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Magnetic Materials (Appendix to *Advanced Magnetic Nanostructures* [2006])

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Appendix

MAGNETIC MATERIALS

The behavior of magnetic nanostructures reflects both nanoscale features, such as particle size and geometry, and the intrinsic properties of the magnetic substances. For example, the magnetization reversal in nanodots crucially depends on the anisotropy of the dot material. Furthermore, nanostructures are often used as bulk materials, so that their extrinsic properties must be evaluated from the point of view of bulk materials. This appendix summarizes the characteristics of some important classes of magnetic materials and provides exemplary data.

A.1. CLASSES OF MAGNETIC MATERIALS

Traditionally, magnetic materials are classified by their magnetic coercivity or hardness. The term is historical and refers to iron, where the addition of carbon increases not only the mechanical hardness (steel) but also the coercivity. In descending order, the hardness gives rise to a classification into hard magnets (permanent magnets), recording media, and soft magnets. Note that some classes of magnetic materials, such as ferrofluids, that do not fall in any of these categories.

A.1.1. Permanent Magnets

These materials have a wide range of applications, from toys and refrigerator magnets to everyday electrotechnology—electromotors, loudspeakers, windshield wipers, locks, and microphones—and high-tech devices such as hard-disk drives. Key requirements for permanent magnets are a high remanent magnetization M_r, a high coercivity H_c, and a nearly rectangular hysteresis-loop shape. These properties are epitomized by the *energy product* $(BH)_{max}$ [1, 2], that is, by the magnets' ability to store magnetostatic energy outside the magnet. Energy products never exceed $\mu_o M_r H_c$ or $\mu_o M_r^2/4$, whichever is smaller. Until the mid 20th century, the main limitation was coercivity, as exemplified by the energy product of hard-magnetic steel, about 1 kJ/m^3. Steel magnets are now obsolete, because their low coercivities and energy products made it necessary to resort to cumbersome horseshoe shapes, but the high sat-

uration induction of $Fe_{65}Co_{35}$ (2.43 T) and its pronounced temperature stability continue to be exploited in ainico-type magnets.

Today, the high anisotropy of rare-earth intermetallics makes it relatively easy to create sufficient anisotropy [3], and the main limitation is the magnetization. The best permanent magnets, currently made from $Nd_2Fe_{14}B$ [4], have room-temperature energy products exceeding 450 kJ/m^3 [5, 6]. This means that a compact Nd-Fe-B magnet of about 2 grams is now able to replace a 1-kg horseshoe magnet—a feature of major importance for advanced consumer electronics, car design, and computer technology. Nanostructuring is a major tool in fully exploiting and exceeding the performance of bulk rare-earth transition-metal intermetallics.

A.1.2. Soft Magnets

Soft-magnetic materials are used for a variety of low- and high-frequency applications. Examples are flux guidance in permanent-magnet and other systems, transformer cores, microwave applications, and recording heads. A feature of soft magnets is their low coercivity, which is often several orders of magnitude smaller than those of hard and semi hard materials. Another figure of merit is the initial permeability $\mu_r = (dM/dH)_0$, which exceeds 1000 in soft magnets [7, 8]. High-frequency applications require small hysteresis losses, so that the small coercivities are often more important than a high permeability.

Iron-based metallic magnets, such as Fe-Si, $Fe_{50}Co_{50}$, and permalloy ($Ni_{80}Fe_{20}$) have long been used as soft-magnetic materials. For example, permalloy has an anisotropy of about 0.15 kJ/m^3, an anisotropy field of about 0.4 mT [4 Oe], and coercivities of about 0.04 mT. Oxides, such as simple ferrites (TFe_2O_4, where T = Mn, Fe, Ni, Zn) and garnets ($R_3Fe_5O_{12}$, R = Y, Gd, ...) have a ferrimagnetic spin structure and, therefore, a rather low magnetization. However, their comparatively large resistivity suppresses eddy-current losses and makes them suitable for high-frequency applications, for example in antennas and microwave devices [7, 9].

More recently, amorphous and nanostructured metals have attracted much attention as soft-magnetic materials. Essentially, they have the composition $T_{100-x}Z_x$ (T = Fe, Co, Ni and Z = B, C, P, Zr, ...) where x ≈ 10–20. An example is the Yoshizawa alloy $Fe_{73.5}S_{13.5}B_9Cu_1Nb_3$], where Fe_3Si grains having the cubic DO_3 structure are embedded in an amorphous matrix [10, 11]. As pointed out by Herzer [12], this random-anisotropy nanostructuring is a powerful tool to reduce the coercivity of soft magnetic materials. It is exploited, for example, in Fe-Si-B-Cu-Nb alloys [10].

An important application of soft materials is inductive and magneto-resistive recording heads [9]. The function of inductive head materials is to realize flux closure for reading and writing on recording media. Typical materials are $Ni_{80}Fe_{20}$ (permalloy, H_c = 0.01 to 0.05 mT), hot-pressed Ni-Zn and Mn-Zn ferrites (H_c = 0.02 mT); Fe-Si-Al (sendust, H_c = 0.025 mT), as well as Fe-Ti-N and Fe-Rh-N alloys [9]. Magnetoresistive read heads exploit the anisotropic magnetoresistance due to the spin-dependent scattering of conduction electrons by magnetic atoms or, more recently, the giant magnetoresistive (GMR) effect exploiting the different Fermi-level spin-up and spin-densities of the involved components. Many ferromagnets exhibit GMR, but soft-magnetic materials—such as permalloy—are easier to switch.

A. 1.3. Recording Media

The first magnetic recording medium, invented by Poulsen in 1898, was the magnetic wire. Until the early 1940s, steel wires were used quite extensively for dictation, telephone recording, and radio broadcasting. Tape recording, invented in 1935 [13], has been used for data storage since 1951 and preceded modern PC hard disks. The first data-storage tapes had an areal storage density of order 0.002 Mb/in^2, as compared to 2.4 Mb/in^2 for the 3½" disks widely used in the 1990s and about 10^5 Mb/in^2 in present-day hard disks.

Magnetic used in magnetic data storage tend to have moderate coercivities of the order of 0.3 T (240 kA/m), although some recently developed materials have higher coercivities, which improves the thermal stability of the stored information but makes the media more difficult to write. Traditional storage media are made using materials such as granular Fe, Fe_2O_3 and CrO_2, whereas advanced high-density recording media are based on materials such as Co-Cr-Pt-B, where the Pt improves the anisotropy. Other classes of materials presently being considered are $L1_0$ magnets, such as FePt, and nanocomposite rare-earth transition-metal films.

The main advantage of magnetic recording is the potential storage density. The bit size of optical and magneto-optical media, such as amorphous $Tb_{22}Fe_{66}Co_{12}$ [9], is limited by the wavelength of the used light, whereas semiconductor devices are difficult to handle on very small length scales. Some limitations in magnetic recording are the present use of longitudinal or in-plane recording media and thermal instabilities at ultrahigh recording densities. These problems can be tackled by suitable nanostructuring, using perpendicular recording and highly anisotropic media to avoid thermal demagnetization. The role of nanostructuring is seen from the quadratic dependence of the areal storage density of the bit size: exceeding 100 Gb/in^2 requires structures with feature size of less than about 50 nm.

A.2. DATA TABLES

Tables A.1 to A.3 show typical intrinsic and extrinsic parameters compiled from various sources [1, 2, 7]. Note that Ba and Sr ferrite (Table A.2) are isostructural and have very similar properties.

Table A.1 Intrinsic properties of some magnetic compounds. Note that γ-Fe_2O_3 crystallizes in a disordered spinel structure

Substance	$\mu_0 M_s$ (T)	T_c (K)	K_1 (MJ/m^3)	Symmetry	Structure
Fe_3O_4	0.60	858	- 0.011	cubic	$MgAl_2O_4$
$MnFe_2O_4$	0.52	573	- 0.0028	cubic	$MgAl_2O_4$
$CoFe_2O_4$	0.50	793	0.270	cubic	$MgAl_2O_4$
$NiFe_2O_4$	0.34	858	- 0.0069	cubic	$MgAl_2O_4$
$CuFe_2O_4$	0.17	728	- 0.0060	cubic	$MgAl_2O_4$
$SrFe_{12}O_{19}$	0.46	733	0.35	hex.	M ferrite
CrO_2	0.56	390	0.025	tetr.	TiO_2
$NiMnO_3$	0.13	437	- 0.26	hex.	$FeTiO_3$
γ-Fe_2O_3	0.47	863	- 0.0046	cubic	(spinel)
$Y_3Fe_5O_{12}$	0.16	560	- 0.00067	cubic	(garnet)
$Sm_3Fe_5O_{12}$	0.17	578	- 0.0025	cubic	(garnet)
$Dy_3Fe_5O_{12}$	0.05	563	- 0.0005	cubic	(garnet)
PtCo	1.00	840	4.9	tetr.	CuAu (I)
PtFe	1.43	750	6.6	tetr.	CuAu (I)
PdFe	1.37	760	1.8	tetr.	CuAu (I)
MnAl	0.62	650	1.7	tetr.	CuAu (I)
MnBi	0.78	630	1.2	hex.	NiAs
$NdCo_5$	1.23	910	0.7	hex.	$CaCu_5$
YCo_5	1.06	987	5.2	hex.	$CaCu_5$
Sm_2Fe_{17}	1.17	389	- 0.8	rhomb.	Th_2Zn_{17}
Y_2Fe_{17}	0.84	320	- 0.4	hex.	Th_2Ni_{17}
$Sm_2Fe_{17}N_3$	1.54	749	8.9	rhomb.	Th_2Zn_{17}
$Y_2Fe_{17}N_3$	1.46	694	- 1.1	hex.	Th_2Ni_{17}
Sm_2Co_{17}	1.20	1190	3.3	rhomb.	Th_2Zn_{17}
Dy_2Co_{17}	0.68	1152	- 2.6	rhomb. or hex.	2:17
Y_2Co_{17}	1.25	1167	- 0.34	rhomb. or hex.	2:17
$Sm(Fe_{11}Ti)$	1.14	584	4.9	tetr.	$ThMn_{12}$
$Y(Fe_{11}Ti)$	1.12	524	0.89	tetr.	$ThMn_{12}$
$Sm_2Fe_{14}B$	1.49	618	- 12.0	tetr.	$Nd_2Fe_{14}B$
$Dy_2Fe_{14}B$	0.67	593	4.5	tetr.	$Nd_2Fe_{14}B$
$Y_2Fe_{14}B$	1.36	571	1.06	tetr.	$Nd_2Fe_{14}B$

Table A.2 Intrinsic and micromagnetic properties of some magnetic materials.

	Fe	Co	Ni	$BaFe_{12}O_{19}$	$SmCo_{15}$	$Nd_2Fe_{14}B$
M_S (T)	2.15	1.76	0.62	0.47	1.07	1.61
T_C (K)	1043	1388	631	723	1003	585
K_1 (MJ/m^3)	0.05	0.53	-0.005	0.33	17	5.0
A (pJ/m)	8.3	10.3	3.4	6.1	22.0	7.7
δ (nm)	40	14	82	14	3.6	3.9
γ (mJ/m^2)	2.6	9.3	0.5	5.7	77	25
l_{ex} (nm)	1.5	2.0	3.4	5.9	4.9	1.9
R_{sd} (nm)	6	34	16	290	764	107
$\mu_0 H_a$ (T)	0.06	0.76	0.03	1.8	40	7.6

Table A.3 Extrinsic properties of some bulk magnets.

	$\mu_0 M_r$ [T]	$\mu_0 H_c$ [T]	$(BH)_{max}$ [kJ/m^3]
Cobalt steel	1.0	0.025	8
Annealed iron	1.0	0.0001	0.04
Sintered Ba-ferrite	0.39	0.30	28
Anisotropic alnico	1.30	0.07	50
Metal-bonded $SmCo_5$	0.92	1.88	175
Polymer-bonded $SmCo_5$	0.58	1.00	60
Sintered Sm-Co	1.08	1.0	225
Sintered Nd-Fe-B	1.33	1.6	400
Polymer-bonded Nd-Fe-B	0.55	0.75	48

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