ELECTROMAGNETIC INTERACTION OF ELECTRODEPOSITED NICKEL NANOWIRES WITH A NIOBIUM THIN FILM

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In this paper we present superconducting properties of a Nb thin film deposited on an array of ferromagnetic (Ni) nanowires embedded in a porous template. By investigating the $T_c(H)$ phase boundary and by measuring $V(I)$ characteristics and critical currents as a function of the applied magnetic field, we find that the Nb film exhibits properties similar to those of a network of one-dimensional superconducting nanowires. We attribute this behavior to the stray fields of the magnetic dipoles, which create an almost regular lattice of normal regions in the superconductor, ultimately changing its topology.

1. Introduction

Arrays of ferromagnetic nanowires (NWs) embedded in porous self-assembled templates received a considerable interest, due to the possibility to prepare in these structures regular magnetic arrays with characteristic dimensions, *i.e.* diameter of the wires and nearest neighbor distance, in the nanometer range. Self-assembled methods are versatile and reliable techniques, which allow one to fabricate low-cost patterns of nanostructures on very large surfaces with a high degree of reproducibility. Recently, these systems were used in conjunction with superconducting films in order to create periodic magnetic pinning centers and study matching effects between the artificial non-superconducting regular structure and the vortex lattice [1]. The system behaves like a superconducting wire network when the superconducting coherence length ξ is of the same order as the width of the channels between the holes w.

Here we present superconducting properties of a 30 nm thick niobium (Nb) film sputtered on a dense array of nickel (Ni) nanowires grown in a nanoporous Si template. Nb is separated from the magnetic dipoles by an insulating Al_2O_3 layer to obtain an F/I/S hybrid.

2. Experimental

Monocrystalline silicon wafers with (100) orientation and 0.01 Ω×cm resistivity were used as the substrates for porous silicon (PS) formation. The electrochemical anodization process provided the formation of an uniform PS layer 10 µm thick with 72 % of porosity and pore diameter of ≈100 nm [2]. After the formation of PS, the sample were washed in deionized water. Ni was electrochemically deposited into the PS matrix from aqueous $NiSO_4$ based electrolyte at the current density of 3.5 mA/cm^2. After that a thin insulating layer of Al_2O_3 (8 nm) was sputtered in vacuum chamber. Then Nb thin film was deposited in the same sputtering system. The sample under investigation is a Nb film of thickness $d = 30$ nm (sample W). Due to the presence of the Al_2O_3 insulating buffer layer between the superconductor (Nb) and the PS filled with the Ni nanopillars, the system under study is a F/I/S hybrid. In this way, the proximity effect and exchange of electrons are completely avoided and the interaction between the superconducting and the ferromagnetic systems is totally electromagnetic. A reference sample (sample F) was also fabricated and analyzed. It was formed by depositing a continuous 1 µm thick Ni layer onto PS template. Subsequently, Al_2O_3 and Nb layers were grown exactly as described previously.

Superconducting electric transport properties of the samples were measured in a ^{4}He cryostat using a standard DC four-probe technique. The superconducting transition temperature in the absence of applied field has been taken as the temperature at which the resistance drops 50 % of the normal state resistance (R_N). It was $T_{c0} = 5.0$ and 5.5 K for the samples W and F, respectively. $V(I)$ characteristics were recorded using a pulsed technique [3]. Before starting the measurements, the Ni NWs were first magnetized at low temperatures in a perpendicular magnetic field of 1 T which is far above the saturation field of Ni NWs.

3. Results and discussion

Fig. 1a shows the $T_c(H)$ phase diagram constructed from the measured resistive transitions in various perpendicular magnetic fields for the sample W. The three curves have been obtained using different resistive transition criteria of the normal state resistance, namely 10 %, 50 %, and 90 % of R_N. The phase boundary shows a pronounced anomaly in the field range of 0.19–0.23 T where the critical temperature apparently increases with respect to what is conventionally expected almost reaching T_{c0}.

The bump is also present at higher fields, in the range of 0.53–0.64 T, though with a lower amplitude. Furthermore, the amplitude of the two bumps decreases when a higher resistance criterion is adopted, consistently with previous observations in similar systems [4]. In particular, the anomaly present at higher fields is smeared out when the criterion of 90 % of R_N is adopted (open circles in Fig. 1a). A selection of the $R(T)$ curves in different fields is shown in Fig. 1b. In Fig. 1c the phase boundary of the reference sample F, constructed with the criterion of 50 % of R_N, is compared with the one of the sample W, obtained using the same resistive criterion. We see that the curve is smooth and does not show any anomalous feature.

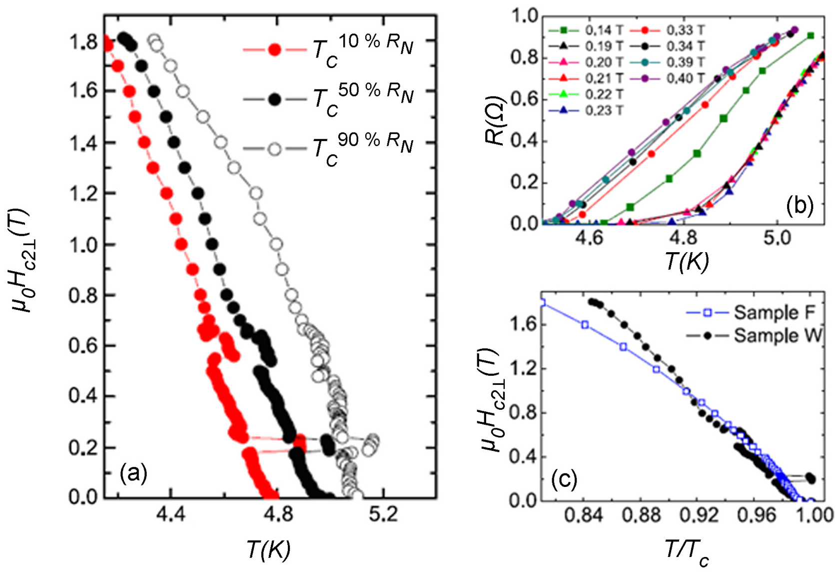

Figure 1. (a) $T_c(H)$ phase diagrams of the sample W obtained with resistive criteria of 10 %, 50 %, and 90 % of R_N. (b) Resistive transitions of the sample W for a selection of applied magnetic fields. The curves from 0.19–0.23 T (at 0.14 T and from 0.33–0.40 T) are representative of the temperature dependence of the resistance at the magnetic fields where the bump is (is not) present in the phase diagram. (c) *H*-*T* phase diagrams of the samples W and F, both obtained with the 50 % of R_N criterion.

By combining magnetoresistance and $V(I)$ measurements, we establish that the matching effects observed in the Nb film are caused by the Little-Parks effect more than by the vortex pinning, in agreement with theoretical predictions [5]. Therefore, the system behaves like a one-dimensional (1D) superconducting wire network where the confinement of the Cooper pairs is not caused by geometrical constrictions, but rather by the stray fields of the magnetic dipoles that modify the topology of the plain film creating regions where the superconductivity is strongly depressed. Due to the values of the parameters ξ and w, the wire network behavior is presented at relatively low temperatures and high magnetic fields.

4. Conclusion

Porous Si templates have been used to host a dense array of electrodeposited Ni NWs that electromagnetically interact with a Nb thin film through the intermediate Al_2O_3 layer to form an F/I/S hybrid. The analyzed F/I/S system, even though not very highly ordered, can be conveniently used to obtain a network of 1D superconducting NWs in the presence of a magnetic array, with the advantage of depositing the superconducting film on a smooth buffer layer instead of an irregular porous template.

Acknowledgments

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