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PHYSICS LETTERS A
Physics Letters A 342 (2005) 188–195
www.elsevier.com/locate/pla

Large linear magnetoresistivity in strongly inhomogeneous planar and layered systems

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Received 1 March 2005; accepted 20 April 2005

Available online 17 May 2005

Communicated by V.M. Agranovich

Abstract

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 $Ag_{2+\delta}Se$. 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.

PACS: 75.70.Ak; 72.80.Ng; 72.80.Tm; 73.61.-r

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 $Ag_{2+\delta}(Se, Te)$ in a wide region of temperatures, from low ($\sim$1 K) till room temperatures ($\sim$300 K). At the moment there exist two approaches in a theoretical explanation of a linear behaviour of

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0375-9601/$ – see front matter
doi:10.1016/j.physleta.2005.04.096

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 $Ag_{2+\delta}Te$ [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 up to room temperatures and for systems where a mean 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 μ) are random and have a continuous wide distribution with $\langle\mu\rangle = 0$ [5,6]. This model is similar to the usual wire network model [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 [8,9]. The existence of this transformation is a direct consequence of the exact Keller–Dykhne duality of two-dimensional systems [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 [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:

$$\hat{\sigma} = \sigma_{ik} = \sigma_d\delta_{ik} + \sigma_t\epsilon_{ik},$$
$$\sigma_d(\mathbf{H}) = \sigma_d(-\mathbf{H}), \qquad \sigma_t(\mathbf{H}) = -\sigma_t(-\mathbf{H}), \tag{1}$$

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

$$\hat{\rho} = \rho_{ik} = \rho_d\delta_{ik} + \rho_t\epsilon_{ik},$$
$$\rho_d(\mathbf{H}) = \rho_d(-\mathbf{H}), \qquad \rho_t(\mathbf{H}) = -\rho_t(-\mathbf{H}), \tag{2}$$

where

$$\rho_d = \frac{\sigma_d}{\sigma_d^2 + \sigma_t^2}, \qquad \rho_t = -\frac{\sigma_t}{\sigma_d^2 + \sigma_t^2}. \tag{3}$$

The effective resistivity $\hat{\rho}_e$ and, consequently, ρ_{ed}, ρ_{et} (we assume here that $\rho_{id} \geqslant 0$) 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

$$\hat{\rho}_e(\hat{\rho}_1, x_1|\hat{\rho}_2, x_2) = \hat{\rho}_e(\hat{\rho}_2, x_2|\hat{\rho}_1, x_1). \tag{4}$$

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