Effect of magnetoresistance sign change in superconducting films

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Abstract

Resistive characteristics of pin-free superconductors with an edge barrier are studied. A model system representing an infinitely long strip of finite width W and thickness $d \ll W$ is employed. The numerical solution of the Maxwell-London equation derived in the hydrodynamic approach makes it possible to calculate both the voltage-current characteristics and magnetoresistance (MR) $R(H)$. It is revealed that positive MR behavior($dR/dH > 0$) actual within sufficiently low current range $I < I^*$ (I^* being the crossover current), changes the sign : $dR/dH < 0$ at $I > I^*$. This is due to asymmetry of the vortex distribution generated by the external magnetic field.

Key words: superconducting film, magnetoresistance

Studying of magnetic and transport properties of low-dimensional superconductors in recent years draws intensive attention of both experimentalists and theorists. The interplay between the surface and bulk contribution to the current-voltage characteristics was theoretically investigated in [1]. To present time equilibrium magnetic characteristics of low-dimensional superconductors with edge barrier are rather well investigated [2-5]; however, resistive characteristics of these systems are still studied insufficiently. In this report the voltage-current characteristics of pin-free superconductors with an edge barrier are studied theoretically. The effect of magnetoresistance sign change (MRSC) in wide superconducting films is predicted, physical mechanism responsible for existence of the MRSC effect is revealed.

For calculations the model system representing an infinitely long strip of finite width $W(|X| \leq W/2)$ and thickness d ($W \gg \lambda > d$; λ - London length) was employed. While the total current I is lower than critical one, I_c, the film is in the Meissner state. When current exceeds I_c, magnetic field H penetrates into the film by means of Pearl-Abrikosov vortices carrying the flux quantum φ_0. The dynamics of the vortex ensemble within the hydrodynamic approach [6], is described by the generalized London equation

$$4\pi \frac{\lambda_{eff} d}{cW} \frac{dj(x)}{dx} + 2\frac{d}{c} \int_{-1}^{1} \frac{j(x')dx'}{x'-x} = H - n\varphi_0, \qquad (1)$$

where $x = 2X/W$, and $\lambda_{eff} = 2\lambda^2/d$, supplemented by the continuity equation for the vortex density $n(x)$

$$n\varphi_0 = \frac{\eta E}{j(x)\varphi_0} sign(x - x_0). \qquad (2)$$

Here η is the vortex viscosity coefficient, and E is the intensity of an induced electrical field. Equations (1),(2) are closed by introducing the London-like relation between non-dimensional vector potential A and current density $j(x)$

$$j(x) = -\frac{cA_c}{2\lambda^2} A(x)(1 - A^2(x)), \qquad (3)$$

which is obtained within the framework of the Ginzburg-Landau theory; here vector potential is expressed in units of $A_c = \varphi_0/(2\pi\xi)$ with ξ being the coherence length. Supplementary boundary conditions at the sample edges $X = \pm W/2$

$$A(\pm 1) = A_s \equiv A(j_s) \qquad (4)$$

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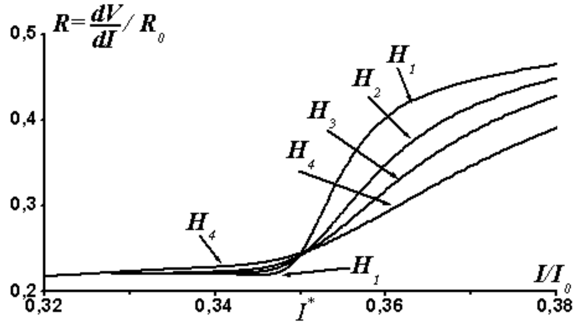

Fig. 1. Differential resistance of a film $R(I)$, at different values of external magnetic field $H < 0.5H_s$ ($H_1 < H_2 < H_3 < H_4$); I and R are expressed in terms of the units $I_0 = \frac{\varphi_0 c}{8\pi^2\xi}$ and $R_0 = \frac{8\pi^2\xi^2}{\eta c}$.

are to be applied, where A_s is expressed from (3) through edge-barrier-suppression current density j_s.

Numerical solution of the equations (1)- (3) with the help of conditions (4) allows one to describe distribution of the current density $j(x)$ for different values of an external magnetic field H ($H < 0.5H_s$, H_s being the edge-barrier suppression field ; given condition provides transition to the resistive state directly from the Meissner one [7, 8]), and also fixed total current I .

We should emphasize that in our theory an arbitrary value of the over-criticality $\triangle I = I - I_c$ may be considered. Numerical calculations show that in the presence of an external field ($H \neq 0$) the distribution $j(x)$ acquires an asymmetric shape. At critical current $I = I_c$, the quantity j reaches value j_s, corresponding to the vortex-entry-barrier suppression at the right edge only. Therefore, vortices enter the sample only at the right edge, and under the action of a transport current, move to the left-hand edge of the film, finally escaping from the sample. At further increase of a current I, current density j eventually reaches value j_s at the left-hand edge, as well. From here vortices of opposite polarity (anti-vortices) start to enter the film, eventually annihilating with the vortices at the annihilation line $x = x_0$, located at some distance from the film edges. At greatest possible current I_{max} current density inside annihilation zone reaches value j_s, which results in a sharp transition to the normal state [6].

On the basis of our method the voltage-current characteristics (VCC) of thin superconducting film are obtained. Numerical differentiation of the VCC allows one to calculate differential resistance of a film $R(I)$ (see fig.1). Three typical sections may be distinguished in the diagram $R(I)$. At current I slightly exceeding I_c the almost linear increase of the resistance R is characterized by a positive magnetoresistance: $dR/dH > 0$ (at a fixed current).

With the increase of current I a strongly nonlinear transition region ($I \approx I^*$) appears where the crossover takes place, beyond which ($I > I^*$) magnetoresistance (MR) changes sign. Note that the first indication on the existence of the MRSC effect in narrow superconducting bridges was claimed by Maksimova *et al* in [9]. In the work [9], however, the MR was studied practically at negligible over-criticality. Here we confirm the presence of negative MR in a sufficiently wide range of the over-criticality parameter (OP) ; $\triangle I < \triangle I^*$; moreover, the effect of the MR sign change (from negative to positive) is predicted in a process of the OP increase.

The predicted effect may be explained on the basis of the following reasoning's. At low transport current the basic role in energy dissipation is related to the transport losses which are due to the vortex flow from the right film edge to the left one. In a process of the current I increase, when antivortices start entering from the left edge, the additional annihilation losses contribute to the transport losses. The former are caused by the energy release during annihilation of the vortex-antivortex pairs occurring at the annihilation line $x = x_0$.

Thorough analysis reveals that for $I > I^*$ the annihilation line shifts sharply from the left-hand edge of a film to a distance of the order 2λ. As a result the replacement of energy dissipation mechanism (from the ballistic-like to the annihilation one) takes place with the current I increase. It is obvious, that intensity of the annihilation losses is controlled mainly by the antivortex density $n_a(x)$ in a film. The analysis of the vortex density distribution $n(x)$ obtained by solving equations (1)-(4), shows that antivortex density (at fixed current $I > I^*$) decreases with the increase of an external magnetic field. Hence, while transport losses dominate over the annihilation losses, a positive magnetoresistance should be observed; otherwise, a sign change of the film magnetoresistance ($dR/dH < 0$) takes place with the increase of transport current I.

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