Ferromagnet-Nonferromagnet Interface Resistance

There has been recent interest in conduction-electron spin injection across a ferromagnet-paramagnet interface as a new phenomenon with many experimental applications. Briefly the idea is as follows. Electric current in a metallic ferromagnet (F) is carried unequally by spin-up and spin-down electrons, in contrast with a normal metal (N) in which the current is shared equally by the two spin subbands. Aronov[1] proposed that the passage of current across an interface from F to N, carried unequally by up and down electrons, would inject a nonequilibrium magnetization δM in N. This δM would diffuse into N from the interface to a depth $\delta_s = (2DT_2)^{1/2}$ where D and T_2 are the conduction-electron diffusion constant and spin-relaxation time. Associated with δM is a difference in spin-up and spin-down chemical potentials $\mu_\uparrow - \mu_\downarrow = 2\mu_B \delta M/\chi$, with μ_B the Bohr magneton and χ the magnetic susceptibility. Silsbee[1] noted that this difference in chemical potential could be detected as an open-circuit voltage across an interface between a second ferromagnetic probe, a spin detector, and the N metal. Johnson and Silsbee[2] demonstrated the validity of all these ideas in a two-probe, injector/detector experiment.

If the probes serving as detector and injector are the same, the voltage due to the magnetic disequilibrium will appear as an excess resistance of the interface. In a recent Letter, van Son, van Kempen, and Wyder[3] have calculated this excess spin-coupled ("current conversion") interface resistance for the limiting case of a clean (no potential barrier) FN interface and have suggested two possible experiments, one of which has already been performed.[2] First, we show how the result based on the extremely limiting assumption of a high-conductance interface may be generalized to include the interface resistance. Second, we present an indispensable technique that unambiguously identifies the spin-coupled signal in any relevant experimental geometry.

van Son, van Kempen, and Wyder take the continuity of the individual spin-subband chemical potentials $\mu_\uparrow$ and $\mu_\downarrow$ as an interfacial boundary condition, neglecting the discontinuity in μ's that would occur in the presence of substantial scattering or a transmission barrier at the interface.[4] Electron-spin-resonance (ESR) experiments on bimetal samples[5] yield transmission coefficients t of 0.001–0.1 which suggests that the ideal interface may be hard to produce and makes the ideality assumption questionable.

The junction-resistance calculation may be generalized by use of the approach of Johnson and Silsbee[4] in the appendix of an article presenting a classical thermodynamic treatment of the spin-injection/detection experiment. The parameter p describes the spin inequivalence in F and is related to the α of van Son, van Kempen, and Wyder by $p = 2\alpha - 1$. A similar parameter η describes the spin asymmetry of the interface. If we take G as the conductance of the interface in the limit of no spin-coupled resistance, the full resistance is

$$R = \frac{1}{G} + \frac{g_N(p-\eta)^2 + g_F\eta^2(1-p^2) + Gp^2(1-\eta^2)}{g_N g_F(1-p^2) + G(1-\eta^2)[g_N + g_F(1-p^2)]}.$$

Here $g_i = \sigma_i/\delta_i$ is the conductance of a length of the bulk material equal to one spin depth δ_i, and the cross section of the conductors is taken to be unity.

In the $G \to \infty$ limit the result $R = p^2/[g_N + (1-p^2)g_F]$ is the same as in Ref. 3, a result valid only if $G \gg g_N, g_F$. A simple estimate gives $G/g_N \approx t_N(T_{2N}/\tau_N)^{1/2} < 0.3$ with (for aluminum) $t_N < 0.01$ from ESR results (Magno and Pifer[5]) and $T_2/\tau \approx 10^3$ from Ref. 2, and thus indicates that the high-G result is not generally valid. We see from the equation displayed above that the interpretation of the spin-coupled signal must include effects of discontinuities of μ at the interface (i.e., η), *and* that it becomes a small fraction of the background resistance $1/G$.

van son, van Kempen, and Wyder remark on the need, but do not suggest a means, to distinguish between the spin-coupled signal and other sources of resistance. We suggest that, just as one can control the amplitude of a charge-imbalance signal by varying the temperature T near T_c (and even turn off the effect for $T > T_c$), in the magnetic problem, for either the interfacial resistance or the two-probe experiment,[2] one can alter the size of the spin-coupled effect by applying a transverse magnetic field B (the Hanle effect). For large enough fields (10 to 100 G), the field-induced precession dephases the spins, destroying δM and equalizing the chemical potentials $\mu_\uparrow = \mu_\downarrow$ so that the spin-coupled resistance disappears.

Mark Johnson and R. H. Silsbee
Laboratory of Atomic and Solid State Physics
Cornell University
Ithaca, New York 14853

Received 19 June 1987
PACS numbers: 73.40.Cg, 73.40.Jn

[1] A. G. Aronov, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 37 (1976). [JETP Lett. **24**, 32 (1976)]; R. H. Silsbee, Bull. Magn. Reson. **2**, 284 (1980).

[2] Mark Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985).

[3] P. C. van Son, H. van Kempen, and P. Wyder, Phys. Rev. Lett. **58**, 2271 (1987).

[4] Mark Johnson and R. H. Silsbee, Phys. Rev. B **35**, 4959 (1987).

[5] P. D. Sparks and R. H. Silsbee, Phys. Rev. B **35**, 5198 (1987); Richard Magno and Joe Pifer, Phys. Rev. B **10**, 3727 (1974).