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Journal of Magnetism and Magnetic Materials 272–276 (2004) e1087–e1088
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Evidence for zero and π phase from superconducting transition temperature in Nb/Co superconducting multilayers

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Abstract

The oscillating phenomena of T_c as a function of ferromagnetic layer thickness have been observed for both the Nb/Co superconductor(S)/ferromagnet(F) tri-layer series (F/S/F) and penta-layer series (F/S/F/S/F). The oscillating characteristics are different between tri-layer and penta-layer, reflecting the 0-phase and π-phase forming of neighboring S-layers, which provides a first evidence of T_c oscillation distinguishing both the phases.

PACS: 74.78.Fk; 74.50.+r

Keywords: Niobium-cobalt; Multilayer; Superconductivity; Transition temperature

1. Introduction

In the several decades, the superconducting properties of superconductor(S)/ferromagnet(F) multilayer have attracted much interest because of its peculiar oscillation behavior of superconducting transition temperature (T_c) as a function of ferromagnetic layer thickness (d_F). First experimental observation of T_c-oscillation was reported for Nb/Gd multilayers [1], where the oscillation behavior has been considered as caused by the π-phase forming as predicted theoretically by Radović et al. [2]. The similar oscillation behavior has been found in Nb/Fe bilayer [3], where the π-phase geometry is impossible. In this case the oscillation behavior has been considered to be due to the magnetic origin. Until now there have been several experimental studies of T_c oscillation or T_c anomaly but no clear confirmation concerning the phase factor has been obtained yet. Because the oscillation phenomena are still a matter of theoretical controversy concerning whether it originates from the appearance of π-phase or from the 0-phase of the superconducting order parameter. Theoretical possibility of T_c oscillation has first be proposed by Radović et al. [2] and recently Tagirov [4] developed the theory including the interface transparency. According to their theory 0-phase and π-phase takes a different ground state, which can be experimentally confirmed by the difference of oscillation form between both phases. The 0-phase has T_c minimum and while π-phase has T_c maximum at nearly the same thickness of d_F. In order to expose the T_c difference between 0-phase and π-phase it is necessary to prepare the samples with layering sequences including only one and at least two Nb layers [5,6]. The purpose of this paper is to find the difference of T_c oscillation between 0-phase and π-phase.

2. Experimental

Multilayers forming 0- and π-phase are realized by preparing Co($x/2$ nm)/Nb(30 nm)/Co($x/2$ nm) tri-layers and Co($x/2$ nm)/Nb(30 nm)/Co(x nm)/Nb(30 nm)/Co($x/2$ nm) penta-layers, where x changes from 0.8 to 5 nm. The thickness of Co-edge layer is taken as $x/2$ so as to satisfy the boundary condition. These multilayers have been synthesized by the RF-

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0304-8853/$ - see front matter
doi:10.1016/j.jmmm.2003.12.644

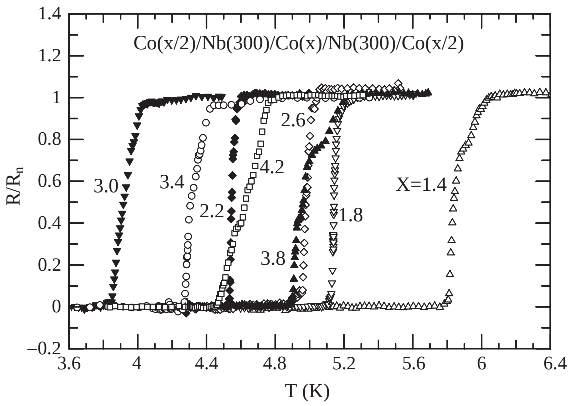

Fig. 1. Normalized resistivity vs. temperature for one of the present penta-layer series. x denotes d_{Co}.

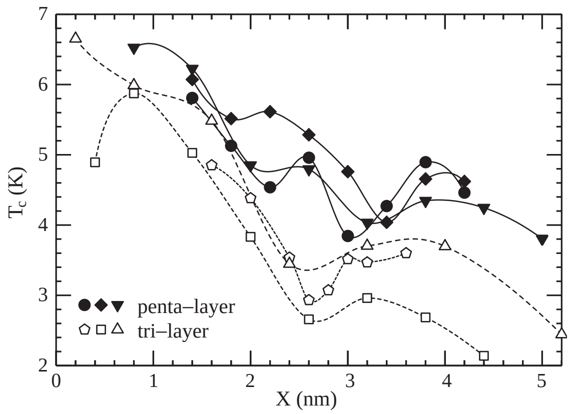

Fig. 2. T_c vs. d_{Co} (x) for present tri-layer (open symbols) and penta-layer (closed symbols) series.

sputtering techniques. Multilayer formation has been confirmed by low angle X-ray diffraction. T_c measurements have been performed by a four-terminal electrical resistance method. T_c is decided as the middle point between 10% and 90% change in resistivity.

3. Results and discussion

Fig. 1 shows the electrical resistivity R/R_n (where R_n is a resistance just above T_c) versus temperature curves for one of the present penta-layers. The superconducting transition occurs within the range of 0.1 K between 10% and 90% change of R/R_n except for $x = 3.8$ and 4.2 nm, showing the good quality for almost all the samples.

Fig. 2 shows the transition temperature T_c as a function of d_{Co} (x). In this figure the six different curves for three of penta-layer series and other three of tri-layer series are shown, where the same symbols are given for the samples sputtered by the same run. The three different curves for tri-layer and penta-layer series are slightly scattered. Despite the scattered behavior, the different tendency between tri-layer series and penta-layer one is clear. The tri-layer series take a local broad minimum in T_c around $x \sim 2.6$ nm, while at around the same position the penta-layer series take a local maximum. This different behavior is a clear evidence of the difference in the T_c oscillation in 0-phase and π-phase. As mentioned above, theory predicted the occurrence of the T_c oscillation for the S/F multilayers irrespective of 0-phase or π-phase. Under a proper condition, T_c of 0-phase multilayer can take a re-entrant behavior at certain d_F where π-phase takes a local maximum. Present behavior just confirms the theory except for the re-entrant behavior. The missing of the re-entrant behavior of present tri-layers may be caused by the low interface transparency for the pair wave function and/or the interface roughness. The present results are the first finding of T_c oscillation behavior in multilayer, which distinguishes the 0-phase and π-phase.

Acknowledgements

We thank Prof. L.R.Tagirov for valuable discussions and suggestions.

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