Magnetic-dipole induced appearance of vortices in a bilayered superconductor/soft-magnet heterostructure

S. V. Yampolskii†, G. I. Yampolskaya† and H. Rauh
Institut für Materialwissenschaft, Technische Universität Darmstadt, 64287 Darmstadt, Germany
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The penetration of the magnetic field of an infinitesimal magnetic dipole into a bilayered type-II superconductor/soft-magnet heterostructure is studied on the basis of the classical London approach. The critical values of the dipole moment for the first appearance of a single magnetic vortex and, respectively, a magnetic vortex-antivortex pair in the superconductor constituent are obtained, when the magnetic dipole faces the superconductor or the soft-magnet constituent. This reveals that the soft-magnet constituent inhibits penetration of vortices into the superconductor constituent, when the dipole faces the soft-magnet constituent.

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Heterostructures built from superconducting and magnetic materials have attracted much attention during the past few years. This is especially true of heterostructures involving planar superconductors (SCs) and ferromagnetic dots (FDs) which bring about an enhancement of vortex pinning and, concomitantly, an increase of the SC critical current and critical field. Soft-magnet (SM) constituents offer the possibility to greatly improve the performance of SCs by shielding the transport current self-induced magnetic field as well as an externally imposed magnetic field. Here, we study the penetration of the magnetic field of a magnetic dipole (MD) of zero extent (deemed to represent a small FD) into a bilayered SC/SM heterostructure, when the MD faces the SC or the SM constituent. Making recourse to the classical London approach, we compare the conditions for the first appearance of a single magnetic vortex and, respectively, a magnetic vortex-antivortex pair in the SC constituent.

Let us consider an infinitely extended heterostructure made up of a type-II SC layer with thickness $d_S$ and a SM layer with thickness $d_M$, and a nearby MD, its moment $\mathbf{m}$ being directed towards the heterostructure. The relative permeability, $\mu$, is assumed as the only material characteristic of the SM constituent, apart from the permeability of free space, $\mu_0$. The condition for the first vortex appearance follows from the Gibbs free energy of the SC/SM heterostructure due to the presence of a single vortex, $G_v$, which is the sum of the vortex self-energy and the MD-vortex interaction energy. Minimization of $G_v$ with respect to the MD-vortex spacing projected onto the SC/SM interface of the heterostructure and imposition of the requirement $G_v = 0$ yields the critical dipole moment $m_{c,1}$ provoking the first vortex appearance in the SC constituent.

As has been established before, $m_{c,1}$ falls monotonically with increasing thickness or relative permeability of the SM constituent, when the MD faces the SC constituent. This means that the presence of the SM constituent reduces the critical dipole moment, and hence facilitates vortex penetration into the SC constituent. By contrast, when the MD faces the SM constituent, $m_{c,1}$ rises monotonically with increasing thickness or relative permeability of the SM constituent, tending to a linear increase for large values of the latter quantity; behaviour resembling that of a magnetically shielded cylindrical SC filament. Hence, for this location of the MD, the SM layer can significantly inhibit vortex penetration into the SC constituent, preserving the latter in the Meissner state.

It is well known that magnetic vortex-antivortex pairs consisting of a vortex positioned directly underneath the MD and an antivortex displaced from it, separated by a potential barrier due to their interaction with the MD, can also be stabilized in the SC constituent. Addressing...
the Gibbs free energy of the SC/SM heterostructure in the presence of such a vortex-antivortex pair, $G_{va}$, and proceeding in the vein remarked on above, we find that the critical dipole moment for the first vortex-antivortex pair appearance is always larger than that for the first single vortex appearance, as demonstrated in Fig. 1. Remarkably, this result holds true even in the absence of the SM constituent. Nevertheless, the SM constituent effects the appearance of a vortex-antivortex pair qualitatively in the same manner as that of a single vortex: it slightly decreases $m_{c1}$, and hence facilitates the appearance of the vortex-antivortex pair, when the MD faces the SC constituent, but significantly increases $m_{c1}$, and hence impedes the creation of a vortex-antivortex pair, when the MD faces the SM constituent.

In conclusion, the presence of the SM constituent can lead to an improvement of the superconducting properties of the heterostructure under consideration by inhibiting penetration of magnetic vortices into the SC constituent, when the MD faces the SM constituent.

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\begin{itemize}
\item \textsuperscript{*} On leave from Donetsk Institute for Physics and Technology, National Academy of Sciences of Ukraine, 83114 Donetsk, Ukraine. Electronic address: yampolsk@tgm.tudarmstadt.de
\item \textsuperscript{†} On leave from Donetsk Institute for Physics and Technology, National Academy of Sciences of Ukraine, 83114 Donetsk, Ukraine.
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