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LETTER TO THE EDITOR

Anomalous magnetoresistance of magnetic multilayers

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Abstract. We examine transport properties of a magnetic superlattice with current perpendicular to the planes. In the limit that the phase-breaking and spin flip scattering lengths are greater than the system size, a multiple-scattering approach is used to calculate the 4-probe conductance. We show that by tuning the strength of tunnelling barriers placed between the current and voltage probes magnetoresistance ratios of arbitrary strength and sign are achievable.

Recent advances in material technology have enabled the fabrication of mesoscopic superlattice (SL) structures, with well defined dimensions and interfaces, where the SL consists of alternating magnetic and non-magnetic layers. The exchange coupling of the magnetic layers through the non-magnetic material gives rise to antiferromagnetic (AF) alignment of adjacent magnetic layers. When such AF alignment is broken by applying a large magnetic field, a global ferromagnetic (F) configuration of the multilayer is achieved and the resistance drops drastically [1–3]. Such functional magnetic materials are the focus of substantial research both from a technological and fundamental viewpoint, due to a wide range of applications in magneto-electronics [4], such as read/write heads for high density magnetic storage systems, and in the miniaturization of magnetic field sensors, such as solid state compasses [5]. All these applications require materials and geometries capable of giving a large signal (i.e. a large drop in resistance) and high sensitivity (so that only a small magnetic field is required). Conventional materials, such as the 3D transition metal multilayers, show large giant magnetoresistance (GMR), but high magnetic fields are necessary to overcome the exchange coupling, making such systems unsuitable for most applications. Inhomogeneous multilayers based on polycrystalline alloys [5] require much smaller fields, but show quite small drops in resistance. Half-metals such as CrO_2, in principle can guarantee an infinite GMR [6, 7], but to date a GMR of only 50% has been measured in CrO_2 powders at low temperature [9].

Finally, the advent of III-V diluted magnetic semiconductors [10, 11] has opened the possibility of incorporating spin-valve-like devices in semiconductor technology. Although the injection of spins into semiconductors by magnetic metallic contacts in the diffusive limit is shown to give virtually no GMR signal [12], very little is known about all-semiconductor devices or about the ballistic transport limit.

In this letter we analyse a 4-probe current perpendicular to the plane (CPP) structure [13], and demonstrate that due to an inherent instability of 4-probe conductance measurements, an infinite magnetoresistance (IMR) and a GMR of arbitrary strength is achievable. Similar structures, based on macroscopic anisotropic magnetoresistance materials [14, 15], have been already studied and have shown that very large changes of the 4-probe conductance can be obtained. Here we argue that similar effects can be achieved in a phase coherent structure, in which complicate materials issues are avoided.

We use a general scattering approach to dc transport, developed to describe phase-coherent transport in dirty mesoscopic structures, based on the fundamental current-voltage relations derived in [16]. In this letter, we focus on the conductance of the structure shown in figure 1(a), which comprises a superlattice, with alternating normal and magnetic layers, in contact with four normal reservoirs at voltages $v_j (j = 1, \ldots, 4)$. The leads connecting the structure to reservoirs 1 and 2 carry a current I, whereas leads 3 and 4 carry no current and hence form the voltage probes. The current/voltage leads are separated by an insulating barrier.

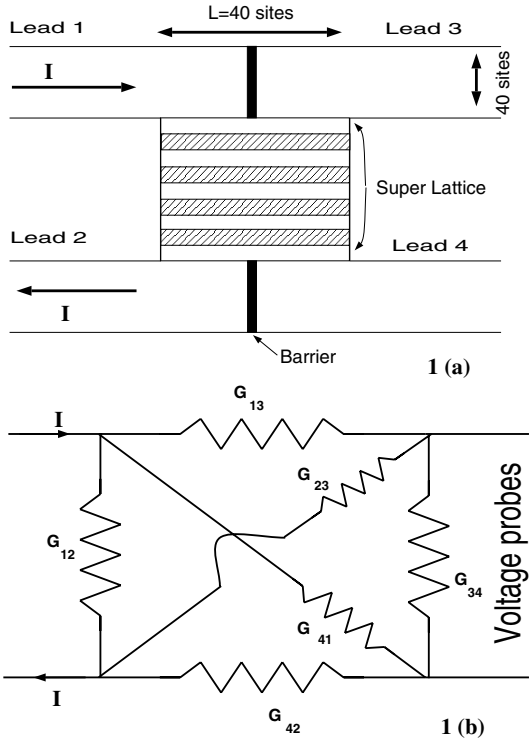

Figure 1. The hashed area represents the magnetic layers and the clear areas represent normal regions. The black strips between the leads represent the portion of the variable-height barrier. (b) shows the equivalent circuit of the structure shown in (a).

In what follows, we consider the zero-temperature, zero-bias limit in which the phase-breaking and spin-flip scattering lengths are greater than the dimensions of the system. In this limit, transport properties depend not only on the electronic structure of the magnetic multilayers, but also on the contacts with external reservoirs. This feature is embodied in the fundamental current/voltage relation due to Büttiker [16],

$$I_i = \sum_{j=1}^{4} G_{ij} v_j \tag{1}$$

which relates the current I_i from a normal reservoir i to the reservoir voltages (v_j). The coefficients G_{ij} satisfy $\sum_{j=1}^{4} G_{ij} = \sum_{i=1}^{4} G_{ij} = 0$. In units of $2e^2/h$, $G_{ii} = N_i - R_i$ and $G_{ij \neq i} = -T_{ij}$, where T_{ij} is the transmission coefficient from probe j to probe i, R_i is the reflection coefficient in probe i and N_i is the number of open scattering channels in lead i. Furthermore, as noted in [16] $G_{ij}(H) = G_{ji}(H^*)$, where H is the Hamiltonian of the system and therefore in the presence of a magnetic field, $G_{ij} \neq G_{ji}$.

Setting $I_1 = -I_2 = I$, $I_3 = I_4 = 0$ and solving equation (1) for the conductance yields

$$\hat{G} = \frac{h}{2e^2}\frac{I}{(v_3 - v_4)} = \frac{d}{(G_{42}G_{31} - G_{41}G_{32})} \tag{2}$$

where $d \geqslant 0$ is the determinant of the 3×3 matrix obtained by removing the third row and column from the G_{ij} matrix of equation (1). The GMR ratio ($\tilde{G}$) is defined as [3]

$$\tilde{G} = \frac{\hat{G}_F - \hat{G}_{AF}}{\hat{G}_{AF}} \tag{3}$$

where $\hat{G}_F$ is the conductance when the structure is in the ferromagnetic state and $\hat{G}_{AF}$ is the conductance for the antiferromagnetic configuration. In the F and AF configurations, the various transmission and reflection coefficients for the separate spins can be computed by solving the Schrödinger equation for a simple cubic lattice described by a tight-binding Hamiltonian with nearest neighbours coupling. In quasi one dimensional geometries involving only two probes, by combining an efficient recursive Green function approach with a material-specific s–p–d tight-binding Hamiltonian one can accurately predict the GMR ratio for a range of materials and layer thickness [18, 19]. For more complex geometries involving several probes, this is beyond the capabilities of currently available computing resources and therefore to demonstrate a generic enhancement of the GMR ratio, we analyse a tight-binding model with a single degree of freedom per spin, as introduced in [20, 21]. Each lattice site is labelled by an index i and possesses a spin degree of freedom σ. The corresponding Schrödinger equation has the form

$$E\psi_i^\sigma = \epsilon_i^\sigma \psi_i^\sigma - \sum_j \gamma_{ij}\psi_j^\sigma \tag{4}$$

where j sums over all neighbours of i. The nearest neighbor hopping elements γ_{ij} fix the band-width and ϵ_i^σ determines the band-filling. The separate spin fluids are assigned a spin-dependent on-site energy ϵ_i^σ. The parameters used in the present calculations are as follows: in the leads and non-magnetic regions of the SL $\epsilon_i^\sigma = 1$ and $\gamma_{ij} = 1$; in the magnetic layers $\gamma_{ij} = 2$ and $\epsilon_i^\sigma = 1.45$ (3.7) for spin up (down). Following the same method as outlined in [18] the hopping elements γ_{ij} joining magnetic-normal sites are chosen to be the geometric mean of the hopping elements in the magnetic/normal regions.

The dc conductance of eqn.(2) is determined by the multi-channel quantum mechanical scattering matrix, which in turn can be found from the Green function for a given structure. The numerical approach involves attaching the scattering region to crystalline semi-infinite leads, in which the Green functions are superpositions of plane waves, and then using Dyson's equation to determine the total Green function [18]. Effectively this procedure requires the inversion of Hamiltonian describing the scatterer, which for the structure analysed here is a 6080×6080 matrix per spin degree of freedom. As we are only interested in the Green functions on the surface of the structure the inversion is carried out after the Hamiltonian has been renormalized in real space using an exact decimation technique [22].

As shown in figure 1(a) the structure analysed consists of four crystalline semi-infinite leads each 40 sites wide. The superlattice consists of five non-magnetic layers alternating with four magnetic layers, each eight sites wide and 40 sites long. The leads are separated by barriers, two sites wide and of strength U. These barriers modify the on-site energy ϵ_i^σ in equation (4) to $\epsilon_i^\sigma + U$. Hence, varying the magnitude of U alters the transmission and reflection coefficients of the current/voltage leads. For a barrier two sites wide, figure 2 shows the dependence on U of the transmission coefficient per open channel, which as expected, decays exponentially with increasing U.

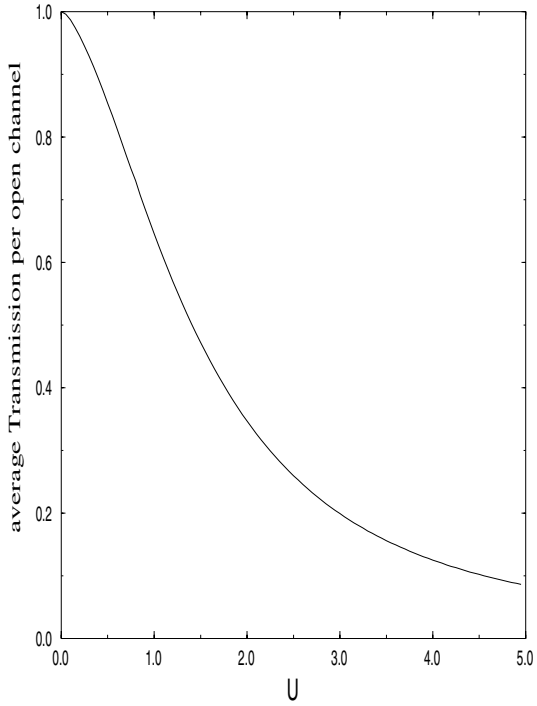

Figure 2. The average transmission coefficient per open channel for a 2D tight-binding lattice. The on-site energy is ϵ_0 and the barrier strength U. The barrier is two lattice sites wide and the on-site energy is $\epsilon_0 + U$.

Figure 3 shows the dependence of $\hat{G}_F$ and $\hat{G}_{AF}$ on barrier strength. We see that $\hat{G}_{AF}$ increases smoothly as U is increased, whereas $\hat{G}_F$ diverges for $U \approx 2.8$, and then returns to a negative constant. This divergence occurs as the transmission coefficient from lead 4 to lead 1 approaches the transmission coefficient from lead 4 to lead 2.

As indicated in figure 1(b), equation (1) can be viewed as an equivalent circuit representation of the phase coherent structure of figure 1(a). However the elements G_{ij} are correlated functionals of the scattering potential generated by contact with external leads, geometry and disorder, and therefore cannot be varied independently. To gain some physical insight into the origin of this divergence, we consider the case of a symmetric structure, where $G_{13} = G_{24}$, $G_{12} = G_{34}$, $G_{14} = G_{23}$ and equation (2) reduces to

$$\hat{G} = \frac{2(G_{43} + G_{42})(G_{43} + G_{41})}{G_{42} - G_{41}} \,. \tag{5}$$

From this expression we see that if $G_{42} < G_{41}$ then the 4-probe conductance will be negative and as G_{42} approaches G_{41}, the conductance diverges. Of course since the quantities G_{ij} are determined by the quantum mechanical scattering properties of the structure in figure 1, there is no guarantee that such a condition can be satisfied. The main result of this letter is to show that such a condition is indeed achievable and can be obtained by a fine tuning of the tunnelling barriers inserted within the current/voltage probes.

Figure 4 shows the dependence of the GMR ratio on barrier strength calculated using equation (3). Due to the behavior of the conductance in the ferromagnetic state ($\hat{G}_F$), the GMR ratio increases with increasing U, diverges for $U \approx 2.8$ giving an infinite magnetoresistance. Further increasing U causes the GMR ratio to return from $-\infty$ and converges to a negative

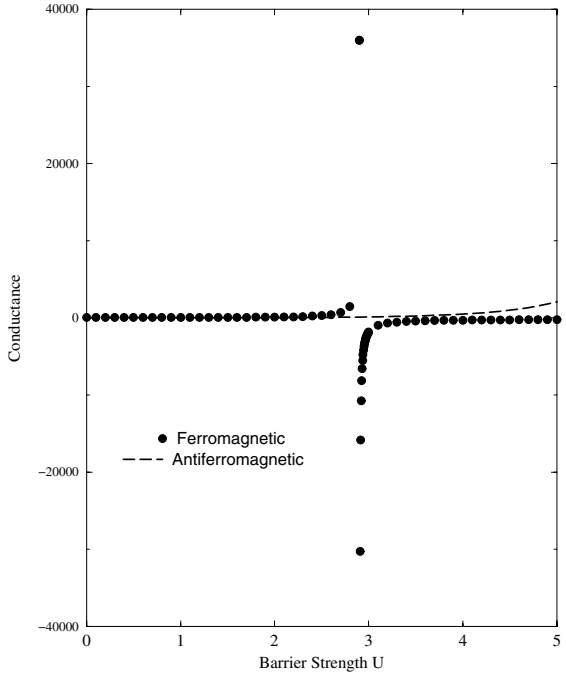

Figure 3. The dependence of the 4-probe conductance's $\hat{G}_F$ and $\hat{G}_{AF}$ on barrier strength, for the structure shown in figure 1.

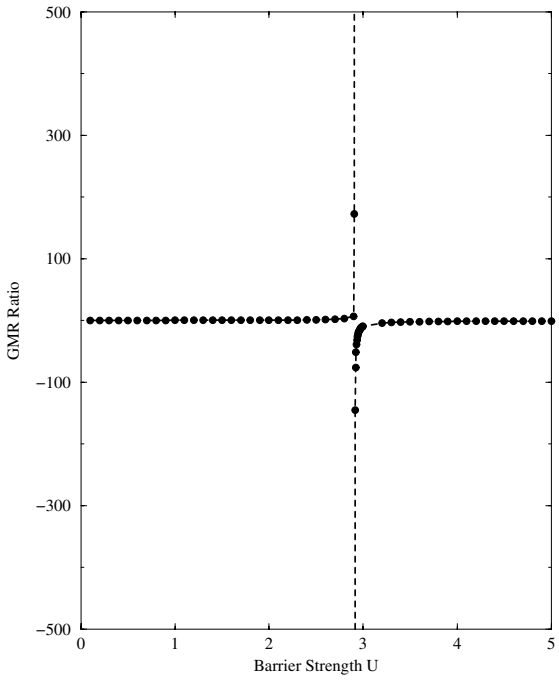

Figure 4. The dependence of the GMR ratio on barrier strength.

value, of around -110%. It should be noted that this negative GMR is not due to an intrinsic scattering asymmetry of the materials as measured in [23], but is due to the peculiar spin-dependent behavior of the 4-probe measurement. Increasing U further does lead to a divergence in $\hat{G}_{AF}$ (not shown in figure 3), which, as seen by equation (3), results in a GMR of around -100%. It is important to point out that the system of figure 1(a) is in principle tunable, for example by applying a gate electrode giving rise to the barrier potential U in an all-semiconductor realization of the proposed device. Hence by changing the external gate potential, arbitrary GMR ratios may be obtained. This uses exactly the same principle as a Wheatstone bridge, despite the fact that the system described is fully quantum mechanical.

In conclusion, we have shown that due to an inherent instability in 4-probe conductance measurements of mesoscopic structures an infinite GMR ratio with arbitrary sign is realizable. To date a great deal of effort has been aimed at optimizing the materials used in GMR devices. The above results suggest that geometry and external gating may be equally crucial in the race to obtain inexpensive magnetoresistive devices. This effect is a generic feature of the 4-probe geometry, and the use of a simple single-band tight-binding model is sufficient to demonstrate the possibility of IMR. Nevertheless more sophisticated material-specific tight-binding models [18, 24], or *ab-initio* calculations [25], will be needed to provide quantitative insights into real device characteristics.

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