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Flux triggered normal to superconducting transitions in F/I/S narrow stripes

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ABSTRACT

We studied superconducting to normal state current-driven transitions in Ferromagnetic Cobalt/Cobalt Oxide/Superconducting Indium stripes of widths ranging from 3 μm 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 non-uniform state of magnetization. In the first case in slightly sub critical currents there is a spontaneous superconducting to normal state transition. In the latter the transition is preceded by the development of normal domains. The spontaneous transition as well as the normal domains are triggered by flux jumps.

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Superconducting ferromagnetic (S/F) layers have recently attracted a lot of attention. Several interesting effects were measured: the spin-valve effect in F/S/F structures [1–4], the inverse spin-valve effect [5,8,9] 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 show 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. We show that these transitions are triggered by flux jumps.

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 μΩ cm (Co) and 60 nm and 6 μΩ cm (In). The stripes had widths of 3 μm, 5 μm, 10 μm and 20 μm.

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. Critical current measurements were performed in two different states, a state of almost uniform (AU) magnetization reached by applying a field substantially higher than the coercive field and then reducing it to zero, and a state of non-uniform (NU) magnetization where domain walls were introduced by reversing the field just below the coercive field and then reducing it to zero [10]. 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. Fig. 3 shows that the critical current in the NU-state ($I_{c,NU}$) is lower by a factor of 2 than the critical current in the AU-state ($I_{c,AU}$). The reduction of the critical current in the NU-state is only effective at stripe widths smaller than 10 μm.

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. 1, corresponding to a few ohms per step. When the magnetization is rearranged into a new NU-state the number of steps observed can change. Using measurements of higher time resolution the dispersed points were verified to be due to the internal averaging of the voltmeter. The voltage steps in Fig. 1 appear only in the narrow stripes that show a large difference between the critical currents in the two states. In the AU-state the behavior is different. Driving a current close to $I_{c,AU}$ after a certain time of the order of a few seconds a spontaneous transition occurs and the whole sample 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. 1. The spontaneous transition occurs at currents within 10% below $I_{c,AU}$, whereas to measure the voltage steps in the NU-state it is necessary to drive a current within 1% below $I_{c,NU}$.

We previously showed [11] that the dynamics are governed by stray fields, which induce nucleation centers. They act as seeds for normal domains [12] which can shrink, thereby giving rise to the

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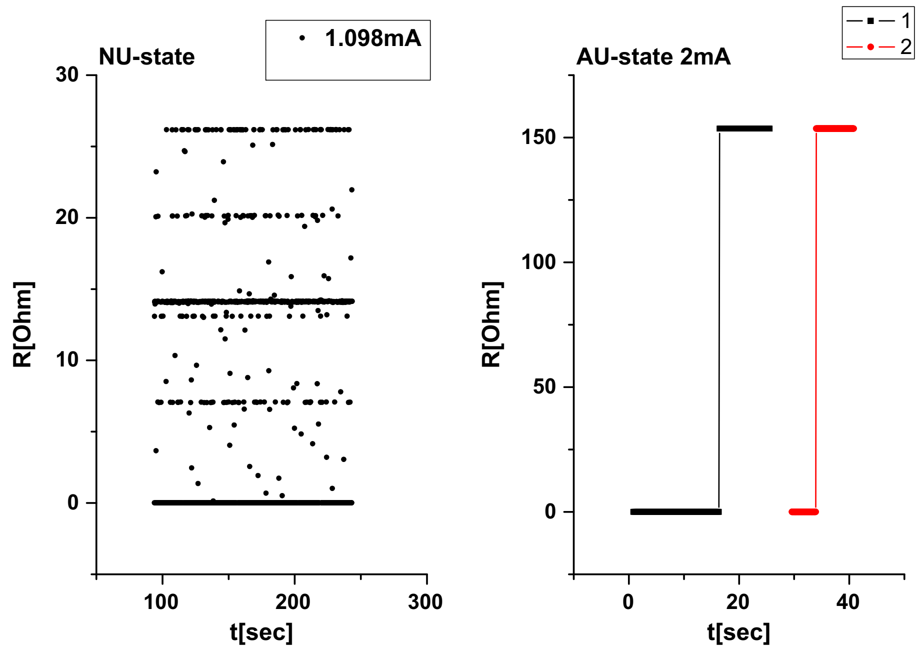

Fig. 1. Voltage as a function of time for a 3 μm stripe at constant currents close to I_c in the two states. The voltages are divided by the current being driven and are shown in units of Ohms. Left panel – discrete voltage jumps in the NU-state. Right panel – spontaneous transitions in the AU-state at a current of 2.0 mA. Between the colors the current was switched off and back on again. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

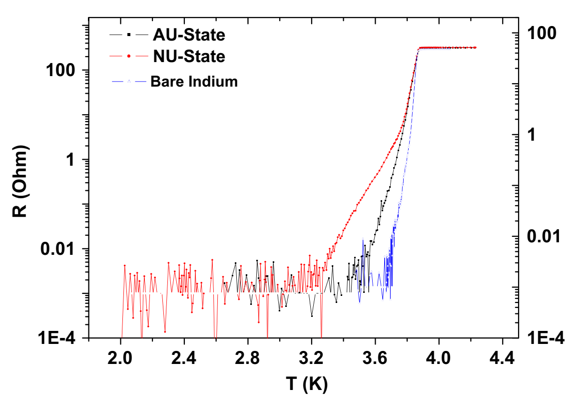

Fig. 2. Log scale resistance as a function of temperature for bare In and in the AU-state and the NU-state for a 3 μm stripe.

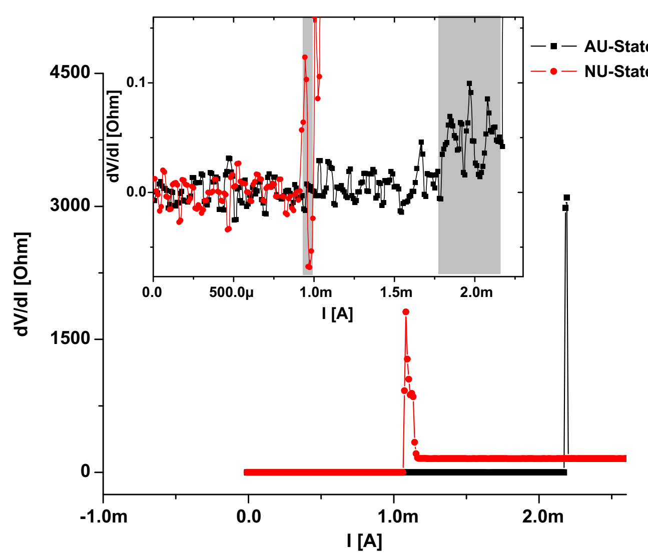

Fig. 3. Differential resistance of a 3 μm wide stripe in the AU-state and the NU-state at 1.5 K. The AU-state and NU-state have critical currents of $I_{c,AU} = 2.2$ mA and $I_{c,NU} = 1.1$ mA. Inset – enlargement of the main figure at low voltages. The grey areas show the current ranges with flux jumps.

finite voltage steps seen in the NU-state, or they can develop to occupy the whole sample giving rise to the spontaneous transition seen in the AU-state. The two transitions seem to be somewhat random in time. In the NU-state the steps seem to appear and go with no periodic time scale. In the AU-state the transition seems spontaneous in time. Here we show that flux jumps trigger the transitions.

The log scale of the resistance as a function of temperature in Fig. 2 shows that although T_c is the same in the two states and equal to T_c of bare In thin film, the transition is widened towards the end with extra resistance. The transition of bare In thin film is ~0.1 K. The transition in the NU-state is wider than in the AU-state. This indicates that there is flux in both states, but there is more flux free to move in the NU-state. The inset of Fig. 3 shows that there are flux jumps within 10% below $I_{c,AU}$ and within 1% below $I_{c,NU}$. These are the current ranges where the transitions in the NU-state and AU-state occur, which means that the trigger for the current-driven transition are the flux jumps.

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 layers. There are two types of dynamics, a spontaneous transition and a transition preceded by normal domains. We showed that the transitions are both triggered by flux jumps.

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