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Critical current of a superconductor measured via injection of spin-polarized carriers

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Abstract. In this paper we report direct evidence of the suppression of critical current due to pair breaking in a superconducting micro-bridge when the measurement is carried out by injecting spin-polarized carriers instead of normal electrons. A thin layer of $La_{0.7}Ca_{0.3}MnO_3$ was used as the source of spin-polarized carriers. The micro-bridge was formed on the $DyBa_2Cu_3O_{7-\delta}$ thin film by photo-lithographic techniques. The design of our spin-injection device allowed us to inject spin-polarized carriers from the $La_{0.7}Ca_{0.3}MnO_3$ layer directly to the $DyBa_2Cu_3O_{7-\delta}$ micro-bridge (without any insulating buffer layer), making it possible to measure the critical current when polarized electrons alone are injected into the superconductor. Our results confirm the role of polarized carriers in breaking the Cooper pairs in the superconductor.

The half-metallic nature [1, 2] of hole doped rare-earth manganites of the form $R_{1-x}A_xMnO_3$ (R = rare-earth, A = bivalent cation) provides a reserve of spin-polarized electrons whose charges as well as spins can be utilized by integrating them in unconventional devices. Towards this end, several prospective applications such as tunnelling magnetoresistance devices with both positive and negative magnetoresistance [3, 4] as well as 'spin injection' devices using a high temperature superconducting layer on the top of a ferromagnetic layer have been proposed [5–9]. In a spin injection device, polarized carriers from a half-metallic ferromagnetic layer are injected into the superconductor through a thin insulating layer. It has been demonstrated that this results in a suppression of critical current in the superconducting layer due to the breaking of the time-reversal symmetry of the Cooper pairs via the polarized electrons. This is analogous to the pair breaking effect caused by magnetic field in a superconductor.

Earlier experiments on spin injection in superconductors [7–9] were carried out by injecting the polarized spins from the ferromagnetic layer through a thin insulating barrier. The necessity of the insulating layer stemmed from the particular geometry of the devices used in those studies. However, the possibility of Joule heating due to the passage of the current through the insulating layers in those experiments restricted the magnitude of the injection current that could be passed from the ferromagnet to the superconductor. For the same reason the current versus voltage (I–V) characteristics by the passage of spin polarized quasiparticle current alone were not reported in those devices. Moreover, since in all these devices the superconducting layer was placed directly on the top of the ferromagnetic layer (and separated by an insulating barrier), vortex nucleation inside the superconductor due to the local field of

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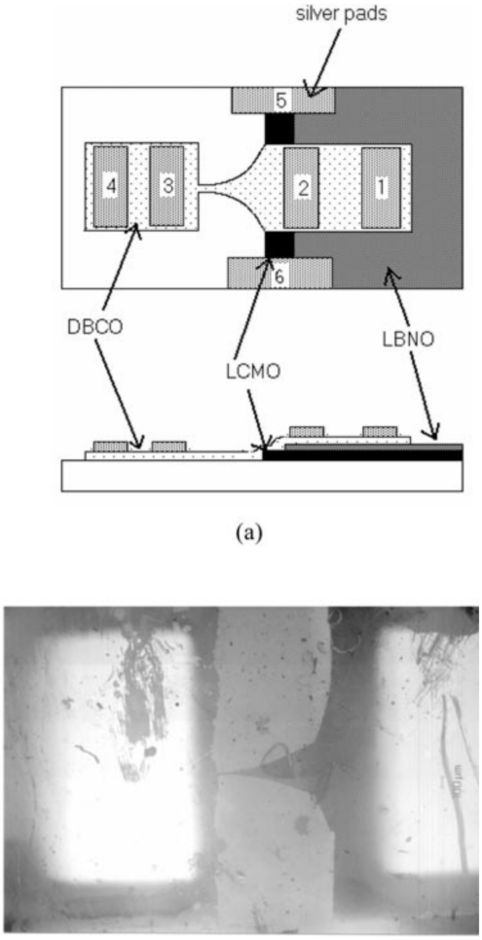

(a)

(b)

Figure 1. (a) Schematic construction of the spin injection device. (b) Optical photograph of the superconducting micro-bridge fabricated through photolithography.

the ferromagnetic layer could not be ruled out. That this is a possibility is suggested from the observed increase in critical current of the superconductor with increasing insulating layer thickness [9].

In this work, we report the I–V characteristic of the superconductor when spin-polarized current alone is passed through a thin superconducting micro-bridge. The spin-polarized current in the present device is injected directly from the ferromagnet to the superconductor without any insulating barrier. The schematic diagram of the device used for our experiments is shown in figure 1(a). The device was fabricated by first depositing a $La_{0.7}Ca_{0.3}MnO_3$ (LCMO) layer (1000 Å) on half of the single crystalline $LaAlO_3$ substrate using pulsed laser deposition (PLD) while covering the remaining half by a metal (SS304) mask. Subsequently a thin insulating layer (300 Å) of La_2BaNbO_6 (LBNO) was deposited on the LCMO layer using PLD by positioning the metal mask such that a 0.5 mm strip of LCMO near the middle of the substrate is not covered by the insulator. Subsequently, a superconducting layer of $DyBa_2Cu_3O_{7-\delta}$ (DBCO, 1000 Å thickness) was deposited on the entire substrate. X-ray diffraction θ–2θ

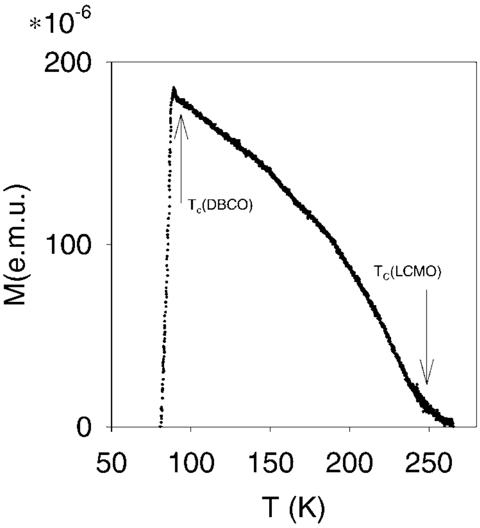

Figure 2. Magnetization versus temperature of the device measured on a vibrating sample magnetometer in a field of 4 kOe. The arrows show the ferromagnetic and superconducting transition temperature of the LCMO and DBCO layers respectively.

scans on the device confirmed that all three layers were oriented with c-axis perpendicular to the substrate. A micro-bridge (10 μm wide) was patterned on the superconducting film (figure 1(b)) using photolithography. The micro-bridge was positioned such that the narrowest region of the micro-bridge was directly on the $LaAlO_3$ substrate. This precaution was taken to remove a possible proximity effect (which will be significant within a length scale of the order of the coherence length ξ) of the LCMO layer, on the critical current of the superconductor. Four silver pads were deposited by evaporation on the DBCO layer for attaching the leads (leads 1–4 in figure 1(a)) to measure the critical current of the superconducting layer. A fifth silver pad (lead 5 in figure 1(a)) was deposited on the bare LCMO layer and was used for the injection of the polarized spin. Finally another silver pad (lead 6) was placed symmetrically with lead 5 on the bare LCMO layer to measure the contact resistance between the LCMO and the DBCO layer. The large silver pads (more than 100 times in width compared to the micro-bridge) both on the superconductor and on the LCMO layer ensured that the heating due to contact resistance was kept to the minimum during the measurements. The normal critical current (I_c) of the superconductor was measured by passing the current between 1 and 4 and measuring the voltage between 2 and 3. The critical current with spin-polarized current ($I_{c(pol)}$) was measured by injecting the current through 5 and 4 and measuring the voltage between 2 and 3. The insulating LBNO layer [10] ensured that the spin-polarized quasi-particles were injected into the superconductor in the vicinity of the micro-bridge.

The ferromagnetic transition temperature (T_{Curie}) of the LCMO layer was measured by measuring the magnetization as a function of temperature (M–T) using a vibrating sample magnetometer in a field of 4 kOe (figure 2). The T_{Curie} determined from the maximum in the double derivative of the M–T curve was at 245 K. Below 87 K, there was a sharp drop in the magnetization due to the superconducting transition (T_c) of the DBCO layer. The T_c of the superconducting film was also confirmed from resistance versus temperature (R–T) measurement. Figure 3(a) shows the R–T curve of the superconducting layer measured by passing a current of 100 μA through 1 and 4 and measuring the voltage between 2 and 3.

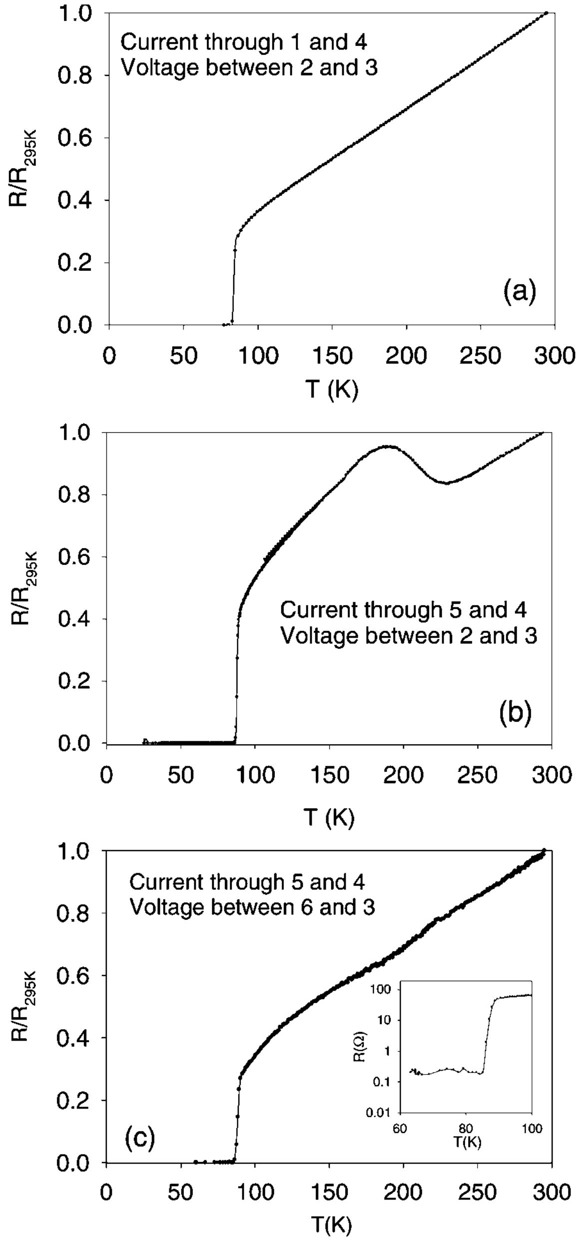

Figure 3. Normalized resistance versus temperature of the superconducting micro-bridge measured between 2 and 3 by passing current through (a) 1 and 4; (b) 5 and 4. (c) Normalized resistance versus temperature of the superconducting micro-bridge measured between 6 and 3 by passing current through 5 and 4; inset, an enlarged view of the resistance versus temperature close to T_c.

The sharp transition (<2 K) confirms the high quality of the superconducting film. No significant change in T_c was observed when the measurement was made by passing the same current through 5 and 4 (figure 3(b)) (voltage between 2 and 3). In order to measure the contact resistance between the LCMO and the DBCO interface we also measured the voltage between

6 and 3 while passing current between 5 and 4 (figure 3(c)). The residual resistance ($\sim$200 mΩ) below the superconducting transition (inset, figure 3(c)) gives the contact resistance between the LCMO and the DBCO layer in the temperature range of our spin injection experiments. For our experiments where the injection current was always less than 10 mA this gives a Joule heating of the order of 2 μW. By looking at the shift in the resistance value in the same temperature range due to self-heating on a $La_{0.7}Ca_{0.3}MnO_3$ film by passing different currents, it was concluded that this would give less than 0.2 K temperature increase of the sample at the maximum injection current. The insensitivity of the measured T_c to the injection of polarized current requires further consideration and will be discussed later.

Figures 4(a) and 4(b) show the I–V characteristic of the superconductor measured by passing normal current and spin-polarized current respectively. As an added precaution the measurements were carried out by passing short pulses ($\sim$1 s duration) of current (up to 100 mA), in order to avoid Joule heating at the current contacts. Two distinct features are observed when the I–V curves measured by passing polarized spins:

(i) The drastic suppression in critical current compared to the case when the measurements are carried out with normal current (passed between 1 and 4).

(ii) The sharp rise in the voltage when the current reaches the critical current.

Figure 4(c) shows the critical current as a function of temperature with normal (I_c) and spin-polarized current ($I_{c(pol)}$). In the same figure we have plotted the ratio $I_c/I_{c(pol)} (= f)$ as a function of temperature, which is a measure of the pair breaking efficiency by the polarized spins. This quantity increases with decreasing temperature signifying that the pair breaking by spin-polarized electrons becomes more efficient at low temperatures.

In a superconductor with no current the electrons are coupled in pairs via time reversal symmetry which requires that their wave-vectors are $\boldsymbol{k}\uparrow$ and $-\boldsymbol{k}\downarrow$ where $\uparrow$ and $\downarrow$ denote spin up and down respectively. When a normal current is passed through the superconductor the wave-vectors are modified as $-\boldsymbol{k}+\boldsymbol{q}\uparrow$ and $\boldsymbol{k}+\boldsymbol{q}\downarrow$ respectively (where $\boldsymbol{q}$ is dependent on the drift velocity of the super-electrons). The critical momentum of the carriers up to which the superconductor can support a current is given by $\hbar/\sqrt{3}\xi(T)$ [11], (where $\xi(T)$ is the Ginzburg–Landau coherence length at temperature T) above which the superconductivity is destroyed due to the vanishing of the energy gap. In an actual measurement of critical current (I_c), this limit is rarely achieved in high temperature superconducting film due the large size of the micro-bridge compared to the coherence length and due to the presence of weak links arising from the grain boundaries in the sample [12]. I_c varies with temperature as $(1 - (T/T_c))^{3/2}$. (Strictly speaking this mean field relation holds only at temperature close to T_c.) In addition to this, in the presence of a spin-polarized current, pair breaking occurs by the destruction of the time reversal symmetry caused due to the imbalance caused by injecting polarized spins. This is somewhat similar to the pair breaking due to a localized magnetic impurity, though significant difference exists. In the case of spin injection the polarized carriers will have a finite lifetime inside the sample after which the polarization will vanish due to various scattering mechanisms of the spin-polarized quasi-particles inside the superconductors. The temperature dependence of this spin diffusion lifetime of the carriers will depend on the mechanism of spin transport in the superconductor. From our data the increase in f with decreasing temperature clearly suggest that *pair breaking due to spin-polarized electrons becomes the dominant mechanism as the temperature is decreased below* T_c. This can be understood considering the geometry of our device. The critical current is measured at the narrowest point of the micro-bridge, whereas the spin is injected from the other end. The distance between the injection point of polarized spins and the narrowest point of the microbridge is around 100 μm. The pair breaking efficiency of polarized spins will depend on the fraction of spin-polarized quasi-particles

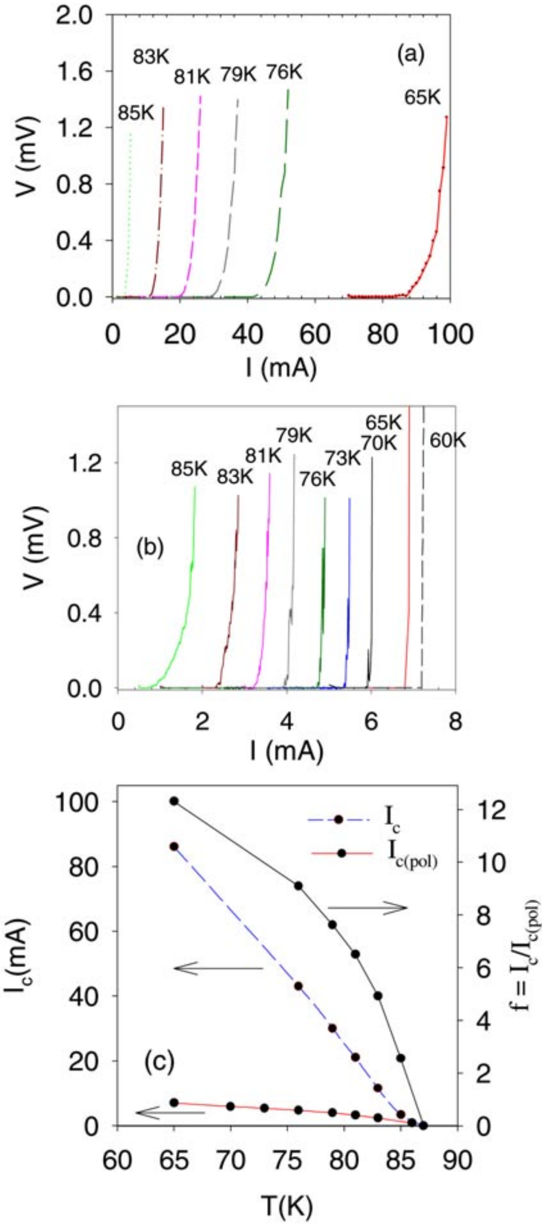

Figure 4. I–V characteristics of the superconducting micro-bridge measured by passing current through (a) 1 and 4; (b) 5 and 4. (c) Variation of I_c, $I_{c(pol)}$ and $f = I_c/I_{c(pol)}$ as a function of temperature.

actually reaching the microbridge, which in turn depends on the spin-polarized quasi-particle lifetime. Therefore, in a phenomenological way f reflects the temperature dependence of the spin-polarized quasi-particle lifetime in the superconductor. The increase in f with decreasing temperatures suggests that the spin-polarized quasiparticle lifetime increases with decreasing temperatures. Though the experimental data contain an uncertainty due to the existence of weak links between various grains in the superconductor, the qualitative behaviour of f is unlikely to be significantly modified by the presence of these junctions. A second source of uncertainty comes from the increase in spin polarization inside the ferromagnet as the temperature is lowered. However, all our measurements are carried out at temperatures less than $0.3T_{Curie}$ of the ferromagnet. We have shown earlier that in half metallic ferromagnets, the polarization $P = M_s(T)/M_s(T = 0) = m$, where M_s is the spontaneous magnetization of the ferromagnet [13]. The change in m from $T = 0.3T_{Curie}$ to $T = 0$ is of the order of 10% and is unlikely to account for the large increase in f observed below the T_c of the superconductor.

One interesting aspect of our experiment is the large spin diffusion length suggested from the distance between the injection point and the narrowest point of the microbridge. Though there has been no direct measurement of the spin diffusion length in high T_c samples, Yeh *et al* [9] have estimated this length to be of the order of 80 nm at T_c, which decreases as the temperature is lowered below T_c. They concluded that the spin-polarized quasiparticle lifetime diverges at T_c. On the other hand our experimental data suggests that the spin diffusion length is order of magnitudes higher and the spin-polarized quasiparticle lifetime increases with decreasing temperature. One difference between our experiment and the earlier experiments is that in our device structure the polarized spins are predominantly injected in the *a*–*b*-plane and not along the *c*-axis. The increase of spin-polarized quasiparticle lifetime with decreasing temperatures is however difficult to understand in terms of conventional non-equilibrium superconductivity where the quasiparticle relaxation time due to electron–phonon interaction diverges at T_c [11]. In general, the temperature dependence of spin-polarized carrier lifetime in a particular system will depend on the mechanism of spin transport. This mechanism is at present not well understood in high T_c cuprates due to the unconventional d-wave symmetry of the order parameter (giving rise to nodes in the superconducting energy gap) and the tendency for spin charge separation. In recent times several authors have also pointed out the role of Andreev reflection [14, 15] at the interface between the ferromagnet and the superconductor. In a conventional superconductor, at low applied voltages an electron with energy less than the superconducting energy gap ($eV < \Delta_0$) will be reflected back in the ferromagnet as a hole and a Cooper pair will propagate inside the superconductor. In the case of a half-metallic ferromagnet such as $La_{0.7}Ca_{0.3}MnO_3$, where the spin polarization is close to 100% the Andreev reflection will be strongly suppressed since the reflected hole occupies opposite spin band compared to the incoming electron. Therefore in the case of a superconductor with a uniform energy gap, Δ (such as an S-wave superconductor) the energy of the polarized excitations should be above the gap. However, in the case high temperature superconductors with d-wave symmetry single particle injection current can propagate even at low energies [15] through the nodes in the superconducting gap causing a more effective suppression in the critical current when spin-polarized current is injected.

Our experiment removes many of the possible artefacts which might have been present in the earlier experiments. Firstly, since the critical current is measured at the narrowest region of the micro-bridge which is far from the ferromagnetic layer compared to the penetration length (λ) and coherence length (ξ) the proximity effect and self-injection of polarized carriers is avoided in our geometry. Furthermore the absence of any insulating barrier between the LCMO and DBCO layer minimizes the possibility of any Joule heating in the sample. The only uncertainty in our experiment stems from the fact that the spin injection and the measured I_c are not on the same point of the superconductor. Some of the polarized spins are depolarized when they pass through the micro-bridge to the narrowest point due to their finite lifetime. This makes it difficult to quantify the exact amount of I_c suppression in a superconductor *when a known number of spin-polarized electrons are present in a steady state*. This quantity can however be estimated by positioning the micro-bridge at various distances from the ferromagnetic layer.

It is also interesting to note from the I–V curves that the voltage (V) increases much more sharply (figures 4(a), (b)) above the critical current when the measurement is carried out with polarized spins. At temperatures below 65 K we were not able to record any data point between 0 V and 5 μV, the criterion used as a measure of $I_{c(pol)}$. Though we do not have at present a theoretical model to explain this observation, it can be inferred that the pair breaking due to polarized spins is much stronger above $I_{c(pol)}$ than the pair breaking by normal electrons above I_c.

In summary, we have fabricated a ferromagnet to superconductor spin-injection device where the polarized spins are directly injected into the superconductor. Our results strongly suggest that the lifetime of the polarized carriers inside the superconductor increases as we decrease the temperature below the superconducting transition temperature. We strongly believe that further experiments with spin injection would give very useful information regarding quasi-particle scattering mechanisms in high temperature superconducting materials.

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