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Domain wall induced magnetoresistance in a superconductor/ferromagnet nanowire

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In a nanowire consisting of a ferromagnet/insulator/superconductor multilayer structure, the superconductivity is shown to depend strongly on the configuration of the magnetic domain walls in the neighboring ferromagnetic layer, yielding a high magnetoresistance within a temperature range near the superconducting transition temperature TC. Micromagnetic simulations confirmed that out-of-plane stray magnetic fields from uncompensated magnetic poles play a dominant role in inducing magnetoresistance in this particular system. © 2011 American Institute of Physics.

A superconductor shows great tunability in its behavior when placed in the vicinity of a ferromagnet and thus has been of intense scientific interest for decades. The two phenomena, ferromagnetism (FM) and superconductivity (SC), are usually incompatible: in a ferromagnetic material, adjacent electron spins align parallel to each other, while in a superconductor, the spins are aligned antiparallel in order to form Cooper pairs. The competition between these two types of spin ordering provides the opportunity to create devices with unique functionalities, for example to achieve very large magnetoresistance.

Superconducting spin valve structures1,2 consisting of bilayer superconducting structures can be designed, and extremely large magnetoresistance has been obtained and attributed to proximity effects10–13 and spin accumulation,14–16 as well as to nucleation of magnetic domain walls.17–21 In this letter, we demonstrate the controllable creation and motion of magnetic domain walls in narrow magnetic stripes and study their influence on a neighboring superconductor. We see that such bilayer superconducting spin valves respond to the formation of domain walls by generating a very large positive magnetoresistance along the wires, as a result of partial suppression of superconductivity in regions near the domain walls. In our system, an Al2O3 insulating barrier is present between the ferromagnet and the superconductor, which prevents direct electronic communication between the layers, precluding proximity effects and spin accumulation. This implies that the stray magnetic fields are the origin of the observed magnetoresistance in this particular system.

The narrow stripes were fabricated by depositing the layers onto Si substrates with pre-patterned electron-beam resist, followed by liftoff processes. A scanning electron microscope (SEM) image of an actual device is shown in Fig. 1(a). The sample stack is (thicknesses in nm): 3 Cr/6 Ni80Fe20/1 Al2O3/20 Al/0.7 Al2O3/3 Cr/5 Au. A 1 nm Al2O3 layer was introduced between the NiFe and Al layers in order to suppress the proximity effect and to maintain a suitable Tc.22 Another 0.7 nm Al2O3 placed above the Al layer cuts down the proximity influence from the top electrode while still allowing good electrical contacts from the top. The wire width was 1 μm and the length between the contacts was 13 μm. The wire contained double-notches ~250 nm deep (forming narrow constrictions with ~500 nm width) placed 1 μm apart. The samples were deposited onto liquid nitrogen cooled substrates through thermal and electron-beam evaporation at a system base pressure of 6 × 10−8 Torr. Electrical contacts of 5 Cr/40 Cu (in nm) were formed by magnetron sputtering after a second step electron-beam lithography. The transport measurement was performed using a standard four terminal method with a fixed dc current of 10 μA, and the samples were fully submerged in a pumped liquid He reservoir during the measurements with precise temperature control (± 2 mK) achieved by varying the vapor pressure above the liquid.

The principle of operation in these devices is illustrated in Fig. 1(b). When the wire is magnetically saturated in the negative direction and held below the superconducting...
critical temperature, the system is in a low resistance state.
As the applied magnetic field increases in the positive direc-
tion to a field $H_1$, two domain walls are injected from the
pads at the ends of the wire and traverse the wire until they
reach the notched region, where they are pinned. The stray
fields from the walls locally destroy the superconductivity
and the system goes into a stable higher resistance state. The
domain wall velocity in NiFe wires can reach hundreds of m/
s (Ref. 23) and is too fast to detect in the dc measurements.
When the applied field reaches $H_2$, it is sufficient to unpin
the domain walls from the notches and saturate the wire, and
the system returns to the low resistance state.

Figure 2 shows the resistance as a function of applied mag-
netic field for one device with notches, and a control device
without any notches (black datapoints) which was fabricated
and measured simultaneously. The wire resistance is about
44 $\Omega$ in its normal state. Near the superconducting transition
temperature, a large MR develops in the notched wires. On the
other hand, the control device does not show any noticeable
magnetoresistance (random sharp spikes arise from dynamic
electronics response due to the series connection), confirming
that the observed MR indeed originates from contributions of
the pinned domain walls. The domain walls were injected at a
field of 25-30 Oe and typically annihilated by about 50 Oe.

To quantify the domain wall stray field, the object ori-
ented micromagnetic framework (OOMMF) code was used to
calculate the magnetization and the stray field distributions
around a model of the wire. The simulation was based on the
actual shape of the device taken from a SEM image, into
which two 180° domain walls were placed and allowed to
equilibrate at remanence. The simulation was carried out with
an in-plane cell size of 4 nm and a cell size of 2 nm in the out-
of-plane direction and used standard parameters for NiFe. The
model shows that the walls are transverse in type and have a
core region that is magnetized perpendicular to the wire
length. The cores of the two walls can be oriented parallel or
antiparallel. Fig. 3(a) illustrates the magnetization distribution
in the case where the cores are parallel, which is the expected
configuration if there is any misalignment between the field
direction and the length of the wire leading to an in-plane field
component perpendicular to the wire. Figs. 3(b) and 3(c) illus-
trate the stray field produced by the pinned domain walls, show-
ing the out-of-plane and in-plane field magnitude at a height of
14 nm above the mid-thickness of the NiFe layer, correspon-
ding to mid-thickness of the Al layer, i.e., the calculated field
strength approximates the average field inside the Al layer.

The stray field from the domain walls has its most dra-
matic effect at temperatures in the range of 1.38 to 1.6 K,
close to $T_C$, where the superconductivity is most vulnerable
to magnetic fields. The maximum observed resistance change
is as large as 15 $\Omega$ or 35% of the normal state resistance. This
is equivalent to suppressing superconductivity over a 4.5 $\mu$m
long portion of the wire. The behavior of the critical field in
thin Al films is well documented. The in-plane critical field
$H_C$ for a 20 nm thick Al film is around 6 kOe at 0.4 K, much
larger than its bulk value (100 Oe) because of the thin film
geometry.
notches, which is magnetostatically stabilized and is more difficult to annihilate. During multiple field cycles, we did occasionally (once in ~30 cycles) observe the high resistance state persisting to a significantly higher field of over 150 Oe. An example of this is shown in the ascending branch of Fig. 2(b). It is notable that the resistance drops gradually before the reversal is completed, which may be a result of compression of the coupled pair of domain walls by the field prior to annihilation.

In summary, the injection and annihilation of magnetic domain walls was used to induce a large magnetoresistance in Al/alumina/NiFe wires held near the superconducting critical temperature. The stray fields generated by the domain walls in the NiFe penetrate the superconducting film and drive it towards its normal state, leading to a large positive MR. The possibility of using controllable domain wall motion to manipulate superconductivity makes it plausible to combine the advantages of superconductor- and domain-wall-based devices with simultaneous control by temperature and field, for future spintronic as well as quantum computing applications.

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FIG. 3. (Color online) (a) Simulation of the remanent magnetic configuration of two trapped 180° domain walls in the notched sample, for the case where the cores of the walls are parallel. (b) The out-of-plane and (c) the in-plane magnetic field magnitude at a height corresponding to mid-thickness of the Al superconductor film. (d) The remanent magnetization configuration for the case where the cores of the 180° domain walls are antiparallel. The x and y directions of the above figures correspond to the actual lateral dimensions of the device, and the colors map out the magnetic field intensity.