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

$$Gi \sim a_0^4/\xi_0^4 \tag{1}$$

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]:

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

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

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

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 to be an exponential function of $(1 - T/T_c)^{-m}$ [11]. For a 2D superconductor with $m = -1$ the theory of critical fluctuations [12] yields

$$[\sigma'(T)]^{-1} \sim R_n \exp[-(1 - T/T_c)/Gi_2]. \qquad (4)$$

For three-dimensional fluctuations the dependence with $m = -1/2$ should occur [11]:

$$[\sigma'(T)]^{-1} \sim R_n \exp\{[-(1 - T/T_c)/Gi_3]^{1/2}\}. \qquad (5)$$

The present paper reports data on the change of the critical index specifying the temperature dependence of the fluctuation conductivity σ' near the superconducting transition point for a superconductor/ferromagnetic (S/F) bilayer of Nb/$Cu_{41}Ni_{59}$ by a strong magnetic field, applied parallel to the layers.

In such an S/F contact, a quasi-one-dimensional Fulde–Ferrel–Larkin–Ochinnikov (FFLO)-like state is established, in which the pairing wavefunction not only decays exponentially into the F metal (as in the usual superconductor/non-magnetic-normal-metal (S/N) proximity effect), but in addition oscillates. Interference effects of the pairing wavefunction thus govern the superconducting behaviour of the S/F bilayer, yielding, for example, a critical temperature, oscillating as a function of the F metal layer thickness d_F. This non-monotonic dependence of the critical temperature on d_F, which may even lead to a reentrant behaviour of the superconducting state, has been recently studied in detail in [13]. The present paper now investigates the superconducting fluctuations in this system, in which superconductivity is governed by the pairing function flux through the S/F boundary.

The samples were prepared by magnetron sputtering on commercial (111) silicon substrates at room temperature from Nb (99.99%) and $Cu_{40}Ni_{60}$ targets. Rutherford backscattering spectrometry (RBS) has been used to evaluate the thickness of the Nb and the $Cu_{1-x}Ni_x$ layers with an accuracy of $\pm 5\%$. The resistance measurements were performed by the DC four-probe method using a 10 μA sensing current in the temperature range 0.4–10 K in an Oxford Instruments 'Heliox' ^{3}He cryostat. For further details see [13].

2. Results and discussion

Figure 1 presents the resistive transitions in a parallel magnetic field $B = B_\parallel$ for one of the investigated Nb/CuNi samples with a 7.3 nm thick Nb layer and 1 nm thick CuNi layer.

The temperature dependence of the fluctuation conductance, $\sigma'(T)$, in semilogarithmic coordinates is demonstrated in figure 2, following a 2D behaviour with the critical index $m = -1$ for zero and weak magnetic field ($B = 0.5$ T). It can analytically be described as $\sigma_n/\sigma' \sim \exp(-\varepsilon_B/Gi_2)$, with $\varepsilon_B = 1 - T/T_c(B)$, where $T_c(B)$ is the superconducting transition temperature, determined as the midpoint of the resistive transitions $R(T)$, in the magnetic field B [11, 14]. For $B_\parallel = 0$ and 0.5 T we have $T_c(B_\parallel) \approx T_c(0)$. For strong magnetic fields another behaviour was observed with the critical index $m = -1/2$:

$$\sigma_n/\sigma' \sim \exp\{(-\varepsilon_B \alpha_B/Gi_3)^{1/2}\},$$
$$\text{where [15] } \alpha_B = -(1 - B/B_{c2\parallel}(T)) \qquad (6)$$

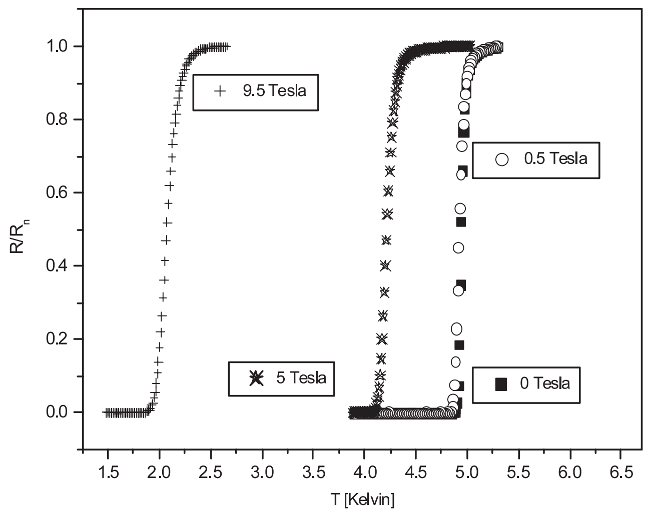

Figure 1. Resistive transitions $R(T)$ in a magnetic field, parallel to the layers, for the sample S3#29, which is an Nb(7.3 nm)/$Cu_{41}Ni_{59}$ (1 nm) bilayer. The value of the magnetic field is marked on the curves.

corresponding to the 3D case in a magnetic field. This effect—a crossover from a 2D behaviour of the Nb/CuNi bilayer in zero and a weak magnetic field to a 3D behaviour in a strong parallel magnetic field at low temperatures—is the main finding of the present work.

From the slope of the straight lines in figure 2, the Ginzburg number Gi can be evaluated. For zero and small field, this is straightforward, because $\ln(\sigma_n/\sigma') = (1/Gi_2)(-\varepsilon_B) + \text{const}$, yielding $Gi_2 = 1.67 \times 10^{-2}$. For high fields we get $[\ln(\sigma_n/\sigma')]^2 = (\alpha_B/Gi_3)(-\varepsilon_B) + \text{const}'$, yielding $\alpha_B/Gi_3 = 1.92 \times 10^2$, i.e. $Gi_3 = \alpha_B \times 5.2 \times 10^{-3}$. To determine α_B, we measured $B_{c2\parallel}(T)$. For the environment below 9.5 T it is, in a linear approximation, $B_{c2\parallel}(T) \approx 9.5\,\text{T} - (1.36\,\text{T}\,\text{K}^{-1})(T - T_c(9.5\,\text{T}))$. For $-(1 - T/T_c(9.5\,\text{T})) = 0.15$, which is at the centre of the linear behaviour in figure 2(b), we have $T - T_c(9.5\,\text{T}) = 0.31$ K. This gives $B_{c2\parallel}(T) = 9.08$ T and thus $\alpha_B = -(1 - 9.5\,\text{T}/9.08\,\text{T}) = 0.046$. Then $Gi_3 = 0.046 \times 5.2 \times 10^{-3} = 2.4 \times 10^{-4}$.

According to equation (2) it is $Gi_3 = Gi_2^2\,(d/\xi(0))^2$. As described in detail in [16], $\xi(0)$ has been determined from measurements of the temperature dependence of the perpendicular critical magnetic field of the present sample, yielding $\xi(0) = 10$ nm, so that $d/\xi(0) = 7.3\,\text{nm}/10\,\text{nm}$. This results in $Gi_3 = (1.67 \times 10^{-2} \times 0.73)^2 = 1.49 \times 10^{-4}$, close to the measured value of 2.4×10^{-4}.

The change of the absolute value of the critical index from 1 to 1/2 specifying the temperature dependence of the fluctuation conductivity can be interpreted as a manifestation of a dimensionality crossover of superconducting fluctuations from two-dimensional in zero and low magnetic fields to three-dimensional in a strong field. In the low magnetic field region at high temperatures (in the vicinity of T_c) the size of the superconducting nucleus, determined by the temperature-dependent Ginzburg–Landau coherence length $\xi(T) = \xi(0)(1 - T/T_c)^{-1/2}$ of the superconductor, is much larger than the thickness of the superconducting Nb/CuNi bilayer

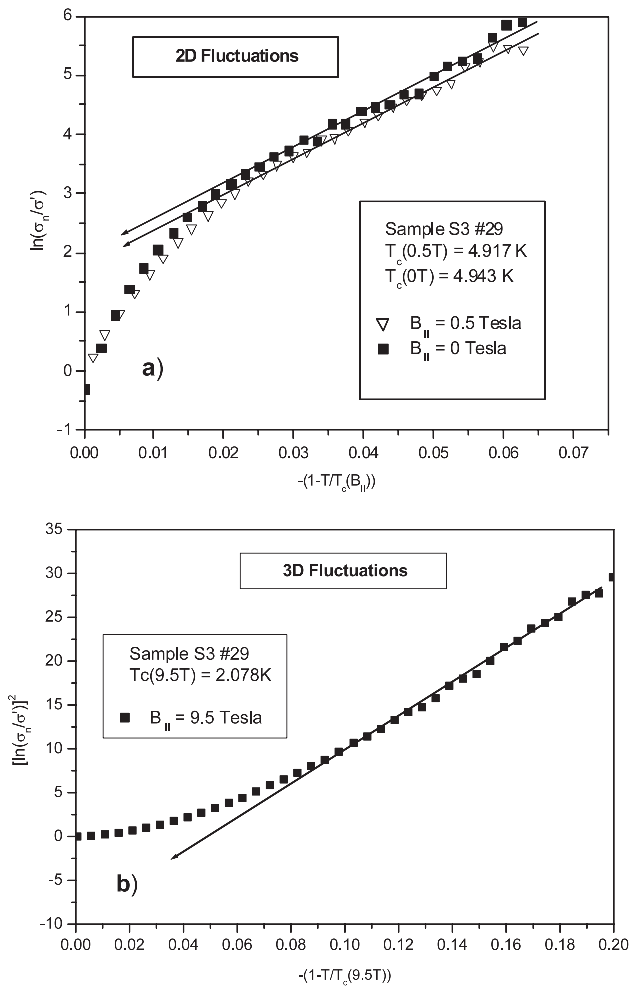

Figure 2. Temperature dependence of $\ln(\sigma_n/\sigma')$ and $[\ln(\sigma_n/\sigma')]^2$, respectively. Data taken from figure 1. The slope of the lines (marked by arrows) gives the value of the Ginzburg number: (a) $Gi_2 = 1.67 \times 10^{-2}$ for $B = 0$ and 0.5 T (2D behaviour) and (b) $Gi_3 = 2.4 \times 10^{-4}$ for $B = 9.5$ T (3D behaviour). For details see the text. The insets give information about the sample number and the superconducting transition temperatures at the mentioned magnetic fields parallel to the surface of the Nb/CuNi bilayer.

and the sample demonstrates two-dimensional behaviour. By lowering the temperature, a reduction of the superconducting nucleus size takes place. As soon as the size of the nucleus becomes smaller than the thickness of the superconducting bilayer structure, the dimensionality changes, because the nucleus is localized inside the superconducting layer [17] and the three-dimensional behaviour occurs. The effective size of the nucleus may be roughly estimated by the equation [18]

$$S_{\mathrm{eff}} \equiv \xi_\perp = [B_{\mathrm{c}2\perp}(T)\varphi_0/2\pi]^{1/2}/B_{\mathrm{c}2\parallel}(T) \qquad (7)$$

with $\varphi_0 = h/2e$ the superconducting flux quantum (where h is Planck's constant and e the elementary charge) and the superconducting coherence length $\xi_\perp = \xi_\perp(0)(1 - T/T_{\mathrm{c}})^{-1/2}$, which we estimated using the values of the measured critical magnetic fields parallel to the sample plane, $B_{\mathrm{c}2\parallel}(T)$, and perpendicular to the plane, $B_{\mathrm{c}2\perp}(T)$.

For the temperature $T = 2.078$ K (which is the transition temperature of the sample in a parallel field of $B = 9.5$ T, i.e. $B_{\mathrm{c}2\parallel}(2.078\ \mathrm{K}) = 9.5$ T) the experimental value of the perpendicular critical field is $B_{\mathrm{c}2\perp}(2.078\ \mathrm{K}) = 1.8$ T. With $\varphi_0 = 2.07 \times 10^{-15}$ T m^2 the value for the nucleus calculated from equation (7) is $S_{\mathrm{eff}} = 2.6$ nm, which is less than the Nb layer thickness of the sample, $d_{\mathrm{Nb}} = 7.3$ nm. Thus, the superconducting nucleus 'considers' the sample as bulk material.

The corresponding 3D temperature dependence of the fluctuation conductivity occurs at such low temperatures that it causes the critical index $m = -1/2$. Alongside, as the transition temperature decreases (for increased magnetic field), the value of the Gi number, obtained from the slope of the linear parts of the $\ln(\sigma_n/\sigma')$ and $[\ln(\sigma_n/\sigma')]^2$ versus $-(1 - T/T_{\mathrm{c}})$ dependences, changes from the value for 2D fluctuations, $Gi_2 = 1.67 \times 10^{-2}$, down to $Gi_3 = 2.4 \times 10^{-4}$ for 3D fluctuations.

3. Conclusions

In conclusion, the temperature dependence of the fluctuation conductivity exhibits a 2D behaviour in zero and weak magnetic fields in the vicinity of the critical temperature, changing to a 3D behaviour in strong magnetic fields at low temperatures. In which way the crossover behaviour depends on the properties of the bilayer (e.g. the thickness of the F metal and thus the pairing function flux across the S/F interface) cannot be concluded from these first measurements. More detailed investigations have to be performed to answer this question.

The dimensional 2D–3D crossover for layered samples can also be detected in the temperature dependence of the parallel critical magnetic field. This phenomenon was recently observed for superconductor/ferromagnet bilayers [19]. A correlation to the fluctuation dimensional crossover would be an interesting issue.

Probably, a deep analysis of how far the S/F proximity effect governs the fluctuation behaviour needs an extension of the theoretical work on fluctuation regimes at the FFLO transition [20] to the quasi-one-dimensional FFLO-like state present in the investigated S/F bilayer.

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