Configurational phase transitions between domain wall states in the inhomogeneous magnetic field

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The effect of a strong inhomogeneous magnetic field on the static parameters of a solitary domain wall in a thin ferromagnetic film is investigated by the magneto-optical technique. A change in the distribution of the magnetization in the domain wall and its shape is observed for critical values of the external field, the gradient of the field, and the field in the plane of the film. The results obtained are interpreted in terms of phase transitions between configurational states of domain walls.

The structure of a domain wall (DW) in a ferromagnet in the absence of an external field is determined by the inhomogeneous exchange interaction, the anisotropy energy, and the internal magnetostatic field. The magnetostatic field depends on the distribution of the effective magnetic poles on the surface of the specimen and will, therefore, in most cases be essentially spatially inhomogeneous; an exception, by the way of illustration, is the domain structure of Landau-Lifshitz,[1] where the magnetostatic field vanishes everywhere. The maximum value of the gradient of the internal field is achieved right next to the DW, since the magnetic poles change sign during a transition across a domain wall. Consequently, the distribution of magnetization in the plane of the DW too is inhomogeneous.[2] When an external inhomogeneous field is turned on, the DW occupies a stationary position near the surface on which the external field vanishes. In this case, the self-field of the DW can be partially cancelled by the external field. As a consequence of the competition between these fields, the total surface energy of the DW depends on the external field, which gives rise, in particular, to a dependence of the equilibrium structure and the configuration of the DW on the inhomogeneous external field.

A ferromagnetic specimen, which in the absence of an external field decomposes into a large number of domains, when located in a sufficiently strong inhomogeneous external field will contain only two domains and, accordingly, one domain wall, where the direction of magnetization in each of the domains is determined by the external field. The presence of the specimen of only one wall allows one to automatically exclude magnetostatic interaction between walls in the collection of domains. Interest, in the first place, in the study of a solitary domain wall is tied to this. Apart from this, an inhomogeneous magnetic field, as already noted, can affect the internal structure of a DW. For example, in thin magnetic films with an easy axis perpendicular to the surface (such films are analyzed in our paper), rather than a twisted domain wall, a purely one-dimensional homogeneous Bloch wall can be realized.[3] A solitary wall was first observed by Sixtus and Tonks[4] in experiments on magnetic reversal of wires made of Fe–Ni alloy. Subsequently, similar experiments were conducted by applying magneto-optical methods in thin magnetic films out of YIG orthoferrite.[5–7] Along with this the attention of the authors was mainly directed to the study of the dynamics of a solitary domain wall, since the behavior of a wall in a static inhomogeneous field has been inadequately studied. Our investigation revealed that the static properties of a DW in an inhomogeneous field can be interpreted in terms of phase transitions.

Measurements were carried out on films based on YIG with the addition of bismuth, having a large uniaxial anisotropy. The period of the labyrinthine domain structure was 3–20 μm. The arrangement of the specimen in the inhomogeneous field, the coordinate system, and the magnetic lines of force of the external and internal fields are shown in Fig. 1. It is assumed that the external field (H_x, H_y, H_z) does not depend on the z coordinate, perpendicular to the plane of Fig. 1, and that the z-component satisfies $H_z \equiv 0$. The coordinate system is chosen so that $H_x = H_y = 0$ at the center. In this case, no matter how the external field is produced, as follows from Maxwell's equations, the expansion of the external field to second order in powers of the displacement from the center has the form

$$H_x = \beta y, \quad H_y = \beta x, \tag{1}$$

where β is the gradient of the magnetic field. The magnetic field lines of such a quadrupole field have a characteristic "saddle" type singularity in the neighborhood of the center of the coordinates with an angle between generators of 90°.

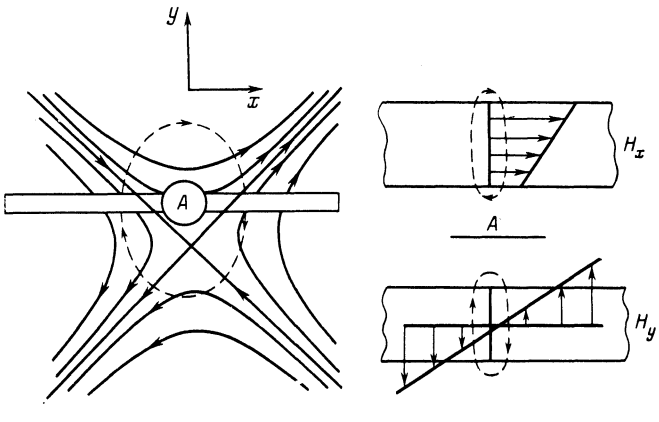

FIG. 1. Magnetic film in a quadrupole magnetic field: coordinate system and magnetic field components H_x and H_y inside the film (shown as A). The solid line is the external field, and the broken one the magnetostatic field of the specimen.

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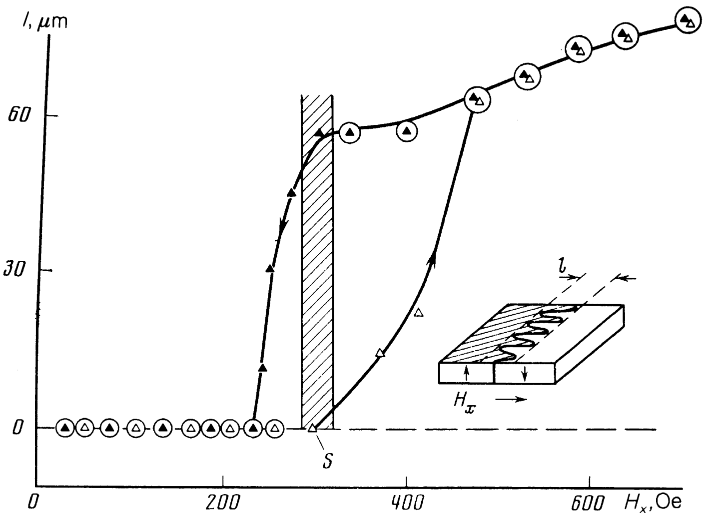

FIG. 2. Sawtooth amplitude l vs the field in the plane H_x. The points ▲ and △ correspond to measurements made when H_x is decreasing and increasing, respectively. The points in the circles are stable domain wall states, and the remaining points are metastable. Metastability and stability are verified by the application of low-frequency magnetic fields and by tapping on the apparatus. In the hatched region the compound is most stable: part of the domain wall is curved, part is straight. If the domain wall is in a stable state, then when H_x changes the length of the sawtooth-shaped part changes, but its amplitude remains constant (on the graph these measurements are not presented).

Shifting the film along the y-axis by Δy, as follows from (1), is equivalent to the application of a homogeneous magnetic field in the plane of the film with a single nonzero component $H_x = \beta\Delta y$. An external magnetic field was created by a quadrupole system, consisting of four symmetrically placed cores made of magnetically soft steel and permanent $SmCo_5$ magnets. Due to the large energy density in such magnets, fields with gradients up to 180 kOe/cm have been successfully obtained. Displacement of the film was accomplished with a precision of 2 μm. The films were reinforced in a holder made from tantalum and mica, which also contained coils for creating magnetic biasing fields and a heater for changing the temperature of the film. The holder of thickness 0.7 mm was located in a gap with a variable width of 1.4–5 mm between the poles of the external magnets. The domain wall was oriented along the z-axis, and imaged by the standard magneto-optical method based on the Faraday effect, in which the film was illuminated by a helium-neon laser beam along the y-axis.

The equilibrium configuration of the DW, represented on a screen,[8,9] depended on the state of the domain wall. It was found that as a function of the parameters of the quadrupole field (the gradient of the field β and the field in the plane H_x) the configuration of the domain wall corresponds to three basic phase states: state A is a straight domain wall, aligned precisely along the z-axis; B is a wall configuration of "sawtooth" type, in which case the image of the DW resembles a sinusoid, whose midline coincides with the z-axis; and C is a wall with a diffuse image, which for brevity we will subsequently call diffuse. Transitions between states occur for critical values of the parameters of the external field. Figure 2 shows the dependence of the sawtooth amplitude l on the field in the plane; for a straight domain wall $l = 0$, and for a sawtooth wall $l \approx 60$ μm. Figure 3 shows how the dependence of the amplitude l depends on the gradient when the field vanishes in the plane. A transition from a straight wall to a diffuse one is seen in the photographs in Fig. 4. The characteristic width of a diffuse DW is 100 μm. The data are presented for a specimen with the following parameters: saturation magnetization $4\pi M = 41$ G (measured by the disappearance of the domain structure), after an anisotropy of 1.7 kOe (from ferromagnetic resonance data), and a domain structure period of 20 μm. The gradient of the external field was measured by the displacement of the DW along the x-axis in the presence of a homogeneous field H_y, and the field in the plane was determined by displacing the film relative to

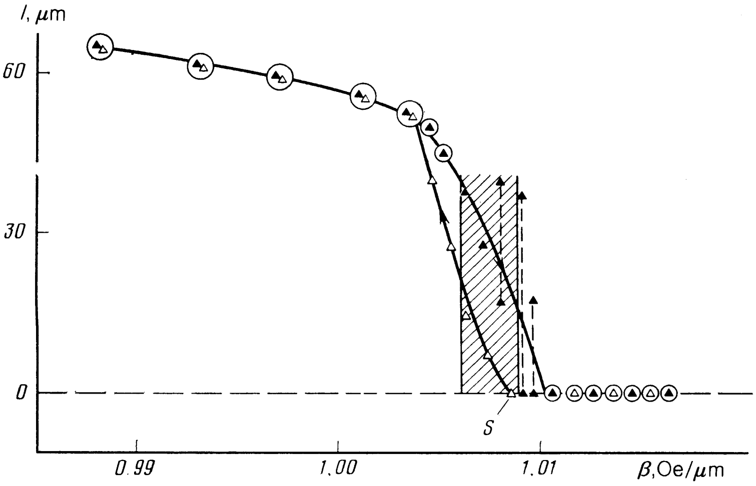

FIG. 3. The dependence of the sawtooth amplitude on the gradient β of the external field when the field in the plane vanishes. The points ▲ and △ correspond to measurements made while β is increasing and decreasing, respectively. The circled points are stable domain wall states and the remaining points are metastable. In the hatched region the compound phase is the most stable. The dark triangles joined by a broken line are another compound phase, in which the wall breaks down into sections with two different amplitudes.

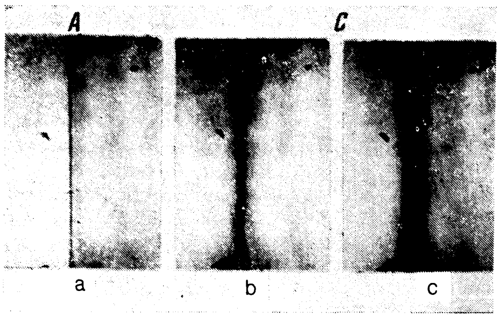

FIG. 4. Transition to diffuse wall. Photographs a–c correspond to an increase of the field in the plane H_x. During photographing, the domain wall is placed near defects to demonstrate the constancy of the optical amplification.

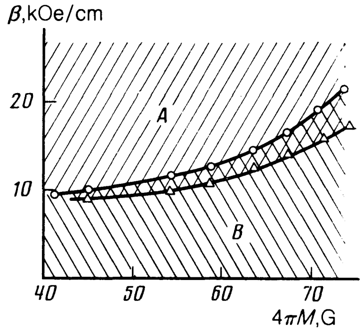

FIG. 6. A change of the critical value of the field gradient during a transition from state A to state B as a function of the magnetization of the film; the field in the plane vanishes.

the saddle point of the external field [see Eq. (1)]. In all the figures the qualitative differences between states are highly visible, and the transitions between them are accompanied by hysteretic phenomena.

In Fig. 5 the phase diagram of the states on the β-H_x plane is shown, where the curves 1 and 2, in fact, correspond to the transition regions. For specimens with other parameters, a transition between B and C was also observed. We were unable to determine the character of the transitions in the neighborhood of the conjectured triple point where the A, B, and C phases coexist. A transition between A and C occurs when the field in the plane approximately equals the anisotropy field. This suggests that the magnetization vector at a wall of type C lies in the plane of the film. Figure 6 shows how the critical values of the field gradient depend on the magnetization of the film when the field in the plane vanishes. The magnetization changed when the film was heated to temperatures in the range 293–333 K. Higher temperatures give rise to a noticeable increase of magnetization evidently associated with the existence of a compensation point below room temperature.

We note that in Ref. 5, a transition was observed between states A and B, but the value of the field in the plane at the transition point was not given. One can only assume that for the orthoferrite of yttrium used in this paper, the experimentally possible values of the field in the plane are negligible. In Refs. 5 and 10 a computation was given of the stability of a straight domain wall for a simplified model, not including the field in the plane. The basic assumption is that the surface energy does not depend on the external field, which is true only for materials with very strong anisotropies.

Let us discuss the character of the observable configurational phase transitions. In Figs. 2, 3, and 6 hyseretic phenomena are clearly seen during the transition from state A to state B, which, at first glance, would establish this as a first-order transition. But a much more complicated situation is not ruled out. For example, in Figs. 2 and 3, the amplitude at the point S of the sawtooth changes smoothly so that on one side of S the amplitude is identically equal to zero and the state is stable, and on the other, the amplitude is finite, and the state is metastable. Such a transition may be regarded as a second-order transition from a stable state to a metastable one. Apart from this, a stable compound phase is observed too. Therefore, it may be more accurate to say that the transition between states A and B occurs in the form of a series of transitions of different type, where the sequence of transitions is determined by the way the external parameters change, and only in a rough approximation is it possible to treat this transition as first-order. In Fig. 7 the range over which phases A and B coexist is plotted as a function of the longitudinal gradient of the field in the plane ΔH, that is, the "width" of curve 1 in Fig. 5 parallel to the H_x-axis. The region to the left of the maximum corresponds to the values of the parameter β for which a straight domain wall can be obtained only in the metastable state. The decrease in ΔH with increasing β allows one to conjecture that in films of

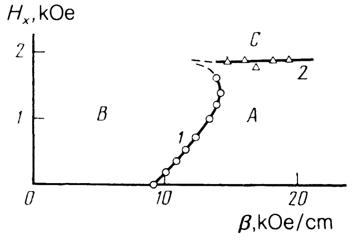

FIG. 5. Phase diagram of the domain wall states: 1 is the line of transition between states A and B, 2 the line of transitions between A and C, and the broken line indicates the conjectured course of lines 1 and 2 in the neighborhood of a possible triplet point.

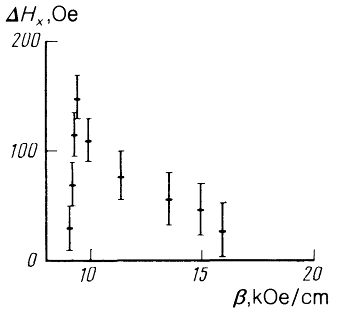

FIG. 7. Range of H_x for which the phases A and B coexist, as a function of field gradient.

another composition, it would be possible to see a critical point in the line of transitions between states A and B—a point where this transition becomes a second-order transition.

In conclusion let us indicate the main thrust of the present paper. It is in fact possible to treat the configurational phase transitions, described above as transitions in a system with a continuous order parameter. Actually, the position of the wall is determined not by a finite number of parameters, but by the function $x(z)$, that is, the number of parameters is infinite. It follows that the free energy of the system is a functional of this function, and therefore the set of stable and equilibrium metastable states of the system may be large enough to allow one to qualitatively explain our results.

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