Magnetoelectric and Magnetoelastic Properties of Ferromagnetic Shell of Frequency-Dependent Resistor

Arif M. Gashimov
Physics and Technics of High Voltage Systems
Institute of Physics of Azerbaijan
National Academy of Sciences
Baku, Azerbaijan
e-mail: arif@physics.ab.az

Narmin R. Babayeva
Modern Information Systems
Institute of Physics of Azerbaijan
National Academy of Sciences
Baku, Azerbaijan
e-mail:narmin.babayeva@rambler.ru

Talat R. Mehdiyev
Modern Information Systems
Institute of Physics of Azerbaijan
National Academy of Sciences
Baku, Azerbaijan
e-mail: joph@physics.ab.az

Abstract— **The dependences of magnetoelectric properties and distribution rate of magnetoelastic vibrations in ferromagnetic sheath of FD (frequency-dependent) - resistor are investigated. The frequency of bending vibrations is obtained and its hysteresis in dependence on electric field strength, in which the investigated sample is put, is observed. The dependences of propagation velocity of magnetoelastic vibrations on external magnetic field for samples differing from each other by annealing mode which is carried out by the way of the passing of electric current of different density, are found.**

The property of FD-resistors to absorb the electro-magnetic radiation in frequency interval 50Hz - 50MHz presents the big interest. The possibility to use in practice of these resistors in devices and high-voltage circuits is essentially defined by electro-physical, heat and magnetic properties of their ferromagnetic shells in impulse or alternating (low- and high-frequency) electric and magnetic fields. Up to now the different constructions of ferromagnetic shells, in which the different mixtures, containing the dielectric or metallic and ferromagnetic powders are used, have been developed and investigated [1-16]. The ferromagnetic shell of FD-resistor is treated by different deformations leading to it destroy under the influence of external electromagnetic fields because of magnetoelectric effects.

The aim of the given work is investigation of dependences of magnetoelectric and magnetoelastic characteristics of ferromagnetic shell of FD-resistor on external magnetic field and density of direct current passing through shell. The actuality of these investigations doesn't give rise to doubt because well magnetoelectric and magnetoelastic characteristics decrease the FD-resistor operation life.

Keywords: magnetoelastic properties, magnitoelectric properties, FD-resistor, ferromagnetic shells, low- and high-frequency.

I. SAMPLE PREPARATION

The experimental investigations are carried out on the samples cut out from ferromagnetic shells of FD-resistors, containing the mixture Zn-Ni of ferromagnetic powder and polymer dielectric, constructed by collaborates of Institute of Physics of Azerbaijan NAS. The sample sizes are (3÷6) cm x 1,0cm x $3\cdot 10^{-3}$cm. The detail substantiation of material choice for ferromagnetic shell of FD-resistor and description of its technology is given in works [10-16].

The ferrite powder of $Zn_{0.6}Ni_{0.4}Fe_2O_4$ composition is prepared by hydrothermal procedure of helium treatment obtained as a result of co-precipitation of corresponding hydroxides by ammonia. This technique allows us to obtain the nano-dimensional particles of sizes less than 200Å as it follows from electron-microscopic investigations [15-16]. It is also shown that the quasi-granular structure appears in ferrite shell during annealing process.

Thus, the shell of FD-resistor is the mixture of small ferromagnetic particles (granules) uniformly volume distributed, mechanically connected with dielectric and therefore they are electrically isolated from each other. The concentration of ferromagnetic particles is chosen so that the layer thickness of non-magnetic polymer dielectric between ferrite particles satisfies to the condition of tunnel current appearance in the given structure. Note that, tunneling electrons take only vacancies with identical spin polarization. The structure ferrite-polymer-ferrite has the least resistance at identical spin orientation of two ferromagnetics

II. INVESTIGATION METHODS

The measurements of magnetoelectric properties and propagation velocity of magnetoelastic vibrations in investigated samples are carried out by resonance-anti-resonance method [17], the scheme of which is given on Fig.1. The constant magnetic field $H \approx 250\ Oe$ is modulated by weak alternating magnetic field $h(f) = h\cos(2\pi f t)$, where $h \approx (2 \div 5)\ Oe$. $R = 500\ kOhm$, $C = 300\ pF$.

Note that the investigated samples are previously annealed by direct current j the density of which varies in interval $(2\cdot 10^7 \div 7\cdot 10^7)\ A/m^2$.

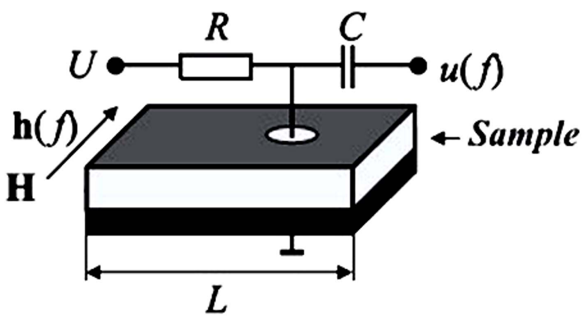

Figure 1. The scheme of experimental investigation of magnitoelectric effect, resonance of magnetoelastic vibrations and obtaining of velocity of their propagation.

The constant and modeling alternating magnetic fields directed along axis of sample difficult magnetizability is created by system of Helmholtz rings and inductor, inside of which the inductor for registration of magnetic flux value change appearing as a result of interaction of sample with external magnetic field is put. The total impedance maximal value of registering inductor corresponds to magnetoelastic resonance frequency f_r. Finally, the propagation velocity of magnetoelastic vibrations in investigated sample is obtained by the relation $V=2Lf_r$, where L is sample length.

III. DISCUSSION OF EXPERIMENTAL RESULTS

The dependences of propagation velocity of magnetoelastic vibrations on external magnetic field for different samples differing from each other by annealing mode are given on Fig.2. The annealing of samples is carried out by direct current the density of which is equal to (A/m^2): 1 - $1\cdot10^7$; 2 -$3\cdot10^7$; 3 – $4\cdot10^7$; 4 – $5\cdot10^7$; 5 – $6\cdot10^7$; 6 – $7\cdot10^7$. The magnetic field variation is (0-1500) A/m.

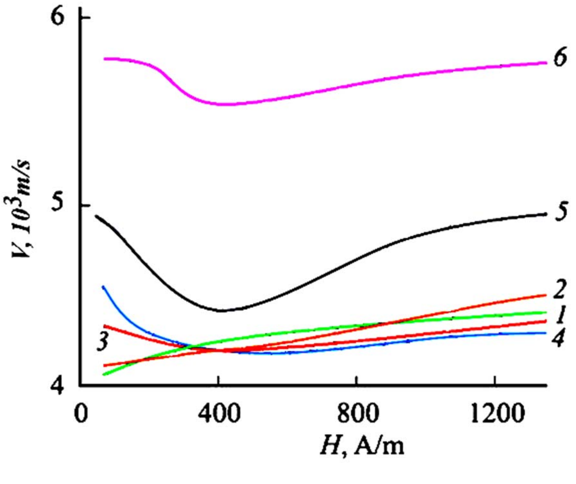

Figure 2. The dependence of propagation velocity of magnetoelastic vibrations on external magnetic field. The annealing of samples is carried out by direct current the density of which is equal to (A/m^2): 1 - $1\cdot10^7$; 2 -$3\cdot10^7$; 3 – $4\cdot10^7$; 4 – $5\cdot10^7$; 5 – $6\cdot10^7$; 6 – $7\cdot10^7$.

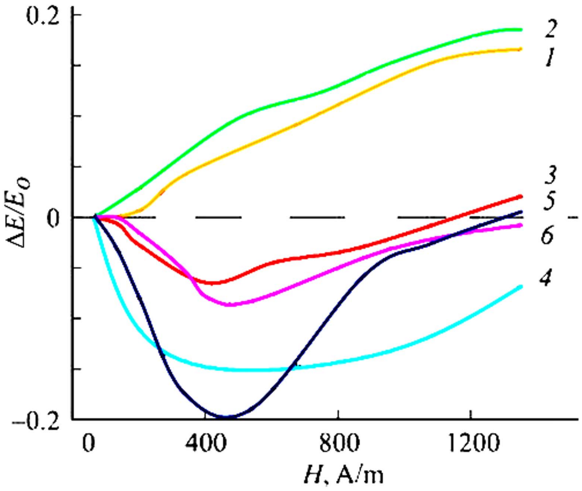

Figure 3. The dependence of relative modulus of elasticity on external magnetic field strength. The annealing of samples is carried out by constant electric field the density of which is equal to (A/m^2): 1 - $1\cdot10^7$; 2 -$3\cdot10^7$; 3 – $4\cdot10^7$; 4 – $5\cdot10^7$; 5 – $6\cdot10^7$; 6 – $7\cdot10^7$.

The minimum appearance on $V(H)$ dependence can be considered as the presence of uniaxial anisotropy with easy magnetization axis perpendicular to along sample direction. Thus, at annealing current of $j<3\cdot10^7$ A/m^2 density the uniaxial anisotropy in investigated sample doesn't appear. The investigations of relative change of modulus of elasticity in the given samples under analogous experimental conditions confirm the given interpretation. The dependences of modulus of elasticity on external magnetic field strength for different samples differing from each other by annealing mode are given on Fig.3. Here E_0 is modulus of elasticity without magnetic field. The absence of uniaxial anisotropy in samples treated at annealing current of $j<3\cdot10^7$ A/m^2 (Fig.3) density is proved by the absence of sign change of relative modulus of elasticity. For sample treated at annealing current of $j=6\cdot10^7$A/m^2 density the strongest changes of value and sign of relative modulus of elasticity are observed. Note that $\Delta E/E_0$ minimum position practically doesn't depend on the annealing current density and external magnetic field strength. It is obvious that minimum position mainly depends on sample length L. The last one is the result of demagnetizing and proves the supposition that the rotation of magnetization axes process is dominating mechanism of uniaxial anisotropy. The oscillogram of dependence of signal $u(f)$ generated by sample on frequency of modeling magnetic field is given on Fig.4. The two resonance peaks on frequencies 23 and 177 kHz corresponding to modes of bending and planar vibrations are observed in spectrum. The planar oscillations appear as a result of displacement of field contact on the one of sample surfaces and consequently don't characterize the investigation object.

The frequency of bending vibrations changes with the variations of electric field in which the test sample is put. Moreover, as it is seen from Fig.5 even at small changes of electric field strength the hysteresis (from 4,0 up to 4,0 kV/cm) is observed. The maximal observable frequency change of bending vibration is not more than 8% at electric field strength ~15,0 kV/cm

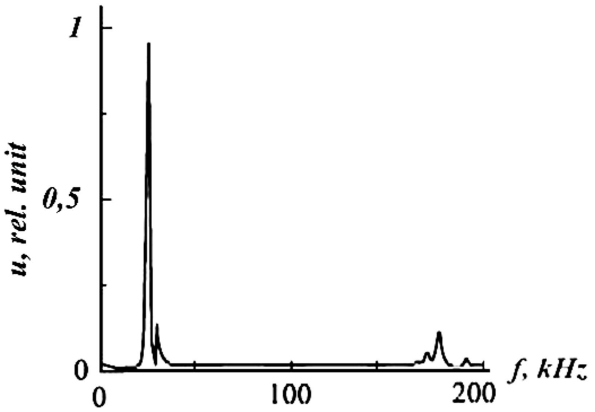

Figure 4. The sample spectrum oscillogram in dependence on frequency of modeling magnetic field.

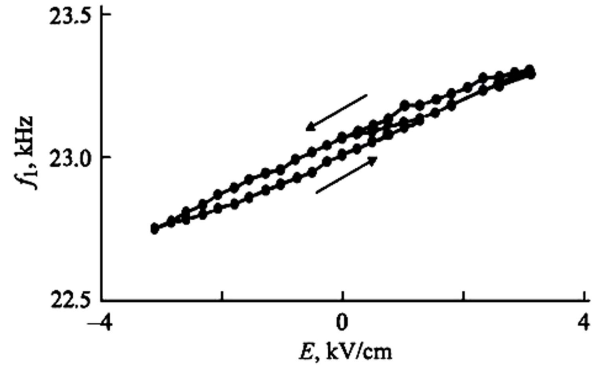

Figure 5. The change of bending vibration frequency in the dependence on electric field strength. It is well seen the hysteresis of bending vibration frequency.

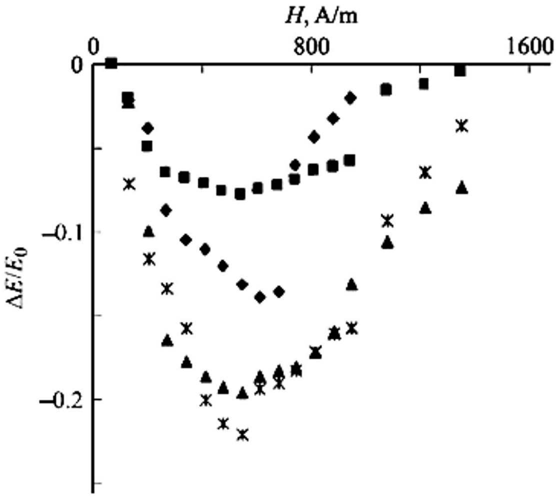

Figure 6. The dependence of ΔE-effect value on sample length: 1- 0.06, 2 - 0.05, 3 - 0.04, 4 - 0.03 m

Note that efficiency of magnetoelectric interaction is characterized by transformation coefficient of magnetic field into electric one, i.e. αE = (u/a)/h, where *a* is structure thickness (Fig.6). For calculation of magnetoelectric transformation coefficient of structure magnetized by parallel and perpendicular polarized to layer surface, we use the math expression from work [18]:

$$\alpha_E = A\frac{qd_{13}}{\varepsilon - Bd_{13}^2}$$

Here *A* and *B* are coefficients depending on sizes and mechanical parameters of layers, $q = \partial\lambda/\lambda H$ is piezomagnetic coefficient, $\lambda(H)$ is magnetostriction of ferromagnetic layer, d_{13} and ε is piezoelectrical modulus and dielectric constant of ferroelectric layer correspondingly. The $A(f)$ coefficient depends on frequency f and describes the resonance increase of efficiency of magnetoelectric interaction at the acoustic resonances frequencies of structure [19]. In [20] it is shown that the change of value of piezomagnetic coefficient $q(H)$ of magnetic layer in dependence on strength and orientation of applied constant magnetic field H influences on coefficient α_E which dependences on applied constant electric field E.

The voltage increase takes place because of deformation resonance increase in structure on frequencies of low mode of bending vibrations f_1 and first mode of planar vibrations f_2 can be defined by formulas [20]

$$f_1 = \frac{k_2}{2\pi L^2}\sqrt{\frac{YI}{\rho S}}, \quad f_2 = \frac{1}{2L}\sqrt{\frac{Y}{\rho}}, \text{ ωηερε}$$
$$Y = \frac{Y_m a_m + Y_p a_p}{a_m + a_p}, \quad \rho = \frac{\rho_m a_m + \rho_p a_p}{a_m + a_p}.$$

Here Y and ρ are effective Yung modulus and structure density; Y_m, Y_p and ρ_m, ρ_p are Yung moduluses and densities of magnetic and ferroelectric layer, correspondingly; $S=b(a_m+a_p)$ is cross-sectional area of structure; $I=b(a_m+a_p)^{3/12}$ is sample inertia moment; k=4.73 is coefficient for lower mode of bending vibrations. The calculated frequency values for investigated sample with parameters: Y_m=21.5·1010 N/m^2, Y_p=7.0·1010 N/m^2, ρ_m=8.9·103 kg/m^3, ρ_p=7.7·103 kg/m^3 are f_1=22 kHz and f_2 =169 kHz and experimentally obtained ones are f_1 =23 kHz and f_2 =177 kHz.

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