Amplitude resonance and spin waves in domain boundaries of a ferromagnetic $CrBr_3$

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The rf susceptibility of a thin, ferromagnetic $CrBr_3$ plate in the region of the domain structure was investigated. An intensive line and a periodic system of absorption lines of lower intensity were observed. The data are interpreted as spin waves in the domain walls.

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The rf properties of ferromagnets in the region of the domain structure (DS) have been widely investigated.[1] The first complete calculation of the spectrum of a ferromagnet in the region of DS was carried out by Winter[2] who notice a change in the spectra of spin waves in the volume and the appearance of new branches corresponding to the domain walls in the sample. More specific and useful calculations of the spectra were performed by Bar'yakhtar *et al.*[3,4] In this paper we investigate the lowest-frequency resonances in a ferromagnetic sample with a domain structure.

A $CrBr_3$, which is a hexagonal layered crystal with a BiI_3 structure, was used as the material to be analyzed. At a temperature $T_c = 34.5$ K it goes over to the ferromagnetic state with an easy-axis-type anisotropy (6-fold symmetry axis). The saturation magnetization was $4\pi M_0 = 3520$ G at $T = 0$, the anisotropy field was $H_A = 6.5$ kOe, and the exchange field was $H_E = 180$ kOe.[5,6] The crystals were grown by Klinkova in the Institute of Solid State Physics, USSR Academcy of Sciences, by means of gas-transport reaction. They had the shape of plates ranging in thickness from tens to hundreds of microns with cross sections of the order of 1 cm. In preparing the samples for the experiment, we took advantage of the cleavability of the crystals (like mica) to obtain a clean, fresh surface. Since the crystals's surface deteriorates rather rapidly, the same sample cannot be analyzed twice.

We analyzed the variation of the signal that was transmitted through the resonant circuit with the sample. The sample was placed next to an induction coil comprised of four turns of copper wire. To eliminate the effect of the crystal's edges which were, as a rule, imperfect, we placed a copper screen with a 3-mm-diam diaphragm between the sample and the coil. This made it possible for us to investigate the rf field absorption by the central, optimum part of the sample in the frequency range of 300 to 1000 MHz. The resonant circuit was connected into the generator-receiver transfer circuit. The observed signals had a large amplitude, and the circuit's Q-receiver was recorded by slowly sweeping the magnetic field oriented horizontally in the plane of the sample, and the sample's plane was oriented vertically. The rf magnetic field was parallel to the stated field. The direction of easy magnetization was perpendicular to the plane of the sample.

Figure 1 shows the power absorbed by the sample (χ'' is the imaginary part of the

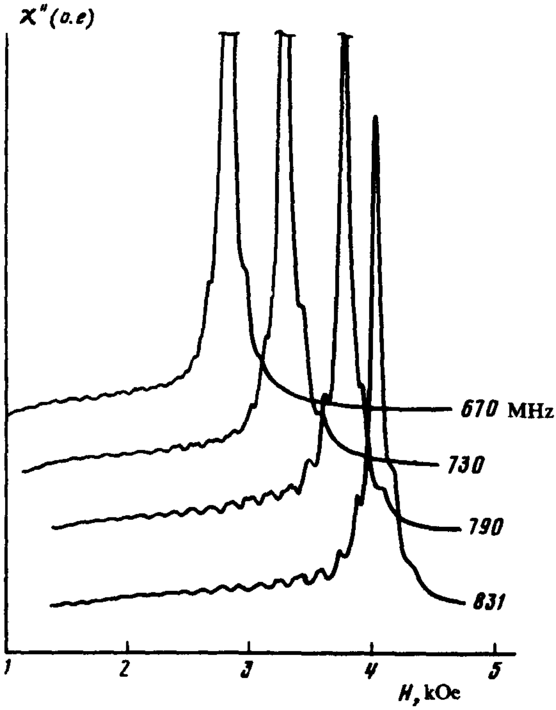

FIG. 1. Dependence of absorption of the $CrBr_3$ sample on the magnetic field.

susceptibility). The absorption in the sample is represented by a single intense line of width ~150 Oe and a much lower intensity structure of equidistant maxima with respect to the field, which are partially slit in a certain range. As the frequency de-

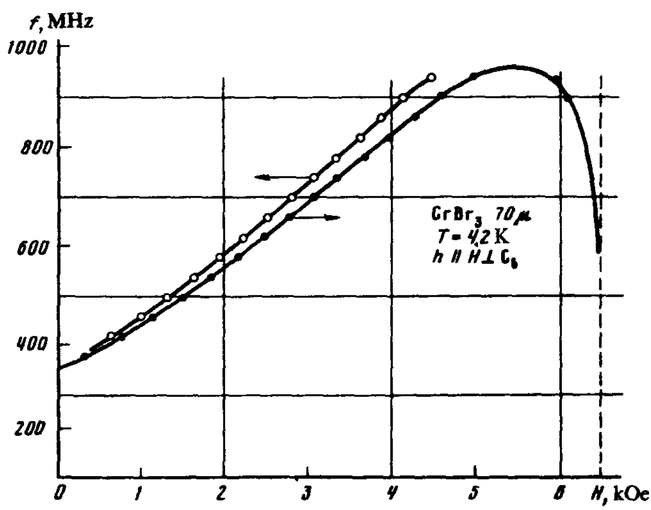

FIG. 2. Dependence of the frequency of an intense absorption peak on the magnetic field.

creases, the splitting range increases and it is difficult to understand this structure at a frequency below 670 MHz (see Fig. 1). Figure 2 shows the dependence of the frequency, at which the intensive absorption line is observed, on the magnetic field. The field, denoted by a vertical dashed line, apparently corresponds to the critical field of the domain structure. There is a peculiar rf susceptibility at all the investigated frequencies in this field, a susceptibility that is small in amplitude but with a sharp drop on the side of the large fields. As the frequency increases near this peculiarity, another absorption line is formed and at a frequency of ~ 900 MHz its intensity approaches that of the line described above. These two lines represent one branch of the resonance whose frequency increases in small fields, as depicted in Fig. 2, and then decreaess sharply on approaching the dashed line. On passing from the zero value and from the field that is larger than the saturation field, a hysteresis of the location of this line occurs. This is depicted in Fig. 2 in which the arrows indicate the direction of motion along the magnetic field.

To describe the observed signal, we used the characteristic equation of Bar'yakhtar and Ivanov[3]

$$m\frac{\partial^2 f_i}{\partial t^2} - \sigma\left(\frac{\partial^2 f_i}{\partial z^2} + \frac{\partial^2 f_i}{\partial y^2}\right) - \frac{M_0^2 \xi}{l_z}(f_i - f_{i+1}) = 0, \qquad (1)$$

where m is the effective mass of a unit area of the domain wall, σ is the surface tension of the domain wall, ξ is a coefficient of the order of unity, f_i is a deviation of the ith domain wall from the equilibrium position, and z and y are coordinate axis in the plane of the domain wall. By using this expression, we can obtain the natural oscillation frequencies of the domain walls

$$\omega^2 = \frac{\sigma}{m}k_\perp^2 + \frac{M_0^2\xi}{l_z m}(1 - \cos k_\parallel l_0). \qquad (2)$$

Here $k_\perp$ is the wave vector in the plane of the domain wall, $k_\parallel$ is the perpendicular wave vector to this plane, l_z is the thickness of the ferro-magnetic plate, and l_0 is the spacing of the domain structure.

The second term corresponds to oscillation waves of the domain width. The mode corresponding to the boundary of the Brillouin zone for the domain structure is clearly identifiable in these oscillations. It corresponds to an increase of the domains with one direction of magnetization and reduction with the other ($k_\parallel = 2\pi/l_0$); this is the so-called displacement resonance of the domain walls.

Assuming that the intensive line corresponds to this resonance, we can say that the coefficient of the second term in Eq. (2), except for the mass of the domain wall, does not have any field-dependent values in a certain range of the magnetic field. Therefore, the increasing section of the curve in Fig. 2 is determined by a reduction of the mass of the domain wall. For our geometry, the magnetization in the domains turns from an antiparallel magnetization (perpendicular to the external field) to a parallel one as the magnetic field increases. This corresponds to a reduction of the

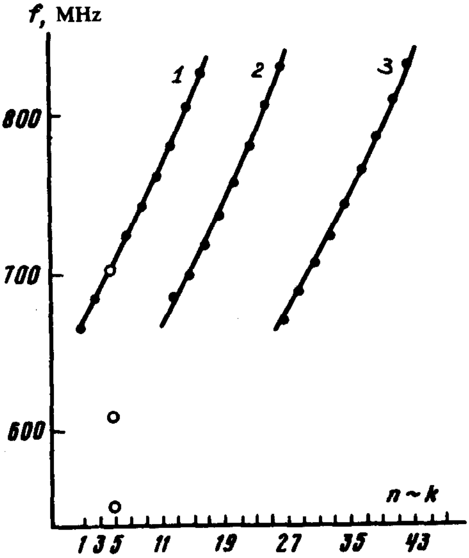

FIG. 3. Dependence of the frequency of the absorption lines of a structure on the line number. Number 1 is assigned to a structure line in the maximum field. 1 — $H = 1.92$ kOe; 2 —2.3 kOe; 3 —3.7 kOe.

angle of turn of the magnetization in the domain wall from 180° to 0° and to a decrease of its specific mass.

Let us go back to the first term in Eq. (2), which corresponds to bending vibrations of the domain wall. This type of spin waves would be represented in our geometry in the form of standing waves across the domain wall. The domain structure in this case is probably a banded structure with a width of the domain wall of the order of the sample's thickness. In this case oscillations with the wave vectors $n\pi/l_z$ are excited, where n is an integer. The waves with an odd value of n are usually associated with the external field. Interpreting the observed equidistant structure in this manner, we can construct a dependence of the frequency of the observed maxima of the structure on their number (at a certain value of the magnetic field). This is shown in Fig. 3. Knowing the sample's thickness, we can obtain the velocity of this type of waves in the observation region.

$$v = \frac{\Delta\omega}{\Delta k} \approx (1.4 \pm 0.15)\times 10^5 \text{ cm/sec} .$$

The splitting may be attributed to coupling of the indicated type of oscillations. The bending waves of one mode may oscillate in phase and out of phase in the neighboring domain walls. If there is a coupling between the described oscillations, then the different phases will correspond to different energies. As the wave vector increases, the coupling decreases.

Thus, we have observed spin waves in the domain of a ferromagnetic $CrBr_3$. This work could not have been performed without crystals and therefore, the author would like to thank L. A. Klinkova for kindly providing the single crystals.

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