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Voltage and Current Resonance in Nanocomposite $(\mathrm{FeCoZr})_x(\mathrm{CaF_2})_{100-x}$ Produced by Ion-Beam Sputtering in Pure Argon Atmosphere

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In this paper the results of investigations of electrical properties of metal–dielectric nanocomposites $(\mathrm{FeCoZr})_x(\mathrm{CaF_2})_{100-x}$ are presented. The samples with the metallic phase content $x = 45.7$ at.% were produced by ion-beam sputtering method in pure argon atmosphere, and subsequently annealed at 398 K for 15 min. The measurements of electrical properties were performed in the frequency range from 50 Hz to 1 MHz. The frequency dependences of phase angle θ, capacity C_{p}, conductivity σ and dielectric loss factor $\tan\delta$ were measured at seven different temperatures ranging from 148 K to 263 K. It was found that the nanocomposite exhibits the phenomena of voltage resonance and current resonance, characteristic of the conventional RLC circuits with series and parallel connections of elements.

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1. Introduction

Recently much attention has been paid to the investigations of nanosized composite structures [1–3]. These materials exhibit a number of interesting mechanical [4], chemical [5], optical and electrical [6] properties. This is mainly related to quantum phenomena which occur in the nanocomposites and surface influence on their properties, and above all, surface energy in comparison to bulk materials.

In the previous papers frequency dependences of electrical properties for the nanocomposites: $(\mathrm{FeCoZr})_x(\mathrm{PZT})_{100-x}$ [7], $(\mathrm{FeCoZr})_x(\mathrm{Al_2O_3})_{100-x}$ [8] and $(\mathrm{FeCoZr})_x(\mathrm{CaF_2})_{100-x}$ [9] produced by ion-beam sputtering in the argon and oxygen atmosphere were presented. After annealing of the nanocomposite samples at temperatures above 398 K some phenomena characteristic of a conventional RLC circuit were observed. Phase angle θ changes its value in the range from −20° to +135°. This is related to the mechanism of charge transfer, whose model was presented and described in [7]. In the low frequency area, where θ assumes values smaler than 0, capacity type of conductivity is observed, and in the high frequency area, where $\theta > 0°$, inductive type of the conductivity occurs.

For the $(\mathrm{FeCoZr})_x(\mathrm{CaF_2})_{100-x}$ samples oxygen from the sputtered ion beam, and fluorine in the dielectric matrix react with the surface of metallic phase particles during annealing and form a coating on some of them [10]. In this way, in the nanocomposite charge transfer can occur: *1* — through the first particle coating — dielectric matrix — to the second particle through coating; *2* — through the first particle coating — dielectric matrix — to the second particle without coating; *3* — from the first particle without coating — dielectric matrix — to the second particle without coating. Therefore in the nanocomposite three different returning jumps of time constants occur which is the reason for transit of phase angle through the values 0° and +90°.

In this paper the frequency–temperature dependences of electrical parameters of the nanocomposite $(\mathrm{FeCoZr})_x(\mathrm{CaF_2})_{100-x}$ fabricated by ion-beam sputtering in a pure argon atmosphere with the metallic phase content $x = 45.7$ at.% are presented.

2. Experimental results and discussion

In Fig. 1 the frequency dependence of phase angle for the nanocomposite $(\mathrm{FeCoZr})_{45.7}(\mathrm{CaF_2})_{54.3}$ samples for seven selected measurement temperatures, which were obtained immediately after fabrication without annealing in the tubular furnace, is presented. The characteristics are similar to those observed in nanocomposites $(\mathrm{FeCoZr})_x(\mathrm{CaF_2})_{100-x}$ produced in oxygen atmosphere [11], $(\mathrm{FeCoZr})_x(\mathrm{PZT})_{100-x}$ [12] and $\mathrm{Cu}_x(\mathrm{SiO_2})_{100-x}$ [13]. The phase angle θ increases with the increasing frequency and changes its value in the range $-15° \le \theta \le +130°$ such as for the measurement temperature $T_{\mathrm{p}} = 248$ K. Nanocomposite annealing at

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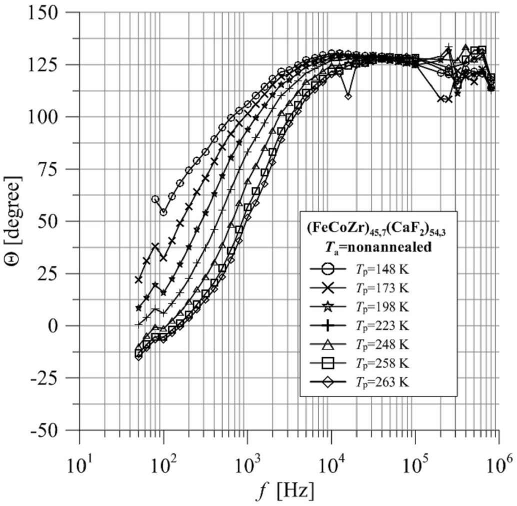

Fig. 1. Frequency dependences of the phase angle θ for the nonannealed nanocomposite $(\mathrm{FeCoZr})_{45.7}(\mathrm{CaF}_2)_{54.3}$ sample measured at different T_{p}.

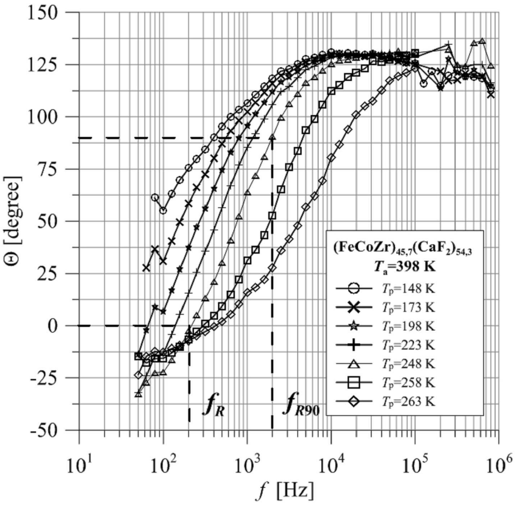

Fig. 2. Frequency dependences of the phase angle θ measured at different T_{p} on the nanocomposite $(\mathrm{FeCoZr})_{45.7}(\mathrm{CaF}_2)_{54.3}$ annealed at $T_{\mathrm{a}} = 398$ K.

$T_{\mathrm{a}} = 398$ K extends the θ changes for the same measurement temperatures toward negative values reaching $\theta = -35°$ (Fig. 2).

Similar to the voltage resonance in the conventional series RLC circuit, compensation of voltages on the capacity and inductance, which gives $\theta = 0$ at the resonance frequency f_{R}, occurs (Fig. 2) with the observed minima at f_{R} in the frequency dependence of the capacity $C_{\mathrm{p}}(f)$ (Fig. 3).

The measurements were performed using an impedance bridge therefore simultaneous measurement of capacitive and inductive components is impossible. As follows from the theory of current resonance

$$\omega_{\mathrm{R}} L - \frac{1}{\omega_{\mathrm{R}} C} = 0, \tag{1}$$

where C is the capacity, L is the inductance of series circuit, $\omega_{\mathrm{R}} = 2\pi f_{\mathrm{R}}$ is the resonance angular frequency. Theoretically, the capacity at the resonance frequency f_{R} exhibits a value close to zero, but the zero value is unlikely to occur because measurements were made with the frequency changes step of 10 points per decade.

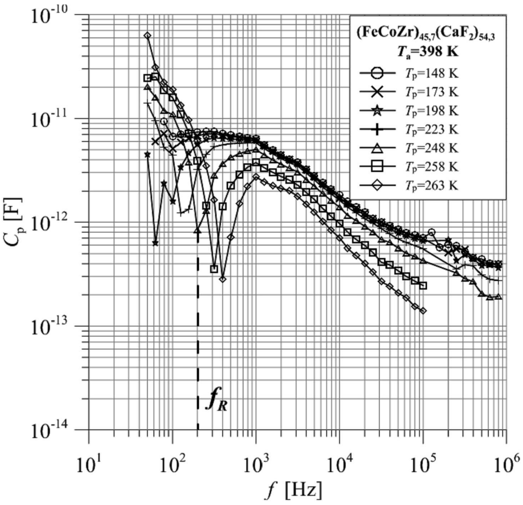

Fig. 3. As in Fig. 2, but for capacity C_{P}.

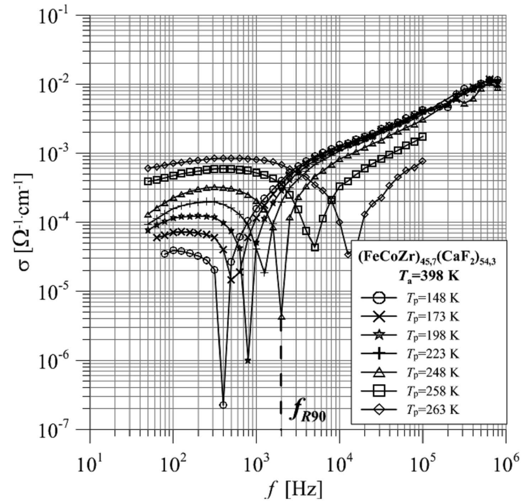

Fig. 4. As in Fig. 2, but for conductivity σ.

When the value θ passes through $+90°$ the phenomena similar to the current resonance in the conventional parallel RLC circuits are observed. This is evident in the case of the frequency dependence of conductivity $\sigma(f)$ (Fig. 4) where σ at the resonance frequency f_{R90} reaches a local minimum. Resonance resistance during the current resonance is much lower than active resistance of the circuit. According to the theory of current resonance, the following condition should be met:

$$R_{\mathrm{R}} = \frac{L_{\mathrm{P}}}{r_{\mathrm{P}} C_{\mathrm{P}}}, \tag{2}$$

where R_{R} is the circuit resistance at the resonance frequency, r_{P} is the circuit active resistance, L_{P} is the inductance measured in a parallel arrangement, and C_{P} is the capacity measured in a parallel arrangement.

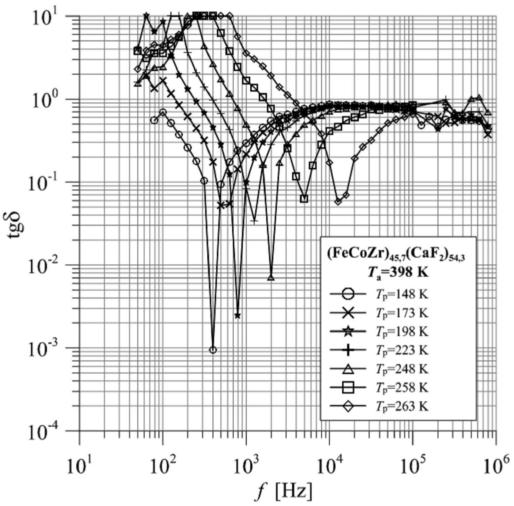

Fig. 5. As in Fig. 2, but for dielectric loss factor $\tan\delta$.

The frequency dependence of the dielectric loss factor $\tan\delta$ confirms that voltage and current resonances occur in the examined nanocomposite, as it is shown in Fig. 5. The maximum of the $\tan\delta$ value corresponds to a voltage resonance — there is only active component of resistance. This would result in an increase of the tangent to infinity, but the maximum range of the meter is limited to the value 10 (see Fig. 5). The minima of $\tan\delta$ are due to large difference between the resistance resonance and active resistance of the circuit at current resonances. From Eq. (2) it follows that:

$$\frac{R_{\mathrm{R}}}{r_{\mathrm{P}}} = \frac{L_{\mathrm{P}}}{r_{\mathrm{P}}^2 C_{\mathrm{P}}} = Q^2 = \frac{1}{\tan^2\delta}, \tag{3}$$

where R_{R} is the circuit resistance at the resonance frequency, Q is the quality factor, and r_{P} is the circuit active resistance.

The angular frequencies at voltage and current resonances (ω_{RS} and ω_{RP}, respectively) can be expressed by the formulae

$$\omega_{\mathrm{RS}} = \frac{1}{\sqrt{L_{\mathrm{S}} C_{\mathrm{S}}}}, \tag{4}$$

where L_{S} and C_{S} are the inductance and the capacity measured in a series arrangement, and analogously

$$\omega_{\mathrm{RP}} = \frac{1}{\sqrt{L_{\mathrm{P}} C_{\mathrm{P}}}}. \tag{5}$$

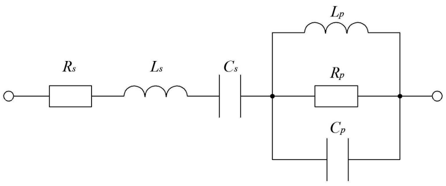

Fig. 6. Equivalent circuit of the nanocomposite $(\mathrm{FeCoZr})_{45.7}(\mathrm{CaF_2})_{54.3}$ annealed at $T_{\mathrm{a}} = 398$ K.

Analyzing the above results there was proposed an equivalent circuit for the studied nanocomposite, consisting of series and parallel RLC circuits which describe the voltage and current resonances, respectively. This scheme is given in Fig. 6.

3. Conclusions

In this paper frequency and temperature dependences of phase angle θ, capacity C_{p}, conductivity σ and dielectric loss factor $\tan\delta$ for the metal–dielectric nanocomposite $(\mathrm{FeCoZr})_x(\mathrm{CaF_2})_{100-x}$ with the metallic phase content $x = 45.7$ at.% produced in pure argon atmosphere were presented.

In low frequency region at the values $\theta < 0$ the nanocomposite demonstrates capacitive type of conduction, while at high frequencies ($\theta > 0°$) it demonstrates inductive type of conduction. Passing of θ through zero in conventional series circuits RLC corresponds to the voltage resonance. The minimum of the dependences $C_{\mathrm{p}}(f)$ and $\sigma(f)$ corresponds to the transit of phase angle θ through 0° and 90°, respectively. The analysis of the results showed that in the nanocomposite there occurs a current resonance phenomenon which results from the transit of the phase angle through the value +90°.

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