Inhomogeneous superconductivity induced in a weak ferromagnet

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Abstract

Under certain conditions, the order parameter induced by a superconductor (S) in a ferromagnet (F) can be inhomogeneous and oscillating, which results e.g. in the so-called π-coupling in S/F/S junctions. In principle, the inhomogeneous state can be induced at T_c as function of the F-layer thickness d_F in S/F bilayers and multilayers, which should result in a dip-like characteristic of $T_c(d_F)$. We show the results of measurements on the S/F system Nb/$Cu_{1-x}Ni_x$, for Ni-concentrations in the range $x = 0.5$-0.7, where such effects might be expected. We find that the critical thickness for the occurrence of superconductivity is still relatively high, even for these weak ferromagnets. The resulting dip then is intrinsically shallow and difficult to observe, which explains the lack of a clear signature in the $T_c(d_F)$ data.

Keywords: Proximity effect, SFS-junctions, LOFF-state

1 Introduction

Recently it was shown that superconductor/ferromagnet/superconductor (S/F/S) junctions made of $Nb/Cu_{1-x}Ni_x/Nb$, where the interlayer is weakly ferromagnetic ($x \approx 0.54$), can support a supercurrent. Moreover, the temperature dependence of the supercurrent shows a sharp cusp, which suggests that the junction changes from a 0-phase to a π-phase state at low temperatures [1]. This implies that the superconducting order parameter induced in the ferromagnet is oscillatory damped, and also that the transparency of the interface is relatively high. A signature for this inhomogeneous state should also be visible in the T_c-dependence of S/F multilayers as the function of the F-layer thickness d_F [2,3]. Specifically, T_c should go through a dip before reaching a maximum and going to an asymptotic value, under the condition, however, that the S-layer thickness d_S is of the order of the superconducting coherence length ξ_S. The dip, which appears to be a stronger signature for the inhomogeneous state than the often searched-for maximum

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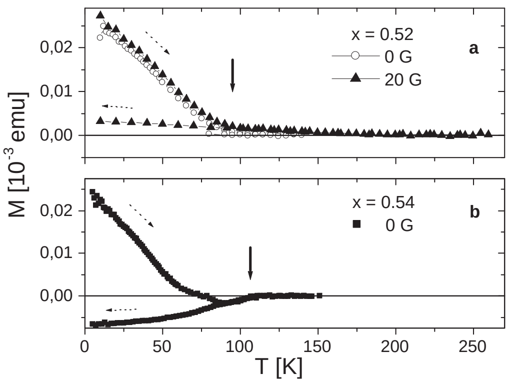

Fig. 1. Magnetization M versus temperature T for single films of $Cu_{1-x}Ni_x$ with (a) $x = 0.52$ (applied field 0 G, 20 G), (b) $x = 0.54$ (0 G). Dotted arrows show the measurement sequence, solid arrows the values of T_{Curie}.

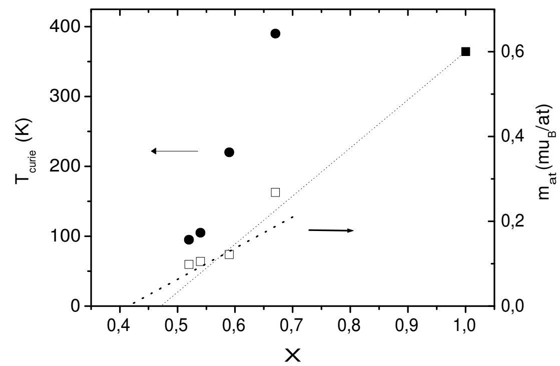

Fig. 2. Ferromagnetic transition temperature T_{Curie} and magnetic moment per atom (formula unit) m_{at} as function of concentration x for alloy films of $Cu_{1-x}Ni_x$. The dotted lines show the behavior of the bulk magnetic moment [9]. The kink in the functional dependence is emphasized by extrapolating the two linear regimes. The solid square shows the bulk moment for pure Ni.

(see e.g [4,5]), signifies a self-interference effect of the inhomogeneous order parameter, and could be used to advantage in constructing a superconducting spin switch [6,7]. The necessary conditions can be reached if the pair breaking by the ferromagnet is not too strong, so that the critical thickness d_{cr}^S of the superconductor is not (much) larger than ξ_S. In principle, given the observation of supercurrents in $Nb/Cu_{0.46}Ni_{0.54}/Nb$, this system might also be a viable candidate for observing the interference effects. Here we present results of the measurements of the magnetic and superconducting properties of $Nb/Cu_{1-x}Ni_x$ for different x. We show that d_{cr}^S even for these weak ferromagnets is high enough to make the predicted effects small.

2 Sample preparation and magnetic properties

Sets of single F-films, S/F bilayers and F/S/F trilayers were DC-magnetron sputtered in an ultra high vacuum system with base pressure 10^{-9} mbar and sputtering argon pressure about $6*10^{-3}$ mbar. $Cu_{1-x}Ni_x$ targets were used with $x = 0.60$, 0.50 and 0.45 atomic percent which yielded a somewhat different Ni concentration in the samples : $x = 0.67$, 0.59 and 0.52 respectively. The samples were measured by SQUID-magnetometry in order to determine the saturation magnetization M_s and the Curie temperature T_{Curie}. For comparison we also measured a set of samples which were sputtered in an RF-sputtering system with a base pressure of 10^{-7} mbar [8]. Fig. 1 shows the typical dependence of the magnetization M on temperature T for a single F-layer, using the following procedure: the sample was magnetized to its saturation at 10 K, then the field was removed (or set to a small value), and $M(T)$ was measured up to 300 K and back down to 10 K. T_{Curie} was defined at the temperature where $M(T)$ deviates from the constant value at high T, which is usually slightly higher than where the hysteresis sets in. The negative part of the $M(T)$ curve in Fig. 1b we associate with a small negative residual field in the cryostat. Fig. 2 and Table 1 show T_{Curie} and the magnetic moment μ_{at} of the CuNi films as function of Ni concentration. In the range $x = 0.52$ - 0.59, μ_{at} changes very little, with a stronger increase

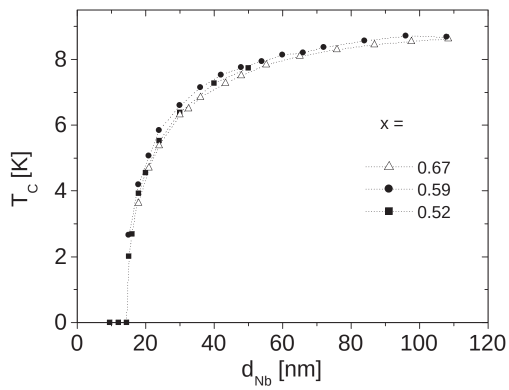

Fig. 3. Critical temperature T_c versus Nb thickness d_{Nb} for F/S/F trilayers with F = $Cu_{1-x}Ni_x$, S = Nb, for x = 0.67, 0.59 and 0.52. Dotted lines are meant to guide the eye.

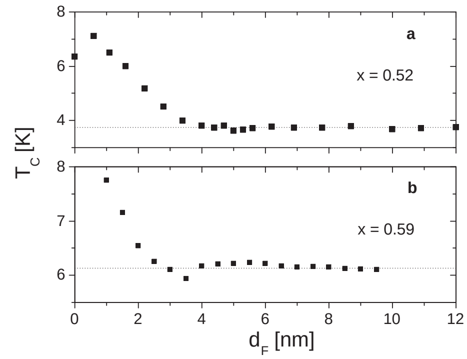

Fig. 4. Critical temperature T_c versus F-layer thickness d_F for S/F bilayers with F = $Cu_{1-x}Ni_x$, S = Nb. (a) $x = 0.59$, $d_{Nb} = 18$ nm; (b) $x = 0.52$, $d_{Nb} = 12$ nm.The dotted lines indicate the asymptotic value at large d_F.

above $x = 0.6$. Also shown in Fig. 2 is the behavior of the bulk magnetic moments according to ref. [9]. The agreement is quite satisfactory and the comparison makes clear that the small changes below $x = 0.6$ accurately mimic the bulk behavior, where a kink in the linear dependence is found at that value. Interestingly, $T_{Curie}(x)$ behaves somewhat differently, with a much larger variation. It suggests that T_{Curie} is a more sensitive measure for x than μ_{at}.

3 Superconducting properties and discussion

The dependence of the critical temperatures T_c on d_{Nb} of $Cu_{1-x}Ni_x$/Nb/$Cu_{1-x}Ni_x$ sandwiches with thick F-layers (50 nm) is shown in Fig. 3 for three Ni concentration: $x = 0.52$, 0.59 and 0.67. Values for d_{cr}^S for all concentrations are presented in Table 1. There is hardly any dependence on Ni concentration. The data for $x = 0.67$ yield a slightly higher value for d_{cr}^S while the data for $x = 0.59$ even lie on the low-d_{Nb} side of the data for $x = 0.52$, but for all sets measured, d_{cr}^S is about 14 nm. In view of the small changes in μ_{at} found above, this indicates that μ_{at} is a better measure for the pair breaking effects in the F-layer than T_c. Using the value $\xi_S = 8$ nm for Nb [5] we find $d_{cr}^S/\xi_S \approx 1.6$. This already implies that the signature of the inhomogeneous superconductivity, namely the dip in $T_c(d_F)$, can only be small [3].

For $T_c(d_F)$, measurements were performed on two sets of S/F bilayers (S-layer on the substrate side), one with (S) $d_{Nb} = 18$ nm and (F) $x = 0.59$, the other with (S) $d_{Nb} = 12$ nm and (F) $x = 0.52$. The data in Fig. 4a,b show a possible dip in the case of $x = 0.59$, but only a kink in the case of $x = 0.52$. Given the small difference in μ_{at} the similar behavior is not surprising. The absence of (stronger) dips is probably due to a combination of the still rather large value for d_{cr}^S/ξ_S and bandstructure effects, which make the interfaces less than fully transparent. Also, growth conditions are very important, and smearing effects likely. A final remark concerns the value of d_F where the kink is found, around 4 - 5 nm. It should be realized that this does not contradict the coupling thickness for reaching the π-state in S/F/S junctions of 15-20 nm : firstly, the $T_c(d_F)$ data are on bilayers and therefore correspond to 8 - 10 nm for the trilayer case;

x	d_{cr}^S/ξ_S	T_{Curie} [K]	μ_{at} [μ_B/at]
0.67	1.63	390	0.27
0.59	1.55	220	0.12
0.54		105	0.11
0.52	1.55	95	0.10

Table 1
Values of d_{cr}^S in units of ξ_S for F/Nb/F trilayers (F = $Cu_{1-x}Ni_x$) and of T_{Curie} and the magnetic moment per atom μ_{at} as determined on single F films for different Ni-concentrations of the ferromagnetic $Cu_{1-x}Ni_x$, as indicated.

secondly because the weak magnetism results in a temperature dependence of ξ_F [1].

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