Reverse–domain superconductivity in superconductor–ferromagnet hybrids: effect of a vortex–free channel on the symmetry of $I – V$ characteristics

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We demonstrate experimentally that the presence of a single domain wall in an underlying ferromagnetic BaFe$_{12}$O$_{19}$ substrate can induce a considerable asymmetry in the current ($I$) – voltage ($V$) characteristics of a superconducting Al bridge. The observed diode–like effect, i.e. polarity–dependent critical current, is associated with the formation of a vortex–free channel inside the superconducting area which increases the total current flowing through the superconducting bridge without dissipation. The vortex–free region appears only for a certain sign of the injected current and for a limited range of the external magnetic field.

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The development of material deposition techniques and lithographic methods has made it possible to fabricate superconductor–ferromagnet (S/F) hybrid structures with controlled arrangements of ferromagnetic layers/elements. These flux– and exchange–coupled S/F hybrids are of fundamental interest for investigations of nontrivial interactions between superconductivity and nonuniform distributions of magnetization. In addition S/F hybrids seem to be potential candidates for the development of tunable elements of superconducting electronics.

It is known that a nonuniform magnetic field can modify the conditions for the appearance of superconductivity due to the effect of a local field compensation. In flux–coupled S/F bilayers the formation of localized superconductivity results in either domain–wall superconductivity (DWS) or reverse–domain superconductivity (RDS), when superconductivity occurs, respectively, above magnetic domain walls or above magnetic domains of opposite polarity with respect to the orientation of an external magnetic field $H_{\text{ext}}$ (see review and references therein). The appearance of localized superconductivity (DWS and RDS) becomes possible if the amplitude of the nonuniform field, $B_0$, is comparable or exceeds the upper critical field, $H_{c2}$, of the superconducting material, which was confirmed experimentally for various planar S/F structures.

A present challenge, associated with these S/F hybrids, is the direct investigation of the transport properties of superconducting channels that are induced by stray magnetic fields. Indeed, this problem seems to be crucial for any practical applications exploring the effect of localized superconductivity and guided vortex motion in tunable magnetic landscapes. Parallel magnetic domains in thick permalloy films were found to lead to a preferential vortex motion and a giant anisotropy of the critical currents in S films and crystals even though the amplitude of the nonuniform field appears to be insufficient for the formation of localized superconductivity ($B_0/H_{c2} < 1$ at low temperatures).

It is important to note that the magnetic field induced by parallel magnetic domains in BaFe$_{12}$O$_{19}$ is rather high and thus suitable for RDS in superconducting Al films since $B_0/H_{c2} > 2.5$ for all temperatures. Using such S/F bilayers with well defined localized superconducting channels in a normal–metal matrix, we continue our previous study with the aim to test the potential of the superconducting channels to carry current. In this Letter we focus on the measurements of the current ($I$) – voltage ($V$) characteristics of a S/F bilayer along a single domain wall in a ferromagnetic substrate as a function of $H_{\text{ext}}$ and analyze the dependence of the critical current $I_c$ on $H_{\text{ext}}$ for different signs of the bias current.

Our sample consists of a ferromagnetic crystal BaFe$_{12}$O$_{19}$ with a thin–film superconducting Al bridge grown on top. Since the ferromagnetic and superconducting parts were electrically isolated by a 5 nm Si buffer layer, the interaction between these parts was...
purely magnetostatic. Being cut along the proper crystallographic direction, the polished crystal BaFe$_{12}$O$_{19}$ exhibits a stripe-type domain structure with dominant in-plane magnetization. The location of the domain walls was determined by magnetic force microscopy, prior to the preparation of the superconducting bridge. The cross-shaped Al microbridge (30 µm wide and 50 nm thick) was fabricated by e-beam lithography, molecular beam epitaxy and lift-off etching [Fig. 1(a)]. A similar structure was used in Ref. 22 for the observation of the anisotropy of the electrical resistance in this S/F bilayer.

The profile of the perpendicular $z$-component of the nonuniform magnetic field is shown in Fig. 2. Its amplitude, even though measured at a rather large distance (400 nm) from the surface, is close to the amplitude, even though measured at a rather large distance of 72 K, $H_{ext} = 0$ and at height 400 nm. The dashed line corresponds to $H_f = H_0 \arctan(y/L)$ ($H_0 = 115$ Oe, $L = 1.5$ µm).

Figure 2 shows the typical $I - V$ characteristics measured at $T = 0.5$ K ($T/T_c0 \approx 0.34$). Depending on the $H_{ext}$ value, there are three different cases:

(i) symmetric normal–type $I - V$ dependence with almost constant slope $dV/dI$ (not shown here);

(ii) symmetric $I - V$ dependence with non-zero critical current (curves labelled 450 Oe and 470 Oe). This is realized in a rather wide $H_{ext}$ range corresponding to the reverse-domain superconductivity;

(iii) asymmetric hysteretic $I - V$ dependence (curves labelled 490 Oe and 510 Oe) with $I^{(+)}_c \neq I^{(-)}_c$. Here we introduce the critical currents $I^{(+)}_c$ and $I^{(-)}_c$ for the ascending branches of the $I - V$ curves both for positive (+) and negative (−) polarities of the transport current. This type of $I - V$ characteristics was found only in the close vicinity of the compensation field ($|H_{ext}| \approx B_0$).

The dependencies of the critical currents $I^{(\pm)}_c$ on $H_{ext}$ are summarized in Fig. 4(a). The relationship between $I^{(+)}_c$ and $I^{(-)}_c$ depends both on the absolute value of $H_{ext}$ and its sign: $I^{(+)}_c > I^{(-)}_c$ at $H_{ext} < 0$ and vice versa. Thus, the most important finding of this paper is the field-induced change of the symmetry of the $I - V$ characteristics. The fact that the transmission capacity of the superconducting channel formed in the non-uniform magnetic field, can be strongly dependent on the polarity of the transport current may look rather unusual and counter-intuitive.

To clarify the physical origin of the difference between
of the superconducting strip, corresponding to the transition between the state with motionless vortices to the flux motion regime, we apply the following conditions:

(i) the maximum of the current density in the vortex-free region should be equal to the critical current density $j_s$, which defines the threshold value for the nucleation of vortices and antivortices inside the superconductor or at its edges:

(ii) in order to guarantee a flux motion regime at $I = I_c$, $j(y)$ should be equal to the depinning current density $j_p$ in the area where $n(y) \neq 0$, with $j_p = j_{p0}/(1 + |B_z|/B_p)$

$$j_p = \frac{j_{p0}}{1 + |B_z|/B_p}$$

(according to Kim-Anderson model\(^{[21]}\)) and $B_z$

$$B_z = H_{ext} + H_f + \frac{d}{c} \int_{-w/2}^{w/2} j(y') dy'$$

is the local magnetic field. As a result, in the vortex–free region, $n(y) = 0$, the current density can be larger than $j_p$.

(iii) the profile $j_s(y)$, which satisfies both conditions (i) and (ii), allows us to define the critical current as follows

$$I_c = \int_{-w/2}^{w/2} j_s(y) dy.$$

In our calculations we use the parameters typical for our system: $w = 30 \, \mu m$, $d = 50 \, \mu m$, $\lambda = 150 \, \mu m$, $B_0 = 520 \, Oe$, $B_p = 30 \, Oe$, $H_0 = 331 \, Oe$, $j_{p0} = 0.14 \, j_{dep}$, $j_s = 0.55 \, j_{dep}$, where $j_{dep}$ is the depairing current density of Al at low temperatures.\(^{[22]}\) Our choice for the parameter $L = 0.35 \, \mu m$ seems to be reasonable since the width of the transient area in the $B_z$-distribution inside the superconducting film (at $h < 50 \, nm$) can be substantially smaller than that measured at large distances ($L = 1.5 \, \mu m$ at $h = 400 \, nm$). Since there is rather good agreement between the experimental data and the calculated dependencies $I_c'(H_{ext})$ [Fig.\([\text{b}])$, we can interpret the asymmetry of the transmission capacity of the superconducting channels as follows.

Provided $H_{ext} \approx B_0$, the magnetic field is effectively compensated in the left part of the bridge, while the right part will be switched to the normal state. Since the local field $H_z = H_{ext} + H_f$ changes its sign inside the superconducting area (in the case $H_{ext} < B_0$), the stable vortex structure should generally consist of vortices and antivortices. However the Lorentz force $F_L = -z \times \Phi_0$ acting on a vortex depends on the direction of the transport current $j$, therefore the resulting vortex pattern, corresponding to the non-dissipative current flow, may be dependent on the sign of $I_z$. Indeed, an injection of the negative bias current ($I_z < 0$) forces vortices (antivortices) to move to the right (left), resulting in a vortex–free channel inside the RDS area [Fig.\([\text{a}])$–$(c1)]$. The exact position $a$ and the width $6$ of such channel depends on $H_{ext}$. Since there are no vortices in a certain area, one can apply a larger current through such a vortex-free channel.
without losing energy and the excess current due to this effect can be roughly estimated as $\delta \times (j_s - j_{p0})$. However, the vortex-free area is absent for a bias current of opposite polarity ($I_x > 0$), since vortices and antivortices move in counter directions and annihilate at the point of zero magnetic field [Fig. 3 (a2)–(c2)]. In this case the current density cannot be larger than $j_{p0}$ and $I_{c}^{(+)2} < I_{c}^{(-)2}$. In the under-compensated regime, when the absolute $H_{ext}$ value is substantially less than $B_0$, the gradient of the local field $(dH_z/dy)_s$ increases rapidly as $H_{ext}$ decreases [compare Fig. 3 (a1)–(c1)], $\delta \rightarrow 0$, and the diode effect vanishes. In the over-compensated regime ($H_{ext} > B_0$) the vortex–free region positioned near the left edge of the bridge becomes very narrow ($\delta \rightarrow 0$) and, as a consequence, the excess current goes to zero and the symmetry of the $I - V$ characteristics is restored. Obviously that for $H_{ext} < 0$ we have the same physics, but the excess current corresponds to the opposite case ($I > 0$) and therefore $I_{c}^{(+)2} > I_{c}^{(-)2}$. All these conclusions are in agreement with our experimental observations [Fig. 4].

Summarizing, we showed that a nonuniform field can cause a pronounced asymmetry of the $I - V$ curves of a superconducting bridge provided $|H_{ext}| \simeq B_0$. The difference in the critical currents can be attributed to a removal of vortices from the inner part of the superconducting bridge under the action of the Lorentz force. Such a vortex–free channel, forming only for a certain polarity of the injected current, is able to carry extra current without dissipation and thus prevents the superconducting bridge from switching to the normal state.

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