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## Controllable $\pi$ junction with magnetic nanostructures

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We propose a Josephson device in which 0 and  $\pi$  states are controlled by an electrical current. In this system, the  $\pi$  state appears in a superconductor/normal metal/superconductor junction due to the nonlocal spin accumulation in the normal metal which is induced by spin injection from a ferromagnetic electrode. Our proposal offers not only possibilities for the application of superconducting spin-electronic devices but also the in-depth understanding of the spin-dependent phenomena in magnetic nanostructures.

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Nowadays spin-electronics is one of the central topics in condensed matter physics.<sup>1-3</sup> There has been considerable interest in the spin injection, accumulation, transport, and detection in ferromagnet/normal metal (F/N) hybrid structures.<sup>4-10</sup> Twenty years ago, Johnson and Silsbee demonstrated the spin injection and detection in a F/N/F structure for the first time.<sup>4</sup> Recently, spin accumulation has been observed at room temperature in all-metallic spin-valve geometry consisting of a F/N/F junction by Jedema *et al.*<sup>5</sup> In their system, the spin-polarized bias current is applied at one F/N junction, and the voltage is measured at another F/N interface, for the parallel (P) and antiparallel (AP) alignments of the Fs magnetizations. They observed the difference of the nonlocal voltages between the P and AP alignments due to spin accumulation in N. Also in a F/I/N/I/F (I indicates an insulator) structure, clear evidence of spin accumulation in N has been shown.<sup>6</sup> In hybrid structures consisting of a ferromagnet and a superconductor (S), a suppression of the superconductivity due to spin accumulation in S has been studied theoretically and experimentally.<sup>11-13</sup>

Furthermore, ferromagnetic Josephson (S/F/S) junctions have been studied actively in recent years.<sup>14-19</sup> In the S/F/S junctions, the pair potential oscillates spatially due to the exchange interaction in F.<sup>14,15</sup> When the pair potentials in two Ss take different sign, the direction of the Josephson current is reversed compared to that in ordinary Josephson junctions. This state is called the  $\pi$  state in contrast with the 0 state in ordinary Josephson junctions because the current-phase relation of the  $\pi$  state is shifted by “ $\pi$ ” compared to that of the 0 state. The observations of the  $\pi$  state have been reported in various systems experimentally.<sup>16-19</sup> The applications of the  $\pi$  state to quantum computing also have been proposed.<sup>20-22</sup> Another system to realize the  $\pi$  state is a S/N/S junction with a voltage-control channel.<sup>23,24</sup> In the system, the nonequilibrium electron distribution in N induced by the bias voltage plays an important role, and the sign reversal of the Josephson critical current as a function of the control voltage has been demonstrated.<sup>23,24</sup>

In this paper, we propose a Josephson device in which the 0 and  $\pi$  states are controlled electrically. In this device, spin accumulation is generated in a nonmagnetic metal by the spin-polarized bias current flowing into the nonmagnetic metal from a ferromagnet. In a metallic Josephson junction consisting of the spin accumulated nonmagnetic metal sand-

wiched by two superconductors, the  $\pi$  state appears due to the spin split of the electrochemical potential in the nonmagnetic metal. The magnitude of the spin accumulation is proportional to the value of the spin-polarized bias current, and therefore the state of the Josephson junction is controlled by the current. Our proposal leads to an in-depth understanding of the spin-dependent phenomena in magnetic nanostructures as well as possibilities for the application of superconducting spin-electronic devices.

We consider a magnetic nanostructure with two superconductors as shown in Fig. 1. The device consists of a nonmagnetic metal N (the width  $w_N$ , the thickness  $d_N$ ) which is connected to a ferromagnetic metal F (the width  $w_F$ , the thickness  $d_F$ ) at  $x=0$  and sandwiched by two superconductors S1, S2 located at  $x=L$ . In this device, the electrode F plays a role as a spin-injector to the electrode N, and the S1/N/S2 junction is a metallic Josephson junction. The spin-diffusion length  $\lambda_N$  in N is much longer than the length  $\lambda_F$  in F,<sup>4-8</sup> and we consider the structure with dimensions of  $\lambda_F \ll (w_{N(F)}, d_{N(F)}) \ll \lambda_N$  which is a realistic geometry.<sup>5,6</sup>

In the electrodes N and F, the electrical current with spin  $\sigma$  is expressed as

$$\mathbf{j}_\sigma = -(\sigma_\sigma/e)\nabla\mu_\sigma, \quad (1)$$

where  $\sigma_\sigma$  and  $\mu_\sigma$  are the electrical conductivity and the electrochemical potential (ECP) for spin  $\sigma$ , respectively. Here ECP is defined as  $\mu_\sigma = \epsilon_\sigma + e\phi$ , where  $\epsilon_\sigma$  is the chemical potential of electrons with spin  $\sigma$  and  $\phi$  is the electric potential. From the continuity equation for charge,  $\nabla \cdot (\mathbf{j}_\uparrow + \mathbf{j}_\downarrow) = 0$ , and that for spin,  $\nabla \cdot (\mathbf{j}_\uparrow - \mathbf{j}_\downarrow) = e \partial(n_\uparrow - n_\downarrow) / \partial t$  ( $n_\sigma$  is the carrier density for spin  $\sigma$ ), we obtain<sup>8,10</sup>

$$\nabla^2(\sigma_\uparrow\mu_\uparrow + \sigma_\downarrow\mu_\downarrow) = 0, \quad (2)$$

$$\nabla^2(\mu_\uparrow - \mu_\downarrow) = (\mu_\uparrow - \mu_\downarrow)/\lambda^2, \quad (3)$$

where  $\lambda = \sqrt{D\tau_{sf}}$  is the spin diffusion length with the diffusion constant  $D = (N_\uparrow + N_\downarrow) / (N_\uparrow D_\uparrow^{-1} + N_\downarrow D_\downarrow^{-1})$  ( $N_\sigma$  and  $D_\sigma$  are the density of states and the diffusion constant for spin  $\sigma$ , respectively) and the scattering time of an electron  $\tau_{sf} = 2 / (\tau_{\uparrow\downarrow}^{-1} + \tau_{\downarrow\uparrow}^{-1})$  ( $\tau_{\sigma\bar{\sigma}}$  is the scattering time of an electron from spin  $\sigma$  to  $\bar{\sigma}$ ). In order to derive Eqs. (2) and (3), we take the relaxation-time approximation for the carrier density,

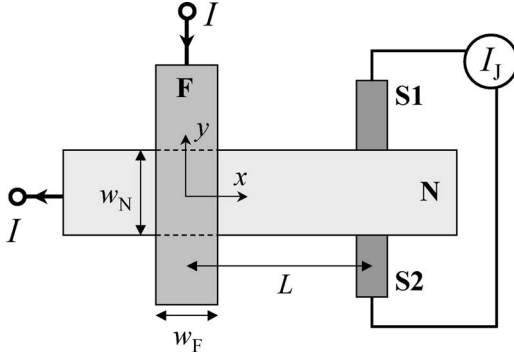


FIG. 1. Structure of a controllable  $\pi$  junction with magnetic nanostructures. The bias current  $I$  flows from a ferromagnet (F) to the left side of a normal metal (N). The Josephson current  $I_J$  flows in a superconductor/normal metal/superconductor (S1/N/S2) junction located at  $x=L$ .

$\delta n_\sigma / \delta t = -\delta n_\sigma / \tau_{\sigma\bar{\sigma}}$ , and use the relations  $\sigma_\sigma = e^2 N_\sigma D_\sigma$  and  $\delta n_\sigma = N_\sigma \delta \epsilon_\sigma$ , where  $\delta n_\sigma$  and  $\delta \epsilon_\sigma$  are the carrier density deviation from equilibrium and the shift in the chemical potential from its equilibrium value for spin  $\sigma$ , respectively. In addition, the detailed balance equation  $N_\uparrow \tau_{\uparrow\downarrow}^{-1} = N_\downarrow \tau_{\downarrow\uparrow}^{-1}$  is also used. We use the notations  $\sigma_N = 2\sigma_N^\uparrow = 2\sigma_N^\downarrow$  in N and  $\sigma_F = \sigma_F^\uparrow + \sigma_F^\downarrow$  ( $\sigma_F^\uparrow \neq \sigma_F^\downarrow$ ) in F hereafter.

At the interface between N and F, the interfacial current  $I_\sigma$  flows due to the difference of ECPs in N and F:  $I_\sigma = (G_\sigma/e)(\mu_F^\sigma|_{z=0^+} - \mu_N^\sigma|_{z=0^-})$ , where  $G_\sigma$  is the spin-dependent interfacial conductance. We define the interfacial charge and spin currents as  $I = I_\uparrow + I_\downarrow$  and  $I_{\text{spin}} = I_\uparrow - I_\downarrow$ , respectively. The spin-flip effect at the interface is neglected for simplicity. In the electrode N with the thickness and the contact dimensions being much smaller than the spin-diffusion length ( $d_N, w_N, w_F \ll \lambda_N$ ),  $\mu_N^\sigma$  varies only in the  $x$  direction.<sup>8</sup> The charge and spin current densities in N,  $j = j_\uparrow + j_\downarrow$  and  $j_{\text{spin}} = j_\uparrow - j_\downarrow$ , are derived from Eqs. (1)–(3), and satisfy the continuity conditions at the interface:  $j = I/A_N$  and  $j_{\text{spin}} = I_{\text{spin}}/A_N$ , where  $A_N = w_N d_N$  is the cross-sectional area of N. From these conditions, we obtain ECP in N,  $\mu_N^\sigma(x) = \bar{\mu}_N + \sigma \delta \mu_N$ , where  $\bar{\mu}_N = (eI/\sigma_N A_N)x$  for  $x < 0$ ,  $\bar{\mu}_N = 0$  for  $x > 0$ , and  $\delta \mu_N = (e\lambda_N I_{\text{spin}}/2\sigma_N A_N)e^{-|x|/\lambda_N}$ . In the electrode F, the spin split of ECP,  $\delta \mu_F^\sigma$ , decays in the  $z$ -direction because the thickness of F and the dimension of the interface are much larger than the spin-diffusion length in F ( $d_F, w_N, w_F \gg \lambda_F$ ).<sup>8</sup> In a similar way to the case of N, ECP in F is obtained from the continuity conditions for charge and spin currents. ECP in F is expressed as  $\mu_F^\sigma(z) = \bar{\mu}_F + \sigma \delta \mu_F^\sigma$ , where  $\bar{\mu}_F = (eI/\sigma_F A_J)z + eV$  and  $\delta \mu_F^\sigma = [e\lambda_F(p_F I - I_{\text{spin}})/2\sigma_F A_J]e^{-z/\lambda_F}$  with the contact area  $A_J = w_N w_F$ , the voltage drop at the interface  $V = (\bar{\mu}_F - \bar{\mu}_N)/e$ , and the polarization of the current in F,  $p_F = (\sigma_F^\uparrow - \sigma_F^\downarrow)/\sigma_F$ . The influence of the electrodes S1 and S2 on ECP in N may be neglected. When the superconducting gap in S1 and S2 is much larger than the spin split  $\delta \mu_N$  at  $x=L$ , almost no quasiparticle is excited above the gap at low temperature. Therefore, the spin current does not flow into S1 and S2, and the behavior of ECP in N is not modified by the connection to the electrodes S1 and S2.

In order to obtain the relation between the bias current  $I$  and the shift of ECP,  $\delta \mu_N$ , at the right side in N ( $x > 0$ ), we

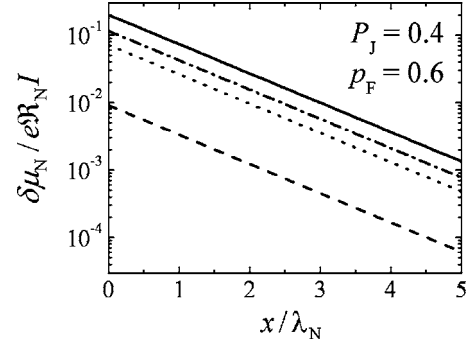


FIG. 2. Spatial variation of the split of the electrochemical potential in N. The solid line is for the tunnel-limit case ( $R \gg \mathfrak{R}_N, \mathfrak{R}_F$ ), the dashed, dotted, and dot-dashed lines are for the metallic-limit cases ( $R=0$ ) with  $r = \mathfrak{R}_F/\mathfrak{R}_N = 0.01, 0.1,$  and  $0.2$ , respectively.

substitute the obtained  $\mu_N^\sigma$  and  $\mu_F^\sigma$  for the expressions of  $I$  and  $I_{\text{spin}}$ , and eliminate  $V$ . As a result, we obtain the relation between  $I$  and  $I_{\text{spin}}$ , and finally we get the relation between  $I$  and  $\delta \mu_N$  as follows:

$$\delta \mu_N(x) = e \mathfrak{R}_N I \frac{\frac{P_J}{1 - P_J^2} \left( \frac{R}{\mathfrak{R}_N} \right) + \frac{p_F}{1 - p_F^2} \left( \frac{\mathfrak{R}_F}{\mathfrak{R}_N} \right)}{1 + \frac{2}{1 - P_J^2} \left( \frac{R}{\mathfrak{R}_N} \right) + \frac{2}{1 - p_F^2} \left( \frac{\mathfrak{R}_F}{\mathfrak{R}_N} \right)} e^{-x/\lambda_N}, \quad (4)$$

where  $\mathfrak{R}_N = \lambda_N / (\sigma_N A_N)$  and  $\mathfrak{R}_F = \lambda_F / (\sigma_F A_J)$  indicate the nonequilibrium resistances of N and F, respectively,  $R = G^{-1} = (G_\uparrow + G_\downarrow)^{-1}$  is the interfacial resistance, and  $P_J = (G_\uparrow - G_\downarrow)/G$  is the polarization of the interfacial current. When the F/N interface is the tunnel junction ( $R \gg \mathfrak{R}_N, \mathfrak{R}_F$ ), Eq. (4) reduces to a simple form  $\delta \mu_N(x) = (e \mathfrak{R}_N I P_J / 2) e^{-x/\lambda_N}$ . On the other hand, when the F/N junction is of a metallic contact ( $R=0$ ), Eq. (4) becomes  $\delta \mu_N(x) = e \mathfrak{R}_N I p_F r e^{-x/\lambda_N} / (2r + (1 - p_F^2))$ , where  $r = \mathfrak{R}_F/\mathfrak{R}_N$  is a mismatch factor of the resistances in F and N. Figure 2 shows the spacial variation of  $\delta \mu_N(x)$  both for the tunnel- and metallic-limit cases with  $P_J = 0.4$  and  $p_F = 0.6$  (Refs. 1 and 25). As shown in this figure, in the case of the metallic contact,  $\delta \mu_N$  becomes larger with decreasing the resistance mismatch.<sup>8</sup>

Next we consider how spin accumulation affects the Josephson current  $I_J$  flowing through the S1/N/S2 junction located at  $x=L$  (Fig. 1). In the metallic Josephson junction, the Andreev bound state plays a key role for the Josephson effect.<sup>18,26</sup> The Andreev bound state is formed by a multiple Andreev reflection of an electron with the wave number  $k_e = (\sqrt{2m/\hbar})\sqrt{E_F + E}$  and a hole with  $k_h = (\sqrt{2m/\hbar})\sqrt{E_F - E}$ , respectively, where  $E$  is the energy of the electron and hole measured from the Fermi energy  $E_F$ . As shown in Fig. 3, when there is the spin split  $\delta \mu_N$  in N, a spin-up (-down) electron with the energy  $E \approx \delta \mu_N$  ( $-\delta \mu_N$ ) is injected into S from N at low temperatures. The injected electron captures another electron with the energy  $E \approx -\delta \mu_N$  ( $\delta \mu_N$ ) from the opposite spin band in order to form a Cooper pair in S. Therefore, a spin-up (-down) hole with the energy  $E \approx \delta \mu_N$

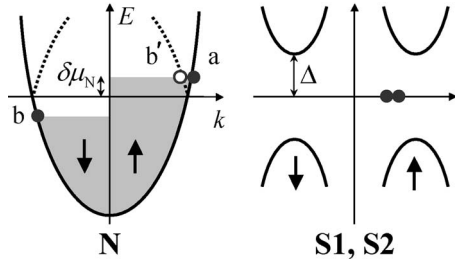


FIG. 3. Schematic diagram of energy vs momentum in the Andreev reflection when there is spin accumulation in N. The filled and open circles represent an electron and a hole, respectively. In N, the solid and dashed lines denote electron and hole bands, respectively, the shaded area indicates an occupation by electrons. In the Andreev reflection, a spin-up electron (a) injected into Ss captures another electron with spin down (b), and a spin-up hole (b') is reflected back to N.

$(-\delta\mu_N)$  is reflected back to N (Andreev reflection).<sup>26</sup> In other words, the spin-up (-down) electron with  $k_e \approx (\sqrt{2m/\hbar})\sqrt{E_F + (-)\delta\mu_N}$  and the spin-up (-down) hole with  $k_h \approx (\sqrt{2m/\hbar})\sqrt{E_F - (+)\delta\mu_N}$  mainly contribute to the formation of a Cooper pair. Note that the values of the wave numbers  $k_e$  and  $k_h$  differ due to the spin split  $\delta\mu_N$  in contrast with the case of a no spin split ( $\delta\mu_N=0$ ) in which  $k_e \approx k_h$ .

The split  $\delta\mu_N$  corresponds to the exchange energy  $E_{ex}$  of a ferromagnet in a superconductor/ferromagnet/superconductor (S/F/S) Josephson junction as follows:<sup>14–19</sup> In the S/F/S systems, Cooper pairs are formed by the Andreev reflection of spin- $\sigma$  electrons with the wave number  $k_{e,\sigma}^F \approx (\sqrt{2m/\hbar})\sqrt{E_F + \sigma E_{ex}}$  and holes with  $k_{h,\sigma}^F \approx (\sqrt{2m/\hbar})\sqrt{E_F - \sigma E_{ex}}$  at the energy  $E \approx 0$ . In the case that the exchange interaction is much weaker than the Fermi energy ( $E_{ex} \ll E_F$ ), the stable state (0 or  $\pi$ ) in the system depends on the dimensionless parameter  $\alpha_F = (E_{ex}/E_F)(k_F d_F)$ , where  $d_F$  is the thickness of F and  $k_F$  is the Fermi wave number.<sup>18</sup> At  $\alpha_F=0$  the system is in the 0 state, and the first 0- $\pi$  transition occurs at  $\alpha_F = \pi/2$ , and then the system is in the  $\pi$  state at  $\alpha_F = \pi$ .<sup>18</sup> Because the value of  $E_{ex}$  is fixed in the S/F/S system, the 0 and  $\pi$  states change periodically with the period  $2\pi(E_F/E_{ex})$  as a function of  $d_F$ . As a result, the  $d_F$  dependence of the Josephson critical current shows a cusp structure and the critical current becomes minimum at the 0- $\pi$  transition.<sup>17,18</sup>

In analogy with the case of the S/F/S junction discussed above, when there is spin accumulation in N as shown in Fig. 3, the 0 or  $\pi$  state is realized in the S1/N/S2 junction depending on the parameter  $\alpha = (\delta\mu_N/E_F)(k_F w_N)$ . In this case, the width  $w_N$  is fixed, and the 0 and  $\pi$  states are controlled through the value of  $\delta\mu_N$  which is proportional to the bias current  $I$  [see Eq. (4)]. The N part of the system is in the nonequilibrium state by the spin current in contrast with F in the equilibrium state of the S/F/S junction. However, one can discuss the critical current in the nonequilibrium S1/N/S2 junction in the same way as the equilibrium S/F/S junction because the critical current is dominated by the energy of the quasiparticles in N, not by the flow of the current.<sup>23,24</sup> Although we discuss the single-channel Josephson junction for simplicity so far, in the multichannel case the Josephson cou-

pling varies in the  $x$  direction because the spin split of ECP decays in the  $x$  direction. The total Josephson coupling is expressed as an integral of the local Josephson coupling for the  $x$  direction, and therefore the ground state in the Josephson junction shows a similar dependence on the bias current to that in the single-channel case.

From the point of view of a more detailed description, the free energy in the system is obtained by the summation of the energy of the Andreev bound states.<sup>20</sup> The bound state energy is calculated from the Bogoliubov–de Gennes equation,<sup>27</sup> and the free energy is minimum for the phase difference 0 ( $\pi$ ) for the 0 ( $\pi$ ) state. In the S1/N/S2 junction with no spin accumulation in N ( $\delta\mu_N=0$ ), the bound states with the energy  $E > 0$  contribute to the free energy. On the other hand, when the spin accumulation exists in N, the spin-up (-down) bound states with the energy  $E > \delta\mu_N$  ( $-\delta\mu_N$ ) contribute to the free energy because ECP is shifted by  $\delta\mu_N$  ( $-\delta\mu_N$ ) in N. The 0- $\pi$  transition occurs due to the shift of the energy region of the Andreev bound states which contribute to the free energy.

As an example, we consider the case that the F/N interface consists of a tunnel junction. The material parameters  $P_J=0.4$ ,  $\rho_N = \sigma_N^{-1} = 2 \mu\Omega \text{ cm}$ ,  $\lambda_N = 1 \mu\text{m}$ ,  $w_N = 800 \text{ nm}$ , and  $d_N = 10 \text{ nm}$ , which lead to  $\mathfrak{R}_N = 2.5 \Omega$ , are taken. The distance between F and Ss is taken to be  $L = 500 \text{ nm}$ . When no bias current is applied between F and N ( $I=0$ ), the S1/N/S2 junction is in the ordinary 0 state because there is no spin split of ECP ( $\delta\mu_N=0$ ). With increasing the bias current, the magnitude of the Josephson critical current decreases because the parameter  $\alpha$  increases due to the increase of the spin split. When the bias current reaches the value  $I=I_0 \approx 3 \text{ mA}$  which induces the spin split  $\delta\mu_N \approx 1 \text{ meV}$  at  $x = 500 \text{ nm}$ , the parameter  $\alpha \approx \pi/2$  and the first transition to the  $\pi$  state from the 0 state occurs (the values of  $E_F = 5 \text{ eV}$  and  $k_F = 1 \text{ \AA}^{-1}$  are taken).<sup>28</sup> As a result, the magnitude of the Josephson critical current takes its minimum at  $I=I_0$ , and increases with the increasing bias current  $I > I_0$ . When the bias current attains  $I=2I_0$ , the magnitude of the Josephson critical current becomes maximum because of  $\alpha \approx \pi$ , and decreases with the increasing bias current  $I > 2I_0$ . For  $I = 3I_0$  corresponding to  $\alpha \approx 3\pi/2$ , the second transition to the 0 state from the  $\pi$  state occurs.

Here we discuss the effect of the spin accumulation on the superconducting gap.<sup>11</sup> The spin split  $\delta\mu_N$  at  $x=L$  in N causes the split of ECP of Ss by  $\delta\mu_N$  near the S/N interfaces. The spin split in Ss decreases exponentially with the spin-diffusion length  $\lambda_S$  from the interface. In the superconductors, the superconducting gap is not suppressed by spin accumulation until  $\delta\mu_N$  exceeds the critical value of the spin split  $\delta\mu_{Nc}$ .<sup>11</sup> At low temperatures much lower than the superconducting critical temperature ( $T \ll T_c$ ), the critical value of the spin split is obtained as  $\delta\mu_{Nc} \leq \Delta_0$  by solving the gap equation,<sup>11</sup> where  $\Delta_0$  is the superconducting gap for  $\delta\mu_N = 0$  at  $T=0$ . In the case discussed above,  $\delta\mu_N \approx 1 \text{ meV}$  at the first 0- $\pi$  transition ( $\alpha \approx \pi/2$ ). For example,  $\Delta_0 \approx 1.5 \text{ meV}$  for niobium,<sup>29</sup> and therefore the superconducting gap is almost not affected by the spin accumulation at the first 0- $\pi$  transition. When superconductors with the higher value of  $T_c$ , e.g.,  $\text{MgB}_2$  ( $T_c \approx 39 \text{ K}$ )<sup>30</sup> or high- $T_c$  materials ( $T_c$  is sev-



eral 10 Ks),<sup>29</sup> are used as the electrodes S1 and S2, the superconductivity is robust even at the second ( $\delta\mu_N \approx 3$  meV,  $\alpha \approx 3\pi/2$ ) and higher  $0-\pi$  transitions.

In summary, we have proposed the Josephson device in which the  $0$  and  $\pi$  states are controlled electrically. The spin split of the electrochemical potential is induced in the electrode N by the spin-polarized bias current flowing from F to N. The  $\pi$  state appears in the S1/N/S2 junction due to the nonlocal spin accumulation in N. Because the magnitude of the spin accumulation is proportional to the value of the spin-polarized bias current, the  $0$  and  $\pi$  states of the Joseph-

son junction are controlled by the current. Our proposal provides not only possibilities for the application of superconducting spin-electronic devices but also a deeper understanding of the spin-dependent phenomena in the magnetic nanostructures.

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