Effect of the nuclear subsystem of a magnetic material on the dynamics of domain walls

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The variation of the dynamic properties of the domain walls (DW) of the ferrite $Eu_3Fe_5O_{12}$ as a result of saturation of the spin system of europium nuclei has been observed experimentally. A model is proposed, which connects the elastic modulus and the damping factor of the DW with the parameters of the nuclear system.

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In the measurement of the magnetic susceptibility of a ferrite garnet $Eu_3Fe_5O_{12}$ using the resonance method[1] at a 50-kHz frequency in the temperature region 1.7–4.2 K, we have observed a variation of the quality factor Q of the induction coil with a sample and of the capacitor C which tunes the circuit to a resonance at the 50-kHz frequency as a result of the action on the sample of a rf field in the frequency range 200–800 MHz. The sample consisted of a set of single crystals ~ 1 mm in dimension and a total volume of ~ 1 cm^3.

We shall summarize the main properties of the observed effect. (a) The variation of Q (Fig. 1a) and of C (Fig. 1b) occurs as a result of the action of the rf field in the

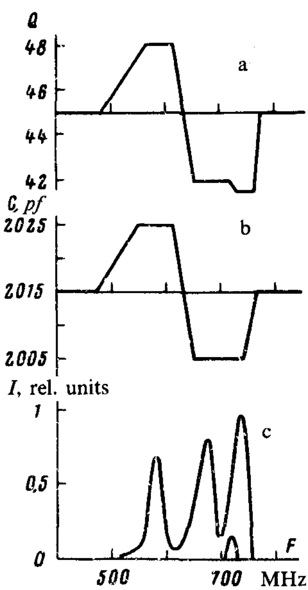

FIG. 1. (a) Dependence of the Q factor of the inductance coil with a sample and (b) of the capacitor C which tunes the circuit to the 50-kHz resonance on the frequency of the rf field that affects the sample. (c) NMR spectrum of Eu^{151} nuclei in the domain wall ($T = 1.8$ K).

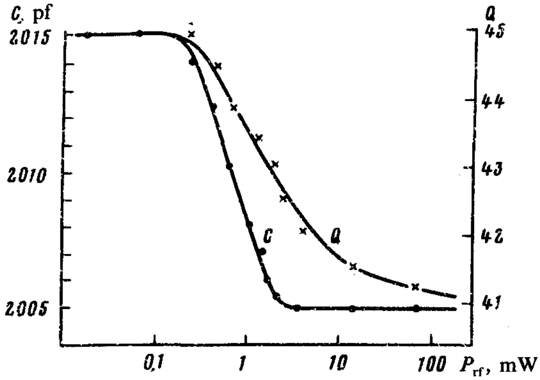

FIG. 2. Dependence of Q and C on the strength of the rf field ($f_{rf} = 680$ MHz, $T = 1.8$ K).

frequency range that correlates with the NMR spectrum of Eu^{151} nuclei in the DW of $Eu_3Fe_5O_{12}$ (Fig. 1c), which was obtained by using the spin-echo method. The action of the rf field reduces Q and C in the range 1 (630–760 MHz) and increases them in the range 2 (500–630 MHz); b) the variation of Q and C decreases by a factor of 2–3 as a result of increasing the temperature of the sample from 1.7 to 4.2 K; c) the variation of Q and C at $P_1 \geqslant 0.1$ mW depends nonlinearly on the power P of the rf field, and at $P_2 > 50$ mW there is a saturation[1)] (Fig. 2). d) This effect has not been observed in constant magnetic fields greater than 5 kOe; the variation of C and Q (Fig. 3) correlates well with the field dependence of the amplitude of the signals of the spin echo of Eu^{151}, which are located in the DW of $Eu_3Fe_5O_{12}$ (Ref. 2); e) an analogous variation of Q and C has also been observed as a result of the action of the rf field in the frequency range of the NMR of Eu^{153} nuclei (200–400 MHz).

The observed variation of Q and C corresponds to the variation of the initial, low-frequency susceptibility of the ferrite, which is determined by displacement of the DW; this displacement is described by the equation for the harmonic oscillator. The variation of Q and C in this case corresponds to the variation of elastic modulus k of the DW and the damping factor b.

We conclude from the analysis of the obtained results that saturation of the nuclear spin system in the DW changes the dynamic properties of the latter.

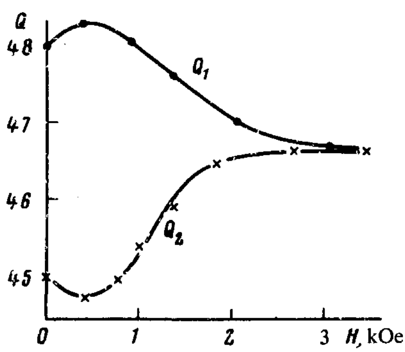

FIG. 3. Dependence of the Q of the inductance coil with a sample on the external magnetic field ($T = 1.8$ K). Q_1—in the presence of 580-MHz rf field; Q_2—without an rf field.

To explain the obtained results, we shall analyze the following model. In the case of anisotropic hyperfine interaction (HFI) the nuclei in the different layers of the DW are effected by the various hyperfine fields of the electron moments. In accordance with the Curie law, nuclear magnetization occurs at right angles to the plane of the DW. The direction and magnitude of the hyperfine fields of the nuclei in the different layers of the DW change periodically as a result of oscillation of the DW. If the oscillation frequency Ω is much smaller than the NMR frequency, then the directions of nuclear magnetization of the individual layers of the DW will almost coincide at any moment of time with the instantaneous directions of the hyperfine fields. On the other hand, because of the relaxation processes, the magnitude of nuclear magnetization may differ from that corresponding to the instantaneous distribution of the hyperfine fields. Since the energy of HFI changes in this case as a result of displacement of the domain wall, we must take into account this energy in addition to the inertial, elastic, and dissipative terms in the analysis of the motion of the DW.

In keeping with the model discussed above, we have carried out a calculation for a uniaxial crystal with a 180° DW. We selected the following distribution of HFI fields[3]: $H = H_D - \Delta H \sin^2\theta$, where H_D is the hyperfine field in the domain, and ΔH is the difference between the magnitudes of the hyperfine fields in the domain and at the center of the DW. A calculation showed that the equation of motion for the DW can be written as follows:

$$m\ddot{q} + (b + b_Y)\dot{q} + (k + k_Y)q = 2Mh\cos\Omega t, \tag{1}$$

where q is the displacement of the DW center from the equilibrium position, m is the mass of the DW, b is the elasticity coefficient, k is the damping factor, if the nuclear system is ignored, b_Y is the contribution of the nuclear subsystem to the damping factor, and k_Y is its contribution to the elasticity coefficient:

$$b_Y = \chi_Y \frac{32(\Delta H)^2 T_1}{5\delta[1 + 4(\Omega T_1)^2][1 + (\Omega T_1)^2]},$$
$$k_Y = \chi_Y \frac{64(\Delta H)^2(\Omega T_1)^4}{15\delta[1 + 4(\Omega T_1)^2][1 + (\Omega T_1)^2]}, \tag{2}$$

where χ_Y is the static susceptibility of the nuclear spin system, δ is the thickness of the DW, and T_1 is the time of the longitudinal relaxation. The numerical estimates show that at $T = 1.7$–4.2 K the parameters b and b_Y are equal in magnitude to the parameters k and k_Y.

Qualitative estimates of the effect of the nuclear subsystem on the properties of the DW produced as a result of saturating action of the rf field showed that b_Y and k_Y can be expected to vary significantly only at frequencies close to the NMR frequencies of the nuclei situated at the DW center. The expressions in (2) for the contributions of b_Y and k_Y in this case vary significantly, but at $\Delta H > 0$ the values of b_Y and k_Y increase and at $\Delta H < 0$ they decrease.

A direct analysis of the proposed model for $Eu_3Fe_5O_{12}$ yields an awkward result because of the existence of six nonequivalent crystallographic positions for the rare-earth ions and because of the possibility of the existence of several types of DW; however, the qualitative characteristics of the effect are preserved. A comparison of the experiment with the calculation shows that the proposed model describes qualitatively the observed effect ($T_1 = 20\text{-}30\,\mu\text{sec}$ for Eu^{151} nuclei). It should be noted that the NMR frequency of Eu^{151} nuclei situated in the DW of $Eu_3Fe_5O_{12}$ in the range 1(2) is higher (lower) than that of the nuclei in the domains [600 and 650 MHz (Ref. 4)], i.e., $\Delta H < 0$ ($\Delta H > 0$). In view of this, the change of sign of the effect due to the action of the rf field in the ranges 1 and 2 is understandable.

In summary, we have shown experimentally and theoretically that nuclear spins can have a substantial influence on the dynamic properties of the DW at low temperatures.

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[1)]We note that the maximum strength of the rf pulses of ~ 1-μsec duration is ~ 10 mW for a two-pulse echo occurring at the frequency of the rf field.

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