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Critical field enhancement in hybrid superconductor/ferromagnet mesoscopic disks

N. Schildermans,[1,a)] A. V. Silhanek,[1] J. Sautner,[2] V. Metlushko,[2] P. Vavassori,[3] and V. V. Moshchalkov[1]
[1]*INPAC-Institute for Nanoscale Physics and Chemistry, Nanoscale Superconductivity and Magnetism and Pulsed Fields Group, K. U. Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium*
[2]*Department of Electrical and Computer Engineering, University of Illinois, Chicago, Illinois 60607, USA*
[3]*CIC nanoGUNE Consolider, E-20009 San Sebastian, Spain and Dipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy*

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We investigated experimentally the nucleation of superconductivity in a mesoscopic hybrid structure, consisting of a thin superconducting disk covered with a ferromagnetic layer with an in-plane magnetic moment. By applying a magnetic field in the plane of the structure, the remanent magnetic state of the ferromagnet can be switched from a flux-closure state where field lines are confined inside the ferromagnet to a polarized state with nonzero stray fields at the edges. This change in the magnetic state causes a drastic modification on the superconductor/normal-state phase boundary of the hybrid sample. In the polarized state a re-entrant transition line and a strong broadening of the phase boundary are observed. © *2009 American Institute of Physics*.
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I. INTRODUCTION

The nontrivial interaction between a ferromagnet (F) and a superconductor (S) combined into a hybrid structure has been studied intensively during the last decade.[1,2] One of the most unusual properties of the S/F layer is the possibility to protect the superconducting state by compensating the applied field with the stray field of a ferromagnet.[3] For S/F bilayers with no lateral structuring this effect can lead to a re-entrance of superconductivity and an increase in the critical field.[4] Thus the combination of superconductors and ferromagnets into hybrid structures is technologically relevant to improve the critical parameters of superconductors. Different kinds of S/F hybrid structures are expected to find applications in nanoelectronics, combining superconductivity with magnetic storage elements.[5]

So far the re-entrant field dependence of the critical temperature $T_c(H)$ has been experimentally observed only for magnetic systems with perpendicular anisotropy. This effect is not expected in hybrid films with an in-plane magnetization, since the stray field becomes zero in the center of magnetic domains, resulting in a preferential nucleation at these locations, which is not shifted in an external magnetic field. However, the situation changes when the system dimensions are decreased to the mesoscopic range, such that the ferromagnet is in a single-domain state. Theoretically Milošević *et al.*[5] predicted a comparable enhancement of $T_c(H)$ in a mesoscopic S/F hybrid structure with well defined in-plane magnetic moment. Indeed, based on the Ginzburg–Landau formalism, these authors showed that the considered S/F system should be dominated by field compensation of the positive/negative stray fields at both ends of the magnetic dot, leading to a substantial increase in $T_c(H)$ for both field polarities. In other words, in contrast to the S/F structures with out-of-plane nanomagnets where an enhancement of superconductivity for positive fields is obtained at expenses of suppressing the critical temperature for negative fields, the phase boundary (PB) of in-plane hybrids should be symmetric around $H=0$. To our knowledge, there are so far no experimental studies confirming these recent predictions.

In Ref. 5 the proposed hybrid system consists of a ferromagnetic square of 800 nm lateral dimensions on top of a superconducting square of 1.5 μm side. Unfortunately, this choice of parameters in a real magnetic material does not ensure a single-domain state, but rather favors the splitting of the magnetic structure into multiple domains thus departing from the theoretical model system. In addition, symmetric micromagnets, as squares and disks, relax to a flux-closure state at remanence.[6] This magnetic vortex state is characterized by a strong and very localized stray field in the magnetic vortex core, as well as stray fields along the lines where the in-plane magnetic moment changes the orientation. To obtain a sizable stray field at remanence a ferromagnetic rectangle with large aspect ratio between length and width can do the job.[7]

Alternatively, it is possible to use a symmetric structure with small indentations in such a way that other states with nonzero net average magnetic moment can be stabilized.[8] In this work, by adding magnetic leads to the F layer, we are able to induce a magnetic dipolar state after magnetizing the sample in a homogeneous in-plane field. The advantage of this configuration is that we are able to compare two situations, namely before magnetization, in the flux-closure state and after magnetization in, the dipolar state. We demonstrate that when the F disk is set in a dipolar state the heterostructure exhibits a clear enhancement of the upper critical field in qualitative agreement with the calculations reported by Milošević *et al.*[5]

[a)]Electronic mail: nele.schildermans@fys.kuleuven.be.

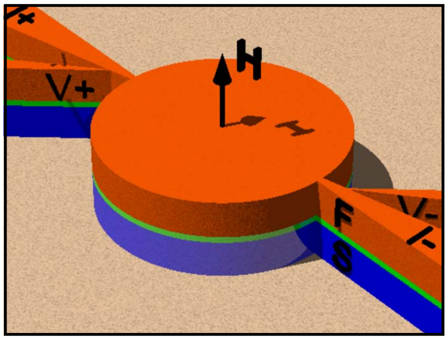

FIG. 1. (Color online) A schematic drawing of the sample: a 50 nm thick superconducting Al disk with $r=0.85$ μm, covered with a 5 nm thick insulating Si layer and 20 nm Py. The voltage/current contacts for the transport measurements are symmetrically attached to the disk. The external field H is applied perpendicular to the surface of the structure.

II. SAMPLE DETAILS AND MAGNETIC CHARACTERIZATION

The investigated hybrid system consists of a 50 nm thick Al disk with a radius of 0.85 μm and contact leads attached to it for the transport measurements as schematically shown in Fig. 1. The complete structure is covered with an insulating Si layer of 5 nm to avoid proximity effects and a 20 nm thick $Ni_{80}Fe_{20}$ layer, with an in-plane magnetic moment. The structure is made by evaporation of the three layers through a lithographic mask, followed by a lift-off procedure.

The geometry dependent magnetic properties of the structure are investigated by measuring the field dependence of the magnetization $M(H)$ at $T=10$ K using a commercial Quantum Design superconductor quantum interference device magnetometer, with the external field H applied parallel to the surface of the disks. In order to obtain a measurable magnetic signal it is necessary to collect the average magnetization of a large array of structures. The magnetization loops of two different arrays, namely Py disks and Py disks with contact leads attached, are compared in Fig. 2. The $M(H)$ curve of the plain disk shows a nearly closed loop at

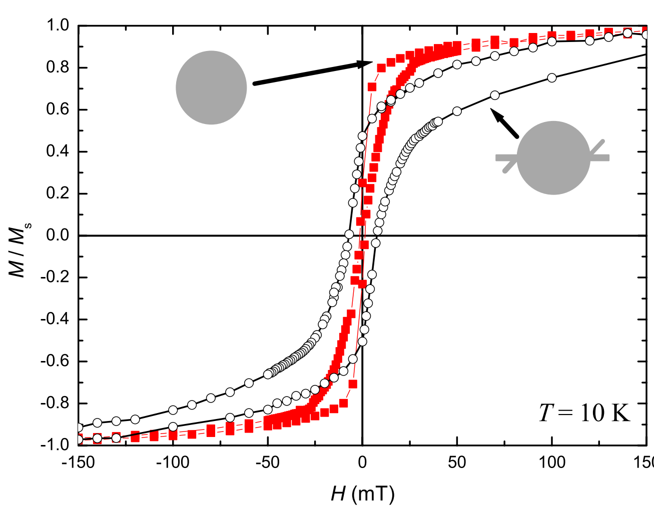

FIG. 2. (Color online) The magnetization loops of an array of Py disk with (open black circles) and without contacts attached (full red squares), measured at 10 K with the external field H applied parallel to the surface of the disks.

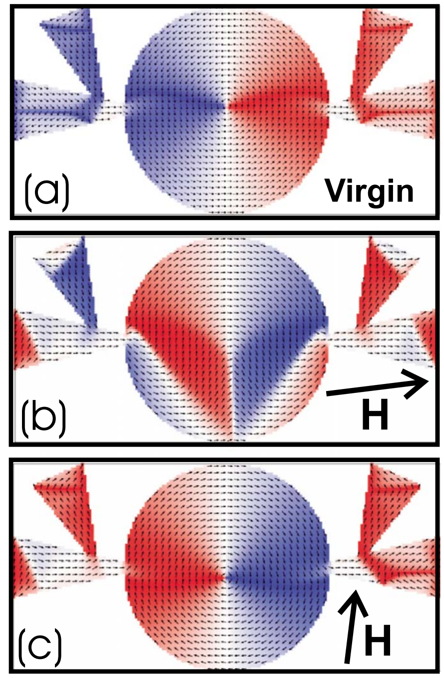

FIG. 3. (Color online) OOMMF simulations of a 20 nm thick Permalloy disk with leads for three different histories: (a) the magnetic state before applying any external field. In this case the disk is in a flux-closure state. (b) The remanent state after an in-plane saturation field has been applied along the contact leads. (c) The remanent state after applying an in-plane field perpendicular to the contacts.

$H=0$ with $M\sim 0$ as expected for a flux-closure or vortex state. In contrast to that the loop of the disk with contacts attached to it exhibits a clear opening with a nonzero remanent magnetization. This behavior indicates that the leads disturb the vortex state in the disk and induce nonzero average magnetic moment.[8] Notice that the remanent magnetization is about half of the saturation value M_s, indicating that the state at remanence is not a single-domain state.

In order to better understand the influence of the magnetic leads on the magnetic state of the F disk, we performed micromagnetic simulations using the OOMMF (object oriented micromagnet framework) code.[9] The results for a 20 nm thick disk with leads are shown in Figs. 3 and 4. A cell size of 5 nm is used of these simulations. In Fig. 3, the arrows are indicating the direction of the magnetic moment and the blue (red) colors the divergence of the magnetization along the positive (negative) z-direction. Figure 3 shows the stray fields of the same simulations plotted in three dimensions. The initial magnetic state of the disk before applying any external magnetic field is a flux-closure state (a). Then a saturation field is applied in the plane of the structure. When the field is turned off after saturation, the magnetic state of the disk remains in a partially polarized state. This remanent state has a net dipolar moment, which, according to the OOMMF simulations, strongly depends on the details of the structure shape and thickness. A well chosen thickness/radius ratio is important to be able to switch between a vortex and a polarized state. When the disk is too thick (>60 nm), the vortex state is the only possible remanent state. On the other hand, in a very thin disk (<10 nm) the vortex state is never obtained. Also the direction of the applied in-plane field in-

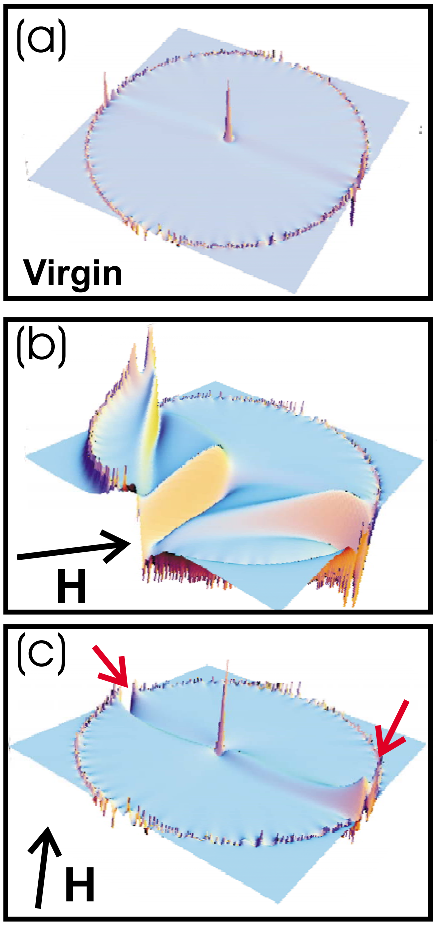

FIG. 4. (Color online) The simulated stray fields of the three magnetic states, shown in Fig. 3, plotted here in three dimensions: (a) the magnetic state before applying any external field. In this case the disk is in a flux-closure state. (b) The remanent state after an in-plane saturation field has been applied along the contact lead and shows strong stray fields. (c) The remanent state after applying an in-plane field perpendicular to the contacts has a vortex state in the center, but shows also stray fields at the edges, indicated by red arrows.

fluences the final magnetic state drastically as shown in Figs. 4(b) and 4(c) for two different orientations of H. The field orientation is chosen along (b) and perpendicular to (c) the contact leads, with in both cases a deviation of 2.5° from the axis. In the first case the polarized state has a complicated stray field profile, while in the second case, besides the magnetic vortex formed at the disk center, there is a dipole at the disk edge at the position of the contacts (indicated by red arrows in Fig. 4). All in one, the presence of the contact leads provides a way to stabilize a remanent state with a strong stray field which can eventually lead to the reentrant $T_c(H)$ as predicted in Ref. 5.

III. SUPERCONDUCTING PROPERTIES

The influence of the magnetic layer on the superconducting nucleation properties is shown in Fig. 5 for three different magnetic states. The superconducting/normal-state PB is measured by electric transport, applying a dc drive of 1 μA and measuring the resistance as a function of magnetic field and temperature. The PB is obtained from these measurements using a criterium $R(T_c,H)=0.5R_N$ (see left panel of Fig. 5) with R_N the normal-state resistance. According to the magnetic simulations, the ferromagnetic layer in the *as-grown* state corresponds to a flux-closure state, with a strong out-of-plane component of the magnetic field only at the center of the disk. In this case, the F layer should have no influence on the nucleation of the superconducting order parameter occurring at the sample boundary. This is in agreement with the fact that the observed PB is nearly identical to that corresponding to an Al disk without magnetic layer. In addition, small oscillations indicate changes in the vorticity in the structure by one flux quantum, as detailed in previous reports.[10–12] These Little–Parks oscillations are more clearly visible for a $0.1R_N$ criterium (see right panel of Fig. 5) and coincides with the values expected for a disk.[12]

After magnetizing the F layer a net magnetic moment is induced in the F layer, and as a consequence the superconducting PB is strongly modified. We compare here the PBs for the two magnetized states mentioned above with the in-plane field applied perpendicular to the contact leads (solid squares in Fig. 5) and with the in-plane field along the contacts (open triangles). For both magnetic states we observe a suppression of the critical temperature around $H=0$ mT and an asymmetric re-entrant effect. At high fields, the PB becomes parallel to that of the as-grown state. The PBs for both magnetic states are qualitatively comparable to the one predicted by Milošević *et al.*: we indeed observe a strong broadening of the PB for both positive and negative fields and a weak re-entrant effect. As pointed out in Ref. 5 this behavior can be attributed to field compensation effects. In the magnetized state T_{c0} is suppressed due to the stray field induced by the ferromagnet. When the external field $|H|$ increases, the

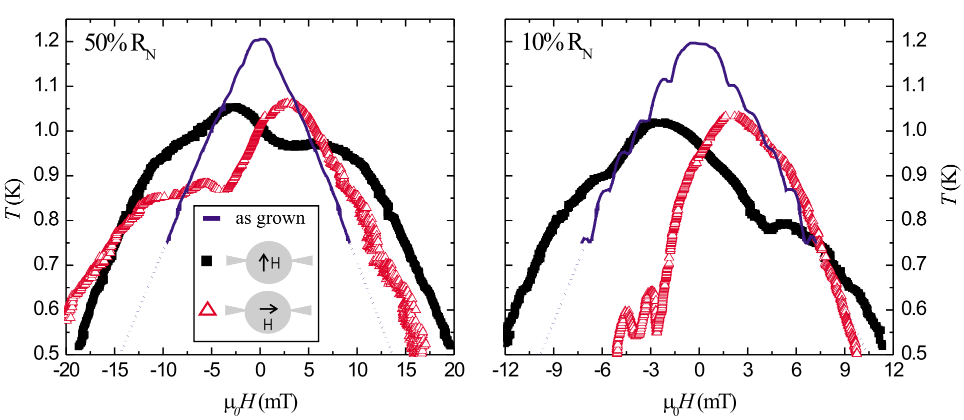

FIG. 5. (Color online) The S/N phase transition line for two different magnetic states of the F layer: the blue open circles are the data measured in the as-grown state; the black filled dots form the S/N PB in the magnetized state. The dotted lines indicate the expected field values for the Little–Parks oscillations. The PBs in the left panel are obtained using a $0.5R_N$ criterium, while for the PBs in the right panel a $0.1R_N$ criterium are used.

positive (negative) pole is compensated and the critical temperature increases again. By further increasing the external field, the positive (negative) stray field of the F layer is overcompensated and T_c starts to decrease again. From that value on, the stray field of the ferromagnet induces only an offset on the applied field and the PB becomes parallel to the one of the as-grown state. According to this interpretation the field enhancement ΔH given by the lateral shift of the PB with respect to the nonmagnetized state should be of the order of the B_0, with B_0 the maximum stray field of the S-layer.

Typically a criterium of $0.5R_N$ is used to define experimentally the superconducting/normal PB, which resulted here in a good qualitative agreement with the predictions. However, we noticed that the shape of the PB strongly depends on the used criterium, and that there are important differences between the predicted and experimentally observed PBs for lower criteria. The PBs, obtained with a $0.1R_N$ criterium, are plotted in right panel of Fig. 5. The observed differences are a consequence of the different geometries of the micromagnets. First of all, the PB is not perfectly symmetric around zero magnetic field as expected for the dipole state. The minimum in the critical temperature is not located exactly around zero, but is shifted to the positive (negative) side for the black (red) curve. Furthermore, the re-entrance effect is stronger for negative (positive) than for positive (negative) fields. This indicates that both magnetic states are not perfectly in plane, but likely have a net out-of-plane magnetization. The simulations in Fig. 4 showed already that the remanent dipole state is not well defined in this ferromagnetic structure and strongly depends on the direction of the in-plane applied field. This has a clear effect on the superconductor, resulting in two different asymmetric PBs.

It is also worth noticing that, unlike in the as-grown state, no regular Little–Parks oscillations are observed experimentally for both magnetic states, except from the two deep oscillations at the negative side of the red curve. The lack of oscillations can be explained by the fact that in the experimental system the F disk has the same size as the S disk. This implies that the out-of-plane component of the field is located at the border of the structure and strongly changes the boundary conditions, suppressing the surface superconductivity. It has been shown recently in out-of-plane magnetized structures that this effect leads to a strong modification of the Little–Parks oscillations.[13] In addition, a vortex entering the disk will be pinned at one of the poles instead of going to the disk center. Each vortex entrance modifies the effective boundary and therefore no regular Little–Parks oscillations should be observed in the PBs. The remarkable deep oscillations, observed in the case that the magnetization field is applied along the contacts, remind the behavior observed in magnetically induced Josephson junctions.[14] Further investigations are needed in order to understand this effect.

IV. CONCLUSIONS

In conclusion, we demonstrated experimentally that a critical field enhancement can be obtained in a mesoscopic S/F hybrid, with an in-plane magnetized F layer. These results are comparable to early theoretically predicted effects.[5] The key challenge for the future superconducting/magnetic hybrid devices will be a suitable technology to integrate and to contact nanostructures in a reliable manner. We found that the shape of the contact lines influences performance to such extent that it modifies the remanent states of magnetic layer, PB in superconductor, and the whole mechanism of operation. Their topography must absolutely be taken into consideration during the design phase since the contact geometry will profoundly affect their magnetization profile.

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