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Symmetry theory of the flexomagnetoelectric effect in the magnetic domain walls

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ABSTRACT

A local flexomagnetoelectric (*A.P. Pyatakov, A.K. Zvezdin*, 2009) effect in the magnetic domain walls (DWs) of the cubic hexoctahedral crystal has been investigated on the basis of a symmetry analysis. The strong connection between magnetic symmetry of the DW and the type of the distribution of the electric polarization was shown. Results were systemized in the scope of the DW chirality. It was shown, that new type of the local flexomagnetoelectric coupling corresponds to the presence of the coupled electric charge in the DW. It was found that all time-noninvariant chiral DWs have identical type of spatial distribution of the magnetization and polarization. There are coincidence between the symmetry predictions and results obtaining from the known term of the flexomagnetoelectric coupling for transverse polarization components.

1. Introduction

Coupling mechanism between magnetic and electric subsystem in magnetoelectric materials [1] is of considerable interest to fundamentals of condensed matter physics and for the applications in the novel multifunctional devices [2]. The electric polarization can be induced by the homogeneous [3–7] and inhomogeneous [8–12] magnetization distributions. The last are micromagnetic structures like domain walls (DWs) [8,12–17] and magnetic vortexes [18]. It was shown [17] that the magnetoelectric coupling in the magnetic DWs can be described in the same manner as the ferroelectricity in the spiral magnets. Such type of the magnetoelectric interaction is described by the Lifshitz invariant-like coupling term $P_iM_j\nabla_kM_n$ [5,8,10–12]. It was called as flexomagnetoelectric interaction [19–25]. In general case such free energy term is allowed by any crystal symmetry [26]. Consequently, the electric polarization induced by the micromagnetic structure can appear in any magnetic material even in centrosymmetric one.

It is well known that magnetoelectric effects are closely related to the magnetic symmetry. This principle has been applied for the DWs with specific symmetry [8,12]. It was not compared with phenomenological description of the flexomagnetoelectric effect. The purpose of this work is to extend the symmetry classification to all possible magnetic point groups and compare results with the phenomenological investigations of the cubic $m\bar{3}m$ crystal.

2. Group-theoretical description of the flexomagnetoelectric coupling in the domain walls

2.1. Symmetry classification of the domain walls

Since DWs can be considered as thin layers, their symmetry is described by one of the 528 magnetic layer groups [28,29]. To determine the layer's physical properties continuum approximation is used, which leads to point-like layer groups [30]. If continuous translation operation is considering as identity then these groups transform to magnetic point groups. It was shown [31] that there are 125 of such groups. It was found that if magnetic point group is pyroelectric and/or pyromagnetic then DW carries **P** and/or **M,** respectively [32]. These criteria were derived from the conditions of the appearing of the uniform **P** [33,34] and/or **M** [35,36]. After their application to any inhomogeneous region they predict existing of even parts in functions of distribution of **P** and/or **M** [37–40]. Identification of the remaining odd parts of these functions were formulated [37–40] based on symmetry transformations which interrelate domains.

Let us choose the coordinate system *XYZ* connected with the DW plane (axis Z is the DW plane normal direction). The distribution of the polarization is $\mathbf{P}(z)=\mathbf{e}_x P_x(z)+\mathbf{e}_y P_y(z)+\mathbf{e}_z P_z(z)$. The magnetic point group of the DW contains two types of symmetry transformations. First type transformations $g^{(1)}$ do not change the spatial coordinate z. If transformation $g^{(1)}$ is a rotation around n-fold ($n>1$) symmetry axis n_z then it allows only $P_x(z)=P_y(z)=0$. Second type transformation $g^{(2)}$ has opposite property: $g^{(2)}z=-z$. This transformation allows only even (S) or odd (A) functions $P_i(z)$, where $i=x,y,z$. If the magnetic point group of the DW is non-polar

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then $\mathbf{P}(z) = -\mathbf{P}(-z)$ and at least component $P_z(z)$ is nonzero. Consequently, all 125 magnetic point groups of DWs allow $\mathbf{P}$.

If magnetic point group of DW is non-pyromagnetic, then $\mathbf{M}(z)=0$ takes place in cases when transformations $g^{(1)}$ are the following: time reversal operation $1'$ and/or rotations around k-fold symmetry axes k_z' $(k>2)$ and/or rotations around n-fold symmetry axes n_z $(n>1)$, which exists simultaneously with reflection in plane $m_\perp$ orthogonal to the DW plane. Otherwise, the DWs with non-pyromagnetic point group have the magnetization distribution $\mathbf{M}(z) = -\mathbf{M}(-z)$. Only 64 from 125 magnetic point groups of DWs allow $\mathbf{M}$ [37]. They correspond to the magnetic DWs. As far as cubic $m\overline{3}m$ crystal does not contain 6-fold symmetry axes (including inversion axes) it is necessary to exclude the magnetic point groups containing such symmetry elements. The remaining set consists of the 57 magnetic point groups [38]. These groups are presented in Tables 1–3. The symbol (A,S) means that the specific function is the sum of odd and even function. The magnetic point groups which allow only two zero components of $\mathbf{M}$ or all odd components correspond to the cases of the $|\mathbf{M}| \neq const$. Such DWs appear near point of the phase transition [39].

The magnetic point group of the DW is the subgroup of the magnetic point group G_P describing the symmetry of the crystal in the paramagnetic phase [39]. If influence of the crystal surfaces on the micromagnetic structure is taken into account then the group G_P should be produced by the intersection of the magnetic point group G_P^∞ (crystallographic class joined with transformation $1'$) and magnetic point group G_S described the symmetry of the crystal surface. For the case of film or plate the G_S is $\infty/\mathrm{mmm}1'$. The corresponding symmetry theory was described in [38].

Group-theoretical methods permit identification of the DW multiplicity [37]: the number of the DWs with identical energy and different structures. The DW multiplicity q_k is determined by the relations of the group orders: $q_k = |G_P|/|G_k|$, where G_k is the magnetic point group of the DW. If neighboring domains are determined then two different multiplicities appear: the DW multiplicity at the fixed boundary conditions $q_k' = |G_B|/|G_k|$ and the multiplicity of the boundary conditions $q_B = |G_P|/|G_B|$. Here the group G_B is a magnetic point group of the boundary conditions (combination of two neighboring domains) [37,39]. G_B is the subgroup of the G_P and is defined by type of DW and orientations of the domains magnetization directions in relation to the crystal surface [38]. It is worth to mention, that all possible groups G_B are the same set as all possible groups G_k (Tables 1–3). There are q_k cosets and corresponding q_k lost transformations $g_i^{(l)}$ (members of adjacent classes [37–40]) in series:

$$G_P = g_0^{(l)} G_k + g_1^{(l)} G_k + g_2^{(l)} G_k + \cdots + g_{qk}^{(l)} G_k \tag{1}$$

where $g_0^{(l)} \equiv 1$. These lost transformations are the transformations which relate all DWs with identical energies and different structures.

Table 1
Types of spatial distribution of electric polarization induced by flexomagnetoelectric effect in magnetic DWs with the time-invariant chirality.

k	Magnetic point group	$M_x(z)$	$M_y(z)$	$M_z(z)$	$P_x(z)$	$P_y(z)$	$P_z(z)$
7	$2_x'2_y2_z'$	A	S	0	0	0	0(A)
8	$2_z'$	A,S	A,S	0	0	0	0(A,S)
10	$2_x'$	A	S	S	S	A	0(A)
13	2_y	A	S	A	A	S	0(A)
16	1	A,S	A,S	A,S	A,S	A,S	0(A,S)
19	2_z	0	0	A,S	0	0	0(A,S)
21	$2_x2_y2_z$	0	0	A	0	0	0(A)
24	3_z	0	0	A,S	0	0	0(A,S)
27	3_z2_x	0	0	A	0	0	0(A)
30	4_z	0	0	A,S	0	0	0(A,S)
33	$4_z2_x2_{xy}$	0	0	A	0	0	0(A)
50	$2_z2_x'2_y'$	0	0	S	0	0	0(A)
53	$3_z2_x'$	0	0	S	0	0	0(A)
57	$4_z2_x'2_y'$	0	0	S	0	0	0(A)

Table 2
Types of spatial distribution of electric polarization induced by flexomagnetoelectric effect in magnetic DWs with the time-noninvariant chirality.

k	Magnetic point group	$M_x(z)$	$M_y(z)$	$M_z(z)$	$P_x(z)$	$P_y(z)$	$P_z(z)$
12	m_x'	0	A,S	A,S	0	A,S	0(A,S)
14	$2_y/m_y'$	A	0	A	A	0	0(A)
15	$\overline{1}'$	A	A	A	A	A	0(A)
17	$m_x'm_z'2_y$	0	S	A	0	S	0(A)
18	m_z'	S	S	A	S	S	0(A)
20	$2_z/m_z'$	0	0	A	0	0	0(A)
22	$m_x'm_y'2_z$	0	0	A,S	0	0	0(A,S)
23	$m_x'm_y'm_z'$	0	0	A	0	0	0(A)
26	$3_zm_x'$	0	0	A,S	0	0	0(A,S)
29	$\overline{3}_z'm_x'$	0	0	A	0	0	0(A)
31	$4_z/m_z'$	0	0	A	0	0	0(A)
32	$4_zm_x'm_{xy}'$	0	0	A,S	0	0	0(A,S)
34	$4_z/m_z'm_x'm_{xy}'$	0	0	A	0	0	0(A)
35	$\overline{4}_z'$	0	0	A	0	0	0(A)
36	$4_z/2_xm_{xy}'$	0	0	A	0	0	0(A)
42	$\overline{3}_z'$	0	0	A	0	0	0(A)
46	$2_z'/m_z'$	S	S	0	0	0	0(A)
47	$2_x'/m_x'$	0	S	S	0	A	0(A)

Table 3
. Types of spatial distribution of electric polarization induced by flexomagnetoelectric effect in magnetic achiral DWs.

k	Magnetic point group	$M_x(z)$	$M_y(z)$	$M_z(z)$	$P_x(z)$	$P_y(z)$	$P_z(z)$
1	$m_xm_zm_y'$	A	0	0	0	0	0(A)
2	$m_y'm_x2_z'$	A,S	0	0	0	0	0(A,S)
3	$m_xm_z2_y$	A	0	0	0	0(S)	0(A)
4	$2_x'/m_x$	A	0	0	0	0(A)	0(A)
5	$2_z'/m_z$	A	A	0	0	0	0(A)
6	m_y	A,S	0	0	0	0(A,S)	0(A,S)
9	$m_zm_y'2_x'$	A	0	S	S	0	0(A)
11	m_z	A	A	S	S	S	0(A)
43	$m_ym_x'm_z'$	0	S	0	0	0	0(A)
44	$m_ym_z'2_x'$	0	S	0	0(S)	0	0(A)
45	$2_y/m_y$	0	S	0	0(A)	0	0(A)
48	$\overline{1}$	S	S	S	A	A	0(A)
49	$2_z/m_z$	0	0	S	0	0	0(A)
51	$m_zm_x'm_y'$	0	0	S	0	0	0(A)
55	$\overline{3}_zm_x'$	0	0	S	0	0	0(A)
56	$4_z/m_z$	0	0	S	0	0	0(A)
58	$4_z/m_zm_x'm_{xy}'$	0	0	S	0	0	0(A)
59	$\overline{4}_z$	0	0	S	0	0	0(A)
60	$\overline{4}_z2_x'm_{xy}'$	0	0	S	0	0	0(A)
64	$\overline{3}_z$	0	0	S	0	0	0(A)

2.2. Application of the theory for description of the flexomagnetoelectric coupling

The local flexomagnetoelectric effect in the magnetic domain walls (DWs) of the cubic $m\overline{3}m$ crystal is described by the following