Possible new effects in multilayer antiferromagnetic macrostructures

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A proposal is made to build multilayer magnetic macrostructures with prescribed symmetry-determined physical properties. © *1995 American Institute of Physics.*

Multilayer antiferromagnetic (AF) film systems (superlattices) are now one of the most popular subjects of investigation in the field of magnetism (see, for example, Ref. 1). We are considering antiferromagnetic ordering of adjacent layers, each of which is ferromagnetic. When the number of layers of this type is large enough so that the system can be regarded as periodic in a direction perpendicular to the film, the structure is said to be a magnetic superstructure. Since the macroscopic magnetic moments of the layers are ordered antiferromagnetically, such structures can also be said to be antiferromagnetic macrostructures.

For obvious reasons (potential practical applications), the magnetoresistive and magnetooptic effects are of greatest interest. However, nature exhibits much richer possibilities. Tens of specific antiferromagnetic (associated with antiferromagnetic order) phenomena — magnetism and magnetic resonance, kinetics and optics, acoustics and acoustooptics, and so on[2] — in antiferromagnetic crystals, where the magnetic moments of the microparticles are ordered antiferromagnetically, have been discovered experimentally or predicted and await discovery.

I propose on the basis of symmetry considerations that, in imitation of nature, multilayer macrostructures (superlattices) imitating specific antiferromagnetic effects observed in antiferromagnetic crystals be specially constructed. In addition to the well-known weak ferromagnetism (WF), piezomagnetism, and the magnetoelectric (ME) effect, there are, for example, the spontaneous Hall effect or Faraday effect which are linear in the antiferromagnetism vector **L** or quadratic in the fields (B or E), magnetoresistance (MR) and linear birefringence (as in optics and acoustics) which are linear in B, giant effective elastic anharmonicity and acoustooptic interaction of an antiferromagnetic nature, and so on.[2]

Most of the effects listed above occur only in antiferromagnets with no antitranslations (the chemical and magnetic primitive cells coincide with one another). Such antiferromagnetic macrostructures are considered below as an example.

The one-dimensional, collinear, antiferromagnetic macrostructures in a multilayer orthorhombic system are shown schematically in Fig. 1 (variants a and b). A special case of this system is a system in which, in addition to a 2_z-symmetry axis, there are axes of

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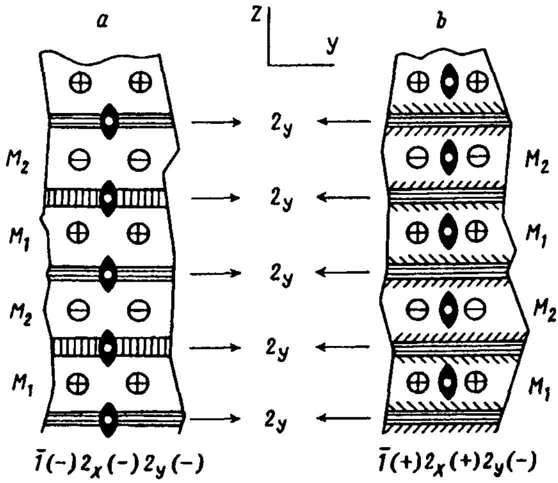

FIG. 1. Centroantisymmetric (a) and centrosymmetric (b) antiferromagnetic macrostructures.

higher order $N_z \geqslant 3$. To avoid antitranslations, the neighboring layers between the ferromagnetic layers must differ in some way from one another (for variant a, at least by thickness; variant b is discussed below). The period of the macrostructure (both magnetic and chemical) is $T=2d$, where d is the distance between the centers of the neighboring layers. Elements with $\bar{1}$, 2_x, and 2_y symmetry are also shown in Fig. 1. These elements can serve as generators of a group which is an analog of the Fedorov crystal-chemical group. The pluses and minuses (inside the circles) indicate antiparallel magnetizations $\mathbf{M}_1$ and $\mathbf{M}_2$ in neighboring ferromagnetic layers, regardless of their orientation with respect to the coordinate axes (the plane of the film).

We consider first the variant a. This exchange magnetic structure (EMS) can be represented as a code in terms of the indicated symmetry elements[3] as follows:

$$\bar{1}(-)2_x(-)2_y(-), \tag{1}$$

where the minus sign in parentheses means that these elements associate layers with opposite magnetizations, i.e., the EMS is odd relative to them [but it is even relative to $m_x(+)=2_x(-)\bar{1}(-)$ and $m_y(+)=2_y(-)\bar{1}(-)$].

Here the oddness of the EMS under inversion $\bar{1}$ is a very important fact. From the standpoint of magnetic symmetry, such an EMS is centrally antisymmetric and a magnetoelectric effect can occur in it. Introducing, as usual, the ferromagnetism and antiferromagnetism vectors

$$\mathbf{M}=\mathbf{M}_1+\mathbf{M}_2, \quad \mathbf{L}=\mathbf{M}_1-\mathbf{M}_2,$$

we obtain the following expression for the magnetization induced by an electric field E [$(ME)_E$-effect]:

$$M_i=a_{ijk}\, L_j E_k, \tag{2}$$

where the specific form of the tensor coefficients a_{ijk} is determined from the requirement that the magnetization given by expression (2) be invariant under the transformations (1). An electric field E can be "pulled" into the volume of the metal sample by passing through the sample a current with density $\mathbf{J}=r\mathbf{E}$. For the symmetry (1) under consideration we can then write the following expressions instead of Eq. (2):

$$
\begin{aligned}
M_x &= r(a_{131} L_z J_x + a_{113} L_x J_z),\\
M_y &= r(a_{232} L_z J_y + a_{223} L_y J_z),\\
M_z &= r(a_{311} L_x J_x + a_{322} L_y J_y + a_{333} L_z J_z).
\end{aligned}
\tag{3}
$$

In particular, according to Eq. (3), a magnetization $\mathbf{M} \parallel Z$, which is geometrically completely different from the magnetization associated directly with the magnetic field generated by the current should arise for $\mathbf{J} \parallel \mathbf{E} \parallel Y$. Another characteristic case is $\mathbf{L} \parallel Z$, $\mathbf{J} \parallel Y$ when magnetization $\mathbf{M} \parallel Y \parallel \mathbf{J}$ appears.

In the inverse effect — the $(\mathrm{ME})_B$-effect — the magnetic field $\mathbf{B}$ gives rise to a potential difference V at the boundaries of a multilayer sample which compensates the ME field so that the total field $\mathbf{E}=0$ in the volume of the sample. The corresponding formulas have the form

$$
\begin{aligned}
V_x/l &= b_{131} L_z B_x + b_{113} L_x B_z,\\
V_y/l &= b_{232} L_z B_y + b_{223} L_y B_z,\\
V_z/l &= b_{311} L_x B_x + b_{322} L_y B_y + b_{333} L_z B_z,
\end{aligned}
\tag{4}
$$

where l is the linear size of the sample in the corresponding direction. In particular, for $\mathbf{L} \perp Z$, $\mathbf{B} \perp Z$, and $\mathbf{L} \perp \mathbf{B}$ we have

$$V_z/l = \tfrac{1}{2}(b_{322} - b_{311}) LB \sin 2u_B,$$

where u_B is the azimuthal angle of $\mathbf{B}$ measured from the X axis. If there is present, in addition to the axis $2_z(+)=2_x(-)2_y(-)$ axis, which exists for the structure a (see Fig. 1), an higher-order symmetry axis, for example, $4_x(+)$, then $b_{322}=b_{311}$ and the effect vanishes.

Another case is $\mathbf{L} \parallel Y$, $B \perp Y$ and makes an angle w_B with the X axis. Here

$$V_y/l = b_{223} L_y B \sin w_B.$$

The effect is maximum for $B \parallel Z$. Finally, for $L \parallel Z$ and $B \perp Z$ we find from relations (4):

$$V_x/l = b_{131} L_z B \cos u_B, \quad V_y/l = b_{232} L_z B \sin u_B.$$

In the absence of anisotropy in the XY plane ($b_{131}=b_{232}$) the potential V is also isotropic in this plane and does not depend on the angle u_B.

In kinetics the antiferromagnetic terms of the form

$$r_{ij} = c_{ijkn} L_k E_n = -r_{ji} \tag{5}$$

in the magnetoresistance tensor are of greatest interest. (Onsager's relations are used.) If the field $\mathbf{E}$ again is "driven" into the sample by passing a current through it, then we obtain a potential difference transverse to the field

$$V_i/l = r c_{ijkn} L_k J_n J_j. \quad (6)$$

[Using relations (5), it is easy to see that in reality **V**⊥**J**.] Two specific examples for the case **L** ∥Y are

a) **J** ∥ **E** ∥ Y

$$V_x/l = r c_{1222} L_y J_y^2,$$

b) **J** ∥ **E** ∥ Z

$$V_x/l = r c_{1323} L_y J_z^2.$$

The LE (or LJ^2) effect thus consists of the appearance of a potential difference which is quadratic in the current and transverse to the current in the absence of a field **B**. This situation distinguishes this effect from the standard "Hall" effect which is linear in **J** and which exists only for **B** (or **M**) ≠ 0.

We now consider the variant b of the antiferromagnetic macrostructure in Fig. 1. The characteristic feature of this structure is that it is even under inversion $\bar{1} \rightarrow \bar{1}(+)$, i.e., *it has a symmetry center* (CS). *The interlayer has the property of polarity* (along the Y axis). For clarity, such a layer can be called a film with a "nap" on both sides. The direction of the nap alternates from one layer to another, so that neighboring layers are related by the symmetry elements $\bar{1}$ and 2_x, as well as by a 2_{1z} screw axis, and others (see also Fig. 2).

As the independent "crystal-chemical" symmetry elements (i.e., ignoring magnetism) we can again use the symmetry elements $\bar{1}$, 2_x, and 2_y. It is easy to see that now the EMS code is

$$\bar{1}(+)2_x(+)2_y(-), \quad (7)$$

which is identical to that of the structure A for an orthorhombic antiferromagnet of the orthoferrite type.[2] All antiferromagnetic effects in kinetics, optics, and acoustics occurring in such an antiferromagnetic crystal can therefore be transferred (with some qualifications) to the case of the antiferromagnetic macrostructure considered here. Some of the corresponding formulas can be taken from Ref. 2 . One must keep in mind only that in Ref. 2 the formulas are most often given for G orthoferrite, so that to switch to the structure A cyclic permutation of the coordinates $x \rightarrow z \rightarrow y \rightarrow x$ must be performed. Specifically, for the centrosymmetric structure we have

$$M_x = 0, \quad M_y = D_{23} L_z, \quad \text{and} \quad M_z = D_{32} L_y.$$

For the antiferromagnetic contribution to the magnetoresistance tensor r_{ij}, only the antiferromagnetic invariants (without the coefficients) for each component can be given:

$$r_{xx}, r_{yy}, r_{zz} : L_i^2, \quad M_i^2 (i = x,y,z), \quad L_y M_z, L_z M_y, \quad (8)$$

$$r_{yz} = r_{zy} : L_x M_x, \quad L_y M_y, \quad L_z M_z, \quad (9)$$

$$r_{xy} = \mp r_{yx} : L_y, \quad L_x M_z, \quad L_z M_x,$$

$$r_{xz} = \mp r_{zx} : L_z, \quad L_x M_y, \quad L_y M_x. \quad (10)$$

Invariants with **M** replaced by the field **B** must be added to these relations.

We note that the system (8)–(10) contains two types of terms which are linear in **L**: L_i and $L_i M_j$. Terms of the type L_i are antisymmetric; they correspond to the minus sign in relation (10) and a spontaneous Hall (Faraday) effect. Terms of the type $L_i M_j M_k$ (or $L_i B_j B_k$), which are not written out here and which determine the "Hall effect" which is quadratic in **B** (Faraday effect in optics),[4] can also contribute to the antisymmetric components of r_{ij}.

Finally, the symmetry components of the type $L_k M_n$ (or $L_k B_n$) of r_{ij} from the system (8)–(10) are responsible for the odd contribution in **B** to magnetoresistance.

For the structure b (see Fig. 1), as a new effect the main interest is therefore the appearance of odd terms in **M** (and **B**), together with even type terms L_i^2, M_i^2, and others in r_{ij}. The latter terms were the only terms investigated in all of the many studies on the magnetoresistance of multilayers.

We note that a similar invariant decomposition of the material tensors with respect to **L** and **M** (or **B**) for structures a and b occurs in optics (for the permittivity) and in acoustics (for the elastic moduli).

The main idea of the present note is to suggest the construction of antiferromagnetic macrostructures with predetermined symmetry properties which are present in superlattices without antitranslations. The well-known antiferromagnets with different atomic magnetic structures can be used as a starting point. The examples of the superstructures a and b, shown in Fig. 1, are the first illustrations. The purpose of the variant was to show that experimenters will probably have to resort to very complicated technological contrivances. However, there is no limit to what can be imagined. In principle, it is possible to model multisublattice and noncollinear, two- and three-dimensional structures.

At present, without a microtheory, it is difficult to say anything definite about the order of magnitude of the effects. Just as in antiferromagnetic crystals, for collinear antiferromagnetic macrostructures, the effects must be associated with relativistic interactions and they result from the competition with exchange interactions between the ferromagnetic layers. These exchange interactions are two to three orders of magnitude weaker for multilayers (the effective field $H_E \approx 10^4$ Oe) than for crystals ($H_E \approx 10^6 - 10^7$ Oe). There are no grounds for believing that for relativistic forces this ratio will change in a direction unfavorable for them. The exactly opposite situation can occur. Additionally, just as in crystals, some effects can apparently become "gigantic" near magnetic orientational (or structural) phase transitions (elastic anharmonicity and acoustooptics of antiferromagnetic nature, and others). Finally, for exchange-noncollinear (triangular, tetragonal) structures, effects such as magnetoelectricity, piezomagnetism, and possibly other effects could be nonrelativistic.

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