Penetration of an external magnetic field into a multistrip superconductor/soft-magnet heterostructure

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Abstract

The magnetization of a planar heterostructure of periodically alternating type-II superconductor and soft-magnet strips exposed to a transverse external magnetic field is studied. An integral equation governing the sheet current distribution in the Meissner state of the superconductor constituents is derived. The field of complete penetration of magnetic flux in the critical state of the superconductor constituents is calculated for different widths of the superconductor and the soft-magnet constituents and a range of values of the relative permeability of the soft-magnet constituents.

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Heterostructures made up of superconductor (SC) and soft-magnet (SM) constituents are being studied extensively because of their potential for improving the performance of SCs. The use of SMs for such structures offers the possibility to alter the pinning of magnetic vortices in the SC constituents through easy tuning of the intrinsic magnetic moment of the SM constituents [1,2]. Furthermore, the large permeability of SMs allows to improve the critical parameters of SC wires and strips by shielding the transport current self-induced magnetic field as well as an externally imposed magnetic field [3–8]. As is known from previous work, the critical current of a periodic structure of SC strips separated by slits is markedly enhanced compared with that of an isolated SC strip [9]. Here, therefore, we study how filling the slits with SM strips controls the penetration of magnetic flux into such a heterostructure.

To this end, we consider a periodic array of infinitely extended type-II SC and SM strips of respective widths $w_S$ and $w_M$, i.e. period $w = w_S + w_M$, and thickness $d$, oriented parallel to the $x$-$y$-plane of a cartesian coordinate system $x,y,z$ and exposed to a transverse external magnetic field $H_0$, as shown in Fig. 1. The SC constituents shall be devoid of magnetic flux penetrated from their infinitely far ends; the SM constituents shall be fully described by the relative permeability $\mu$. Assuming, in addition, $d/w \ll 1$, variations of the current over the thickness of the SC strips may be ignored and, up to an error of order $d/w$, the state of these strips characterized by the sheet current $J$ alone.

The magnetic field $H$ created by an arbitrary sheet current distribution in the heterostructure under consideration is conveniently decomposed according to $H = H_S + H_M$, where $H_S$ stands for the magnetic field created by the SC strips in the absence of the SM constituents [10] and $H_M$ denotes a magnetic correction field induced by fictitious magnetic charges distributed over the surfaces of the SM constituents [11]. The requirement of vanishing of the $z$-component of the total magnetic field on the surfaces $z = \pm d/2$ of the SC constituents,

$$H_z(x) = H_0 + H_{S,z}(x) + H_{M,z}(x)$$
with
\[ H_{S_z}(x) = \frac{1}{2\mu_0 w} \int_{-w_s/2}^{w_s/2} d\xi J_1(\eta) \cot(\pi(\xi - x)/w) \]
and
\[ H_{M_z}(x) = -\frac{d}{\pi w^2} \left( \frac{q}{1 + q} \right) \int_{-w_m/2}^{w_m/2} d\xi [H_0 + H_{S_z}(\xi + w/2)] \]
\[ \times \sum_{n=0}^{\infty} q^n \left\{ \psi((w/2 + nw_m - (1)^n \xi - x)/w) \right. \]
\[ + \left. \psi(\psi(w/2 + nw_m - (1)^n \xi + x)/w) \right\}, \]
yields an integral equation which determines the sheet current distribution in the Meissner state. Here, \( \mu_0 \) means the permeability of free space and \( q = (\mu - 1)/(\mu + 1) \) signifies the strength of the image current induced by the SM constituents; \( \psi \) is the digamma function.

The field of complete penetration of magnetic flux, \( H_p \), corresponds to the transition of the SC constituents into the full critical state; it is found by setting \( H_z = 0 \) for \( x = 0 \) in conjunction with the sheet current distribution \( J(x) = -J_c \, \text{sgn} \, x \) which, in turn, is governed by the critical sheet current \( J_c \). Fig. 2 displays the calculated dependence of \( H_p \) on the relative width of the SM constituents using different values of \( d \) and \( \mu \). Evidently, due to the presence of even narrow SM strips, \( H_p \) slightly increases compared to the respective field \( H_p^0 \) for the case of a periodic array of isolated SC strips. A pronounced rise of \( H_p \) occurs when the width of the SM constituents grows relative to the width of the SC constituents; behaviour which can be explained by the fact that, owing to their high permeability, the SM strips attract part of the external magnetic flux so as to decrease the effective local magnetic field applied to the SC constituents. This redistribution of the field also occurs in a periodic array of isolated SM strips, where maximum reduction of the total magnetic field halfway between the strips, \( \Delta H_z = (H_0 d/\pi w)\psi((w - w_m)/2) \), is attained in the limit \( \mu \gg 1 \).

References