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Quantum phase transition in Fe/Cr magnetic multilayers

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Abstract

Spin-dependent electron transport properties have been studied in magnetic multilayers by magnetic field tuning through the orientation transition from a ferromagnetic (FM) into an antiferromagnetic (AF) state. We find that in the $[Fe/Cr]_{10}$ multilayers the resistivity ρ_S associated with the AF scattering varies in the temperature interval below 100 K as $\rho_S(T) = \rho_S(0) - AT^\alpha$ with $0.5 < \alpha(H) \leqslant 2$. As $T \to 0$ K, the antiferromagnetic contribution ρ_S saturates except for a narrow magnetic field region near $H = H_S^0$, which tunes the AF transition temperature down to 0 K. For $H > 1.2H_S^0$, the spin-dependent part in resistivity depends exponentially on temperature above 2 K, indicating a possible spin gap from localized antiferromagnetic correlations.

Keywords: Giant magnetoresistance; Magnetic multilayer; Quantum phase transition

Study of the temperature scaling, especially in electron transport, is shown to be particularly important in identifying quantum phase transitions (QPT) in nearly antiferromagnetic (AF) metals [1]. In all reported systems sofar, the QPT into magnetically ordered phase has taken place from the paramagnetic state and, to our best knowledge, critical behavior with AF fluctuations developed from the ferromagnetic state has not yet been reported.

Here we present an experimental study of the electron transport in a magnetic system in which the transition between two magnetically different ground states is tuned by an in-plain magnetic field. The epitaxial antiferromagnetically coupled [Fe(12 Å)/Cr(12 Å)]$_{10}$ multilayers are prepared in an MBE system on MgO (1 0 0) substrates held at 50°C and covered by a 12 Å thick Cr seed layer.

The largest part of parallel magnetoresistance (MR) is linear: $\rho(0) - \rho(H) \sim H$. The characteristic saturation field H_S is defined as the magnetic field which corresponds to the deviation from the linear decrease of MR. By using isothermal MR measurements we reconstructed the magnetic phase diagram and determined the characteristic fields corresponding to the appearance of a non-zero Néel vector (see the inset to Fig. 1). The temperature dependence of the resistivity measured at different magnetic fields enables us to determine the spin-dependent contribution due to AF coupling nearby and far away from the QPT point: $\rho_S = \rho(T,H) - \rho(T, 2H_S^0)$ (here H_S^0 is obtained by linear extrapolation of $H_S(T)$ to $T = 0$ K).

We observe that over a wide temperature range above 4 K the spin-dependent contribution varies as $\rho_S(T) = \rho_S(0) - AT^\alpha$, with α a function of the magnetic field (see Fig. 1a). Fig. 1b plots the dependence of α on the normalized field H/H_S^0 for field orientations along "easy" (1 0 0) and "hard" (1 1 0) axes. At $H \geqslant 1.2H_S^0$, the spin-dependent resistivity above 2 K scales with temperature in a different way: $\Delta\rho_S \sim e^{-T/\Delta}$ with Δ strongly dependent on magnetic field.

For the temperatures below 2 K the spin-dependent scattering saturates: $\Delta\rho_S(T) = \rho_S(0) - \rho_S(T) \sim T^2$ except when the QPT is tuned exactly. In this case $\Delta\rho_S$ varies as $\Delta\rho_S \sim T^\beta$. The magnetic field dependence of β is shown in Fig. 1b. At $H = H_S^0$, ρ_S varies linearly as a function of temperature between 20 mK and 120 K: $\Delta\rho_S(T) \sim CT$ with C changing around 2–3 K.

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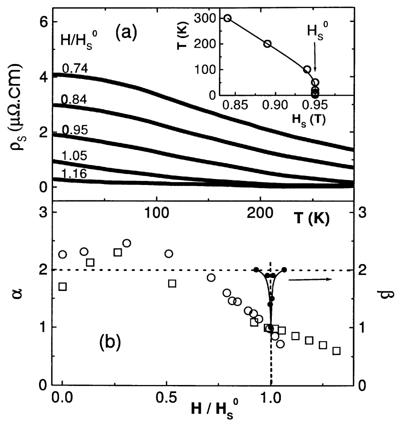

Fig. 1. (a) Temperature dependences of the spin-dependent contribution in resistivity $\rho_S(T)$ along (1 0 0). The inset shows the corresponding saturation field variation as a function of temperature. (b) α versus normalized magnetic field H/H_S^0 determined for both (1 0 0) (open circles) and (1 1 0) (open squares) field orientations. The horizontal dotted line corresponds to $\alpha = 2$, expected for the Fermi liquids. The vertical line marks QPT. Closed circles show the variation of $\beta(H)$ near $H = H_S^0$.

In our view, the transition between two different linear temperature dependences in spin-dependent electron transport may reflect a quantum-classical crossover [2,3] from dominating quantum to classical spin fluctuations. The narrow field range, where QPT is observed in this work, is consistent with theoretical predictions [2] and contradicts an explanation in terms of a disorder-induced NFL [4]. The nature of the ground state at $H/H_S^0 \gg 1$, where a spin gap appears, will be addressed in forthcoming publications.

In summary, in the AF coupled $[Fe/Cr]_{10}$ magnetic multilayers for the interval of magnetic fields where formation of the Néel vector at $T = 0\,K$ is expected, we observe a linear temperature variation of spin-dependent part in resistivity, ρ_S, over almost two decades in T above 20 mK. This behavior is followed by quantum-classical crossover above 2–3 K and an extended temperature region with also a linear dependence $\Delta\rho_S \sim T$, which could be due to electron scattering on critical thermal spin fluctuations.

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