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Change of the effective dimensionality of an Nb/CuNi bilayer in an external magnetic field

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Abstract
A dimensional crossover of superconducting fluctuations in an external magnetic field, applied parallel to the layers, has been found for superconductor/ferromagnet bilayers of Nb/$Cu_{41}Ni_{59}$. By lowering the temperature, a reduction of the superconducting nuclei size occurs. As soon as the size of the nuclei becomes smaller than the thickness of the superconducting bilayer structure, the dimensionality changes. The temperature dependence of the fluctuation conductivity exhibits a 2D behaviour in zero and weak magnetic fields in the vicinity of the critical temperature, switching to a 3D behaviour in a strong magnetic field at low temperatures.

1. Introduction

There exists a fundamental reason for the resistive transition broadening of a superconductor due to an intrinsic transition width associated with thermodynamic fluctuations of the superconducting order parameter. This intrinsic width, ΔT_c, is given by the Ginzburg criterion [1], $\Delta T_c = Gi\,T_c$, where

$$Gi \sim a_0^4/\xi_0^4 \qquad (1)$$

is the Ginzburg number, with a_0 being the lattice parameter, $\xi_0 = \hbar v_F/2\pi k_B T_c$ the coherence length, v_F the Fermi velocity of the superconducting material and T_c the critical temperature. The value of Gi is extremely small for pure 3D conventional superconductors like bulk Sn or Al ($Gi_3 \sim 10^{-13}$–10^{-14}), rising by many orders of magnitude for dirty and low-dimensional systems [2, 3]. For low-dimensional superconductors, such as thin films or thin wires, with one characteristic scale (thickness of the film or diameter of the wire) comparable to the coherence length ξ_0, the intrinsic width ΔT_c may be much larger than for bulk material. In particular for thin films with thickness d, electron mean free path l and Ginzburg–Landau coherence length $\xi(0) \sim (\xi_0 l)^{1/2}$, the value of the Ginzburg number Gi_2 increases dramatically in comparison with the respective value Gi_3 for bulk material [2]:

$$Gi_2 = (E_F/k_B T_c)[k_F^3\xi(0)^2 d]^{-1} \equiv (Gi_3)^{1/2}\xi(0)/d \qquad (2)$$

making the fluctuation effects observable experimentally, as was investigated in detail in [4, 5]. Here, E_F and k_F are the Fermi energy and wavenumber, respectively, and k_B is Boltzmann's constant.

In many works the broadening of the resistive transition of thin films and layered superconductors was interpreted in terms of superconducting fluctuations, rising in the vicinity of the critical temperature T_c [6–9]. The fluctuation or excess conductance, $\sigma' = \sigma(T) - \sigma_n \equiv 1/R(T) - 1/R_n$ (R_n is the resistivity of the sample above the superconducting transition at $T \gg T_c$) strongly depends on the superconductor dimensionality. It is $\sigma' \sim (T/T_c - 1)^m$, with the critical index $m = (D-4)/2$, which depends on the superconductor dimensionality D, leading to $m = -1/2, -1$ and $-3/2$ for 3D, 2D and 1D superconductors, respectively [6].

For a two-dimensional superconductor ($D = 2$) in the weak fluctuation region, at temperatures $T > T_c$, the excess conductance $\sigma' \sim (T/T_c - 1)^m$ is inversely proportional to the temperature. According to Aslamazov–Larkin [10] one gets

$$[\sigma'(T)]^{-1} = (R_n/\tau_{AL})(T - T_c^{AL})/T_c^{AL} \qquad (3)$$

where $\tau_{AL} = (R_n^{\square} e^2)/16\hbar$, and $R_n^{\square}$ is the normal state sheet resistance of the film [7, 10] and T_c^{AL} is the Aslamazov–Larkin critical temperature [7].

In the critical fluctuation region at temperatures $T \sim T_c$, the inverse fluctuation conductivity $[\sigma']^{-1}$ is expected

