Current-driven transitions in ferromagnetic/insulator/superconductor narrow stripes

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(Received 23 July 2009; accepted 2 September 2009; published online 23 September 2009)

We have studied superconducting to normal state current-driven transitions in ferromagnetic Co/Co oxide/superconducting In stripes of widths ranging from 3 to 20 μm. The narrower stripes can be set up in a high or low critical current state by driving the magnetic domain structure of the thin Co film either in an almost uniform or nonuniform state of magnetization. In the latter the critical current transition is preceded by the development of normal domains, whose dynamics are determined by the Co magnetization pattern. © *2009 American Institute of Physics*.
[doi:10.1063/1.3236780]

Over the past decade, there has been great interest in hybrid superconducting ferromagnetic (S/F) layers. Several interesting effects were measured: the spin-valve effect in F/S/F structures,[1–4] the inverse spin-valve effect,[5–9] and domain wall superconductivity.[6,7] These effects are related to the relative magnetization of the ferromagnetic layers in F/S/F structures, and in S/F structures they are related to the domain structure inside the magnetic layer. These studies have employed devices with a good electrical contact between the layers, leading to proximity effects. The case where there is a poor electrical contact has not been considered. In this work we investigate the effect that the stray fields alone have on the properties of the superconductor at currents close to the superconducting critical current. We explore the dynamics of the current-induced transition from the superconducting state to the normal state in different configurations of the stray fields and as a function of stripe width. Our main results are that when the stripe is driven into a state where domain walls extend across its width, the critical current is reduced by a factor of about 2, and the transition is preceded by a regime where well-defined normal regions appear and disappear on a time scale of milliseconds.

We fabricated ferromagnetic Co/Co oxide/superconducting In layers in a bar geometry allowing a 4-wire measurement. The stripes were defined by standard optical lithography. The Co was evaporated first at room temperature using an e-beam evaporator with a base pressure of 10^{-8} Torr. After exposing the Co layer to get its surface oxidized, the In was evaporated at 77 K using a thermal source. Thicknesses and resistivities of the films were 20 nm and 20 $\mu\Omega$ cm (Co), and 60 nm and 6 $\mu\Omega$ cm (In). The stripes had widths of 3, 5, 10, and 20 μm. Measurements were carried out in a He^4 immersion cryostat down to a temperature of 1.5 K. All stripes have a critical temperature (T_c) of 3.8 K, the same T_c as that of a bare In thin film. This shows that proximity effects have little or no effect on the system. The magnetic behavior above T_c is shown in Fig. 1, with the magnetic field applied parallel to the stripe. Measurements were performed in two different states, a state of almost uniform (AU) magnetization reached by applying a field higher than the coercive field and then reducing it to zero, and a state of nonuniform (NU) magnetization where domain walls were introduced by reversing the field just below the coercive field and then reducing it to zero.[10] The device can be switched from one state to the other above or below T_c. Apart from preventing proximity, the CoO has an additional effect of pinning the domain walls.[11] This helps to keep the domain walls inside the stripe when the field is lowered to zero.

The main contribution to the magnetoresistance of a ferromagnet is the relative direction of the magnetization in the film and the current. When the width of a ferromagnetic stripe is lowered close to the size of a magnetic domain the magnetization tends to align along the stripe at zero external field. We define $R_{AU/NU}$, as the resistance in the AU state/NU state, R_{H_c} as the resistance at the coercive field, and R_{sat} as the resistance at fields substantially higher than the coercive field. When the stripe gets wider than the size of a magnetic domain the ratio $(R_{AU}-R_{sat})/(R_{H_c}-R_{sat})$ should increase.[10] The tendency to align also means that for the narrow stripes the resistance in the NU state will gradually approach that of the AU state so the ratio $(R_{AU}-R_{NU})/(R_{AU}-R_{H_c})$ should decrease as we approach the domain size. Figure 1 shows these ratios for our stripes, which reveals that when the stripe width falls below 10 μm the stripe is approaching the size

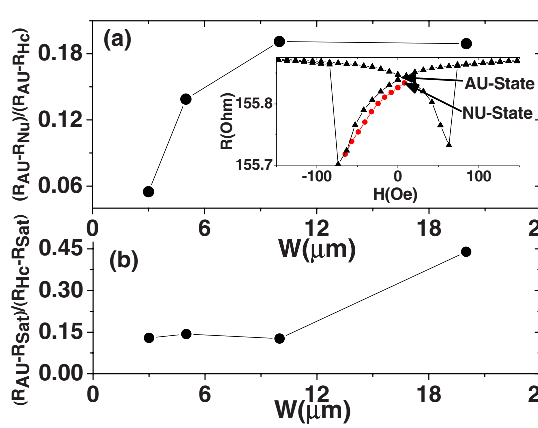

FIG. 1. (Color online) Ratios between resistances showing that when the stripe width falls below 10 μm, the stripe is approaching the size of a magnetic domain. The inset is a measurement of the resistance as a function of magnetic field at 4.2 K for a 5 μm stripe. It shows how the AU state and the NU state, indicated by the arrows, are reached.

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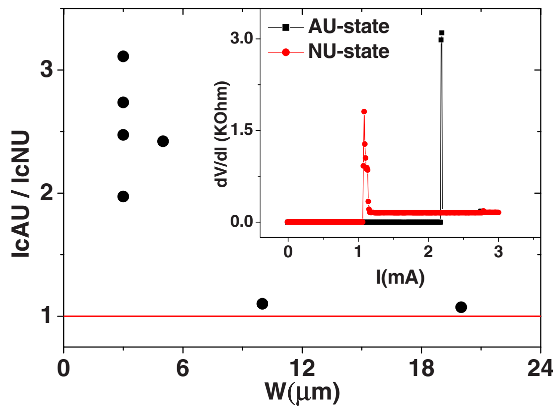

FIG. 2. (Color online) Ratio between the critical current in the AU state and the NU state as function of stripe width at 1.5 K. (inset) Differential resistance of a 3 μm wide stripe in the AU state and the NU state at 1.5 K. The AU state and NU state have critical currents of $I_{c,\mathrm{AU}}=2.2$ mA and $I_{c,\mathrm{NU}}=1.1$ mA.

of a magnetic domain. In the NU state, domain walls extend across the stripe width, creating the stray field configuration effects that we describe below. We measured the critical current (I_c) of the samples at 1.5 K in the two states. The inset of Fig. 2 shows that the critical current in the NU state ($I_{c,\mathrm{NU}}$) is lower by a factor of 2 than the critical current in the AU state ($I_{c,\mathrm{AU}}$), T_c is the same in both states. Figure 2 shows that the reduction in the critical current in the NU state is only effective at stripe widths smaller than 10 μm, on the order of the magnetic domain size.

To get a better understanding of the dynamics of the transition we measured the voltage as a function of time at currents just below I_c in each of the two states. In the NU state we observed voltage jumps at discrete steps as can be seen in the left panel of Fig. 3, corresponding to a few ohms per step. When the magnetization is rearranged into a new NU state the number of steps observed can change. In the AU state the behavior is different. Driving a current close to $I_{c,\mathrm{AU}}$ the voltage remains zero up to a certain time of the order of a few seconds where a spontaneous transition occurs and the whole stripe is driven into the normal state and stays there as long as the current is kept on; this is shown on the right panel of Fig. 3. The spontaneous transition occurs at

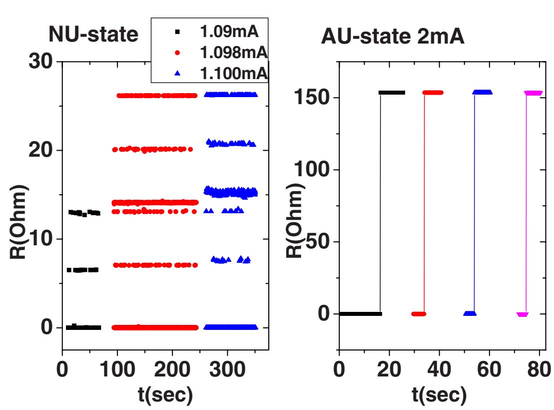

FIG. 3. (Color online) Voltage as a function of time for a 3 μm stripe at constant currents close to I_c in the two states. The voltages are divided by the current being driven and are shown in units of ohms. (Left panel) Discrete voltage jumps in the NU state for three different currents. (Right panel) spontaneous transitions in the AU state at a current of 2.0 mA. The data change color every time the current was switched off and back on again.

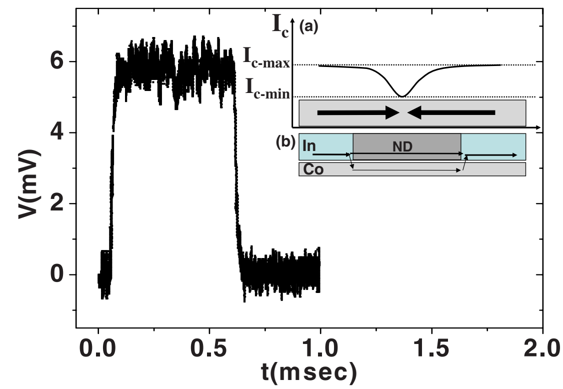

FIG. 4. (Color online) Voltage as a function of time in the NU state measured using a scope on the same stripe as shown in Fig. 3. The measurement shows one of the voltage jumps corresponding to a normal domain developing and collapsing. (Inset) (a) Schematics of a critical current profile induced by the structure of a magnetic domain wall. The bold arrows indicate the magnetization in the ferromagnetic layer. (b) (Side view) Schematic illustration showing that at places where a normal domain develops a small part of the current is pushed out into the Co film. The small arrows show the current flow.

currents within 10% below $I_{c,\mathrm{AU}}$, whereas to measure the voltage steps in the NU state it is necessary to drive a current within 1% below $I_{c,\mathrm{NU}}$. Flux jumps are observed at currents within 10% below $I_{c,\mathrm{AU}}$ and 1% below $I_{c,\mathrm{NU}}$. The voltage steps in Fig. 3 appear only in the narrow stripes that show a large difference between the critical currents in the two states. A better time resolution of one of the voltage steps is shown in Fig. 4, the voltage at the plateau corresponds to the first step in the left panel of Fig. 3. The duration of the step is half a millisecond, but the duration of most of the steps was much longer ranging up to hundreds of milliseconds. We attribute the finite voltage steps seen close to $I_{c,\mathrm{NU}}$ to the formation of normal domains in the In film due to stray fields generated at Neel domain walls in the Co film. When the stripe width is of the order of a magnetic domain size, these stray fields are highly NU along the stripe and cut across the stripe width. They generate local nucleation of normal regions in the In layer. If the current is high enough, then a normal domain can develop across the width of the In layer.

Normal domains in current-carrying superconductors expand or shrink depending on the current and cooling conditions.[12] If a shunt exists then the current being driven can bypass the normal domain stopping its expansion through the stripe and stabilizing it. Without a shunt normal domains are unstable. In our samples the Co in parallel to the superconducting In is a poor shunt. Its resistance per unit length is an order of magnitude higher than the In in the normal state, $(\rho_{\mathrm{Co}}/d_{\mathrm{Co}})/(\rho_{\mathrm{In}}/d_{\mathrm{In}})=10$, where ρ_{Co} and ρ_{In} are the resistivities and d_{Co} and d_{In} are the thicknesses of the Co and In layers, respectively. In addition there is the oxide layer, which gives additional contact resistance. The contact resistance is $\sim 10^{-6}$ Ω cm^2 measured independently in Co/In contacts in a cross geometry similar to previous work.[13] If a normal domain develops then only a few percent of the current can bypass it through to the Co. However in our case the pattern of stray fields induced in the stripe can act as the dominant stabilizer for the domains. Consider the simplified situation illustrated in the inset of Fig. 4. The magnetic pattern creates regions with lower critical current $I_{c_{\min}}$ and higher critical current $I_{c_{\max}}$. When the current is between $I_{c_{\min}}$

and $I_{c_{\max}}$ domains can start to develop. If there is no strong overheating, even in the complete absence of a shunt, a domain developing at a nucleation center will stop expanding at a region where the critical current of the In is high enough. This size will be roughly a magnetic domain size. The size of the voltage steps corresponds to normal domain sizes of $\sim 15\ \mu$m, roughly the magnetic domain size of our samples. In stripes wider than the domain size the normal domains will not occupy the whole cross section of the stripe and the effect will be absent.

For the domain to shrink back there has to be some mechanism for cooling. The ratio of the typical values of the Joule heating and cooling by liquid helium can be estimated as[12] $\alpha=\rho_n j_c^2 d/\Delta T h$, where $\rho_n=6\ \mu\Omega$ cm is the In resistivity, $j_c=5\times 10^5\ \mathrm{A/cm^2}$ is the critical current density, $d=60$ nm is the thickness, $\Delta T\approx 3$ K is the temperature difference between the coolant and the sample, and $h\sim 1\ \mathrm{W/cm^2\,K}$ (Ref. 14) is the heat transfer coefficient. If $\alpha>1$ then the normal state is stable and if $\alpha<1$ then the superconducting state is stable. We are in the borderline case of $\alpha\approx 1$, so even a small additional cooling could have an effect. The Co is a high resistance bypass but there still is a few percent of the current bypassing the normal domain into the Co. This gives a mechanism for some cooling and sets the domains finite lifetime.

In summary we showed that by changing the magnetization pattern of the ferromagnetic layer we can change the dynamics of the superconducting to normal state current driven transition in Co/Co oxide/In bilayers. The dynamics are governed by the stray fields, which induce nucleation centers. They act as seeds for normal domains, which can shrink or develop to occupy the whole stripe. When the stripe width is roughly the size of a magnetic domain, normal domains extending across the stripe can develop in the In layer when the Co layer is in a state of NU magnetization. Apart from the dynamics the device is a low field operated switch. Below T_c the switch has two states: a resistive state (NU state) and a nonresistive state (AU state). The switching can be performed above or below T_c by applying relatively low fields, changing the temperature does not affect the states, thus making the switch nonvolatile. The switch is probed below T_c by driving a current between $I_{c,\mathrm{NU}}$ and $I_{c,\mathrm{AU}}$. Even more interestingly patterning the stripes into wider and narrower regions could give control over the number of steps at currents just below $I_{c,\mathrm{NU}}$ or gain control over the number of regions of high and low critical current.

This work was supported in part by the Israel National Science Foundation (Grant No. 481/07).

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