Scaling of $H_{c2\perp}(T)$ in Nb/CuMn Multilayers

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Abstract

Measurements of the perpendicular upper critical magnetic field $H_{c2\perp}(T)$ are reported for several Nb/CuMn multilayers. It is found that, despite the magnetic nature of the samples, the data for samples with low Mn percentage in the CuMn layers are simply described by the Werthamer-Helfand-Hohenberg theory for conventional type-II superconductors, neglecting both Pauli spin paramagnetism and spin orbit impurity scattering. For high Mn concentration a different theoretical approach is needed.

Key words: superconductivity, spin glass, multilayers, critical magnetic field.

Running head: Nb/CuMn multilayers

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I. INTRODUCTION

The issue of the proximity effect in superconducting multilayers has been intensely studied since the early sixties\textsuperscript{1,2}. In particular since superconductivity and magnetism are two mutually excluding phenomena a lot of interest has been devoted to the analysis of superconducting (S)/magnetic (M) multilayers\textsuperscript{3,4}. Several theoretical and experimental studies have been done on these systems, in particular about the existence of the so-called \(\pi - \text{phase} \) state which manifests itself in a nonmonotonic behavior of the transition temperature \(T_c\) of the S/M multilayers as a function of the magnetic layers thickness \(d_M\). Numerous experiments about the behavior of \(T_c\) versus \(d_M\) have been reported on different S/M multilayers\textsuperscript{5–12}: However the presence of \(T_c\) oscillations is still an open question and further theoretical investigation is needed. In particular in the case of Nb/CuMn multilayers (where CuMn is a spin glass) the presence of a small Mn percentage (\(\geq 0.7\%\)) in copper gives rise to a nonmonotonic behavior of \(T_c\) versus \(d_M\)\textsuperscript{11,12} which cannot be explained in the framework of the conventional proximity theory even when taking into account a paramagnetic pair breaking mechanism\textsuperscript{3}.

Another interesting feature of S/M multilayers is the temperature behavior of the upper critical magnetic field, both in the direction parallel, \(H_{c2\parallel}(T)\), and perpendicular, \(H_{c2\perp}(T)\), to the plane of the film, which shows deviations from the S/N case (here N is a normal metal). Measurements performed on V/Fe multilayers\textsuperscript{13} revealed a good agreement with the theoretical predictions for S/M multilayers\textsuperscript{13}. Both \(H_{c2\parallel}(T)\) and \(H_{c2\perp}(T)\) could be consistently described using the same value for the only free parameter of the theory. On the other hand the same measurements performed on Nb/CuMn samples with 2.7\% and 4.5\% of Mn could be only qualitatively described by the same theory, probably due to the much more complicated nature of a spin glass system with respect to the ferromagnetic case\textsuperscript{14}.

In this paper we report on measurements of the perpendicular upper critical magnetic field as a function of temperature in Nb/CuMn multilayers. A large number of samples have been measured with different Mn percentage and different layering, also in the presence of
a regular array of antidots\textsuperscript{14,15}. Regardeless of the specific nature of the multilayers, the measurements for the samples with low percentage of Mn in the CuMn layers (up to 2.7 \%) are in agreement with the Werthamer-Helfand-Honenberg (WHH) theory, which describes the behavior of conventional type-II superconductors\textsuperscript{18}. This result indicates that $H_{c2\perp}(T)$ measurements are less sensitive to the presence of Mn than the measurements of $T_c$ versus the magnetic layers thickness. However for sufficiently high Mn concentration a different theoretical approach is needed to describe the data.

II. EXPERIMENT

Nb/CuMn multilayers have been fabricated by using a dual-source magnetically enhanced dc triode sputtering system with a movable substrate holder on Silicon (100) substrates\textsuperscript{11}. The bottom layer is CuMn and the top layer is Nb for all the samples. Some of the samples are patterned into $200 \times 200 \mu m^2$ zones with a regular array of antidots and suitable contact pads. The preparation details for these samples, obtained by lift-off procedure, are reported elsewhere\textsuperscript{16,17}. All the samples present good superconducting properties and a well defined layered structure as shown by low angle X-ray diffraction patterns\textsuperscript{14}.

Transport measurements have been performed with a standard dc four probe technique with magnetic field applied perpendicular to the plane of the film. In figure 1 the resistive transitions of one of the analyzed samples (sample A(20)1) are reported at different values of the external perpendicular magnetic field. The $H_{c2\perp}(T)$ values have been obtained from the $R(T)$ curves, at different applied magnetic fields, using the 50\% $R_N$ criterion, where $R_N$ is the normal state resistance just before the transition to the superconducting state. However, even if different criteria are used to extract the $H_{c2\perp}(T)$ from $R(T,H)$ curves, no substantial differences are observed in the results. We have also occasionally performed $R(H)$ measurements at different temperatures to extract the $H_{c2\perp}$ value for each temperature at the intersection point between the flux flow regime and the normal state resistance\textsuperscript{19}. The critical magnetic field values obtained with the two different methods are always in good
agreement with each other.

Table I shows the sample characteristics: Nb thickness $d_S$, CuMn (Cu) thickness $d_M$, Mn percentage, number of bilayers, superconducting critical temperature $T_c(K)$ and anisotropy ratio $\zeta = H_{c2\perp}(0)/H_{c2\parallel}(0)$. A column is added in the end to point out the patterned samples with the array of antidots.

III. RESULTS AND DISCUSSION

The upper critical field measurement allows us to investigate the nature of the pair-breaking mechanism present in our superconducting-spin glass multilayers. Figure 2 shows the reduced perpendicular critical magnetic field $h_{c2} = H_{c2\perp}/[T_c(-dH_{c2\perp}/dT)|_{T=T_c}]$ as a function of the reduced temperature $t = T/T_c$ for all the investigated samples. The data have been analyzed in the framework of the WHH theory which widely describes the $H_{c2}(T)$ behavior of bulk type-II superconductors, including the case where the effect of applied magnetic field on the electron spin magnetic moments cannot be neglected. In particular Pauli spin paramagnetism and spin-orbit scattering are taken into account, respectively through the parameters $\alpha$ and $\lambda_{so}$, which appear in the implicit equation for the reduced field $h_{c2}$:[3]

$$\ln\left(\frac{1}{t}\right) = \left(\frac{1}{2} + \frac{i\lambda_{so}}{2\gamma}\right)\Psi\left(\frac{1}{2} + \frac{\bar{h}_{c2} + \frac{1}{2}\lambda_{so} + i\gamma}{2t}\right) + \left(\frac{1}{2} - \frac{i\lambda_{so}}{2\gamma}\right)\Psi\left(\frac{1}{2} + \frac{\bar{h}_{c2} + \frac{1}{2}\lambda_{so} - i\gamma}{2t}\right) - \Psi\left(\frac{1}{2}\right)$$

(1)

where $\psi$ is the digamma function, $\bar{h}_{c2} = (4/\pi^2)h_{c2}$ and $\gamma = [(\alpha\bar{h}_{c2})^2 - ((1/2)\lambda_{so})^2]^{1/2}$.

While data for all the multilayers with high Mn percentage are not described by the WHH theory, for the samples with Mn percentage up to 2.7 all the experimental points collapse on the WHH curve calculated for the case $\alpha = \lambda_{so} = 0$. This quite surprising result indicates that a small percentage of Mn does not significantly influence the $H_{c2\perp}(T)$ curves and Nb/CuMn multilayers behave, at least for temperatures down to $t = 0.3$, like ordinary type-II superconductors. $H_{c2\perp}(T)$ measurements are then less sensitive to Mn concentration.
than measurements of $T_c$ versus $d_M$. A nonmonotonic $T_c(d_M)$ dependence was observed even for 0.7 % of Mn, revealing an unconventional proximity effect in the system, while 2.7 % of Mn is still not sufficient to cause an appreciable deviation from a conventional $H_{c2\perp}(T)$ behavior.

In figure measurements for a Nb/Cu multilayer, the sample M(0), are also shown. Again these data collapse on the WHH curve with $\alpha = \lambda_{so} = 0$. Same results have been obtained for Nb/Pd multilayers. On the other hand data from samples with high Mn percentage cannot be fitted to the WHH theory even in the case $\alpha \neq 0$ and $\lambda_{so} \neq 0$. In fact in the $h_{c2} - t$ plane all these data lie above the points obtained in the small Mn percentage case, while theoretical curves with $\alpha, \lambda_{so} \neq 0$ are always below the $\alpha = \lambda_{so} = 0$ curve. Similar results apply for V/Fe and Nb/Gd multilayers and Nb/Pd$_{1-x}$Fe$_x$/Nb triple layers, with $x \neq 0$, when plotted in the WHH fashion. Also in these cases the data lie above the WHH curve with $\alpha = \lambda_{so} = 0$. These results show that an additional pair breaking mechanism, which is not taken into account in the WHH theory, is present both in superconducting/ferromagnetic and some superconducting/spin glass multilayers, such as Nb/CuMn with high Mn percentage ($> 2.7 \%$). In this case a realistic explanation requires theories which explicitly take into account the magnetic nature of the non superconducting material in the multilayers.

**IV. CONCLUSIONS**

Measurements of $H_{c2\perp}(T)$ have been performed on several Nb/CuMn multilayers with different Mn percentage in the CuMn layers, also in the presence of regular array of antidots. It is found that the $H_{c2\perp}(T)$ curves for samples having low Mn percentage are described by a conventional theory for type-II superconductors despite the magnetic nature of the samples, regardless of the layering and of a more complicated structure, i.e. if a regular array of antidots is present.
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Table I. Relevant sample parameters. See the text for the meaning of the listed quantities.

| Sample   | $d_S$ (Å) | $d_M$ (Å) | % Mn | N_{bil} | $T_c$(K) | $\zeta$ | Antidot lattice |
|----------|-----------|-----------|------|---------|---------|--------|----------------|
| M(27)1   | 260       | 6         | 2.7  | 10      | 6.02    | 1.0    | No            |
| M(27)2   | 260       | 9         | 2.7  | 10      | 5.42    | 1.0    | No            |
| M(27)3   | 260       | 11        | 2.7  | 10      | 4.96    | 1.2    | No            |
| M(27)4   | 260       | 16        | 2.7  | 10      | 4.22    | 1.8    | No            |
| M(27)5   | 260       | 19        | 2.7  | 10      | 4.03    | 3.3    | No            |
| M(27)6   | 260       | 24        | 2.7  | 10      | 4.58    | 3.1    | No            |
| M(27)7   | 260       | 29        | 2.7  | 10      | 4.50    | 5.0    | No            |
| M(45)1   | 350       | 4         | 4.5  | 10      | 6.67    | 1.37   | No            |
| M(45)2   | 350       | 11        | 4.5  | 10      | 5.46    | 1.74   | No            |
| M(45)3   | 350       | 15        | 4.5  | 10      | 3.78    | 1.45   | No            |
| M(45)4   | 350       | 29        | 4.5  | 10      | 3.67    | 7.23   | No            |
| M(45)5   | 350       | 32        | 4.5  | 10      | 3.61    | 5.41   | No            |
| A(20)1   | 250       | 8         | 2    | 6       | 7.54    | 1.46   | Yes           |
| A(20)2   | 250       | 12        | 2    | 6       | 7.38    | 1.36   | Yes           |
| A(20)3   | 250       | 20        | 2    | 6       | 6.96    | 1.41   | Yes           |
| A(20)4   | 250       | 24        | 2    | 6       | 6.66    | 1.72   | Yes           |
| A(20)5   | 250       | 28        | 2    | 6       | 6.5     | 1.76   | Yes           |
| M(0)     | 200       | 200       | 0    | 10      | 6.67    | 1.6    | No            |
FIG. 1. Transition curves for different perpendicular magnetic fields for the sample A(20)1. The curves correspond to increasing fields, from right to left, equal to 0.0, 0.4, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 3.0 T.
FIG. 2. Reduced perpendicular magnetic field $h_{c2}$ versus reduced temperature $t$ for all the analyzed samples. Diamonds refer to the samples of the series M(45); open squares to the samples of the series M(27); circles to the samples of the series A(20) and full triangles to the sample M(0). The solid line is the WHH theoretical curve obtained for $\alpha = \lambda_{so} = 0$. 