Spin-Transfer Torque Switching in Nanopillar Superconducting-Magnetic Hybrid Josephson Junctions

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(Received 30 October 2014; published 9 January 2015)

The combination of superconducting and magnetic materials to create superconducting devices has been motivated by the discovery of Josephson critical current ($I_{cs}$) oscillations as a function of magnetic layer thickness and the demonstration of devices with switchable critical currents. However, none of the hybrid devices has shown any spintronic effects, such as spin-transfer torque, which are currently used in room-temperature magnetic devices, including spin-transfer torque random-access memory and spin-torque nano-oscillators. We develop nanopillar Josephson junctions with a minimum feature size of 50 nm and magnetic barriers exhibiting magnetic pseudo-spin-valve behavior at 4 K. With a bias current higher than $I_{cs}$, these devices allow current-induced magnetization switching that results in tenfold changes in $I_{cs}$. The current-induced magnetic switching is consistent with spin-transfer torque models for room-temperature magnetic devices. Our work demonstrates that devices that combine superconducting and spintronic functions show promise for the development of a nanoscale, nonvolatile, cryogenic memory technology.

DOI: 10.1103/PhysRevApplied.3.011001

Superconducting-magnetic hybrid devices [1–10] are being investigated as potential switching elements for low-energy cryogenic memory, which is essential for the realization of a high-performance energy-efficient superconducting computer [11–19]. A Josephson junction (JJ) incorporating a pseudo-spin-valve (PSV) barrier (a barrier containing two magnetic layers with different switching fields) is one of the simplest hybrid structures that allows switching of the superconducting critical current ($I_{cs}$) through control of the magnetic state [20–22]. Bell et al. [7] modulated $I_{cs}$ of such a device by changing the magnetization state of their PSV barrier. Recently, we showed that such a modulation can originate from either an exchange-field effect or a remanent-field effect and that the former may be used to build a nanopillar device in which digital information is stored as either Josephson energy or phase [10].

In a qualitative picture of superconductor-ferromagnet (S-F) physics, a Cooper-pair spin state evolves sinusoidally in the ferromagnetic barrier $F$ of an S-F-S JJ, which results in a spatial modulation of the order parameter and an oscillation in $I_{cs}$ with magnetic layer thickness $d_F$, including sign changes with a period of $2\pi \xi_F$ where $\xi_F$ is the characteristic oscillation length in $F$ [4,23,24]. These sign changes indicate where the JJ switches the phase by $\pi$, called 0–$\pi$ transitions. This effect can be extended to a PSV barrier with two magnetic layers $F_1$ and $F_2$ in which the oscillatory order-parameter modulation is given by the different effective magnetic barrier thicknesses $x^p = x_{F_1} + x_{F_2}$ and $x^{AP} = x_{F_1} - x_{F_2}$, where $x_{F_i} \equiv d_{F_i}/\xi_{F_i}$ ($i = 1, 2$) for the parallel (P) and antiparallel (AP) magnetization states, respectively. Thus, by controlling the magnetization orientation of $F_2$ relative to $F_1$ (selecting either P or AP states), the Josephson coupling can be switched in amplitude ($I_{cs}$) or phase (0 or $\pi$) [Fig. 1(a)][10].

Nanoscale JJs have not been extensively studied, because the superconducting critical current density $J_{cs}$ of typical insulating or high-resistivity barriers yields correspondingly small $I_{cs}$, which is difficult to measure. JJs with low-resistance metal barriers allow for a higher $J_{cs}$ at a cost of JJ speed (due to a longer single-flux quantum pulse width of approximately $\Phi_0/I_{cs}R_n$, where $\Phi_0$ is the magnetic flux quantum and $R_n$ is the normal-state resistance). This trade-off may be acceptable depending on the application. Room-temperature measurements of PSVs show that, as the device size is reduced, current-induced magnetization switching (CIMS), based on the spin-transfer torque (STT) effect, is possible [25–27] and may be applicable to JJ systems. In a nanopillar PSV, electrons flowing from the reference layer to the free layer are spin polarized and result in a torque on the free-layer moment that aligns the moment parallel to the reference layer. If the current is reversed, the free-layer moment can be aligned in the antiparallel orientation. This STT effect is scalable, because the switching current decreases with the device area [25,27]. Here, we develop nanopillar JJs with PSV barriers and find that the exchange-field effect on $J_{cs}$ persists to at least the 50-nm scale and allows for the differentiation between P and AP states with a significant change in $I_{cs}$ in the superconducting state. We demonstrate complete magnetization reversal by the STT effect by comparing it with field-induced magnetization switching.

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(FIMS) in Ni$_{0.8}$Fe$_{0.2}$/Cu/Ni-based JJ devices and showing the same relative changes in $I_{cs}$ across multiple Ni/Cu/Ni-based devices through the scalable exchange-field effect on the superconducting order.

The device structure we investigate is Si/SiO$_2$/Nb(100)/Cu(3)/PSV/Cu(3)/Nb(200), where the numbers in parentheses indicate the layer thickness in nanometers. We deposit Ni$_{0.8}$Fe$_{0.2}$(0.8 or 1)/Cu(5)/Ni(1.2 or 2.4) or Ni(1)/Cu(5)/Ni(2.4) for the PSV. We fabricate JJ devices by using common magnetic nanopillar fabrication processes to produce ellipses with dimensions ranging from 50 nm × 100 nm to 300 nm × 600 nm. Figure 1(b) shows the
schematic for our device, which is mounted in a cryogenic probe and measured in a liquid-helium bath at 4 K. We use a superconducting magnet to apply a magnetic field parallel to the major axes of the elliptical devices. $I_{cs}$ and $R_n$ are extracted from the measured I-V curves by use of least-squares fits to the expected electrical characteristics of the resistively shunted junction [28]. In order to fit data with a low $I_c (<5 \mu A)$ having significant electrical-noise rounding, we apply a theory that incorporates the effect of thermal noise [29] with an effective noise temperature parameter.

Our S-PSV-S JJ devices show I-V characteristics with different $I_{cs}'s$ depending on the relative orientations of the magnetizations of the two magnetic layers [Fig. 1(c)]. While the normal resistance $R_n$ in our PSVs changes by less than 1% at approximately 10 K as a result of the giant magnetoresistance effect, we achieve a dramatic 1000% change in $I_{cs}$ at 4 K due to our careful selection of materials and thicknesses to produce a very small critical current $\Delta I_{cs}$ switching at approximately 5 mT (resulting in an increase in superconducting magnet to apply a magnetic field parallel probe and measured in a liquid-helium bath at 4 K. We use a

Figure 1(c)–1(e), the equivalent metric is $|\Delta I_{cs}|/I_{cs} \approx 1000\%$, where $\Delta I_{cs} = I_{cs}^P - I_{cs}^AP$, with $I_{cs}^P \approx 1 \mu A$ and $I_{cs}^AP \approx 11 \mu A$. The field required to saturate the PSV magnetization is higher than 200 mT, but at around 100 mT the magnetic flux gets trapped in the device and complicates the subsequent zero-field characterization. To address this problem, we heat the chip just above the Nb superconducting transition temperature $T_{cs} \approx 9 K$ after applying the quasistatic magnetic field pulse that sets the PSV state and then cool to 4 K in zero field before measuring each $I_{cs}$. We vary the field pulse height and obtain hysteretic changes in $I_{cs}$ resulting from the different magnetization switching fields of the two magnetic layers. Figure 1(d) shows that the lower-coercivity layer Ni$_{0.8}$Fe$_{0.2}$ switches at approximately 5 mT (resulting in an increase in $I_{cs}$) and Ni switches over a field range from 40 to 120 mT (resulting in a decrease in $I_{cs}$). Separately, we measure the coercivities from magnetization loops of unpatterned Ni$_{0.8}$Fe$_{0.2}$ and Ni films and obtain 1 and 40 mT, respectively. In a lower field range (below the Ni switching fields), we could control the Ni$_{0.8}$Fe$_{0.2}$ magnetization direction without flux trapping to obtain high and low $I_{cs}$ states associated with AP and P states, respectively, as shown in Fig. 1(e).

Figures 1(f) and 1(g) show that different results can be obtained with a different fixed layer thickness (2.4 nm Ni). The opposite signs in $\Delta I_{cs}$ result from the oscillatory $I_{cs}$ vs magnetic layer thickness characteristics. If the slopes in $I_{cs}$ vs $d_{Ni}$ are opposite to each other [e.g., the two regions marked by the solid and dashed blue curves in Fig. 1(a)], the same change in effective thickness from P-to-AP switching can result in opposite signs in $\Delta I_{cs}$. The opposite signs of $\Delta I_{cs}$ with $d_{Ni} = 1.2$ and 2.4 nm are consistent with the results obtained in Ref. [10]. The curvature in the data for a 300 nm x 600 nm elliptical device [Fig. 1(g)] is a part of the common Fraunhofer-like $I_{cs}$ response to the applied fields [28]. Although this effect, when combined with the remanent fields in the magnetic barrier, could result in a significant modulation in the maximum supercurrent at a zero applied field in a large JJ [10,15], this effect is not significant in our nanopillar devices due to the broad Fraunhofer-like patterns and the dominant behavior of the exchange-field effect [10].

We study CIMS in the same devices and compare the results with those from FIMS. The initial PSV state was set to P with a magnetic field pulse. We hold the Ni$_{0.8}$Fe$_{0.2}$ magnetization fixed by applying a magnetic field of a magnitude between the switching fields of Ni$_{0.8}$Fe$_{0.2}$ and Ni and then apply a current pulse to switch the Ni magnetization. (The applied field changes the Ni$_{0.8}$Fe$_{0.2}$ magnetic energy landscape from bistable to monostable, effectively fixing the magnetization in one direction.) If the bias current density exceeds approximately $5 \times 10^8 A/cm^2$, the device resistance increases by a factor of 2 or more, because the Nb electrodes in the nanopillar become resistive [30,31]. This resistive transition also results in a change in $I_{cs}$ due to trapped magnetic flux, which we remove by briefly heating the chip above $T_{cs}$ before measuring each $I_{cs}$; see Fig. 2(a) for the control pulse sequence. Figure 2(b) shows hysteretic switching of $I_{cs}$ to high or low values depending on the current pulse polarity. Positive current is associated with electron flow from Ni to Ni$_{0.8}$Fe$_{0.2}$.
[Fig. 1(a)]. Switching to an AP (or P) state with a positive (or negative) current is a signature of the standard STT effect. This asymmetry rules out the Oersted field effect as the prevailing factor in this CIMS [27,32]. The P and AP states are reached at $3 \times 10^7$ and $5 \times 10^7$ A/cm$^2$, respectively, which are of the same order of magnitude as the switching current density $J_{cs}$ found in comparable studies on room-temperature devices [27,32,33] but higher than the maximum supercurrent density (approximately $5 \times 10^6$ A/cm$^2$) of the Nb electrodes in the nanopillars. CIMS consists of multiple jumps during the transitions [Fig. 2(b)] as in the FIMS of the Ni magnetization [Fig. 1(d)]. These multiple jumps may indicate the presence of magnetic nanodomains.

We also obtain FIMS loops that can be used to determine the Ni magnetization orientation after CIMS. Figure 2(c) shows a loop obtained after both the Ni$_{0.8}$Fe$_{0.2}$ and Ni magnetizations are saturated with a high field. For CIMS, we apply a +5-mA current pulse (as well as a field that holds the Ni$_{0.8}$Fe$_{0.2}$ magnetization direction only) after such a saturating field [Fig. 2(d), inset]. A FIMS loop measured subsequently has the reversed symmetry indicating a reversed (negative) Ni magnetization [Fig. 2(d)]. With consecutive +5- and −5-mA current pulses after a saturating field, we obtain a positive Ni magnetization (through two magnetization reversals) and confirm that a negative current pulse also switches the Ni magnetization [Fig. 2(e)].

According to the standard STT theory, the switching current threshold increases with $M_s V$ of the free layer, where $M_s$ and $V$ are the saturation magnetization and volume, respectively, if other parameters are fixed [25,27]. Since this theory suggests that the same magnetic materials of different thicknesses may be used to obtain CIMS in the resulting S-PSV-S JJs, we develop nanopillar JJs with a Ni(1)/Cu/Ni(2.4)-based PSV barrier. Without Ni$_{0.8}$Fe$_{0.2}$, there is a smaller number of material parameters for analysis, and the reduced electron scattering associated with a nonalloyed Ni film results in less supercurrent decay, enabling us to explore a higher $J_{cs}$ regime. The switching field ranges of Ni (1) and Ni(2.4) layers are not well separated from each other (as confirmed with magnetization measurements on unpatterned Ni films), which limits the control of the PSV magnetization state with a field between P and partially switched states. Figure 3(a) shows an $I_{cs}$ vs field-pulse height characteristic measured the same way as the case of Fig. 1(d). Non-P states result in $I_{cs} < I_{cs}^P$, which indicates $I_{cs}^P$ is also lower than $I_{cs}^P$ similar to the Ni$_{0.8}$Fe$_{0.2}$ crystals (0.8 or 1)/Cu/Ni(2.4)-based devices as expected.

Figures 3(b)–3(f) show the hysteretic loops in the measured $I_{cs}$ vs current-pulse height without an applied magnetic field. Switching to a P (or AP) state with a positive (or negative) current is consistent with the switching of the lower (thin) Ni relative to the upper Ni through the standard STT effect. The switching current increases with area (or total magnetic moment) as expected. P and AP states are reached at current densities slightly higher than those of Ni$_{0.8}$Fe$_{0.2}$/Cu/Ni devices. There are fewer or no intermediate states in smaller devices, which indicates they are more nearly single domain, approaching a two-state regime. Comparing Figs. 3(a) and 3(b), we find that CIMS results in the same maximum $I_{cs}$ (resulting from the same P state) and a lower minimum $I_{cs}$ compared with FIMS. Although this finding alone does not confirm that the minimum $I_{cs}$ obtained with CIMS is from the AP state, the maximum and minimum $I_{cs}$ values have about the same ratio (approximately 3:1) in different devices [Figs. 3(b)–3(f)], and each also scales with area without significant scatter [Fig. 3(g)], which suggest that the maximum and minimum $I_{cs}$’s are likely to be associated with well-defined P and AP states instead of intermediate states. Figure 3(h) shows the mean...
The current $I_{c}R_{n}$ of the devices presented in Fig. 3(g) together with the calculated $I_{c}R_{n}$ vs the thickness of the hard layer Ni characteristics obtained by use of the fitted material parameters given in Ref. [10] (except the prefactor). The calculation predicts the correct sign in $\Delta I_{c}$. The slight underestimation in the $I_{c}$ ratio may be due to the uncertainty in estimating the magnetic layer thicknesses (or the effective magnetic dead layer thicknesses [10,34]). The calculation suggests that both states are in the $\pi$-JJ regime and, with the upper Ni layer thickness of approximately 1.9 nm, we could obtain $0-\pi$ phase-switching devices that are controlled with the STT effect [7,10,35].

Only a few studies discuss the impact of superconducting electrodes on STT [36–40] and spin transport across an $S$-$F$ interface [41,42]. The major difference between a superconducting and a nonsuperconducting system is the presence of Andreev reflections below the superconducting gap voltage at the superconductor–normal-metal interfaces, resulting in zero spin current [36]. In our devices, the contribution from the Andreev reflections should not be significant, and the STT effect should be similar to a nonsuperconducting case, since the CIMS occurs at higher voltages (approximately 20 mV) than $2\Delta$$_{N_{B}}$ (approximately 3 mV at the bulk limit where $\Delta$$_{N_{B}}$ is the Nb gap voltage). In future work, $J_{cm}$ may be reduced by appropriately engineering the magnetic materials. This reduction may make the STT effect practical for high-density superconducting memory applications and also allow observation of an STT effect that is significantly different from a nonsuperconducting case.

Fundamentally, how small a memory element can be made is limited by its thermal stability and the required data retention time. Using our experimental results, we estimate the FIMS magnetic energy barrier is on the order of $10^{-20}$ and $10^{-19}$ J for a 1-nm-thick, 50 nm $\times$ 100 nm elliptical Ni$_{0.8}$Fe$_{0.2}$ and Ni, respectively. This estimate is well above $60k_{B}T = 3 \times 10^{-21}$ J at 4 K ($k_{B}$ is the Boltzmann constant), the energy barrier commonly required for long-term memory stability, and our results suggest that even smaller devices with lower switching energies are possible [43]. On the other hand, JJs for superconducting digital electronics are commonly designed to have $I_{c}$ of at least approximately 100 $\mu$A to make the Josephson energy $E_{J} = I_{c}\Phi_{0}/2\pi$ much larger than $k_{B}T$ [11], which is a more stringent requirement. However, a lower $I_{c}$ and $E_{J}$ may be allowed for cryogenic memory elements, because retention is determined by the magnetic properties of the PSV, while the Josephson effect could be considered a function of a magnetic-to-electrical transducer and needs to be stable for only the short duration of a memory-read operation.

This work is supported by NIST and by the U.S. National Security Agency under Agreements No. EAO156513 and No. EAO176792. This work is a contribution of NIST, an agency of the U.S. Government, and not subject to U.S. copyright.


