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Classical Hall transition and magnetoresistance in strongly inhomogeneous planar systems

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Abstract

The magneto-transport properties of planar and layered strongly inhomogeneous two-phase systems are investigated, using the explicit expressions for the effective conductivities and resistivities obtained by the exact dual transformation, connecting effective conductivities of in-plane isotropic two-phase systems with and without magnetic field. These expressions allow to describe the effective resistivity of various inhomogeneous media at arbitrary concentrations x and magnetic fields H. The corresponding plots of the x-dependence of the Hall constant $R_H(x, H)$ and the magnetoresistance $R(x, H)$ are constructed for various values of magnetic field at some values of inhomogeneity parameters. These plots for strongly inhomogeneous systems at high magnetic fields show a sharp transition between partial Hall resistivities (or Hall conductivities) with different dependencies of R_H on the phase concentrations. It is shown that there is a strong correlation between large linear magnetoresistance effect and this sharp Hall transition. Both these effects are a consequence of the exact duality symmetry. A possible physical explanation of these effects and their correlation is proposed.

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1. Introduction

The experimental discovery of the abnormal magnetotransport properties in thin films of some inhomogeneous systems even at room temperatures T and high magnetic fields H, such as a large [1] and a linear magnetoresistance (MR) [2], has turned out a challenge for theoretical physics, since the existing theories of the magnetotransport in inhomogeneous systems (see, for example [3]) (using presumably the effective medium approximation, based on the wire-network type model of inhomogeneous media [4]) cannot describe properly these properties [3,5].

Recently, the new network type model, generalizing the standart wire-network type model and using as

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the building blocks the 4-terminal discs, was proposed [5,6]. This model can describe magnetotransport properties of thin films. The authors of this model have shown by numerical methods that the disc-network model can reproduce the large linear MR (LLMR), when the conducting parameters of the discs, in particular, a mobility μ, have random continuous and wide distribution with an average value $\langle\mu\rangle = 0$. It was noted also in [5,6], that the investigation of the Hall resistivity of this model by the same methods require much more time and work.

In the framework of the classical theory there is another approach for a description of the magnetotransport properties of some inhomogeneous two-dimensional (or layered, inhomogeneous in planes, but constant in the direction orthogonal to planes) systems in perpendicular magnetic field. It is based on the exact dual symmetry of these systems [7] and is connected with an existence of the exact dual, linear fractional transformation, relating the effective conductivity $\hat{\sigma}_e$ (and the effective resistivity $\hat{\rho}_e = \hat{\sigma}_e^{-1}$) of planar self-dual two-phase systems with and without (σ_{e0}) magnetic field at arbitrary magnetic fields and phase concentrations [8,9].

In the papers [10–12], using this exact transformation (we call it the magnetic dual transformation (MDT)) and the known expressions for σ_e of three inhomogeneous models with different random structures of inhomogeneities without H from [13], the explicit expressions for $\hat{\sigma}_e$ [10,11] and for the magnetoresistance $R(x, H)$ [12] have been obtained. It have been shown also there ([11,12]) that these expressions give the LLMR effect even in two-phase systems and without the restriction $\langle\mu\rangle = 0$, and that a form and a position of the LLMR effect as functions of phase concentrations depend on models and the corresponding inhomogeneity structures.

In this Letter, using the explicit approximate expressions obtained in [10–12] and applicable at arbitrary values of phase concentrations and magnetic fields and in a wide region of partial conductivities, we will investigate a behaviour of the effective resistivities ρ_{et} and ρ_{et} of the planar self-dual two-phase systems. We will present also the x-dependence plots of the Hall constant $R_H(x, H)$ for some characteristic values of magnetic field H at different values of the inhomogeneity parameters. These plots, together with the previous results for the effective conductivity from [10,11] and for the magnetoresistance $R(x, H)$ from [12], show the existence of the following properties in these inhomogeneous systems at high magnetic fields: (1) the sharp transition between partial Hall constant plateaus under a change of phase concentrations with a position and a width of the region of transition depending on the model inhomogeneity structure; (2) the strong correlations between the LLMR effect and the sharp transition between the Hall plateaus. These properties are a consequence of the exact duality relation. A possible physical explanation of these properties is also proposed. A comparison with the existing experimental data shows a good qualitative agreement.

2. Magnetic dual transformation at high H

The effective conductivity of inhomogeneous isotropic systems in magnetic field has the following form

$$\hat{\sigma}_e = \sigma_{e(ik)} = \sigma_{ed}\delta_{ik} + \sigma_{et}\epsilon_{ik},$$
$$\sigma_{ed}(\mathbf{H}) = \sigma_{ed}(-\mathbf{H}), \quad \sigma_{et}(\mathbf{H}) = -\sigma_{et}(-\mathbf{H}), \tag{1}$$

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

$$\hat{\rho}_e = \rho_{e(ik)} = \rho_{ed}\delta_{ik} + \rho_{et}\epsilon_{ik},$$
$$\rho_{ed}(\mathbf{H}) = \rho_{ed}(-\mathbf{H}), \quad \rho_{et}(\mathbf{H}) = -\rho_{et}(-\mathbf{H}), \tag{2}$$

where

$$\rho_{ed} = \sigma_{ed}/\left(\sigma_{ed}^2 + \sigma_{et}^2\right), \qquad \rho_{et} = -\sigma_{et}/\left(\sigma_{ed}^2 + \sigma_{et}^2\right). \tag{3}$$

The Hall constant $R_H(x, H)$ is determined as follows

$$R_H(x, H) = \rho_{et}(x, H)/H. \tag{4}$$

In two-phase systems the effective conductivity $\hat{\sigma}_e$ (and effective resistivity $\hat{\rho}_e$) can be expressed by the "magnetic" dual transformation (MDT) through the effective conductivity of the same system without magnetic field [8,9]

$$\sigma_{ed}\left(\{\sigma\}, \{x\}\right) = \frac{\sigma'_{e0}(ac + b)}{(\sigma'_{e0})^2 + a^2},$$
$$\sigma_{et}\left(\{\sigma\}, \{x\}\right) = c\frac{(\sigma'_{e0})^2 - ab'}{(\sigma'_{e0})^2 + a^2}, \tag{5}$$