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RARE-EARTH MAGNETIC MATERIALS

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In the last 10–15 years, the magnetic properties of rare-earth metals, alloys, ferrites, and other compounds have been investigated. Extensive data were obtained on spontaneous magnetization, magnetic anisotropy, magnetostriction, magnetooptical phenomena, magnetic phase transitions, etc. It has been shown that magnetically ordered rare-earth substances (ferro- and ferrimagnets) have magnetic properties that differ in many respects from the properties of similar substances synthesized on the basis of the iron group. For example, some of the rare-earth metals and their compounds have record high values of the magnetic anisotropy and of the magnetostriction[1], large values of the Faraday-rotation effect[2], and of the magnetocaloric effect[3], unique temperature dependences of the magnetization, and magnetic phase transitions[1]. It is possible to generate in these substances very small cylindrical or "bubble" domains which have high mobility[4]. The magnetic behavior of rare-earth ferro- and ferrimagnets have other interesting features.

The magnetism of rare-earth substances was for a long time of pure scientific interest, and only most recently, after rare-earth elements have become available in sufficiently large amounts and at sufficiently low cost, did interest in the use of their unique magnetic properties in technology increase. At present there are already examples of practical application of rare-earth materials (or proposed applications) in radio engineering, electrical engineering, automation, and computer technology. We present in this article some of these examples.

1. LARGE SATURATION MAGNETIZATIONS OF RARE-EARTH METALS AND THEIR ALLOYS

The saturation magnetizations of the metals Tb, Dy, Ho, and Er at 0°K are much larger than those of Fe and Ni. For example, for Dy at 0°K we have $I_0 \approx 3000$ G, as against 1750 G for iron. The large value of I_0 of rare-earth metals is due to the fact that not only spin magnetic moments but also orbital magnetic moments take part in their magnetization (the orbital moments because of their "freezing-in" by the crystal field). However, the use of rare-earth metals as materials with large magnetic saturation is practically impossible because of the presence of tremendous magnetic anisotropy; tremendous magnetic fields are needed to magnetize polycrystalline dysprosium, terbium, etc. to saturation, and this cannot be effected in practice. There are two ways of decreasing the saturation field.

The first is to alloy the metal Er, which has a negative magnetic anisotropy constant, with the metals Tb, Dy, or Ho, which have a positive anisotropy constant. Such alloying decreases the anisotropy constants and accordingly the saturation fields, while the saturation magnetizations remain sufficiently high. Optimal compositions of such alloys, both binary and ternary, yielding magnetic induction saturations up to 35 kG in magnetizing fields ~50 kOe have been found[5].

The second method of decreasing the saturation field is to grind the metals Tb, Dy, etc. into a powder and press the powder in a magnetic field. At such a technology, the small crystallites are rotated to align their easy-magnetization axis along the applied field, as a result of which an easy-magnetization texture arises, and the saturation field is greatly reduced (production of texture with multidomain particles). A polycrystalline sample without a texture has a saturation field higher than 300 kOe, and after this technology is employed the field drops to 30–40 kOe.

Rare-earth metals and alloys with high magnetic saturation are already used as cores for superconducting magnets[6,13] and in other devices operating at low temperatures.

2. ALLOYS OF THE $SmCo_5$ TYPE AS PERMANENT MAGNETS OF HIGH MAGNETIC ENERGY

The intermetallic compounds RCo_5, where R is a rare-earth element of the cerium subgroup (Ce, Pr, Nd, Sm), have a ferrimagnetic structure, i.e., the indicated rare-earth atoms form in these compounds one magnetic sublattice, and the Co atoms another sublattice; there is an antiferromagnetic coupling between these sublattices. Ferrimagnets, generally speaking, are characterized by low and even zero (at the compensation point) magnetization. The situation in the RCo_5 alloys, however, is different and leads to an increased magnetization. The point is that in the rare-earth elements of the cerium subgroup (Ce, Pr. Nd, Sm), according to Hund's rule, the spin (S) and orbital (L) moments in the electron 4f-layer are oppositely oriented ($J = L - S$), with $L > S$. In the RCo_5 crystal, the spin moments S_R and S_{Co} are oriented antiparallel, since there is an antiferromagnetic coupling between them, but the orbital moment of the rare-earth ion occupies a position parallel to the spin moment S_{Co} (Fig. 1). This leads to an increased value of the magnetization of the ferrimagnetic layer RCo_5. Naturally, the RCo_5 alloys will have also an increased residual magnetization.

Alloys of the type RCo_5 have very high magnetic anisotropy. As shown by investigations, they are larger by 1–2 orders of magnitude than the magnetic aniso-

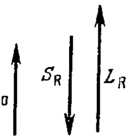

FIG. 1. Diagram showing the orientation of the spin and orbital moments in alloys of RCo_5.

tropy of Fe and Co ($\sim 10^8$ erg/cm^3). The mechanism whereby such a tremendous anisotropy is produced is still not clear. Consequently the RCo_5 alloys, following a suitable technological treatment (pressing of powders) that ensures the production of single-domain particles, can acquire high coercive forces (H_C) reaching tremendous values $\sim 10^4$ Oe[7]. Because of the tremendous residual magnetization and the large H_C, the RCo_5 alloys make it possible to produce permanent magnets with much better parameters than the magnets made of earlier materials. It was shown recently that the magnetic demagnetization energy of the $SmCo_5$ alloy reaches the record value $(BH)_{max} \approx (20-23) \times 10^6$ G-Oe[7]. Such materials uncover great possibilities of a breakthrough in the production of minature sources of constant magnetic fields. In the near future alloys of the RCo_5 type will occupy a leading place among the materials from which one can construct strong and compact magnets for the use in electrical engineering, radio engineering, and automation (e.g., for the development of miniature electric motors, magnetic elements of vacuum devices such as travelling-wave tubes and magnetrons, magnetic-focusing systems, etc.). The history of materials for permanent magnets can be traced in the table. We see that the $SmCo_5$ alloy has clear-cut advantages over the remaining materials.

Further improvements in materials for permanent magnets calls for a better understanding of the physics of the RCo_5 magnetization of ferrimagnetic systems, and also a study of the magnetic properties of different mixed systems, for example $(Sm_{1-x}Pr_x)Co$[14]. It has been calculated that the theoretical limit of $(BH)_{max}$ for this system of alloys is 30×10^6 G-Oe.

3. RARE-EARTH IRON GARNETS AND ORTHOFERRITES AS MATERIALS FOR THE DEVELOPMENT OF NEW MAGNETIC MEMORY ELEMENTS

For further development of electronic computers it is important to produce magnetic memory (and logic) devices of high operating speed and high capacity. The problem is to store and process the maximum information in the volume of a small magnet. Recently, fundamentally new types of magnetic memory devices have been proposed, based on the use of the magnetic properties of rare-earth iron garnets ($R_3Fe_5O_{12}$) and orthoferrites ($ReFeO_3$). There are two trends in this research. The first is connected with the use of the anomalies of the temperature dependence of the magnetic characteristics of rare-earth iron garnets and orthoferrites. The second is connected with the use of the properties of so-called "cylindrical" or "bubble" domains, which can arise under different conditions in these materials. Let us consider the first of these trends.

Progress in the production of permanent-magnet materials

Year	Material	H_c, Oe	B_r, G	$(BH)_{max}$ at the optimal point of the magnetization curve, 10^6G-Oe
1880	Carbon steel	50	10000	0.26
1917	Cobalt steel	240	9200	0.9
1933	Fe-Ni-Al alloy	480	6100	1,05
1952	Barium hexaferrite	1800	2000	0,9
1958	Pt-Co alloy	4300	6450	9,5
1968	$SmCo_5$	9500	9000	20,0

a) Rare-earth orthoferrites and iron garnets possess a sharp temperature dependence of the magnetic properties and abundance of different magnetic phase transitions[1]. The occurrence of such properties is connected with the physics of the uncompensated antiferromagnetism and with the existence of noncollinear magnetic moments of the sublattices, produced by competition between the sublattice exchange interactions, the energy of the magnetic and magnetoelastic anisotropy, and the external magnetic field. Investigations have established that in rare-earth orthoferrites there are several magnetic phase transitions, namely, the temperature of magnetic ordering of the iron ions (at ~600°K), the ordering temperature of the rare-earth ions (4–20°K), the so-called spin-reorientation transition, wherein the system of ordered spins rotates relative to a definite crystal axis, and the magnetic compensation point, at which two sublattices with different dependences of the spontaneous magnetization are balanced (in the presence of an external magnetic field the compensation point is the point of a magnetic phase transition).

Rare-earth iron garnets are also characterized by the presence of analogous transitions (with the exception of the spin-reorientation transition).

Recently, the anomalous temperature dependence of the coercive force (H_C) in the region of the compensation point (T_C) has attracted practical attention for the purpose of creating magneto-optical memory elements of high capacity. These anomalies of H_C in rare-earth iron garnets (and in orthoferrites) were first observed in[8,9].

The magnetic recording can be effected here by changing the magnetic state (magnetization reversal) of very small sections of a plate of rare-earth iron garnet, with the aid of localized heating by a laser (or electron) beam at temperatures near T_C and in the presence of a magnetic field of definite direction. The size of the field is chosen to be somewhat weaker than H_C, so that no reversal of the magnetization of the section of the plate occurs without heating. By local action of the laser beam (Fig. 2), the value of H_C is strongly reduced and the field H turns out to be sufficient to reverse the magnetization of the section, i.e., to record the sign of the magnetization. The laser light beam can be focused into a spot whose diameter, bounded by diffraction, is approximately equal to the wavelength of the laser beam, i.e., of the order of a micron or several tenths of a micron. The IBM Company has succeeded[10] in recording on a film of gadolinium iron garnet $Gd_3Fe_5O_{12}$ at a density of 1.5×10^6 bits per cm^2. The speed of such a thermomagnetic recording is determined by the time of the optical pumping (the time of phonon absorption) and by the time of the conversion of the optical excitation into heat (it is much shorter than the thermal relaxation time or the diffusion process). Near the temperature T_c, owing to the sharp decrease of H_c, very small values of ΔT are needed to reverse the magnetization. For such recording it is necessary to use ferrites in the form of thin plates and films, since their heat capacity is low.

To effect magnetic recording based on the described principle, it is possible to use also anomalies of the temperature dependence in other transitions observed in rare-earth ferrites, for example the anomalies of H_c near the ordering temperature of the rare-earth ions in garnets and orthoferrites. It is also possible to use for this purpose the anomalies of H_c and of the hysteresis loop observed in rare-earth orthoferrites near the spin-reorientation temperature[11]. The plates and films of rare-earth iron garnets and orthoferrites are transparent to the visible and infrared light. It is therefore possible to read the information without destroying the record. To read the information, the rare-earth ferrite plate is illuminated with a laser beam of lower intensity. Rotation of the plane of polarization of the light passing through the plate is registered as the presence of information.

The second trend is connected with the use of the properties of the domains in rare-earth ferrites.

b) The memory function is performed by "cylindrical" or "bubble" domains. It was shown recently[4] that the conditions for the occurrence of "bubble" domain structure are particularly favorable in thin crystalline plates of rare-earth orthoferrites and uniaxial iron garnets (yttrium-iron garnets with small admixtures of rare-earth elements that distort the cubic structure of the garnet). The condition for the occurrence of such domains is $H_a > 4\pi I_s$, i.e., the magnetic anisotropy field H_a in the ferrite should be stronger than the saturation magnetization. In this case the magnetization vector will be perpendicular to the plate. When a definite external magnetic field is applied, the strip domains close on themselves, as it were, (Fig. 3), and ultimately are transformed into small cylinders or bubbles of very small radius (on the order of several microns) with magnetizations perpendicular to the plate. These domains can become remagnetized and can move in the plate when local magnetic bias fields are applied with the aid, for example, of very small windings attached to the plate (Fig. 3). The domains can be controlled by using special circuits printed on the surface of the plate. It is thus possible to develop very compact memory elements and logic elements with magnetostatic control. In addition, it was shown that the size of the cylindrical domain is a function of the local bias field and of the energy of the domain boundary, something that can also be used for compact magnetic recording of information. Memory and logic elements using the properties of small and mobile cylindrical domains have a large memory capacity, high interference immunity, and high operating speed. The conditions for the occurrence of cylindrical domains exist also in other magnetically ordered substances, for example in hexagonal ferrites and Co alloys. The advantage of rare-earth orthoferrites and iron garnets lies, however, in the fact that thin plates of these substances are transparent to light, and can thus be used for non-destructive reading of the information.

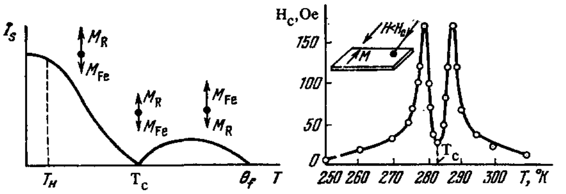

FIG. 2. Scheme for magnetic recording of information at high density using the anomalies of the coercive force near the compensation point of gadolinium iron garnet.

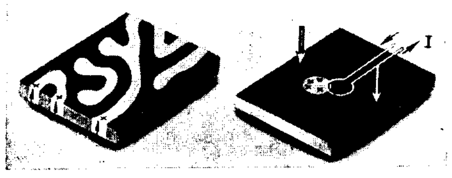

FIG. 3. Scheme for formation of "bubble" domains in rare-earth orthoferrites.

Rare-earth orthoferrites and iron garnets are promising also for the development of effective holographic devices, in which pictures are recorded with the aid of moving cylindrical domains on a thin crystal plate of such a material, and are then projected on a screen by a laser beam passing through the plate. The timeliness of the use of rare-earth ferrites having cylindrical domain structures is indicated by the fact that their discussion was the subject of not less than half of all the papers delivered at the "Intermag-71" conference in Denver in 1971.

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We note that the transparency of the rare-earth orthoferrites and iron garnets makes it possible to use them successfully to produce modulators and optical switches in laser technology. The iron garnet $Y_3Fe_5O_{12}$ with small additions of rare-earth ions can be used to produce coherent radiation of high power[12]. A laser based on an yttrium garnet crystal, while retaining all the advantages of lasers based on non-magnetic crystals, has the important advantage that the magnetically-ordered nature of this material makes it possible to control the frequency and polarization of the beam with the aid of a magnetic field.

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