Boundary Resistance of the Ferromagnetic-Nonferromagnetic Metal Interface

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It is shown theoretically that the conversion of spin-up into spin-down current near a ferromagnetic-nonferromagnetic metal interface gives rise to an electrochemical potential difference of spin-up and spin-down electrons. The effect shows up as an additional boundary resistance. The situation is analogous to the normal-metal–superconductor interface. Experimental methods that may be used to observe the effects are discussed.

The electrical transport properties of ferromagnetic metals can be described in terms of a two-current model (see the review article by Fert and Campbell[1]). The model is based on the suggestion by Mott[2] that, at temperatures low with respect to the Curie temperature, most scattering events will conserve the direction of the electron spin. Therefore, spin-up and spin-down electrons will be almost independent and carry current in parallel. As in ferromagnets the band structures of spin-up and spin-down electrons are different; the two conductivities will in general not be equal. An extreme example of this is found in a new class of materials, half-metallic ferromagnets,[3] in which the spin-down electrons are semiconducting while the spin-up electrons show metallic behavior and carry all of the current.

When a current flows from a ferromagnetic metal (F) to a nonferromagnetic (normal) metal (N), its distribution over spin-up and spin-down current has to change. This consequence of the two-current model has never been discussed before. An analogous situation, which has been studied both experimentally and theoretically, occurs at an interface between a normal metal (N) and a superconductor (S) (see the review articles of de Groot and co-workers[4]). The conversion of a normal current into a supercurrent gives rise to an electrochemical potential difference between quasiparticles and Cooper pairs in the superconductor near the interface. In this Letter, we will describe the current conversion at the F-N interface, using the basic ideas of the theory of the N-S interface. In fact these ideas may be applied to any system that can be described in terms of a two-current model. We will also discuss how the effects of the current conversion at the F-N interface may be measured, using the analogies and the differences with the measurements of the N-S interface. Half-metallic ferromagnets (HMF) are in principle very well suited for these kinds of experiments.

We will consider the one-dimensional case: The ferromagnetic metal occupies the half-space $x < 0$, the normal metal occupies the half-space $x > 0$, and a current with density j flows in the positive x direction (see Fig. 1). Indices F and N refer to the ferromagnetic and the

normal metal, respectively. It is assumed that, for both F and N, the rate of scattering events without spin flip of spin-up ($\uparrow$) and spin-down ($\downarrow$) electrons is much larger than the spin-flip rate τ_{sf}^{-1}. This implies that at any point two electrochemical potentials $\mu_\uparrow$ and $\mu_\downarrow$ may be defined, which need not be equal. The conductivity σ and the current density are separated into two components: $\sigma_\uparrow = \alpha\sigma$, $\sigma_\downarrow = (1-\alpha)\sigma$, $j_\uparrow = \beta j$, and $j_\downarrow = (1-\beta)j$. The current determines the gradient of the electrochemical potential:

$$\partial\mu_{\uparrow,\downarrow}/\partial x = -(e/\sigma_{\uparrow,\downarrow})j_{\uparrow,\downarrow}.$$

Far from the interface, spin-up and spin-down electrons will be in equilibrium ($\mu_\uparrow - \mu_\downarrow$), so that $\beta(x \ll 0) = \alpha_F$ and $\beta(x \gg 0) = \alpha_N = \frac{1}{2}$. At the F-N interface α changes abruptly, but β has to be continuous (unless there is very strong spin-flip scattering at the interface). In a region near the interface, $\partial\beta/\partial x \neq 0$ and $\mu_\uparrow - \mu_\downarrow \neq 0$; the potential difference is the driving force of the current conversion. The potential difference obeys a diffusion equation, which in steady state is given by

$$(\mu_\uparrow - \mu_\downarrow)/\tau_{sf} = D\,\partial^2(\mu_\uparrow - \mu_\downarrow)/\partial x^2. \tag{1}$$
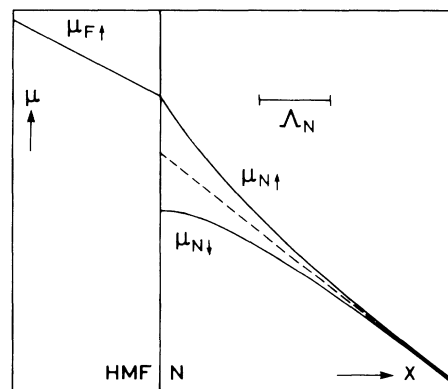

FIG. 1. Position dependence of the electrochemical potentials $\mu_\uparrow$ and $\mu_\downarrow$ near a HMF-N interface ($\mu_{F\downarrow}$ has been omitted because it is irrelevant). The dashed line in N represents μ_0; in the HMF, $\mu_0 = \mu_{F\uparrow}$.

$D = \frac{1}{3} v_F l$ is the diffusion constant, v_F is the Fermi velocity, and l is the electron mean free path. For the normal metal $D_{N\uparrow} = D_{N\downarrow} = D_N$, but for the ferromagnet a weighted average should be chosen: $D_F = (1 - \alpha_F) D_{F\uparrow} + \alpha_F D_{F\downarrow}$. From Eq. (1) it follows that the potential difference decays exponentially on the scale of the spin-flip diffusion length $\Lambda = (D\tau_{sf})^{1/2}$.

The boundary conditions at the F-N interface demand that $\beta(x=0) = \beta_I$ is continuous and that $\mu_\uparrow$ and $\mu_\downarrow$ are continuous. This determines the value of β_I (naturally $\alpha_N \leq \beta_I \leq \alpha_F$):

$$(2\beta_I - 1) = \frac{2\alpha_F - 1}{1 + 4\alpha_F(1 - \alpha_F)(\sigma_N^{-1}\Lambda_N)/(\sigma_F^{-1}\Lambda_F)}.$$

We took $\alpha_N = \frac{1}{2}$ but it is simple to extend the theory to an interface of two ferromagnetic metals. For a HMF ($\alpha_F = 1$), we find $\beta_I = 1$ because all spin flip has to take place in N.

For the discussion of $\mu_\uparrow$ and $\mu_\downarrow$, it is convenient to define μ_0 as the value that the electrochemical potential would have without a nonequilibrium current distribution,

$$\partial\mu_0/\partial x = -(e/\sigma)j.$$

If far from the interface one takes $\mu_0 = \mu_\uparrow - \mu_\downarrow$, it can be shown that $\mu_0 = \alpha\mu_\uparrow + (1 - \alpha)\mu_\downarrow$. We will first consider the HMF-N interface. The position dependence of the electrochemical potentials is drawn in Fig. 1. The dashed line in N represents μ_0. The $\mu_{F\downarrow}$ curve has been omitted because, in the HMF, μ_0 is determined completely by $\mu_{F\uparrow}$. Moreover, $\mu_{F\downarrow}$ will tend to $\mu_{F\uparrow}$ away from the interface but the length scale of that process, Λ_F, is not well defined for a HMF. Although $\mu_\uparrow$ and $\mu_\downarrow$ are continuous at the interface, μ_0 is not: The current conversion process in N gives rise to an additional voltage drop. The boundary resistance equals $\sigma_N^{-1}\Lambda_N$: Over a length Λ_N only half of the conductivity of N is used, so that the resistance of this slab is $2(\sigma_N^{-1}\Lambda_N)$ instead of $\sigma_N^{-1}\Lambda_N$.

At a general F-N interface, the current conversion process takes place both in F and in N. The boundary resistance R_b is given by

$$R_b = \frac{\mu_{F0}(x=0) - \mu_{N0}(x=0)}{ej}$$
$$= \frac{(2\alpha_F - 1)^2(\sigma_N^{-1}\Lambda_N)(\sigma_F^{-1}\Lambda_F)}{(\sigma_F^{-1}\Lambda_F) + 4\alpha_F(1 - \alpha_F)(\sigma_N^{-1}\Lambda_N)}.$$

In Fig. 2, the potential differences $\mu_\uparrow - \mu_0$ and $\mu_\downarrow - \mu_0$ are drawn as functions of the position near the interface. The lengths Λ_F and Λ_N over which the potential differences extend in F and N, respectively, do not depend on the parameters of the other metal. The magnitude of the potential differences is determined by the ease with which the current conversion process can take place and, for this process, F and N are two parallel
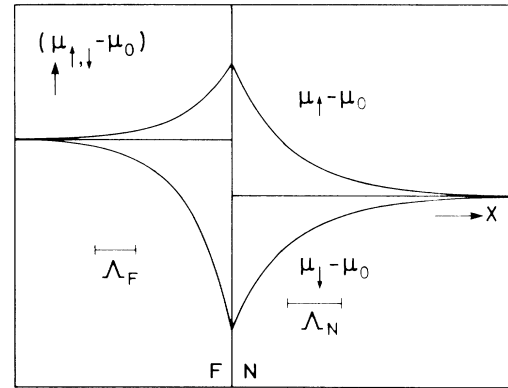

FIG. 2. Position dependence of the potential differences $\mu_\uparrow - \mu_0$ and $\mu_\downarrow - \mu_0$ near an F-N interface.

channels. If $(\sigma_F^{-1}\Lambda_F) \ll 4\alpha_F(1 - \alpha_F)(\sigma_N^{-1}\Lambda_N)$, all spin flip takes place in F, $\beta_I = \frac{1}{2}$, and the potential differences do not depend on $\sigma_N^{-1}\Lambda_N$. However, for a HMF ($\alpha_F = 1$), all spin flip has to take place in N, however large $\sigma_N^{-1}\Lambda_N$ is.

The nonequilibrium effects will be largest at an interface between a HMF and a normal metal in which the spin-flip time is large. In Al with little magnetic impurities, τ_{sf} is of the order of nanoseconds.[5] Then, in an evaporated thin film, the spin-flip diffusion length is several micrometers long. The boundary resistance is equal to the resistance of the sample over a length Λ_N and is of the order 0.1 Ω for a 100-nm thick, 2-μm-wide Al thin-film strip. The main problem is that the additional voltage drop has to build up over a length that is a few times Λ_N. This means that intrinsically there is a series resistance that is larger than the boundary resistance. The diffusion length that governs the conversion of normal current into supercurrent near an N-S interface is also several micrometers long. There the boundary resistance is easily identified because the diffusion length diverges as the temperature approaches the critical temperature of the superconductor. As the spin-flip diffusion length at an F-N interface cannot be manipulated that easily, it will be much harder there to identify part of the resistance as being due to the current conversion process.

The problem of the series resistance may be avoided by attachment of voltage probes very close to the interface. This has already been done to study the current conversion in superconductors which happens on a similar length scale. Small voltage probes are coupled through tunnel junctions to the nonequilibrium region near a so-called phase-slip center in a superconducting strip.[6] Normal-metal and superconducting probes measure the quasiparticle and the pair potential, respectively, and the measurements confirm the exponential decay of the potential difference. To measure directly $\mu_\uparrow$ and $\mu_\downarrow$ near an F-N interface, one would need two HMF probes that are magnetized in opposite directions. However, an

F and an N probe also measure a potential difference. This can be seen in Fig. 2, which may also be interpreted as giving the potentials in two voltage probes attached at $x = 0$ to a sample with $\mu_\uparrow \neq \mu_\downarrow$. Because in a voltage probe no net current flows, μ_0 is constant in each probe. The potential difference of the two probes is direct evidence of the nonequilibrium effects near the F-N interface.

In conclusion, we have shown theoretically that at an F-N interface a current conversion process takes place, which leads to a potential difference of spin-up and spin-down electrons. The situation is analogous to the N-S interface. With some adjustments, the experimental techniques used there may also be used to study the nonequilibrium effects at the F-N interface.

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