Superconducting properties of fractal Nb/Cu multilayers

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Multilayers of Nb and Cu with a fractal or periodic stacking sequence were prepared by electron-beam evaporation onto sapphire substrates. Their superconductivity was investigated by measurements of T_c and the temperature and angular dependence of the upper critical field B_{c2}. For low temperatures $T \ll T_c$, all samples show the characteristic behavior of two-dimensional superconductivity independent of the stacking sequence, whereas for temperatures near T_c the type of layering determines the effective dimensionality, resulting in a ''multicrossover'' behavior in fractal samples.

I. INTRODUCTION

The possibility of new mechanisms of superconductivity in layered materials[1] and the recent advances in deposition techniques have led to the intensive study of artificial modulated structures.[2] In addition, these investigations were motivated by the search for superconducting systems with a higher transition temperature T_c and new superconductive phenomena. These studies have become particularly important after high-T_c superconductivity was discovered in layered metal-oxide compounds. Experimental studies on artificial superconducting multilayers (SM) have mainly focused on the dependence of T_c on the modulation period Λ of the SM,[3–6,8] on the effects of dimensionality, e.g., the so-called dimensional crossover,[9] and on vortex motion and vortex dynamics.[10]

The possibility of using artificial SM for obtaining new superconducting materials was illustrated by PbTe/PbS multilayers[5] with a critical temperature $T_c = 5.5$ K, which were composed of individually nonsuperconducting layers of the semiconductors PbTe and PbS (with an electron concentration of $\sim 10^{19}$ cm^{-3}). Another example for dimensional effects in SM is the oscillatory dependence of T_c on the thickness of the superconducting layer and of a number of kinetic characteristics on the compositional modulation period Λ in Mo/Si multilayers.[6]

SM can be composed of either superconductor–insulator (or semiconductor) layers which are coupled by the Josephson effect (S/I type), or superconductor–normal-metal layers coupled by the proximity effect (S/N type). Of course, a superconductor with a much lower T_c can play the role of the normal metal in the S/N type SM.

Because of the strong temperature dependence of the superconducting Ginzburg-Landau coherence length $\xi(T) = \xi(0)/\sqrt{1-T/T_c}$, a dimensional crossover can occur as a function of temperature T. Near T_c the perpendicular coherence length $\xi_\perp$ is large, $\xi_\perp(T) \gg \Lambda$, and superconductivity extends over many layers. In this region a three-dimensional (3D) anisotropic behavior with a linear temperature dependence of the parallel critical field is observed:[7]

$$B_{c2\parallel}(T) = \phi_0 / 2\pi \xi_\parallel(T) \xi_\perp(T) \sim (1 - T/T_c). \tag{1}$$

Below a crossover temperature $T_{cr} < T_c$ where $\xi_\perp(T)$ becomes comparable to the SM period Λ, the behavior becomes two-dimensional (2D) with[7]

$$B_{c2\parallel}(T) = \phi_0 / \sqrt{2}\pi \Lambda \xi_\parallel(T) \sim (1 - T/T_c)^{1/2}. \tag{2}$$

Such a dimensional crossover has been observed in the temperature dependence $B_{c2\parallel}(T)$ and in the angular dependence $B_{c2}(\theta)$ in both types of SM, i.e., in the S/I type [Mo/Si,[6] Nb/Ge,[11] Pb/C (Ref. 12)] and S/N type [Nb/Cu,[13] V/Cu,[14] Nb/Ta (Ref. 15)].

At temperatures $T > T_c$ the dimensional crossover can also be observed in the T dependence of the fluctuation conductivity $\sigma'(T)$. A change from 3D- to 2D-like behavior of $\sigma'(T)$ with increasing T has been measured in Nb/Si (Ref. 16) and V/Cu.[17] The dimensional crossover was also observed in the fluctuation conductivity $\sigma'(T)$ of $YBa_2Cu_3O_x$ single crystals[18] and in the $B_{c2\parallel}(T)$ and $B_{c2\parallel}(\theta)$ dependences of $Bi_2Sr_2CaCu_2O_x$ single crystals.[19]

In a simple periodic SM there is only one characteristic geometric length scale, the modulation period Λ. However, it is possible to prepare multilayers with several different geometric length scales, i.e., one-dimensional quasiperiodic structures[20] and self-similar or fractal geometries.[21] In these systems the temperature-dependent ratio of $\xi_\perp$ to the different geometric length scales may lead to new physical phenomena. The motivation to study such geometries stems in part from the numerous examples of fractal structures that exist in nature, and also because of their relation to inhomogeneous materials—percolative thin films, ceramics, and networks. A particularly nice example are two-dimensional superconducting fractal networks like Sierpinski gaskets, where the fractal structure is directly reflected in the (B,T) phase-transition line.[22]

In this paper we present the results of our investigation of the superconducting properties of Nb/Cu multilayers with a fractal stacking sequence, in particular the behavior of T_c and B_{c2}, extending the previous work on fractal Nb/Cu multilayers, where a preliminary report of some B_{c2} data was already given.[23] However, for practical reasons one is limited to only a few self-similar length scales. Nevertheless, fractal features can be clearly identified.

