 2005, Institute of Physics.

appropriate temperature. A large MCE is anticipated not far from $\left(\frac{\partial M}{\partial T}\right)_B$ peaks at the magnetic-ordering temperature since the order parameter of the phase transition changes intensely within a narrow temperature interval. In the magnetic-refrigeration cycle, shown in **Figure 4** [19, 20], initial random-oriented magnetic moments are ordered by a magnetic field, resulting in heating of the magnetocaloric material and the heat is then transmitted from the material to the surrounding atmosphere. Upon removing the field, the magnetic moments disorder resulting in cooling of the material below ambient temperature. Heat from the system can then be withdrawn by a heat-transfer medium which may be water, air, or helium depending on the working temperature. Consequently, magnetic refrigeration is considered an ecofriendly cooling technology.

3. Magnetic nanoparticles

Over time, nanotechnology has penetrated all branches of science like physics, chemistry, and especially biomedical research and related industries. Broadly, nanoparticles are defined as materials having particle sizes in the range of 1–100 nm [21]. Bulk materials have definite physical properties, which, however, get altered when they are converted to nanoparticles, depending on their final size. One of the main changes in the properties of nanoparticles is the substantial increase in number of atoms/molecules on the surface of particles, and hence availability of effectively high surface area compared with bulk material. The high surface area of particles can be used to attach ligands and/or capping agents, which make them more suitable for effective labeling of drug/tracer molecules. The change in physicochemical properties during conversion of bulk material to nanoparticles makes them suitable for reaching the diseased site because of their better diffusion ability. A diversity of nanoparticles, including magnetic nanoparticles (MNs), has been synthesized and characterized for different industrial, biomedical, and clinical applications.

MNs are the nanoparticles synthesized from magnetic elements like iron, nickel, and cobalt or their chemical derivatives [21–26]. Each particle of bulk magnetic materials has many domains separated by walls, and each domain represents a region with a specific direction of magnetization. When bulk material is converted to MN, each particle can approach a single domain [22–24]. In larger particles (micrometer size), surrounding thermal energy [kT, where k is the Boltzmann constant and T is the temperature (K)] is much less [when T = 300 K (room temperature), kT = 0.026 eV] than particle energy (Kv, where K is the anisotropic constant and v is the particle volume) and thus the direction of magnetic moment does not change with time. When particle size decreases (sub-micro-meter size), particle energy decreases and thus direction of magnetic moment also changes with respect to original direction, that is, with angle (θ). However, with further decrease of particle size (nanosize), the direction of magnetic moment changes to the opposite direction (θ = 180), which is known as superparamagnetic behavior of magnetic nanoparticles. Super paramagnetism is due to particle size, whereas paramagnetism is an intrinsic property of the material caused by its atomic nature (e.g., Na). Superparamagnetic particles have high magnetic moment of 10^3–10^4 μ_B [27, 28] and thus the term "super" is prefixed to "paramagnetic" because particles show paramagnetic behavior in the absence of a magnetic field and no magnetization is retained after removal of the magnetic field. Decreasing particle size below the critical size, ferromagnetic particles can be changed to superparamagnetic particles. Paramagnetic materials (e.g., Na and K) [22] do not have magnetic interactions between the atoms; hence, the net magnetic moment is equivalent to the number of atoms in the particle. However, the interatomic magnetic interaction in ferromagnetic or superparamagnetic materials gives the net magnetic moment of the particle. On either decreasing temperature or increasing magnetic field, there is a possibility of transition from superparamagnetic to ferromagnetic (**Figure 5**) [29, 30] because of increasing extent of the arrangement of spins of MN.

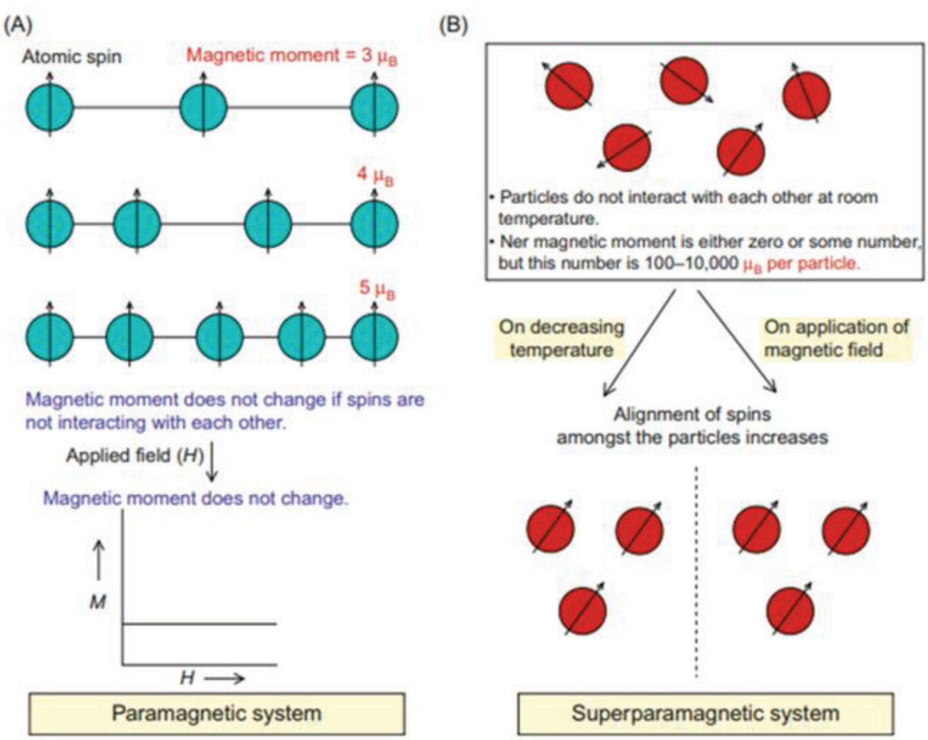

Figure 5.
(A) Paramagnetic particles under a magnetic field. No variation of magnetization is shown and (B) superparamagnetic particles under a magnetic field or at low temperature [30]. Copyright 2003, Institute of Physics.

Owing to their unique feature of attraction and interaction under magnetic field conditions, these MNs have been applied for separation of cells/biological materials and drug delivery. MNs have attracted the researchers' attention because of their ability to act as contrast agents in magnetic resonance imaging (MRI) for diagnostic applications. It may be apposite to observe here that lower toxicity, biocompatibility, and significant accumulations of MNs at the diseased site make them suited for remedial applications. When these MNs are placed under magnetic field effects, a phase interval between the applied magnetic field and the direction of magnetic moments results in thermal losses. The orientation of magnetic moment fluctuates thermally, involving two main mechanisms: (i) Neel's fluctuations of the magnetic moment relative to the crystal lattice (internal dynamics) and (ii) Brownian fluctuations of the particle itself relative to the medium in which the particle is placed (external dynamics). These are affected by viscosity of the medium and other processes, which can affect the movement of particle. These external and internal frictions generated on MN under external magnetic field conditions result in "foci" of heat generation, which may be sufficient enough to kill the cell. Thus, selective heat generation by MN at the tumor site can provide the significant advantage of killing tumor cells without affecting the normal tissues much.

4. Applications of functional magnetic nanoparticles

The unique chance to control coercivity in magnetic nanomaterials has led to a number of significant technological applications, particularly in the field of information storage. Small magnetic particles are promising candidates for a further increase of the density of magnetic storage devices toward 100 $G_{bit}/inch^2$ up to a few $T_{bit}/inch^2$ [31]. Other than data storage, many applications of magnetic nanoparticles are known; examples are: ferrofluids, high-frequency electronics, high-performance permanent magnets, and magnetic refrigeration. Magnetic particles are also employed in many biological and medical applications such as drug-targeting, cancer therapy, lymph node imaging, or hyperthermia [32–34]. Lately, researchers have succeeded to produce multifunctional MN. There are mainly two approaches: (i) molecular functionalization, which comprises attaching the magnetic nanoparticles to antibodies, proteins, and dyes, and so on and (ii) blending of MNs with other functional nanoparticles, such as quantum dots or metallic nanoparticles [35]. As an example, magnetic nanoparticles could be used as seeds for growing semiconducting chalcogenides. In this case, the final product is core-shell or hetero nanostructures having both magnetic and fluorescent properties. This results in the display of intracellular control of nanoparticles for promising dual-functional molecular imaging (i.e., combined MRI and fluorescence imaging). MNs can be used as MRI contrast improvement agents, as the signal resulting from proton magnetic moments around magnetic nanoparticles can be recorded by resonant absorption [24]. These multifunctional MNs could be used in many biological applications such as protein purification, bacteria detection, and therapeutic removal of toxins [32]. **Figure 6** illustrates these two approaches for making multifunctional MNs and their various biological applications.

In the last three decades, magnetic data storage has seen a linear rise in terms of storage capacity. The physics of magnetic nanostructures is at the heart of magnetic hard disk drive technology. In the future, it is very probable that areal densities will increase well beyond 1 Terabit/inch^2 by employing new technologies like bit-patterned media (BPM) or heat-assisted magnetic recording [31, 36].

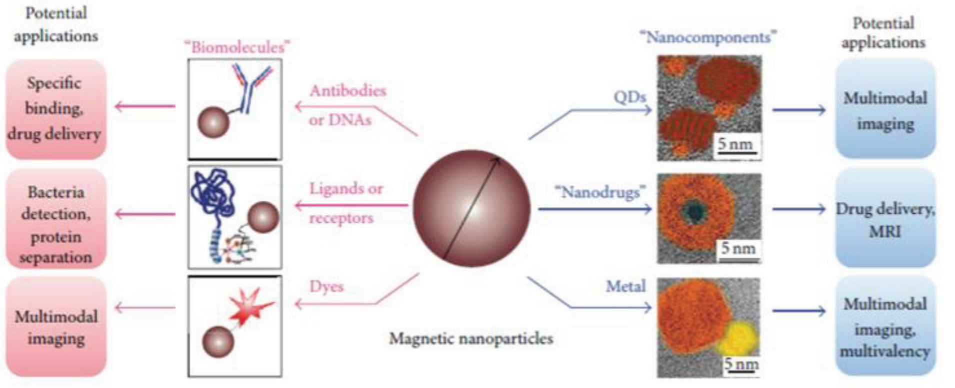

Figure 6.
Various potential applications of multifunctional magnetic nanoparticles in biology. Reproduced with permission from [24]. Copyright 2009, American Chemical Society.

Patterned magnetic nanostructures, such as two-dimensional dot-arrays have attracted the interest of researchers due to their potential applications such as magnetic information storage [37] or nonvolatile magnetic random access memory (MRAM) [38]. The demand for ultrahigh-density magnetic storage devices drives the bit size into the nanometer scale. As the volume $V = \pi D2t/4$ (where D and t are the diameter and thickness, respectively) of the grains is reduced in the scaling process, the magnetization of the grains may become unstable due to thermal fluctuations, and data loss may occur [33]. As the physical size of the nanostructures in the patterned array decreases, loss of data due to the thermal instability [also known as "superparamagnetic (SPM) effect"] would become a very crucial issue [39]. Therefore, future data storage technology has to overcome the SPM effect. In this regard, the L10-FePt alloy is one of the most promising materials for future ultrahigh-density magnetic storage devices because it possesses a huge uniaxial magneto-crystalline anisotropy ($Ku = 7 \times 10^7$ erg/cc), which leads to a high thermal stability of magnetization. Also, the present longitudinal data storage media may be considered as a collection of independent particles because of their weak intergranular exchange coupling. However, as we have discussed in the super-ferromagnetic section, strong intergranular interactions can drive the system to form long-range ordered super-ferromagnetic (SFM) domains, which are clearly unsuitable for applications in data storage. Also, the SFM alignment counteracts large tunneling magnetoresistance (TMR) values, so magnetic random access memory applications are not promising for SFM systems. However, super-ferromagnetic materials are soft magnetics, which make them nearly ideal materials for high permeability, low-loss materials for microelectronics, power management, and sensing devices designed for high frequencies.

4.1 Magnetic materials in hyperthermia

Recently, thermotherapy for cancer using MN has emerged as a potential mode of hyperthermia [23–26]. Hyperthermia is a type of medical treatment in which body tissue is exposed to a temperature (42–44°C) higher than physiological temperature (37°C) to kill the cancer cells. This approach is one of the modalities of cancer treatment used in combination with radiation and certain chemotherapeutic drugs. There could be two ways to heat the cancer cells: (i) applying external sources (e.g., using a water bath, microwave, ultrasound, infrared sauna), which is also called "external or extracellular hyperthermia," and (ii) delivering MN inside the cancer cells [under alternating current (AC) field], which is known as intracellular hyperthermia. Because cell membrane composed of lipids is thermally insulating, tumor cells heated from external sources do not achieve hyperthermic temperature. Consequently, extra heat from an external source has to be provided to achieve the therapeutic temperature. However, this causes blisters, burns, swelling, blood clots, and bleeding in clinical conditions. Therefore, application of hyperthermia using this approach has faced practical limitations. On the other hand, intracellular heating using internalized MN at the tumor site provides an efficient and safe approach for hyperthermia application. The therapeutic efficacy and clinical advantages of intracellular hyperthermia over extracellular hyperthermia is a matter of further investigation. In addition, development of surface-functionalized nanoparticles using advanced technologies may present a better therapeutic modality for future clinical applications. Could all MNs be used in hyperthermia? Common MNs are Fe_3O_4; γ-Fe_2O_3; and Mn-, Co-, and Ni-doped ferrites because they have high magnetic moment (50–60 emu/g) under external magnetic field, which can give hysteresis loss and result in significant rise in temperature sufficient for hyperthermia therapy. However, some materials (e.g., ZnO and TiO_2) become ferromagnetic when particle size decreases to the nanometer range (510 nm) [40, 41]. Owing to their very low magnetic moment (1 emu/g or less), such types of material may not be useful for hyperthermia treatment. It may be important to mention that Fe and Co nanoparticles are prone to oxidation in acidic and alkaline conditions, which are likely to be different in tissue compartments in body. In contrast, oxide nanoparticles (e.g., Fe_3O_4) are highly stable in slightly acidic and alkaline conditions and are biocompatible. Very small Fe_3O_4 (cubic phase) nanoparticles (5 nm) are not useful for hyperthermic applications because of low magnetic moment [29, 30]. However, FePd, FePt, CoPt, and CoPd (tetragonal phase) nanoparticles would result in significant heat generation, even with a particle size of 35 nm [27], but their stabilities in acidic and alkaline mediums are less than their oxide counterparts.

4.2 Magnetic materials in data storage

Magnetic materials are used in high-capacity disk drives and magnetic-semiconductor memory devices. The disk drive devices have reached the largest growth in data capacity over time, making disk drives the preeminent storage system for digital data [42]. The growth in areal density is more than 100% per year recently. The overall data capacity of a disk is nearly the areal density times the recording area depending on the disk size (the most common diameter is 2.5 and 3.5 inches, that is, 64 and 90 mm, respectively). Many technologies have aided in this speedy increase in areal density, together with enhancement of the technology of "flying" heads with shrunk space of the disk surface, data coding, error discovery and rectification, advanced servo-control systems for correct management of magnetic recording heads on data tracks, and advances in the mechanical structures comprising a disk drive, together with advances in the motors used to push the disks. Recently, there has been a significant emerging technology for fast memory devices—the magnetic random-access memory or MRAM. The MRAM device is a possible substitute for the familiar semiconductor memories used in modern computers—dynamic and static random-access memory (DRAM and SRAM). The MRAM technology combines a magnetic storage technology together with metal-oxide semiconductor (MOS) devices to result in fast and high-density data memory devices. The technology on which the magnetic part of MRAM is based is an extension of the technology used in magnetic-recording devices identified as the magnetic tunneling junction or MTJ.

5. Technology of magnetic recording

The technology of magnetic recording is over one century old [43]. The fundamental concept of magnetic recording is to use a magnetic structure (as the "write" head) driven by a current that represents the data to be recorded, to create a magnetic field capable of changing the state of the magnetization in a closely spaced magnetic medium, which was formerly a magnetic wire, and today it is the known tape or a magnetic layered hard drive. The data are retrieved by an output electromotive force generated in the "red head" by sensing the magnetization in the recording medium, for example, by Faraday's law. The magnetic recording system is that used to store digital data, in which instance the current supplied to the write head as pulses coded to represent the digital information (1 or 0 s) [44–47]. In the case of disk drives, the write and read heads are distinct thin-film structures deposited on the back of a mechanical slider that uses a hydrodynamic air bearing to "fly" over the surface of the disk [46]. The read and write parts are viewed together with the magnetic recording surface, which is a thin cobalt metal alloy film. The digital data are written in the magnetic film in the form of transitions among the two magnetization states (the "left" or "right") and with the width almost equal to the write head width. The transition region between the oppositely directed directions of the magnetization is similar to that between magnetic domains and has a length (l). The write head is formed from thin films of ferromagnetic alloys patterned in the form of a magnetic chain. The current is coupled to the chain to generate a magnetic field at the gap by a pancake coil of 10 or less turns. The coil is insulated from the metallic magnetic bondage by layers of polymer photoresist. The most frequently used alloy in the past for the magnetic films in the write head is $Ni_{80}Fe_{20}$ permalloy which can be deposited in thin films using electroplating. The ability to record on recording media with increased coercivity is not the only issue with the magnetic materials used in write heads. It is also important that the write head have high efficiency. Efficiency (η) in this case is defined as the ratio

$$\eta = \frac{H_g \cdot g}{N_\omega \cdot I} \tag{2}$$

where H_g is the value of the magnetic field in the gap of the write head and I is the amplitude of the write current pulse. High efficiency is important to allow write-current amplitudes that are easily supplied from integrated circuits.

6. Summary and perspectives

Functional magnetic materials are a huge source of technological applications because they can simultaneously display intriguing properties such as tunable mechanical, magnetic, electric/dielectric, thermal, and optical properties. These materials have the potential to be used in information storage and processing, refrigeration, hyperthermia, and recording technology. Though most attention is paid to the pure magnetocaloric properties and materials costs, other properties like mechanical properties, heat conductivity, electrical resistivity, and environmental impact are recently getting attention. With the refrigeration market being a multibillion dollar market, this novel technology offers great opportunities. The ideal magnetic refrigerant should contain at least 80% transition metals having large magnetic moment such as Fe or Mn. In addition, it should contain some inexpensive p-metal such as Al or Si, which can be used to tune the working point of the material. A wide range of magnetic materials is essential for the advance of magnetic recording and the fast random access memory, MRAM, technology. Magnetic data storage has seen a linear rise in terms of storage capacity. The physics of magnetic nanostructures is at the core of magnetic hard disk drive technology; and in the future, it is very likely that areal densities will increase well beyond 1 Terabit/inch^2 by employing new technologies. In hyperthermia application, the target is the higher value of magnetic heat generation by a stable fluid in a lower exposure time. Nanoferrites are good candidates for hyperthermia applications since they offer a moderate magnetic moment, chemical stability, and a high specific absorption rate (SAR). Based on which heat generation mechanism is wanted, a suitable selection of magnetic core, surfactant layer, and liquid type can influence the cancer treatment.

Acknowledgements

The authors would like to extend their sincere appreciation to Central Metallurgical Research and Development Institute, Egypt, for its financial support to pursue this work.

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