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Horacio E. Camblong
University of San Francisco, camblong@usfca.edu

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Effective internal fields and magnetization buildup for magnetotransport in magnetic multilayered structures

Peter M. Levy, Horacio E. Camblong,[a] and Shufeng Zhang
Department of Physics, New York University, New York, New York, 10003

Starting with the Kubo formula for electric conductivity we derive a set of equations that define the spin diffusion that is present when current is driven through inhomogeneous magnetic media. We show the spin accumulation, or nonequilibrium magnetization, attendant to charge transport through regions of inhomogeneous magnetization is governed by the same equations found in a thermodynamic approach to magnetoelectric transport.

There have been two approaches to understand the giant magnetoresistance (MR) of magnetic multilayered structures for currents perpendicular to the plane of the layers (CPP). The first has been a linear response theory based on either the Kubo formula[1,2] or the Boltzmann equation,[3] in which one calculates the current in response to an external electric field. The second is a thermodynamic approach,[4] in which one introduces a magnetization potential H^* in addition to the electric potential V, to describe charge and nonequilibrium magnetization transport.[5,6] For some systems both H^* and V are externally applied potentials, e.g., when one discusses the spin-polarized transport between the injector and detector in a spin-injection experiment,[5] one introduces both electric and magnetization currents. However the CPP-MR, one applies *only* a voltage, and only an electric current flows into and out of the multilayered structure. While there may be a nominal magnetic field applied to the structure, it is largely irrelevant as a thermodynamic variable; the magnetization current and potential H^* are *internal* to the system. They represent the rearrangement of spin (magnetization) when an electric current is driven through the structure.

With this background in mind, there has been some questions[7] as to whether the linear response approach,[1] which considers only the voltage V or electric field as the only variable in calculating the current neglects the effects of the nonequilibrium (current-driven) magnetization, or spin accumulation on the CPP-MR. Here we point out that the CPP-MR calculated by linear response theory *does* contain the effects of spin accumulation, even though one only considers the externally applied potential V. By using the Kubo formalism for charge transport in magnetic multilayered structures, we derive the equation that controls the spin accumulation. When one uses the approximation of a local self-energy, the spin-diffusion equation reduces to that assumed by the thermodynamic approach. We are able to clarify the conditions for the validity of the thermodynamic approach.

We begin with the linear response to an electric field, which for multilayered structures with *collinear* magnetization, i.e., ferro- and antiferromagnetically aligned layers, reduces to a one-dimensional problem[2]

$$j^s(z)=e\int \sigma^s(z,z')\frac{\partial}{\partial z'}V(z')dz', \tag{1}$$

where s is the spin index, and we have expressed the *external* electric field in terms of the classical potential, i.e., $E_{\rm ext}(z)=e(\partial/\partial z')V(z')$. The conductivity is given in the Kubo formalism by the diagrams shown in Fig. 1. It includes the simple bubble diagram Fig. 1(a), the ladder diagrams due to non-spin-flip scattering Fig. 1(b) and the spin-flip diagrams represented by the wiggly lines [Fig. 1(c)]. Other diagrams, in which wiggled lines cross the shaded ladders have been neglected. Therefore, we only focus on spin-flip and non-spin-flip scattering processes, which are *local*. This type of scattering includes spin-orbit and paramagnetic impurity scattering, but excludes the magnon scattering, which is not local.

Rather than dealing with these diagrams explicitly in the conductivity $\sigma^s(z,z')$, we introduce an effective field $E^s(z')$,

$$j^s(z)=\int \sigma_b^s(z,z')E^s(z')dz', \tag{2}$$

where σ_b^s is the bubble diagram contribution to the conductivity, Fig. 1(a), and

$$E^s(z')=e\frac{\partial}{\partial z'}V(z')+e\int \Gamma^s(z',z'')\frac{\partial}{\partial z''}V(z'')dz'', \tag{3}$$

where Γ^s is the sum of the ladder diagrams, Figs. 1(b) and 1(c), without external legs. Γ^s is also called the diffusion propagator. The key difference between the diffusion propa-

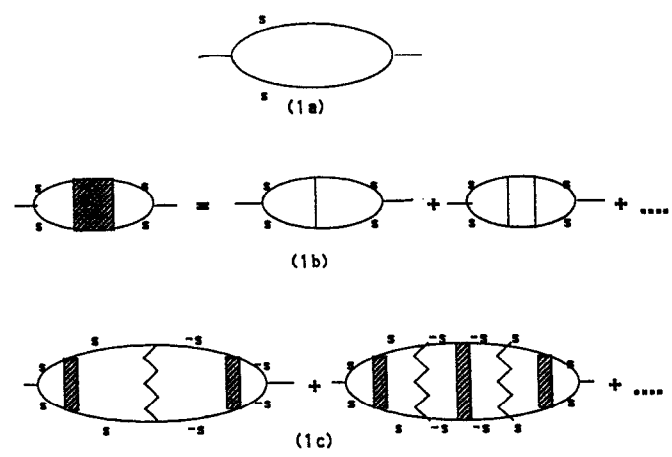

FIG. 1. Diagrams contributing to $\sigma^s(z,z')$. (a) is the bubble conductivity $\sigma_b^s(z,z')$ and (b) is the ladder contribution due to non-spin-flip processes and (c) is that due to spin-flip processes.

[a]Present address: Department of Physics, University of San Francisco, San Francisco, CA 94117.

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gator and the bubble conductivity is that the former is long range while the latter has a length scale of the mean-free path. The asymptotic form of Γ in three dimensions is $1/|\mathbf{r}'-\mathbf{r}''|$.[8] The main contribution of the diffusion propagator to the effective field, Eq. (3), is from the contribution for large separations of $z'-z''$, and one can assume that Γ^s in Eq. (3) only depends on the $z'-z''$. By integrating the second term in Eq. (3) by parts, and by using $(\partial/\partial z'')\Gamma^s(z',z'') = -(\partial/\partial z')\Gamma^s(z',z'')$, we find that Eq. (3) can be written as

$$E^s(z') = e\frac{\partial}{\partial z'}\left(V(z') + \int \Gamma^s(z',z'')V(z'')dz''\right) \equiv e\frac{\partial}{\partial z'}\mu^s(z'), \tag{4}$$

where the last identity defines the spin-dependent chemical potential μ^s.

In the following, we assume the spin-diffusion length is much larger than the mean-free paths, $\lambda_{sdl} \gg \lambda_{mfp}$, i.e., that spin-flip processes are much rarer than non-spin-flip scattering. In this case $\sigma_b^s(z',z'')$ varies on the length λ_{mfp} (the Green's functions decay over distances given by the elastic mean-free paths), while the current $j^s(z)$ varies over distances λ_{sdl}. We now invert Eq. (2) and treat the current density as a constant within the mean-free path. We can remove the current density from the integration, and arrive at

$$j^s(z) = \frac{e}{\rho^s(z)}\frac{\partial}{\partial z}\mu^s(z), \tag{5}$$

where

$$\rho^s(z) = \int \rho_b^s(z,z')dz', \tag{6}$$

and $\rho_b^s(z,z')$ is the inverse of the conductivity $\sigma_b^s(z,z')$. In the local relaxation time approximation, $1/\rho^s(z) = Cl^s(z)$, where $C = (e^2/h)(2k_F^2/3\pi)$ and $l^s(z)$ is a local mean-free path. This local relation between current density and the chemical potential is Ohm's law for each spin channel. It is valid as long as the current density for each spin channel does not change significantly within a mean-free path.

To obtain information about spin-diffusion, one has to calculate the ladder diagrams. From Figs. 1(b) and 1(c), the diffusion propagator satisfies the following integral equation:

$$\Gamma^s(z',z'') = d^s(z',z'') + \int d^s(z',z_1)P_{sf}(z_1)\Gamma^{-s}(z_1,z'')dz_1, \tag{7}$$

where P_{sf} is the probability of spin-flip scattering and d^s is the diffusion propagator in the absence of the spin-flip scattering; see Fig. 1(b). In general, P_{sf} depends on energy. In our case we only consider nearly elastic spin-flip scattering, so that we set all the energy variables at the Fermi level. Equation (7) is the spin-diffusion equation in integral form. To write it in differential form, we use the fact that the diffusion propagator in the absence of spin-flip scattering satisfies[8,9]

$$\frac{1}{3}\frac{\partial^2}{\partial z'^2}d^s(z',z'') = -\left\{\frac{1}{l^s(z')}\right\}^2\delta(z'-z''). \tag{8}$$

By taking the Laplacian of both sides of Eq. (7) and by using the above identity, we find

$$\frac{\partial^2}{\partial z'^2}\Gamma^s(z',z'') = -3\left[\frac{1}{l^s(z')}\right]^2\{\delta(z'-z'') + P_{sf}(z)\Gamma^{-s}(z',z'')\}. \tag{9}$$

Upon taking the derivative of the definition of the spin-dependent chemical potential Eq. (4) and by using Eq. (9), we arrive at

$$3\{l^s(z)\}^2\frac{\partial^2}{\partial z^2}\mu^s(z) = -\frac{l^s(z)+l^{-s}(z)}{l_{sf}(z)}\{\mu^{-s}(z)-V(z)\}, \tag{10}$$

where we have used $(\partial^2/\partial z^2)V(z)=0$ for the classical potential, and we have defined the spin-flip mean-free path $l_{sf} \equiv (l^s+l^{-s})/P_{sf}$ to express the diffusion equation in terms of l_{sf}, as one usually does. Note that we have dropped the first term in Eq. (9) in calculating the chemical potential from the second term of Eq. (4) because it has already been included in the first term of Eq. (4).

Equation (10) is our main result; it controls the spin diffusion. To write it in a more familiar form for layered structures, we assume the local mean-free path is piecewise constant, i.e., $l^s(z)$ is a constant in a specific layer. In this case, Eq. (10), along with the equation given by interchanging s and $-s$ in Eq. (10), can be written as

$$\frac{\partial^2}{\partial z^2}[\mu^s(z)-\mu^{-s}(z)] = \frac{\mu^s(z)-\mu^{-s}(z)}{\lambda_{sdl}^2(z)}, \tag{11}$$

where we have defined the spin-diffusion constant $\lambda_{sdl}(z)$ as $1/\lambda_{sdl}^2 \equiv [3l^s l_{sf}]^{-1} + [3l^{-s}l_{sf}]^{-1}$ and

$$\frac{\partial}{\partial z}\left\{l^s(z)\frac{\partial}{\partial z}\mu^s(z) + l^{-s}(z)\frac{\partial}{\partial z}\mu^{-s}(z)\right\} = 0. \tag{12}$$

Equation (11) is exactly the one assumed by the thermodynamic approach,[5,6] while Eq. (12) represents the conservation of charge, i.e., the total current is constant. These two equations determine the spin-dependent chemical potentials; then the electric current and the magnetization current are obtained from Eq. (5). We point out that one should use Eq. (10) rather than Eqs. (11) and (12) when the local mean-free paths and local spin-diffusion constant are not piecewise constants. For example, one could grow multilayers with continuously varying compositional differences.

We have reproduced and generalized the equations that define spin-diffusion in magnetic multilayered structures, when they are subject to an electric field. To understand the range of validity of these equations, we consider the different thicknesses of the layers d_{in} relative to the mean-free path and spin-diffusion length. The current derivation is in the limit $\lambda_{mfp} \ll \lambda_{sdl}$, so that one can view it as a spin-diffusion process. The general solution of Eq. (11) contains an exponentially decaying part, with respect to the spin-diffusion length. For $d_{in} \ll \lambda_{sdl}$, which includes the cases of $d_{in} \ll l^s$ (homogeneous limit) and $d_{in} \approx l^s$, the solution to Eq. (11) is simple; all the quantities, e.g., chemical potentials, are peri-

odic functions with a period of d_{in}, so that the exponential decay within the length of d_{in} is negligible and one can neglect the right side of Eq. (11).

We should point out that if one neglects spin-diffusion processes, this does not imply that one is omitting the spin accumulation or magnetization buildup. In fact, the magnetization buildup is largest when one neglects spin-flip processes. One can easily check this conclusion by calculating the chemical potential difference $\mu^s(z)-\mu^{-s}(z)$ from one layer to the next; the variation is largest when the spin-diffusion length is infinite. Most experiments are actually in this limit. Therefore, our original model[1] predicated on neglecting spin-flip processes can be used to analyze data on multilayered structures currently being studied. The diffusion equation begins to play a role when the layer thicknesses are comparable to the spin-diffusion length. In this case, one is in the local limit because the mean-free path is much smaller than the layer thicknesses. It is precisely in this limit that the diffusion equation, Eq. (10), has been derived. However, when λ_{mfp} is comparable with λ_{sdl},[10] additional terms in Eqs. (5) and (10) will appear, and the derivation presented here fails. The derivation for the vertex corrections and effective fields where $\lambda_{mfp}\approx\lambda_{sdl}$ will be presented elsewhere.[11]

In summary, we have shown that a linear response theory of transport for CPP is able to reproduce the spin-diffusion equations derived in the thermodynamic approach, provided one is in the limit where the concept of spin diffusion makes sense, i.e., far fewer spin-flip scattering processes than non-spin-flip ones, so that $\lambda_{mfp}\ll\lambda_{sdl}$.[12] When λ_{mfp} is comparable to λ_{sdl}, the concept of spin diffusion is not valid *nor are the spin-diffusion equations*. From this derivation, we can unequivocally respond in the affirmative as to whether linear response theory[1,2] accounts for the spin accumulation, attendant to charge driven through regions of inhomogeneous magnetization, i.e., the case of CPP of magnetic multilayered structures. For currents in the plane of the layers (CIP) there is no spin accumulation, provided the size of the magnetic domains in the layers are larger than the spin-diffusion length. The reason is that, in the direction of magnetic inhomogeneities perpendicular to the layers, there is no net charge transport for CIP.

While not a difference in results, there is one in outlook between the linear response and thermodynamic approaches. In linear response theory single-site (local) spin-flip processes contribute on an equal footing with nonlocal spin-flip processes due to magnons; although they produce quite different results, and we have not discussed magnons in this paper. In the thermodynamic approach the single-site spin-flip processes contribute to changing the magnetization potential and nonequilibrium magnetization, while the magnons contribute as momentum conserving spin-flip processes, and are accounted for by the potentials that fix the currents. This distinction that appears in the thermodynamic approach is a result of discriminating between spin accumulation and electric currents. This may be useful in spin injection experiments, where one applies spin-polarized (charge and magnetization) currents to a system. However, for CPP in magnetic multilayered structures, magnetization currents develop only *inside* the structures; these convert the external electric field into the internal fields seen by the electrons. When the medium is magnetized or when the scattering of the electrons is spin dependent, these effective internal fields are spin dependent. This accounts for both the electric and magnetization currents that develop in CPP in magnetic multilayered structures.

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