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Electron interaction effect on the spin diffusion and transport in half metallic magnets

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ABSTRACT

For half metallic magnets, spin fluctuation is the same as charge fluctuation. The length scale is controlled by electron–electron interaction and is of the order of the screening length, typically of the order of an Angstrom whereas the ordinary spin diffusion length is of the order of 100 Å or more. We examine the eigenstates for charge and spin transport for systems close to half-metallicity. Due to the electron–electron interaction, the decay length of the eigenstate that corresponds to the longitudinal spin diffusion length is much reduced, consistent with recent experimental results. We explore the consequence of this. We find that there are two parameters that characterize half-metallicity and illustrate our results numerically with a simple model.

1. Introduction

Half metallic magnets such as the Heusler alloys are material with only one spin component at the Fermi surface. Because of its large polarization, there has been much interest in this class of material and its application as spintronics devices [1]. In this paper we show that when the electron–electron interaction is included the length scale for the transport eigenstates that corresponds to spin diffusion is much reduced, consistent with recent experimental results [2]. We study how this length changes and its effect on transport as half-metallicity is approached. We find that half-metallicity is characterized by *two* parameters, the ratio of the diffusion constants and the ratio of the densities of states of the spin up and the spin down bands. These ratios become big as half-metallicity is approached. The dependence of the spin diffusion length and the magneto resistance ratio on the two parameters are illustrated numerically with a simple model. We hope that our result will provide a basis to better understand the physics of the system and to optimize device designs.

The physical reason why the relevant length scale is reduced for half metallic magnets is simple. As half-metallicity is approached, spin transport becomes the same as charge transport. The length scale is controlled by electron–electron interaction and is of the order of the screening length, typically of the order of an Angstrom whereas the ordinary spin diffusion length is pf the order of 100 Å or more.

The charge transport across interfaces such as the p–n junction, the Schottky barrier and the electrolyte–electrode has been much studied. A dipole layer at the interface is expected to form. This dipole layer consists of accumulation of charge densities on opposite sides of the interface. For a spin current across an interface, a spin accumulation layer is expected to form. In general we expect the charge and spin degrees of freedom to be coupled for a ferromagnet and the dipole layer and the spin accumulation layer to be coupled [4]. This effect becomes particularly important for the Heusler alloy as the charge degree of freedom and the spin degrees of freedom are becoming the same.

To describe the transport in a more general manner quantitatively, we consider the spin polarized transport where the screening length is included, which comes in when the electron–electron interaction effect is incorporated. A simple example of this is for the p–n junction. This can be extended for each spin component and include the effect of spin accumulation. We have previously discussed an extension of this idea for spin polarized transport [4]. In this paper we simplify this and apply this to the case of half-metallicity.

2. No spins

We first recapitulate the formation of the dipole layer within our formalism. Under steady state conditions, the equations for the charge current J are extremely simple, we obtain

$$\nabla \cdot \mathbf{J} = 0, \quad (1)$$

The diffusion constants can be expressed in terms of that of individual spin components. The current J of electrons is related to

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the density n of electrons in terms of the diffusion constant D and conductivity σ as

$$\mathbf{J} = -D\nabla n + \sigma\nabla V. \tag{2}$$

where

$$V = V_e + W, \tag{3}$$

with V_e being the electric potential describing the external electric field and W being the local electric (screening) potential due to the other electric charges determined self-consistently by

$$W(\mathbf{r}) = \int d^3\mathbf{r}' U(\mathbf{r} - \mathbf{r}')\delta n(\mathbf{r}') \tag{4}$$

with U being the Coulomb potential.

We next determine the eigenstates of the above coupled transport equations. We focus on the relaxation of the charge density away from a source given by

$$\delta n(x) = \delta n^0 \exp(-x/l)$$

with a relaxation length l. Substituting this ansatz into Eqs. (6) and (7) we obtain

$$\nabla\cdot J = -\sigma\nabla^2 V - D\delta n/l^2 = 0.$$

From Poisson's equation, $\nabla^2 V = -4\pi\delta n$, we finally get

$$\nabla\cdot J = \sigma 4\pi\delta n - D\delta n/l^2 = (1/\lambda_0^2 - 1/l^2)D\delta n^0 = 0 \tag{5}$$

where $\lambda_0^2 = D/(4\pi\sigma)$. The length scale of the dipole layer, the screening length, is determined by the condition that the diffusion current is counterbalanced by that from the self consistent electric field.

3. With spins

We next include the effect of spins and the effect of spin accumulation. We examine the transport equations under linear response. We assume that the magnetization is in the direction of the unit vector $\mathbf{p}_0$. In this paper we focus on the change of the longitudinal component of the magnetization along $\mathbf{p}_0$. Under steady state conditions, the equations for the charge ($\mathbf{J}$) and the longitudinal magnetization currents ($\hat{\mathbf{J}}_M$) are extremely simple, we obtain [3]

$$\nabla\cdot\mathbf{J} = -\partial\delta n/\partial t,$$

$$\nabla\cdot\hat{\mathbf{J}}_M = -\delta M/\tau - \partial\delta M/\partial t \tag{6}$$

where τ is the bare longitudinal spin relaxation time, describing the relaxation of the system towards its local equilibrium value of magnetization. τ measures the probability of converting up electrons to down and vice versa by spin flip scattering from defects. As half-metallicity is approached, τ should not change much.

Extending Eq. (2) for each spin component, the current J_s of electrons of spin component s is related to the density n_s of electrons of spin s in terms of the diffusion constant D_s and conductivity σ_s for spin s as

$$J_s = -D_s\nabla n_s + \sigma_s\nabla V. \tag{7}$$

with V given by Eqs. (3) and (4) where now δn is the total charge density change including both spin up and spin down electrons. The diffusion constant is related to the conductivity through the density of states N_s by

$$D_s N_s \approx \sigma_s. \tag{8}$$

We shall use this approximation in this paper. We shall also use units so that the Bohr magneton and the electric charge is equal to 1. The total (spin) current J (J_M) can be expressed in terms of that of the individual components as

$$J = \sum_s J_s, \quad J_M = \sum_{s=\pm 1} sJ_s.$$

Similarly, the charge (magnetization) density n (M) can be expressed in terms of that of individual components as

$$n = \sum_s n_s, \quad M = \sum_{s=\pm 1} sn_s.$$

We thus have

$$n_s = (n + sM)/2.$$

From these, we find that the currents are driven by density gradients (diffusion) and external forces.

$$\mathbf{J}_e = -\sigma\nabla V - eD\nabla\delta n - D_M\nabla(\delta\mathbf{M}\cdot\mathbf{p}_0)$$
$$\hat{\mathbf{J}}_M = -\sigma_M\nabla(V\mathbf{p}_0) - D'_M\nabla\delta\mathbf{M} - D'\nabla(\delta n\mathbf{p}_0) \tag{9}$$

where σ and σ_M are the effective conductivities for the charge and magnetization, respectively. D, D', D_M, D'_M are the effective diffusion constants. From Eq. (7) we obtain

$$D = \sum_s D_s/2, \quad D_M = \sum_s sD_s/2. \tag{10}$$

Similarly,

$$D' = D_M, \quad D'_M = D.$$

For a half-metallic magnet with exactly only one spin component $DD'_M = D_M D'$. We next determine the eigenstates of the above coupled transport equations.

In this paper we focus on the relaxation of the longitudinal magnetization density and the charge density away from a source given by

$$\delta\mathbf{M}(x) = \delta M^0\mathbf{p}_0\exp(-x/l)$$

$$\delta n(x) = \delta n^0\exp(-x/l)$$

with a relaxation length l determined by the coupling between the spin and the charge degrees of freedom. Substituting these into Eqs. (6) and (9) we obtain

$$\delta M^0(1/l^2 - 1/l_{sf}^2 - i\omega/D'_M) = D'/D'_M\delta n^0(\alpha/\lambda_0^2 - 1/l^2).$$

$$\delta M^0/\delta n^0 = (1/\lambda_0^2 - 1/l^2 + i\omega/D)l^2 D/D_M, \tag{11}$$

$\alpha = \sigma_M D/(\sigma D')$, $l_{sf}^2 = \tau D'_M$ and $\lambda_0^2 = \frac{\epsilon_0 D}{\sigma}$. For $D = D'_M$ we redefine $1/l'^2 = 1/l^2 - i\omega/D$. From these we obtain a quadratic eigenvalue equation for l'^2. The solutions for the renormalized decay lengths are

$$2l_\pm'^2 = b \pm \left\{b^2 + 4\lambda_0^2 l_{sf}^2[D'D_M/(DD'_M) - 1)]\right\}^{0.5}. \tag{12}$$

$\zeta = \alpha D'D_M/(DD'_M) = \sigma_M D_M/(D'_M\sigma)$, $b = l_{sf}^2(1-\zeta) + \lambda_0^2$. The decay length l depends on two parameters, D and σ or N and D. There are two parameters that characterize the properties of the system. We have previously observed the renormalization of the relaxation lengths in the investigation of voltage induced switching in tunnel junctions [5] but have not explored their implications.

Far away from half-metallicity, we obtain the approximate solutions

$$l_-'^2 = \lambda_0^2 \tag{13}$$