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Abstract

A multiterminal superconducting device with the $S_1IS_2FIS_3$ structure (where S, I, and F denote a superconductor, an insulator, and a ferromagnetic material) is fabricated and characterized. Introducing a thin ferromagnetic layer into the middle electrode dramatically reduces parasitic back action of the acceptor junction (S_1IS_2) bias current on the injector junction (S_2FIS_3)current-voltage characteristic as compared with that for the formerly reported quiteron, a device exploiting similar operation principle.

Keywords

superconducting, transistorlike, device, having, good, input, output, isolation

Disciplines

Engineering | Physical Sciences and Mathematics

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A superconducting transistorlike device having good input-output isolation.

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A multiterminal superconducting device with the $S_1IS_2FIS_3$ structure (where S, I, and F denote a superconductor, an insulator, and a ferromagnetic material) is fabricated and characterized. Introducing a thin ferromagnetic layer into the middle electrode dramatically reduces parasitic back action of the acceptor junction (S_1IS_2) bias current on the injector junction (S_2FIS_3) current-voltage characteristic as compared with that for the formerly reported quiteron, a device exploiting similar operation principle. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3189283]

Since pioneering studies of the superconducting tunnel junctions by Giaever,[1] many attempts were made to use a remarkable nonlinearity of their current-voltage characteristics (CVCs) in devices with transistorlike properties. One of the most popular superconducting devices intended for the transistorlike operation was the quiteron.[2] While possessing essential transistorlike characteristics, this device, however, had a drawback that was detrimental for real-life circuit applications: lack of isolation between the input and output terminals.[3,4] A conventional quiteron device has a symmetric $S_1IS_2IS_3$ structure (where S and I denote a superconductor and an insulator, respectively), where one tunnel junction (say S_1IS_2) is an acceptor, and the second tunnel junction (S_2IS_3), stacked on top of the first one, is an injector. The injector is current-biased at a voltage $V \geq (\Delta_2+\Delta_3)/e$ (here Δ_i is the superconducting energy gap in the respective superconductor S_i) to produce a nonequilibrium quasiparticle population in the middle S_2 layer, thereby suppressing its energy gap Δ_2 and modifying the CVC of the acceptor. However, since the S_2 layer is common for both the injector and the acceptor, biasing the acceptor junction at $V \approx (\Delta_1+\Delta_2)/e$ affects the CVC of the injector junction almost to the same degree as the injector junction affects the CVC of the acceptor. This parasitic back action leads to lack of isolation between the input and output terminals and to latching logic operation.

Here we propose to solve this problem by introducing a thin nonsuperconducting metal layer (N) into the middle electrode on the injector junction side so that the device structure now becomes $S_1IS_2NIS_3$, where S_2NIS_3 is the modified injector junction. The function of the additional N layer is to prevent the superconducting energy gap of the neighbor S_2 layer to appear in the CVC of the injector. In order to provide efficient injection into the S_2 layer, and, at the same time, to considerably reduce the back action of the acceptor on the injector, interplay of several physical conditions must be realized in the proposed device configuration.

First, the diffusion length of the injected quasiparticles should exceed the thickness of the S_2N bilayer, in order to provide a homogeneous quasiparticle excitation over the S_2 thickness, d_2. This condition is easy to satisfy because usually the quasiparticle diffusion length in superconductors is of the order of 10 μm, and the film thickness used in devices ranges from a few to a few hundreds of nanometers. Next, the N layer should not become superconducting due to proximity with S_2, i.e., the induced superconducting order parameter should decay within the N layer thickness. This can be achieved using a thick N layer, but we need to keep it thin in order to reduce the amount of injected quasiparticles that relax within the layer. These two conflicting conditions can be reconciled if we choose such a N layer where Cooper pairs penetrate over a short distance. The best choice is a ferromagnetic material (F) because ferromagnetic ordering is incompatible with ordinary (*s*-wave) superconducting ordering. Finally, we want the thin N layer to have a very small electron mean free path (MFP), shorter than the N layer thickness, d_N; in this case, the CVC of the injector junction will look as that for the NIS_3 junction (and therefore, will not feel any gap reduction in S_2) because tunneling characteristics represent electron structure of the junction electrodes only to the depth of the order of MFP. On the other hand, the CVC of the detector junction will be of the S_1IS_2 type as usually, provided the S_2 layer is thick enough to avoid noticeable gap suppression due to proximity with the N layer.

We have chosen Ni as a material for the nonsuperconducting layer. The coherence length in the ferromagnetic Ni layer can be expressed as $\xi_{Ni}=\sqrt{\hbar v_F l_{Ni}/6\pi k_B T_C}$, where T_C is the Curie temperature, $T_C \approx 600$ K for Ni film.[5] From the resistivity measurements of our reference Ni films, with $\rho_{Ni}=6.9$ $\mu\Omega$ cm and the MFP $l_{Ni}\approx 3$ nm in Ni (Ref. 6) at 300 K, we deduce $l_{Ni}=3.5$ nm at 4.2 K. Using $v_F=0.28\times 10^8$ cm/s,[7] we estimate the ξ_{Ni} to be 0.8 nm. The penetration depth of the superconducting order parameter in the normal metal is $b_N \cong [\rho_N/\rho_S]\xi_N$, where ρ_N and ρ_S are the resistivity of the normal and superconducting layer, respectively, and ξ_N is the coherence length of the normal layer.[8] Applying this relation to the Ni layer, we obtain $b_{Ni}\cong 0.9$ nm; hence, the CVC of $Nb_{(2)}/Ni/Al/AlO_x/Nb_{(3)}$ junction in our devices will not display any superconducting energy gap of the $Nb_{(2)}/Ni$ bilayer even if the thickness of the Ni layer, d_{Ni}, is considerably less than 7.5 nm, the minimum value used in our experiments. Therefore the CVC of the injector junction will be rather insensitive to the gap suppression in the $Nb_{(2)}$ layer, the property that we propose to exploit in order to

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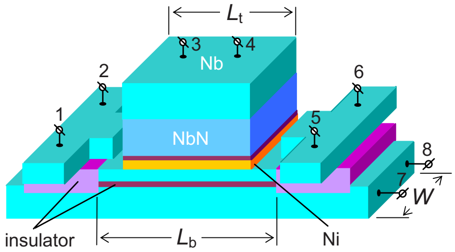

FIG. 1. (Color online) Schematic view of the multiterminal device. Electric current through the top (injector) junction can be fed through the contacts 1 or 2 (or 5 or 6) and 3 or 4. Bottom (acceptor) junction can be current-biased using the contacts 1 and 2 (or 5 and 6) and 7 and 8.

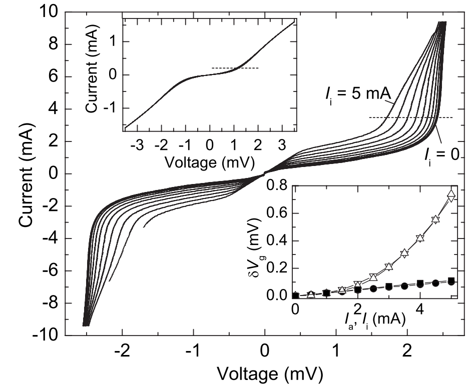

FIG. 2. Characteristics of the $Nb_{(1)}/Al/AlO_x/Nb_{(2)}/Ni/Al/AlO_x/NbN/Nb_{(3)}$ device. Main panel: family of the CVCs of the acceptor ($Nb_{(1)}/Al/AlO_x/Nb_{(2)}$) junction measured at of 4.2 K for various injector current levels from 0 to 5.0 mA with the step of 0.5 mA. Upper inset: family of the CVCs of the injector ($Nb_{(2)}/Ni/Al/AlO_x/NbN/Nb_{(3)}$) junction for the current levels 0–5 mA through the acceptor junction. Horizontal dashed lines mark bias current levels (3.5 mA for the acceptor and 0.2 mA for the injector junction) for which the apparent gap voltage reduction, δV_g, was determined. Lower inset: dependence of δV_g on the injection current for two identical devices; open and solid symbols are for the acceptor and injector junction, respectively.

improve the isolation in the transistorlike devices.

Taking into account the fact that the acceptor junction is biased at a voltage $V \cong (\Delta_1 + \Delta_2)/e$, further improvement of isolation can be achieved if the energy gap Δ_3 of the superconductor S_3 satisfies condition $\Delta_3 > \Delta_1, \Delta_2$; then injection of quasiparticles and recombination phonons from acceptor junction into S_3 will not break Cooper pairs therein. In our case, an available superconductor with the superconducting transition temperature, T_c, higher than that for Nb, was NbN with $T_c \approx 13$ K.

For the reasons described above, we fabricated and characterized multiterminal devices with the structure $Nb_{(1)}/Al/AlO_x/Nb_{(2)}/Ni/Al/AlO_x/NbN/Nb_{(3)}$ (cf. Fig. 1). The devices were fabricated from multilayer structures (using optical lithography), deposited *in situ* onto *R*-plane sapphire substrates by dc magnetron sputtering of the respective metals; the tunnel barriers were grown by thermal oxidation of the Al overlayers. The top $Nb_{(3)}$ layer did not influence the injector characteristic and was deposited to provide better bonding of the contact wires. The electric current through the acceptor junction was fed through terminals 1 and 7, and the voltage was measured using terminals 2 and 8. The CVC of the injector junction was recorded using the current and voltage terminals 1 and 3 and 2 and 4, respectively. Measurements were carried out in liquid 4He at 4.2 K. Injector and acceptor junctions were biased by two independent battery-powered current sources with floating grounds.

Results of a typical injection experiment are presented in Fig. 2. A set of CVCs in the main panel is for the acceptor $Nb_{(1)}/Al/AlO_x/Nb_{(2)}$ junction recorded at different currents from 0 to 5.0 mA (with the step of 0.5 mA) through the injector $Nb_{(2)}/Ni/Al/AlO_x/NbN/Nb_{(3)}$ junction. The thickness of $Nb_{(1)}$, $Nb_{(2)}$, Ni, NbN, and $Nb_{(3)}$ layers was 126.0, 37.1, 7.5, 50.0, and 42 nm, respectively. The lateral dimensions of the acceptor and injector junctions were $L_t = 14$ μm, $L_b = 20$ μm, and $W = 14$ μm (cf. Fig. 1). The upper inset in Fig. 2 shows a family of CVCs of the injector junction measured under current levels 0–5 mA through the acceptor junction. The lower inset shows dependence of the gap voltage reduction, δV_g, on the injection current, *I*, for the acceptor (open triangles) and the injector junction (solid circles and squares). The gap voltage, V_g, was measured at $I_a = 3.5$ mA for the acceptor junction, and at $I_i = 0.2$ mA for the injector junction (i.e., at the onset of the steep portion of the CVC). These current levels are marked by dashed lines.

One can see from Fig. 2 that the influence of the injector current on the CVC of the acceptor junction is much more significant than the reverse influence of the acceptor current on the CVC of the injector. The isolation between the acceptor and the injector circuits can be characterized[4] by the ratio of transresistances, $R_{m(a)}/R_{m(i)} \equiv [\delta V_{g(a)}/\delta I_i]/[\delta V_{g(i)}/\delta I_a]$. For the medium injection current levels (3.0–3.5 mA), one can deduce from characteristics shown in Fig. 2 the value $R_{m(a)}/R_{m(i)} = 15.7$, which is considerably higher than previously reported value of 3 for the quiteron.[4] For reference, we fabricated (from the multilayer structures deposited in the same run) and studied injection characteristics of similar $Nb_{(1)}/Al/AlO_x/Nb_{(2)}/Al/AlO_x/NbN/Nb_{(3)}$ devices without any Ni layer. These devices showed $R_{m(a)}/R_{m(i)}$ value of about 3.1 for the same injection current range. Obviously, devices involving the Ni layer show improvement of the isolation. It should be noted that because Ni is a ferromagnetic (we measured magnetization of our as-deposited structures with Ni, which clearly showed ferromagnetic ordering), it could cause spin injection into the $Nb_{(2)}$ layer, leading to additional gap suppression. However, our estimation shows that the spin split energy produced in $Nb_{(2)}$ layer is much less than the energy gap in $Nb_{(2)}$ at the injection current levels used in the experiment; therefore, spin injection effect can be neglected here. We believe the role of Ni layer is merely to prevent the superconducting energy gap of adjacent $Nb_{(2)}$ layer from manifestation in the injector CVC. Our simulations within the Rothwarf–Taylor model[9] show that further increase of the $R_{m(a)}/R_{m(i)}$ ratio is possible by reducing the $Nb_{(2)}$ and Ni layer thickness (to be published elsewhere).

The experimental results discussed here are concerned with static characteristics. It is interesting to measure dynamic characteristics of this device to determine its response in the time domain. Earlier measurements on quiteron showed transient response of the order of 1 ns,[10] although the speed on the order of 50 ps was predicted.[2] Indeed, a short quasiparticle recombination time [$\tau_R \cong 18$ ps for Nb (Ref. 11)] would allow for the faster response, but a common problem in these and other superconductor-based devices (such as detectors) is trapping of the recombination phonons within the superconducting film. In order to achieve short phonon escape time, one has to use thin layers and provide good acoustic matching between the materials composing the device, and especially between the device and its environment (substrate and bath). Another approach is to exploit ultrafast anharmonic phonon decay in the N layer, which is supposed to be responsible for the dramatic reduction of the slow bolometric component in the photoresponse of the Nb/NiCu bilayer as compared with the response of the pure Nb film.[12] Also, faster response can be achieved in small-size devices due to outdiffusion of quasiparticles, if the device dimensions are much less than the quasiparticle diffusion length.[13]

We believe that optimization of the proposed device within these lines will enable its high-speed operation, and hence, implementation in various circuits. Specifically, it may by useful for interfacing the rapid single-flux quantum circuits with room-temperature electronics. Furthermore, it may be a building element for a new class of superconductor-based digital electronics.

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