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Micromagnet-superconducting hybrid structures with directional current flow dependence for persistent current switching

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This letter reports on a microfabricated magnet-superconducting hybrid structure ($Co-SiO_2-Pb_{82}Bi_{18}$) showing the dependence of the critical current (I_c) on the current flow direction. With external magnetic field, intermittent superconducting and normally conducting regions are formed on the $Pb_{82}Bi_{18}$ film due to field localization created by the Co stripes, which is verified by scanning Hall probe microscopy measurements. Superconducting and normal conduction paths are created parallel and perpendicular to the Co stripes, providing directional dependency on the current flow. By changing the orientation of the ferromagnetic stripes with respect to the superconducting film, the hybrid structure could be adapted to realize a low-power persistent current switch. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3176481]

Superconducting (SC) magnets are useful for generating high magnetic fields with good stability and minimum power consumption. Some applications of SC magnets include magnetic resonance imaging,[1] magnetic levitation (Maglav),[2] and particle accelerators.[3] In these applications, part of the SC magnet coil needs to be switched between "normal (resistive)" and "persistent (SC)" modes. This can be achieved with a persistent current switch (PCS). Traditional PCSs usually consist of a SC wire with integrated heaters which allow control of the SC wire temperature to either below or above its critical temperature (T_c).[4] To switch the SC magnet into the normal mode, a small part of the SC wire in the PCS is heated to a temperature above its T_c. Thus it becomes resistive and enables gentle ramping of the drive current for the SC magnet. After the drive current reaches the desired value, heating is stopped to allow the SC wire to cool down below its T_c to form a low-loss, SC closed loop for persistent operation. However, due to the slow heating/cooling cycles involved, this type of PCS is neither energy efficient nor fast. A good alternative to heating was proposed by magnetically switching SC, but it still required external current sources to create the necessary magnetic field for switching.[5–7]

Previous theoretical studies by several groups have shown that in a magnet-superconductor hybrid structure, the critical current I_c or critical current density J_c can be dependent on the current flow direction in the SC film.[8–11] In this letter, we report on the design and characterization of a micromagnet-superconductor hybrid structure, which can provide fast and efficient switching between SC and normal states. Based on this structure, PCS that does not require external electrical current or thermal inputs can be realized. A schematic of the micromagnet-superconductor hybrid structure consisting of parallel microstripes of soft magnetic materials positioned in close proximity of a SC film is shown in Fig. 1.

When the magnet-superconductor hybrid structure is placed in a constant homogeneous external magnetic field (H), the magnetic field is amplified and redistributed over the SC film due to the high magnetic permeability of the underlying ferromagnetic stripes. This leads to the creation of alternating parallel stripes of low and high magnetic fields. In the regions of the SC film directly above the stripes, the local magnetic field strength (B) can be high enough to exceed the second critical field (H_{c2}). As a result, superconductivity in this portion of the film is suppressed. On the other hand, the magnetic field strength (B) in regions above the nonmagnetic material is still well below H_{c2}. Therefore, this portion of the film remains SC. Thus, for any current flowing on the SC layer, there could be two possible configurations depending on the relative orientation between the ferromagnetic stripes and the current direction (Fig. 2). In the case of current flowing parallel to the stripes, the flow path is made up of a parallel network of SC and resistive ribbons, and the current flows over the SC regions. In the case of current flowing perpendicular to the stripes, the path is made up of a series connection of SC and resistive ribbons, thus the current experiences an overall resistance and a voltage drop is gener-

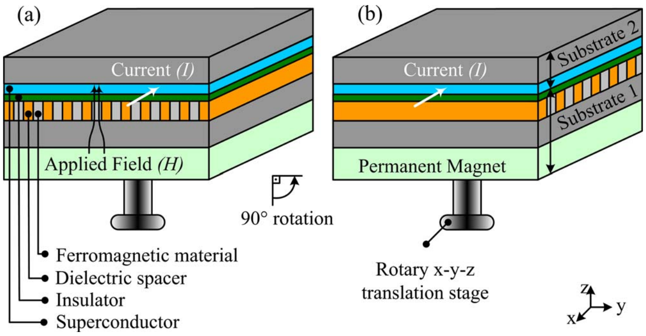

FIG. 1. (Color online) Schematic of the magnet-superconductor hybrid structure consisting of a permanent magnet, a ferromagnetic stripe array, and an insulating layer (substrate 1) positioned below a SC layer (substrate 2). Uniform applied field (H) is redistributed and amplified over the ferromagnetic regions. The use of a rotary x-y-z translation stage attached to substrate 1 allows accurate positioning and 90° rotations of the ferromagnetic stripe array with respect to the superconductor layer for switching between (a) persistent and (b) normal states.

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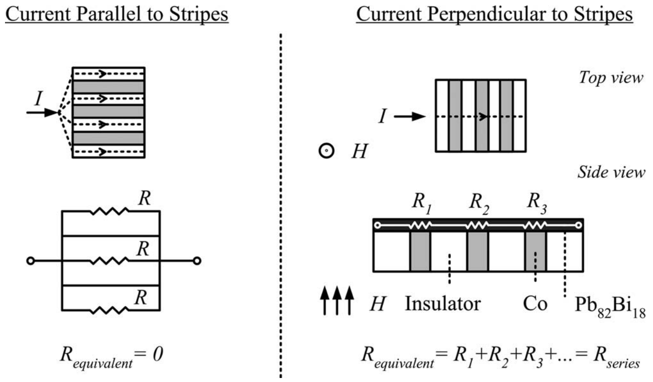

FIG. 2. Illustration of the directional current flow dependence of the magnet-superconductor hybrid structure.

ated between the two ends. Therefore, this directional current flow dependence naturally forms both the “normal” and “persistent” states of PCS. By changing the direction of the current flow relative to the orientation of the stripes, the structure can be switched between normal and persistent states. This could be achieved by mechanically rotating the underlying ferromagnetic stripes 90° with respect to the SC film with the use of a rotary *x*-*y*-*z* translation stage. In the configuration shown in Fig. 1(a), initially the stripes are aligned parallel to the current flow direction and the switch is in the persistent state. To switch to the normal state, the ferromagnetic stripe assembly is briefly retracted and then rotated 90° with respect to the SC film. Following rotation, the stripe array is raised back to its initial position. This causes the stripes to align perpendicular to the current flow direction and the switch goes into the normal state [Fig. 1(b)]. Such a PCS would eliminate the need for either Joule heating or mechanical contacts, addressing many issues in current PCS designs. In contrast to other mechanical switch designs,[12–14] this technique uses permanent contacts between the SC magnet coil and the switch leads; therefore, wear over many switching cycles is minimized and sharp changes in the current value during switching process can be avoided.

To study the directional current flow dependence of the magnet-superconductor hybrid structure, we fabricated test samples comprised of a single crystal silicon substrate with three layers (ferromagnetic, dielectric, and SC) stacked on top of each other. The fabrication process is illustrated in Fig. 3. First, a 150-nm-thick Cr seed layer was deposited onto the silicon substrate with thermal evaporation [Fig. 3(a)]. Next, SU-8 5 photoresist (from MicroChem) was spin coated at 2000 rpm and patterned to create 7.5 μm deep and 3.5 μm wide trenches to serve as the mold for subsequent Co electroplating [Fig. 3(b)]. After electroplating Co to fill the SU-8 trenches, a 200-nm-thick SiO_2 layer was deposited with e-beam evaporation to serve as an insulator [Fig. 3(c)]. Finally, 100 nm of lead bismuth ($Pb_{82}Bi_{18}$) alloy is thermally evaporated and quench condensed onto the substrate at 77 K [Fig. 3(d)]. Scanning electron micrographs of a completed test sample are shown in Fig. 3(e).

With the fabricated samples, the magnetic field distribution over the Co–$Pb_{82}Bi_{18}$ hybrid structure was characterized to determine the necessary conditions required to form intermittent SC and normal regions in the $Pb_{82}Bi_{18}$ film. Then, critical current and critical field measurements were conducted to show the directional current dependence that would be expected in the hybrid micromagnet SC system.

A SC magnet (Quantum Design PPMS) was used to provide constant homogeneous external magnetic field of 5000 Oe. Due to the high magnetic permeability of Co stripes, the applied uniform field is redistributed over the SC film, forming an alternating pattern of high and low magnetic field regions. To quantify the magnetic field distribution, a scanning Hall probe microscope (SHPM) (NanoMagnetics Instruments) was used. SHPM allows the characterization of the perpendicular component of the surface magnetic field distribution with high spatial resolution. Using SHPM the sample was scanned 200 nm above the $Pb_{82}Bi_{18}$ film at room temperature. During the scan, the scanning tunneling microscope tip located near the Hall probe tracks the sample surface to ensure a constant scanning height. Figure 4(a) shows the surface magnetic field distribution over Co stripes obtained from the SHPM, and Fig. 4(b) shows the magnetic field profile along the diagonal of the SHPM image. It is shown that the peak magnetic field above the Co stripes reaches about ~6800 G. Next, resistance versus temperature data for a $Pb_{82}Bi_{18}$ control film (without the Co stripes) were obtained using a standard dc four-point method at various fields up to 1.0 T. These data are used to determine the second critical field $H_{c2}(T)$ of the $Pb_{82}Bi_{18}$ control film at different temperatures. T_c was determined by the lowest 1% point of the resistive transition curve $R_H(T)$. Figure 4(c) shows the H_{c2} versus temperature plot for a control film. At 4.2 K (typical operation temperature for a PCS), the H_{c2} for the $Pb_{82}Bi_{18}$ film is ~6500 G. Thus, the peak magnetic field above the Co stripes (6800 G) is high enough to drive the SC $Pb_{82}Bi_{18}$ film into normal states, while the field above the SU-8 stripes (4300 G) remains below H_{c2} (4.2 K), keeping the $Pb_{82}Bi_{18}$ film SC.

To test the directional current dependence in the hybrid structure, *I*-*V* measurements were conducted for the “parallel” and “perpendicular” current flow configurations. The *I*-*V* curves for both cases were measured at different temperatures and field values to determine $J_c(H)$. Figure 5(a) shows the *I*-*V* curve measured under the operating conditions $T=4.2$ K and $H=5$ kOe. From the *I*-*V* curves, the current value at which a voltage of 10 μV is induced across the

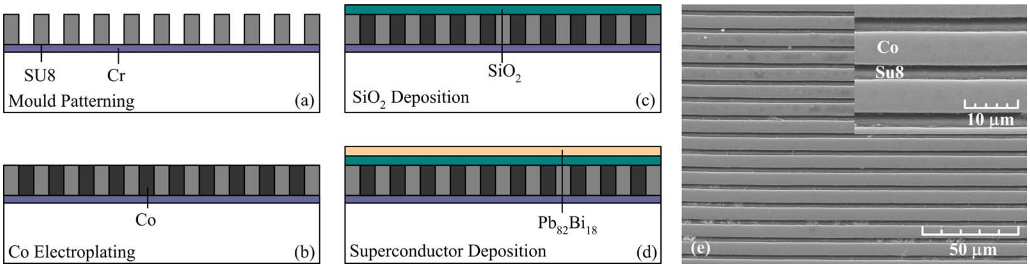

FIG. 3. (Color online) [(a)–(d)] Fabrication process flow of the test structure and (e) scanning electron micrographs of the fabricated test structure.

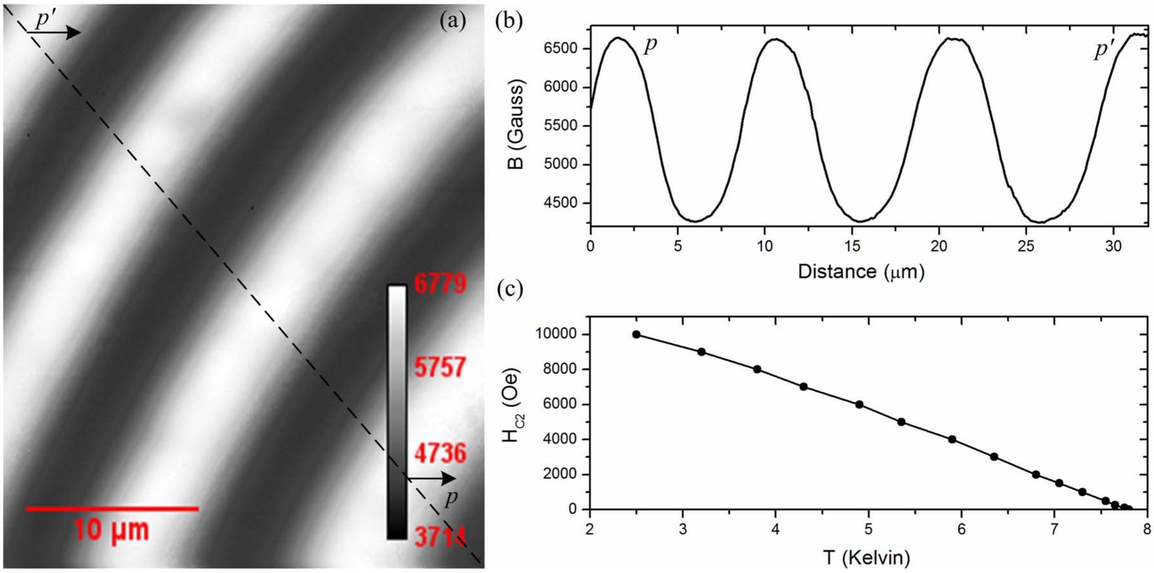

FIG. 4. (Color online) (a) SHPM image of the sample at 300 K and 5 kOe applied field. (b) Magnetic field profile across the Co stripes. (c) $H_{c2}(T)$ plot of the $Pb_{82}Bi_{18}$ control film without Co stripes.

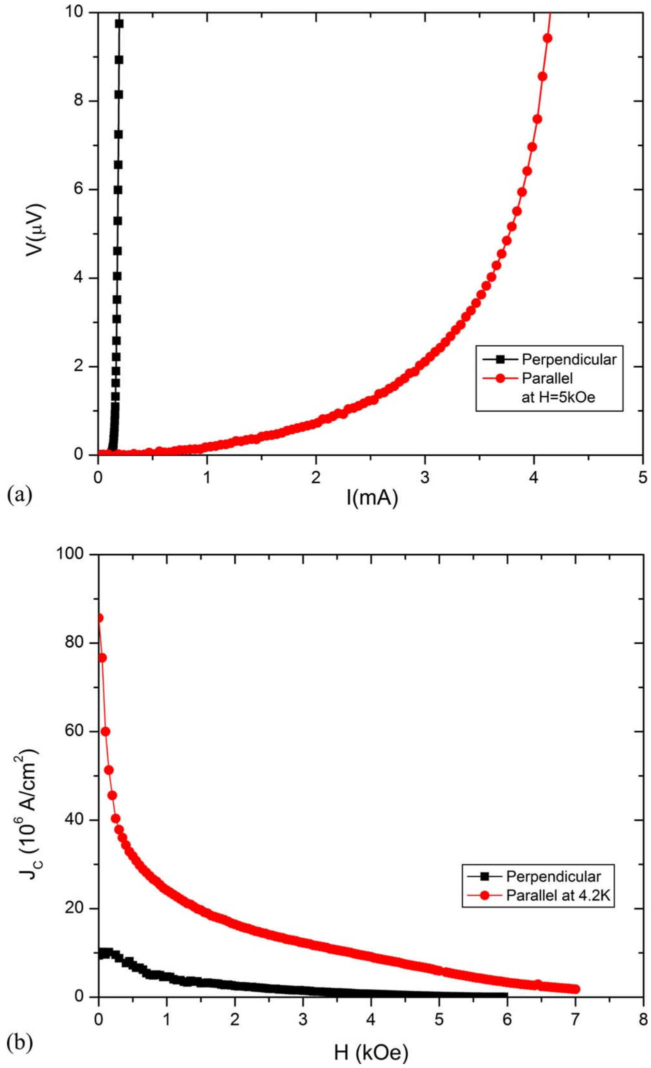

FIG. 5. (Color online) (a) *I-V* curves at 4.2 K and 5 kOe for both current directions. (b) Critical current density $J_c(H)$ plot. The difference in J_c at zero applied field is due to remnant magnetization of Co stripes.

sample is chosen as I_c and these data are used to calculate J_c [Fig. 5(b)]. It is seen that the J_c ratio between the SC state and the normal state is about 40, which is sufficient for functional SC current switching.

In summary, we have investigated a microfabricated magnet-superconductor hybrid structure with directional current flow dependence. Both SC and normal regions are created on the SC film with the use of patterned magnetic stripes. Depending on the direction of the current flow, the SC and normal regions are naturally configured into either parallel or series connections to realize SC and normal current conduction correspondingly. By implementing a simple mechanical rotation mechanism, the directional current dependency effect could be applied to realize efficient persistent current switching for SC magnets.

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