Co/Nb/Co low field superconducting spin switch

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Abstract

We report experiments on a superconducting spin switch based on technologically relevant materials as elemental ferromagnetic Co and elemental superconducting Nb. The Co/Nb/Co structure exhibits inverse spin switch effect, can be operated at liquid helium temperature and can switch from superconductive to normal state in rather weak applied magnetic fields. Relevant critical currents as a function of temperature and magnetic field as well as preparation of superconductive or resistive state are addressed here.

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In a Ferromagnet/Superconductor/Ferromagnet (FSF) spin switch, superconductivity can be controlled by the relative orientation of the magnetizations of the outer ferromagnetic electrodes sandwiching the superconductor. Recently, spin switches based on proximity coupled metallic ferromagnets\textsuperscript{1,2} and classic metal superconductors\textsuperscript{3,4,5,6,7} or high T\textsubscript{c} superconductors\textsuperscript{8} have been widely investigated. The experimental results suggest that superconductivity can be depressed both in the parallel (|P\rangle) state of the magnetizations (standard spin switch effect) and in the antiparallel (|AP\rangle) state (inverse spin switch effect). As a general trend, it seems that standard spin switch effect is observed when exchange biasing is used\textsuperscript{3,4,5} to achieve the antiparallel state, while the inverse effect is observed when antiparallel orientation is achieved using different coercive fields\textsuperscript{6,7,8} for the ferromagnetic materials.

Most of the experiments reported in the literature focused on the individuation of two critical temperatures corresponding to the |AP\rangle or |P\rangle state of the spin switch, an important issue from the point of view of fundamental physics. Here, beside the use of two technologically relevant materials, as Nb and Co, we report a complementary experimental study, that may be of some interest for applied physics. In particular, we report current-voltage curves and critical currents as a function of magnetic field and temperature, as well as a test on preparation of superconductive or resistive state at liquid helium temperature.

The Co/Nb/Co trilayers were deposited onto glass substrates by rf magnetron sputtering in a high vacuum system with a base pressure of $2 \times 10^{-7}$ Torr in pure Argon pressure at $3.1 \times 10^{-3}$ Torr at room temperature. Co was deposited at the rate of 0.1 nm/s, producing a roughness smaller than 0.5 nm. The Nb was deposited with the rate of 2.2 nm/s, producing a roughness below 1.5 nm, while affected by very low contamination from magnetic materials present in the chamber. To achieve different coercive fields, the bottom and the top Co films were deposited with different thicknesses, in a pseudo spin valve configuration\textsuperscript{6,7,8}. In all the devices the bottom Co layer is 8 nm thick, the top Co layer is 16 nm thick, while Nb thickness ranges from 18 nm to 32 nm. The trilayer is covered by a 2 nm Al cap layer to prevent the oxidation of the top layer. The whole trilayer was patterned by photolithography and lift-off in a Hall geometry, as sketched in the insets of Fig. 1, that allows four contacts measurements. The width of the strips is 200 $\mu$m and voltage contact are 3 mm apart. All samples showed similar behavior, with a zero resistance critical temperature decreasing as Nb spacer thickness was decreased. Here we report about a sample with 30 nm thick Nb,
that allows us to operate easily in a standard liquid helium cryostat.

FIG. 1: Magnetoresistance of the trilayer at a temperature slightly larger than $T_c$ for in plane magnetic field applied perpendicularly [(a)] or longitudinally [(b)] to the bias current direction. The arrows show the direction of the magnetizations. (c) Voltage at fixed bias current versus temperature at two fixed magnetic fields promoting $|P>$ or $|\text{AP}>$ states.

In the top panels of Fig. 1 we show the magnetoresistance curves of the spin switch at a temperature slightly larger than the zero resistance critical temperature. The magnetic field is applied in the plane of the trilayer and (see insets), it is perpendicular to the current flow in Fig. 1(a) and longitudinal to the current flow in Fig. 1(b). The magnetoresistance ratio $\Delta R/R$ is found very large, of the order of the one observed$^8$ in spin switch based on a highly polarized ferromagnet. At temperatures where the Nb is normal (above 6 K) the magnetoresistance curves (not shown) exhibit peaks of resistance approximately at same locations as in the Fig. 1 but a vanishingly small $\Delta R/R \approx 0.09\%$, as we should expect for a pseudo spin valve with a rather thick normal spacer layer. Coherently with a pseudo spin valve behavior in the normal state, we can expect that relative orientations for magnetizations of outer electrodes stay the same at lower temperature and are directed as shown by the arrows in the Fig. 1. Resistance is found to be larger in the $|\text{AP}>$ state, i.e., an inverse spin switch effect is exhibited by the Co/Nb/Co trilayer, in agreement with other reported spin switch where the pseudo spin valve configuration$^6,7,8$ was used to
achieve the antiparallel state. Moreover, the absence of any dips in the curve of Fig. (b) and the presence of well defined peaks in the resistance for both the orientations of the in plane magnetic field strongly suggest that the whole trilayer is operated, as opposite to a FS bilayer effect. In Fig. (c) we show curves of the voltage at constant current (proportional to resistance) versus temperature for two values of the magnetic field that induce an |AP > or a |P > state for magnetizations. The field is applied perpendicularly to the current direction, as shown in the inset, but similar results were obtained applying the field longitudinally to the current flow. V-T curves apparently differ of about 30 mK in the middle of transition. This difference is of the same order of magnitude of the ones reported for other spin switches. Moreover, as expected from proximity effect, the zero voltage critical temperature of the trilayer ($T_{c}^{FSF} \approx 4.5$ K when $I_{BIAS} = 50 \mu$ A) is found lower than the critical temperature of a single Nb film having the same thickness, that we measured as $T_{c}^{S} \approx 6$ K. The behavior of the spin switch was found qualitatively the same for both the directions of the magnetic field with respect to the current direction, therefore
in the following discussion we shall consider the magnetic field applied perpendicularly to the current.

In Fig. 2(a) we show the $I - V$ curves of the spin switch at different magnetic fields, recorded at 4.58 K. The curves are modulated by magnetic fields much weaker than the parallel critical field of the Nb film, that at this temperature is estimated to be several thousands G. The critical current as a function of magnetic field (increased from negative to positive fields) is shown in Fig. 2(b). The critical current in the $|P>$ state $I^P_c$, achieved for high negative or positive fields [$B = \pm 100$ G in Fig. 2(b)], is much larger than the critical current in $|AP>$ state $I^{AP}_c$, achieved at about 30 G. Biasing the device with current in-between the two relevant critical currents, and sweeping the field up and down, the Voltage vs Field curve shown in Fig. 2(c) is recorded, evidencing a clear transition from the zero-voltage state to the resistive state. The arrows in Fig. 2(c) identify the branch traced in the same magnetic field half-loop used to record data in panel (b).

![Graph](image)

FIG. 3: Critical current versus temperature in the $|P>$ or $|AP>$ state. The solid line is a fit with theory. In the inset it is shown the $I(V)$ of the spin switch prepared in the two states recorded at 4.2 K.

The Current-Voltage curves of the spin switch prepared in the $|P>$ or $|AP>$ state recorded at liquid helium temperature are shown in the inset of Fig. 3, together with the identification of the two critical currents $I^P_c$ and $I^{AP}_c$ at this temperature. From data we estimate a critical current density in the parallel state at 4.2 K $J^P_c \approx 2 \times 10^5$ A/cm$^2$. The two
critical currents as a function of temperature are reported in the Fig. 3. The two currents are always appreciably different, with $I_{c|P\rangle}$ about doubling $I_{c|AP\rangle}$ at 4.2 K and also much larger than $I_{c|AP\rangle}$ near the transition temperatures. Both critical currents are adequately fitted with the formula valid for isolated thin films near the transition temperature

$$I_{c}^{i} = I_{c0}^{i} [1 - T/T_{c}^{i}]^{3/2}$$

where $i = |P\rangle, |AP\rangle$. From the fit we estimated $T_{c|P\rangle} = 4.63$ K and $T_{c|AP\rangle} = 4.60$ K. Moreover, the critical current densities at $T = 0$ can be extrapolated as $J_{c0|P\rangle} = 5.7 \times 10^{6}$ A/cm$^2$ and $J_{c0|AP\rangle} = 3.1 \times 10^{6}$ A/cm$^2$. So, although a weakening due to the proximity effect is unavoidable, the spin switch is found capable to operate with critical currents of almost the same order of magnitude as the critical current of the isolated superconductive film, as it was theoretically predicted. The fact that in the magneto-quenched state, i.e., our $|AP\rangle$ state, the critical current follows again a genuine thin superconducting film behavior allows us to rule out mechanisms of local weakening of superconductivity (e.g., the

FIG. 4: (a) Voltage versus Field curve during a loop of the magnetic field at 4.2 K. The biasing current is chosen in between the critical currents of the $|AP\rangle$ and $|P\rangle$ states at the working temperature. (b) Magnetic field waveform used to prepare the ON or OFF states together with the Voltage waveform of the spin switch.
ones caused by fringe field effects discussed by Clinton and Johnson\textsuperscript{11}). Moreover, in the framework in which the above formula is derived\textsuperscript{10}, the critical current is proportional to the squared superconducting energy gap. So data in Fig. 3 suggest that an appreciable gap suppression is associated to the $|AP>$ state of our spin switch.

As can be inferred from Fig. 3 and Fig. 2, biasing the device with a constant current $I_{c|AP}| < I_{BIAS} < I_{c|P}|$, a transition from zero-voltage state to the resistive state and vice versa can be achieved at all temperatures below the critical ones during a cycle of the applied magnetic field. This is shown in Fig. 4(a) for our device operated at 4.2 K while biased with 7 mA. The arrows indicate a single cycle of the applied magnetic field. Depending on history, at the same magnetic field can correspond two different voltage levels. Choosing properly the bias current, these voltage levels can either be $V = 0$ or $V \neq 0$, labeled as ON and OFF states in the Fig. 4(a). In an application as a bit, it is convenient to choose the voltage of the ON state as large as possible, i.e., the magnetic field should take the value that produce $|AP>$ state. An example of magnetic field waveform that can be used to set the two states is shown in Fig. 4(b), where we show also the time trace of the Voltage measured across the spin switch. The upward section of the B(t), labeled $\text{up}$ in 4(b), prepares the ON state, while the downward section, labeled $\text{down}$, prepares the OFF state. After preparation, the device stay stable in the states. In the 4(b) the two states are prepared in a sequence, as an example. We used the magnetic field generated by a superconductive solenoid to build the B(t) waveform, but, due the very low magnetic fields involved, an insulated superconductive control line deposited on the top of the spin switch could do as well.

The inverse spin switch effect reported here is possibly accounted for gap suppression\textsuperscript{6-7,8} by means of spin imbalance\textsuperscript{12} in the $|AP>$ state, since the spin polarization of the metallic Co (P $\approx$ 0.4) is relatively large and Nb thickness here is close to its spin diffusion length (estimated\textsuperscript{7} around 30 nm for Nb at cryogenic temperature).

Summarizing, we reported inverse spin switch effect in a Co/Nb/Co trilayer at liquid helium temperature. To the parallel and antiparallel state correspond two appreciably different critical currents pointing at two slightly different critical temperatures. This suggests a superconductive energy gap suppression in the antiparallel configuration of magnetizations. Biasing the device with a constant current comprised between the two relevant critical currents, the preparation of the device in the superconductive or resistive state can be reliably
achieved using weak magnetic fields.

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