

## MAGNETIC MATERIALS

### HISTORICAL BACKGROUND

Magnetic materials have been known since ancient times—for example, in 380 B.C.E. Plato wrote (1) of the “stone which Euripides calls a magnet,” which we infer was  $\text{Fe}_3\text{O}_4$ , now known as magnetite. The scientific quality of magnetism studies abruptly and dramatically jumped with the publication in 1600 by Gilbert of the classic text *De Magnete* (2). Quantitative measurements of magnetic materials were enabled by the 1820 discovery by Oersted that an electric current creates a magnetic field. In 1846 Faraday made system-

atic studies of the attraction and repulsion of materials in a gradient field and classified materials as *diamagnetic* if they are repelled by a region of increased flux density and *paramagnetic* if they are attracted. To this we add *ferromagnetic* (strongly magnetic, like iron) to form the set of three basic classes of magnetic response.

Since the early part of the twentieth century, magnetic materials have been the subject of deep and broad research and development due to their economic and scientific importance, and much of our knowledge is mature. Nevertheless, startling discoveries continue to be made, such as the discovery of Nd–Fe–B permanent magnets and the “giant magnetoresistance” effect in thin-film multilayers.

## MAGNETIC FIELDS AND THE MAGNETIC RESPONSE OF MATERIALS

The magnetic properties of matter may be viewed as a response to an applied stimulus, namely the magnetic field strength  $\mathbf{H}$ . The macroscopic response of a material is given by its magnetization,  $\mathbf{M}$ , and the overall field is the sum of the two, called the magnetic induction  $\mathbf{B}$ . In a vacuum the magnetization is strictly zero. For this article we adopt SI units, so we have  $\mathbf{B} = \mu_0 \mathbf{H}$  in a vacuum, where  $\mathbf{B}$  is measured in tesla (Wb/m<sup>2</sup>),  $\mathbf{H}$  is measured in amperes per meter, and by definition  $\mu_0 = 4\pi \times 10^{-7}$  H/m<sup>2</sup>. The magnetic response adds directly to the applied field, giving  $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$ .

The issue of units in magnetism is perennially vexing. In the past, cgs (Gaussian) units have been commonly used by scientists working with magnetic materials. In that system,  $\mathbf{B}$  is measured in gauss,  $\mathbf{H}$  in Oersteds, and  $\mathbf{M}$  in emu/cm<sup>3</sup>, where emu is short for the uninformative name *electromagnetic unit*. The constitutive relation in Gaussian units is  $\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$ . Important conversion factors to keep in mind are  $10^4$  Gauss = 1 T and 12.5 Oe = 1 kA/m. A definitive discussion of units and dimensions is given in the Appendix of Jackson’s *Classical Electrodynamics* (3).

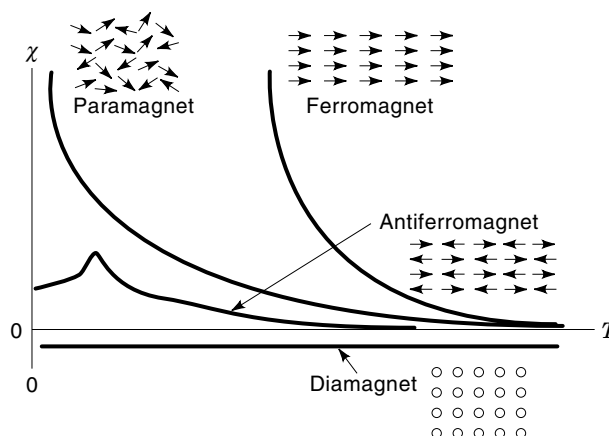
## TYPES OF MAGNETIC MATERIALS: TAXONOMY

### Basic Families

Two of the basic families of magnetic materials involve a highly linear response (i.e.,  $\mathbf{M} = \chi\mathbf{H}$ , where  $\chi$  is defined as the magnetic susceptibility). The main magnetic response of all materials is due to the magnetic moment of individual electrons, a property directly connected to their spin. The moment of a single electron is 1 Bohr magneton,  $\mu_B = 1.165 \times 10^{-29}$  Wb·m. Due to the Pauli principle, in many cases the electrons in an atom are precisely paired with oppositely directed spins, leading to an overall cancellation. Nevertheless, a magnetic response can be discerned in all materials, as observed by Faraday.

### Diamagnetism

Diamagnets have a negative value for  $\chi$ , that is, the induced moment is opposite to the applied field. The susceptibility is



**Figure 1.** Schematic temperature dependence of the susceptibility of a diamagnet, paramagnet, ferromagnet, and antiferromagnet.

temperature independent and typically small (see Fig. 1). Diamagnetism is due to the effect of a magnetic field on orbital motion of paired electrons about the nucleus (superficially comparable to Lenz’s law). The diamagnetic susceptibility of most materials is very small—in the vicinity of  $-1 \times 10^{-5}$ . A tabulation of diamagnetic susceptibilities of various atoms, ions, and molecules is given by Carlin (4).

A large negative magnetic susceptibility is characteristic of only one class of materials (namely, superconductors). A Type I superconductor in the Meissner state exhibits complete exclusion of magnetic flux from the interior of the sample,  $\mathbf{M} = -\mathbf{H}$ , or  $\mathbf{B} = 0$ . Superconductors can also exhibit partial flux penetration,  $0 < B < \mu_0 H$ . In both cases the spectacular observation of stable levitation is possible, something that cannot be achieved using only materials with  $\chi > 0$  (as proven by Earnshaw’s theorem). Note that stable levitation is possible even for bodies that are only weakly diamagnetic given a sufficiently large magnetic field gradient (5).

### Paramagnetism

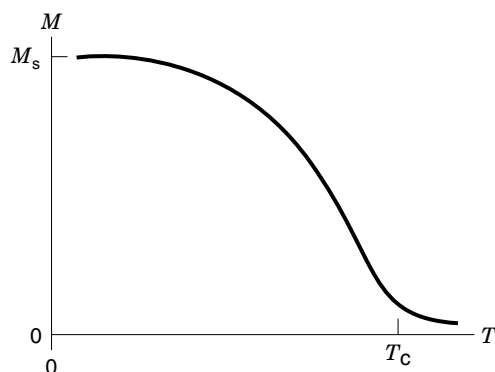
Paramagnets have a positive value for  $\chi$ , that is, the induced moment is in the same direction as the applied field. Paramagnetism is chiefly due to the presence of unpaired electrons—either an overall odd number of electrons or an unfilled inner shell. Nuclei can also show paramagnetism, though typically of an extremely small magnitude. The electron gas of a metal is also usually slightly paramagnetic, though exchange coupling can sometimes lead to ordering (e.g., ferromagnetism). Independent unpaired electrons give each atom or molecule a small permanent dipole moment, which tends to be aligned by an external magnetic field. Langevin showed that thermal energy disrupts this alignment, leading to a susceptibility  $\chi = Nm^2/3k_B T$ , where  $N$  is the density of dipoles,  $m$  is the moment of each dipole,  $k_B$  is the Boltzmann constant, and  $T$  is the absolute temperature. Curie and Weiss found that the temperature in this formula should be replaced by  $T \rightarrow (T - T_c)$  for materials with an ordering temperature  $T_c$  (the “Curie temperature.”) The paramagnetic susceptibility of a material can give important insights into its chemistry and physics, but it is an effect of limited engineering significance at present.

## Ferromagnetism

Ferromagnetism is the spontaneous magnetic ordering of the magnetic moments of a material in the absence of an applied magnetic field. Nearly all technologically important magnetic materials exhibit some form of ferromagnetism. In such materials, the magnetic moments of electrons couple together, so that they respond collectively. In this manner it is possible for all of the magnetic moments in an entire sample to point in the same direction, potentially giving a very strong effect. The details of how the individual moments couple with each other can be understood in terms of quantum mechanics. There are three types of “exchange” interaction generally found:

- The first is direct exchange, in which an unpaired electron on one atom interacts with other unpaired electrons on atoms immediately adjacent via the Coulomb interaction. This is the strong mechanism that dominates in most metallic magnetic materials, such as Fe, Ni, Co, and their alloys. It results in a positive exchange energy, so the spins on adjacent atoms tend to align parallel.
- The second is indirect exchange, or superexchange, in which the moment of an unpaired electron on one atom polarizes the (paired) electron cloud of a second atom, which in turn interacts with the unpaired electron on a third atom. This is the mechanism that dominates in most oxide materials, such as ferrites. For example, in  $\text{Fe}_3\text{O}_4$  the Fe ions (with unpaired electrons) interact through O ions (which have only paired electrons). Superexchange creates a negative exchange energy.
- Finally, there is the possibility of interaction between electrons that are not localized but can move freely as in a metal. This interaction, known as the RKKY interaction after its discoverers (Ruderman, Kittel, Kasuya, and Yoshida), is usually weaker than direct exchange. It plays an important role in the behavior known as giant magnetoresistance and can result in either a positive or negative exchange energy.

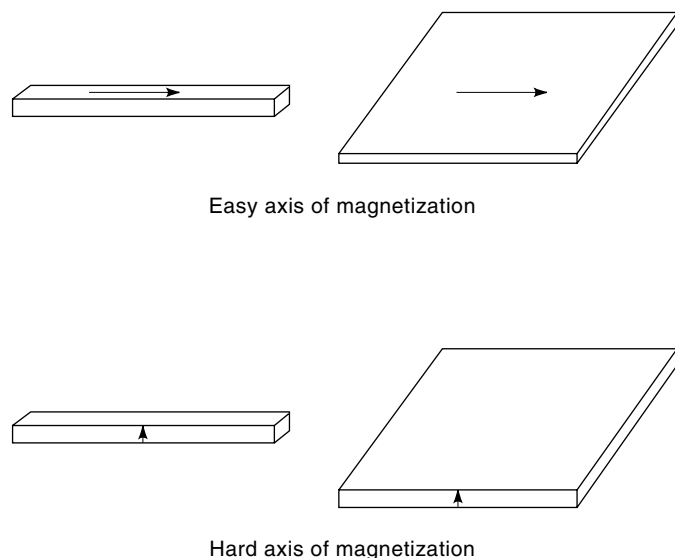
The main properties that characterize ferromagnetic materials are the Curie temperature,  $T_c$ , the saturation magnetization,  $M_s$ , the magnetic anisotropy energy,  $K$ , and the coercive field,  $H_c$  (see Fig. 2). The first two are intrinsic to a material.



**Figure 2.** Schematic temperature dependence of the saturation magnetization,  $M_s$ , for a ferromagnet.

The third has both intrinsic and extrinsic factors. The last is extrinsic and depends on the form (microstructure, overall shape, etc.) of the material and will be discussed later.

- The exchange interaction that leads to ferromagnetism can be disrupted by thermal energy. At temperatures above  $T_c$ , the disruption is so great that the ferromagnetism ceases, and the material exhibits only paramagnetism. Thus  $T_c$  measures the magnitude of the exchange coupling energy. For example, the  $T_c$  of Fe is  $770^\circ\text{C}$  while for Co,  $T_c = 1115^\circ\text{C}$ , and for Ni,  $T_c = 354^\circ\text{C}$ . The ferromagnetic transition is a second-order phase transition, which means that the order parameter (magnetization) increases continuously from zero as the temperature is lowered below  $T_c$ .
- The saturation magnetization is the macroscopic magnetic moment of all of the spins averaged over the volume of the sample. Thus, in a material with many unpaired electrons per atom,  $M_s$  will be large (e.g., Fe with  $\mu_0 M_s = 2.16 \text{ T}$  at room temperature). Conversely,  $M_s$  will be much smaller in materials that also contain nonmagnetic atoms or ions (e.g.,  $\text{Fe}_3\text{O}_4$  with  $\mu_0 M_s = 0.60 \text{ T}$  at room temperature).
- The electron spins couple weakly to their orbital motion in a process known as spin-orbit coupling, a relativistic effect. As a result, the energy of the system depends on the orientation of the spins (i.e., the magnetization) with respect to the orbitals of the atoms (i.e., the orientation of the sample). This results in an intrinsic coupling of the magnetization to the crystal lattice. It leads to magnetic anisotropy—that is, the energy of the system depends on the orientation of the magnetization with respect to the sample. The direction along which the magnetic moment tends to lie is known as the easy axis. The magnitude of the anisotropy may be large, as in  $\text{SmCo}_5$  permanent magnets that strongly resist demagnetization with  $K \sim 10^7 \text{ J/m}^3$ , or it may be quite small, as in the high-permeability materials  $\text{Ni}_{0.8}\text{Fe}_{0.2}$  (Permalloy) or a— $\text{Fe}_{0.80}\text{P}_{0.13}\text{C}_{0.07}$  (an amorphous alloy).
- Another source of anisotropy can arise from the shape of the specimen, or from the shape of individual grains within the specimen. This is a local magnetostatic effect, rather than an intrinsic effect, and is called shape anisotropy (see Fig. 3). It is an extremely important factor in any real application. Two extremes are illustrative: A long thin needle (i.e., an acicular particle) can be readily magnetized along its long axis but will require a large field to force the magnetization to be across a short axis. The magnitude of field required is  $H_a = M_s/2$  (i.e.,  $H_a = 8.5 \times 10^5 \text{ A/m}$  for the case of an Fe needle). A flat plate, on the other hand, will require twice that field, i.e.,  $H_a = M_s$  to magnetize it parallel to the normal.
- A third source of anisotropy is due to the magnetostriction of magnetic materials, coupled with stresses in the material. Magnetostriction is the change in dimensions of a sample when the magnetization is aligned along various crystallographic directions; it occurs as a response that minimizes the magnetocrystalline energy. Conversely, when a sample is strained along some crystallographic direction, this contributes to the magnetic anisotropy. This is called stress anisotropy. It can be an



**Figure 3.** Shape anisotropy quantitatively describes the observation that needles and plates are most easily magnetized along a long dimension.

important effect in low-anisotropy materials that are highly strained, such as almost all thin films.

- The various magnetic anisotropies that may exist in a material all act simultaneously. The best way to analyze their cumulative effect is in terms of the anisotropy energy, which is the sum of all of the energies arising from individual anisotropies. The details of this analysis can be complex; see Bozorth or Brailsford, listed in the Reading List, for examples and guidance.

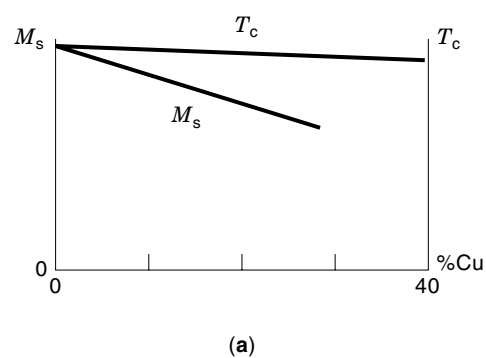
Useful magnetic materials almost inevitably consist mostly of Fe, Co, or Ni or a combination of these three elements, because these are the elements that are ferromagnetic at room temperature and above. A great variety of other elements may be added to form alloys or compounds with specific useful properties, but inevitably a large fraction of Fe, Co, or Ni will be present. When a nonmagnetic metal is alloyed with these elements,  $M_s$  and  $T_c$  generally decrease rapidly due to dilution. For example, Fig. 4(a) (Bozorth pp. 308–309) shows the effect of alloying Ni with Cu (which together form a continuous solid solution), showing the monotonic decrease in  $M_s$  with increasing Cu content. Other effects may occur, such as band-structure effects or the formation of compounds, which will alter the trends with alloying [e.g., formation of  $\text{Fe}_3\text{Al}$ , as shown schematically in Fig. 4(b)].

Alloying with rare-earth metals is often used in cases where a high intrinsic anisotropy is desired, such as in permanent magnets. The lanthanide rare-earth metals are all highly magnetic due to unpaired electrons in the  $4f$ -shell (inner) orbitals. The  $T_c$  of these materials is below room temperature because the exchange interaction between inner orbitals of adjacent atoms is small, but the intrinsic anisotropy is generally large because the spin-orbit interaction is largest in atoms with high atomic number (and therefore highly relativistic orbitals). Adding a small amount of a rare earth can dramatically increase the magnetocrystalline anisotropy of an Fe-, Co-, or Ni-based compound, often with only a modest de-

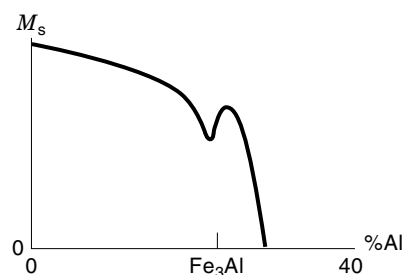
crease in  $T_c$  and  $M_s$ . The modern “rare-earth” permanent magnetic materials use this effect, as in  $\text{SmCo}_5$  and  $\text{Nd}_2\text{Fe}_{14}\text{B}$ .

### Domains and $M$ - $H$ Loops

While positive exchange coupling tends to align all of the spins in the same direction, real materials generally exhibit this uniformly oriented state only if they are very small ( $<100$  nm). Larger samples “demagnetize” by breaking up into magnetic domains. In each domain the local magnetic moments are uniformly aligned, usually along an easy axis. The directions of magnetization of the various domains can balance such that the overall magnetization is zero and the magnetostatic energy is small. When an external field is applied along an easy axis, domains aligned with the field tend to grow, while those antialigned tend to shrink. At high enough field the sample will be forced into a single-domain state, and the saturation magnetization will be observed. The formation of domains implies the presence of domain walls—boundaries between adjacent domains—that have increased exchange and anisotropy energies due to misalignment of neighboring spins. The density and orientation of domains in a sample is partly determined by energy balance between the domain wall and magnetostatic terms, but is also strongly affected by nonequilibrium considerations such as domain wall nucleation and pinning. In general, the growth and shrinking of domains (i.e., the motion of domain walls) dissipates energy,

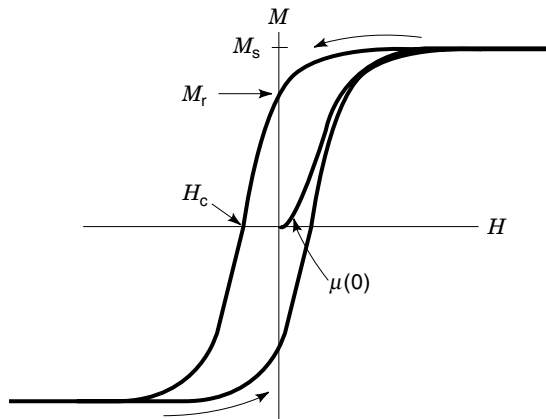


(a)



(b)

**Figure 4.** (a) Saturation magnetization and  $T_c$  for Fe–Cu alloys, normalized to the values for pure Fe. The monotonic decrease is typical of systems that form a continuous solid solution. (b) Saturation magnetization of Fe–Al compositions, normalized to the value for pure Fe. The anomalous behavior near the composition  $\text{Fe}_3\text{Al}$  (25% Al) is due to the formation of the  $\text{Fe}_3\text{Al}$  phase.



**Figure 5.** Schematic  $M$ - $H$  curve, showing saturation magnetization,  $M_s$ , remanent magnetization,  $M_r$ , coercive force,  $H_c$ , and initial permeability,  $\mu(0)$  (defined for an initially demagnetized sample, i.e., with  $H = 0$  and  $M = 0$ ).

so the  $M$ - $H$  curve is hysteretic, as shown schematically in Fig. 5.

This hysteretic, sigmoidally shaped  $M$ - $H$  curve is very typical of ferromagnetic materials. Four important parameters are immediately evident from examination of the  $M$ - $H$  curve.

- First, the limiting magnetization is just  $M_s$ , the single most important measure of a ferromagnetic material.
- Second, the slope of the  $M$ - $H$  curve at  $M = 0$  is the small-signal permeability  $\mu(0)$ , which measures the responsiveness of the magnetic material to an external field when it is close to its demagnetized state. This parameter is particularly important for soft magnetic materials, which use the magnetic material to obtain a flux multiplication by the factor  $\mu(0)$ . This parameter is determined partly by the magnetic anisotropy that is characteristic of the material but is also affected by factors that impede domain-wall motion, such as physical grain structure, microscopic inclusions, dislocations, or magnitude of the magnetocrystalline anisotropy.
- Third, the magnetization observed at zero field (after the sample has been fully magnetized) is called the remanence,  $M_r$ . This is an important parameter for permanent magnets, as it measures the magnitude of  $M$  available when the material is isolated. Note that the “squareness ratio,”  $M_r/M_s$ , is dominated by extrinsic aspects of the material, such as grain structure and defect, along with underlying anisotropies including the shape of the specimen.
- Fourth, the field required to reduce the external magnetization to zero (again, defined only after the sample has first been fully magnetized) is called the “intrinsic coercivity” or coercive field,  $H_c$ . At this field, the sample is in a multidomain state and the magnetizations from all of the various domains exactly cancel out. The coercive field is an important property for permanent magnets, as it measures the ability of a material to withstand the action of an external magnetic field, whether applied or self-generated. It is also determined mainly by extrinsic aspects of the material such as grain structure.

The interpretation of  $M$ - $H$  loops can often involve subtle aspects of the loop, including directional properties, the approach to saturation, possible nonsigmoidal curving, discrete jumps (known as Barkhausen jumps), and so on. These may reflect coherent rotation of spins in a domain when the external field is not aligned with an easy axis or may be due to subtleties of domain wall motion. Development of superior magnetic materials often involves intensive research into these issues, but usually the designers of devices need only focus on a few properties.

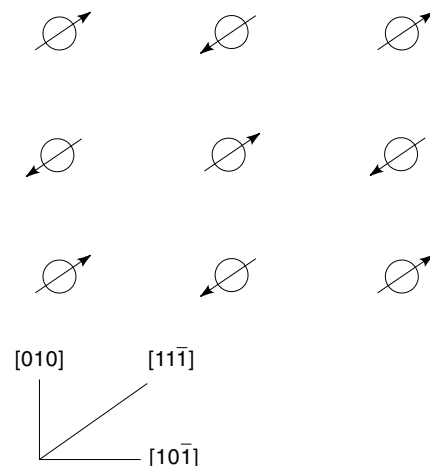
### Negative Exchange Interaction

The exchange interaction, as mentioned previously, need not be positive, inducing alignment of adjacent spins. When it is negative, adjacent spins will tend to align antiparallel. This can lead to a variety of behaviors depending on the structure of the material.

### Antiferromagnetism

The simplest configuration that can be obtained with a negative exchange energy is antiferromagnetism, in which the spins on adjacent sites in a unit cell cancel to give no net magnetic moment. A simple example is NiO, which forms in the rock salt (NaCl) structure (see Fig. 6). The ordering temperature for antiferromagnetic materials is called the Néel temperature,  $T_N$ , after the discoverer of antiferromagnetism, and is analogous to the Curie temperature of a ferromagnet. Above  $T_N = 250^\circ\text{C}$ , NiO is, of course, paramagnetic. In the antiferromagnetic state the susceptibility is not negative, as in the case of a diamagnet (which has no permanent dipoles) but is positive, small, and depends on the direction of the external field due to intrinsic magnetocrystalline anisotropy. The details of spin configurations and other properties of antiferromagnets can be very complicated. Antiferromagnetism is difficult to detect by conventional magnetic measurements. Neutron scattering measurements are typically required to confirm the existence of antiferromagnetism.

Antiferromagnetic materials have been known and understood since the work of Néel beginning in 1932, but there are



**Figure 6.** Antiferromagnetic structure of NiO, showing Ni atoms in the  $(\bar{1}01)$  plane. The spins are aligned along  $[11\bar{1}]$  directions as shown. The magnetic unit cell is twice the length of the crystallographic unit cell.

presently no important applications of bulk antiferromagnetic materials. Thin films (~1 nm to 100 nm thick) of antiferromagnetic materials now play an important role in state-of-the-art magnetic recording, specifically in magnetoresistive read heads. The antiferromagnetic thin films are used to magnetically bias the magnetoresistive sensor using a phenomenon called exchange anisotropy: the surface interaction between a ferromagnetic and antiferromagnetic material in intimate contact (see Fig. 7). Since this is an interfacial phenomenon, its magnitude is only significant when the surface/volume ratio is high, as in a very thin film.

### Ferrimagnetism

In a compound with two magnetic sublattices and antiferromagnetic coupling, the magnetic moments of each sublattice will generally not cancel exactly. Then the material will exhibit an overall magnetization that in many regards will appear exactly like that of a ferromagnet, with a hysteretic  $M$ - $H$  loop, a coercivity, and a remanence. Such materials are called ferrimagnets, because the prototypical examples are ferrites, because the properties, such as the temperature dependence of the magnetization, can be radically different from those of ferromagnets. For example, the different temperature dependencies of the magnetization on two sublattices can sometimes lead to exact cancellation of the net magnetization at a particular temperature, called the compensation temperature,  $T_{\text{comp}}$  (often denoted  $T_c$ , which leads to confusion with the Curie temperature). At that temperature the material behaves as if it were an antiferromagnet.

While ferrimagnets behave in many ways like ferromagnets, the highest saturation flux density in ferrimagnets is typically only about 0.6 T, and they cost significantly more than iron or silicon iron. Their crucial advantage is that they are usually good insulators and therefore are useful at high frequencies due to low eddy-current losses. Three classes of ferrimagnetic materials are predominant in applications:

- Garnets have a generic formula of  $R_3\text{Fe}_5\text{O}_{12}$ , where  $R$  represents a lanthanoid (Sc, Y, or lanthanide rare earth). These compounds have a  $T_c$  around 275°C and a rather low saturation flux density at room temperature,  $B_s = 0.18$  T. They have proven useful for bubble memories because high-quality single-crystal garnets can be prepared, and they continue to be used for UHF applications

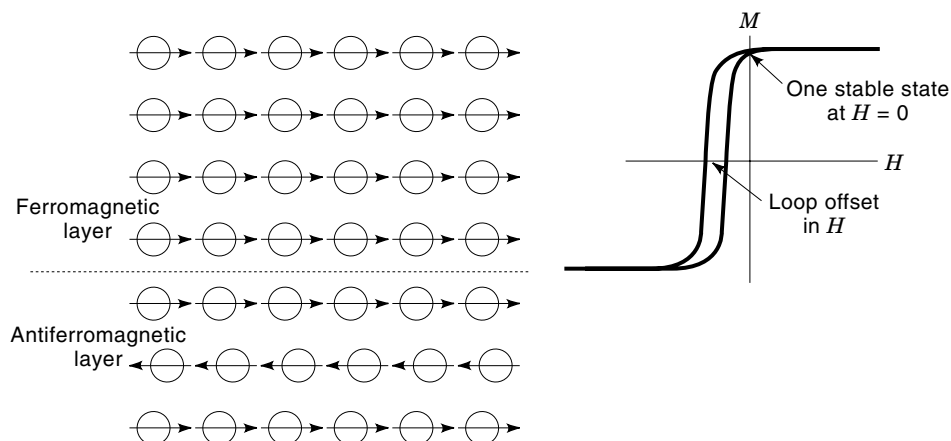
because they have particularly low losses in that frequency regime.

- Spinel ferrites are an especially large class of materials with a wide range of properties. The generic formula unit is  $AB_2O_4$ , where  $A$  is a divalent ion and  $B$  is a trivalent ion, usually  $\text{Fe}^{3+}$ . Most of the useful spinel ferrites are magnetically soft (that is, they have a low anisotropy energy and a high permeability). The prototypical spinel ferrite is  $\text{Fe}_3\text{O}_4$ , but Zn-substituted  $\text{MnFe}_2\text{O}_4$  and  $\text{NiFe}_2\text{O}_4$  are the soft ferrites used in most applications. Another extremely important ferrite is commonly used as a magnetic recording medium—namely,  $\gamma\text{-Fe}_2\text{O}_3$ , which is a modified spinel in which one in nine Fe sites is systematically vacant.
- Hexagonal ferrites are a much smaller class of materials, but this class includes the important ceramic permanent magnet materials. A typical formula unit for a hard hexagonal ferrite is  $\text{BaFe}_9\text{O}_{12}$ . These materials have a platelet-type growth habit with a very high uniaxial anisotropy and an easy axis normal to the platelet. This makes it difficult for the magnetization of a platelet to change, which accounts for the hard magnetic properties. The fact that these materials are insulating is often not an important issue since they are used to create a dc magnetic field.

When a magnetic dipole is aligned (e.g., by intrinsic anisotropy) along an axis and a radiofrequency (RF) field is applied perpendicular to that axis, the dipole does not respond simply by oscillating in the direction of the RF field, but it precesses around its axis in accordance with classical mechanics. The precession frequency is commonly expressed as  $\omega = \gamma H_{\text{an}}$ , where  $\gamma$  is the gyromagnetic constant [ $\gamma = 35$  kHz/(A/m) for most materials] and  $H_{\text{an}}$  is the anisotropy field. If the RF field is at exactly this frequency, the dipole can readily absorb energy from the field (and convert it into heat via coupling to the lattice). This phenomenon is known as ferromagnetic resonance, FMR, though it is most important in insulating ferrimagnets where eddy currents do not already dominate the losses. Above the FMR frequency the magnetic material has a nonmagnetic response.

At very high frequencies the response of ferrimagnets is not dominated by domain-wall motion, which is sluggish, but by coherent rotation of the spins in the sample. Then the per-

**Figure 7.** Schematic illustration of exchange anisotropy arising from interface coupling between an antiferromagnetic and ferromagnetic material. The schematic  $M$ - $H$  loop indicates that the loop is offset in  $H$  and that with no external field there is only one stable state (namely, the saturated state). That is, at  $H = 0$  there can be no domain structure.



meability is given simply by  $\mu_c = B_s/H_{an}$ , so  $\omega_{\text{FMR}}\mu_c = \gamma B_s$ . This equation, known as Snoek's law, says that for a given material, a higher FMR frequency can only be obtained at the cost of a correspondingly smaller permeability. It is a basic limitation to the use of ferrimagnetic materials at frequencies above about 10 MHz. Other issues, such as domain-wall resonances, may reduce the maximum frequency even further.

### Metamagnetism

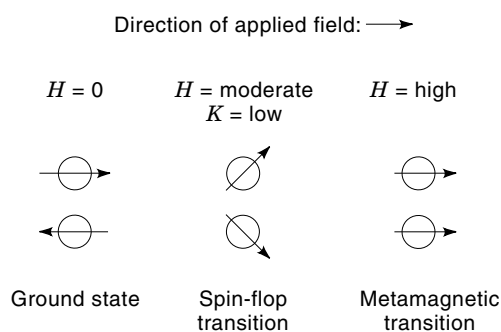
If a large enough magnetic field is applied to an antiferromagnet along an easy axis, the spins that are antialigned with the field will suddenly flip their orientation to achieve a lower energy state. That is, for a sufficiently high magnetic field,  $\mathbf{H}$ , the magnetostatic energy  $\mathbf{m} \cdot \mathbf{H}$  (where  $\mathbf{m}$  is the dipole moment of an individual atom) will inevitably outweigh the exchange energy. In some antiferromagnetic materials this flipping can be observed with achievable magnetic fields; it is then called metamagnetism. Note that in principle all antiferromagnets will exhibit this behavior at high enough field—the distinction is only in whether the required field can be produced in the laboratory.

Antiferromagnets with a relatively low anisotropy energy can exhibit an intermediate state between the antiferromagnetic and metamagnetic states as the field is increased. In this case, application of the field along the easy axis will cause the spins to reorient perpendicular to the magnetic field, and still in an approximately antiferromagnetic configuration, as shown schematically in Fig. 8. This transition is called spin flopping.

Neither metamagnetism nor the spin-flop transition are of practical significance in bulk applications of magnetism. However, the metamagnetic transition is an essential feature of the phenomenon of giant magnetoresistance (GMR), which is observed in metallic thin-film ferromagnet/paramagnet multilayers (vide infra).

### Spin Glass State

When a magnetic material has structural disorder, it is sometimes not possible for the exchange interaction among various neighbors to be satisfied, and no long-range orientational order (either ferromagnetic or antiferromagnetic) can be achieved. At low enough temperature such a "frustrated" material will achieve a quasi-ordered configuration in which the



**Figure 8.** The spin-flop transition and metamagnetic transition in antiferromagnetic materials. The spin-flop transition only occurs in materials with relatively low magnetic anisotropy energy,  $K$ , binding the spins to the easy axis (in this case, the horizontal axis).

spins are static but aligned in random directions. This is the "spin glass" state. In a given sample, the magnetic properties are found to be history dependent: For example, the saturation magnetization depends on whether the sample was cooled in a magnetic field or in zero field. So-called spin glass materials should not be confused with the metallic glasses discussed later. The nature of the spin glass state has been a productive area of study for physicists for many years, but the phenomenon has no current engineering significance (6).

A related concept is that of "geometrical frustration," which occurs in materials that have triangular site coordination and that therefore are frustrated even in a perfectly ordered material. These materials are presently being explored intensively by physicists, but also have no current engineering significance (7).

### Double-Exchange Materials

Along with the exchange mechanisms listed previously, there is a fourth mechanism, double exchange, that is relevant only to a small class of materials. The prototype material is  $(\text{La,Ca})\text{MnO}_3$ , a perovskite oxide, in which the Ca substituted for La acts as an electron donor. Electrons hopping from one Mn atom to another do not change their spin orientation during the hop, so the Mn atoms orient ferromagnetically. The most interesting property of these materials is observed in the paramagnetic state: In zero field the Mn spins are randomly oriented, inhibiting electron hopping and yielding a high resistivity. When the Mn spins are partially aligned by applying a large magnetic field, the hopping probability is enhanced, and the resistivity decreases dramatically. At an optimum temperature (near  $T_c$ ), a resistivity decrease by a factor of  $10^5$  to  $10^6$  has been observed at a field of 4 MA/m, a result that has led the effect to be known as colossal magnetoresistance (CMR). The effect is colossal at low temperatures and for only a small temperature range, and it requires very large fields to be applied, so it has not proven useful for engineering applications at present.

### Superparamagnetism

In small single-domain particles of ferromagnetic material, the magnetization tends to align along the easy axis, and the energy barrier required to move the magnetization is on the order of  $KV$ , where  $K$  is the anisotropy energy density and  $V$  is the volume of the particle. For the simple case of uniaxial anisotropy,  $\Delta E = KV$ . If the thermal energy  $k_B T$  is greater than this energy, then fluctuations in the orientation of the magnetization will lead to zero spontaneous magnetization and a response to an applied field that is analogous to the local moments of a normal paramagnetic material. The effect is seen, for example, in Co particles smaller than about 7.5 nm. The moment of a Co sphere of diameter 7.5 nm is roughly 20,000 times larger than the moment of single Co atom, so the effect is called superparamagnetism. While superparamagnetism is not technologically useful itself, it does represent an important limitation to the particle size of future magnetic recording media, and is therefore being intensively investigated.

### Thin Films

Thin films of magnetic materials behave exactly like bulk magnetic materials in most respects, albeit in profoundly dif-

ferent regimes for some parameters. For example, thin films have a high demagnetization factor normal to the film and essentially zero demagnetization factor in the plane of the film. Thus it is generally very hard to magnetize a thin film normal to the plane but fairly easy to move the magnetization in the plane. A simple consideration such as this can have wide-ranging implications, from an increased FMR frequency to gross effects on the structure of domain walls (i.e., the transition from conventional Bloch walls to Néel walls as the film thickness is decreased below about 100 nm). Thin films also tend to have stresses that are extremely high compared to stresses in bulk materials—500 MPa values are not uncommon. These stresses couple to the magnetostriction of the material to create a stress anisotropy that can strongly influence the magnetic behavior.

Thin films are used in a wide variety of applications, the most important of which are as media in hard disks and magneto-optic disks, miniature electromagnets in hard disk write heads, and magnetoresistive sensors in hard disk read heads.

Thin films inherently possess a unique direction, the growth direction. This is usually the normal, although it can be oblique if the incident atomic flux used to grow the film arrives from an oblique angle. For some materials the growth direction directly leads to a large intrinsic uniaxial anisotropy. For example, in amorphous Tb–Fe one might expect that there would be no anisotropy at all. Instead, films grown with the incident Tb and Fe atoms arriving essentially perpendicular to the substrate exhibit a large intrinsic uniaxial anisotropy oriented along the normal, and with a sense that leads to a perpendicular easy axis. The anisotropy is sufficient to overcome demagnetization, so domains form in which the magnetization is oriented perpendicular to the film. Such materials are used in magneto-optic recording (vide infra) (8).

Some behaviors seen in thin films are either absent or not commonly observed in bulk magnetic materials. An important example is the phenomenon of so-called giant magnetoresistance in thin-film multilayers. These multilayers are typically formed by sequentially depositing metallic ferromagnetic and paramagnetic layers, each  $\sim 1$  nm to 3 nm thick, using sputtering or evaporation in a high-vacuum chamber. Between two and a hundred layers might be built up in this way. The ferromagnetic layers couple with each other by the RKKY interaction through the paramagnetic metal, so depending on the thickness of the paramagnetic layer, the interlayer coupling may be antiferromagnetic or ferromagnetic. For example, a film consisting of 100 repeats of 1.0 nm-thick Co adjacent to 0.6 nm-thick Cu exhibits an antiferromagnetic state at zero field: Even though each Co layer is individually ferromagnetic, alternate layers have oppositely directed magnetizations. When a moderate field,  $H$ , is applied, the magnetizations of all of the layers align with the external field, producing a metamagnetic transition.

Baibich et al. (9) discovered the most interesting aspect of the metamagnetic transition in metallic multilayers: the effect it has on the resistivity of the sample. The aligned state has a greatly reduced resistivity compared to the antialigned state. The magnetoresistance ratio  $(R(H = 0) - R(H = H_s))/R(H = H_s)$  can be as high as  $\sim 100\%$  depending on the choice of materials. This is far greater than the highest normal magnetoresistance observed in any material at room temperature; hence the name giant magnetoresistance. It is attributed to spin-dependent scattering of electrons, which is

enhanced when magnetizations of adjacent layers are anti-aligned. This effect is crucial for the highest-performance magnetic disk read heads being currently designed (vide infra) (10).

## MAGNETIC MATERIALS USED IN APPLICATIONS

Useful magnetic materials are often divided into three categories:

- Soft magnets, in which the magnetization is readily changed with an external field, thereby providing a flux-multiplying effect
- Hard magnets (permanent magnets), which have high coercive fields and which therefore resist demagnetization by stray fields including their own
- Magnet recording media, which combine aspects of softness and hardness

### Soft Magnetic Materials

Soft magnetic materials are used in applications such as transformers and inductors. An obvious example would be the iron, known as electrical steel, used in transformers for inexpensive power supplies. At frequencies above about 10 kHz, eddy currents limit the use of metallic magnetic materials, so high-resistivity ferrites such as  $(\text{Mn,Zn})\text{Fe}_2\text{O}_4$  are used.

**Permeability.** An important property of soft magnetic materials is their relative permeability, nominally defined by  $\mu_r = B/\mu_0 H$ . Actually, since the  $B(H)$  curve is neither linear nor single valued, a large number of useful permeability parameters can be defined, such as the initial permeability, the maximum permeability, and the anhysteretic permeability. For simplicity, we will consider only the initial small-signal permeability, defined as  $\mu(0) \equiv \partial B/\partial H|_{H=0}$ . Values from  $\mu(0) = 10$  (high-frequency ferrites) to  $\mu(0) = 10,000$  (low-frequency inductors) are typically encountered in applications.

**Power Devices.** Probably the main use of magnetic materials at present, on a weight basis, is in power transformers. These can range from huge transformers used in substations, to miniature transformers used to convert line voltage to a level suitable for small consumer devices, to small ferrite transformers used in switching power supplies.

Low-frequency power applications almost inevitably employ low Si percentage Fe–Si alloys known as “silicon iron” or “electrical steel.” This is because Fe is by far the cheapest magnetic material available. The coercive field of pure Fe is typically about 80 A/m. The addition of a small amount of Si to Fe lowers the anisotropy, resulting in lower losses and a coercive force of about 40 A/m. It also substantially increases the resistivity, which decreases eddy currents. Eddy currents in transformers are usually further reduced by lamination (i.e., using a stack of Fe–Si plates, each electrically insulated by a coating layer, rather than a single thick piece). The laminations are arranged so that eddy currents are interrupted by the presence of the insulator and forced to circulate only within each lamination (i.e., so that any ac magnetic flux is perpendicular to the normal). Properly designed, the thickness of each plate should be smaller than a skin depth,  $\delta$ , given by  $\delta = (2\rho/\omega\mu)^{1/2}$ , where  $\rho$  is the resistivity,  $\omega$  is the



angular frequency of the ac magnetic field, and  $\mu$  is the permeability. Note that the permeability can also be frequency dependent.

Improved varieties of silicon iron are prepared using specific sequences of forging (rolling) and annealing to obtain a grain-oriented microstructure. In such materials the crystallographic orientation of individual grains is forced to be aligned over the entire piece. The advantage is that materials with lower losses are obtained, though the material is also somewhat more expensive. At present, most power transformers utilize grain-oriented silicon iron.

The highest-performance materials for low-frequency transformer applications are the metallic glasses, amorphous alloys of Fe and Co with one or more metalloid additions (usually B, C, Si, and P). These materials can have losses that are 10 times smaller than silicon iron and coercive fields below 0.5 A/m. But the saturation flux density is generally  $\sim 1.5$  T, and the materials are substantially more expensive than silicon iron. These negative aspects of metallic glasses have precluded their widespread use.

Power supplies with low weight and volume are highly desirable for some electronic applications, and this can be achieved with the design called “switching” power supplies. An additional benefit is circuit versatility and flexibility, while the main tradeoffs are increased cost and design complexity. A switching power supply uses power electronics [typically Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs)] to chop and rectify power at high frequency, a power transformer or inductor to change the voltage, and control electronics to synchronize and control the system. The frequencies used range from about 50 kHz to a present upper limit of 1 MHz.

At these frequencies, metallic ferromagnets cannot be used as the desirable lamination thickness would be prohibitively small. Fortunately at such high frequencies, the energy that must be stored in the transformer or inductor is correspondingly small for a given power capacity ( $E \sim P/\omega$ , where  $E$  is the maximum stored energy,  $P$  is the maximum power, and  $\omega$  is the angular frequency). Therefore, the cost of the magnetic part need not dominate, especially considering the cost of the electronics involved, so the use of relatively expensive but very high resistivity ferrites is feasible. In most cases an (Mn,Zn)Fe<sub>2</sub>O<sub>4</sub> spinel ferrite is chosen as a compromise between saturation flux density, losses, resistivity, and cost. At the highest frequencies, (Ni,Zn)Fe<sub>2</sub>O<sub>4</sub> may prove useful, as it has a higher resistivity and therefore is less susceptible to eddy current losses.

Motors and generators inevitably employ iron or silicon iron to act as a flux concentrator. The armature and stator are commonly constructed of grain-oriented silicon iron, though small motors often employ nonoriented silicon iron or metallic-glass materials. As in transformers, the ferromagnetic parts must be laminated to reduce eddy current losses.

**Inductors.** Small-signal transformers and inductors are used in a variety of circuit applications, as in impedance-matching and isolation transformers, antennas, and chokes. Signal-level devices do not have to carry substantial power, so they can be small and the cost of materials can easily be outweighed by performance considerations. Thus a wider variety of magnetic materials is used in these devices.

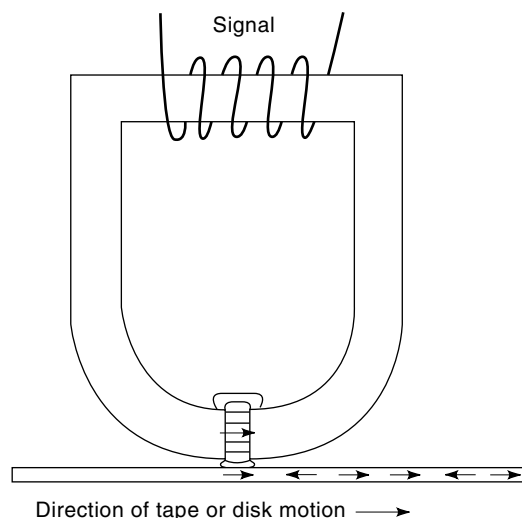
At audio frequencies and below, transformers and inductors were once commonly used for signal applications. For example, long-distance analog telephone circuits were balanced by the periodic addition of loading coils—inductors designed to match the large distributed capacitance of phone lines. A common choice for the magnetic core in those coils was Permalloy (Ni<sub>80</sub>Fe<sub>20</sub>) or a related alloy, and the cores were formed by rolling a long tape into a toroidal core. However, in modern telecommunications systems the analog signals are quickly converted to digital signals at the central exchange and then transmitted by fiber-optic, satellite, or microwave relay. The need for loading coils is minimal. Similarly, the function of audiofrequency impedance-matching transformers and other inductive electronic components has largely been displaced by more elaborate but much cheaper integrated circuit designs. Low-frequency magnetics are used in modem isolation transformers to provide dc electrical isolation with audio coupling; these are made with either laminated metallic or solid ferrite cores.

At RF frequencies (50 kHz to 50 MHz) magnetic cores are widely used; for example, in antennas, RF transformers, chokes, and resonant circuits. The usual choices for magnetic cores are the spinels (Mn,Zn)Fe<sub>2</sub>O<sub>4</sub> (up to about 1 MHz) and (Ni,Zn)Fe<sub>2</sub>O<sub>4</sub> (up to about 10 MHz to 50 MHz). The manganese zinc ferrites are cheaper but have a resistivity typically less than 1000  $\Omega$ -cm. Eddy current losses limit their usefulness at high frequencies. The initial permeability is roughly 1000 to 3000. Nickel zinc ferrites can have resistivities as high as 10<sup>5</sup>  $\Omega$ -cm and initial permeabilities on the order of 1000. Their upper frequency limit is dictated by the need to avoid FMR losses. Material designed for operation above about 10 MHz typically is prepared with moderate porosity to inhibit domain-wall motion and losses associated with domain-wall resonance. The permeability mechanism then is limited to that of coherent rotation of the spins, which implies a much smaller value ( $\mu_c \sim M_s/H_k \sim 10$  to 100).

Above about 50 MHz, magnetic materials are not commonly used in transformers and inductors, as Snoek's law demands that the permeability be uselessly small in order for the FMR frequency to be sufficiently greater than the frequency of operation. Snoek's law can be circumvented by the use of materials with a large biaxial anisotropy (e.g., the hexagonal magnetoplumbite-type ferrites) or by using thin films with a high saturation magnetization. At present, however, those approaches are not commercially important.

**Write Heads.** An important application of soft magnetic materials is in the recording heads used in tape and disk systems. Write heads essentially consist of an electromagnet with a toroidal magnetic core and a very small air gap ( $\sim 100$  nm to 300 nm). The flux that extends from the air gap, called the fringing field, is used to magnetize the magnetic medium passing nearby (see Fig. 9). In tape and floppy disk systems the magnetic medium is in actual contact with the head, while in hard disk systems the head flies aerodynamically over the spinning medium at a height of 25 nm to 75 nm. The maximum magnetic field available for magnetizing the medium is proportional to the saturation magnetization of the head material.

Originally the magnetic recording heads were made from laminated metal alloys, such as Permalloy or Sendust (an alloy of Fe, Si, and Al notable for being magnetically soft and



**Figure 9.** Schematic of a magnetic recording head. Recording is accomplished using the magnetic fringing field (i.e., the field that leaks from the gap).

physically very hard), but as recording densities and frequencies increased, an inevitable move was made to ferrite materials. Ferrite heads are made from cast pieces that are carefully polished to form a precise air gap and then are assembled with the driving coil. As recording densities have increased, media with higher coercivities are necessary, so head materials with high-saturation magnetization are needed. Unfortunately this is where the ferrites are most deficient, with maximum  $B_s \sim 0.6$  T. One approach to obtain improved performance is to add a thin film of relatively high  $B_s$  material (such as Permalloy,  $B_s = 0.9$  T to 1.1 T) on the inside edge of the gap of each piece. The thin film acts as a flux concentrator and increases the fringing field significantly. This approach is called the metal-in-gap (MIG) design.

The highest-performance recording heads are constructed using thin films and photolithography. They have the advantage of great precision in layout, leading to extremely narrow pole tips, precise gap widths, and precise placement of the driving coils. Permalloy and related alloys are most commonly used at present, but soft amorphous alloys such as  $\text{Co}_{0.85}\text{Nb}_{0.05}\text{Zr}_{0.7}$  offer significant improvements with  $B_s \sim 50\%$  greater than Permalloy. The resistivity of the amorphous alloys is in the range  $\rho \sim 100 \mu\Omega\text{-cm}$ , about 5-fold higher than Permalloy, which reduces eddy current losses, allowing recording at higher frequencies. Further advantage can be obtained by using the recently developed nanocrystalline (grain size  $\sim 1$  nm to 5 nm) alloys such as  $\text{Fe}_{0.92}\text{Ta}_{0.05}\text{N}_{0.03}$ , which have extremely high  $B_s \sim 2.0$  T and also have resistivities in the range of  $100 \mu\Omega\text{-cm}$  to  $150 \mu\Omega\text{-cm}$ . These materials are being vigorously developed for future generations of high-performance recording, especially hard disk drives.

**Read Heads.** The same magnetic structure that is used for magnetic recording can also be used for reading the recorded signal. The passage of recorded domains across the gap of the recording head will induce a small voltage on the driving coil, which is amplified and processed. Indeed, this inductive read head is the simplest and cheapest approach to magnetic recording. However, the signal level is very low and limits the

performance of hard disk drives. The present generation of hard disk drives uses a separate magnetic structure (incorporated in a single read/write head) for reading the recorded magnetic signal. The sensor in this device is a magnetoresistive thin film made of Permalloy and biased with a dc current. External flux from the recording medium couples to the Permalloy film, rotating the magnetization with respect to the fixed direction of the dc current. This changes the resistance of the Permalloy (the so-called conventional or anisotropic magnetoresistance effect, AMR) and therefore the voltage developed across the device. The AMR effect is relatively small, about 5%, but is sufficient to deliver signal superior to that of an inductive head.

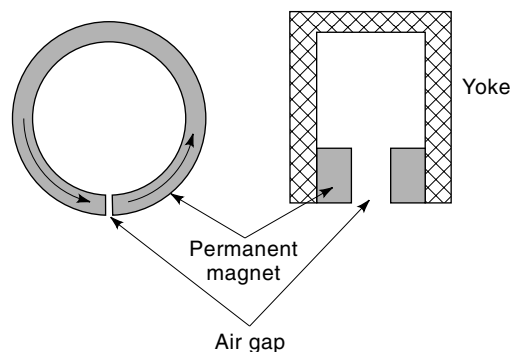
Superior performance can be obtained by incorporating materials that exhibit giant magnetoresistance. These can have responses that are about 10-fold higher than AMR materials. So-called spin valves employ the same physical principle as GMR (namely, spin-dependent scattering) in a more highly controlled and responsive magnetic structure. The higher signal output of spin-valve read heads, in conjunction with careful redesign of the entire magnetic recording system (including media, head structure, electronics, signal processing, etc.), can lead to substantial increases in recording density.

**Shields.** Soft magnetic materials are also used to make magnetic shields, typically used to protect electronic components from magnetic interference or to contain the external field around a component that generates magnetic flux. An example of the former are shields for cathode-ray tubes, such as computer monitors, while an example of the latter are shields for speakers, such as “multimedia” speakers intended for placement close to a (unshielded) monitor. These shields are usually formed from Permalloy and related alloys. Often “Mumetal” is specified for these applications—this originally designated a particular Fe–Ni–Cu alloy but it is now used generically to refer to many high-permeability alloys. Note that RF shields (unlike dc magnetic shields) rely on eddy current screening and use high-conductivity paramagnetic metals such as Cu.

A related application is the use of materials that absorb RF energy. These are typically lossy ferrites and are used in the form of beads threaded on wires, where it is desired to suppress high-frequency signals. Manganese-zinc ferrites are generally used for this purpose, although nickel-zinc is used to obtain the highest cutoff frequencies. Lossy ferrites can also be used as an antiradar coating on military aircraft.

#### Hard (Permanent) Magnets

Permanent magnets are used in a wide variety of applications where a static magnetic field is desired. The dominant uses are in speakers and dc motors and as holding magnets. The field available from a given permanent magnet depends on the physical configuration but is limited to  $B_s$ , the saturation flux density in the optimum case. Specifically, for a toroidal part with a small air gap (see Fig. 10), the flux density in the gap will be  $B_s$ . For Fe this is  $B_s = 2.15$  T, while for  $\text{Fe}_{0.6}\text{Co}_{0.4}$  it is  $B_s = 2.43$  T (11, p. 190), the highest value for any known bulk material. In less optimum geometries, the available flux density can be greatly reduced, as determined by magneto-statics. For arbitrary-shaped parts, the usual approach is to



**Figure 10.** Air gap in magnetic circuits. The gray regions represent permanent magnet material, with the direction of magnetization shown. The hatched region represents soft magnetic material, which is used to complete the magnetic circuit.

employ finite-element numerical calculations to infer the flux distribution.

In general, where the design figure of merit is the flux available per unit volume of magnetic material, the corresponding figure of merit for the magnetic material is the energy product  $(BH)_{\max}$  (i.e., the largest value measured at any point in the second quadrant [positive  $B$ , negative  $H$ ] of the  $B$ - $H$  curve). This is only a crude way to evaluate the usefulness of a material; nevertheless it is indicative and is commonly quoted by permanent magnet manufacturers. Four main types of permanent magnet materials are commonly used:

- Alnico, a class of Fe-Al-Ni-Co-Cu alloys. The properties of this material are entirely dependent on complex metallurgical processing and microstructural control. Commonly used Alnico materials have  $(BH)_{\max} = 50 \times 10^3 \text{ J/m}^3$ .
- Barium ferrite, typically  $\text{BaO} \cdot (\text{Fe}_2\text{O}_3)_6$ , is the standard “ceramic” magnetic material. The typical value  $(BH)_{\max} = 25 \times 10^3 \text{ J/m}^3$  is smaller than that of Alnico, but the material is both lower density and cheaper to produce than Alnico and has almost entirely replaced Alnico in highly cost-sensitive applications. The high value of  $(BH)_{\max}$  in this and the following materials is due to the very high intrinsic anisotropy.
- Sm-Co is the standard high-performance “rare-earth” permanent magnet, with  $(BH)_{\max} = 160 \times 10^3 \text{ J/m}^3$ . The major disadvantage of this material is its cost.
- Nd-Fe-B, a more recent material, has an even higher value for  $(BH)_{\max} = 320 \times 10^3 \text{ J/m}^3$  than Sm-Co, and it is less expensive. The major disadvantage of this material in some applications is that the  $T_c$  is somewhat low,  $T_c \sim 150^\circ\text{C}$ .

Loudspeakers have long been a dominant application for permanent magnetic materials. The permanent magnet is used to establish a magnetic field in an annular region in which the voice coil is mounted. When a current is driven through the voice coil, an axial force is produced, in accordance with the Lorentz relation,  $\mathbf{F} = e\mathbf{v} \times \mathbf{B}$ , where  $\mathbf{F}$  is the force on an electron,  $e$  is the charge on an electron, and  $\mathbf{v}$  is the velocity of the electron. Motion of the voice coil is coupled

to a speaker cone to move the air efficiently and thereby produce sound waves.

The energy product of a magnetic material is a good figure of merit for speaker applications, since for a given design, a higher-energy product will result in a higher flux density in the annular gap. Most loudspeakers are low-priced components, so the cost of the magnetic material is the other key factor. For this reason, barium-ferrite is the dominant material used. In some applications, such as high-performance earphones, the amount of magnetic material is small so materials cost is less critical. In the past, Sm-Co magnets have been used for these applications, though Nd-Fe-B magnets are now clearly the best overall choice.

The materials used for permanent magnets inevitably cost more than silicon iron, so large motors and generators always use soft magnetic materials wound with coils to create the required magnetic field. In small motors, the economics are dominated by the cost of fabrication: The small coils and fine tolerances needed for electromagnet motors outweigh the added cost of permanent magnetic materials. A vast number of small dc motors are produced for a very wide range of applications, from clock motors to the dozens of motors in modern automobiles used to drive windows, locks, seats, windshield wipers, and so on.

An economically important use of permanent magnets is in the low-tech application of holding magnets. These range from decorative magnets for holding notes to a refrigerator door to functional magnets for holding and sealing the refrigerator door shut to strong magnetic chucks for holding ferrous materials for machine-forming operations. In almost all cases cost is paramount, and barium ferrite is used. For some applications the ferrite powder is mixed with a polymer precursor, formed into a tape, and polymerized to form a flexible magnet, albeit with reduced net flux density and therefore reduced holding power.

#### Magnetic Recording Media—Intermediate Between Soft and Hard

Magnetic recording is a huge business, dominated by the hard disks and floppy disks pervasive in personal computers and by tape recording—audio, video, instrumentation, digital data storage, and so on. The media used in recording are magnetic materials that must have a relatively high coercive force so that they do not spontaneously demagnetize and lose information. But the coercive force cannot be much greater than about 100 kA/m because the leakage flux from the recording head is limited and must nevertheless be sufficient to saturate the medium.

The standard material used in tape and floppy-disk media is gamma iron oxide,  $\gamma\text{-Fe}_2\text{O}_3$ . It is moderately expensive to prepare (compared to conventional ferrites) because extremely reproducible and controllable properties are required. Acicular (needle-shaped) particles  $\sim 50 \text{ nm}$  in diameter are prepared in order to obtain good recording characteristics. The coercivity of most tapes is about 20 kA/m to 30 kA/m. Recent high-performance formulations use cobalt-modified  $\gamma\text{-Fe}_2\text{O}_3$ , which has a thin cobalt-rich region on the surface of the particles. This material has an increased coercivity of about 50 kA/m and is routinely used for video tape. In the past,  $\text{CrO}_2$  was used as a high-performance medium because it has a higher  $M_s$  than  $\gamma\text{-Fe}_2\text{O}_3$  and can be prepared with a

coercivity as high as 80 kA/m. However, it has a low  $T_c$  (only 130°C) and is relatively expensive, so it has been displaced by cobalt-modified  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub>.

Hard disks used in digital recording are aluminum platters coated with paramagnetic Ni-P or Cr and then a recording medium such as Co-Cr. An extremely thin layer of C is usually then deposited along with an even smaller amount of lubricating fluid, in order to avoid catastrophic head contact with the medium ("head crashes"). The coercivity of hard disk media is in the range 60 kA/m to 100 kA/m, and the saturation magnetization is about 1000 kA/m.

For many years it was expected that magnetic bubble memory might find a role for data storage in computers. However, bubble memory is slow and expensive compared to hard disks and semiconductor random access memory (RAM). Its only advantages are that it is mechanically more robust than a hard-disk system, and it is more radiation resistant than semiconductor RAM. Therefore, the only present use for bubble memory is in certain military applications.

Bubble memories store data in cylindrical domains, perpendicular to the surface, that are generated in liquid-phase epitaxy (LPE) grown garnet films. The films are designed to have a large uniaxial anisotropy perpendicular to the film plane and are chosen to meet a number of other criteria. The bubbles are moved around using a rotating external magnetic field created by a miniature electromagnet, and they are detected using a magnetoresistance bridge.

Finally, there is magneto-optic recording. In this scheme data are stored on a plastic disk coated with an amorphous metallic thin film such as Tb<sub>0.2</sub>Fe<sub>0.8</sub> or similar compositions doped with Dy and Co. They have a large uniaxial anisotropy, with an easy axis perpendicular to the plane of the film, so as with the garnet films designed for magnetic bubble applications, cylindrical domains are stable. Data are written by focusing a laser on the desired spot, which heats the films above its  $T_c$ , ~100°C to 150°C. If the film is exposed to a moderate magnetic field while it cools, the heated region will magnetize in the direction of the applied field. Thus alternating regions of, say, north-up and south-up can be written. The data are read with the same laser at lower power to avoid heating, using a polarizer to detect Faraday rotation (i.e., rotation of the polarization of light when it interacts with a magnetic material). This effect is known as Kerr rotation when it occurs on reflection from a metallic magnetic surface. The Kerr rotation in a magnetic material is in the opposite sense for regions magnetized north-up versus south-up. The maximum Kerr rotation in Tb-Fe films is rather small, ~0.2°, which gives a low signal/noise ratio and correspondingly low data rate.

The data density in magneto-optic recording is comparable to that of a conventional CD-ROM but has the great advantage of being endlessly rewriteable. Magneto-optic drives are slower for writing data and more expensive than conventional hard drives, but they confer the advantage of cheap removable media and good archiveability and have found a small but significant market niche.

### Miscellaneous

Along with the three conventional classes of applications for magnetic materials, there are a wide variety of specialized applications, too numerous to list exhaustively.

**Nonreciprocal Materials.** Some of the most interesting magnetic devices are based on the nonreciprocal propagation of UHF signals in insulating magnetic materials. The behavior is formally identical to the small optical Faraday rotation observed in some nonferromagnetic materials, but the effect in ferrites can be very large and is commonly used in microwave applications (for example in isolators and circulators).

The nonreciprocal phenomena are due to interaction of the incident radiation with the precessing electron spin (see MAGNETIC RESONANCE). A particularly straightforward case arises when the incident microwaves are circularly polarized with a propagation vector parallel to the easy axis of the magnetic material and at a frequency equal to the natural precession frequency of the electron spins. Then, if the sense of the circular polarization is the same as that of the electron spin precession, energy is readily transferred to the spins and dissipated as loss. If the sense is opposite (corresponding to propagation in the opposite direction), then there is little interaction and the loss is minimized. It is easy to imagine an isolator based on the directionality of this phenomenon, though the practical design of this and other nonreciprocal microwave devices can be very complex. In general, a moderately large external biasing magnet is required to set the FMR frequency equal to the operating frequency (a larger field is required for a higher operating frequency).

Three classes of materials dominate the magnetic materials used for microwave applications. The figure of merit for microwave devices is usually proportional to  $1/\Delta H$ , where  $\Delta H$  is the FMR linewidth.

- First, the garnet-structure ferrites exhibit the highest performance available because they have the lowest FMR linewidths: A typical value for polycrystalline ceramic yttrium iron garnet, YIG, is  $\Delta H = 4000$  A/m. Single crystals with linewidths as low as 40 A/m have been reported. Single crystals are relatively expensive but are usually the best choice at low frequencies.
- Second, the spinel ferrites are useful in a number of cases. Nickel zinc ferrite is particularly useful at high powers because it has a higher  $T_c$  than garnets, and it is often used in the range above 10 GHz. Manganese-magnesium ferrites are used in the range of 5 GHz to 10 GHz because their lower saturation magnetization allows biasing at lower field.
- Third, the Z-type hexagonal ferrites have a hard axis normal to the basal plane, so the need for external biasing is reduced. They require expensive processing to produce oriented, high-quality ceramics. They are most useful for mm-wave applications.

In general, the key issues in developing materials for microwave applications are related to processing and microstructure control rather than exploring new compositions. Small grain size is important to minimize losses from domain-wall resonance, to maximize the resistivity, and to make stronger materials that resist the thermal stresses caused by high-power operation. Obtaining a high density is always important, but densification usually is accompanied by grain growth. The art of designing or choosing a microwave magnetic material is in balancing these conflicting requirements.

**Ferrofluids.** Ferrofluids are liquid suspensions of magnetic particles coated to avoid agglomeration. Typically the liquid is a hydrocarbon or silicone, and the magnetic particles are ferrites, but a wide range of combinations is possible. The behavior of ferrofluids is unique and scientifically interesting, and ferrofluids are commercially used for such diverse applications as gas-tight seals for rotary shafts, heat transfer agents for loudspeaker voice coils, and damping systems.

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