

Carrier-Induced Magnetic Solitons and Metal-Insulator Transition in Diluted Magnetic Semiconductors $\text{Ga}_{1-x}\text{Mn}_x\text{As}$

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Abstract

We discuss hole-induced magnetic solitons and metal-insulator transition of transport properties in diluted magnetic semiconductors $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ from the standpoint of a field theoretical formulation, and analyze experimental data of transport properties, using the supersymmetry sigma formula and the effective Lagrangian of diffusion model.

Keywords

Diluted Magnetic Semiconductor, Magnetic Soliton, Metal-Insulator Transition, Localization

1. Introduction

Diluted magnetic semiconductors (DMSs), which are formed by substitution of several percent of cation sites in a host semiconductor with magnetic impurities, are actively investigated both theoretically and experimentally, due to their potential applications in new generations of semiconductor spintronic devices [1]. Because the carriers in DMSs are considered to mediate the magnetic interaction between the magnetic ions [2], these materials are very important for semiconductor-based spintronic devices to control the spin degree of freedom of the carriers. Due to the mediation mechanism, the ferromagnetism in DMSs is called carrier-induced ferromagnetism. Prototypical DMS systems such as $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ and $\text{In}_{1-x}\text{Mn}_x\text{As}$ show severely limited chemical solubility due to the substitution of divalent Mn atoms for the trivalent Ga or In sites. In order to prevent phase separation, these materials should be grown at low temperature (T from 200°C to 300°C), which results in an abundance of different types of crystal defects. As a

result, a theoretical study of DMSs is very difficult owing to two factors (strong disorder and exchange interaction), which must be taken into account non-perturbatively.

Understanding the mechanism behind the carrier-induced ferromagnetism is of significance for further development of semiconductor spintronic devices. Several theoretical models for carrier-induced ferromagnetism in (Ga, Mn)As have been proposed [1]-[6]. In addition, interesting phenomena such as the photo-induced magnetic polaron in DMSs have been reported [7] [8] [9] [10]. These studies stimulate us to investigate the hole-induced magnetic solitons. It has been required to consider the behavior of the hedgehog-like magnetic soliton and the domain wall from a viewpoint of quantum theory. Kanazawa [11] has discussed the hole-induced magnetic solitons in DMSs from the standpoint of a field-theoretical formulation. Metal-insulator transition (MIT) and large magnetoresistance (MR) effects in DMSs (Ga, Mn)As have been reported [12] [13] [14] [15] [16]. Kanazawa and coworkers [17] [18] [19] [20] [21] have discussed these anomalous properties in DMSs theoretically.

In this study, the anomalous transport properties in DMSs are discussed using a field-theoretical formulation. Then we analyze some conductivity data in DMSs (Ga, Mn)As, using the gauge-invariant effective Lagrangian density and quantized magnetic solitons.

2. A model System and Hole-Induced Magnetic Solitons

According to the aggregation of hole-induced magnetic solitons, the non-monotonic temperature dependence of the transport properties of (Ga, Mn)As is qualitatively explained as being due to the hole localization around the Mn ions. It has been suggested that the ferromagnetic ordering might be due to a double-exchange-like interaction and the remarkable change of spin exchange interaction among Mn ions by the hole seems to be cooperative and non-linear (Yang Mills like). Kanazawa and coworkers [22] [23] [24] [25] have proposed that in quasi-(2 + 1) dimensions in a quantum antiferromagnet the hole-induced magnetic disorder leads to hedgehog-like solitons, which are composed of the doped hole and the cloud of SU(2) Yang-Mills fields with spin disorder around the hole. In addition, based on the important ideas in Refs. [26] [27] [28] [29], it has been proposed that the hedgehog-like soliton in a three-dimensional system is specified by rigid-body rotation, which is related to gauge fields of SO(4) symmetry for S^3 [30] [31] [32] [33] [34].

Then the Yang-Mills fields A_μ^a induced by the doped hole have a local SO(4) symmetry. Here we have thought that the SO(4) symmetry fields A_μ^a are spontaneously broken around the hole through the Anderson-Higgs mechanism, in the III-V-based diluted magnetic semiconductors with magnetic manganese ion-doping. Through the spontaneous symmetry breaking $\langle 0 | \phi_a | 0 \rangle = \langle 0, 0, 0, \mu \rangle$, the effective Lagrangian density has been introduced [11] [19]. That is, the effective Lagrangian density reveals that the ferromagnetically aligned Mn spins create

the cluster, in which the hole is trapped, with the radius $R_c \sim 1/m_2$. Katsumoto *et al.* [16] have shown that the localization length l_c of the wave function of holes plays an important role in the metal-insulator transition in DMS (Ga, Mn)As. It is suggested strongly that the l_c might correspond to $R_c \sim 1/m_2$. In III-V-based DMSs, the resistivity increases remarkably as the temperature decreases. In addition, in the same temperature region, the negative magnetoresistance grows rapidly as the temperature decreases. To explain the electron hopping and spin dynamics, we introduce an effective Hamiltonian, H , for the magnetic soliton $O(r_i)$ [18] [20]

$$H = -J \sum_{\langle \tilde{i}, \tilde{j} \rangle} \cos(\theta_{\tilde{i}\tilde{j}}/2) O(r_{\tilde{i}}) \cdot O(r_{\tilde{j}}) + \frac{1}{2} K \sum_{\tilde{i} \neq \tilde{j}} \frac{O(r_{\tilde{i}}) \cdot O(r_{\tilde{j}})}{|r_{\tilde{i}} - r_{\tilde{j}}|}. \quad (1)$$

Here the first sum $\sum_{\langle \tilde{i}, \tilde{j} \rangle}$ is taken only over nearest neighbors (the distance between each magnetic soliton is $\leq 2R_c$), while the second sum is taken over all pair ($\tilde{i} \neq \tilde{j}$ means $|r_{\tilde{i}} - r_{\tilde{j}}| > 2R_c$) [18] [20]. $\theta_{\tilde{i}\tilde{j}}$ is the angle between $N_{\tilde{i}}$ and $N_{\tilde{j}}$. Here $N_{\tilde{i}}$ and $N_{\tilde{j}}$ represent the effective spins of the solitons $O(r_{\tilde{i}})$ and $O(r_{\tilde{j}})$, respectively. $N_{\tilde{i}}$ is the summation of the ferromagnetic spin, N_i , of Mn within $\sim (4/3)\pi R_c^3(\tilde{i})$ around the hole at the site $r_{\tilde{i}}$. J is defined in Equation (2). K , which is introduced in Ref. [18], is the effective long-range interaction constant. The first term shows short-range ferromagnetic ordering interaction and the second one shows long-range frustration.

$$-J = -\frac{g_2^2}{4\pi} \frac{e^{-m_1 r}}{r} \Big|_{r \sim \frac{1}{m_1}} \sim -\frac{g_2^2}{4\pi} m_1 e^{-1} \quad (2)$$

is the short-range attractive potential, which is derived from massive gauge fields A_μ^1 , A_μ^2 , and A_μ^3 exchange interaction. When the magnetic soliton, $O(r_{\tilde{i}})$, with the effective spin $N_{\tilde{i}}$ is located at the nearest-neighbor site of the magnetic soliton, $O(r_{\tilde{j}})$, with the effective spin $N_{\tilde{j}}$, holes are hopping between the two solitons $O(r_{\tilde{i}})$ and $O(r_{\tilde{j}})$. If $N_{\tilde{i}}$ is parallel to $N_{\tilde{j}}$, the p-d exchange interaction induces large reduction of the kinetic energy. The hopping term between the nearest neighbors of hedgehog-like solitons (clusters) leads to an additional term in the σ -model describing a coupling of the supermatrices, $Q_{\tilde{i}}$, corresponding to different magnetic solitons (clusters) [18]. We discuss the transport properties of DMSs for connected clusters, where the radius is $R_c \sim 1/m_2$, of DMSs. Approximately we introduce the following approximate free energy by using the formula for the model of granulated clusters [35] [36]

$$\tilde{F}(Q) = \text{str} \left(-\sum_{\langle \tilde{i}, \tilde{j} \rangle} J_{\tilde{i}\tilde{j}} Q_{\tilde{i}} Q_{\tilde{j}} + \frac{i}{4} (\omega + i\delta) \sum_{\tilde{i}} \Delta_{\tilde{i}}^{-1} \Lambda Q \right), \quad (3)$$

where $J_{\tilde{i}\tilde{j}} = J \cos(\theta_{\tilde{i}\tilde{j}}/2) \frac{1}{\Delta_{\tilde{i}} \Delta_{\tilde{j}}}$. Then $\Delta_{\tilde{i}}$ is the mean energy level spacing at the hedgehog-like soliton (cluster) $O(r_{\tilde{i}})$ and $J > 0$. The diffusion coefficient D_0 is introduced as follows,

$$\begin{aligned}
 D_0 &\sim \frac{4\Delta}{\pi} \sum_j J_{ij} (r_i - r_j)^2 \\
 &\sim \frac{4\Delta}{\pi} \sum_j J \cos(\theta_{ij}/2) \frac{1}{\Delta^2} (r_i - r_j)^2 \\
 &\sim \frac{4}{\pi\Delta} \sum_j J \cos(\theta_{ij}/2) (r_i - r_j)^2
 \end{aligned}
 \tag{4}$$

Here $\Delta = \frac{1}{v\pi R_c^2}$ and v is the density of states of the carriers at the Fermi surface. In the case of the low frequency limit of ω , the localization length L_{loc} is shown as follows,

$$L_{loc} \propto \pi^2 v R_c^2 D_0 \sim \pi^2 v R_c^2 \frac{4}{\pi\Delta} \sum_j J \cos(\theta_{ij}/2) (r_i - r_j)^2
 \tag{5}$$

We shall consider the variable range hopping conductivity and the system length $L \gg L_{loc}$ as follows,

$$\sigma \propto \exp\left[-(A/T)^{1/(d+1)}\right]
 \tag{6}$$

where d is the dimensionality of the system.

$$A \propto \left(\frac{1}{L_{loc}}\right)^{d/(d+1)} \sim \left(\frac{1}{\pi^2 v R_c^2 D_0}\right)^{d/(d+1)}
 \tag{7}$$

Figure 1 shows the temperature dependence of the conductivity σ for as-grown and annealed samples (experimented data) [15] and the fitting lines (solid lines) of $\text{Ga}_{0.95}\text{Mn}_{0.05}\text{As}$. The annealing is performed at 310°C for 15 mins.

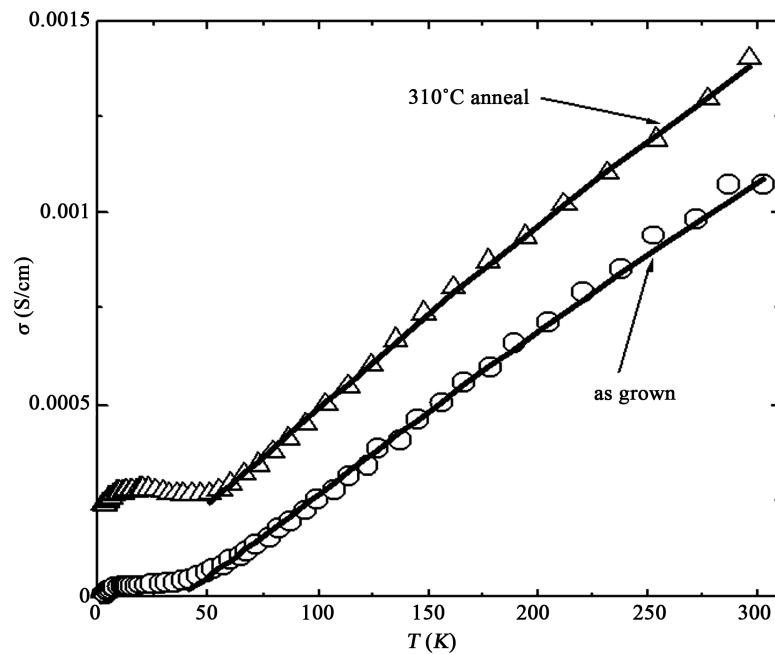


Figure 1. Temperature dependence of conductivity of the diluted semiconductor $\text{Ga}_{0.95}\text{Mn}_{0.05}\text{As}$ [15]. The annealing time is 15 min. The solid lines have been fitted to the measured data.

The as-grown sample and the sample annealed at 310°C show insulating behavior above ~30 K and ~50 K, respectively. The annealing at 310°C increases the conductivity. Annealing might reduce concentration of As antisites and interstitial Mn. As the conductivity σ increases, the high-temperature structure moves to higher temperatures, which means T_c (Curie temperature) increases. Thus the concentration ρ of mobile holes and T_c are enhanced by the annealing. The experimental data are fitted well with Equations (6) and (7), as shown with solid lines in **Figure 1**. Comparing the experimental data (annealing at 310°C) with those (as grown), it is thought that the value of L_{loc} (after annealing at 310°C) is much larger than of those (as grown), as seen from Equation (7).

3. Conclusion

The hole-induced magnetic solitons and metal-insulating transition of transport properties in DMSs have been discussed based on a field theoretical formulation. We have analyzed experimental data on the transport properties of GaMnAs by using the effective Lagrangian of diffusion model.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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