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Tuning the critical current in nanoscale superconductor-ferromagnet multilayers

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ABSTRACT

Technological applications of type-II superconductors crucially depend on the value of the critical current I_c, which is determined by the pinning of vortices. Enhancement of pinning in such materials remains to be one of the major goals in developing novel superconducting materials.

In the past, the pinning enhancement in conventional superconductors was done through manufacturing samples with microscopic defects. Several new approaches have been developed in recent years. They include macroscopic tuning the pinning potential, e.g., by modulating the thickness of a superconducting film, manufacturing films with micrometer-scale holes, or putting magnetic particles on the surface of superconducting layers.

All the above techniques are based upon introducing defects suppressing superconductivity. In this approach, the pinning arises due to the tendency of the vortex normal core to match with the region where the superconductivity is suppressed.

Bulaevskii et al. [1] proposed to enhance the I_c value of superconducting layers by pinning magnetic fluxes of superconducting vortices in the nearby ferromagnetic films, rather than their cores inside the superconducting films. Notice that magnetic pinning, different from the conventional one introduced by non-magnetic defects, has no temperature limitation since it does not weaken with increasing temperature. Hence, this way is very perspective for superconducting materials science.

Our experiments on NbN - NiCu heterostructures suggest the possibility to tune the critical current in superconducting (NbN) layers proximitized to ferromagnetic (NiCu) films.

1. Bulaevskii L.N., Chudnovsky E.M., Maley M.P. *Appl. Phys. Lett.* - 2000. - **76**, N 18. P. 2594-2596.

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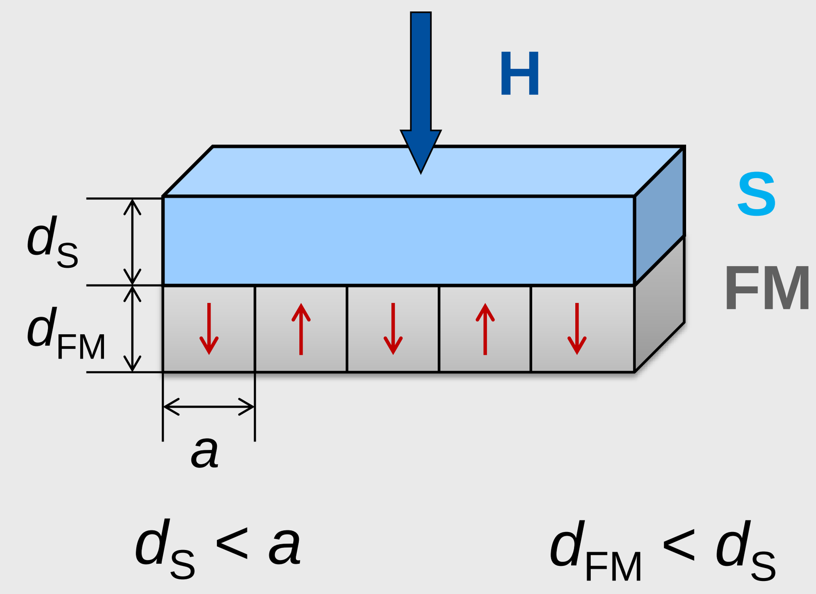
BASIC IDEA

Magnetic pinning can be implemented in multilayer structures based on superconducting and magnetic films superimposed on each other. The ferromagnetic films should have a strong perpendicular magnetic anisotropy and coercitivity. In the external magnetic field **H**, perpendicular to the films plane, the domain structure is emerging which 'pins' the vortices in the proximitized superconductor.



The periodic potential of pinning $U_{MP}(x) \approx \Phi_0 M(x) d_S$ $\quad M(x) = \pm M_0$ $\quad H_m = 4\pi M_0$

EXPERIMENTAL RESULTS

In this work, we have applied NbN as a superconductor with a weak 50 nm thick F alloy $Ni_{0.45}Cu_{0.55}$. The deposition temperature of the NbN films was 600 ºC, and that of the NiCu ferromagnetic layers was about 200 ºC.

Five types of the heterostructures on a sapphire substrate were fabricated:

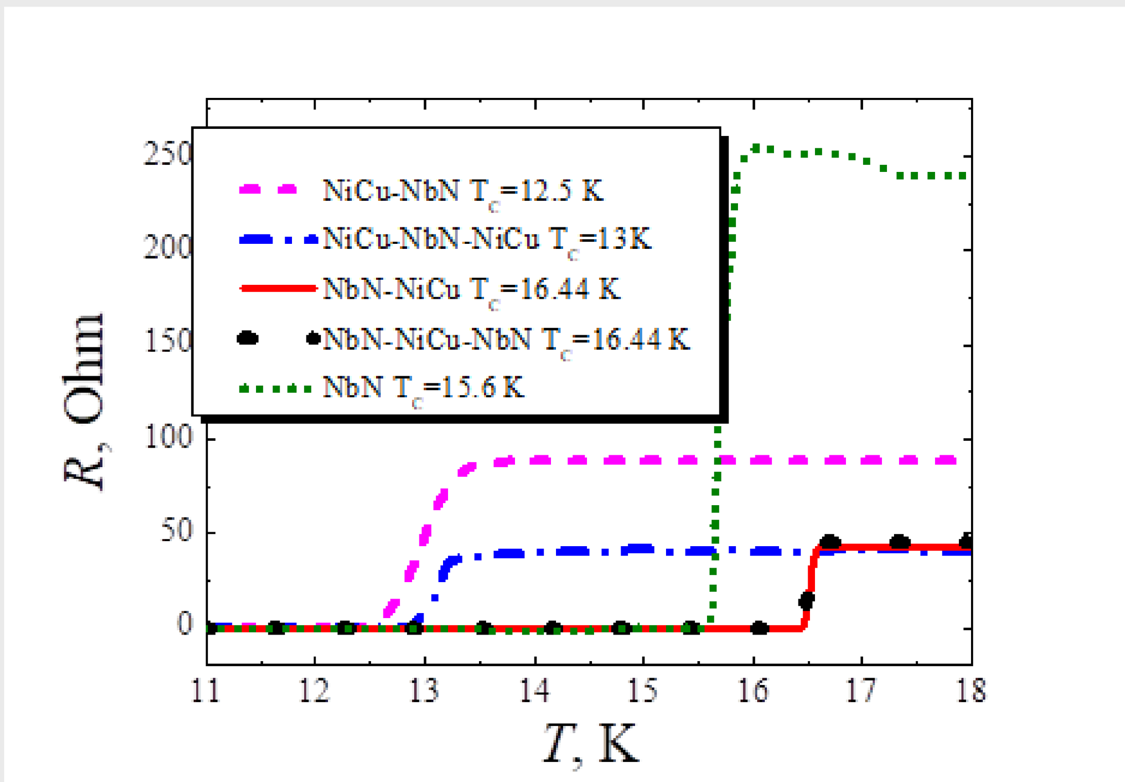
(1) NbN films with a critical temperature T_C = 15 - 16 K;

(2) superconducting NbN films coated with a NiCu layer with T_C slightly above 16 K;

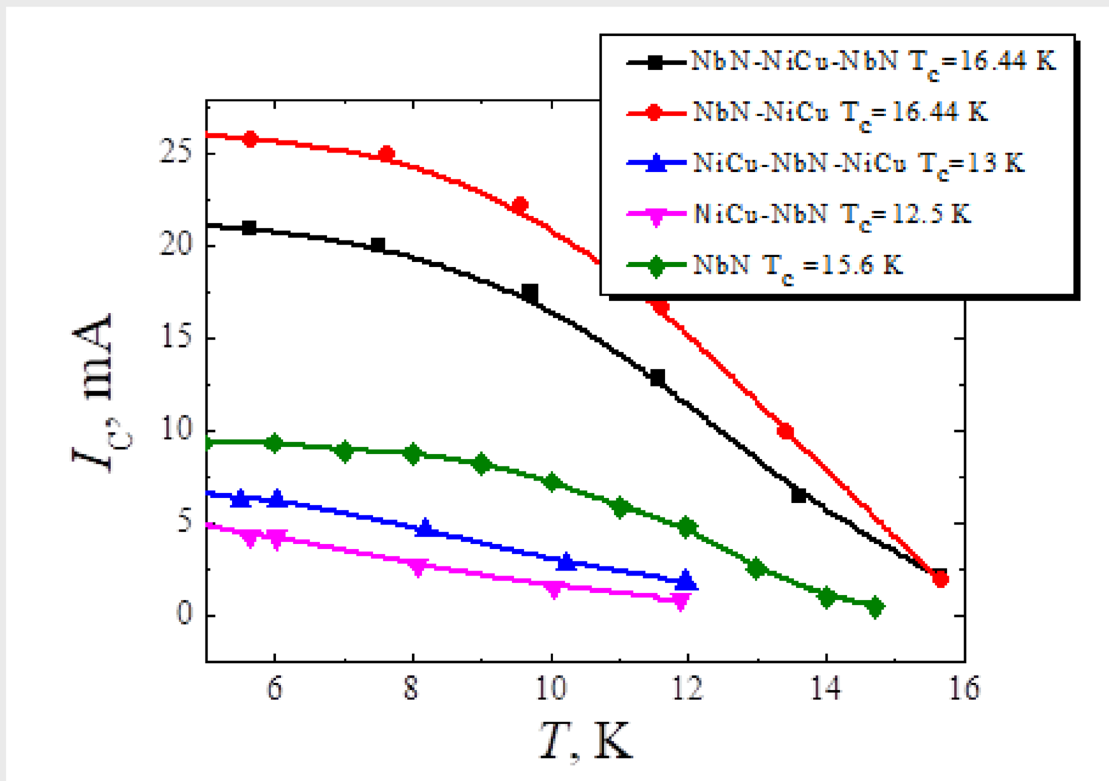
(3) NbN/NiCu/NbN trilayers with a critical temperature T_C of approximately 16 K;

(4) weak ferromagnet NiCu layers coated with superconducting NbN films, T_C about 13 K;

(5) NiCu/NbN/NiCu "sandwiches" with T_C = 12 - 13 K.



Temperature effect on the resistance of the heterostructures studied. The data indicate a near-surface degradation of NbN films whose critical temperature increases even after coating with NiCu ferromagnetic films. However, a relatively small positive effect of the coating disappears in the presence of another (lower) NiCu film. It leads to a decrease in T_C compared to samples without such a layer.



The measured values of the critical currents for the five types of heterostructures exhibiting the trend expected for systems with the magnetic pinning effect. The I_C values for two-layer NbN/NiCu structures were the highest, and the increase in I_C significantly exceeded the increase in T_C in comparison with a NbN film. The lowest I_C values were for NiCu/NbN/NiCu trilayers and NiCu/NbN bilayers.

CONCLUSIONS

We have tested a new type of the magnetic pinning effect. In this approach, the magnetic flux is captured due to its interaction with the domain structure in the ferromagnetic layer in magnetic fields smaller than the coercive field (unlike ordinary defects playing the role of non-magnetic centers capturing the Abrikosov vortices).

These experimental results clearly indicate in favor of the implementation of the magnetic pinning in the structures, where the presence of magnetic coating increased the critical current density, despite some suppression of superconductivity, as evidenced by the decrease in the critical temperature of the superconducting junction.

The obtained results are an important step towards creation of new type-II superconducting materials with high critical currents for needs of applied superconductivity.