Mesoscopic field and current compensator based on a hybrid superconductor-ferromagnet structure

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A rather general enhancement of superconductivity is demonstrated in a hybrid structure consisting of submicron superconducting (SC) sample combined with an in-plane ferromagnet (FM). The superconducting state resists much higher applied magnetic fields for both perpendicular polarities, as applied field is screened by the FM. In addition, FM induces (in the perpendicular direction to its moment) two opposite current-flows in the SC plane, under and aside the magnet, respectively. Due to the compensation effects, superconductivity persists up to higher applied currents. With increasing current, the sample undergoes SC-“resistive”-normal state transitions through a mixture of vortex-antivortex and phase-slip phenomena.

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Over the last years, the superconductor-ferromagnet (SC-FM) hybrids received a lot of attention as one of the rare systems where ferromagnetism and singlet superconductivity coexist (for review, see [1]). These hybrid structures are looked upon as candidates for futuristic nanoelectronics, combining superconducting circuits with magnetic storage elements. As better understanding is needed, the ongoing studies are mainly focused on fundamental properties of nanoscale SC-FM samples and plethora of related phenomena.

For example, although ferromagnetism in general suppresses superconductivity, direct SC-FM coupling appears to be crucial for the π-phase state with the critical current inversion in SC-FM-SC junctions [2] and Josephson current enhancement in SC-FM tunnel structures with very thin FM layers [3]. On the other hand, the nontrivial interplay between magnetism and superconductivity can be achieved even if SC and FM are not electronically coupled, as they still interact through the emerging magnetic fields. In that respect, arrays of submicron magnetic particles are used for applying well-defined local magnetic fields in the underlying superconductor [4].

One of the first applications of these nano-magnets was to engineer the pinning force of superconducting films, such that the critical current $j_c$ as a function of applied magnetic field is increased due to a collective locking of the flux lattice to the magnetic array [4, 5]. Since then, because of the technological relevance, enhancement of critical parameters in SC-FM heterostructures is of vast theoretical and experimental interest. Genenko et al. predicted theoretically an increased edge barrier critical current in superconductors completely surfaced by magnetic material [6]. In that case, a demagnetized magnetic layer acts as a magnetic screen, effectively shielding the Meissner state. Two years ago, Lange et al. measured higher critical field in SC films regularly structured by out-of-plane magnetized dots [7]. However, this behavior strongly depended on the polarity of the applied field $H_{ext}$: for given FM-magnetization $M$, an enhancement of the critical parallel field ($H_{ext} \parallel M$) was achieved at expense of the antiparallel one. The same behavior was found both experimentally [8] and theoretically [9] in mesoscopic SC disks with out-of-plane FM dot on top.

The first objective of the present Letter is to design a SC-FM hybrid structure where most critical properties can be tailored practically at will. For that matter, we consider a thin submicron superconducting sample with a ferromagnetic dot with in-plane magnetization on top (see Fig. 1). Such a device realization offers full exploitation of the magnetic flux pinning [10], dynamical properties of mesoscopic superconductors [11], and related vortex-antivortex phenomena [12]. Due to the opposite magnetic field at the poles of the magnet, the field-compensation effects lead to the critical field enhancement for both positive and negative applied field (see Fig. 1). At the same time, our SC-FM sample might act as a current compensator as well: as a novel concept, the applied current is met by opposing FM-induced supercurrents, resulting in a larger critical current.

In our theoretical treatment of this system, we rely upon the Ginzburg-Landau (GL) formalism. In, the sta-
tional case, we solve self-consistently two GL equations, derived from the Gibbs energy functional. For all details of this approach, we refer to Refs. [12, 13].

To understand the dynamical properties of the device, we studied the current-voltage characteristics using the time-dependent Ginzburg-Landau (TDGL) equation

\[
\frac{\phi}{\sqrt{1 + \Gamma^2 |\psi|^2}} \left( \frac{\partial}{\partial t} + i \varphi + \frac{\Gamma^2}{2} \frac{\partial |\psi|^2}{\partial t} \right) \psi = \\
= (\nabla - iA)^2 \psi + (1 - T - |\psi|^2) \psi,
\]

coupled with the equation for the electrostatic potential \(\Delta \varphi = \text{div}(\text{Im}(\psi^* \nabla - iA) \psi))\). Here, the distance is measured in units of the coherence length \(\xi(0)\), \(\psi\) is scaled by its value in the absence of magnetic field \(\psi_0\), time by \(\tau_{GL}(0) = \pi \hbar/8k_B T \tau\), vector potential \(A\) by \(c \hbar/2e \xi(0)\), and the electrostatic potential by \(\hbar/2e \tau_{GL}(0)\).

\(\Gamma = 2T \tau \psi_0/\hbar\), with \(\tau\) being the inelastic electron-collision time. For Al samples \(\tau E \sim 10\text{ns}\), which results in \(\Gamma \approx 1000\). Parameter \(u = 5.79\) is taken from Ref. [14]. Note that in Eq. (1) the screening of the magnetic field is neglected, as we restrict ourselves to thin SC samples \((d < \xi)\). The points where external current \(j_{ext}\) is injected in the sample (see Fig. 1) were simulated as normal metal-superconductor contacts, i.e. with \(\psi = 0\) and \(-\nabla \varphi = j_{ext}\). At the remaining of the sample edges, Neumann boundary condition was used \((j_{\parallel} = 0)\).

We consider a square Al sample with parameters easily achievable with modern lithographic techniques: size \(a_x = a_y = 1.5\mu m\), thickness \(d = 80nm\), separated by an oxide layer of thickness \(t = 20nm\) from the square FM with size \(w_x = w_y = 800nm\) and thickness \(D = 50nm\).

The SC material is characterized by its coherence length at zero temperature, which we take as \(\xi(0) = 100nm\) (typical value for mesoscopic Al samples), and FM material by its saturation magnetization \(M\). In our calculations, the FM is positioned at the center of the SC square, and since its stray field has opposite polarity at the FM-poles (see inset (a) in Fig. 2), the total flux \(\Phi_{FM}\) penetrating the SC equals zero. This feature inevitably leads to the appearance of vortex-antivortex configurations for sufficiently strong magnetization \(M\).

Fig. 2 shows the Gibbs free energy \(G\) of the superconducting state, obtained after sweeping up/down the FM-magnetization, where the number of induced vortex-antivortex (VAV) pairs is denoted by Roman numbers. Note that these VAV states are the first found vortex states with zero total vorticity in finite mesoscopic SC samples. Insets (b,c) in Fig. 2 show the \(|\psi|^2\)-density plots of successive VAV states. As vortices and antivortices are confined at the FM-poles (where the stray field is maximal), they are effectively kept apart by the FM. In other words, the superconducting region under the FM always remains (anti)vortex-free. As a result, superconductivity can be sustained in the sample up to very large FM-magnetization (as the slope \(\partial G/\partial M\) decreases in Fig. 3).

FIG. 2: The Gibbs free energy diagram \((G_0 = H_0^2V/8\pi)\) as a function of FM-magnetization. Roman numbers denote number of FM-induced vortex-antivortex pairs. Inset (a) illustrates the FM-stray field lines; (b) the Cooper-pair density (upper figure, darkest color - zero density [online blue/red-low/high density]) and superconducting phase contour plot (gradation of grey color shows the circulation of phase \(0 - 2\pi\) [online blue/red-0/2\pi phase]) for state I; (c) the \(|\psi|^2\)-density plots (scale adjusted for clarity) under the positive pole of the magnet, for states II to V (FM-edge depicted by white lines).

Note that this is not the case if FM has perpendicular magnetization, when total flux \(\Phi_{FM}\) captured by SC is positive and FM-induced vortices destroy superconductivity in the heart of the sample. The experiment of Ref. [8] revealed that when such a sample is exposed to homogeneous external field \(H_{ext}\), the \(H_{ext} - T\) boundary is shifted towards positive fields due to the compensation with \(\Phi_{FM}\), resulting in higher positive critical field (and consequently reduced negative one).

In Fig. 3 the \(H_{ext} - T\) superconducting/normal (S/N) phase boundary of our sample is shown, in the case of FM with bulk Co magnetization \(M = 1400G\) (solid line), compared to the case without FM (dashed line). The S/N boundary exhibits three novel features: (i) the M-shaped boundary - the critical temperature for \(H_{ext} = 0\) is reduced \((T_{cm} < T < T_{cm})\); and is maximal for two symmetric non-zero \(H_{ext}\) values \((T_{cm}):\) (ii) for \(T_{cm} < T < T_{cm}\) the N-S-N-S-N multi-reentrant behavior is observed during \(H_{ext}\) sweep; and (iii) substantial critical field enhancement is found for both \(H_{ext}\) polarities.

The physical reason for these phenomena lies in the magnetic field compensation. In this particular case, for \(H_{ext} = 0\), the S/N transition at \(T = T_{cm}\) occurs for 2 vortex-antivortex pairs induced by the FM (state II in Fig. 2). Although their centers are pin-pointed at the FM-poles, these (anti)vortices are covering the whole sample as \(\xi(T)\) becomes large. When \(H_{ext} > 0\) is applied, the external flux is “absorbed” by the FM-induced antivortex. This effectively recovers superconductivity,
and increases $T_c$. Each kink in the Little-Parks-like S/N boundary with increasing $H_{\text{ext}}$ corresponds to a change in total vorticity of $\Delta L = 1$, where external flux lines are first annihilated by FM-induced antivortices, and in the absence of antivortices pinned on the positive pole of the FM, where the stray field and $H_{\text{ext}}$ are aligned (as found in Refs. [10]). In the latter case, each additional vortex suppresses superconductivity and $T_c$ decreases. However, the SC state remains protected at the opposite pole of the magnet which results in significantly higher critical field. In Fig. 3 an enhancement as high as $\sim 40\%$ is achieved. This percentage can be even larger, if stronger magnetic materials are used (note high $M_r$ in Fig. 2). The reduced zero-field critical temperature $T_{cm0}$ is only within few percent from $T_{c0}$, but maximal $T_{cm}$ (at $H_{\text{ext}} = 1.97\text{mT}$) is several percent higher than the corresponding $T_c$ value in the absence of the FM.

For $H_{\text{ext}} < 0$, the scenario is completely analogous, and S/N boundary is therefore symmetric. Note that this symmetry directly leads to feature (ii), which is actually a very rare magnetic field-induced superconductivity (FIS) phenomenon. Similar unconventional behavior was reported earlier for materials like (EuSn)Mo$_6$S$_8$ and $\lambda$-(BETS)$_2$FeCl$_4$, and for SC films with out-of-plane FM-arrays on top [7]. However, our sample holds a unique property - FIS is achieved for both perpendicular polarizations of applied field $H_{\text{ext}}$ (e.g. Fig. 3 for $T = 0.985T_{c0}$).

Obviously, the above described phenomena are directly related to the strongly inhomogeneous FM-stray field (with zero average). Yet another interesting feature can be found in the stray-field-induced currents $j_{FM}$. Due to the field landscape, these currents are actually circulating around the poles of the magnet, which ultimately results in two opposite current flows, under and aside the FM, in a direction perpendicular to the FM-polarization (see Fig. 4a)). Obviously, with increasing FM-magnetization, the amplitudes of $j_{FM}$ grow (as shown in Fig. 4b), until the depairing current is reached and vortex-antivortex (VAV) pair nucleates at the FM-poles. Consequently, $j_{FM}$ completely reverses (Fig. 4b, yellow line), but changes polarity again with increasing $M$, before the appearance of the following VAV pair (see Fig. 2). This dual, step-like $j_{FM}$ profile may strongly affect the response of the device on the applied current in the $x$-direction (see Fig. 1). In order to investigate the critical current and dynamical properties of the system, we employ TDGL formalism. The key results are shown in Fig. 5 as differential resistance (obtained from calculated I-V characteristics) as function of applied current $j_{\text{ext}}$. Two critical currents, denoted as $j_{c1}$ and $j_{c2}$ in Fig. 5, can be identified. $j_{c1}$ is the current at which the sample loses its zero-resistance and transits to the so-called “resistive” state. $j_{c2}$ has the more conventional meaning of the current at which the SC state becomes unstable.

When external current is applied to a plain SC square (Fig. 6a), it is non-uniformly distributed in the sample, with its maxima at the side-edges (see cartoon in the inset). It is at these weak points where the vortex nucleates when the depairing current is reached (for corresponding $j_{\text{ext}} = j_{c1}$). Due to the Lorentz force, this vortex

![FIG. 3: The superconducting/normal (S/N) phase boundary for a square SC sample, without (dashed curve) and with (solid curve) an in-plane FM dot on top. The total vorticity of the sample is denoted by $L$, while indices $a, b$ show the number of vortices and antivortices (induced and/or pinned by FM) at corresponding FM poles, respectively ($L = a - b$).](image)

![FIG. 4: (a) Vectorplot of the SC-current $j_{FM}$ induced by an in-plane FM (Meissner state), superimposed on the contourplot of $j_{FM}$ component. (b) The $j_{FM}$-profile in the central cross-section for different FM-magnetization ($T = 0.97T_{c0}$).](image)
A phase-slip can serve as a tool for experimental detection of remarkable enhancement of $j_{c2}$ for a low $j_{ext}$ value (Fig. 5(c)). Following VAV creation, $j_{FM}$ changes polarity, and now compensates $j_{ext}$ between the contacts instead of at the edges. Eventually, with further increase of $j_{ext}$, $j_{FM}$ is overwhelmed by the applied current, and VAV pair is expelled from the sample; the influence of FM becomes negligible as further scenario resembles the one of Fig. 5(a): current is again maximal at the edge, phase-slip occurs, and superconductivity is destroyed. However, due to described VAV nucleation and current compensation between the contacts, for $M = 450$ G we obtained a remarkable enhancement of $j_{c2}$ of $\sim 21.5\%$ (Fig. 5(c)).

For higher $M$, FM may induce a VAV pair in the sample (Fig. 2(b)). In that case, even for very low applied current, a finite resistance was found ($j_{c1} = 0$). This feature can serve as a tool for experimental detection of VAV pairs in contrast to the Meissner state in SC-FM hybrids. For certain value of $j_{ext}$, vortex and antivortex are depinned and leave the sample, followed by an immediate phase-slip and consequent transition to the normal state. Due to the absence of the zero-resistance state, both $j_{c1}$ and $j_{c2}$ are significantly decreased (Fig. 5(d)).

In conclusion, we proposed a SC-FM device where both critical field and critical current can be substantially enhanced. Although our dynamical simulations are valid only in close vicinity of $T_c$, the main idea is generally applicable. Detailed influence of parameters and different dynamic regimes will be analyzed in a separate article.

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