

## Microscopic theory of the influence of dipole superparamagnetics (type $\langle\beta - CD\langle\text{FeSO}_4\rangle\rangle$ ) on current flow in semiconductor layered structures (type GaSe, InSe)

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A statistical approach to description of the charge carrier transfer processes in hybrid nanostructures taking into account electromagnetic fields is proposed using the method of the nonequilibrium statistical operator Zubarev. Generalized transfer equations are obtained, which describe non-Markov processes of charge transfer in the system taking into account magnetic and polarization processes under the influence of external and induced internal electromagnetic fields. Weakly nonequilibrium charge transfer processes in nanostructures are considered, and a nonequilibrium statistical operator is obtained, by means of which the magneto-diffusion transfer equations for electrons in layered nanostructures are obtained. A generalized Cattaneo-type diffusion equation in time fractional derivatives is obtained for electrons with a characteristic relaxation time and a generalized model is proposed that takes into account the complexity of relaxation electro-magnetic diffusion processes for electrons in layered nanostructures.

**Keywords:** *nonequilibrium statistical operator Zubarev, Cattaneo-type diffusion equation, fractional derivatives.*

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### 1. Introduction

Studies of the influence of magnetization and polarization processes in the electronic subsystem and intercalated layers of complexes on the current flow in the system remain relevant [1–4]. In a recent paper [2] for the system  $\text{SiO}_2(\text{SmCl}_3)$  Nyquist diagrams were constructed — display of full impedance in a complex plane with coordinate axes its real and imaginary parts —  $\text{Re } Z$  —  $\text{Im } Z$ . The diagram shows that after encapsulation of  $\text{SmCl}_3$  the real component of the specific complex impedance ( $\text{Re } Z$ ) in the lowest frequency region (corresponding to the current passage of mainly delocalized carriers) decreases more than four times. At the same time, appearance of the impedance hodograph in the dark changes — a horizontal low-frequency “tail” appears. It is most likely related to the distribution of active resistance (due to the discretization of the energy spectrum). Interestingly, it is stored in a constant magnetic field of 2.75 kOe, which causes a negative magnetoresistive effect, due to Zeeman’s delocalization of carriers from trap centers located near the Fermi level. In addition, the effect of the transition in the low-frequency section of the impedance hodograph to the IV-inductive quadrant of the complex impedance plane under illumination was interesting. Similar behavior was observed in Nyquist diagrams for GaSe [4–6] and from the point of view of theoretical research was interpreted as a subdiffusion impedance based on the Cattaneo-type subdiffusion equations in time fractional derivatives.

The detected phenomenon of photoinduced “negative” capacitance can find its application to solve the problem of forming non-gyrotory nano-dimensional delay lines with optical control. The appearance of a giant negative photocapacity is most likely related to the photoexcitation of electrons from occupied

states below the Fermi level and thus the formation of trap centers for injected electrons with a relaxation time greater than half the sinusoidal signal. To elucidate the mechanisms of such processes, the microscopic approaches to the description of current flow in such systems are required, taking into account their electromagnetic nature.

The effect of external magnetic field on the molecular structure of nanolayers  $\langle\beta - \text{CD}\langle\text{FeSO}_4\rangle\rangle$  containing iron sulfate, the cationic structure of which has a large magnetic moment in the layered structure of GaSe can lead to magnetization of these layers, which affects the change in resistance. If the magnetizations of the layers are parallel, then the electric current associated with the tunneling electrons between these layers through the semiconductor layer will increase, and therefore the resistance will decrease. Conversely, if the magnetizations of the layers are antiparallel, then the probability of electron tunneling decreases sharply, and therefore the resistance increases. The effect of giant magnetoresistance arises due to dependence of the electrons scattering on the direction of their spin relative to the magnetization vector. Electrons whose spin is directed opposite to the direction of magnetization scatter more intensely than those electrons whose spin is oriented in the direction way as the magnetization. Therefore, when magnetizations in the layers are antiparallel, the resistance will increase, and vice versa, when the magnetizations are parallel, the resistance will decrease. It is obvious that the magnetization processes in the layers affect the spin dynamics of the electronic subsystem. This can lead to significant correlations between electron charge fluxes (holes) with correspondingly directed spins and electron charge density gradients. A significant change in charge flux can occur due to induced magnetoelectric interactions. These processes are essentially nonlinear with the complex behavior of relaxation processes associated with magnetoelectric interactions (including internal electric and magnetic fields), leading to magnetization and polarization processes, as evidenced by the dielectric function dependence on frequency and impedance. Internal electric and magnetic fields have a significant effect on the asymmetry of the density of states above and below the Fermi level, which ensures the nature of the current flow. Such processes can also stimulate the emergence of traps for charge carriers, which will affect the current flow, as evidenced by the impedance dependences. The answer to these questions should be sought in studies of the magnetization and polarization processes in the electronic subsystem and intercalated layers of complexes  $\langle\beta - \text{CD}\langle\text{FeSO}_4\rangle\rangle$ . It is important to take into account the system fractality when construction the electron transfer equations and Maxwell's equations for electromagnetic fields. The possible processes of electron tunneling between the modified complexes through the semiconductor matrix layer require a separate study. Similar physical processes of current passage will occur in clathrates GaSe $\langle\text{SmCl}_3\rangle$  with the greatest possible manifestation of magnetic processes.

In terms of models that could be used to describe the correlations between particle fluxes and their density gradients, this is primarily a subdiffusion model based on the Cattaneo equations [4–7], which was used for the modeling system by modifying  $\beta$ -cyclodextrin without FeSO<sub>4</sub>. However, the modification of the Cattaneo equation must take into account the influence of FeSO<sub>4</sub>, as well as the influence of an external magnetic field. It is important to note that a number of phenomenological [8–11] and semi-phenomenological [12, 13] studies are devoted to the development of kinetic theory on the basis of fractional-differential transfer equations to describe the processes of charge carrier transfer in semiconductor structures.

The second section presents the Hamiltonian model of hybrid multilayer nanostructures in an electromagnetic field. The third section proposes a statistical approach to the description of transfer processes in these systems using the method of non-equilibrium statistical operator (NSO) Zubarev [14,15]. To describe the nonequilibrium processes of charge carrier transfer in hybrid nanostructures taking into account magnetism, the nonequilibrium average values of the electron density operators  $\langle n_\sigma(\mathbf{r}) \rangle^t$ , complexes  $\langle n_\sigma^c(\mathbf{r}) \rangle^t$ , and their corresponding densities of magnetic moments  $\langle \mathbf{m}(\mathbf{r}) \rangle^t$ ,  $\langle \mathbf{M}_{\text{ef}}(\mathbf{r}) \rangle^t$  are chosen for the parameters of the reduced description. Here averaging is performed using the nonequilibrium statistical operator  $\varrho(t)$ , which is the NSO method as a delayed solution of the Liouville quantum equation. In the fourth section, using the nonequilibrium statistical operator for the parameters of

the reduced description, generalized transfer equations are obtained, which describe non-Markov current flow processes in the system taking into account magnetic and polarization processes under the influence of external and induced internal electromagnetic fields. In the fifth section, weakly nonequilibrium current-flow processes in nanostructures are considered and a nonequilibrium statistical operator is obtained, by means of which the magneto-diffusion transfer equations for electrons in layered nanostructures are written in the sixth section. In the seventh section, a generalized Cattaneo-type diffusion equation with time fractional derivatives is obtained for electrons with a characteristic relaxation time, and in the eighth section, a generalized model is proposed that takes into account the complexity of relaxation electromagnetic diffusion processes for electrons in layered nanostructures.

## 2. Hamiltonian of the system

From the point of view of theoretical research, it is important to consider the model of a hybrid multilayer nanostructure  $\text{GaSe}\langle\beta - \text{CD}\langle\text{FeSO}_4\rangle\rangle$  in the fields of light, electric and magnetic fields. The Hamiltonian of this model can be represented as:

$$H(t) = H_e + H_{e-\text{ph}} + H_{e-m} + H_{m-\text{ph}} + H_{m-m} + H_{\text{ph}}, \quad (1)$$

$$H_e(t) = \frac{\hbar^2}{2m_2} \sum_{j=1}^{N_e} \left( \nabla_j - \frac{e}{c} \mathbf{A}(\mathbf{r}_j; t) \right)^2 + H_{ee} + H_s + H_{\text{ef}}(t) + \sum_{j=1}^{N_e} e\Phi(\mathbf{r}_j; t) \quad (2)$$

is the Hamiltonian of the electronic subsystem,  $H_{ee}$  is the Hamiltonian of effective electron-electron interaction and  $H_{e-\text{ph}}$  is the Hamiltonian of the electron-phonon interaction in the nanostructure.  $\mathbf{A}(\mathbf{r}_j; t)$ ,  $\Phi(\mathbf{r}_j; t)$  there are vector and scalar potentials of the electromagnetic field acting on electrons and macromolecules in the nanostructure, including internal and external fields.  $H_{e-m}$  is the Hamiltonian of the interaction of electrons and polarized macromolecules, in particular  $\beta$ -cyclodextrin modified  $\text{FeSO}_4$ .

The complexes  $\langle\beta - \text{CD}\langle\text{FeSO}_4\rangle\rangle$  are dipole superparamagnetics in a layered GaSe structure. Therefore, in electric and magnetic fields, they will be polarized and magnetized, respectively, and through magnetoelectric interaction with the electronic subsystem can affect the current flow in the system.

The current passage through the molecular structure of nanolayers, which contain iron sulfate, may be due to primarily by the charge carriers interaction of the matrix with  $d$ -electrons of iron.

$H_{m-\text{ph}}$  is the Hamiltonian of the interaction of complexes  $\langle\beta - \text{CD}\langle\text{FeSO}_4\rangle\rangle$  in layers with a matrix structure, and  $H_{m-m}$  is the Hamiltonian interaction between complexes in layers and between layers.

$$H_s = -\hbar\omega_s \sum_j s_j^z \quad (3)$$

is a Zeeman energy of electrons,  $s_j^z$  is a component of the electron spin vector,

$$\begin{aligned} H_{\text{ef}}(t) &= -g_s\mu_0 \left( \sum_j \mathbf{s}_j \mathbf{B}(\mathbf{r}_j; t) + \sum_j \mathbf{S}_j \mathbf{B}(\mathbf{r}_j; t) \right) \\ &= \int d\mathbf{r} \mathbf{m}(\mathbf{r}) \mathbf{B}(\mathbf{r}; t) + \int d\mathbf{r} \mathbf{M}_{\text{ef}}(\mathbf{r}) \mathbf{B}(\mathbf{r}; t) \end{aligned} \quad (4)$$

is an interaction of electron spins and complexes with an alternating magnetic field  $\mathbf{B}(\mathbf{r}_j; t)$ ,  $\mathbf{m}(\mathbf{r}) = \sum_j \mathbf{s}_j \delta(\mathbf{r} - \mathbf{r}_j)$  is the density of the magnetic moment of electrons,  $\mathbf{M}_{\text{ef}}(\mathbf{r}) = \sum_j \mathbf{S}_j \delta(\mathbf{r} - \mathbf{r}_j)$  is the operator of the magnetic moment density of complexes intercalated into a nanostructure.

$$H_{ee} = V_{ee} + H_d + H_{\text{ds}}, \quad (5)$$

$V_{ee}$  is a potential for effective electrostatic interaction of electrons,

$$H_d = -\frac{1}{2} \sum_{l \neq j} J(\mathbf{r}_{lj}) \mathbf{s}_l \mathbf{s}_j \quad (6)$$

is an exchange magnetic interaction of conduction electrons with the exchange integral  $J(\mathbf{r}_{lj})$ ,

$$H_{ds} = -U \sum_{\mathbf{q}} \mathbf{s}_{\mathbf{q}} \bar{\mathbf{s}}_{-\mathbf{q}} \quad (7)$$

is an exchange magnetic interaction of conduction electrons and localized electrons with the exchange integral  $U$ ,  $\mathbf{s}_{\mathbf{q}}$  and  $\bar{\mathbf{s}}_{\mathbf{q}}$  are Fourier components of the spin densities of conduction electrons and localized electrons,  $\bar{\mathbf{s}}_{\mathbf{q}} = \sum_f e^{i\mathbf{q}\mathbf{r}_f} \bar{\mathbf{s}}_f$ ,  $\bar{\mathbf{s}}_f$  is the spin of an electron localized at the  $f$ -node.

Obviously, this is not a complete Hamiltonian of such a complex system, but the magnetic component is taken into account the most. In addition, it is important to take into account in  $H_{m-m}$  the dipole-dipole interaction of complexes  $\langle \beta - \text{CD}(\text{FeSO}_4) \rangle$  in the layered structure of GaSe, as well as in  $H_{m-e}$  an interaction of electrons with these dipole superparamagnetics.

In the next section, we propose a statistical approach to the description of these processes by the method of nonequilibrium statistical operator and obtain generalized transfer equations for charge carriers with Hamiltonian (1) to describe the processes of current passage in such hybrid nanostructures.

### 3. Non-equilibrium statistical system operator

To describe the nonequilibrium processes of charge carrier transfer in hybrid nanostructures taking into account magnetism, we choose the nonequilibrium average values of the electron density operators  $\langle n_{\sigma}(\mathbf{r}) \rangle^t$ , complexes  $\langle n_{\bar{\sigma}}^c(\mathbf{r}) \rangle^t$ , and their respective densities of magnetic moments  $\langle \mathbf{m}(\mathbf{r}) \rangle^t$ ,  $\langle \mathbf{M}_{\text{ef}}(\mathbf{r}) \rangle^t$  as the parameters of the reduced description. Here  $\langle (\dots) \rangle^t = \text{Sp}(\dots \varrho(t))$  averaging is performed using the nonequilibrium statistical operator  $\varrho(t)$ , which is the method of NSO [14, 15], as delayed solutions of the Liouville quantum equation:

$$\varrho(t) = \varrho_{\text{rel}}(t) - \int_{-\infty}^t e^{\varepsilon(t'-t)} T(t, t') (1 - P_{\text{rel}}(t')) iL(t') \varrho_{\text{rel}}(t') dt', \quad (8)$$

where  $iL(t')$  is the Liouville operator corresponding to the Hamiltonian of the problem (1),  $T(t, t') = \exp(-\int_{t'}^t (1 - P_{\text{rel}}(t'')) iL(t'') dt'')$  is a generalized evolution operator with the Kawasaki–Ganton projection  $P_{\text{rel}}(t')$ , the structure of which depends on the parameters of the reduced description and the relevant (quasi-equilibrium) statistical operator  $\varrho_{\text{rel}}(t)$ .

In Zubarev's method  $\varrho_{\text{rel}}(t)$  is found from the extremum of information entropy (the Gibbs entropy) at fixed values of the observed variables (in our case fixed) and preserved normalization conditions  $\int d\Gamma \varrho_{\text{rel}}(t) = 1$  [14, 15]:

$$\varrho_{\text{rel}}(t) = \exp \left\{ -\Phi(t) - \beta(t) \left( H(t) - \sum_{\sigma} \int d\mathbf{r} n_{\sigma}(\mathbf{r}) \nu_{\sigma}(\mathbf{r}; t) - \sum_{\bar{\sigma}} \int d\mathbf{r} n_{\bar{\sigma}}^c(\mathbf{r}) \nu_{\bar{\sigma}}^c(\mathbf{r}; t) - \int d\mathbf{r} \mathbf{m}(\mathbf{r}) \mathbf{b}(\mathbf{r}; t) - \int d\mathbf{r} \mathbf{M}_{\text{ef}}(\mathbf{r}) \mathbf{b}'(\mathbf{r}; t) \right) \right\}, \quad (9)$$

where  $n_{\sigma}(\mathbf{r})$  is an electron density operator with the corresponding spin direction  $\sigma = \uparrow, \downarrow$ , and  $n_{\bar{\sigma}}^c(\mathbf{r})$  is the operator of the density of complexes in the direction of spins  $\bar{\sigma} = \uparrow, \downarrow$ , intercalated into a nanostructure,  $\beta(t)$  is the inverse of the nonequilibrium temperature of the system,  $\nu_{\sigma}(\mathbf{r}; t) = \mu_{\sigma}(\mathbf{r}; t) - e\varphi(\mathbf{r}; t)$ ,  $\mu_{\sigma}(\mathbf{r}; t)$  is an electrochemical and chemical potential of electrons with the corresponding direction of spins, respectively,  $\nu_{\bar{\sigma}}^c(\mathbf{r}; t) = \mu_{\bar{\sigma}}^c(\mathbf{r}; t) + \mathbf{d}_{\text{ef}} \cdot \mathbf{e}(\mathbf{r}; t)$  is a dipole-chemical potential of complexes with the corresponding direction of spins,  $\mathbf{d}_{\text{ef}}$  is their effective dipole moment,  $\varphi(\mathbf{r}; t)$  is a scalar potential of the internal electromagnetic field with voltages  $\mathbf{e}(\mathbf{r}; t)$  and  $\mathbf{b}(\mathbf{r}; t)$ .  $\Phi(t)$  is the Masier–Planck functionality:

$$\Phi(t) = \ln \text{Sp} \exp \left\{ -\beta(t) \left( H(t) - \sum_{\sigma} \int d\mathbf{r} n_{\sigma}(\mathbf{r}) \nu_{\sigma}(\mathbf{r}; t) - \sum_{\bar{\sigma}} \int d\mathbf{r} n_{\bar{\sigma}}^c(\mathbf{r}) \nu_{\bar{\sigma}}^c(\mathbf{r}; t) - \int d\mathbf{r} \mathbf{m}(\mathbf{r}) \mathbf{b}(\mathbf{r}; t) - \int d\mathbf{r} \mathbf{M}_{\text{ef}}(\mathbf{r}) \mathbf{b}'(\mathbf{r}; t) \right) \right\}, \quad (10)$$

in which the non-equilibrium Lagrange parameters  $\beta(t)$ ,  $\nu_{\sigma}(\mathbf{r}; t)$ ,  $\nu_{\bar{\sigma}}^c(\mathbf{r}; t)$ ,  $\mathbf{b}(\mathbf{r}; t)$ ,  $\mathbf{b}'(\mathbf{r}; t)$  are determined from the terms of self-agreement:

$$\begin{aligned} \langle H(t) \rangle^t &= \langle H(t) \rangle_{\text{rel}}^t, & \langle n_{\sigma}(\mathbf{r}) \rangle^t &= \langle n_{\sigma}(\mathbf{r}) \rangle_{\text{rel}}^t, & \langle n_{\bar{\sigma}}^c(\mathbf{r}) \rangle^t &= \langle n_{\bar{\sigma}}^c(\mathbf{r}) \rangle_{\text{rel}}^t, \\ \langle \mathbf{m}(\mathbf{r}) \rangle^t &= \langle \mathbf{m}(\mathbf{r}) \rangle_{\text{rel}}^t, & \langle \mathbf{M}_{\text{ef}}(\mathbf{r}) \rangle^t &= \langle \mathbf{M}_{\text{ef}}(\mathbf{r}) \rangle_{\text{rel}}^t. \end{aligned} \quad (11)$$

Based on the Gibbs entropy definition and the conditions of self-agreement (11), we obtain the Gibbs entropy of nonequilibrium processes in the system under consideration:

$$\begin{aligned} S(t) &= -\langle \ln \varrho_{\text{rel}}(t) \rangle_{\text{rel}}^t \\ &= \Phi(t) + \beta(t) \left( H(t) - \sum_{\sigma} \int d\mathbf{r} \langle n_{\sigma}(\mathbf{r}) \rangle^t \nu_{\sigma}(\mathbf{r}; t) - \sum_{\bar{\sigma}} \int d\mathbf{r} \langle n_{\bar{\sigma}}^c(\mathbf{r}) \rangle^t \nu_{\bar{\sigma}}^c(\mathbf{r}; t) - \int d\mathbf{r} \langle \mathbf{m}(\mathbf{r}) \rangle^t \mathbf{b}(\mathbf{r}; t) - \int d\mathbf{r} \langle \mathbf{M}_{\text{ef}}(\mathbf{r}) \rangle^t \mathbf{b}'(\mathbf{r}; t) \right), \end{aligned} \quad (12)$$

where

$$\begin{aligned} S(t) &= -\langle \ln \varrho_{\text{rel}}(t) \rangle_{\text{rel}}^t \\ &= \Phi(t) + \beta(t) \left( H(t) - \sum_{\sigma} \int d\mathbf{r} \langle n_{\sigma}(\mathbf{r}) \rangle^t (\mu_{\sigma}(\mathbf{r}; t) - e\varphi(\mathbf{r}; t)) - \sum_{\bar{\sigma}} \int d\mathbf{r} \langle n_{\bar{\sigma}}^c(\mathbf{r}) \rangle^t (\mu_{\bar{\sigma}}^c(\mathbf{r}; t) + \mathbf{d}_{\text{ef}} \cdot \mathbf{e}(\mathbf{r}; t)) - \int d\mathbf{r} \langle \mathbf{m}(\mathbf{r}) \rangle^t \mathbf{b}(\mathbf{r}; t) - \int d\mathbf{r} \langle \mathbf{M}_{\text{ef}}(\mathbf{r}) \rangle^t \mathbf{b}'(\mathbf{r}; t) \right), \end{aligned} \quad (13)$$

where, in particular,  $\langle n_{\sigma}(\mathbf{r}) \rangle^t e = \rho_{e\sigma}(\mathbf{r}; t)$  is the nonequilibrium value of the electron charge density with the appropriate direction of the spins,  $\langle n_{\bar{\sigma}}^c(\mathbf{r}) \rangle^t \mathbf{d}_{\text{ef}} = \mathbf{d}_c(\mathbf{r}; t)$  is the nonequilibrium value of the dipole charge density of magnetic complexes  $\langle\beta - \text{CD}\langle\text{FeSO}_4\rangle\rangle$ .

Explaining the action of the operators  $iL(t)$ ,  $(1 - P_{\text{rel}}(t'))$  on  $\varrho_{\text{rel}}(t)$ , for the nonequilibrium statistical operator we obtain:

$$\begin{aligned} \varrho(t) &= \varrho_{\text{rel}}(t) - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t'-t)} T(t, t') \left( \sum_{\sigma} I_{n_{\sigma}}^e(\mathbf{r}'; t', \tau) \beta(t') \nu_{\sigma}(\mathbf{r}'; t') + \sum_{\bar{\sigma}} I_{n_{\bar{\sigma}}^c}^c(\mathbf{r}'; t', \tau) \beta(t') \nu_{\bar{\sigma}}^c(\mathbf{r}'; t') + I_m(\mathbf{r}'; t', \tau) \beta(t') \mathbf{b}(\mathbf{r}'; t') + I_M(\mathbf{r}'; t', \tau) \beta(t') \mathbf{b}'(\mathbf{r}'; t') \right) dt', \end{aligned} \quad (14)$$

where  $I_l(\mathbf{r}'; t', \tau) = \int_0^1 \varrho_{\text{rel}}^{\tau}(t') I_l(\mathbf{r}'; t') \varrho_{\text{rel}}^{-\tau}(t') d\tau$ ,

$$I_{n_{\sigma}}^e(\mathbf{r}'; t') = (1 - P(t')) iL(t') n_{\sigma}(\mathbf{r}'), \quad I_{n_{\bar{\sigma}}^c}^c(\mathbf{r}'; t') = (1 - P(t')) iL(t') n_{\bar{\sigma}}^c(\mathbf{r}'), \quad (15)$$

$$I_m(\mathbf{r}'; t') = (1 - P(t')) iL(t') \mathbf{m}(\mathbf{r}'), \quad I_M(\mathbf{r}'; t') = (1 - P(t')) iL(t') \mathbf{M}_{\text{ef}}(\mathbf{r}')$$

are generalized flows with the Mori projection operator  $P(t')$ , built on operators  $A_l(\mathbf{r})$ :  $A_1(\mathbf{r}) = n_{\sigma}(\mathbf{r})$ ,  $A_2(\mathbf{r}) = n_{\bar{\sigma}}^c(\mathbf{r})$ ,  $A_3(\mathbf{r}) = \mathbf{m}(\mathbf{r})$ ,  $A_4(\mathbf{r}) = \mathbf{M}_{\text{ef}}(\mathbf{r})$ :

$$P(t)A(\mathbf{r}) = \langle A(\mathbf{r}) \rangle_{\text{rel}}^t + \sum_l \int d\mathbf{r} \frac{\delta \langle A(\mathbf{r}) \rangle_{\text{rel}}^t}{\delta \langle A_l(\mathbf{r}) \rangle^t} (\langle A_l(\mathbf{r}) \rangle - \langle A_l(\mathbf{r}) \rangle^t) \quad (16)$$

with properties  $P(t)P(t') = P(t)$ ,  $P(t)(1 - P(t')) = 0$ ,  $P(t)A_l(\mathbf{r}) = A_l(\mathbf{r})$ . Generalized fluxes describe the processes of electron transfer taking into account the magnetic-polarization processes in a system with magnetic complexes embedded in the structure under the influence of light, magnetic field.

The nonequilibrium statistical operator (14) is a functional of the reduced description parameters for the average values of the electron densities operators  $\langle n_\sigma(\mathbf{r}) \rangle^t$ , complexes  $\langle n_{\bar{\sigma}}^c(\mathbf{r}) \rangle^t$  and their corresponding densities of magnetic moments  $\langle \mathbf{m}(\mathbf{r}) \rangle^t$ ,  $\langle \mathbf{M}_{\text{ef}}(\mathbf{r}) \rangle^t$  and generalized streams  $I_l(\mathbf{r}'; t')$  is the basis for constructing generalized transfer equations for the parameters of the reduced description.

#### 4. Generalized transfer equations

Using the nonequilibrium statistical operator (14) for parameters of the reduced description, the generalized transfer equations can be obtained, which are presented in matrix form:

$$\frac{\partial}{\partial t} \langle \tilde{A}(\mathbf{r}) \rangle^t = \langle \dot{\tilde{A}}(\mathbf{r}) \rangle_{\text{rel}}^t - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t-t')} \tilde{W}_{II}(\mathbf{r}, \mathbf{r}'; t, t') \tilde{F}(\mathbf{r}'; t') dt', \quad (17)$$

where  $\tilde{A}(\mathbf{r}) = \text{col}(n_\sigma(\mathbf{r}), n_{\bar{\sigma}}^c(\mathbf{r}), \mathbf{m}(\mathbf{r}), \mathbf{M}_{\text{ef}}(\mathbf{r}))$  is a vector column,  $\tilde{A}^{(+)}(\mathbf{r}) = (n_\sigma(\mathbf{r}), n_{\bar{\sigma}}^c(\mathbf{r}), \mathbf{m}(\mathbf{r}), \mathbf{M}_{\text{ef}}(\mathbf{r}))$  is a row vector,  $\tilde{F}^{(+)}(\mathbf{r}; t) = (\beta(t)\nu_\sigma(\mathbf{r}; t), \beta(t)\nu_{\bar{\sigma}}^c(\mathbf{r}; t), \beta(t)\mathbf{b}(\mathbf{r}; t), \beta(t)\mathbf{b}'(\mathbf{r}; t))$  is a row vector,  $\dot{\tilde{A}}(\mathbf{r}) = iL\tilde{A}(\mathbf{r})$ .

$$\tilde{W}_{II}(\mathbf{r}, \mathbf{r}'; t, t') = \text{Sp} \left( \tilde{I}(\mathbf{r}; t) T(t, t') \int_0^1 \varrho_{\text{rel}}^\tau(t') \tilde{I}^{(+)}(\mathbf{r}'; t') \varrho_{\text{rel}}^{1-\tau}(t') d\tau \right) = \begin{vmatrix} \tilde{W}_{I_n I_n} & \tilde{W}_{I_n I_m} \\ \tilde{W}_{I_m I_n} & \tilde{W}_{I_m I_m} \end{vmatrix}_{(\mathbf{r}, \mathbf{r}'; t, t')} \quad (18)$$

is a block matrix of transfer nuclei, where  $\tilde{I}(\mathbf{r}; t) = \text{col}(I_{n\sigma}^e(\mathbf{r}; t), I_{n\bar{\sigma}}^c(\mathbf{r}; t), I_m(\mathbf{r}'; t'), I_M(\mathbf{r}'; t'))$  is a column vector and  $\tilde{I}^{(+)}(\mathbf{r}; t) = (I_{n\sigma}^e(\mathbf{r}; t), I_{n\bar{\sigma}}^c(\mathbf{r}; t), I_m(\mathbf{r}'; t'), I_M(\mathbf{r}'; t'))$  is a row vector of generalized flows. The matrix  $\tilde{W}_{I_n I_n}(\mathbf{r}, \mathbf{r}'; t, t')$  is a block matrix with the following structure:

$$\tilde{W}_{I_n I_n}(\mathbf{r}, \mathbf{r}'; t, t') = \begin{vmatrix} \tilde{W}_{I_n I_n}^{ee} & \tilde{W}_{I_n I_m}^{ec} \\ \tilde{W}_{I_m I_n}^{ce} & \tilde{W}_{I_m I_m}^{cc} \end{vmatrix}_{(\mathbf{r}, \mathbf{r}'; t, t')} \quad (19)$$

where

$$\tilde{W}_{I_n I_n}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') = \begin{vmatrix} W_{I_n \uparrow I_n \uparrow}^{ee} & W_{I_n \uparrow I_n \downarrow}^{ee} \\ W_{I_n \downarrow I_n \uparrow}^{ee} & W_{I_n \downarrow I_n \downarrow}^{ee} \end{vmatrix}_{(\mathbf{r}, \mathbf{r}'; t, t')} \quad (20)$$

is a matrix whose elements describe the temporal-spatial correlations of electron flows with the corresponding orientations of the spins,

$$\tilde{W}_{I_n I_n}^{ec}(\mathbf{r}, \mathbf{r}'; t, t') = \begin{vmatrix} W_{I_n \uparrow I_n \uparrow}^{ec} & W_{I_n \uparrow I_n \downarrow}^{ec} \\ W_{I_n \downarrow I_n \uparrow}^{ec} & W_{I_n \downarrow I_n \downarrow}^{ec} \end{vmatrix}_{(\mathbf{r}, \mathbf{r}'; t, t')} \quad (21)$$

$$\tilde{W}_{I_n I_n}^{ce}(\mathbf{r}, \mathbf{r}'; t, t') = \begin{vmatrix} W_{I_n \uparrow I_n \uparrow}^{ce} & W_{I_n \uparrow I_n \downarrow}^{ce} \\ W_{I_n \downarrow I_n \uparrow}^{ce} & W_{I_n \downarrow I_n \downarrow}^{ce} \end{vmatrix}_{(\mathbf{r}, \mathbf{r}'; t, t')} \quad (22)$$

are the matrices, elements of which describe the temporal-spatial correlations of electron flows with flows (dipole orientations) of complexes with corresponding spin orientations,

$$\tilde{W}_{I_n I_n}^{cc}(\mathbf{r}, \mathbf{r}'; t, t') = \begin{vmatrix} W_{I_n \uparrow I_n \uparrow}^{cc} & W_{I_n \uparrow I_n \downarrow}^{cc} \\ W_{I_n \downarrow I_n \uparrow}^{cc} & W_{I_n \downarrow I_n \downarrow}^{cc} \end{vmatrix}_{(\mathbf{r}, \mathbf{r}'; t, t')} \quad (23)$$

is a matrix whose elements describe temporal–spatial correlations between flows (dipole orientations) of complexes with corresponding spin orientations.

$$\tilde{W}_{I_n I_M}(\mathbf{r}, \mathbf{r}'; t, t') = \begin{vmatrix} W_{I_n \uparrow I_M}^e & W_{I_n \uparrow I_M}^e \\ W_{I_n \downarrow I_M}^e & W_{I_n \downarrow I_M}^e \\ W_{I_n \uparrow I_M}^c & W_{I_n \uparrow I_M}^c \\ W_{I_n \downarrow I_M}^c & W_{I_n \downarrow I_M}^c \end{vmatrix}_{(\mathbf{r}, \mathbf{r}'; t, t')} \quad (24)$$

$$\tilde{W}_{I_M I_n}(\mathbf{r}, \mathbf{r}'; t, t') = \begin{vmatrix} W_{I_M I_n \uparrow}^e & W_{I_M I_n \uparrow}^e & W_{I_M I_n \uparrow}^c & W_{I_M I_n \uparrow}^c \\ W_{I_M I_n \downarrow}^e & W_{I_M I_n \downarrow}^e & W_{I_M I_n \downarrow}^c & W_{I_M I_n \downarrow}^c \end{vmatrix}_{(\mathbf{r}, \mathbf{r}'; t, t')} \quad (25)$$

are the matrices, elements (transfer nuclei) of which describe the temporal-spatial correlations of the electron fluxes (dipole orientations) of complexes with corresponding spin orientations with generalized magnetic fluxes of electrons  $I_m(\mathbf{r}; t)$  and magnetic complexes  $I_M(\mathbf{r}; t)$ ,

$$\tilde{W}_{I_M I_M}(\mathbf{r}, \mathbf{r}'; t, t') = \begin{vmatrix} W_{I_M I_M} & W_{I_M I_M} \\ W_{I_M I_M} & W_{I_M I_M} \end{vmatrix}_{(\mathbf{r}, \mathbf{r}'; t, t')} \quad (26)$$

is a matrix whose elements (transfer nuclei) describe time-space correlations between generalized magnetic fluxes of electrons  $I_m(\mathbf{r}; t)$  and generalized fluxes of magnetic complexes  $I_M(\mathbf{r}; t)$ . In expanded form, the transfer equations have the following structure:

$$\begin{aligned} \frac{\partial}{\partial t} \langle n_\sigma(\mathbf{r}) \rangle^t &= - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_n \sigma I_n \sigma'}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') (\mu_{\sigma'}(\mathbf{r}'; t') - e\varphi(\mathbf{r}'; t')) dt' \\ &\quad - \int d\mathbf{r}' \sum_{\bar{\sigma}'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_n \sigma I_n \bar{\sigma}'}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') (\mu_{\bar{\sigma}'}(\mathbf{r}'; t') + \mathbf{d}_{ef} \cdot \mathbf{e}(\mathbf{r}'; t')) dt' \\ &\quad - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_n \sigma I_m}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') \mathbf{b}(\mathbf{r}'; t') dt' \\ &\quad - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_n \sigma I_M}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') \mathbf{b}'(\mathbf{r}'; t') dt', \end{aligned} \quad (27)$$

$$\begin{aligned} \frac{\partial}{\partial t} \langle \mathbf{m}(\mathbf{r}) \rangle^t &= \langle \dot{\mathbf{m}}(\mathbf{r}) \rangle^t - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_m I_n \sigma'}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') (\mu_{\sigma'}(\mathbf{r}'; t') - e\varphi(\mathbf{r}'; t')) dt' \\ &\quad - \int d\mathbf{r}' \sum_{\bar{\sigma}'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_m I_n \bar{\sigma}'}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') (\mu_{\bar{\sigma}'}(\mathbf{r}'; t') + \mathbf{d}_{ef} \cdot \mathbf{e}(\mathbf{r}'; t')) dt' \\ &\quad - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_m I_m}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') \mathbf{b}(\mathbf{r}'; t') dt' \\ &\quad - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_m I_M}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') \mathbf{b}'(\mathbf{r}'; t') dt', \end{aligned} \quad (28)$$

$$\begin{aligned} \frac{\partial}{\partial t} \langle n_{\bar{\sigma}}(\mathbf{r}) \rangle^t &= - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_n \bar{\sigma} I_n \sigma'}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') (\mu_{\sigma'}(\mathbf{r}'; t') - e\varphi(\mathbf{r}'; t')) dt' \\ &\quad - \int d\mathbf{r}' \sum_{\bar{\sigma}'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_n \bar{\sigma} I_n \bar{\sigma}'}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') (\mu_{\bar{\sigma}'}(\mathbf{r}'; t') + \mathbf{d}_{ef} \cdot \mathbf{e}(\mathbf{r}'; t')) dt' \end{aligned}$$

$$\begin{aligned}
& - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_n \bar{\sigma} I_m}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') \mathbf{b}(\mathbf{r}'; t') dt' \\
& - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_n \bar{\sigma} I_M}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') \mathbf{b}'(\mathbf{r}'; t') dt', \tag{29}
\end{aligned}$$

$$\begin{aligned}
\frac{\partial}{\partial t} \langle \mathbf{M}_{\text{ef}}(\mathbf{r}) \rangle^t &= \langle \dot{\mathbf{M}}_{\text{ef}}(\mathbf{r}) \rangle^t - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_M I_n \sigma'}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') (\mu_{\sigma'}(\mathbf{r}'; t') - e\varphi(\mathbf{r}'; t')) dt' \\
& - \int d\mathbf{r}' \sum_{\bar{\sigma}'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_M I_n \bar{\sigma}'}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') (\mu_{\bar{\sigma}'}(\mathbf{r}'; t') + \mathbf{d}_{\text{ef}} \cdot \mathbf{e}(\mathbf{r}'; t')) dt' \\
& - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_M I_m}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') \mathbf{b}(\mathbf{r}'; t') dt' \\
& - \int d\mathbf{r}' \sum_{\sigma'} \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I_M I_M}^{ee}(\mathbf{r}, \mathbf{r}'; t, t') \beta(t') \mathbf{b}'(\mathbf{r}'; t') dt', \tag{30}
\end{aligned}$$

where

$$\dot{\mathbf{m}}(\mathbf{r}) = - \frac{\partial}{\partial \mathbf{r}} \mathbf{J}_m^{(1)}(\mathbf{r}) - \frac{\partial}{\partial \mathbf{r}} \mathbf{J}_m^{(2)}(\mathbf{r}) - R_m(\mathbf{r}; t), \quad \mathbf{J}_m^{(1)\alpha}(\mathbf{r}) = \sum_j \frac{p^\alpha}{m_e} \mathbf{s}_j \delta(\mathbf{r} - \mathbf{r}_j),$$

$$\mathbf{J}_m^{(2)\alpha}(\mathbf{r}) = \frac{1}{2} \sum_{l \neq j} r_{lj}^\alpha [\mathbf{s}_l \times \mathbf{s}_j] \int_0^1 d\xi \delta(\mathbf{r} - \mathbf{r}_j + \xi \mathbf{r}_l), \quad R_m(\mathbf{r}; t) = - \int d\mathbf{r} [\mathbf{B}(\mathbf{r}; t) \times \mathbf{m}(\mathbf{r}')] \delta(\mathbf{r} - \mathbf{r}')$$

with a characteristic contribution of the spin component to the magnetic flux. Generalized transfer equations (27)–(30) describe non-Markov current processes in the system taking into account magnetic and polarization processes under the influence of external and induced internal electromagnetic fields, which are reflected in the right parts of these equations. And obviously, these equations must be supplemented by an appropriate system of Maxwell's equations for electromagnetic fields. The obtained transfer equations can describe both strong and weakly nonequilibrium processes in strong and weak (or constant) electromagnetic fields, respectively. In the case of strongly nonequilibrium processes, the transfer equations are open and require approximate (numerical) calculation methods. Due to the fact that experimental studies use weak or constant electric and magnetic fields in the next section we consider the case of weakly nonequilibrium processes, taking into account that paramagnetic complexes in layers are oriented in a certain way under the action of a constant external magnetic field, creating an effective constant magnetic field acting on the electronic subsystem, affecting the processes of current flow. That is, in this consideration, the implemented complexes are in equilibrium.

## 5. Weakly nonequilibrium processes

We will consider weakly nonequilibrium processes in the system, when the values of thermodynamic parameters and magnetic field differ little from their locally equilibrium values, ie fluctuations of parameters  $\delta\beta(t) = \beta(t) - \beta$ ,  $\delta\nu_\uparrow(\mathbf{r}; t) = \nu_\uparrow(\mathbf{r}; t) - \nu_\uparrow(\mathbf{r})$ ,  $\delta\nu_\downarrow(\mathbf{r}; t) = \nu_\downarrow(\mathbf{r}; t) - \nu_\downarrow(\mathbf{r})$ ,  $\delta\mathbf{b}(\mathbf{r}; t) = \mathbf{b}(\mathbf{r}; t) - \mathbf{b}(\mathbf{r})$  are small, where  $\nu_\sigma(\mathbf{r}) = \mu_\sigma(\mathbf{r}) - e\varphi(\mathbf{r})$ ,  $\mu_\sigma(\mathbf{r})$ ,  $\varphi(\mathbf{r})$ ,  $\mathbf{b}(\mathbf{r})$  are the locally equilibrium values of the electrons chemical potential, electric potential and internal magnetic field. In addition, we assume that the temperature has become:  $\beta(t) = \beta$ , namely,  $\delta\beta(t) = 0$ . In this case, the relevant statistical operator in the linear approximation for these fluctuations will look like:

$$\varrho_{\text{rel}}^0(t) = \left( 1 - \int d\mathbf{r} \beta \delta\nu_\uparrow(\mathbf{r}; t) n_\uparrow(\mathbf{r}; \tau) - \int d\mathbf{r} \beta \delta\nu_\downarrow(\mathbf{r}; t) n_\downarrow(\mathbf{r}; \tau) - \int d\mathbf{r} \beta \delta\mathbf{b}(\mathbf{r}; t) \mathbf{m}(\mathbf{r}; \tau) \right) \varrho_0, \tag{31}$$

where  $n_\sigma(\mathbf{r}; \tau) = \int_0^1 d\tau \varrho_0^\tau n_\sigma(\mathbf{r}) \varrho_0^{-\tau}$ ,  $\mathbf{m}(\mathbf{r}; \tau) = \int_0^1 d\tau \varrho_0^\tau \mathbf{m}(\mathbf{r}) \varrho_0^{-\tau}$ ,

$$\varrho_0 = \exp \left\{ -\Phi - \beta \left( H - \sum_\sigma \int d\mathbf{r} \nu_\sigma(\mathbf{r}) n_\sigma(\mathbf{r}) - \int d\mathbf{r} \mathbf{b}(\mathbf{r}) \mathbf{m}(\mathbf{r}) \right) \right\} \quad (32)$$

is a large canonical Gibbs distribution, which fully describes the equilibrium thermodynamic and structural properties of the system. To further use  $\varrho_{\text{rel}}^0(t)$ , it is necessary to determine the fluctuations of the corresponding thermodynamic parameters and the magnetic field. The parameter  $\delta\nu_\uparrow(\mathbf{r}; t)$  will be determined from the self-agreement condition:

$$\langle n_\uparrow(\mathbf{r}) \rangle^t = \langle n_\uparrow(\mathbf{r}) \rangle_{\text{rel}}^t, \quad (33)$$

then taking into account (31), we obtain:

$$\begin{aligned} \langle n_\uparrow(\mathbf{r}) \rangle^t &= \langle n_\uparrow(\mathbf{r}) \rangle_0 \\ &- \int d\mathbf{r}' \Phi_{\uparrow\uparrow}(\mathbf{r}, \mathbf{r}') \beta \delta\nu_\uparrow(\mathbf{r}'; t) - \int d\mathbf{r}' \Phi_{\uparrow\downarrow}(\mathbf{r}, \mathbf{r}') \beta \delta\nu_\downarrow(\mathbf{r}'; t) - \int d\mathbf{r}' \Phi_{\uparrow m}(\mathbf{r}, \mathbf{r}') \beta \delta\mathbf{b}(\mathbf{r}'; t), \end{aligned} \quad (34)$$

where  $\langle (\dots) \rangle_0 = \text{Sp}(\dots) \varrho_0$  averaging is performed with equilibrium distribution  $\varrho_0$ ,

$$\Phi_{\uparrow\uparrow}(\mathbf{r}, \mathbf{r}') = \langle n_\uparrow(\mathbf{r}) n_\uparrow(\mathbf{r}'; \tau) \rangle_0, \quad \Phi_{\uparrow\downarrow}(\mathbf{r}, \mathbf{r}') = \langle n_\uparrow(\mathbf{r}) n_\downarrow(\mathbf{r}'; \tau) \rangle_0 \quad (35)$$

are the equilibrium correlation functions ‘‘density–density’’ of the Green–Kubo type for electrons with corresponding spin orientations,

$$\Phi_{\uparrow m}(\mathbf{r}, \mathbf{r}') = \langle n_\uparrow(\mathbf{r}) \mathbf{m}(\mathbf{r}'; \tau) \rangle_0 \quad (36)$$

is an equilibrium correlation function of the Green–Kubo type, which describes the magnetostrictive properties. Fourier images of correlation functions (35) in the space of wave vectors are equilibrium structural factors of electrons that can be measured in neutron scattering experiments.

From (34) we find the parameter  $\delta\nu_\uparrow(\mathbf{r}; t)$ . To do this, we introduce the function  $\Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}, \mathbf{r}')$ , which is inverse to  $\Phi_{\uparrow\uparrow}(\mathbf{r}, \mathbf{r}')$ , by the integral relation:

$$\int d\mathbf{r} \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}'', \mathbf{r}) \Phi_{\uparrow\uparrow}(\mathbf{r}, \mathbf{r}') = \delta(\mathbf{r}'' - \mathbf{r}'). \quad (37)$$

Then we multiply the equation (34) by  $\Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}, \mathbf{r}')$  and integrate by  $\int d\mathbf{r}$ , and after simple transformations we get the following expression for the parameter  $\delta\nu_\uparrow(\mathbf{r}; t)$ :

$$\begin{aligned} \beta \delta\nu_\uparrow(\mathbf{r}; t) &= - \int d\mathbf{r}' \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}, \mathbf{r}') \langle \delta n_\uparrow(\mathbf{r}') \rangle^t - \int d\mathbf{r}' \int d\mathbf{r}'' \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}, \mathbf{r}'') \Phi_{\uparrow\downarrow}(\mathbf{r}'', \mathbf{r}') \beta \delta\nu_\downarrow(\mathbf{r}'; t) \\ &- \int d\mathbf{r}' \int d\mathbf{r}'' \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}, \mathbf{r}'') \Phi_{\uparrow m}(\mathbf{r}'', \mathbf{r}') \beta \delta\mathbf{b}(\mathbf{r}'; t), \end{aligned} \quad (38)$$

where  $\delta n_\uparrow(\mathbf{r}') = n_\uparrow(\mathbf{r}') - \langle n_\uparrow(\mathbf{r}') \rangle_0$  are fluctuations of the operator of the microscopic electrons density with the spin direction  $\uparrow$  relative to the equilibrium value of the density distribution. Now, substituting (38) in (31) we get for  $\varrho_{\text{rel}}^0(t)$ :

$$\begin{aligned} \varrho_{\text{rel}}^0(t) &= \left( 1 + \int d\mathbf{r} \int d\mathbf{r}' \langle \delta n_\uparrow(\mathbf{r}') \rangle^t \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}', \mathbf{r}) n_\uparrow(\mathbf{r}; \tau) \right. \\ &\left. - \int d\mathbf{r} \beta \delta\nu_\downarrow(\mathbf{r}; t) \bar{n}_\downarrow(\mathbf{r}; \tau) - \int d\mathbf{r} \beta \delta\mathbf{b}(\mathbf{r}; t) \mathbf{m}'(\mathbf{r}; \tau) \right) \varrho_0, \end{aligned} \quad (39)$$

where

$$\bar{n}_\downarrow(\mathbf{r}) = n_\downarrow(\mathbf{r}) - \int d\mathbf{r}' \int d\mathbf{r}'' \Phi_{\downarrow\uparrow}(\mathbf{r}, \mathbf{r}'') \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}'', \mathbf{r}') n_\uparrow(\mathbf{r}') = (1 - P_{n\uparrow}) n_\downarrow(\mathbf{r}), \quad (40)$$

$$\mathbf{m}'(\mathbf{r}) = \mathbf{m}(\mathbf{r}) - \int d\mathbf{r}' \int d\mathbf{r}'' \Phi_{m\uparrow}(\mathbf{r}, \mathbf{r}'') \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}'', \mathbf{r}') n_\uparrow(\mathbf{r}') = (1 - P_{n\uparrow}) \mathbf{m}(\mathbf{r}) \quad (41)$$

are new electron density operators with spin direction  $\downarrow$  and magnetic moment projected onto the space of electron density operators with spin direction  $\uparrow$ .  $P_{n\uparrow}$  is a Mori-type projection operator, which has the following structure:

$$P_{n\uparrow}A = \int d\mathbf{r}' \int d\mathbf{r}'' \langle A n_\uparrow(\mathbf{r}'') \rangle_0 \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}'', \mathbf{r}') n_\uparrow(\mathbf{r}'). \quad (42)$$

It is important to note that the operators  $\bar{n}_\downarrow(\mathbf{r})$ ,  $\mathbf{m}'(\mathbf{r})$  are orthogonal to  $n_\uparrow(\mathbf{r}')$  in the sense of average values:

$$\langle \bar{n}_\downarrow(\mathbf{r}) n_\uparrow(\mathbf{r}'') \rangle_0 = \langle \mathbf{m}'(\mathbf{r}) n_\uparrow(\mathbf{r}'') \rangle_0 = 0. \quad (43)$$

Now, having defined the parameters  $\delta\nu_\downarrow(\mathbf{r}; t)$ ,  $\delta\mathbf{b}(\mathbf{r}; t)$  in a similar way from the corresponding terms of self-agreement conditions:

$$\langle \bar{n}_\downarrow(\mathbf{r}) \rangle^t = \langle \bar{n}_\downarrow(\mathbf{r}) \rangle_{\text{rel}}^t, \quad \langle \mathbf{m}'(\mathbf{r}) \rangle^t = \langle \mathbf{m}'(\mathbf{r}) \rangle_{\text{rel}}^t, \quad (44)$$

we get for  $\varrho_{\text{rel}}^0(t)$  the following expression:

$$\begin{aligned} \varrho_{\text{rel}}^0(t) = & \left( 1 + \int d\mathbf{r} \int d\mathbf{r}' \langle \delta n_\uparrow(\mathbf{r}') \rangle^t \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}', \mathbf{r}) n_\uparrow(\mathbf{r}; \tau) \right. \\ & \left. + \int d\mathbf{r} \int d\mathbf{r}' \langle \delta \bar{n}_\uparrow(\mathbf{r}') \rangle^t \bar{\Phi}_{\downarrow\downarrow}^{-1}(\mathbf{r}', \mathbf{r}) \bar{n}_\downarrow(\mathbf{r}; \tau) + \int d\mathbf{r} \int d\mathbf{r}' \langle \delta \bar{\mathbf{m}}(\mathbf{r}') \rangle^t \Phi_{\bar{m}\bar{m}}^{-1}(\mathbf{r}', \mathbf{r}) \bar{\mathbf{m}}(\mathbf{r}; \tau) \right) \varrho_0, \end{aligned} \quad (45)$$

where  $\delta \bar{n}_\uparrow(\mathbf{r}') = \bar{n}_\uparrow(\mathbf{r}') - \langle \bar{n}_\uparrow(\mathbf{r}') \rangle_0$ ,  $\bar{\Phi}_{\downarrow\downarrow}^{-1}(\mathbf{r}', \mathbf{r})$ ,  $\Phi_{\bar{m}\bar{m}}^{-1}(\mathbf{r}', \mathbf{r})$  are functions inverse to equilibrium correlation functions, respectively,

$$\bar{\Phi}_{\downarrow\downarrow}(\mathbf{r}', \mathbf{r}) = \langle \bar{n}_\downarrow(\mathbf{r}') \bar{n}_\downarrow(\mathbf{r}; \tau) \rangle_0, \quad \Phi_{\bar{m}\bar{m}}^{-1}(\mathbf{r}', \mathbf{r}) = \langle \bar{\mathbf{m}}(\mathbf{r}') \bar{\mathbf{m}}(\mathbf{r}; \tau) \rangle_0 \quad (46)$$

by integral relations:

$$\int d\mathbf{r} \bar{\Phi}_{\downarrow\downarrow}^{-1}(\mathbf{r}'', \mathbf{r}) \bar{\Phi}_{\downarrow\downarrow}(\mathbf{r}, \mathbf{r}') = \delta(\mathbf{r}'' - \mathbf{r}'), \quad (47)$$

$$\int d\mathbf{r} \Phi_{\bar{m}\bar{m}}^{-1}(\mathbf{r}'', \mathbf{r}) \Phi_{\bar{m}\bar{m}}(\mathbf{r}, \mathbf{r}') = \delta(\mathbf{r}'' - \mathbf{r}'), \quad (48)$$

in which  $\bar{\mathbf{m}}(\mathbf{r})$  is a new operator of the following structure:

$$\bar{\mathbf{m}}(\mathbf{r}) = \mathbf{m}'(\mathbf{r}) - \int d\mathbf{r}' \int d\mathbf{r}'' \Phi_{m'\downarrow}(\mathbf{r}, \mathbf{r}'') \bar{\Phi}_{\downarrow\downarrow}^{-1}(\mathbf{r}'', \mathbf{r}') \bar{n}_\downarrow(\mathbf{r}') = (1 - P_{\bar{n}_\downarrow}) (1 - P_{n\uparrow}) \mathbf{m}(\mathbf{r}), \quad (49)$$

where  $P_{\bar{n}_\downarrow}$  is a projection operator built on operators  $\bar{n}_\downarrow(\mathbf{r})$

$$P_{\bar{n}_\downarrow}A = \int d\mathbf{r}' \int d\mathbf{r}'' \langle A \bar{n}_\downarrow(\mathbf{r}''; \tau) \rangle_0 \bar{\Phi}_{\downarrow\downarrow}^{-1}(\mathbf{r}'', \mathbf{r}') \bar{n}_\downarrow(\mathbf{r}'), \quad (50)$$

in this case  $\bar{\mathbf{m}}(\mathbf{r})$  and  $\bar{n}_\downarrow(\mathbf{r}')$  are orthogonal in the sense of the mean values:

$$\langle \bar{\mathbf{m}}(\mathbf{r}) \bar{n}_\downarrow(\mathbf{r}'; \tau) \rangle_0 = 0. \quad (51)$$

The correlation function  $\bar{\Phi}_{\downarrow\downarrow}(\mathbf{r}', \mathbf{r})$  has the following form:

$$\begin{aligned} \bar{\Phi}_{\downarrow\downarrow}(\mathbf{r}', \mathbf{r}) &= \Phi_{\downarrow\downarrow}(\mathbf{r}', \mathbf{r}) - \langle P_{n\uparrow} n_\downarrow(\mathbf{r}') \rangle_0 - \langle P_{n\uparrow} n_\downarrow(\mathbf{r}) \rangle_0 + \langle P_{n\uparrow} n_\downarrow(\mathbf{r}') P_{n\uparrow} n_\downarrow(\mathbf{r}) \rangle_0 \\ &= \Phi_{\downarrow\downarrow}(\mathbf{r}', \mathbf{r}) - \int d\mathbf{r}'' \int d\mathbf{r}''' \Phi_{\downarrow\uparrow}(\mathbf{r}, \mathbf{r}'') \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}'', \mathbf{r}''') \Phi_{\uparrow\downarrow}(\mathbf{r}''', \mathbf{r}'). \end{aligned} \quad (52)$$

Another correlation function  $\Phi_{\bar{m}\bar{m}}(\mathbf{r}, \mathbf{r}')$ , which describes the magnetic properties, has the following structure:

$$\begin{aligned} \Phi_{\bar{m}\bar{m}}(\mathbf{r}, \mathbf{r}') = & \Phi_{mm}(\mathbf{r}, \mathbf{r}') - \langle \mathbf{m}(\mathbf{r})(P_{\bar{n}\downarrow} + P_{n\uparrow} - P_{\bar{n}\downarrow}P_{n\uparrow})\mathbf{m}(\mathbf{r}') \rangle_0 - \langle \mathbf{m}(\mathbf{r}')(P_{\bar{n}\downarrow} + P_{n\uparrow} - P_{\bar{n}\downarrow}P_{n\uparrow})\mathbf{m}(\mathbf{r}) \rangle_0 \\ & + \langle (P_{\bar{n}\downarrow} + P_{n\uparrow} - P_{\bar{n}\downarrow}P_{n\uparrow})\mathbf{m}(\mathbf{r})(P_{\bar{n}\downarrow} + P_{n\uparrow} - P_{\bar{n}\downarrow}P_{n\uparrow})\mathbf{m}(\mathbf{r}') \rangle_0, \end{aligned} \quad (53)$$

where  $\Phi_{mm}(\mathbf{r}, \mathbf{r}')$  is a spatially inhomogeneous magnetic susceptibility of the system, the following terms in (53) describe complex magnetostrictive correlations.

In the found linear approximation in fluctuations of nonequilibrium thermodynamic parameters and magnetic field for  $\varrho_{\text{rel}}^0(t)$  (45), the nonequilibrium statistical operator of the system will look like:

$$\begin{aligned} \varrho(t) = & \varrho_{\text{rel}}^0(t) - \int d\mathbf{r} \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t'-t)} T_0(t, t') \left( I_{n\uparrow}(\mathbf{r}'; \tau) \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}', \mathbf{r}) \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^{t'} \right. \\ & \left. + I_{\bar{n}\downarrow}(\mathbf{r}'; \tau) \Phi_{\downarrow\downarrow}^{-1}(\mathbf{r}', \mathbf{r}) \langle \delta \bar{n}_{\downarrow}(\mathbf{r}) \rangle^{t'} + I_{\bar{m}}(\mathbf{r}'; \tau) \Phi_{\bar{m}\bar{m}}^{-1}(\mathbf{r}', \mathbf{r}) \langle \delta \bar{\mathbf{m}}(\mathbf{r}) \rangle^{t'} \right) \varrho_0 dt', \end{aligned} \quad (54)$$

where

$$I_{n\uparrow}(\mathbf{r}) = (1 - P)iLn_{\uparrow}(\mathbf{r}), \quad I_{\bar{n}\downarrow}(\mathbf{r}) = (1 - P)iL\bar{n}_{\downarrow}(\mathbf{r}), \quad I_{\bar{m}}(\mathbf{r}) = (1 - P)iL\bar{\mathbf{m}}(\mathbf{r}) \quad (55)$$

are generalized electron fluxes with corresponding spin orientations and magnetic flux of spins in the linear approximation, in which  $P$  is a Mori projection operator having the following structure:

$$P = P_{n\uparrow} + P_{\bar{n}\downarrow} + P_{\bar{m}}, \quad (56)$$

where

$$P_{\bar{m}}(\dots) = \int d\mathbf{r}' \int d\mathbf{r}'' \langle (\dots)\bar{\mathbf{m}}(\mathbf{r}'') \rangle_0 \Phi_{\bar{m}\bar{m}}^{-1}(\mathbf{r}'', \mathbf{r}') \bar{\mathbf{m}}(\mathbf{r}') \quad (57)$$

and has the following properties  $P^2 = P$ ,  $(1 - P)P = 0$ .  $T_0(t, t') = e^{-(1-P)iL(t'-t)}$  is an evolution operator (linear approximation) in time for a system corresponding to the well-known Mori theory.

## 6. Magneto-diffusion transfer equations for electrons in layered nanostructures

Using a nonequilibrium statistical operator (54), we can construct a system of transfer equations to describe the processes of electronic transfer in the system, taking into account magnetic processes. This system has the form:

$$\begin{aligned} \frac{\partial}{\partial t} \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^t = & - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}'; t, t') \langle \delta n_{\uparrow}(\mathbf{r}') \rangle^{t'} dt' \\ & - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I\uparrow I\downarrow}(\mathbf{r}, \mathbf{r}'; t, t') \langle \delta \bar{n}_{\downarrow}(\mathbf{r}') \rangle^{t'} dt' \\ & - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I\uparrow I\bar{m}}(\mathbf{r}, \mathbf{r}'; t, t') \langle \delta \bar{\mathbf{m}}(\mathbf{r}') \rangle^{t'} dt', \end{aligned} \quad (58)$$

$$\begin{aligned} \frac{\partial}{\partial t} \langle \delta \bar{n}_{\downarrow}(\mathbf{r}) \rangle^t = & - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I\downarrow I\uparrow}(\mathbf{r}, \mathbf{r}'; t, t') \langle \delta n_{\uparrow}(\mathbf{r}') \rangle^{t'} dt' \\ & - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I\downarrow I\downarrow}(\mathbf{r}, \mathbf{r}'; t, t') \langle \delta \bar{n}_{\downarrow}(\mathbf{r}') \rangle^{t'} dt' \\ & - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t'-t)} W_{I\downarrow I\bar{m}}(\mathbf{r}, \mathbf{r}'; t, t') \langle \delta \bar{\mathbf{m}}(\mathbf{r}') \rangle^{t'} dt', \end{aligned} \quad (59)$$

$$\begin{aligned}
\frac{\partial}{\partial t} \langle \bar{\mathbf{m}}(\mathbf{r}) \rangle^t &= - \int d\mathbf{r}' i\Omega_{\bar{\mathbf{m}}\bar{\mathbf{m}}}(\mathbf{r}, \mathbf{r}') \langle \bar{\mathbf{m}}(\mathbf{r}') \rangle^t \\
&\quad - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t-t')} W_{I_{\bar{\mathbf{m}}}I_{\uparrow}}(\mathbf{r}, \mathbf{r}'; t, t') \langle \delta n_{\uparrow}(\mathbf{r}') \rangle^{t'} dt' \\
&\quad - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t-t')} W_{I_{\bar{\mathbf{m}}}I_{\downarrow}}(\mathbf{r}, \mathbf{r}'; t, t') \langle \delta \bar{n}_{\downarrow}(\mathbf{r}') \rangle^{t'} dt' \\
&\quad - \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t-t')} W_{I_{\bar{\mathbf{m}}}I_{\bar{\mathbf{m}}}}(\mathbf{r}, \mathbf{r}'; t, t') \langle \delta \bar{\mathbf{m}}(\mathbf{r}') \rangle^{t'} dt', \tag{60}
\end{aligned}$$

where

$$i\Omega_{\bar{\mathbf{m}}\bar{\mathbf{m}}}(\mathbf{r}, \mathbf{r}') = \int d\mathbf{r}'' \langle iL\bar{\mathbf{m}}(\mathbf{r}) \cdot \bar{\mathbf{m}}(\mathbf{r}'') \rangle_0 \Phi_{\bar{\mathbf{m}}\bar{\mathbf{m}}}^{-1}(\mathbf{r}'', \mathbf{r}') \tag{61}$$

is a normalized correlation function that describes non-dissipative magnetic properties,

$$W_{I_{\uparrow}I_{\uparrow}}(\mathbf{r}, \mathbf{r}'; t, t') = \int d\mathbf{r}'' \langle I_{n_{\uparrow}}(\mathbf{r}) T_0(t, t') I_{n_{\uparrow}}(\mathbf{r}'') \rangle_0 \Phi_{\uparrow\uparrow}^{-1}(\mathbf{r}'', \mathbf{r}'), \tag{62}$$

$$W_{I_{\uparrow}I_{\downarrow}}(\mathbf{r}, \mathbf{r}'; t, t') = \int d\mathbf{r}'' \langle I_{n_{\uparrow}}(\mathbf{r}) T_0(t, t') I_{\bar{n}_{\downarrow}}(\mathbf{r}'') \rangle_0 \bar{\Phi}_{\downarrow\downarrow}^{-1}(\mathbf{r}'', \mathbf{r}'), \tag{63}$$

$$W_{I_{\downarrow}I_{\downarrow}}(\mathbf{r}, \mathbf{r}'; t, t') = \int d\mathbf{r}'' \langle I_{\bar{n}_{\downarrow}}(\mathbf{r}) T_0(t, t') I_{\bar{n}_{\downarrow}}(\mathbf{r}'') \rangle_0 \bar{\Phi}_{\downarrow\downarrow}^{-1}(\mathbf{r}'', \mathbf{r}'), \tag{64}$$

$$W_{I_{\uparrow}I_{\bar{\mathbf{m}}}}(\mathbf{r}, \mathbf{r}'; t, t') = \int d\mathbf{r}'' \langle I_{n_{\uparrow}}(\mathbf{r}) T_0(t, t') I_{\bar{\mathbf{m}}}(\mathbf{r}'') \rangle_0 \Phi_{\bar{\mathbf{m}}\bar{\mathbf{m}}}^{-1}(\mathbf{r}'', \mathbf{r}'), \tag{65}$$

$$W_{I_{\downarrow}I_{\bar{\mathbf{m}}}}(\mathbf{r}, \mathbf{r}'; t, t') = \int d\mathbf{r}'' \langle I_{\bar{n}_{\downarrow}}(\mathbf{r}) T_0(t, t') I_{\bar{\mathbf{m}}}(\mathbf{r}'') \rangle_0 \Phi_{\bar{\mathbf{m}}\bar{\mathbf{m}}}^{-1}(\mathbf{r}'', \mathbf{r}') \tag{66}$$

$$W_{I_{\bar{\mathbf{m}}}I_{\bar{\mathbf{m}}}}(\mathbf{r}, \mathbf{r}'; t, t') = \int d\mathbf{r}'' \langle I_{\bar{\mathbf{m}}}(\mathbf{r}) T_0(t, t') I_{\bar{\mathbf{m}}}(\mathbf{r}'') \rangle_0 \Phi_{\bar{\mathbf{m}}\bar{\mathbf{m}}}^{-1}(\mathbf{r}'', \mathbf{r}') \tag{67}$$

are generalized transfer nuclei (memory functions) that describe electronic diffusion processes taking into account the spins orientations and against the direction of the effective magnetic field, and magnetic diffusion processes in the system. In particular, the nucleus  $W_{I_{\uparrow}I_{\uparrow}}(\mathbf{r}, \mathbf{r}'; t, t')$  describes dissipative temporal and spatial correlations between electron fluxes with the direction of spins in the field,  $W_{I_{\downarrow}I_{\downarrow}}(\mathbf{r}, \mathbf{r}'; t, t')$  describes the dissipative temporal and spatial correlations between electron fluxes with the spin direction against the field, and  $W_{I_{\uparrow}I_{\downarrow}}(\mathbf{r}, \mathbf{r}'; t, t')$  describes dissipative temporal and spatial correlations between electron fluxes with spin orientations for and against the direction of the magnetic field. The transfer core  $W_{I_{\bar{\mathbf{m}}}I_{\bar{\mathbf{m}}}}(\mathbf{r}, \mathbf{r}'; t, t')$  describes the magnetic diffusion in the system, and  $W_{I_{\downarrow}I_{\sigma}}(\mathbf{r}, \mathbf{r}'; t, t')$  describes the mutual spatio-temporal correlations of electron fluxes with the corresponding spin direction and magnetic flux. As we can see, the structure of the system of equations (58)–(60) is closed. Using the Fourier transform of time to these equations, we can find exact equations for the corresponding Fourier images of the corresponding nonequilibrium values of the electron density operators with the selected spin direction and the magnetic moment operator by solving the corresponding integral equations. In particular, for fluctuations of the nonequilibrium mean value of the electron density operator with the spin direction in the magnetic field  $\langle \delta n_{\uparrow}(\mathbf{r}) \rangle^{\omega}$ , we obtain the corresponding integral equation:

$$i\omega \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^{\omega} = - \int d\mathbf{r}' D_{I_{\uparrow}I_{\uparrow}}(\mathbf{r}, \mathbf{r}'; \omega + i\varepsilon) \langle \delta n_{\uparrow}(\mathbf{r}') \rangle^{\omega}, \tag{68}$$

where  $\omega$  is the frequency

$$D_{I_{\uparrow}I_{\uparrow}}(\mathbf{r}, \mathbf{r}'; \omega) = \bar{W}_{I_{\uparrow}I_{\uparrow}}(\mathbf{r}, \mathbf{r}'; \omega) - \int d\mathbf{r}'' \int d\mathbf{r}''' \bar{W}_{I_{\uparrow}I_{\downarrow}}(\mathbf{r}, \mathbf{r}''; \omega) \Sigma_{I_{\downarrow}I_{\downarrow}}^{-1}(\mathbf{r}'', \mathbf{r}'''; \omega) \bar{W}_{I_{\downarrow}I_{\uparrow}}(\mathbf{r}''', \mathbf{r}'; \omega) \tag{69}$$

is a generalized transfer core that takes into account complex dissipative correlations through transfer cores (62)–(67) and complex renormalizations due to magnetic dissipative processes, expressed through the corresponding transfer nuclei:

$$\bar{W}_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}'; \omega) = W_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}'; \omega) - \int d\mathbf{r}'' \int d\mathbf{r}''' W_{I\uparrow I\bar{m}}(\mathbf{r}, \mathbf{r}''; \omega) \Sigma_{I\bar{m}I\bar{m}}^{-1}(\mathbf{r}'', \mathbf{r}'''; \omega) W_{I\bar{m}I\uparrow}(\mathbf{r}''', \mathbf{r}'; \omega), \quad (70)$$

$$\bar{W}_{I\uparrow I\downarrow}(\mathbf{r}, \mathbf{r}'; \omega) = W_{I\uparrow I\downarrow}(\mathbf{r}, \mathbf{r}'; \omega) - \int d\mathbf{r}'' \int d\mathbf{r}''' W_{I\uparrow I\bar{m}}(\mathbf{r}, \mathbf{r}''; \omega) \Sigma_{I\bar{m}I\bar{m}}^{-1}(\mathbf{r}'', \mathbf{r}'''; \omega) W_{I\bar{m}I\downarrow}(\mathbf{r}''', \mathbf{r}'; \omega), \quad (71)$$

$$\bar{W}_{I\downarrow I\uparrow}(\mathbf{r}, \mathbf{r}'; \omega) = W_{I\downarrow I\uparrow}(\mathbf{r}, \mathbf{r}'; \omega) - \int d\mathbf{r}'' \int d\mathbf{r}''' W_{I\downarrow I\bar{m}}(\mathbf{r}, \mathbf{r}''; \omega) \Sigma_{I\bar{m}I\bar{m}}^{-1}(\mathbf{r}'', \mathbf{r}'''; \omega) W_{I\bar{m}I\uparrow}(\mathbf{r}''', \mathbf{r}'; \omega), \quad (72)$$

$$\bar{W}_{I\downarrow I\downarrow}(\mathbf{r}, \mathbf{r}'; \omega) = W_{I\downarrow I\downarrow}(\mathbf{r}, \mathbf{r}'; \omega) - \int d\mathbf{r}'' \int d\mathbf{r}''' W_{I\downarrow I\bar{m}}(\mathbf{r}, \mathbf{r}''; \omega) \Sigma_{I\bar{m}I\bar{m}}^{-1}(\mathbf{r}'', \mathbf{r}'''; \omega) W_{I\bar{m}I\downarrow}(\mathbf{r}''', \mathbf{r}'; \omega), \quad (73)$$

in which the function  $\Sigma_{I\bar{m}I\bar{m}}^{-1}(\mathbf{r}'', \mathbf{r}'''; \omega)$  is from the integral equation

$$\int d\mathbf{r}'' \Sigma_{I\bar{m}I\bar{m}}^{-1}(\mathbf{r}, \mathbf{r}''; \omega) \Sigma_{I\bar{m}I\bar{m}}(\mathbf{r}'', \mathbf{r}'; \omega) = \delta(\mathbf{r} - \mathbf{r}') \quad (74)$$

and is inverse of a function that already takes into account the renormalization through the magnetic subsystem

$$\Sigma_{I\bar{m}I\bar{m}}(\mathbf{r}, \mathbf{r}'; \omega) = i\omega \delta(\mathbf{r} - \mathbf{r}') - \Omega_{\bar{m}\bar{m}}(\mathbf{r}, \mathbf{r}') + W_{I\bar{m}I\bar{m}}(\mathbf{r}, \mathbf{r}'; \omega). \quad (75)$$

Accordingly, the function  $\Sigma_{I\downarrow I\downarrow}^{-1}(\mathbf{r}'', \mathbf{r}'''; \omega)$  is determined from the integral relation

$$\int d\mathbf{r}'' \Sigma_{I\downarrow I\downarrow}^{-1}(\mathbf{r}, \mathbf{r}''; \omega) \Sigma_{I\downarrow I\downarrow}(\mathbf{r}'', \mathbf{r}'; \omega) = \delta(\mathbf{r} - \mathbf{r}') \quad (76)$$

and is inverse of a function that already takes into account the renormalization through the magnetic subsystem

$$\begin{aligned} \Sigma_{I\downarrow I\downarrow}(\mathbf{r}, \mathbf{r}'; \omega) &= i\omega \delta(\mathbf{r} - \mathbf{r}') + \bar{W}_{I\downarrow I\downarrow}(\mathbf{r}, \mathbf{r}'; \omega) \\ &= i\omega \delta(\mathbf{r} - \mathbf{r}') + W_{I\downarrow I\downarrow}(\mathbf{r}, \mathbf{r}'; \omega) \\ &\quad - \int d\mathbf{r}'' \int d\mathbf{r}''' W_{I\downarrow I\bar{m}}(\mathbf{r}, \mathbf{r}''; \omega) \Sigma_{I\bar{m}I\bar{m}}^{-1}(\mathbf{r}'', \mathbf{r}'''; \omega) W_{I\bar{m}I\downarrow}(\mathbf{r}''', \mathbf{r}'; \omega). \end{aligned} \quad (77)$$

Performing the inverse Fourier transform in (68), we obtain a generalized diffusion equation for fluctuations of the mean nonequilibrium values:

$$\begin{aligned} \frac{\partial}{\partial t} \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^t &= \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t'-t)} D_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}'; t, t') \langle \delta n_{\uparrow}(\mathbf{r}') \rangle^{t'} dt' \\ &= \int d\mathbf{r}' \int_{-\infty}^t e^{\varepsilon(t'-t)} \frac{\partial}{\partial \mathbf{r}} \cdot \bar{D}_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}'; t, t') \cdot \frac{\partial}{\partial \mathbf{r}'} \langle \delta n_{\uparrow}(\mathbf{r}') \rangle^{t'} dt', \end{aligned} \quad (78)$$

where  $\bar{D}_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}'; t, t')$  is a generalized diffusion coefficient for electrons with spin orientation in the direction magnetic field and, which is determined through the nucleus (69), respectively. It should be noted that the structure of the functions (69)–(77) is important from the point of view of both understanding and modeling the mechanisms of the corresponding processes of current flow in systems.

## 7. Cattaneo–type diffusion equation in time fractional derivatives for electrons

The generalized diffusion equation (78) for electrons describes non-Markov spatially inhomogeneous processes, ie memory effects that are associated with the characteristic relaxation times of electronic (including tunneling) magnetic processes in accordance with the behavior of transfer nuclei (69)–(77). At present, it is impossible to accurately calculate the transfer nuclei. Therefore, an approximate calculation is performed based on certain assumptions about the main possible mechanisms of current flow in the system. For further study of the features of impedance behavior, associated with the effects of delay, inductance, memory effects will be described on the basis of assumptions that lead to fractional dynamics [7, 16].

For  $\bar{D}_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}'; t, t')$  we apply the following approximation:

$$\bar{D}_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}'; t, t') \approx R_{I\uparrow I\uparrow}(t, t') \bar{D}_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}'), \quad (79)$$

where  $R_{I\uparrow I\uparrow}(t, t')$  can be defined as a function of memory over time. Using this approximation, we can present the equation (78) as:

$$\frac{\partial}{\partial t} \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^t = \int_{-\infty}^t e^{\varepsilon(t'-t)} R_{I\uparrow I\uparrow}(t, t') \Psi_{I\uparrow I\uparrow}(\mathbf{r}; t') dt', \quad (80)$$

where

$$\Psi_{I\uparrow I\uparrow}(\mathbf{r}; t') = \int d\mathbf{r}' \frac{\partial}{\partial \mathbf{r}} \cdot \bar{D}_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}') \cdot \frac{\partial}{\partial \mathbf{r}'} \langle \delta n_{\uparrow}(\mathbf{r}') \rangle^{t'}. \quad (81)$$

Applying the Fourier transform to the equation (80), we obtain:

$$i\omega \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^{\omega} = R_{I\uparrow I\uparrow}(\omega) \Psi_{I\uparrow I\uparrow}(\mathbf{r}; \omega). \quad (82)$$

Entering the relaxation time  $\tau_{\uparrow}$  (which characterizes the processes of electron transfer with the spin orientation  $\uparrow$  in the system), the frequency dependence of the memory function is given as:

$$R_{I\uparrow I\uparrow}(\omega) = \frac{(i\omega)^{1-\xi}}{1 + i\omega\tau_{\uparrow}}, \quad 0 < \xi \leq 1. \quad (83)$$

Then the equation (82) can be written as follows:

$$(1 + i\omega\tau_{\uparrow}) i\omega \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^{\omega} = (i\omega)^{1-\xi} \Psi_{I\uparrow I\uparrow}(\mathbf{r}; \omega). \quad (84)$$

Next, we use the Fourier transform to fractional derivatives of the functions:

$$L({}_0D_t^{1-\xi} f(t) : i\omega) = (i\omega)^{1-\xi} L(f(t) : i\omega), \quad {}_0D_t^{1-\xi} f(t) = \frac{1}{\Gamma(\xi)} \frac{d}{dt} \int_0^t \frac{f(\tau)}{(t-\tau)^{1-\xi}} d\tau \quad (85)$$

is a fractional Riemann–Liouville derivative. The inverse transition to the time dependence in the equation (84) gives a generalized diffusion equation of the Cattaneo type, taking into account the time fractality:

$$\tau_{\uparrow} \frac{\partial^2}{\partial t^2} \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^t + \frac{\partial}{\partial t} \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^t = {}_0D_t^{1-\xi} \int d\mathbf{r}' \frac{\partial}{\partial \mathbf{r}} \cdot \bar{D}_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}') \cdot \frac{\partial}{\partial \mathbf{r}'} \langle \delta n_{\uparrow}(\mathbf{r}') \rangle^t. \quad (86)$$

Equations (86) contain significant spatial inhomogeneity in  $\bar{D}_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}')$ . If the spatial heterogeneity is neglected:  $\bar{D}_{I\uparrow I\uparrow}(\mathbf{r}, \mathbf{r}') = \bar{D}_{I\uparrow I\uparrow} \delta(\mathbf{r} - \mathbf{r}')$ , then we get:

$$\tau_{\uparrow} \frac{\partial^2}{\partial t^2} \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^t + \frac{\partial}{\partial t} \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^t = {}_0D_t^{1-\xi} \bar{D}_{I\uparrow I\uparrow} \frac{\partial^2}{\partial r^2} \langle \delta n_{\uparrow}(\mathbf{r}) \rangle^t \quad (87)$$

is a Cattaneo-type diffusion equation with time fractality and constant electron diffusion coefficient with the spin orientation in the magnetic field.

## 8. Electro-magnetic diffusion relaxation processes

Modeling of subdiffusion processes based on the Cattaneo-type diffusion equations in fractional derivatives for charge carriers was characterized by a corresponding relaxation time and diffusion coefficient. However, such a model obviously does not take into account the complexity of relaxation electro-magnetic diffusion processes, which are generally described by a system of equations (58)–(60). We will consider the model taking into account a number of relaxation processes by modeling the functions of memory (62)–(67), for which we have a relation with generalized coefficients:

$$W_{I_j I_l}(\mathbf{r}, \mathbf{r}'; t, t') = \frac{\partial}{\partial \mathbf{r}} \cdot D_{I_j I_l}(\mathbf{r}, \mathbf{r}'; t, t') \cdot \frac{\partial}{\partial \mathbf{r}'} \quad (88)$$

for electrons with the corresponding orientation of spins, magnetic diffusion and diffusion coefficients describing cross-processes. Next, we accept the following approximations for generalized transfer coefficients:

$$D_{I_j I_l}(\mathbf{r}, \mathbf{r}'; t, t') \approx W_{I_j I_l}(t, t') \bar{D}_{I_j I_l} \delta(\mathbf{r} - \mathbf{r}'), \quad (89)$$

where  $W_{I_j I_l}(t, t')$  are memory functions in time,  $\bar{D}_{I_j I_l}$  are the corresponding constant diffusion coefficients, respectively, for electrons, magnetic diffusion, which in principle can be estimated from experimental studies. Using approximation (89), the system of equations (58)–(60) in the frequency-wave Fourier image is given as:

$$i\omega \langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega} = -k^2 W_{I_{\uparrow} I_{\uparrow}}(\omega) \bar{D}_{I_{\uparrow} I_{\uparrow}} \langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega} - k^2 W_{I_{\uparrow} I_{\downarrow}}(\omega) \bar{D}_{I_{\uparrow} I_{\downarrow}} \langle \delta n_{\downarrow}(\mathbf{k}) \rangle_{\omega} - k^2 W_{I_{\uparrow} I_{\bar{m}}}(\omega) \bar{D}_{I_{\uparrow} I_{\bar{m}}} \langle \delta \bar{\mathbf{m}}(\mathbf{k}) \rangle_{\omega}, \quad (90)$$

$$i\omega \langle \delta n_{\downarrow}(\mathbf{k}) \rangle_{\omega} = -k^2 W_{I_{\downarrow} I_{\uparrow}}(\omega) \bar{D}_{I_{\downarrow} I_{\uparrow}} \langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega} - k^2 W_{I_{\downarrow} I_{\downarrow}}(\omega) \bar{D}_{I_{\downarrow} I_{\downarrow}} \langle \delta n_{\downarrow}(\mathbf{k}) \rangle_{\omega} - k^2 W_{I_{\downarrow} I_{\bar{m}}}(\omega) \bar{D}_{I_{\downarrow} I_{\bar{m}}} \langle \delta \bar{\mathbf{m}}(\mathbf{k}) \rangle_{\omega}, \quad (91)$$

$$i\omega \langle \delta \bar{\mathbf{m}}(\mathbf{k}) \rangle_{\omega} = i\Omega_{\bar{m}\bar{m}}(\mathbf{k}) \langle \delta \bar{\mathbf{m}}(\mathbf{k}) \rangle_{\omega} - k^2 W_{I_{\bar{m}} I_{\uparrow}}(\omega) \bar{D}_{I_{\bar{m}} I_{\uparrow}} \langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega} - k^2 W_{I_{\bar{m}} I_{\downarrow}}(\omega) \bar{D}_{I_{\bar{m}} I_{\downarrow}} \langle \delta n_{\downarrow}(\mathbf{k}) \rangle_{\omega} - k^2 W_{I_{\bar{m}} I_{\bar{m}}}(\omega) \bar{D}_{I_{\bar{m}} I_{\bar{m}}} \langle \delta \bar{\mathbf{m}}(\mathbf{k}) \rangle_{\omega}. \quad (92)$$

We find the solutions of this system of equations. From (92) we find  $\langle \delta \bar{\mathbf{m}}(\mathbf{k}) \rangle_{\omega}$ :

$$\langle \delta \bar{\mathbf{m}}(\mathbf{k}) \rangle_{\omega} = -k^2 \Sigma_{I_{\bar{m}} I_{\bar{m}}}^{-1}(\mathbf{k}; \omega) W_{I_{\bar{m}} I_{\uparrow}}(\omega) \bar{D}_{I_{\bar{m}} I_{\uparrow}} \langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega} - k^2 \Sigma_{I_{\bar{m}} I_{\bar{m}}}^{-1}(\mathbf{k}; \omega) W_{I_{\bar{m}} I_{\downarrow}}(\omega) \bar{D}_{I_{\bar{m}} I_{\downarrow}} \langle \delta n_{\downarrow}(\mathbf{k}) \rangle_{\omega}, \quad (93)$$

where the function  $\Sigma_{I_{\bar{m}} I_{\bar{m}}}^{-1}(\mathbf{k}; \omega)$  is inverted to  $\Sigma_{I_{\bar{m}} I_{\bar{m}}}(\mathbf{k}; \omega)$

$$\Sigma_{I_{\bar{m}} I_{\bar{m}}}(\mathbf{k}; \omega) = i\omega - i\Omega_{\bar{m}\bar{m}}(\mathbf{k}) + W_{I_{\bar{m}} I_{\bar{m}}}(\omega) \bar{D}_{I_{\bar{m}} I_{\bar{m}}}. \quad (94)$$

Next (93) is substituted in (90) and (91), respectively, the result is:

$$i\omega \langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega} = -k^2 \Sigma_{I_{\uparrow} I_{\uparrow}}(\mathbf{k}; \omega) \langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega} - k^2 \Sigma_{I_{\uparrow} I_{\downarrow}}(\mathbf{k}; \omega) \langle \delta n_{\downarrow}(\mathbf{k}) \rangle_{\omega}, \quad (95)$$

$$i\omega \langle \delta n_{\downarrow}(\mathbf{k}) \rangle_{\omega} = -k^2 \Sigma_{I_{\downarrow} I_{\uparrow}}(\mathbf{k}; \omega) \langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega} - k^2 \Sigma_{I_{\downarrow} I_{\downarrow}}(\mathbf{k}; \omega) \langle \delta n_{\downarrow}(\mathbf{k}) \rangle_{\omega}, \quad (96)$$

where

$$\Sigma_{I_{\uparrow} I_{\uparrow}}(\mathbf{k}; \omega) = W_{I_{\uparrow} I_{\uparrow}}(\omega) \bar{D}_{I_{\uparrow} I_{\uparrow}} - k^2 W_{I_{\uparrow} I_{\bar{m}}}(\omega) \bar{D}_{I_{\uparrow} I_{\bar{m}}} \Sigma_{I_{\bar{m}} I_{\bar{m}}}^{-1}(\mathbf{k}; \omega) W_{I_{\bar{m}} I_{\uparrow}}(\omega) \bar{D}_{I_{\bar{m}} I_{\uparrow}}, \quad (97)$$

$$\Sigma_{I_{\uparrow} I_{\downarrow}}(\mathbf{k}; \omega) = W_{I_{\uparrow} I_{\downarrow}}(\omega) \bar{D}_{I_{\uparrow} I_{\downarrow}} - k^2 W_{I_{\uparrow} I_{\bar{m}}}(\omega) \bar{D}_{I_{\uparrow} I_{\bar{m}}} \Sigma_{I_{\bar{m}} I_{\bar{m}}}^{-1}(\mathbf{k}; \omega) W_{I_{\bar{m}} I_{\downarrow}}(\omega) \bar{D}_{I_{\bar{m}} I_{\downarrow}}, \quad (98)$$

$$\Sigma_{I_{\downarrow} I_{\uparrow}}(\mathbf{k}; \omega) = W_{I_{\downarrow} I_{\uparrow}}(\omega) \bar{D}_{I_{\downarrow} I_{\uparrow}} - k^2 W_{I_{\downarrow} I_{\bar{m}}}(\omega) \bar{D}_{I_{\downarrow} I_{\bar{m}}} \Sigma_{I_{\bar{m}} I_{\bar{m}}}^{-1}(\mathbf{k}; \omega) W_{I_{\bar{m}} I_{\uparrow}}(\omega) \bar{D}_{I_{\bar{m}} I_{\uparrow}}, \quad (99)$$

$$\Sigma_{I_{\downarrow} I_{\downarrow}}(\mathbf{k}; \omega) = W_{I_{\downarrow} I_{\downarrow}}(\omega) \bar{D}_{I_{\downarrow} I_{\downarrow}} - k^2 W_{I_{\downarrow} I_{\bar{m}}}(\omega) \bar{D}_{I_{\downarrow} I_{\bar{m}}} \Sigma_{I_{\bar{m}} I_{\bar{m}}}^{-1}(\mathbf{k}; \omega) W_{I_{\bar{m}} I_{\downarrow}}(\omega) \bar{D}_{I_{\bar{m}} I_{\downarrow}}. \quad (100)$$

From the system of equations (95), (96) for  $\langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega}$  we get the following equation:

$$i\omega \langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega} + k^2 \left( \Sigma_{I_{\uparrow} I_{\uparrow}}(\mathbf{k}; \omega) - k^2 \Sigma_{I_{\uparrow} I_{\downarrow}}(\mathbf{k}; \omega) \frac{1}{i\omega + k^2 \Sigma_{I_{\downarrow} I_{\downarrow}}(\mathbf{k}; \omega)} \Sigma_{I_{\downarrow} I_{\uparrow}}(\mathbf{k}; \omega) \right) \langle \delta n_{\uparrow}(\mathbf{k}) \rangle_{\omega} = 0. \quad (101)$$

and as a result we come to the features of the frequency-wave spectrum:

$$i\omega + k^2 \left( \Sigma_{I_\uparrow I_\uparrow}(\mathbf{k}; \omega) - k^2 \Sigma_{I_\uparrow I_\downarrow}(\mathbf{k}; \omega) \frac{1}{i\omega + k^2 \Sigma_{I_\downarrow I_\downarrow}(\mathbf{k}; \omega)} \Sigma_{I_\downarrow I_\uparrow}(\mathbf{k}; \omega) \right) = 0. \quad (102)$$

calculation, which requires setting the frequency dependence of the memory time functions  $W_{I_j I_l}(\omega)$ , by introducing the appropriate relaxation times that characterize the electro-magnetic diffusion processes.

## 9. Conclusions

A model for describing the dipole-magnetic properties of superparamagnetics  $\langle \beta - \text{CD} \langle \text{FeSO}_4 \rangle \rangle$  encapsulated in a semiconductor layer is constructed. The model takes into account the interaction of matrix charge carriers with iron d-electrons, the exchange magnetic interaction of conduction electrons and localized electrons, as well as the dipole-dipole interaction of complexes in the layered GaSe structure. The main parameters of the reduced description of current-carrying processes are determined taking into account magnetism in hybrid nanostructures  $\langle \beta - \text{CD} \langle \text{FeSO}_4 \rangle \rangle$ . A nonequilibrium statistical system operator is obtained as a functional of the parameters of the reduced description.

Generalized transfer equations (27)–(30) are obtained, which describe non-Markov processes of current passage in layered nanostructures taking into account magnetic and polarization processes under the influence of external and induced internal electromagnetic fields, which are reflected in the right parts of the data. equations. The obtained transfer equations can describe both strong and weakly nonequilibrium processes in strong and weak (or constant) electromagnetic fields, respectively.

In the case of weakly nonequilibrium processes, the magneto-diffusion transfer equations (58)–(60) are determined for electrons in layered nanostructures. By solutions through integral equations, a generalized equation of electron diffusion is determined with the spin orientation in the magnetic field. The generalized diffusion equation (78) for electrons describes non-Markov spatially inhomogeneous processes, ie memory effects that are associated with the characteristic relaxation times of electronic (including tunneling) magnetic processes according to the behavior of transfer nuclei (70)–(77).

By modeling the memory function with the introduction of the characteristic relaxation time, a generalized diffusion equation of the Cattaneo type is obtained, taking into account the time fractality for electrons with the spin orientation in the magnetic field.

A generalized model is proposed that takes into account the complexity of relaxation electro-magnetic diffusion processes for electrons in layered nanostructures. In the approximation (89), the system of equations (58)–(60) was solved, which led to the calculation of the corresponding frequency-wave spectrum of electro-magnetic diffusion processes in layered nanostructures.

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## Мікроскопічна теорія впливу дипольних суперпарамагнетиків (типу $\langle\beta - CD\langle FeSO_4 \rangle\rangle$ ) на струмопроходження у напівпровідникових шаруватих структурах (типу GaSe, InSe)

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Запропоновано статистичний підхід опису процесів переносу носіїв заряду у гібридних наноструктурах з врахуванням електромагнітних полів із застосуванням методу нерівноважного статистичного оператора Зубарева. Отримано узагальнені рівняння переносу, які описують немарковські процеси переносу заряду у системі з врахуванням магнітних та поляризаційних процесів під впливом зовнішніх та індукованих внутрішніх електромагнітних полів. Розглянуто слабо нерівноважні процеси переносу заряду у наноструктурах та отримано нерівноважний статистичний оператор, за допомогою якого записано магніто-дифузійні рівняння переносу для електронів у шаруватих наноструктурах. Отримано узагальнене рівняння дифузії типу Кеттано у часових дробових похідних для електронів з характерним часом релаксації та запропоновано узагальнену модель, що враховує складність релаксаційних електро-магніто-дифузійних процесів для електронів у шаруватих наноструктурах.

**Ключові слова:** *нерівноважний статистичний оператор Зубарева, рівняння дифузії типу Кеттано, дробові похідні.*