

ELECTROMAGNETIC PROCESSES IN FREQUENCY-DEPENDENT RESISTOR SHEATH

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The electrical and magnetic properties of frequency-dependent resistor sheath consisting of the heterogeneous ferrite powder and polymer dielectric mixture are investigated. The charge carries transfer processes, concentration and temperature dependences of electroconductivity are researched. The character of current transport process through the heterogeneous mixture, two mechanisms of hopping and spin current presence are established. The influence of skin-effect on alternating current passing through the heterogeneous mixture is considered. The spectrums of absorption of frequency-dependent resistor sheath are investigated experimentally and theoretically.

INTRODUCTION

The electromagnetic radiation absorption power of frequency-dependent resistor in the frequency interval from 50Hz up to 50MHz presents the big interest because the availability of these resistors in the devices and of high voltage network is essentially defined by electrophysical, heat and magnetic properties of their ferromagnetic sheaths in strong impulses or alternating (low-or high-frequency) fields. Nowadays the different constructions of ferromagnetic sheaths, in which the different mixtures containing the dielectric and ferromagnetic powders or metallic and ferromagnetic ones are used, have been developed and investigated [1-12]. In these works the ferromagnetic sheath is considered as (see [9-11]) percolation mixture and its electric and magnetic properties are studied. The theoretic works [13-14] in which two variants of dielectric constant determination for mixtures in approximation of particle sphericity in constant electric field when the mixture can be considered as homogeneous and isotropic medium with respect of average electric field are investigated, are well known. In first case, fine-dispersed mixtures in which all mixture particles are isotropic ones and difference between their dielectric constants is small one in the comparison with dielectric constant of. In the second case, the emulsions with arbitrary difference between medium dielectric constant and dispersed extrinsic phase of small concentration are considered.

The theory of absorption of electromagnetic radiation by strongly heterogeneous two-component systems is considered in work [15]. The composite presents itself the thin film of two-component mixture consisting of dielectric matrix and macroscopic magnetic particles. It is shown that the absorption of electromagnetic radiations can be changed

adding the magnetic, metallic and other foreign substances in main matrix. In the case of metallic inclusions, the absorption region shifts to the side of frequency increase that is connected with decrease of relaxation time of electronic subsystem.

Note that dipolar polarization not depending on frequency is observed in dipole dielectrics in radio-frequency region $10^{13} - 10^{11}$ Hz. The relaxation losses are observed in the region of relaxation dispersion when dipoles haven't time in order to reorient in half-period of electric field variation. The structures and losses connected with them having maximum on the relaxation frequency of interlayer polarization at which the electric charges accumulate on the heterogeneity interfaces during long time, are observed on low frequencies in heterogeneous dielectrics in polarization spectrum.

The investigation results of electric and magnetic properties of frequency-dependent resistor ferromagnetic sheath by thickness from 2 up to 5 mm in alternating electric field carried out on the base of strongly heterogeneous mixture of dielectric (polyvinylchloride) and ferromagnetic (nickel-zinc) powders are presented in the given work.

THE SAMPLE PREPARATION

The photos of microstructure of frequency-dependent resistor sheath obtained on electronic microscope in different increase regimes at 45% volume concentration of filler are given on fig.1.

The photos have been obtained for sheath section which is perpendicular to resistor "z" axis (see.fig.2). As analysis shows, the ferromagnetic powder component has the similar volume density upon the average along whole resistor sheath.

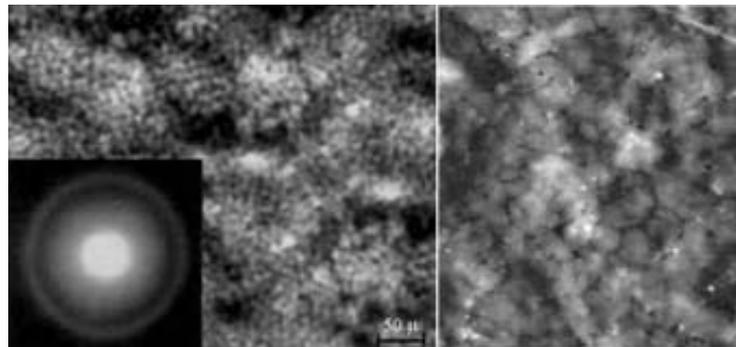


Fig.1. The photos of sheath microstructure of frequency-dependent resistor obtained on electronic microscope in different increase regimes at 45% volume concentration of filler.

The matrix produced on the base of polyvinylchloride, is filled by ferromagnetic powder preliminary treated for better adherence with matrix in solution of stearic acid and benzene. The solvent excess is eliminated by drying of ferromagnetic powder at temperature 23°C.

The matrix filling by filler is carried out gradually by the method of hot roll-forging up to achievement of necessary concentration. In the given experiments the concentration of ferromagnetic particles in the volume is achieved $x=0.65$. It is known [16], that limit concentrations of filler are defined by its properties and degree of interaction with polyvinylchloride. As it is shown in [16] the peculiarities of temperature dependences of mixture volume expansion at filler high concentrations can be explained by thermoelastic voltages appearing as a result of difference of coefficient of expansion of polymer and filler. Note that obtained filler concentrations up to temperature 100°C don't lead to the destruction of powder mixtures. Further, the created composition is reduced and pressed round current-carrying-rod of created frequency-dependent resistor in vacuum furnace under the pressure about 10^{-1} Pa and temperature 160°C. The forms of ferromagnetic particles uniformly distributed enough on matrix volume are close to spherical ones and their dimensions don't exceed 50μ . Note [23] that the dimensional effects don't affect in samples by thickness up to 0,8 cm and at frequencies from 0,1-50MHz and

therefore the complex magnetic permeabilities of nickel-zinc ferrite filler can be defined by results of magnetic and electric measurements. By other hand, the ferromagnetic sheath of frequency-dependent resistor has the big dimensions and therefore the observation of volume resonance is quite possible.

THE EXPERIMENT, FREQUENCY PROPERTIES OF SHEATH DIELECTRIC MATRIX OF FREQUENCY-DEPENDENT RESISTOR

The differential spectrums of frequency dependences of real and imaginary parts of dielectric constant and also dielectric loss tangent are investigated on automatic measuring device realizing the method of susceptance variation. The measurements are carried out in frequency interval from 1Hz up to 100MHz. The relative error of measurements is no more than 2%. The experiment control and experimental data processing are carried out by computer connected to measurement module. The differential spectrums are obtained by direct differentiation of experimental dependences.

The differential frequency spectrums of real and imaginary parts of dielectric constant and also dielectric loss tangent of dielectric matrix, which are given on the fig.2, have been obtained for calibration of experimental device.

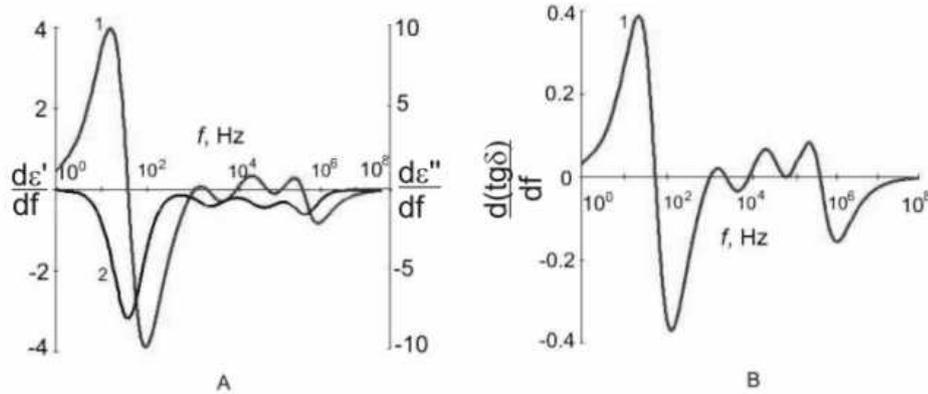


Fig. 2. Differential frequency spectrums a - ε' , ε'' and b - $(tg \delta)'$ of dielectric constant of PVCh matrix. Here 1 is imaginary part of dielectric constant, 2 is real part of one.

The polyvinylchloride is related to linear polar polymer with big value of dielectric constant and dielectric loss tangent that is caused by construction asymmetry of macromolecule elementary units because of which the dipole-relaxation polarization appears. The polar groups in polyvinyl chloride are strongly connected with main chain. The connectedness of orientation movement of side polar group in respect of the main chain changes in the dependence on dipole position. It is obvious that dipole C-Cl in polyvinyl chloride, in the composition of which the carbon of main chain includes, can shift in glassy state only at presence of some part of main chain. Naturally, that this relaxation process has some features which are character ones to orders of dipole-elastic losses, but it can be observed at the temperature that is essentially lower than the glass-transition one. Thus, this process isn't connected with heat motion of chain segments.

As would be expected the real part of dielectric constant weakly depends on external alternating field frequency higher 700Hz and its fuzzy structure corresponds to contribution of

different polar groups and radicals in spectrum of dipole-orientation polarization.

The quantity of observable structures in the spectrum in real part of polyvinylchloride permeability at 23°C shows on the fact that spectrum can be interpreted by the set of four Debye's functions, i.e.:

$$\varepsilon' = \varepsilon_{\infty} + \Delta\varepsilon \sum_{i=1}^4 \frac{g_i}{1 + (\omega\tau_i)^2};$$

$$\varepsilon'' = \Delta\varepsilon \sum_{i=1}^4 \frac{g_i(\omega\tau_i)}{1 + (\omega\tau_i)^2}; \quad tg \delta = \frac{\varepsilon''}{\varepsilon'}$$

where ε_{∞} is dielectric constant for frequency $\omega \gg \frac{1}{\tau_0}$, equal to 4.289; τ_0 is relaxation time of i -th process; $\Delta\varepsilon = (\varepsilon_c - \varepsilon_{\infty}) = 10.0$ is total dispersion width of i -th set of

relaxation time; ε_c is dielectric constant for $\omega \ll \frac{1}{\tau_0}$, equal to 14.289; g_i is weighting coefficient for i -th relaxation oscillator. The obtained values of weighting coefficients and relaxation times coincide with data [17] in the investigated frequency region.

The analysis of obtained spectrums shows that dielectric constant dispersion peculiarities are defined dipole-group polarization of polyvinylchloride molecules. As it was shown in work [17] even insignificant content of polar plasticizers, for example lead zirconate titanate, differing on chemical composition in polymer volume should lead to the set of relaxation times of dipole-orientation polarization in wide frequency region of external electric field. The dispersions of spectrum structures of complex dielectric constant are caused by the content of investigated polymer of polar radicals C-Cl in main chain by one hand, by another one, they are caused by the content of molecule polar groups in plasticizers. Note that plasticizers decrease the polymer toughness because of decrease of intermolecular interaction energy and change the relaxation times of processes of dipole-orientation polarization of polar groups and radicals. The using of

powder of nickel zinc ferrite in the capacity of filler for polyvinylchloride is caused by the following reasons. Firstly, the nickel zing ferrites widely use in electronic devices for the frequency turning. That allows us to solve the problem of the construction of frequency-dependent ferromagnetic sheath with given magnetic properties. Secondly, as well known, zing compounds are stabilizers for polyvinylchloride and these mixtures widely use in window glass production. The relatively big dielectric constant, which depends on frequency and material content, is character for nickel zinc ferrites. The ferrite dielectric constant decreases with frequency increase. Thus, nickel zinc ferrites have $\varepsilon = 400$ on frequency 1kHz, but $\varepsilon = 15$ on frequency 10MHz. By other hand it is well known that alternating valence ions the concentration increase of which leads to increase of material dielectric constant, strongly influence on ferrite polarized properties. The differential spectrums of dielectric constant and functions of dielectric loss $\text{tg}\delta$ in the dependence on frequency of alternating electric field and filler concentration are shown on fig.3. Here curve 1 corresponds to filler volume concentration (on 1 cm³) equal to 0.25, curve 2 corresponds to one equal to 0.45, and 3 corresponds to one equal to 0.65.

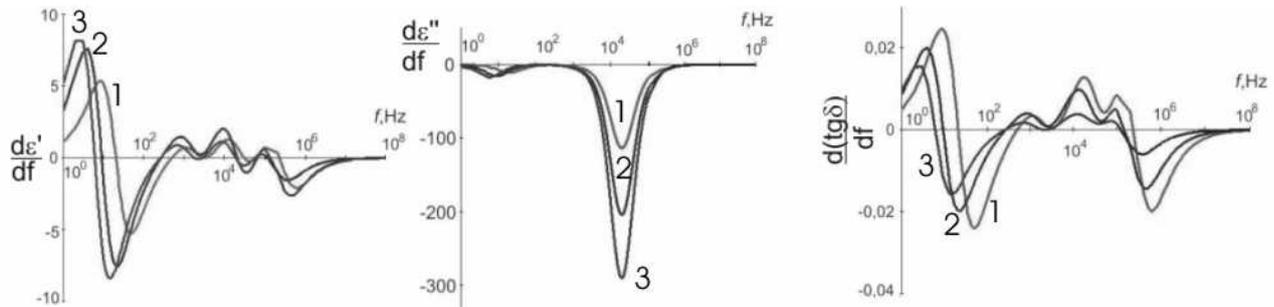


Fig.3. The differential spectrums of dielectric constant (a,b) and functions of dielectric loss $\text{tg}\delta$ (c) in dependence on frequency of alternating electric field and filler concentration (ferrous powder). Here curve 1 corresponds to filler concentration equal to 0.25, curve 2 corresponds to one equal to 0.45, and 3 corresponds to one equal to 0.65.

As it was mentioned above, the orientation and deformation components make the main contribution to polarization of polar polymers. The deformation polarization is steadied during the time from 10^{-14} up to 10^{-12} sec. The induced dipoles appear so quickly that their shift reveals at any frequencies of alternating field, i.e. this process practically doesn't depend on frequency ω . The dipole orientation doesn't take place immediately, but for enough long time. Thus, dielectric loss corresponding to the quantity of heat emitting at current going in dielectric volume unit shows on the fact that the sluggishness of orientation polarization is energy dissipation reason. Thus, the dependence of dielectric constant of polar polymers on alternating field frequency is defined by orientation dipole polarization, i.e. by the dipole moment value and group polarity, their number, position, temperature accordingly. As it is shown in the work [17], the observable shift of complex dielectric constant spectrums and dielectric loss of investigated mixture to the region of more low frequencies at increase of filler concentration in matrix is explained by the interaction of ferromagnetic powder particles with matrix polar radicals (-C-Cl). At lack of above mentioned interaction, the positions of maximums of dielectric loss function shouldn't be practically changed. The big value of

ferrite filler dielectric constant on low frequencies should lead to strong domain polarization and the interactions of matrix polar radicals with filler particles will lead to dielectric constant dispersion spectrums, correspondingly. By other hand, the essential decrease of dielectric constant on high frequencies (after 10MHz) decreases the domain polarization and dielectric constant dispersion of resistor sheath decreases in high-frequency spectrum region correspondingly. Confirming the above mentioned, the obtained experimental results show (fig.3) on dispersion of first maximum observable on fig.2 at 37Hz and practical lack of dispersion of rest spectrum maximums. This means that observable spectrum changes reflect the interaction of matrix polar radicals (-C-Cl) with filler particles.

THE SHEATH ELECTRIC CONDUCTIVITY

As it was above mentioned, the sheath of frequency-dependent resistor sheath presents itself the heterogeneous mixture, conglomerate of small ferromagnetic particles enough uniformly distributed in the volume, connected mechanically with dielectric and electrically isolated from each other at small concentrations.

Such heterogeneous structure is similar to structure of magnetodielectrics under the conditions that electric

conductivity of dielectric is insignificantly small, has the small electric loss and constant of magnetic permeability. The task solving of influence of material heterogeneity on frequency dependence of its electric polarization is connected with taking into consideration the processes of movable charges in the model of composite conductivity. The diffusion “smears” the charge in volume changing the field distribution in the system and the diffusion is stronger, the size of heterogeneities is smaller than Debye’s radius. The charge distribution will be equilibrium at small frequencies independently of the value of alternating electric field every time moment. The diffusion plays the progressively less important role with concentration increase, the charge presses to the surface. The concentration gradient of moveable charges hasn’t time to appear on the frequencies essentially exceeding the dispersion frequency and diffusion current becomes inessential one. Thus, physical meaning of conductivity increase with increase of frequency of alternating electric field lies in the limitation of the establishment velocity of polarization equilibrium state. From above mentioned, we can conclude that low-frequency region is connected with sample polarization as a whole, but high-frequency region is connected with polarization of separate conducting inclusions.

The using of nickel zinc ferrite powder makes task difficult because the mechanism of semiconductor electric conductivity of transition elements (Fe, Ni and etc) isn’t explained in the framework of band theory, because the eigenfunctions of 3-d electrons of neighbor atoms or ions in the lattice don’t cover because of weak interaction. The electric conduction mechanism in these compounds is caused by processes of electron exchange between ions of alternating valence (“hopping mechanism”), i.e. it is necessary that ions of the one and the same element with different charges are in equivalent places of crystalline lattice. It is known that the compounds of transition element oxides with spinel structure, for example magnet, have such lattice. The unit cell of spinel ferrite has space group (O7h – F3dm) and presents itself the cube formed by 8 MeOFe₂O₃ molecules and consisting of 32 of O²⁻ anions. Here Me is Ni²⁺, Co²⁺, Fe²⁺, Mn²⁺, Mg²⁺, Li¹⁺ and Cu²⁺.

The oxygene anions form the close face-centered cube packing consisting in 64 tetrahedral (A) and 32 octahedral (B) empty spaces partly populated by Fe³⁺ and Me²⁺ cations. There are direct spinels (non-magnetic) and reverse ones (ferrimagnetic) in the dependence on the fact what kind of ions and in what order A and B take empty spaces. In reverse spinels the half of Fe³⁺ ion number is in tetrahedral interspaces, but Me²⁺ ions and the second half of Fe³⁺ ion number are in octahedral ones. Moreover, M_A magnetization of octahedral sublattice is bigger than M_B magnetization of tetrahedral one that leads to ferrimagnetism formation. The nickel zinc ferrites are reverse spinels and present themselves the displacement solid solutions formed by two simple ferrites the one of which NiFe₂O₄ is ferromagnetic, but another ZnFe₂O₄ doesn’t have the magnetic properties. The zinc cations in spinel structure always take tetrahedral points of lattice that cause the antiparallel spin orientation of Fe³⁺ iron cations being in the one octahedral sublattice. The composition of solid solution with taking into consideration the cation distribution on oxygen interstices is characterized by formula: $(Zn_x^{2+}Fe_{1-x}^{3+})[Ni_{1-x}^{2+}Fe_{1+x}^{3+}]O_4$. The static

distribution on octahedral empty spaces of Ni²⁺ and Fe³⁺ ions and high compound electric conductivity are explained by the fact that Fe²⁺ ions are easily displaced by bivalent Ni²⁺ and Zn²⁺ ions. As the cations with different valences take crystallographically and energy-wise equivalent positions in lattice, then reactions of electron exchange should carry out with inessential (ΔE) activation energy which is about 0,05eV. The zinc inclusion into crystalline lattice is accompanied by iron transition on octahedral positions. The magnetization of tetrahedral (A) sublattice and compensation factor of cation magnetic moments being in different sublattices (A and B) decrease correspondingly. As a result, the increase of concentration of non-magnetic moment leads to increase) of solid solution magnetization (and B_s consequently), weakens the exchange interaction of A-O-B type that leads to monotonous decrease of Curie temperature (T_c) at increase of mole fraction of ZnFe₂O₄ in ferrosinell composition. In $x > 0,5$ region the ion magnetic moments in tetrahedral sublattice don’t have possibility to orientate the cation moments being in B-sublattice antiparallel to themselves, that leads to fast droop of saturation induction, decrease of crystalline anisotropy, increase of initial ferrite permeability. The point in composition triangle with orientation coordinates 50%Fe₂O₃, 15%NiO and 35%ZnO to which the solid solution Ni_{1-x}Zn_xFe₂O₄ corresponds where $x \approx 0,7$, corresponds to maximal value of permeability.

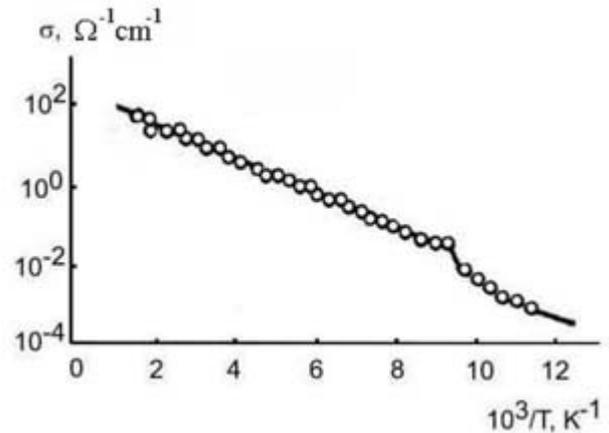


Fig. 4. The temperature dependence of $(Zn_{0.6}^{2+}Fe_{0.4}^{3+})[Ni_{0.4}^{2+}Fe_{1.6}^{3+}]O_4$ ferrite electroconductivity.

The temperature dependence of ferrite $(Zn_{0.6}^{2+}Fe_{0.4}^{3+})[Ni_{0.4}^{2+}Fe_{1.6}^{3+}]O_4$ electroconductivity is given on the fig.4. Note that the break which is analogous to revealed one in magnetite is observed on temperature dependence near 120K. The strong decrease of magnetite electroconductivity nowadays is interpreted by following way. The electrons under the influence of exchange field formed by Fe²⁺ and Fe³⁺ cations being in octahedrons localize on these cations orientating by their spins antiparallel to magnetic moments of iron cations at temperature decrease up to some critical value. This process forms the magnetic short range ordering in temperature interval up to critical one, but it forms the magnetic long range ordering at achievement of critical temperature. Thus, the magnetic phase transition of induced type takes place at critical temperature.

As appears from the above [18,19] the electroconductivity of nickel zinc ferrite is explained by

electron transitions of $\overset{e}{\text{Fe}^{2+} + \text{Fe}^{3+}} \rightarrow \text{Fe}^{2+} + \text{Fe}^{3+}$ type or hole transitions of $\overset{e}{\text{Ni}^{3+} + \text{Ni}^{2+}} \rightarrow \text{Ni}^{3+} + \text{Ni}^{2+}$ type which take place with activation energy consumption without lattice change. The transition from Ni^{2+} to Fe^{3+} requires energy consumption and is less probable.

The electrons taking part in exchange can be considered as charge carriers the concentration of which doesn't depend on temperature. However, it is shown that probability of transition between ions of alternating valence increases with temperature increase and temperature dependence of ferrite specific resistance is expressed with enough accuracy by the following relation $\rho = \rho_{\infty} \cdot \exp\left(\frac{E_a}{kT}\right)$, where k is Boltzman

constant, T is temperature, E_a is activation energy. The last one proves the investigation results of electroconductivity temperature dependence shown on the fig.4. The ferrite conductivity linearly increases and activation energy decreases with increase of concentration of iron bivalent ions. It follows from this that the height of energy barriers which overcome the electrons at the transition between neighbor ions decreases at approach of alternating valence ions. For example, the electroconductivity activation energy of nickel zinc ferrites decreases from 0,5 up to 0,1eV. (The magnetite has the most concentration of Fe^{2+} ions the specific resistance of which is equal to $5 \cdot 10^{-5} \text{Om}\cdot\text{m}$).

It is known [20] that value of limit particle radius at which the homogeneous magnetization is kept, can be defined from the following expression:

$$R_c \approx \frac{0.95}{J_s} (10A)^{\frac{1}{2}} \left(Q - \frac{2K}{J_s^2} - \frac{H}{J_s} \right)^{\frac{1}{2}}$$

where J_s is saturation magnetization; A is parameter of exchange energy; K is anisotropy constant; Q is demagnetizing factor; H is field strength. Note that particle with radius satisfying to given equation at all field values $H > -\frac{2K}{J_s}$ stays one-domain. The condition of absolute one-

domain lattice for simple OCC and FCC lattices has the following form:

$$R < R_c \approx \frac{0.95}{J_s} \left(\frac{10cB}{a_0 Q_R} \right)^{\frac{1}{2}}$$

where $c = 1/2, 1$ and 2 are for OCC and FCC lattices correspondingly; $B = z^2 A$ is parameter of exchange energy; z is number of uncompensated spins per atom; A is exchange integral; a_0 is parameter of crystalline lattice; Q_R is demagnetizing factor of one-domain ellipsoid along short axis.

It is significant that one-domain particle with critical radius has maximal coercitive force. At further radius decrease the particle keeps the homogeneous magnetization, because the atomic moments are taken by exchange forces, however, the probability of Brownian motion of summary magnetic moment vector increases in particle system. The probability of such process is proportional to $\exp(E/k_B T)$, where E depends on anisotropy constant and particle volume and has the meaning of energy barrier at overcoming of

which the heat fluctuations can cause the magnetic moment rotation. Thus, particle system with radiuses less than critical ones behaves itself similar to ensemble of paramagnetic atoms having the big magnetic moment. The estimation of relaxation time is the value by 10^{-6} order for particles having diameter of 30nm order at $T=300\text{K}$. Evidently, that value of energy barrier and consequently relaxation time depend on external magnetic field strength. The total impurity magnetization is defined by the following expression:

$$J = J_s V_0 \int_0^{\infty} \left(cth \frac{J_s WH}{k_B T} - \frac{k_B T}{J_s WH} \right) f(W) dW$$

where $f(W)$ is the dimension distribution function

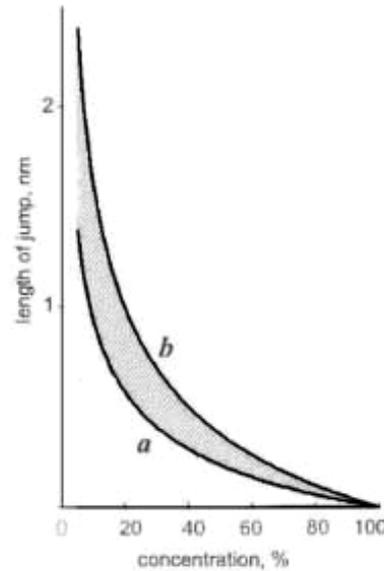


Fig.5. The dependences of jump lengths on concentration of ferrite component in mixture.

The dependence of jump lengths on concentration of ferrite component in mixture is given on the fig.5. As analysis shows all experimental data on jump lengths take place in hatched region limited by "a" and "b" curves corresponding to minimal and maximal distances between two particles at the given concentration and uniform distribution on ferrite particle volume. The jump length of

charge carriers is estimated by $l(T) = \frac{3}{8} a \left(\frac{B}{T} \right)^{\frac{1}{4}}$ expression

in which "B" value is obtained from experimental data on electroconductivity of whole mixture. The dependence of jump length distribution on temperature obtained from experiments evidences about presence at least two mechanisms of hopping, the first of which is connected with jump mechanism in ferrite impurity component, and second one is connected with jump mechanism in ferrite-dielectric-ferrite structure.

The experimental results of investigations of temperature dependences of electric conductivity of ferrite- polymer dielectric-ferrite structure in temperature interval 70-120K shows on domination of hopping mechanism [22] with alternating jump length on localized states for three concentrations of ferrite components: 1 is 25%; 2 is 45%; 3 is

65%. The observable temperature dependence of jump mechanism is character for amorphous mediums. That's why localized states are connected not with impurities but with structural defects of dielectric matrix and presence of interfaces of dielectric matrix-ferrite particle. Such interesting interpretation is quite real one, because the density of localized states has the big values changing in the limits from 10^{21} up to $10^{22} \text{eV}^{-1} \text{cm}^{-3}$ in the dependence on ferrite component concentration.

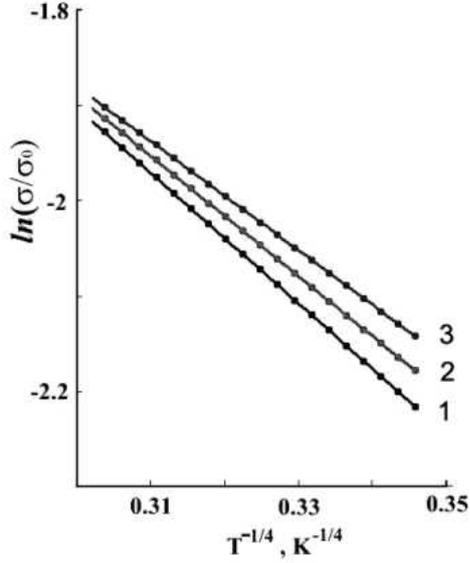


Fig.6. The temperature dependence of electroconductivity of ferrite-polymer dielectric mixture in interval from 70 up to 120K. Here 1 is 25%; 2 is 45%; 3 is 65% of concentration of ferrite component in the mixture.

As it is shown on the fig.7, the character of electric conductivity change with temperature has $T^{1/2}$ dependence in the temperature interval from 120 up to 300K that is probably the consequence of essential influence of phonon processes on transfer of charge carriers. It is shown in [25] that the density distribution of states in neighborhood of Fermi level doesn't depend on interaction nature on small distances. Thus, the appearance of coulomb crack in density distribution of states in neighborhood of Fermi level, which observe near metal-dielectric transition where state radius and dielectric constant are abnormal big ones, because tend to infinity near transition point, is the reason of appearance of following

$$\sigma \sim \exp\left[\left(-\frac{B_1}{T}\right)^{\frac{1}{2}}\right], \quad B_1 = \frac{2.8e^2}{k\epsilon a}, \quad \text{where } a \text{ is}$$

state radius.

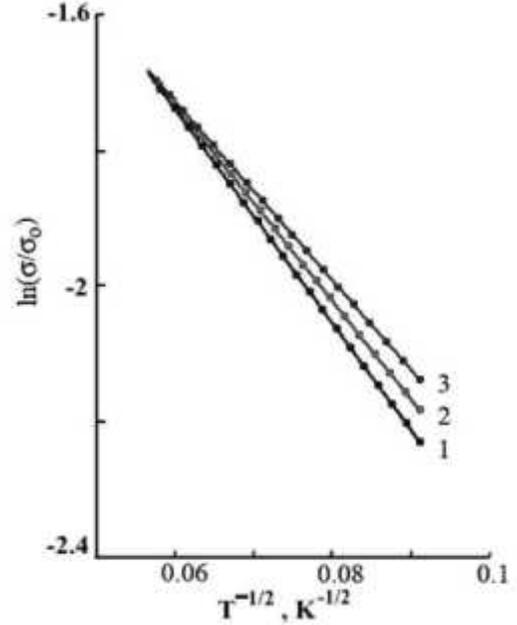


Fig.7. Temperature dependence of electroconductivity of ferrite-polymer dielectric mixture in the region from 120 up to 300K. Here 1 is 25%; 2 is 45%; 3 is 65% concentration of ferrite component in mixture.

Moreover, the thickness of layer of non-magnetic polymer dielectric between ferrite particles corresponds to condition of tunnel current appearance in the given structure. The appearing tunnel current has two components corresponding to two possible orientations of electron spins. Tunneling electrons take only vacancies with similar spin polarization. It follows from this that ferrite-polymer-ferrite structure will have the less resistance at similar spin orientation of two ferromagnetics, but at opposite orientation it will have the biggest one. If we take into consideration that all ferrite grains have similar parameters and dimensions and their spin volume distribution has chaotic character then the summary tunnel current must be equal to zero. The model of spin-dependent electron transfer through ferromagnetic-dielectric-ferromagnetic structure supposed in work [21], shows on essential role of parameters of tunnel barrier and ferromagnetic and on the oscillations appearing of the magnetoresistance at the dielectric thickness change or shift external voltage change as a result of wave function interference change.

According to this model the value of tunnel current can be estimated using Tsu-Isaki equation [22] by the following form:

$$I = \frac{2\pi e}{\hbar^3} m_{j\sigma}^* \iint T(E_z, E_{\parallel})(f_1 - f_3) dE_z dE_{\parallel}$$

$$T = \frac{k_{col} m_{em}^*}{k_{em} m_{col}^* |t_{ii}|^2}; \quad t_{ii} = \left(\prod_i t_i \right); \quad t_i = \begin{pmatrix} e^{ik_i z_i} + e^{-ik_i z_i} \\ \frac{ik_i}{m_i^*} e^{ik_i z_i} - \frac{ik_i}{m_i^*} e^{-ik_i z_i} \end{pmatrix}^{-1} \begin{pmatrix} e^{ik_{i+1} z_i} + e^{-ik_{i+1} z_i} \\ \frac{ik_{i+1}}{m_{i+1}^*} e^{ik_{i+1} z_i} - \frac{ik_{i+1}}{m_{i+1}^*} e^{-ik_{i+1} z_i} \end{pmatrix};$$

$$k_{col} = \frac{\sqrt{2m_{col}^* \left(E_z \pm \frac{\hbar_0}{2} + eV \right)}}{\hbar}; \quad k_{em} = \frac{\sqrt{2m_{em}^* \left(E_z \pm \frac{\hbar_0}{2} \right)}}{\hbar};$$

$$k_i = \frac{\sqrt{2m_d^* \left(E_z - U_0 + \frac{I}{n} eV - eV_S \delta(z - z_1)(z - z_2) \right) + e\varphi_i \frac{n^2}{i(n-i+1)} - \left(1 - \frac{m_d^*}{m_{em}^*} \right) E_{\parallel}}}{\hbar};$$

$i = 1, 2, \dots, n$

Here I is tunnel current: f_1 and f_3 are Fermi-Dirac distribution functions in emitter and collector regions correspondingly;

T is wave transmission coefficient; k_i and m_i^* are wave vector and effective mass of i -th barrier region correspondingly;

z_i is division coordinate of i -th and $(i+1)$ -th barrier regions;

$m_{em}^*, m_{col}^*, m_d^*$ are effective masses in emitter, collector and dielectric;

E_z, E_{\parallel} are longitudinal and transversal components of electron energy;

V is voltage applied to ferrite-polymer dielectric-ferrite structure;

t_{ii} is element of matrix transmission;

a is barrier thickness;

U_0 is height of potential barrier;

V_S is potential of wave scattering; φ_i is image force potential in i -th region;

\hbar is Plank constant;

\hbar_0 is molecular field inside dielectric.

The transversal component of electron energy is constant, i.e. $k_{\parallel} = const$ at electron tunneling through potential barrier.

The following parameters have been accepted for calculations in the capacity of examples: height of potential barrier is 2.0 eV; width of potential barrier is 1-2 nm; effective masses of electrons having spin-up, spin-down and being in barrier are $1.27m_0$, $1.36m_0$ and $0.4m_0$, correspondingly; molecular field is 1.9eV; potential of wave scattering is 0-0.2eV.

The presence of frequency dependence of current passing through mixture of ferrite and dielectric, i.e. the skin-effect, are also taken into consideration at calculation. Thus, the value of current density on r distance on wire axis is defined by the $j_0 \frac{M_0(kr)}{M_0(ka)}$ value, where $M_0(kr)$ is modified

Bessel function at passing of alternating electric current on cylindrical semiconductor. If we consider the mixture of ferrite and polymer dielectric used in our work as percolation system and use the [11] work results, then we notice that character of current passing is defined by scale of mixed conductivity at skin effect.

The current distribution in the structure will have two-dimensional character at skin-effect depth less than scale of mixed conductivity, but current will have three-dimensional one at skin-effect depth bigger than scale of mixed conductivity. The conductivity in the region of small frequencies is mainly defined by conductivity of "good"

conductor. As it follows from experiments and it was mentioned in [11] earlier the conductivity change and position one of boundary of mixed conductivity in small frequency region doesn't practically take place [24]:

$$\sigma(\omega) \approx \omega \left[\ln \left(\frac{\omega_{ph}}{\omega} \right) \right]^4, \quad \text{где } \omega_{ph} \text{ is phonon}$$

frequency. It is equal to $10^{12} \text{ sec.}^{-1}$ approximately.

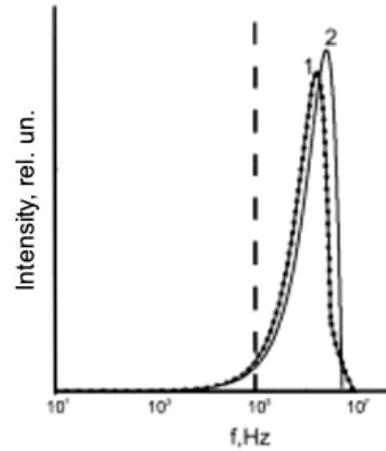


Fig.8. Experimental (1) and theoretical (2) of absorption spectrums of frequency-dependent resistor sheath in region from 10 up to 10^7 Hz.

The experimental and theoretical absorption spectrums of frequency-dependent resistor sheath in frequency region from 10 up to 10^7 Hz are shown on the fig.8. The changes of experimental absorption spectrum aren't practically observed up to 1000 B voltages, 10A current.

The presence of maximum on the curves absorption spectrum (Fig. 8) is caused by frequency dependence of ferrite permeability, frequency dependence of resistor inductance, and transition from three-dimensional character to two-dimensional one of current passing, and also by difference of spin-up spin current and spin-down one.

CONCLUSION

The operation of frequency-dependent resistor sheath presenting itself the heterogeneous mixture Zn-Ni of ferrite powder with polar polymer dielectric-polyvinylchloride and physical properties of sheath components have been considered in detail. The ferromagnetic powder component has the similar volume density on whole resistor sheath in average. The properties of polymer matrix with ferrite filler have been studied.

The mechanisms of charge transport in both separate components and along whole ferrite-polymer dielectric ferrite

structure have been considered. The presence of two types of hopping mechanisms of charge transfer in the given structure has been established experimentally. The theoretical analysis of current passing in alternating field, in which the uniform distribution of current density on section of frequency-

dependent resistor as a result of skin-effect, the presence of spin-up spin current and spin-down one and also frequency dependence of ferrite permeability have been taken into consideration, are presented.

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TEZLİKDƏN ASILI REZİSTOR ÖRTÜYÜNDƏ ELEKTROMAQNİT PROSESLƏRİ

Məqalədə ferrit tozu və polimer dielektrik qeyri-bircins qatışıqından ibarət tezlikdən asılı rezistor örtüyünün elektrik və maqnit xüsusiyyətlərinin tədqiqinin nəticələri təqdim olunmuşdur. Yükdaşıyıcıların keçid prosesləri, elektrikkeçiriciliyinin konsentrasiya və temperatur asılılıqları araşdırılmışdır. Qeyri-bircins qatışıqdan cərəyanın ötürülməsi proseslərinin xarakteri, sıçrayış keçiriciliyinin azı iki mexanizminin və spin cərəyanının olması müəyyən edilmişdir. Qeyri-bircins qatışıqdan keçən dəyişən cərəyan axınına skin-effektin təsirinə baxılmışdır. Tezlikdən asılı rezistor örtüyü ilə yüksək tezlikli küylərin udulma spektrləri eksperimental və nəzəri olaraq araşdırılmışdır.

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ЭЛЕКТРОМАГНИТНЫЕ ПРОЦЕССЫ В ОБОЛОЧКЕ ЧАСТОТНОЗАВИСИМОГО РЕЗИСТОРА

В настоящей работе представлены результаты исследований электрических и магнитных свойств оболочки частотнозависимого резистора, состоящей из неоднородной смеси ферритового порошка и полимерного диэлектрика. Исследованы процессы переноса носителей заряда, концентрационные, температурные зависимости электропроводности. Установлен характер процессов транспорта тока через неоднородную смесь, наличие, по крайней мере, двух механизмов прыжковой проводимости, наличие спинового тока. Рассмотрено влияние скин-эффекта на протекание переменного тока через неоднородную смесь. Экспериментально и теоретически исследованы спектры поглощения высокочастотных помех оболочкой частотнозависимого резистора.

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