Sudden Critical Current Drops Induced in S/F Structures

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Received: date / Revised version: date

Abstract. In the search for new physical properties of S/F structures, we have found that the superconductor critical current can be controlled by the domain state of the neighboring ferromagnet. The superconductor is a thin wire of thickness $d_s \approx 2\xi_S$. Nb/Co and Nb/Py (Permalloy Ni$_{80}$Fe$_{20}$) bilayer structures were grown with a significant magnetic anisotropy. Critical current measurements of Nb/Co structures with ferromagnet thickness $d_F > 30$ nm show sudden drops in two very defined steps when the measurements are made along the hard axes direction (i.e. current track parallel to hard anisotropy axes direction). These drops disappear when they are made along the easy axis direction or when the ferromagnet thickness is below 30 nm. The drops are accompanied by vortex flux flow. In addition magnetoresistance measurements close to $T_C$ show a sharp increase near saturation fields of the ferromagnet. Similar results are reproduced in Nb/Py bilayer structure with the ferromagnet thickness $d_F \sim 50$ nm along the easy anisotropy axes. These results are explained as being due to spontaneous vortex formation and flow induced by Bloch domain walls of the ferromagnet underneath. We argue these Bloch domain walls produce a 2D vortex-antivortex lattice structure.

PACS. 72.25.Sv Critical Currents – 72.25.Qt Vortex lattices, flux pinning, flux creep – 72.25.Ha Magnetic Properties

1 Introduction

The proximity effect in superconductor (S) ferromagnet (F) bilayer structures has been subject of intensive research in the past ten years. This has been specially due to the effect exchange field has on Cooper pairs generating the so called Fulde Ferrel Larkin Ovchinnilov (FFLO) state. In this state the real part of the order parameter penetrates the ferromagnet and oscillates in proximity to the interface leading to the theoretically predicted oscillations of $T_C$ as a function of the ferromagnet thickness $d_F$. The effect was attributed to a reduction of the average exchange field sampled by the Cooper pairs within the domain wall giving rise to an enhancement of superconductivity so called domain wall superconductivity (DWS)\textsuperscript{[5]}. However, in these experiments the effect of stray fields, from the mask geometry used, in the measurements could not be completely eliminated. Later a similar effect was reported in Nb/CuNi trilayers by Rusanov et al.\textsuperscript{[6]} again in this case the stray fields from the mask geometry were present (i.e. magnetic voltage contacts perpendicular to the current track). In an experiment, by the same authors\textsuperscript{[7]}, on Nb/Pt (Permalloy Ni$_{80}$Fe$_{20}$), with 21 nm of Nb and 20 nm of Pt, suggests evidence of DWS. In this experiment Rusanov et al.\textsuperscript{[8]} found enhancement of superconductivity at coercive fields of the ferromagnet, by measuring magnetoresistance at the transition region between normal and superconducting state. Dips in magnetoresistance measurements at coercive fields were attributed to be evidence of this effect. Nevertheless this effect was only found for large samples ($0.5$ mm $\times$ $4$ mm) and absent in small samples ($1.5$ $\mu$m $\times$ $20$ $\mu$m), where the authors argued that no stable domains form in small samples. In other experiments on Nb/CuNi bilayers performed by Ryazanov et al.\textsuperscript{[8]}, they found magnetoresistive peaks in differential resistance measurements at coercive field of the ferromagnet. They explained this observations by spontaneous vortex formation perpendicular to the current track, which led to stray fields on the current track. In these earlier studies an increase in the critical current measurements of the patterned wire was found by applying a magnetic field of the order of the coercive field of the ferromagnet. This
formation and flow from stray fields from the domain walls of the ferromagnet. A theoretical work has been published by Burnistrov et al. [9] investigating the effect of Bloch domain walls on the current distribution in the superconductor. They also determine a lower critical value of domain wall magnetization above which vortex formation is favorable. Based on this idea experiments, performed by Steiner et al. [10] on Fe/Nb and Co/Nb bilayers, found a reduction of $T_C \approx 0.5\%$ as a function of magnetic state of the ferromagnet. Additionally Bell et al. [11] have found a double peak structure in magnetoresistance measurements of MoGe/GdNi bilayered structures as a function of the magnetic state of the ferromagnet attributed to vortex formation and flux flow.

The aim of the present work is to further investigate the influence of Néel and Bloch domain walls in the superconducting pairing and vortex generation in S/F hybrids. This investigation differs from previous ones in that it considers a wide range of ferromagnet’s thickness and eliminates stray fields from the mask geometry. We also used Co and Py as ferromagnets where the domain wall structures is fairly well understood at least at room temperature.

2 Critical Current and Magneto-Resistance Measurements

In our experiment we have grown Nb/Co and Nb/Py bilayers (Nb on top) on Si (100) substrates using a UHV DC-magnetron sputtering system in a chamber cooled to $-100^\circ\text{C}$ using liquid nitrogen. The base pressure was less than $3 \times 10^{-9}$ mbar. The partial oxygen base pressure measured using a mass spectrometer showed a value less than $0.1 \times 10^{-10}$ mbar. The Nb, Co and Py sputtering targets were 99.95 % pure, deposited under Ar pressure of 0.5 Pa, in an in-plane magnetic field $H$ of approximately 400 Oe. Under these conditions the F layer in the bilayer structures grown had a strong magnetic anisotropy showing easy and hard axes anisotropy and coercive fields of about 35 and 16 Oe for the Co and 4.5 and 1.2 Oe for Py respectively. Several bilayer structures with Nb thickness $d_{Nb} = 25$ nm (i.e. of twice the superconducting low temperature coherence length, $\xi_S \approx 12$ nm) and Co thickness, $d_{Co}$, between 2 and 50 nm were made where $d_{Co} \gg \xi_{Co} \approx 0.3$ nm, the ferromagnet’s coherence length. The interface RMS roughness, measured using AFM, was about 0.3 nm. The superconducting transition temperature $T_C$ for these Nb/Co bilayer structures determined by four point resistivity measurements either with the field perpendicular to the track or normal to the superconducting state determines the value of the critical current ($I_{dp}$). The small voltage onset below $I_{dp}$ is due to vortex motion, unavoidable close to $T_C$.

First Nb/Co bilayers were patterned into tracks along the hard axis direction of the ferromagnet and then inplane critical current measurements were made with the field parallel to the track. Between a Cobalt thickness of 2 nm and 30 nm no appreciable changes in critical current in Nb/Co bilayer structures were observed. However, for a ferromagnet thickness $d_F \geq 30$ nm critical current measurements exhibit sudden drops at fields of the order of the coercive and saturation fields. The dips observed on a 25nm Nb on 42 nm Co, depicted in Fig. 4 for a sample of 25 nm Nb on 50 nm Py (Nb(25)/Py(50)), is observed at the same field range for each of the samples where the dips occur. Note that in our experiments both critical configurations for doing four point measurements of narrow tracks include; the voltage contacts within the same structure and current tracks with sharp edges. Due to the presence of the ferromagnet in the S/F hybrid-structures the free surfaces from, the voltage contacts or sharp edges, perpendicular to the ferromagnet’s magnetization form free magnetic poles which effectively act as “external magnets”. Depending upon the geometry and type of ferromagnet used these source of stray fields affect the superconductor to a lower or greater extent.

The current track was patterned using a mask without sharp edges at the center, where the measurements are made. The shape of the mask should mean that if there are free poles they contribute very little stray fields to the measurement section of the track. The voltage is measured using non magnetic Cu contacts. These prevent the wires acting as “external magnets”. The center of the mask used to make the device is shown in Fig. 1. The geometry of the designed mask for the photolithography consists of three different current tracks of 2, 5 and 7 $\mu$m wide (drawn in blue color). This allowed us to take measurements with different aspect ratios. Only further away from the center the tracks width gradually increases in size to avoid sharp edges. Non magnetic Cu contacts (black color), spaced $\approx 7$ $\mu$m, were deposited by sputter deposition in order to measure the voltage. This eliminates stray fields from the voltage contacts. The Cu contacts also play an important role in dissipating the heat generated by the Nb track in the normal state.

Current voltage (I-V) characteristics have been obtained. A plot of typical I-V characteristics at different temperatures is shown in Fig. 2. A clear jump from the normal to the superconducting state determines the value of the critical current ($I_{dp}$). The small voltage onset below $I_{dp}$ is due to vortex motion, unavoidable close to $T_C$.

Finally magnetoresistance measurements were made after stabilizing the temperature near $T_C$ at the transition region just above the zero resistance. A sudden increase in magnetoresistance as the one depicted in Fig. 3 for a sample of 25 nm Nb on 50 nm Py (Nb(25)/Py(50)), is observed at the same field range for each of the samples where the dips occur. Note that in our experiments both critical
Fig. 1. Diagram of the mask used in experiment including dimensions in microns. The figures show an enlargement of the mask middle section. The current tracks pattern is drawn in blue and the voltage contacts pattern is drawn in black color. This mask gives the possibility to pattern tracks of three different widths: 7, 5, and 3 μm (zoomed view bottom the figure).

Fig. 2. Current-voltage characteristics, taken at zero field, shows when the normal state is reached. The largest value of current below the voltage onset defines the critical current value. I-V characteristics are shown for three different temperatures, dashed line indicates the normal state resistance.

In order to understand these results the I-V characteristics were analyzed close to \( T_C \) at the dip region. As shown in the inset in Fig. 5 when the applied field is increased from -25 Oe towards -30 Oe where the dip in critical current takes place a voltage onset below the normal critical current value is observed indicating that vortex motion is involved. Because the measurements are made in a Lorentz force free configuration (current parallel to the field) this vortex motion indicates the presence
of vortices perpendicular to the plane which causes this voltage onset. These are shown in the inset of Fig. 3.

3 Analysis of Results

In this letter we present a mechanism by which the experimental observations can be explained. As pointed out previously the magnitude of the dips depends on the ferromagnet’s thickness and are only observable beyond a thickness of the ferromagnet of the order of thickness where domain walls of the ferromagnet, Co or Py, are thought to gradually mutate from being in plane i.e. Néel domain walls towards the out of plane direction Bloch domain walls. At the range of film thickness; between 35 to 100 nm the domain structure is formed by cross tie domain walls.

For Co films with a thickness of 50 nm cross-tie domain walls have been experimentally confirmed using magnetic force microscopy [1]. In this case Bloch lines are located periodically with alternating polarity, i.e. pointing outwards or inwards producing strong stray fields in this direction, resembling a checkerboard of antiparallel stray fields.

Similar observations for Py films in the domain structure, were found using the Kerr effect, for thicknesses between 30 and 200 nm [14]. The out of plane stray field above a Bloch line can be roughly estimated for 50 nm Co films based on the observations reported in [1]. Here each Bloch line has an approximate width \( \delta \approx 0.15 - 0.3 \mu m \) with magnetic fields > 2800 Oe and a magnetic flux between 3-13 \( \Phi_0 \), where \( \Phi_0 \) is the flux quantum. Moreover considering the number of Bloch lines, pointing in the same direction, divided by the interface area, an out of plane effective field of \( H_{c_{\text{eff}}}^{BDW} \approx \pm 48 \text{ Oe} \) is calculated (this is the maximum value of stray field used later as \( B_o \) parameter in Eq. 1). Since the lower critical field for a thin Nb film \( H_{c1}(0) \) in the out of the plane direction is about 10-20 Oe, vortex formation perpendicular to the film is expected.

Furthermore due to the fact that Bloch lines are antiparallel to one another a 2D vortex-antivortex array pinned by the domain walls must form as shown in the inset Fig. 3. Note also that as the film gets thicker the domains reduce in size, increasing the number of domain walls and Bloch lines that can fit in the same interface area [15] thus augmenting \( H_{c_{\text{eff}}}^{BDW} \) on the superconductor. These leads to a lower critical current as observed in our experiments after increasing the ferromagnet’s thickness.

To have a better understanding of the observed experimental effects the following simple model is employed. As the ferromagnet, initially in the remanent state, lowers its magnetization as result of an in-plane external field \( H \), the number of Bloch domain walls \( N \) increases augmenting the effective field \( H_{c_{\text{eff}}}^{BDW} \) (out of plane). This field reaches its maximum value \( B_o \) at coercive field \( H_c \) and begins to decrease for \( H > H_c \). This behavior has been modeled using the following expression:

\[
H_{c_{\text{eff}}}^{BDW} = B_o \left(1 - \frac{M(H)}{M_S}\right)
\]

where \( M_S \) is the saturation magnetization.

Using the value of \( H_c = 20 \text{ Oe} \) for a Co film and a value of \( B_o = 48 \text{ Oe} \) (estimated in the previous paragraph) for Eq. 1 a double peak structure of \( H_{c_{\text{eff}}}^{BDW} \) is obtained as shown in Fig. 6. This explains the results since when the ferromagnet is in a single domain state the patterned track is in a Lorentz force free configuration (i.e. current parallel to the field). However when the ferromagnet breaks into domains \( H_{c_{\text{eff}}}^{BDW} \) develops and the patterned track shifts to a Lorentz force configuration where the current is now perpendicular to \( H_{c_{\text{eff}}}^{BDW} \) resulting in a lower critical current measurement.

3.1 Discussion

The absence of any anomalous observations between Cobalt thicknesses 2 nm < \( d_{Co} < 30 \text{ nm} \), permits us to conclude that previous observations [4] were probably due to either stray fields from the device geometry or dipole stray fields.

Regarding the observations in magnetoresistance measurements made on Nb/Py bilayers [7], the observation of dips is accompanied by peaks in magnetoresistance measurements. These imply the presence of stray fields and thus should be considered in the interpretation of the results. Recently the same author reported additional results on Nb/Py bilayers [16], where two different thicknesses of Py were used; 20 and 60 nm. Here small dips and large peaks in magnetoresistance were respectively found. The experiment description indicates that the device geometry includes magnetic voltage contacts; thus is likely that
these dips are due to stray fields. However the large peaks for a Py thickness of 60 nm are explained by the authors in [10] as the result of Bloch domain wall stray fields. This result is qualitatively similar to the one shown in Fig. 4 and previously described on [17] by the present author. The main difference to our results is the two step structure observed in figures 4 and 5.

Although the previous suggested mechanism in the research investigations [17,10] (the enhancement of superconductivity at the domain walls i.e. DWS) is probably correct, we believe that an unambiguous experimental evidence of DWS has not yet been successfully produced.

4 Conclusions

In summary the dips between coercive field and saturation come as a result of vortex-antivortex 2D lattice formation (perpendicular to plane) which reduces the critical current. These are the result of Bloch lines formed with strong antiparallel stray fields at the domain walls. Increasing the field further and fully magnetizing the sample (where Bloch domain walls are absent) results in a re-entrant behavior to superconductivity as seen in magnetoreistance measurements. Similar properties of so called field-induced superconductivity (FIS) have only been realized by magnetic dots array deposited on top of a superconducting Pb film [15] and in 50 nm Niobium films deposited on the single crystal ferrimagnet BaFe12O19. Both experiments were performed with a magnetization along the perpendicular direction and with an insulator between the superconductor and ferromagnet [19].

Our inference of Bloch domain induced 2D vortex-antivortex array in the superconductor makes it possible to experimentally investigate 2D vortex crystal lattice without the need of superconductors with unconventional pairing symmetry or π- Josephson junctions configurations [20].

In both critical and magnetoresistance measurements two sharp steps in the region where dips and peaks are observed indicate an abrupt reconfiguration of the 2D vortex-antivortex array. These two well defined vortex arrangements deserve further investigation, for example using scanning tunnelling microscopy (STM) with resolution on the nm scale to visualize the vortex dynamics as this could be of great interest for both applied and fundamental research.

Finally, by confining superconductivity to nano dimensions ≤ 2ξS together with the effect from Bloch domain wall formations makes these structures very sensitive to small magnetic fields. This opens up potential applications such as small field detectors and switching devices.

References

1. Z. Radović, M. Ledvij, L. Dobrosavljević-Grujić, A.I. Buzdin, and J. R. Clem, Phys. Rev. B 44, 759 (1991).
2. V. V. Ryazanov, V. A. Oboznov, A. Y. Rusanov, A. V. Veretennikov, A. A. Golubov, and J. Aarts, Phys. Rev. Lett. 86, 2427 (2001).
3. J. S. Jiang, D. Davidović, Daniel H. Reich, and C. L. Chien, Phys. Rev. Lett. 74, 314 (1995).
4. R. J. Kinsey, G. Burnell and M. G. Blamire, IEEE Trans. Appl. Supercond., 11, 904, (2001).
5. M. Houset and A. I. Buzdin, Phys. Rev. B 74, 214507, (2006).
6. A. Rusanov, M. Hesselberth, S. Habraken and J. Aarts, Physica C, 404, Issue 1-4, 322 (2004).
7. A. Yu. Rusanov, M. Hesselberth, J. Aarts and A. I. Buzdin, Phys. Rev. Lett. 93, 57002 (2004).
8. V. V. Ryazanov, V. A. Oboznov, A.S. Prokof’ev, and S. V. Dubonos, JETP Lett. 77, 39 (2003).
9. I. S. Burmistrov and N.M. Chulketchkachev, Phys. Rev. B, 72, 144520 (2005).
10. R. Steiner and P. Ziemann, Phys. Rev. B, 74, 94504 (2006).
11. C. Bell, S. Tursucu and J. Aarts, Phys. Rev. B, 74, 214520 (2006).
12. In most of our measurements well bellow Tc we did not observed flux flow at the dip region but an abrupt reduction of the critical current value. However as shown in Fig. 5 close to Tc the pinning barrier is easily overcome by thermal activation.
13. M. Löhndorf, A. Wadas, H. A. M. van den Berg, and R. Wiesendanger, Appl. Phys. Lett., 68, 25, (1996).
14. S. Methfessel, S. Middelhoek, H. Thomas, IBM Journal, 96, (1959).
15. A. Stankiewiczysz, S. J. Robinsonsz, G. A. Gehringzx and V. V. Tarasenkoy, J: Phys: Condens. Matter 9,10191030, (1997).
16. A.Yu. Rusanov, T.E. Golikova, and S.V. Egorov. JETP Lett. 87, 175 (2008)
17. E. J. Patiño, “Study of the Influence of Domain Walls in The Superconductor/Ferromagnet Proximity Effect”. Ph.D Thesis [Non-Published], Cambridge University, (2005).
18. M. Lange, M. J. Van Bael, Y. Bruynseraede, and V. V. Moshchalkov, Phys. Rev. Lett. 90, 197006 (2003).
19. Z. Yang, M. Lange, A. Volodin, R. Szmyczak and V. V. Moshchalkov, Nature Mat. 3, 793, (2004).
20. H. Hilgenkamp, Ariando, Henk-Jan H. Smilde, Dave H. A. Blank, G. Rijnders, H. Rogalla, J. R. Kirtley and C. C. Tsuei, Nature 422, 50 (2003).