Contribution to the theory of motion of domain walls in magnetically ordered crystals

V. G. Bar'yakhtar, B. A. Ivanov, and A. L. Sukstanskiĭ

Physicotechnical Institute, Ukrainian Academy of Sciences
(Submitted 12 January 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **27**, No. 4, 226–229 (20 February 1978)

The dependence of domain-wall thickness in ferrites and antiferromagnets on their velocity is investigated. It is shown that in a ferrite with n magnetic sublattices there can be realized n different domain walls.

PACS numbers: 75.60.Ch

In connection with the problem of determining the maximum velocities of cylindrical magnetic domains (CMD), the question of the motion of domain walls (DW) in magnetically ordered crystals and of the change of the structure of these walls in the course of motion has become timely.

Obviously, the DW velocity cannot exceed the minimal phase velocity of the spin waves, since in this case there is always some concrete mechanism that leads to coherent emission of the magnons. However, as is known with ferromagnets as an example, the maximum DW velocity is less than the minimal phase velocity of the spin waves.

A complete solution of this problem calls for investigation of a system of nonlinear differential equations, which becomes particularly complicated in the case of a magnet with several magnetic sublattices. This is apparently why neither the problem of maximum DW velocities in crystals with complex magnetic structure nor the question of the changes occuring in the DW in the course of this motion has been investigated until recently.

In an analysis of DW motion in a ferromagnet, Schlömann[1] has noted that both the limiting velocities and the change in the DW thickness with velocity can be obtained on the basis of an investigation of the dispersion of the spin wave in a ferromagnet, if one changes from real values of the wave vector to pure imaginary ones. The reason is that at large distances from the DW center the distribution of the magnetization is in the zeroth approximation uniform, and the perturbations due to the DW are small. It is easily seen that the system of equations for these perturbations is a system of linear differential equations with constant coefficients. Their dependence on the time and coordinate is therefore of the form

$$\mathbf{m}^{(\alpha)}(x - vt) = \sum_i \mathbf{m}_{0i}^{(\alpha)} e^{\pm\kappa[x - v_i(\kappa)t]}, \qquad (1)$$

where the index α numbers the magnet sublattices and the index i numbers the solutions of the dispersion equation. If the spin-wave dispersion law $\omega^2 = \omega^2(k^2)$ is known, then the relation between the DW thickness $z = \kappa^{-1}$ and its velocity is determined from the formula

$$-v_i^2\kappa^2 = \omega_i^2(-\kappa^2), \qquad (2)$$

which corresponds to the analytic continuation $k \to -i\kappa$, $\omega \to -i\kappa v$.

This method makes it possible to investigate in simple fashion the question of the maximum velocities in magnets with complex magnetic structure, to obtain the dependence of the DW thickness on the velocity, and, finally, to determine the new "microscopic" DW.

We consider first an antiferromagnet (AFM), for which the dispersion law is of the form

$$\omega_i^2 = \Delta_i^2 + s_i^2 k^2, \tag{3}$$

where Δ_i are the activations and s_i the velocities of the spin waves.[2] From (2) and (3) we get

$$z_i(v) = z_i(0)\left(1 - \frac{v^2}{s_i^2}\right)^{1/2}, \qquad z_i(0) = \frac{s_i}{\Delta_i}. \tag{4}$$

Since the activation Δ_i in the spin-wave spectrum is due to weak relativistic interactions, $\Delta_i \sim (H_A H_E)^{1/2}$, and the spin-wave velocity is due to exchange interactions $s_i \sim H_E/a$ (a is the lattice constant), it follows that $z_i(0)/a \sim (H_E/H_A)^{1/2} \gg 1$, i.e., the DW has macroscopic thickness.

From (4) we see that the DW velocity cannot exceed the spin-wave velocity s_i. As v approaches s_i, the DW thickness decreases; naturally, the vicinity of $|s_i - v| \ll s_i$ must be described by the formulas obtained from the microscopic treatment of the spectra.

A dispersion law similar to (3) holds for the optical modes of spin waves in ferrites with several magnetic sublattices.[1)] Relation (4) therefore holds formally for various types of DW in ferrites. It is important to note that, in contrast to AFM, for the optical modes of ferrites both the activation Δ_i and the spin-wave velocity s_i is of exchange origin. Therefore the macroscopic DW in ferrites can be connected only with the low-frequency mode, and the optical modes to lead to microscopic DW ($z_i(0) \sim a$) and call for a microscopic treatment, i.e., for concrete models of the exchange interaction in the ferrite.

Near the phase-transition points, namely, near the fields $H_{tr}(T)$ corresponding to transitions from the collinear to the noncollinear magnetic structure,[3] one of the optical modes, as is well known, "softens" in accordance with the law $\Delta_i \sim |H - H_{tr}(T)| \to 0$, and the corresponding DW becomes macroscopic.

In the case of AFM, for which an important role is played by exchange interaction not only between the sublattices but also within the sublattices, an analysis of the spin-wave spectrum[3] shows that microscopic DW are possible with "thicknesses" determined by the formula

$$z(0) \approx a\left[2 \ln \frac{3}{2\xi}\right]^{-1}, \tag{5}$$

where $\xi = -I_{11}(0)/I_{12}(0) \ll 1$, and $I_{11}(0)$ and $I_{12}(0)$ are the respective zeroth Fourier components of the exchange integrals inside the sublattices and between the sublattices. We see that $z(0) < a$; this means that the DW thickness actually coincides with the lattice constant.

Let us dwell, finally, on the DW connected with the low-frequency of the spin waves in ferrites; the spectrum of this branch is of the form

$$\omega^2 = A + Bk^2 + Ck^4. \tag{6}$$

We note that in contrast to the AFM, in uncompensated magnets relativistic interactions govern not only the activation A, but also the value of B,[2)] so that it is necessary to retain the term with k^4 whose coefficient C is determined only by the exchange interaction. Starting from (2) and (6), we obtain

$$\kappa_{1,2}(v) = \frac{\pm 1}{2\sqrt{C}}\left[\sqrt{v_{(+)}^2 - v^2} \pm \sqrt{v_{(-)}^2 - v^2}\right], \tag{7}$$

where

$$v_{(\pm)}^2 = B \pm 2\sqrt{AC}. \tag{8}$$

From relation (7) it is easily seen that at $v > v_{(+)}$ the parameter κ is pure imaginary and this is the spin-wave region, with $v_{(+)}$ the minimal velocity of the spin waves.

At $v_{(-)} < v < v_{(+)}$, the parameter κ is complex. Analysis shows that in this velocity interval there exist solutions of the type of a solitary domain or magnetic soliton. As $v \to v_{(+)}$ the amplitude of the soliton is small, and the localization region is large; as $v \to v_{(-)}$, the soliton is a moving solitary domain with dimension on the order of $z(v)|\ln[(v - v_{(-)})/v_{(-)}]|$, with almost homogeneous magnetization, and is separated from the remainder of the crystal by two DW.[5]

It follows from the foregoing that a solution of the type of a solitary DW can exist only in the velocity interval $v < v_{(-)}$, where the parameter κ is real and has the meaning of the reciprocal thickness of the DW ($\kappa = z^{-1}$). Consequently the quantity $v_{(-)}$ defined by (8) is the limiting velocity of the DW motion.

It is important to note that the quantity $v_{(-)}$ for a ferrite with several magnetic sublattices can differ substantially (by several orders) from the value of $v_{(-)}$ in a simple ferromagnet.

In conclusion, the authors are grateful to I. E. Dzyaloshinskiĭ and B. N. Filippov for valuable discussions, and to A. I. Akhiezer, A. S. Borovik-Romanov, and E. A. Turov for a discussion of the work.

1)We recall that the number of sublattices, say in iron garnets, amounts to several dozens.

2)By virtute of the Bogomolov theorem[4] concerning $1/q^2$, we have in an isotropic ferromagnet or ferrite $\omega \sim k^2$, i.e., $A = B = 0$.

1E. Schlömann, Appl. Phys. Lett. **19**, 274 (1971).

2A. S. Borovik-Romanov, Itogi Nauki **4**, Izd. Akad. Nauk SSSR, Moscow, 1962; E. A. Turov, Fizicheskie svoĭstva magnitouporyado-chennykh kristallov (Physical Properties of Magnetically Ordered Crystals), Moscow, Izd. Akad. Nauk SSR, 1963; A. I. Akhiezer, V. G. Bar'yakhtar, and S. V. Peletminskiĭ, Spinovye volny (Spin Waves), Nauka, 1967.

3D. A. Yablonskiĭ, Fiz. Tverd. Tela (Leningrad) **14**, 2849 (1972) [Sov. Phys. Solid State **14**, 2468 (1973)].

4N. N. Bogolyubov, Izbrannye trudy **3**, 216, Kiev, Naukova Dumka, 1971.

5A. M. Kosevich, B. A. Ivanov, and A. S. Kovalev, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 516 (1977) [JETP Lett. **25**, 486 (1977)]; Fiz. Nizk. Temp. **3**, 906 (1977) [Sov. J. Low Temp. Phys. **3**, 440 (1977)].