Nanoscale Spin Valve Josephson Junction Devices

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April 14, 2015 (STH29, HP94). Traditionally, superconductivity and magnetism have had a mutually exclusive relationship. However, the physics of superconductor-ferromagnet hybrid structures turned out to be far from being simply destructive, which has led to the hope of a new breed of electronic devices with advantages from both worlds [1-3]. In our recent publications, we experimentally show that a magnetic spin-valve embedded in a Josephson junction can change the superconductivity within the junction in a scalable way [4] and that the spin valve states can be switched by a spintronic effect [5].

The basic device structure is superconductor-spin valve-superconductor (S-SV-S) as shown in Figure 1 (inset). A spin valve consists of two ferromagnetic layers with different magnetic switching fields and a nonmagnetic spacer to decouple them magnetically. In magnetic memory applications, the two stable magnetization configurations – parallel and antiparallel – represent the two different memory bit states. A remarkable twist in the proximity effect in such a hybrid structure is that the Josephson coupling strength and phase can change (oscillate) depending on the magnetic configuration of the magnetic layers. If the magnetization state of a spin valve is changed between parallel and antiparallel by proper field application, the Josephson coupling changes as a consequence; parallel and antiparallel magnetization orientations are equivalent to long and short total effective magnetic thicknesses, respectively (Figure 1).

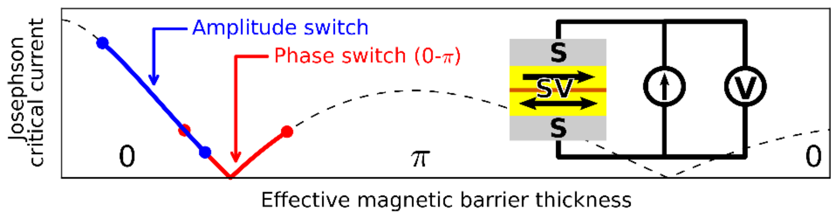

Fig. 1. S-SV-S hybrid Josephson junction device model.

However, the remanent (stray) fields of the embedded magnetic layers can also induce changes in maximum supercurrent by inducing a nonuniform supercurrent distribution (Fraunhofer or Airy pattern). We differentiated these two effects by measuring the maximum supercurrent vs. applied magnetic field [4]. The remanent field effect introduces a field offset so that the two different magnetization states result in two partial Airy patterns shifted horizontally. On the contrary, the exchange field effect changes the vertical scales of the Airy patterns because it directly changes the Josephson coupling itself [Figure 2(a)]. We find the changes in maximum supercurrent due to the exchange field effect are independent of device area and are oscillatory (indicating 0-π Josephson phase shift) in magnetic layer thickness, consistent with hybrid proximity theory.

In reference [5], we go a step further to make nanoscale devices comparable in size to room-temperature magnetic memory devices (down to 50 nm). The current between two ferromagnetic layers is spin-polarized and can induce a torque by transferring electron spins to the magnetic moments. This “spin-transfer torque” (STT) effect [6,7] is well known to be capable of magnetization reversal in nanoscale magnetic devices without a scaling problem, although in those structures the state of the device is read-out through its resistance. Our measurements show that the magnetization state is clearly reversed back and forth by the STT effect in our hybrid devices and consequently the maximum (critical) supercurrent is switched by a large factor [Figure 2(b)].

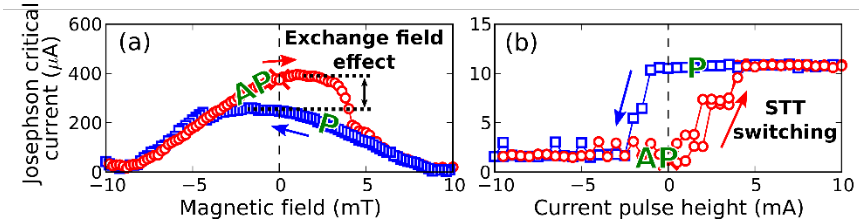

Fig. 2. Measured changes in maximum supercurrent. (a) Field switching in a micrometer-scale device. (b) Spin-transfer torque switching in a nanoscale device.

Similar to room-temperature spintronic devices, random access memory may be one of the most promising applications of superconducting-magnetic hybrid devices if they can be made to work together with superconducting logic circuits. Superconducting digital electronics based on single flux quantum were developed decades ago and have demonstrated their potential for high speed, low power computing [8,9]. However, the lack of practical memory technology has been pointed out as a major challenge towards building a high-performance computer [10]. In our publications, we have shown a new kind of device can be made at the interface between superconductivity and spintronics. Such devices may help realize fast and efficient superconducting computers.

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