Superconducting spintronic devices based on nanostructures ferromagnet/superconductor

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Abstract. The layered nanostructures ferromagnet/superconductor (F/S) due to combination of incompatible in homogeneous materials properties are the most perspective materials for use in the new field of electronics – a superconducting spintronics. A new type of logical devices based on the layered F/S nanostructures and combining the advantages of the superconducting and magnetic recording channels in one sample is offered. Each channel can be separately controlled by weak magnetic field or current pulse and the switching time is of order of $10^{-10}$ - $10^{-11}$ s. The implementation of such devices on base of high-temperature superconductors will allow using nitrogen instead of expensive helium for cooling.

1. Introduction

The coexistence of the superconducting and ferromagnetic order parameters (OPs) is unlikely in a uniform system, although it is easily achievable in artificially prepared layered F/S systems consisting of alternating ferromagnetic (F) and superconducting (S) layers. Owing to the proximity effect, a superconducting order parameter can be induced in the F layer; on the other hand, the neighboring pair of F layers can interact with one another via the S layer. Such systems exhibit rich physics, which can be controlled by varying the thicknesses of the F and S layers or by placing the F/S structure in an external magnetic field [1].

The modern technologies of production of layered structures, such as molecular-beam epitaxy, permit one to apply layers of atomic thicknesses and study the properties of layered F/S systems as function of the thickness of the ferromagnetic ($d_f$) and superconducting ($d_s$) layer. Numerous experiments on the F/S structures (junctions and superlattices) revealed nontrivial dependences of the temperature of the superconducting transition $T_c$ on the thickness of the ferromagnetic layer. Of special interest is the study of multilayered F/S structures, in which various types of magnetic order can arise in F layers due to their indirect interaction via S layers. Recently, logical elements of a new type (spin switches) were suggested based on the interrelation between the superconducting and magnetic OPs in three-layer F/S/F and four-layer F/S/F/S structures. The general theoretical interest in the problem of the mutual influence of superconductivity and magnetism in F/S structures and possible engineering applications make the problem discussed quite topical.
2. Results and Discussion
The three-dimensional model of proximity effect for layered F/S structures is expounded in [2]. In the framework of this model the phase diagrams $T_c$ versus $d_{sf}$ and $d_s$ have been calculated. On the base of these results we propose logical elements/control devices of a new type (spin switches).

Let us consider the superconducting spin valve, cryotron, based on the three-layered F/S/F nanostructure (figure 1). The calculated phase diagram of this structure is depicted on figure 2. The state of F/S structure can be managed by a weak magnetic field $H$, which affects the phase diagram slightly. In this case there are three characteristic quantities of this magnetic field: coercive field $H_{coer}$, critical field $H_c$ and pinning field $H_p$. The value of critical field $H_c$ is determined by the difference between critical and operating temperatures ($T_c - T$), which can be negligibly small.

Let the system be in one of the state depicted on figure 2 by points. In zero magnetic field the system is in the base antiferromagnetic superconducting (AFS) state. Let us suppose, that the magnetic fields are related as follows: $H_{coer} < H_c < H_p$. When we apply an external magnetic field at the direction of pinning field $H_p$, transition from the base AFS state to the ferromagnetic normal state (FN) occurs at $H \approx H_{coer}$. If the orientation of magnetization of the left F-layer, for example, up ($\uparrow$), then the transition can be represented as $\uparrow S \downarrow \rightarrow \uparrow N \uparrow$. Applying of an external magnetic field of opposite direction makes possible two other transitions: first form the base AFS state to antiferromagnetic normal state (AFN) at $H \approx H_c$ ($\uparrow S \downarrow \rightarrow \downarrow N \downarrow$), and then to the FN state at $H \approx H_p$ ($\uparrow N \downarrow \rightarrow \downarrow N \downarrow$).

Thus, for a given choice of operating points, we have up to 4 possible different logical states (one superconducting state $\uparrow S \downarrow$ and three normal states $\uparrow N \uparrow$, $\downarrow N \downarrow$, $\downarrow N \uparrow$), and we can choose the recording of information on the superconducting current (the first channel) and the relative orientation of magnetization (the second channel). Note that you can get up to five different states ($\uparrow S \downarrow$, $\uparrow S \uparrow$, $\uparrow N \uparrow$, $\downarrow N \downarrow$, $\downarrow N \uparrow$), if slightly shift the operating points below the 3D (FS) curve on figure 2.

Let us consider the concept of cryotron based on the four-layered F/S/F'/S' nanostructure. The phase diagram of this structure is depicted on figure 3. Add an additional layer of a magnetic dielectric to the left of the outer layer with a purpose to fix the direction of magnetization in the F layer. One

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**Figure 1.** The sketch of a superconducting spin valve with two channels, separately controlled by an external magnetic field.

**Figure 2.** Reduced critical temperature $t$ (down) and pair’s momentum $q_f$ (up) versus reduced thickness of the FM layer $d_f/a_f$. The thin line corresponds to AFS state, the thick dashed line corresponds to FS state. The solid and dashed lines correspond to 3D ($q_f \neq 0$) and 1D ($q_f = 0$) cases, respectively.
possible consequence is the return of our system to its initial state after turning the magnetic field off. Thus, formally our system becomes MI/F/S/F/′/S. Changing an external magnetic field \( H \), directed along the pinning field \( H_p \) which sets the direction of magnetization in the outer left F layer (call it a direction “up”), we can call the system transitions between the ground antiferromagnetic superconductor (AFMS) state, mixed state FM with an unrelated superconductivity and ferromagnetic normal (FMN) state. An external magnetic field of opposite orientation can cause the other three transitions between the ground state AFMS, the mixed state AFM, AFMN state, and, finally, FMN state. Fix the orientation of the magnetization of the outer layer of F, for example, up (\( \uparrow \)). At \( H = 0 \) the system is in AFMS state. If we apply a weak external magnetic field \( H \), greater than the coercive field \( (H_{coer} < H < H_c) \), in the direction of magnetization \( M \) of the F layer and the pinning field \( (H \uparrow \uparrow H_p) \), the direction of magnetization \( M' \) in the F′ layer reversed. The system goes into a state with ferromagnetic magnetizations. Thus, we can say that as a result of the transition \( \uparrow S \downarrow S \xrightarrow{H_{coer}} \uparrow N \uparrow S \xrightarrow{H_c} \uparrow N \uparrow N \). An external magnetic field of opposite orientation \( (H \downarrow \uparrow H_p) \) can cause three other transitions in the system.

![Figure 3. The generalized phase diagram of four-layered F/S/F′/S′ system. The vertical arrows indicate the direction of magnetization in corresponding ferromagnetic layer. The letters S and N are used to denote the superconducting and normal state of superconducting layers respectively.](image)

If \( H \) is a little more than \( H_c \), but less than \( H_c' \), then the system undergoes a transition from the AFMS state into a mixed AFM state \( \uparrow S \downarrow S \xrightarrow{H_c} \uparrow N \downarrow S \). In this case, only information recorded using the conductive properties of S-layer is changed, while the information recorded on the relative orientation of magnetizations of the layers F and F′ and superconducting current layer S′, remains unchanged.

The following transitions in this series are observed with further increase of the magnetic field in the same direction "down" (from \( H_c < H < H_{c'} \) to \( H > H_p \)). Thus, the system F/S/F′/S′ has six logically different states: \( \uparrow S \downarrow S, \uparrow N \uparrow S, \uparrow N \uparrow N, \uparrow N \downarrow S, \uparrow N \downarrow N, \downarrow N \downarrow N \).
A possible physical realization is depicted on figure 4. In the absence of the magnetic field (current in the coil 1) the system is in the ground state $\uparrow S \downarrow S$. Magnetization reversal in the ferromagnetic layers is achieved by applying a current in the coil 1 of an appropriate direction and magnitude. For reading information a current pulse is passed through the coil 2, which creates a magnetic field in the direction of carrying the system to its original state. If the information was recorded, the respondent pulse creates alternating magnetic flux, inducing a current pulse in the reading coil 3. In the opposite case, the reversal does not occur and the signal does not appear in the reading coil. When the magnetic field is turned off the system is restored to the ground state $\uparrow S \downarrow S$.

3. Conclusion
The three-layered F/S/F and four-layered F/S/F/S nanostructures are the most perspective candidates for the use in the superconducting spin nanoelectronics (spintronics). These structures possess two data-record channels, namely, on the superconducting current and the magnetic order of the FM layer magnetizations. We can separately manage these channels by weak magnetic field or current pulse. The advantages of such spin devices linked to small size (thickness $d_f \sim 0.5$–5 nm, thickness $d_s \sim 25$–80 nm), high switching speed ($\sim 10^{-10} - 10^{-11}$ s), high enough critical currents. Combination of both channels in a single sample would significantly increase the information recording density. Currently, an implementation of such nanodevices on base of high-temperature superconductors (HTSC) is considered, which would allow using cheap liquid nitrogen rather than expensive helium.

References
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