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Scaling description of positive magnetoresistivity in doped dilute magnetic semiconductors

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ABSTRACT

The effect of a large positive magnetoresistance (MR) in $Zn_{1-x}Mn_xSe$: Cl materials in the hopping regime is studied experimentally and theoretically. A possible mechanism of this effect has been recently suggested [Nenashev et al., Phys. Rev. B 88 (2013) 115210] [4] based on the increase of energy disorder in the distribution of dopant levels caused by the exchange interaction between magnetic Mn atoms and the electrons localized on nonmagnetic Cl impurities. In the current work we confirm this mechanism experimentally by comparison between the MR in samples with finite Mn content x and the MR in a sample with $x=0$. At $x=0$, a negative MR is observed, while at finite x a large positive MR is evidenced with the dependence on magnetic field similar to that of the macroscopic magnetization, confirming the suggested MR mechanism at finite x. Scaling description of the positive MR [Nenashev et al., Phys. Rev. B 88 (2013) 115210] [4] has been suggested so far only for the case of the nearest-neighbor-hopping or Mott variable-range-hopping regimes. In the current work, we present experimental data to analyze the underlying transport regime and extend the scaling description for the Efros–Shklovskii variable-range-hopping regime, in which many-particle Coulomb interactions play a decisive role for the distribution of electron energies on dopant atoms.

1. Introduction

The topic of this report is a large positive magnetoresistance (MR) in doped dilute magnetic semiconductors $Zn_{1-x}Mn_xSe$: Cl at dopant concentrations below the metal–insulator transition, when the low-temperature transport is due to hopping of electrons via non-magnetic Cl donors. Isovalently incorporated magnetic Mn atoms affect the energies of electrons on donors via the s–d exchange interaction leading to the Giant Zeeman splitting [1–3].

Fluctuations in the spatial distribution of Mn atoms have been recently suggested [4] as responsible for the large positive MR. When the Mn spins are aligned by an external magnetic field [5,6], the Mn density fluctuations cause a broadening of the donor energy distribution leading to the increase in the resistivity of the material. General scaling arguments were developed to describe the MR effect quantitatively [4]. However, the scaling approach given in Ref. [4] holds only for the case of the nearest-neighbor-hopping (NNH) or Mott variable-range-hopping (VRH) regimes, when many-particle Coulomb interactions are not significant for the distribution of electron energies on dopant atoms.

In the current work, we check experimentally the validity of the suggested MR mechanism by comparison between the MR in samples with finite Mn content and the MR in a sample without magnetic atoms. Furthermore, we extend the scaling approach for description of the Efros–Shklovskii (ES) VRH regime, in which many-particle Coulomb interactions play the decisive role.

In Section 2, experimental data will be presented for a series of $Zn_{1-x}Mn_xSe$: Cl samples with different concentrations of Cl and Mn atoms. The effect of the positive MR in the hopping regime will be highlighted and the appropriate MR mechanism will be discussed. The corresponding mechanism has been recently suggested by Nenashev et al. [4], who, however, have not provided yet a straightforward experimental evidence that the positive MR is related to the presence of magnetic Mn atoms and is not just caused by the effect of magnetic field on various features of dopant

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atoms involved in the hopping transport. In Section 3, a scaling theory from Ref. [4] will be briefly sketched as valid for the NNH or for Mott VRH regimes. In Section 4, the transport regime in $Zn_{1-x}Mn_xSe$: Cl at low temperatures will be verified. While only theoretical features were discussed in Ref. [4], experimental data missing in Ref. [4] are given in Section 4 in order to distinguish between the Mott VRH and the ES VRH regimes. In Section 5, scaling theory will be developed for description of the MR in the ES VRH transport regime. Concluding remarks are gathered in Section 6.

2. Experimental data and the choice of the MR mechanism

Epitaxial layers of n-type $Zn_{1-x}Mn_xSe$ with $x < 8\%$ were grown by molecular beam epitaxy on a semi-insulating (100) GaAs substrate using chlorine as n-type dopant (provided by evaporating $ZnCl_2$). The layer structure consists of an undoped ZnSe buffer followed by the n-type $Zn_{1-x}Mn_xSe$: Cl layer with a thickness of about 1 μm [7,8]. The MR measurements were performed in magnetic fields up to 10 T in the temperature range from 1.6 to 280 K. A van-der-Pauw configuration was used. Fig. 1 shows the temperature dependence of the resistivity of several $Zn_{1-x}Mn_xSe$ samples. Concentrations of carriers n and Mn-contents in these samples are given in Table 1.

Temperature dependences of the resistivity in Fig. 1 give evidence that at carrier concentrations above $n \simeq 10^{18}$ cm^{-3} (samples f and g) conductivity is of metallic type, while at concentrations below $n \simeq 10^{18}$ cm^{-3} (samples a–e) conductivity at low temperatures is due to tunneling (hopping) of carriers between donors and at higher temperatures due to activation of carriers from donors into conduction band [9]. Although the existence of the hopping transport regime in dilute magnetic semiconductors has been proven for decades [5], there is no consensus among researchers on the basic mechanisms of the MR effects in the hopping transport.

In Fig. 2, the measured MR in a sample of the composition $Zn_{0.94}Mn_{0.06}Se$: Cl is shown for low temperatures, $T \leq 10$ K, at

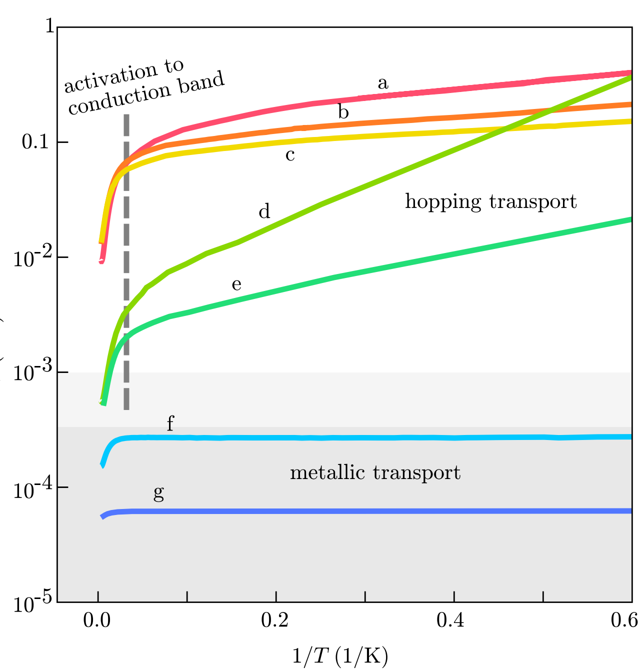

Fig. 1. Temperature dependence of the resistivity of various Cl-doped $Zn_{1-x}Mn_xSe$ layers. The carrier concentration n and Mn content x of the samples are given in Table 1.

Table 1
Carrier concentration n and Mn content x of all the samples in Fig. 1

Sample	a	b	c	d	e	f	g
n (10^{17} cm^{-3})	2.6	8.0	1.9	3.4	4.5	13	44
x (%)	2	0	0.75	7.1	6	6.2	5.5

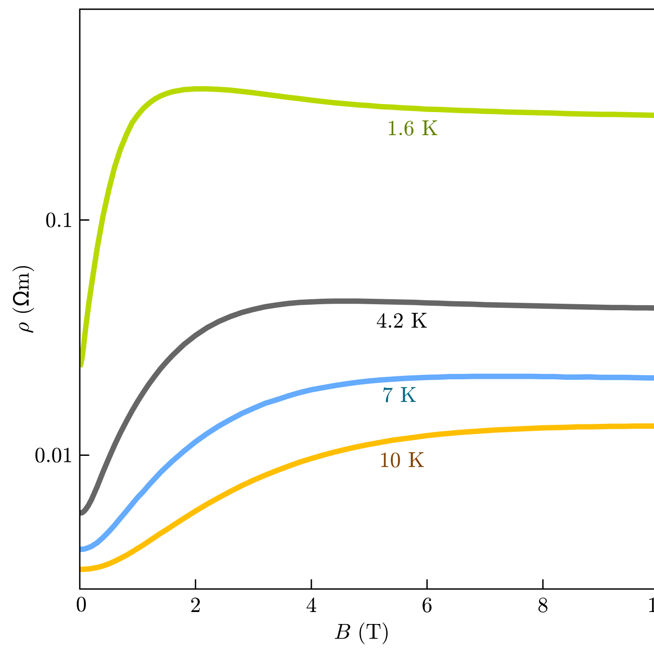

Fig. 2. Resistivity dependent on magnetic field in n-type $Zn_{0.94}Mn_{0.06}Se$: Cl with donor concentration 4.5×10^{17} cm^{-3}.

which activation of electrons into the conduction band can be neglected and the conductivity is due to hopping of electrons via donor atoms. This sample with chlorine concentration $N_D = 4.5 \times 10^{17}$ cm^{-3} estimated from room-temperature Hall measurements was studied in detail in Ref. [4]. Other samples containing Mn atoms (samples a, c, d in Table 1) demonstrate a similar behavior [10]: the resistivity first increases with magnetic field B, and then saturates, or slightly decreases after reaching a maximum. Our goal is to clarify the mechanism responsible for the observed positive MR contribution.

In attempts to account for the positive MR effect one should distinguish between mechanisms related to the presence of magnetic atoms and those valid also in non-magnetic semiconductors. The most prominent one among the latter effects is a positive MR due to shrinkage of the wavefunctions of localized states [9]. In order to find out whether the shrinkage of the donor wave functions in magnetic field could be responsible for the positive MR in Fig. 2, we compare in Fig. 3 the MR behavior of the sample ZnSe:Cl without magnetic atoms (sample b in Table 1 and Fig. 1) with the MR behavior of the sample $Zn_{0.94}Mn_{0.06}Se$: Cl containing Mn atoms (sample e in Table 1 and Fig. 1). The drastic difference in the MR curves for samples with and without magnetic atoms seen in Fig. 3A and B demonstrates the decisive role of the Mn atoms for the positive MR effect in the $Zn_{1-x}Mn_xSe$: Cl material.

Remarkably, very similar effects in the hopping transport regime, including the MR behavior, have been recently observed in zinc oxide films with Co magnetic atoms [11–13]. In that system, hopping transport at low temperatures occurs via localized states in the non-crystalline film and the large positive MR effects are caused by isovalently incorporated Co atoms [11–13]. The temperature dependences of the resistivity of samples $Zn_{0.937}Co_{0.063}O$