Journal of Nano- and Electronic Physics
Vol. **16** No 4, 04001(7pp) (2024)

Журнал нано- та електронної фізики
Том **16** № 4, 04001(7cc) (2024)

OPEN ACCESS

REGULAR ARTICLE

Impedance Spectroscopy of Fe Nanofilms Grown in a Magnetic Field on Gd_2O_3 and Glass

A.M. Kasumov[1], A.I. Dmitriev[1], V.V. Netyaga[1], K.A. Korotkov[1,*] ✉,
Yu.O. Shkurdoda[2], A.I. Yevtushenko1[1]

[1] *Institute for Problems of Materials Science, National Academy of Sciences of Ukraine, 03142 Kyiv, Ukraine*
[2] *Sumy State University, 40007 Sumy, Ukraine*

(Received 10 May 2024; revised manuscript received 14 August 2024; published online 27 August 2024)

The frequency characteristics of impedance, phase difference between current and voltage, hodographs, and corresponding equivalent circuits of Fe nanofilms grown in a constant magnetic field on Gd_2O_3 and silicate glass substrates are investigated. It is shown that with increasing magnetic field strength from 40 E to 1200 E, the morphology of Fe films changes from labyrinthine to continuous, consisting of coalesced iron islands. This complex morphology of the films is the source of the induction and capacitance components of the imaginary part of the impedance. It was found that at a frequency of 630 Hz, a consistent electrical resonance is observed in Fe films, as well as a minimum value of the total impedance. At frequencies above 104 Hz, a sharp change in the impedance components and phase difference is observed in Fe films, which is probably due to the peculiarities of the film morphology. The Nyquist hodographs were constructed and the parameters of the corresponding equivalent circuits were calculated using the ZView computer program. It is shown that both the equivalent schemes of the hodographs and the peculiarities of the frequency dependence of the impedance and phase difference components depend largely on the morphology of the films, which is determined by the elasticity of the magnetic field applied during their growth, as well as by the chemical composition of the substrates. Gd_2O_3 substrates affect Fe films due to the *d-f* exchange interaction between the unfilled f and d electron shells of the atoms that make up the Gd_2O_3 and Fe layers. Silicate glass has an effect due to the ions of technological impurities contained in its composition, which can act as traps for electrons passing through the Fe film.

Keywords: Impedance spectroscopy, Oxide nanofilms, Fe, Gd_2O_3, *d-f* exchange interaction.

DOI: 10.21272/jnep.16(4).04001 PACS number: 73.20. – r

1. INTRODUCTION

The interaction of thin films in contact with and containing atoms with unfilled *d*- and *f*-electron shells has long attracted the attention of researchers due to the prospect of using them to control the magnetic properties of nanoscale devices [1-4].

The next step, which opens up wider possibilities for the use of exchange *d-f* interaction, was the study of contacts of thin films of *d*-metals of the iron group (Fe, Co, Ni) and their oxides (Fe_3O_4) with layers of rare earth *f*-metal oxides (REFMs). An overview of such work carried out in recent years is given in [5]. It has been shown that the exchange *d-f* interaction that occurs in the contact area of Fe, Co, Ni, Fe_3O_4/REM oxide layers leads to an ordering of their magnetic structure, an increase in magnetization, and, accordingly, enhancement of many properties that depend on this characteristic, such as magnetoresistance [6, 7], Faraday effect [8], electron paramagnetic resonance [9], anomalous Hall effect [10, 11], and conductivity of MDM structures [12]. The fact that the amplification occurs in a nanoscale volume without energy consumption and the use of amplifying equipment is particularly valuable, which is promising for use in nanotechnology.

Currently, the effect of exchange *d-f* interaction is used as a method to study the interaction of spins in complex condensed media [1]. The latter is relevant to the creation of flexible high-temperature superconducting materials for use in long-distance power transmission, as well as to the creation of single-electron components of computer technology.

The aim of this work is to study the impedance spectroscopy characteristics [13] of *d*-metal/*f*-oxide RSM structures and the influence of experimental conditions on them: magnetic field during film deposition, as well as substrates of different chemical nature.

The subject of the study were nanoscale Fe films grown in a constant magnetic field on substrates made of a layer of REM oxide (Gd_2O_3) and, for comparison, on silicate glass. The metals Fe and Gd were used because in the iron group (Fe, Co, Ni) and in a number of REMs they have one of the highest values of effective magnetic moment $(\mu)_{Fe}$ =7.13 μ_B and $(\mu)_{Gd}$ = 7.95μ_B according to theory [14], a significant energy of exchange d-f interaction. Fe films were also deposited on silicate glass substrates, with which there was no exchange d-f interaction. The process of growing Fe films in a magnetic field made it possible to control the morphology of these layers. Fe and Gd_2O_3 films were deposited and studied under the following conditions.

* Correspondence e-mail: k.korotkov@ipms.kyiv.ua

Cite this article as: A.M. Kasumov et al., *J. Nano- Electron. Phys.* 16 No 4, 04001 (2024) https://doi.org/10.21272/jnep.16(4).04001

2. CONDITIONS OF THE EXPERIMENT

The Fe and Gd_2O_3 films were deposited on a glass substrate by electron beam evaporation of targets of similar composition from chemically pure reagents. Deposition conditions were as follows: Fe – vacuum $p = 3 \cdot 10^{-3}$ Pa, film growth rate υ = (5-10) nm/min, substrate temperature t = (30-40) °C; Gd_2O_3 – chamber O_2 partial pressure $p_{O2} = 2 \cdot 10^{-2}$ Pa, film growth rate υ = (3-10) nm/min, substrate temperature t = (30-50) °C. The thickness of the Fe film was 30 nm for all samples and 60 nm for Gd_2O_3. For comparison, Fe films were deposited both on the Gd_2O_3 layer and directly on the silica glass substrate. Cu film electrodes were applied to the ends of the Fe film by thermal evaporation to solder conductive wires.

Fe nanofilms were deposited under the influence of a constant magnetic field with a strength in the range of (40÷1200) Oe. The field vector $\vec{H}$ was in the plane of the film and was directed parallel to the current $\vec{I}$ flowing between the Cu electrodes, $\vec{H} \parallel \vec{I}$.

To stabilize the resistance of Fe films, which increases due to oxidation in air after removal from the sputtering chamber, the samples were kept in the atmosphere at room temperature for 3 days. At the same time, the film was covered with a thin layer of oxide, which significantly slows down further oxidation and resistance changes, which made it possible to measure the impedance and its frequency dependence. The surface oxidation of the Fe film was not dangerous, since earlier in [5] we showed that the *d-f* exchange interaction occurs not only at the interface of the RZM oxides with Fe, but also with Fe_3O_4. The Fe_3O_4 magnetite is a semi-metal in terms of conductivity, so it does not interfere with the passage of electrons through the Fe film with a complex morphology.

The following equipment was used for the experiments. The films were deposited on a VU-1A electron beam evaporation apparatus. Microscopic studies of the morphology of the films were performed on a Tescan Mira 3 LMU scanning electron microscope. Electrophase analysis of the Fe films was performed on a JEM 2100 F transmission electron microscope. The impedance frequency response was measured on a Solarton 1250 FRA using the ZPlot computer program. The data were analyzed using the ZView program.

3. RESULTS AND DISCUSSION

3.1 Morphology of Fe Films Grown in a Magnetic Field

Fig. 1 shows the electron microscope images and electron micrographs of Fe films grown on a Gd_2O_3 layer in a constant magnetic field H with an elasticity of 40 Oe (a) and 1200 Oe (b). Fe films grown on silicate glass under similar conditions have similar morphology and structure.

The morphology of Fe films grown on Gd_2O_3 in the absence of a magnetic field (Fig. 1a) is island-like. The islands have an asymmetric shape, which is a consequence of their growth during the oxidation process. The average size of the islands varies in the range of 20 ÷ 100 nm, the surface is heterogeneous with a cluster nanostructure. The size of the coherent scattering regions determined from the electron micrograph by the Selyakov-Scherrer method is 9.8 nm.

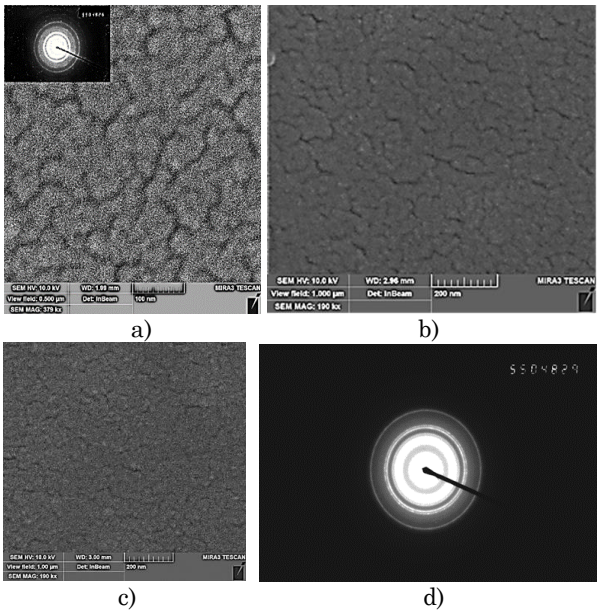


Fig. 1 – The morphology of Fe films grown on Gd_2O_3 in the absence of magnetic field (a) and in a constant magnetic field of 40 Oe (b), 1200 OE (c), their electron pattern (d)

The kinetics of the growth of the resistivity ρ of an Fe film as a function of the exposure time was considered in [5]. It was shown that, at room temperature, the exposure of the films to air, under the influence of a strong electric field, realizes the mechanism of low-temperature Mott oxidation in a double surface layer formed by sorbed O_2 molecules and Fe atoms. This mechanism has a low growth rate of the oxide film.

The Fe islands are separated by gaps with an average width of less than 5 nm (Fig. 1a). This provides a tunneling mechanism of conductivity [7, 15]. An indirect confirmation of this is the linearity of the voltammetric characteristic (Fig. 2), since its linearity is characteristic of both metallic and tunneling mechanisms of charge transfer [7].

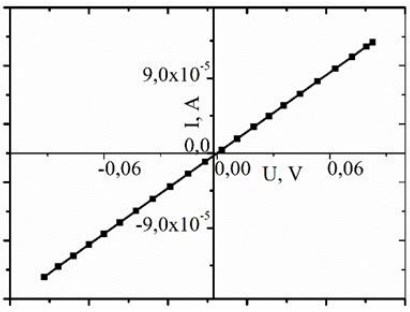


Fig. 2 – Voltammetric characteristic of the sample shown in Fig. 1a

A characteristic feature of 30 nm thick Fe films grown at low field strength H = 40 Oe (Fig. 1b) is the presence of islands with sizes from 20 to 50 nm, which coalesced with each other into chains or areas of various shapes and sizes. The boundaries of the islets' fusion with each other are clearly visible. The chains and areas of coalesced islands are separated by sinuous gaps of about 20 nm in width. The direction of the gap line is chaotic. Taking into account the ferromagnetic

properties of Fe, it can be assumed that the islands observed in the image and the more complex configurations composed of them are of a domain nature. The arrangement of domains observed in Fig. 1b is known in the literature as a labyrinthine arrangement [16].

Electrons in such films move in islands across the boundaries that connect them. Such structures are characterized by a percolation mechanism of charge transfer. This is demonstrated by the dependence of the resistivity ρ of Fe films on the intensity $H < 200$ Oe of the magnetic field applied during their growth on the Gd_2O_3 substrate (1) (Fig. 3).

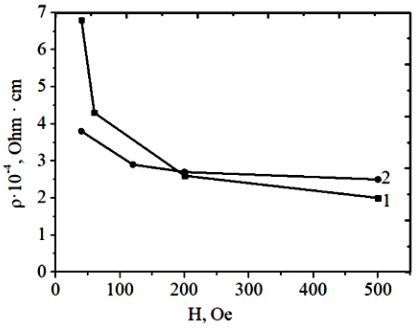


Fig. 3 – The resistivity ρ of Fe films as a function of the intensity i of the magnetic field applied during their growth on Gd_2O_3 (1) and silica glass (2) substrates

At the magnetic field strength used, $H > 200$ E, the coalescence of islands in the growing Fe film (Fig. 1c) increases, forming them into complex configurations and reducing the number of tortuous gaps separating them. The film is formed by large areas of islands that Fig. 4 shows the chemical composition of the surface of the silicate glass in contact with the Fe (a) film are practically fused together. This morphology is characterized by a metallic conduction mechanism. This is demonstrated by the dependence of the resistivity ρ of Fe films on the stress $H > 200$ Oe applied during their growth on the Gd_2O_3 substrate (1) (Fig. 3).

The change in domain structure with increasing intensity of the magnetite field applied to the growing Fe film can occur for many reasons. It is known [17] that in most cases the division of a sample into domains reduces its magnetostatic energy, i.e. the magnetic poles formed on the surface. At the same time, the magnetic structure depends on the magnetic anisotropy and magnetization of the material, the shape of the sample, the presence of defects, the temperature and magnetic field, the type of surface treatment, and the history of the sample. This sensitivity of the domain structure is due to the fact that it is determined by relatively weak magnetodipole interactions.

In the electron diagram (Fig. 1a, c) there are strong lines corresponding to the interplanar distances for Fe: $d_1 = 0.20268$ nm, $d_2 = 0.14332$ nm, $d_3 = 0.17202$ nm [17], and for Fe_3O_4: $d_1 = 0.2967$ nm, $d_2 = 0.2532$ nm, $d_3 = 0.1485$ nm [18]. The Fe film is polycrystalline and the Gd_2O_3 film is amorphous. It can be assumed that the films are a polycrystalline Fe layer coated with a layer of amorphous Fe_3O_4 REM oxide.

The change in the morphology of the Fe film with an increase in the magnitude H of the magnetic field applied to it (Fig. 1) also affects its electrical properties. Fig. 3 shows the dependence of the resistivity ρ on H for Fe films grown on a Gd_2O_3 layer (1) and on silicate glass (2).

From Fig. 3 it can be seen that for both Gd_2O_3 and glass substrates, the magnitude ρ of the Fe film decreases as H increases. This can be explained by the merging of the islands observed in Fig. 1 and the emergence of a percolation mechanism of the conductivity, which at $H > 200$ Oe takes on a metallic character.

Other factors can also affect the ρ of an Fe film. For Fe films deposited on a Gd_2O_3 layer, it is the *d-f* exchange interaction between Fe and Gd_2O_3 [5]. For films deposited on silicate glass, it is the atoms of technological impurities in its structure. The *d-f* exchange interaction further organizes the magnesium nitride structure and the electron spins in the Fe islands. This facilitates the movement of electrons through these formations without the energy required to rotate the spin, i.e. reduces the resistance ρ of the Fe film. The capture of electrons moving in the Fe film by impurity atoms located on the surface of the silicate glass should interfere with the movement of charges, i.e., contribute to an increase in the resistivity ρ. Therefore, at high magnetic field intensity $H > 100$ Oe, when the morphology of the films is homogeneous (Fig. 1b), a decrease in ρ occurs in the Fe film on Gd_2O_3 and, correspondingly, its increase on the glass. At low $H < 100$ Oe, when the films have a labyrinthine morphology (Fig. 1b), the effect of the above factors on ρ becomes chaotic, which does not cause the changes observed at $H > 100$ Oe, as shown in Fig. 3.

Fig. 4 shows the chemical composition of the silicate glass surface in contact with the Fe film.

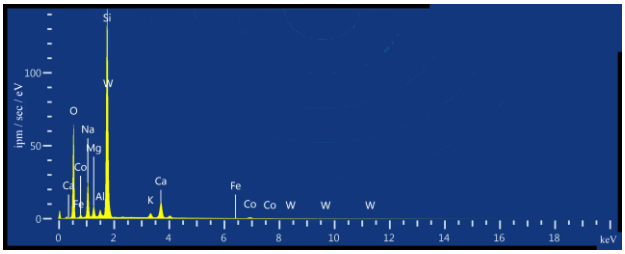


Fig. 4 – Chemical composition of the silicate glass substrate

As can be seen from Fig. 4, the surface of the silica glass contains, in addition to the SiO_2 matrix, atoms of the elements Ca, Al, Mg, Na, K, Co. Since many of these atoms can be in an ionized state (K^+, Na^+, Ca^{2+}, etc.), they will act as traps for electrons moving in the Fe film.

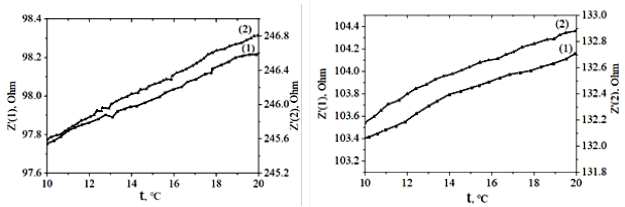


Fig. 5 – Temperature dependence of the active resistance Z' of Fe films grown on Gd_2O_3 (a) and silicate glass (b) at H = 1200 Oe (1) and 40 Oe (2).

Fig. 5 shows the temperature dependence of the active resistance of Fe films grown on Gd_2O_3 substrates (a) and on silicate glass (b) at a magnetic field strength of 1200 Oe (1) and 40 Oe (2).

The growth of the $Z'(t)$ dependence curves corresponds to the charge transfer mechanism in metals described by the well-known relation $R_t = R_0(1 + \alpha t)$. This indicates that electrons in Fe films grown on any substrate (Gd_2O_3, glass) at any magnetic field strength in the range (40÷1200) Oe move along a percolation path composed of coalesced iron islands. At the same time, it is known [16] that Fe films of the same thickness of 30 nm, grown in the absence of magnetic field on the same substrates, have an island morphology and a tunneling mechanism of charge transfer between the islands, characterized by a negative temperature coefficient of resistance. Thus, it is clear that the main factor affecting the charge transfer mechanism in this case is the magnetic field, which controls the growth of the domain structure of the ferromagnetic Fe film.

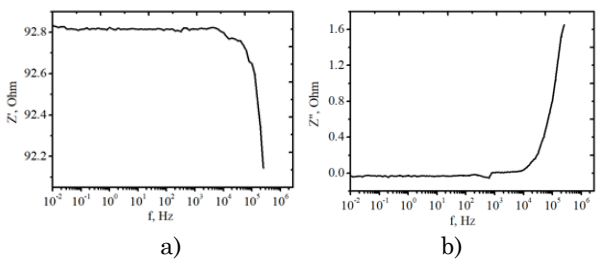
The morphology of Fe films grown in a magnetic field affects not only the active Z' but also the reactive Z'' component of the impedance Z, contributing to the appearance of its inductive ωL and capacitive $1/\omega C$ resistances. Parallel currents passing through islands or island formations will experience induction interaction, resulting in the appearance of the inductive resistance ωL of the entire Fe film. Currents flowing through the boundaries between islands or island formations, which are an obstacle to them due to the accumulation of charge at their edges, are affected by the capacitor effect and, accordingly, the capacitive resistance $1/\omega C$. Thus, the characteristics of the morphology of Fe films grown in a magnetic field will determine the values of ωL, $1/\omega C$ and Z''.

3.2 Characteristics of Impedance Spectroscopy by Fe Nanofilms Grown in a Magnetic Field on a Gd_2O_3 Layer

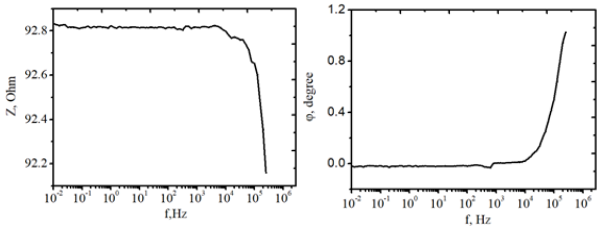
Fig. 6 shows the frequency dependence of the active Z' (a) and the imaginary Z'' (b) components of the impedance Z (c), as well as the phase difference $\varphi(d)$ between the applied voltage $V(\omega t)$ and the current $I(\omega t + \varphi)$ in the Fe film grown on Gd_2O_3 in a magnetic field with a strength of H = 1200 Oe and the direction of the vector $\vec{H} \,||\, \vec{I}$.

Fig. 7 shows a complex hodograph [19] of the frequency dependence of the impedance of an Fe film grown on Gd_2O_3 in a magnetic field.

For all values of the magnetic field strength at frequencies f > 104 Hz, the inductive component dominates in the reactive impedance Z'' (Fig. 6), so that the impedance $Z'' = \omega L$ on the hodograph has a positive value.



a) b)



c) d)

Fig. 6 – Frequency dependence of the components Z' (a) and Z'' (b) of the impedance Z (c) and the phase difference $\varphi(d)$ of the Fe film grown on Gd_2O_3 at H = 1200 Oe

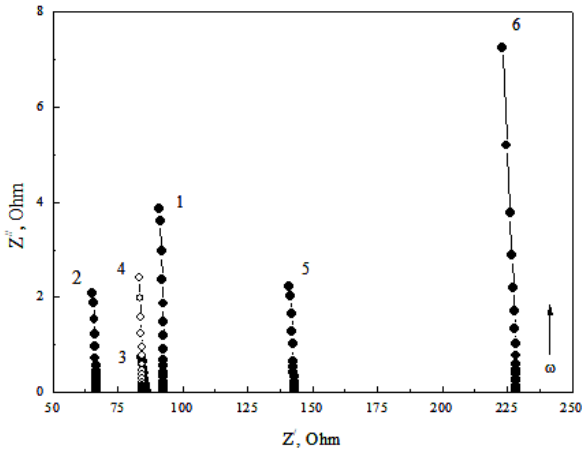


Fig. 7 – Complex hodograph of frequency dependence of impedance of Fe films grown on Gd_2O_3 in magnetic field with strength: 1 – 1200 Oe, 2 – 500 Oe, 3 – 200 Oe, 4 – 120 Oe, 5 – 60 Oe, 6 – 40 Oe and vector direction $\vec{H} \,||\, \vec{I}$

In addition, the value of the active resistance Z' is 2-3 orders of magnitude higher than that of the reactive component Z'' of the impedance in the entire frequency range $f = (10^{-2} \div 10^6)$ Hz studied. This indicates a low value of the inductive ωL and capacitive $1/\omega C$ resistances of the Fe film compared to the active resistance Z' for the current flowing by the percolation type of conduction in the coalesced islands. The value of the total impedance Z is obtained from eq.

$$Z^2 = (Z')^2 + (Z'')^2 \qquad (1)$$

and is approximately equal to the active resistance ($Z \approx Z'$).

For all Fe films grown in a magnetic field on Gd_2O_3, the value of Z'' at f < 630 Hz has a negative sign. From the equation

$$Z'' = \omega L - \frac{1}{\omega C} \qquad (2)$$

it follows that $\omega L < 1/\omega C$. That is, at low frequencies (f < 630 Hz), the main contribution to the imaginary part of the impedance is made by the capacitive resistance $1/\omega C$ between the islands and the island connections $\omega L < 1/\omega C$.

At a frequency of f = 630 Hz, the sign of Z'' changes from negative to positive. This means that at this frequency, where Z'' = 0, then $\omega L = 1/\omega C$. As is well known, this state is defined as an electrical resonance at which the total impedance Z has the smallest value.

The equality of $Z'' = 0$ at $f = 630$ Hz is observed for all Fe films grown on Gd_2O_3. Fig. 8 shows the dependence of Z'' (f) at the lowest 40 Oe (1) and the highest 1200 Oe (2) of the magnetic field strengths used.

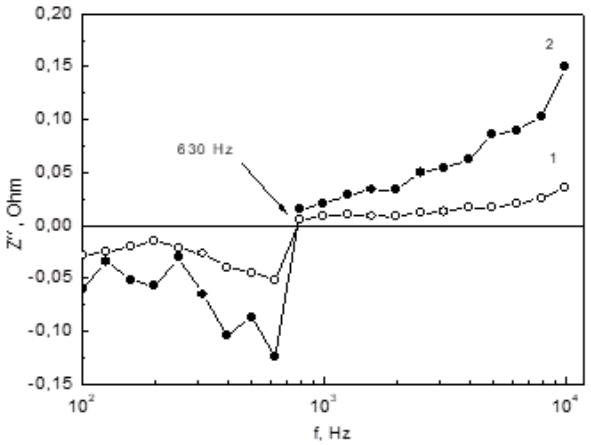


Fig. 8 – Frequency dependence of Z'' for Fe films grown on Gd_2O_3 at $H = 1200$ Oe (1) and 40 Oe (2)

The most likely cause of the resonance at $f = 630$ Hz is the presence of Fe islands of similar shape and size in the morphology of the films (Fig. 1).

The impedance response plots at different magnetic field voltages were modeled using the equivalent circuit shown in Fig. 9.

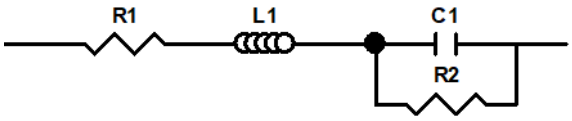


Fig. 9 – Model of the equivalent circuit

The equivalent circuit consists of a resistor $R1$ in series with an inductor $L1$ and a parallel combination of capacitor $C1$ and resistor $R2$. This equivalent circuit provides a satisfactory data fit for all magnetic field voltages applied during film growth. The resistor $R1$ represents the volume resistance of the islands and island groups of the conductive phase. The inductance $L1$ models the effect of shunt current paths through the conductive phase particles on the dielectric matrix layers of the substrate. The capacitor $C1$ and the resistor $R2$ take into account the capacitance of the matrix layers between the particles (or between the clusters) and the resistance of the dielectric matrix interlayers.

Table 1 – Values of the elements of the equivalent substitution scheme for samples of Fe nanofilms on a Gd_2O_3 layer

H, (Oe)	$L1$, (H)	$R1$, (Ohm)	$C1$, (F)	$R2$, (Ohm
1200	$6.31 \cdot 10^{-6}$	0.015	$5.9 \cdot 10^{-10}$	92.79
500	$3.95 \cdot 10^{-6}$	0.11	$7.4 \cdot 10^{-10}$	66.71
200	$4.89 \cdot 10^{-6}$	0.2	$6.3 \cdot 10^{-10}$	85.43
120	$4.90 \cdot 10^{-6}$	0.1	$5.6 \cdot 10^{-10}$	84.44
60	$8.20 \cdot 10^{-6}$	0.047	$3.5 \cdot 10^{-10}$	143
40	$2.67 \cdot 10^{-5}$	0.15	$4.3 \cdot 10^{-10}$	228.4

The resistance $R2$ decreases as the magnetic field strength increases. This is due to the increase in size of the iron nanoparticles along the magnetic direction of the magnetic field in the process of their growth.

3.3 Characteristics of Impedance Spectroscopy of Fe Nanofilms Grown on Silica Glass in a Magnetic Field

In Fe films grown on silicate glass, the resonance state In Fe films grown on silicate glass, the resonance state is reached only when a magnetic field in the range $H = (200 \div 1200)$ Oe is applied. In this case, at $f = 630$ Hz, as for Fe films on Gd_2O_3 (Fig. 6), the equality $Z'' = 0$ and $\omega L = 1/\omega C$, and the sign of Z'' changes. When weak fields with $H = (40 \div 120)$ Oe are used in the growth of Fe films, in the region of $f = 630$ Hz, the value of Z'' is close to but not equal to zero, and its sign remains negative. The described situation is shown in Fig. 10, where the dependence $Z''(f)$ is given for Fe films grown on silicate glass at $H = 120$ Oe (1) and $H = 1200$ Oe (2).

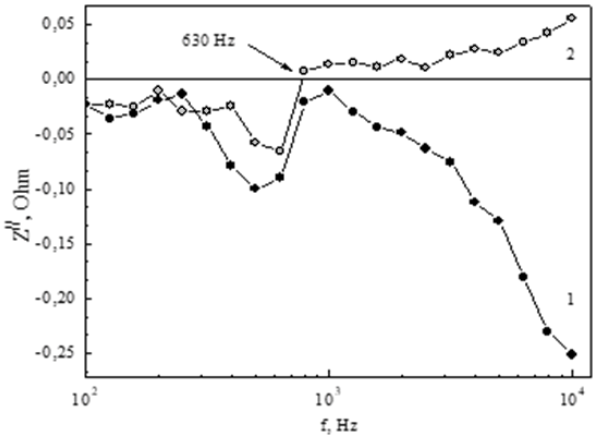


Fig. 10 – Frequency dependence of Z'' for Fe films grown on silicate glass at $H = 120$ Oe (1) and 1200 Oe (2)

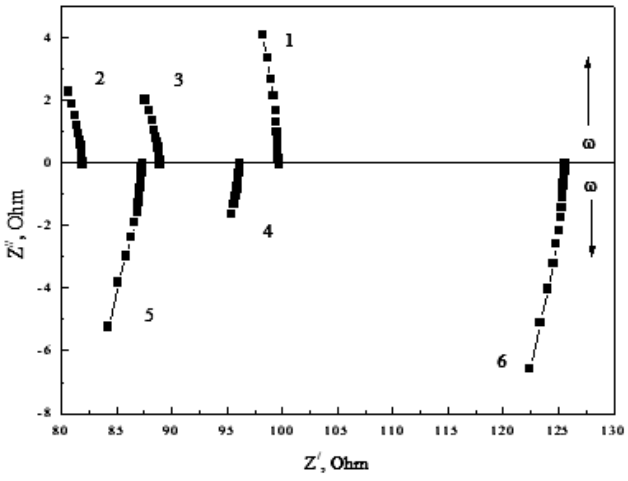


Fig. 11 – Complex hodograph of frequency dependence of impedance of Fe films grown on silicate glass in magnetic field with voltage: 1 – 1200 Oe, 2 – 500 Oe, 3 – 200 Oe, 4 – 120 Oe, 5 – 60 Oe, 6 – 40 Oe

The preservation of the negative sign of Z'' in the region $f < 630$ Hz in Fe films grown in weak fields with $H = (40 \div 120)$ Oe is associated with the presence of electron traps located on the surface of silicate glass

(Fig. 3) and with the labyrinthine morphology of these layers formed at weak magnetic fields (Fig. 1a). In fact, electron capture by impurity ions in glass will be particularly effective in the tortuous gaps between island formations, a large number of which are characteristic of the labyrinthine morphology. Such electron capture by ions will reduce the dielectric constant of the glass and the capacitance C of the capacitor effect, i.e. increase the capacitive resistance $1/\omega C$, leading to the achievement of the inequality $\omega L > 1/\omega C$ and the preservation of the negative sign $Z'' < 0$.

Fig. 11 shows a complex hodograph of the frequency dependence of the impedance of Fe films grown on silicate glass in a magnetic field and in the $\vec{H} \| \vec{I}$ vector direction. The impedance response curves for these films have been modeled using an equivalent circuit, the same as in Fig. 9, and the elements of the equivalent circuit correspond in their physical content to the same processes modeled by them.

The values of the elements of the equivalent substitution scheme for samples of Fe nanofilms on silica glass are given in Table 2.

Table 2 – Values of the elements of the equivalent substitution scheme for samples of Fe nanofilms in silicate glass

H, (Oe)	$L1$, (H)	$R1$, (Ohm)	$C1$, (F)	$R2$, (Ohm)
1200	$2.12 \cdot 10^{-6}$	98.76	$7.84 \cdot 10^{-7}$	0.947
500	$2.78 \cdot 10^{-6}$	77.26	$6.41 \cdot 10^{-8}$	4.51
200	$1.97 \cdot 10^{-6}$	84.55	$6.47 \cdot 10^{-8}$	4.39
120	$5.50 \cdot 10^{-8}$	88.4	$9.33 \cdot 10^{-8}$	7.72
60	$3.10 \cdot 10^{-9}$	81.83	$5.65 \cdot 10^{-8}$	5.51
40	$3.10 \cdot 10^{-9}$	115.6	$2.89 \cdot 10^{-8}$	10

The influence of the magnetic field during film growth leads to an increase in the inductance of the sample. A sharp increase in inductance by more than 2 times occurs at values of the magnetic field H 200 Oe. In this case, the capacitive component dominates the impedance on the complex frequency dependence hodograph for samples grown in a magnetic field from 40 to 120 Oe, so $Z'' = -1/\omega C$ and Z'' has a negative sign. For samples grown in a magnetic field of 200 to 1200 Oe, the inductive component dominates the impedance and $Z'' = \omega L$ has positive values. Such a sharp change in the nature of the conductivity behavior is associated with the effect of the magnetic field on the morphology of the samples under study.

4. CONCLUSIONS

The magnetic field acting on a growing Fe film with a thickness of 30 nm significantly affects the morphology, which allows technological control of its performance characteristics. As the field strength increases in the range (40-1200) Oe, the morphology of Fe films changes from labyrinthine to continuous areas of coalesced islands. The main mechanism of charge transfer in such films is the percolation path composed of coalesced iron islands. In this case, the influence of inductive and capacitive resistances on the film impedance is 2-3 orders of magnitude smaller than that of the active resistance.

At a frequency of 630 Hz, an electrical resonance condition is observed. This may be caused by the equality of the inductive and capacitive resistances of the iron islands forming the film. At frequencies above 10^4 Hz, there is a sharp change in all impedance components and the phase angle between current and voltage.

The influence of substrates on the impedance components of Fe films is due to Gd_2O_3 – the presence of a d-f exchange interaction between Fe and Gd_2O_3, and silicate glass – the presence of impurity ions in it that act as traps for electrons passing through the film.

The work was carried out at the expense of the budgetary topic of the National Academy of Sciences of Ukraine "Optical, magnetic and thermoelectric properties of the newest nanocomposites based on oxide materials" (code III-6-22).

REFERENCES

1. H. Kumar, K.C. Kharkwal, K. Kumar, et al., *J. Phys. Rev. B* **101**, 064405 (2020).
2. P. Farkašovský, H. Čenčariková, *Eur. Phys. J. B* **47**, 517 (2005).
3. K. Kumari, A. Vij, M. Hashim, et al., *AIP Conf. Proc.* **2006**, 030026 (2018).
4. S.K. Sharma, P. Thakur, Sh. Kumar, et al., *Thin Solid Films* **519** No 1, 410 (2010).
5. A.M. Kasumov, A.I. Dmitriev, K.A. Korotkov, et al., *Chem., Phys. Technol. Surf.* **13** No 4, 434 (2022).
6. K. Kawaguchi, M. Sohma, T. Manago, *J. Magn. Magn. Mater.* **198–199**, 513 (1999).
7. J.M. De Teresa, A. Fernández-Pacheco, L. Morellon, et al., *J. Microelectron. Eng.* **84** No 5-8, 1660 (2007).
8. A.M. Kasumov, V.M. Karavayeva, K.O. Shapoval, et al., *Nanosistemi, Nanomateriali, Nanotehnologii* **16** No 1, 181 (2018).
9. H. Han, L. Zhang, H. Liu, et al., *Philosophical Magazine* **95** No 27, 3014 (2015).
10. A.M. Kasumov, A.I. Dmitriev, M.V. Radchenko, et al., *Chem., Phys. Technol. Surf.* **13** No 1, 105 (2022).
11. S.N. Nikolaev, K.Y. Chernoglazov, V.A. Demin, et al., *J. Surf. Investig.* **11**, 549 (2017).
12. A.M. Kasumov, K.O. Shapoval, V.M. Karavayeva, et al., *Powder Metall Met. Ceram.* **58**, 576 (2020).
13. E. Barsukov, I.R. Macdonald, *Impdance Spectroscopy. Theory, Experiment and Applications, Second Edition* (Published by John Willey and Sons: New Jersey: 2005).
14. Priyanka Banerjee, Kausik Mukhopadhyay, *Comput. Theoret. Chem.* **1220**, 114016 (2023).
15. K.A. Korotkov, A.M. Kasumov, A.I. Dmiriev *MSSE2023*, 17 (Lviv, 27-29 September 2023).
16. Zvezdin, V.A. Kotov, *Modern Magnetooptics and Magnetooptical Materials (Condensed Matter Physics)* (Publisher: CRC Press: 1997).
17. *Powder diffraction files (PDF [06-0696]).* https://www.icdd.com/pdfsearch – Powder Diffraction FileTM (PDF ®) Search
18. *Powder diffraction files (PDF [19-629]).* https://www.icdd.com/pdfsearch/.–Powder Diffraction FileTM (PDF ®) Search
19. A.O. Ivanov, *Theory of Automatic Treatment: Pidruchnik* (Dnipropetrovsk: National University of Girnic: 2003) [In Ukrainian].

Імпедансна спектроскопія наноплівок Fe, вирощених у магнітному полі на Gd_2O_3 і склі

А.М. Касумов[1], О.І. Дмитрієв[1], В,В. Нетяга[1], К.А. Коротков[1], Ю.О. Шкурдода[2], А.І. Євтушенко[1]

[1] *Інститут проблем матеріалознавства НАНУ ім. І.М. Францевича, 03142 Київ, Україна*
[2] *Сумський державний університет, 40007 Суми, Україна*

Досліджено частотні характеристики імпедансу, різниці фаз між струмом і напругою, годографи та відповідні їм еквівалентні схеми наноплівок Fe, вирощених у постійному магнітному полі на підкладках Gd_2O_3 і силікатного скла. Показано, що зі зростанням напруженості магнітного поля від 40 Е до 1200 Е морфологія плівок Fe змінюється від лабіринтової до суцільної, що складаються з острівців заліза, які коалесціювали. Така складна морфологія плівок є джерелом виникнення індукційної та емнісної складових уявної частини імпедансу. Встановлено, що за частоти 630 Гц у плівках Fe, спостерігається послідовний електричний резонанс, а також мінімальне значення повного імпедансу. За частот понад 10^4 Гц у плівках Fe спостерігається різка зміна складових імпедансу і різниці фаз, що, імовірно, пов'язано з особливостями морфології плівки. Побудовано годографи Найквіста і виконано програмне обчислення параметрів еквівалентних схем, що їм відповідають, з використанням комп'ютерної програми ZView. Показано, що як еквівалентні схеми годографів, так і особливості частотної залежності складових імпедансу і різниці фаз значною мірою залежать від морфології плівок, що визначається напруженістю магнітного поля, застосованого при їх вирощуванні, а також хімічним складом підкладок. Підкладки Gd_2O_3 впливають на плівки Fe за рахунок обмінної *d-f* взаємодії між незаповненими *f*- і *d*-електронними оболонками атомів, що входять до складу шарів Gd_2O_3 і Fe. Силікатне скло впливає за рахунок йонів технологічних домішок, що входять до його складу, які можуть бути пастками електронів, що проходять плівкою Fe.

Ключові слова: Імпедансна спектроскопія, Осторовкові наноплівки, Fe, Gd_2O_3, Обмінна *d-f* взаємодія.