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LARGE LINEAR MAGNETORESISTIVITY
IN STRONGLY INHOMOGENEOUS
PLANAR AND LAYERED SYSTEMS

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Explicit expressions for magnetoresistance $R$ of planar and layered strongly inhomogeneous two-phase systems are obtained, using exact dual transformation, connecting effective conductivities of in-plane isotropic two-phase systems with and without magnetic field. These expressions allow to describe the magnetoresistance of various inhomogeneous media at arbitrary concentrations $x$ and magnetic fields $H$. All expressions show large linear magnetoresistance effect with different dependencies on the phase concentrations. The corresponding plots of the $x$- and $H$-dependencies of $R(x; H)$ are represented for various values, respectively, of magnetic field and concentrations at some values of inhomogeneity parameter. The obtained results show a remarkable similarity with the existing experimental data on linear magnetoresistance in silver chalcogenides $\text{Ag}_{2+\delta}\text{Se}$. A possible physical explanation of this similarity is proposed. It is shown that the random, stripe type, structures of inhomogeneities are the most suitable for a fabrication of magnetic sensors and a storage of information at room temperatures.

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1. Introduction

It was established recently that new materials, such as oxides and chalcogenides, have often unusual magneto-transport properties. For example, the magnetoresistance becomes very large (the so called colossal magnetoresistance) in manganites [1] or grows approximately linearly with magnetic field up to very high fields in silver chalcogenides [2]. The large linear magnetoresistance (LLMR) takes place in thin films of $\text{Ag}_{2+\delta}\text{Se}, \text{Te}$ in a wide region of temperatures, from low ($\sim 1K$) till room temperatures ($\sim 300K$). At the moment there exist two approaches in a theoretical explanation of a linear behaviour of the magnetoresistance. The first, a quantum one, is proposed by Abrikosov and is based on the quantum theory of possible changes of spectrum properties of semimetals or narrow gap semiconductors [3]. It can be applied, for example, for an explanation of low temperature properties of $\text{Ag}_{2+\delta}\text{Te}$ [4]. The second approach is pure classical and is based on the importance of the phase inhomogeneities, which take place in these materials on small (till nanometer) scales, for an existence of the LLMR effect at moderate temperatures [2]. This approach is applicable at moderate temperatures and for systems where a mean

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size or some characteristic size of inhomogeneities $l_c \gg l_0$ (here $l_0$ is a free path length of the charge carriers). In the framework of the second approach Parish and Littlewood have proposed the network model constructed from conducting discs and have shown by its numerical simulation that the LLMR appears in this model, when the parameters of a disc’s impedance (in particular, a mobility $\mu$) are random and have a continuous wide distribution with $\langle \mu \rangle = 0$ \cite{5,6}. This model is similar to the usual wire network model \cite{7}, but, in order to describe a dependence of the effective resistivity on magnetic field, it uses as building blocks the four terminal discs instead of wires.

In the framework of the classical approach there is another possibility to describe magneto-transport properties of inhomogeneous planar (or layered, inhomogeneous in planes, but constant in the direction orthogonal to planes) systems in perpendicular magnetic field. It is connected with an existence of the exact dual transformation, relating the effective conductivity $\hat{\sigma}_e$ (and the effective resistivity $\hat{\rho}_e = \hat{\sigma}_e^{-1}$) of planar inhomogeneous self-dual two-phase systems without and with magnetic field \cite{8,9}. The existence of this transformation is a direct consequence of the exact Keller - Dykhne duality of two-dimensional systems \cite{10,11}.

In this letter, using this exact transformation and the known expressions for $\hat{\sigma}_e$ of three inhomogeneous models with different random structures from \cite{12}, we will give the explicit approximate expressions for the effective resistivity $\hat{\rho}_e$ of self-dual two-phase systems applicable at arbitrary values of phase concentrations and magnetic fields and in a wide region of partial conductivities. We will present also the $x$- and $H$-dependencies plots of the magnetoresistance $R(x, H)$ at some characteristic values, respectively, of magnetic field $H$ or phase concentrations. These plots unambiguously show the existence of the large linear magnetoresistance effect in these classical systems. A comparison of results, obtained here analytically, with the known experimental data on the magnetoresistance behaviour in silver chalcogenides $Ag_{2+\delta}Se$ demonstrates their remarkable qualitative similarity. A physical explanation of this similarity is proposed. A possibility of an application of random, stripe type, inhomogeneities for a construction of magnetic sensors and magnetic read-write technologies is indicated.

2. Effective resistivity in magnetic field

The effective conductivity of two-phase isotropic systems in magnetic field has the following form

$$\hat{\sigma} = \sigma_{ik} = \sigma_d \delta_{ik} + \sigma_i \epsilon_{ik}, \quad \sigma_d(H) = \sigma_d(-H), \quad \sigma_i(H) = -\sigma_i(-H),$$  

(1)

Here $\delta_{ik}$ is the Kronecker symbol, $\epsilon_{ik}$ is the unit antisymmetric tensor. The effective resistivity $\hat{\rho}_e$ is defined by the inverse matrix

$$\hat{\rho} = \rho_{ik} = \rho_d \delta_{ik} + \rho_i \epsilon_{ik}, \quad \rho_d(H) = \rho_d(-H), \quad \rho_i(H) = -\rho_i(-H),$$  

(2)

where

$$\rho_d = \sigma_d / (\sigma_d^2 + \sigma_i^2), \quad \rho_i = -\sigma_i / (\sigma_d^2 + \sigma_i^2),$$  

(3)
The effective resistivity \( \hat{\rho} \) and, consequently, \( \rho_{ed}, \rho_{et} \) (we assume here that \( \rho_{id} \geq 0 \)) for self-dual systems must be a symmetric function of pairs of partial arguments \( (\hat{\rho}_i, x_i) \) and a homogeneous (a degree 1) function of \( \rho_{di,ti} \). For this reason it is invariant under permutation of pairs of partial parameters

\[
\hat{\rho}_e(\hat{\rho}_1, x_1 \mid \hat{\rho}_2, x_2) = \hat{\rho}_e(\hat{\rho}_2, x_2 \mid \hat{\rho}_1, x_1). \tag{4}
\]

The effective resistivity of inhomogeneous systems must also reduce to some partial \( \hat{\rho}_i \), when \( x_i = 1 \) (\( i = 1, 2 \)).

In our previous paper [13] we have obtained explicit expressions for effective conductivities of planar inhomogeneous self-dual systems in magnetic field and have shown that they have properties qualitatively compatible with the large linear magnetoresistance effect. Since the people usually measure in experiments the effective resistivities and such value as the magnetoresistance, we consider in this letter the properties of the \( \rho_{ed}(x, H) \) and the magnetoresistance \( R(x, H) \) of strongly inhomogeneous two-phase planar (and layered) systems. The investigation of properties of the classical Hall effect in these systems will be done in the subsequent paper. The magnetoresistance of two-dimensional inhomogeneous media is determined as follows

\[
R(x, H) = (\rho_{ed}(x, H) - \rho_{ed}(x, 0))/\rho_{ed}(x, 0). \tag{5}
\]

One needs to note here that there is another definition of the magnetic resistance in the literature, which differs from (5) by the normalization

\[
R_1(x, H) = (\rho_{ed}(x, H) - \rho_{ed}(x, 0))/\rho_{ed}(x, H). \tag{5’}
\]

We will use here a definition (5), since it allows to show in a more obvious way the LLMR effect. For isotropic systems without magnetic field \( \rho_{ed}(x, 0) \equiv \rho_{e0} = (\sigma_{e0})^{-1} \), where \( \sigma_{e0} \) is the effective conductivity at \( H = 0 \), and, for self-dual systems, \( \rho_{ed} \) has the same functional form as \( \sigma_{e0} \). Then one can write \( R \) as

\[
R(x, H) = \sigma_{e0}\rho_{ed}(x, H) - 1 = \sigma_{e0}\frac{\sigma_{ed}}{\sigma_{ed}^2 + \sigma_{et}^2} - 1. \tag{6}
\]

It follows from (5) that \( R(x, 0) = 0 \) and can be nonzero only for \( H \neq 0 \). Thus, it describes only transport properties connected with magnetic field. Note that for large values \( R \) can be approximated by \( \sigma_{e0}\rho_{ed} \). In order to describe the dependence of the \( R(x, H) \) of inhomogeneous system on magnetic field one must know also the functional dependences on \( H \) of partial conductivities \( \sigma_{ed}(H), \sigma_{et}(H) \) (\( i = 1, 2 \)). They usually can be approximated by the standard (metallic type) formulae [11]

\[
\sigma_{ed}(H) = \frac{\sigma_{i0}}{1 + \beta_i^2}, \quad \sigma_{et}(H) = \frac{\sigma_{i0}\beta_i}{1 + \beta_i^2}, \quad \beta_i = \mu_i H, \quad i = 1, 2, \tag{7}
\]

where \( \sigma_{i0} \) are the partial conductivities of phases without magnetic field, \( \mu_i = e_i\tau_i/m_i \) are the corresponding mobilities, \( \tau_i, e_i, m_i \) are, respectively, carrier’s
times of life, charges and masses. Thus $R(x, H)$ depends also on 4 partial parameters: $\sigma_i$, $\mu_i$. Since $\sigma_{ed,i}$ are homogeneous functions of $\sigma_{i0}$ and the mobilities enter always in a combination with magnetic field, really $R(x, H)$ depends (besides $x$ and renormalized magnetic field $H' = \mu_1 H$, below we will assume that $\mu_1 = 1$), on two inhomogeneity parameters: $z$, connected with an inhomogeneity of conductivities, and $\eta$, connected with an inhomogeneity of mobilities. They may be chosen as the corresponding ratios (we choose also that $\sigma_{20}/\sigma_{10} \leq 1$)

$$z = \sigma_{20}/\sigma_{10} \quad (0 \leq z \leq 1), \quad \eta = \mu_2/\mu_1 \quad (-\infty \leq \eta \leq \infty). \quad (8)$$

It is useful also to note that $\rho_d$ for homogeneous systems with conductivities from (7) has the form

$$\rho_{id}(H) = \sigma_{i0}^{-1}, \quad i = 1, 2,$$

and, consequently, for these homogeneous systems

$$R(x, H) = \sigma_{ed}(x, 0)\rho_{ed}(x, H) - 1 \xrightarrow{x=0,1} 0. \quad (9)$$

The equation (9) defines the boundary values of $R(x, H)$ at $x = 0, 1$ for inhomogeneous systems, satisfying the representation (7).

3. Magnetoresistance of planar inhomogeneous systems.

Recently, using exact "magnetic" duality transformation, connecting the effective conductivities of inhomogeneous systems with and without magnetic field [9], we have obtained three explicit approximate expressions for the effective conductivity $\hat{\sigma}_e$ of planar two-phase strongly inhomogeneous systems with different structures of inhomogeneities in magnetic field [12]. Two of them describe systems with various real "bulk" inhomogeneities (i.e. having real 2D bulk inhomogeneities): the compact inclusions of regions of different sizes and forms ("random droplets") of one phase into another and the "random parquet" structure constructed from square plaquettes with randomly distributed stripes of two phases [13]. The third one has the effective conductivity, obtained by a dual "magnetic" transformation from the known effective medium approximation (EMA) formula, based on the wire-network representation of inhomogeneous systems [6] (we will name it the effective medium (EM) model).

The corresponding effective conductivities have the following forms

$$\sigma_{ed}^{'}(\sigma, \{x\}) = \frac{\sigma_{ed}^{'}(ac + b)}{(\sigma_{ed}^{'})^2 + a^2}, \quad \sigma_{ed}(\sigma, \{x\}) = \frac{(\sigma_{ed}^{'})^2 - ab'}{(\sigma_{ed}^{'})^2 + a^2}, \quad (10)$$

where $\sigma_{ed}^{'}$ is the effective conductivity of the models without magnetic field, but it depends on transformed partial arguments $\sigma_{id}^{'} = \sigma_{id}/\sigma_{ai}$ with $\sigma_{ai} = \sigma_{it} + a$. The parameters of the "magnetic" transformation $a, b' = b/c, c$ depend on the partial conductivities and have the following form

$$a_\pm = \frac{|\sigma_2|^2 - |\sigma_1|^2 \pm \sqrt{B}}{2(\sigma_{1t} - \sigma_{2t})}, \quad b'_\pm = \frac{|\sigma_1|^2 - |\sigma_2|^2 \pm \sqrt{B}}{2(\sigma_{1t} - \sigma_{2t})}, \quad c = -a,$$

$$B = [(\sigma_{1t} - \sigma_{2t})^2 + (\sigma_{1d} - \sigma_{2d})^2][\sigma_{1t} - \sigma_{2t}]^2 + (\sigma_{1d} + \sigma_{2d})^2], \quad (11)$$
where $|\sigma_i|^2 = \sigma_{id}^2 + \sigma_{it}^2$, and, evidently, $B \geq 0$. The effective conductivities $\sigma_{ed}(\{\sigma\}, \{x\})$ of the three inhomogeneous models without magnetic field have simple forms:

1. a ”random droplets” model
   \[ \sigma_{ed}(\{\sigma\}, \{x\}) = (\sigma_1)^x_1(\sigma_2)^x_2; \] (12)

2. a ”random parquet” model
   \[ \sigma_{ed}(\{\sigma\}, \{x\}) = (\sigma_1 \sigma_2)^{1/2} \left( \frac{x_1 \sigma_1 + x_2 \sigma_2}{x_1 \sigma_2 + x_2 \sigma_1} \right)^{1/2}; \] (13)

3. an effective medium model
   \[ \sigma_{ed}(\{\sigma\}, \{x\}) = (x - \frac{1}{2})(\sigma_1 - \sigma_2) + \sqrt{(x - \frac{1}{2})^2(\sigma_1 - \sigma_2)^2 + \sigma_1 \sigma_2}. \] (14)

All formulas (10,12-14) correctly reproduce boundary values of the effective conductivities as well as their exact values at equal phase concentrations $x = 1/2$ \[ 1 \]

\[ \sigma_{ed}(x = 1/2) = \sqrt{\sigma_{1d}\sigma_{2d}}A, \quad A = \left[ 1 + \left( \frac{\sigma_{1t} - \sigma_{2t}}{\sigma_{1d} + \sigma_{2d}} \right)^2 \right]^{1/2}, \]

\[ \sigma_{et}(x = 1/2) = \frac{\sigma_{1t}\sigma_{1d} + \sigma_{2t}\sigma_{2d}}{\sigma_{1d} + \sigma_{2d}}. \] (15)

This permits us to write the exact expression for $R$ at $x = 1/2$

\[ R(1/2, H) = \sigma_{ed}(1/2, 0) - \frac{\sigma_{ed}(1/2, H)}{\sigma_{ed}^2(1/2, H) + \sigma_{et}^2(1/2, H) - 1}, \]

where

\[ \sigma_{ed}(1/2, H) = \frac{\sqrt{\sigma_{10}\sigma_{20}}}{\sqrt{(1 + H^2)(1 + \eta^2 H^2)}}A(H), \]

\[ A(H) = \left[ 1 + H^2 \left( \frac{(1 + \eta^2 H^2) - \eta z(1 + H^2)}{(1 + \eta^2 H^2) + z(1 + H^2)} \right) \right]^{1/2}, \]

\[ \sigma_{et}(1/2, H) = \frac{\sigma_{20}(1 + \eta)H}{(1 + \eta^2 H^2) + z(1 + H^2)}. \] (16)

One can obtain an asymptotic behaviour of $R$ at high $H, \eta H \gg 1$. Since in this limit

\[ \sigma_{ed}(1/2, H) = \frac{\sqrt{\sigma_{10}\sigma_{20}}}{H} \left| \frac{\eta - z}{\eta^2 + z} \right|, \quad \sigma_{et}(1/2, H) = \frac{\sigma_{20}(1 + \eta)}{(\eta^2 + z)H}, \]
then

\[ R(1/2, H) = cH + o(H), \quad c = \frac{|\eta - z|}{(\eta - z)^2 + z(1 + \eta)^2} + o(H). \] (16')

Thus, the exact value \( R(1/2, H) \) has a linear dependence on \( H \) at high \( H \) with the coefficient \( c \), which becomes 0 for homogeneous media as well as for inhomogeneous systems with \( \eta = z \). It is interesting that \( c = 1 \) at \( \eta = -1 \). Just in this case \( \sigma_{et}(x = 1/2) = 0 \). At \( \eta = 1 \) \( c \) reduces to a simple formula \( c = \frac{\eta}{|\eta + 1|} \).

Substituting (11) and (12-14) into (10) and then into (6), one can obtain the explicit expression for the magnetoresistance \( R(x, H) \) of the corresponding systems at arbitrary concentrations and magnetic fields. Since these formulae are rather complicate we will analyze their behaviour by constructing the plots of their dependencies on \( x \) and \( H \).

Using explicit formulae (6),(7),(10-14) we have constructed the plots of \( H \)- and \( x \)-dependencies of \( R(x, H) \) for inhomogeneous systems, whose inhomogeneity structures are similar to three considered models, for different values of the inhomogeneity parameter \( z \) and \( \eta \). The corresponding plots of \( H \)- and \( x \)-dependencies at \( z = 10^{-2} \) and \( \eta = 1 \) are represented, respectively, in Fig.1 and Fig.2 ((a)-(c)).

One can see from fig.1 and fig.2 that the behaviour of the magnetoresistance, though different for various expressions (i.e. various models) and saturated in some regions of \( x \), has two common characteristic features:

1) absolute values of \( R \) are very large, especially at peaks;
2) all values in the regions with large values of \( R \) increase with a growth of \( H \) at relatively high \( H \) approximately linearly.

Both these properties are the consequences of the high \( H \) behaviour of the effective conductivities [12]

\[ \sigma_{ed} \sim \sigma_{et} \sim 1/H, \] (17)

and are qualitatively consistent with the experimental results from [2] [14] [15], which show a large magnetoresistivity and its approximately linear growth with an increase of \( H \). Practically the same plots for \( R(x, H) \) are obtained for the case, when two partial phases have carriers with opposite charges, i.e. at \( \eta = -1 \). It follows also from (6), since \( \sigma_{et} \), sensitive to a sign of \( \eta \), enters in \( R \) only as squared. Some dependence on a sign of \( \eta \) appears for the Hall resistivity (see next paper).

More detailed analysis shows a number of interesting specific properties. Let us start with the "random droplets" model. In this case \( R \) has evident one peak asymmetrical structure positioned for the inhomogeneity parameter \( z = 10^{-2} \) in the region of concentration \( x \sim 0.37 \) with a maximum growing almost linearly and slightly shifting to the higher values of concentration and with a width narrowing with an increase of \( H \). Note that the maximal value of \( R \) is much larger then the exact value (15). It appears that a decline of linear dependence also changes becoming maximal \( \approx 2.7 \) at the peak and \( H = 300 \). For higher
values of inhomogeneity parameter $z$ the peak slightly shifts to the lower values of $x$ (for $z = 10^{-3}$ it is situated at $x \approx 0.3$).

Very remarkable pictures are obtained for the "random parquet" model. The magnetoresistance shows approximately constant large values, almost coinciding with the exact value at $x = 1/2$ in a wide region of concentrations and very sharp changes in small regions $x, 1-x \ll 1$ near the boundary concentrations $x = 0, 1$. In this model the exact value is a maximal one. The width of the plateau region, which is approximately symmetrical, slightly grows with a growth of $H$. For the concentrations in the plateau region $R$ increase linearly with $H$ with an approximately constant coefficient, which coincides with its exact value at $x = 1/2$ from (16). The width of the narrow regions near boundaries decreases with an increase of $H$ and a decrease of $z$.

For the effective medium model we have obtained very unusual pictures. $R(x, H)$ shows strongly asymmetrical very narrow and high peak, situated just below $x = 1/2$, with a sharp decrease to negligibly small values in the narrow region near $x = 1/2$ and long small tale in the region $x < 1/2$. The exact value of $R$ is significantly smaller than the maximal one.

In order to compare $R(x, H)$ for different models in more detail we represent also the plots of their $x$-dependencies at $H = 50$ in one Fig.2(d). One can see
Fig. 2. The plots of the $x$ dependence of the magnetoresistance $R(x,H)$ for three explicit expressions obtained above (respectively, (a), (b), (c)) at the inhomogeneity parameter $z = 0.01$, and at the four different (dimensionless) values of magnetic field $H$: (1) 50, (2) 100, (3) 300 and (4) 900 (the corresponding plots go from the lower to the upper ones; on (c) $H = 25, 50, 100$, since in this case for higher $H$ the peaks are very narrow and almost coincide). (d) shows a comparison of all $R(x,H)$ at $H = 100$.

from Fig. 2(d) the relative widths and maximal values of $R$ for three models. The highest values $R$ achieves for the "random droplet" and effective medium models, meanwhile the "random parquet" model has the widest region of relatively large values. At equal phase concentrations $x = 1/2$ all models give exact value (16,16').

4. Discussion and comparison with the experiments

The obtained formulae and the constructed plots unambiguously show an existence of the large magnetoresistance effect with almost linear growth at relatively large magnetic fields in various planar inhomogeneous models. In different models it has different dependences on concentration. The analysis of these dependences and the structures of the considered models allows to conclude that the different inhomogeneous fluctuations have different influence on the magnetoresistance. The random compact (droplet like) fluctuations have the most strong influence in the range of concentrations $0.3 \leq x \leq 0.5$. In this
region the randomly distributed droplets of higher conducting component serve as traps for charge carriers. They work the most effectively for concentrations in the region $0.3 \leq 0.4$ where all droplets have finite sizes and rather rare intersections. For larger concentrations the large droplets appear. Though the carriers are confine inside them for a long time, they already can propagate on significant distances due to their large size. The last effect induces a decrease of $R$. The almost linear growth of $R$ with $H$ means that the stronger magnetic fields help to confine carriers inside droplets.

At the same time, the stripe-like inhomogeneities, as it follows from the results for the "random parquet" model, begin to work as traps already at very small concentrations $x$, when they have a form of rare, randomly distributed, stripes of highly conducting component. If a length of these stripes is constrained and they do not form any effectively large or dense cluster (what takes place in this model due to a construction), these stripes gives approximately the same contribution to $R$, very weakly depending on their concentration. Only in very narrow regions near $x = 0$ and $x = 1$, where a number of highly or badly conducting stripes is very small, the rare randomly distributed stripes give sharp changes of $R$, which quickly saturate. We suppose that a similar behaviour will take place in the models with other randomly distributed stripe-like inhomogeneities. For example, we expect that such behaviour (maybe, a more smoother than in the original "random parquet" model) will take place in models constructed from plaquettes of different forms and sizes with isotropic discrete (or even continuous) distributions of stripe orientations.

The most unusual behaviour shows the "magnetically" transformed effective medium model. It does not influence on $R$ almost for all concentrations, except very narrow region near $x = 1/2$ and long tail with non large values in the region $0 \leq x \leq 0.4$. It can be explained by the tight connection of this model with the wire-type networks, which cannot be used for a description of magneto-transport effects, connected with bulk properties. Only in the narrow region near $x = 1/2$, where the large dense clusters with many "dead" ends appear, they give strong contribution to $R$.

Now we can compare the considered models with the known results for silver chalcogenides ($Ag_{2+\delta}Se$ and $Ag_{2+\delta}Te$), which show large linear magnetoresistance effect (see, for example, [2, 14]) for different concentrations of $Ag$ [15]. As it was noted in [2] silver chalcogenides have a tendency to a formation of different phases on small scales (including nanometre one). The additional $Ag$ ions strive to situate on various defects and grain boundaries [15, 16]. The latter presumably have a form of intersecting straight lines. When concentration of the excess $Ag$ ions is small, they form randomly distributed stripes of different size along these boundaries [15]. This structure is very similar to the corresponding structure of the "random parquet" model. The dependences of $\rho_{e0}$ and $R(x, H)$ on $x$ in the "random parquet" model at small $x$ (the $x$-dependences of $\rho_{e0}$ in all three considered above models can be found, for example, in [13], where they are represented for corresponding $\sigma_{e0}$, one only needs to change $\sigma_1, \sigma_2$ into $\rho_2$ and $\rho_1$ respectively) are also very similar to the behaviour of $\rho_{e0}$ and $R(x, H)$ observed in experiments [2, 15], where very small excess of $Ag$ ions gives sharp
increase of $R$. Moreover, for the larger concentrations, in some finite region, the experiment shows an approximately constant behaviour of $\rho_{e0}$ and $R$, which changes again on, respectively, decreasing and increasing behaviour [15]. We can explain this behaviour as a result of a crossover from the presumably striped structure of excess $Ag$ ions to the mixed structure, including also their compact islands [15]. The latter forms a structure, which is similar to that of the "random droplets" model. The corresponding contribution into $R$ is firstly small relative to "random parquet" model. But, as follows from our Fig.2(d) (its envelope in the region $0 \leq x \leq 0.5$ qualitatively coincides with Fig.3 from [15]), at approximately $x_c = 0.25$ (the exact values of the crossover $x_c$ can depend on magnetic field and inhomogeneity parameters) a contribution of the "random droplets" model becomes larger than that of the "random parquet" model and again appears the increasing behaviour of $R$ (or a decreasing behaviour of $\rho_{e0}$). It means that the structure of inhomogeneities with the excess $Ag$ ions in $Ag_{2+\delta}Se(Te)$ is very similar to the structures of our models (at least, in the region $0 \leq x \leq 0.5$) and the latter can give the necessary formulae for a description of the magneto-transport properties of silver chalcogenides in this region of concentrations. Moreover, our formulae give also numerical values, which are in a good agreement with the experimental ones (see our forthcoming papers).

At the end we would like to note a possible importance of the obtained results for practical applications. As is known, a behaviour of $R$ such as it takes place in the "random" parquet model and models related with it is the most suitable for magnetic sensors and information storage technologies (see, for example, [17]). For this reason, the "random parquet" type models with random stripe-like structures of inhomogeneities show us what kind of inhomogeneous structure one needs to fabricate sensors and other high-technology devices, having small sizes and working at room temperatures.

5. Conclusion

Using three explicit approximate expressions for the effective conductivity of 2D isotropic two-phase systems in a magnetic field, we have obtained explicit expressions for the magnetoresistance $R(x, H)$ of planar isotropic two-phase systems. The plots of the $x$- and $H$-dependencies of $R(x, H)$ at the different values of the inhomogeneity parameters $z$ and $\eta$ are constructed. They show the evident large, almost linear, magnetoresistance effect. The behaviour of the constructed plots is very similar and qualitatively compatible with the experimental data for silver chalcogenides $Ag_{2+\delta}Se$ from [2] [15]. A possible physical explanation of such behaviour is proposed. It is noted that the random, stripe type structures of inhomogeneities, are the most suitable for a fabrication of magnetic sensors and a storage of information at room temperatures. We hope that the constructed models and their modifications as well as the obtained results can be applied also for a description of magneto-transport properties of various real heterophase systems (regular and nonregular as well as random), satisfying the symmetries and having the similar structures, in a wide range of inhomogeneity parameters and at arbitrary concentrations and magnetic fields.
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References


