NEGATIVE MAGNETORESISTANCE OF LAYERED HIGH-T_c COMPOUNDS

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(*Received July 8, 1999*)

Magnetoresistance of layered high-T_c systems with *quasi*-two-dimensional superconductivity in magnetic field H applied parallel to superconducting planes was investigated theoretically. In such configuration an increase in the magnetic field intensity decreases the critical temperature of superconducting regions. It causes both a suppression of the gap parameter Δ and an increase in the tunneling current between the decoupled superconducting planes and, as a consequence, leads to negative magnetoresistance. The dependence of tunneling current on H was calculated for superconducting layer thickness d_S smaller than the superconducting correlation length. The results can be used for analysis of current–voltage characteristics of both superconductor–insulator–superconductor and superconductor–insulator–normal metal multilayered tunnel structures.

PACS numbers: 74.72.Jt, 74.80.Dm

1. Introduction

It is known that the new highly anisotropic layered high-T_c superconductors (HTS) with weak enough Josephson coupling between the layers display two- or *quasi*-two-dimensional superconductivity [1]. The electrodynamics of these compounds, and transport properties in particular, are now intensively studied, both experimentally and theoretically.

There is considerable interest in the study of layered superconductors in magnetic fields applied parallel to layers. In high magnetic fields in these materials, first-order phase transitions take place between the lattices of the Josephson vortices having different lattice periods $L = 2ks$ in the direction perpendicular to the layers ($k = 1, 2, \ldots$, and s is the interlayer distance) [2]. These jumps in the vortex structure are caused by the layered crystal structure in the presence of interlayer Josephson interactions. The above property of vortex lattice together with the effect of superconductivity suppresion by magnetic field leads to a non-monotonous (jump-like) dependence of the superconducting transition temperature T_c on magnetic field H value [3].

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In the two-dimensional regime the interlayer conductivity is of tunneling origin. It is due to this fact that HTS crystals can exhibit negative magnetoresistance in magnetic fields applied parallel to layers. Such effect was observed in granular superconducting films exhibiting tunneling intergrain conductivity [4]. It was also found experimentally in $NdBa_2Cu_3O_{6+x}$ ceramics at the edge of the superconducting region [5] and in HTS monocrystals at temperatures higher than T_c [6]. The authors of Ref. [6] observed also that the c-axis resistivity below T_c of Bi2212 crystals attains a maximum and then decreases in higher fields.

2. Magnetoresistance

We investigated the magnetoresistance (MR) of layered superconducting systems in magnetic field applied parallel to layers. We consider the HTS crystal as a set of alternating superconducting (S) and insulating (I) layers with thickness d_S and d_I, respectively. In this model the negative MR can be explained very simply. The conductivity in the direction perpendicular to the decoupled layers is determined by the quasiparticle tunneling current (TC). The TC value depends on the S gap parameter Δ, which is proportional to T_c. The decrease in T_c value due to applied magnetic field causes both a suppression of S gap parameter and an increase in the number of normal charge carriers and, consequently, leads to negative MR.

To estimate the effect numerically we used the results of T_c calculations for small specimens [7]:

$$t(H) = \frac{T_c(H)}{T_c(0)} = \exp\left[\frac{1}{\alpha}(1-\eta^{-1})\right]. \tag{1}$$

Here α is the coupling constant, η depends both on sample parameters and on external field value H:

$$\eta^{1/2}(H, d_S) = \frac{1}{\sqrt{h}}F(\sqrt{h}), \quad h = Hd_S^2/\Phi_0, \tag{2}$$

Φ_0 is the flux quantum, $F(x) = \mathrm{e}^{-x^2}\int_0^x \mathrm{e}^{y^2}\mathrm{d}y$ is the Dawson integral [8]. The conductivity is determined by the quasiparticle tunneling current J_t, which depends on the S gap parameter Δ. In the low temperature limit $T \ll T_c$ of the BCS theory Δ is [9]:

$$\Delta(H,T) = \Delta(H,0)\left\{1 - 2\pi\sqrt{\frac{T}{\Delta(H,0)}}\exp\left[-\frac{\Delta(H,0)}{T}\right]\right\}, \tag{3}$$

$$\Delta(H,0) = 1,76t(H),$$

Δ and T are measured in $k_B T_c(0)$ and $T_c(0)$ units, respectively.

Let us consider two cases. The first one corresponds to a symmetric S–I–S tunnel junction. The TC of such junction is [10]:

$$J_t \propto 2\exp\left[-\frac{\Delta(H,T)}{T}\right]\sqrt{\frac{2\Delta(H,T)}{eV+2\Delta(H,T)}}\,[eV+\Delta(H,T)] \times \sinh\left(\frac{eV}{2T}\right)K_0\left(\frac{eV}{2T}\right), \quad 0 < eV < 2\Delta(H,T), \tag{4}$$

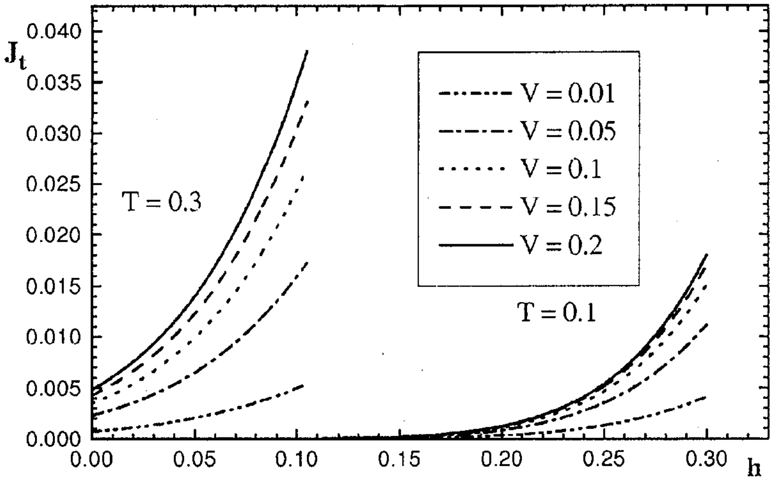

Fig. 1. Magnetic field dependence of tunneling current J_t through S–I–S junction at different temperatures T and voltages V. Magnetic field is scaled to d_S^2/Φ_0, temperature normalized to T_c, and both current and voltage are expressed in units of $k_B\Delta(0)$.

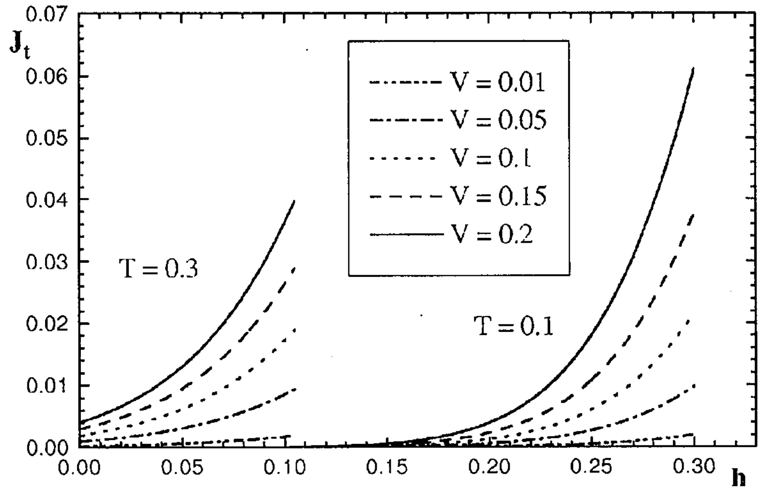

Fig. 2. Magnetic field dependence of tunneling current J_t through S–I–N junction at different temperatures T and voltages V. The units are as in Fig. 1.

where $K_0(x)$ is the McDonald function, and J_t and eV are also measured in $k_B T_c(0)$ units. In Fig. 1 the calculated magnetic field dependence of J_t value is presented for different temperature T and voltage V values (we used the coupling constant value from [3]: $\alpha = 0.3$).

The second case corresponds to the S–I–N junction. The TC in this case can be expressed as [10]:

$$J_t \propto 2\Delta(H,T) \sum_{m=1}^{\infty} (-1)^{m+1} \sinh\left(m\frac{eV}{T}\right) K_1\left[m\frac{\Delta(H,T)}{T}\right], \tag{5}$$

$$0 < eV < \Delta(H,T)$$

($K_1(x)$ is the McDonald function). The field dependence of J_t for S–I–N junction is presented in Fig. 2 for the same parameters as in Fig. 1.

One can see that an increase in magnetic field leads to a decrease in the junction resistance (as shown by the increase in tunneling current J_t). Let us notice that the J_t values of S–I–S and S–I–N junctions become equal in higher temperatures T.

3. Conclusions

It should be noted in conclusion that the role of the layered structure in the formation of properties of superconducting systems has a number of additional aspects. Advances in technology have made it possible to synthesize artificially high-quality multilayered tunneling structures and to simulate some properties of HTS systems experimentally on the macroscopic scale. In a strong magnetic field such systems must inevitably exhibit the suppression of superconductivity by magnetic field parallel to the layers.

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