Spin-transfer switching of orthogonal spin-valve devices at cryogenic temperatures


1Department of Physics, New York University, New York, New York 10003, USA
2Raytheon BBN Technologies, Cambridge, Massachusetts 02138, USA
3HYPRES, 175 Clearbrook Road, Elmsford, New York 10523, USA

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We present the quasi-static and dynamic switching characteristics of orthogonal spin-transfer devices incorporating an out-of-plane magnetized polarizing layer and an in-plane magnetized spin valve device at cryogenic temperatures. Switching at 12 K between parallel and anti-parallel spin-valve states is investigated for slowly varied current as well as for current pulses with durations as short as 200 ps. We demonstrate 100% switching probability with current pulses 0.6 ns in duration. We also present a switching probability diagram that summarizes device switching operation under a variety of pulse durations, amplitudes, and polarities. © 2014 AIP Publishing LLC.

Magnetic devices based on the spin-transfer torque (STT) effect are of significant technological interest to realize a new generation of fast, energy efficient, non-volatile memories. Parallel to efforts to reduce power consumption in memory storage devices, there is a novel approach toward energy efficiency computing based on superconducting Josephson junction circuits. For example, energy-efficient Single Flux Quantum (eSFQ and ERSFQ) logic promises ultrafast signal transmission and significant reduction in power consumption. To ensure fast operation of superconductor-based computers, cryogenic memories are needed that operate in proximity with the superconducting circuitry.

Orthogonal spin-valve (OST) nanopillar devices containing an out-of-plane magnetized polarizing layer (OP) and an in-plane magnetized spin-valve structure show promise as cryogenic magnetic memory elements. OST devices exhibit ultrafast switching (sub-ns) and low energy consumption per operation (sub-100 fJ) due to the large initial spin-transfer torque from the perpendicular polarizer. Furthermore, these device are well-suited to Josephson junction circuits as they are comprised of magnetic and non-magnetic transition metals and therefore have low impedances (1–30 Ω).

In this article, we present the characteristics of OST-spin valve devices at cryogenic temperatures, which is part of a project to explore OST-spin valve devices potential as a cryogenic non-volatile memory. Quasi-static current sweep and dynamic current pulsed statistics of representative OST devices at low temperatures are used to determine their switching behavior. Current sweep measurements at 12 K demonstrate reliable switching between parallel (P) and anti-parallel (AP) states at a 2–3 mA direct current (for a 50 × 100 nm² device). We also investigated the statistics of switching for short (0.2–10 ns) current pulses. In contrast to conventional collinear STT devices, we observe bipolar switching for the AP → P transition, as reported previously in OST magnetic tunnel junction based devices. We also find a non-monotonic dependence of the switching probability on pulse duration for the P → AP transition due to spin-transfer induced precession, which also can be attributed to the influence of the perpendicular polarizer.

We present results on OST-spin valve (SV) and OST-pseudo spin valve (PSV) devices, in which in the latter the dipole field from the in-plane reference layer is left uncompensated. The two distinct layer stacks are depicted schematically in the insets of Figs. 1(a) and 1(b). The structures were deposited on oxidized silicon wafers and consist of three ferromagnetic layers: an out-of-plane magnetized polarizer (OP), an in-plane magnetized reference layer (RL), and a magnetically softer free layer (FL). The OP is composed of a Co/Pd and Co/Ni multilayer (6.2 nm) and has a strong perpendicular anisotropy and high spin polarization. The FL is a CoFeB alloy (3 nm). In the PSV, the RL is composed of a simple CoFeB (12 nm) alloy, while in the SV stack the RL is a composite structure consisting of a CoFeB (2.3 nm) layer and a CoFe (2 nm) layer, separated by a thin Ru (0.9 nm) layer chosen to give a large antiferromagnetic RKKY coupling to significant reduce the magnetostatic coupling between the FL and the RL. A PtMn (16 nm) antiferromagnet is used to exchange bias the CoFe layer. In both structures, a thin Cu spacer (10 nm) separates the FL from the OP and the RL. Following deposition, the full film stack was annealed in a moderate magnetic field to set a unidirectional magnetization orientation. The annealed film was patterned to create nanopillar devices using a combination of e-beam and optical lithography and ion-milling. Here, we shall discuss devices patterned into ellipses that are 50 nm × 100 nm in cross section.

The magnetic state of the free layer of OST devices was determined with four-probe transport measurements of the differential resistance using standard lock-in techniques. Direct currents were applied perpendicular to the device

*a)Author to whom correspondence should be addressed. Electronic mail: ly17@nyu.edu."
plane from a constant current source. Current pulses were coupled to our measurement circuit through a bias tee from an arbitrary waveform generator. All transport measurements were conducted in a closed cycle cryostat at 12 K. Figure 1(a) shows major and minor hysteresis loops of an OST-SV device. The free layer minor loop is nearly centered about zero field with only a small offset of approximately 5 mT. In the OST-PSV shown in Fig. 1(b), the free layer is always in an antiparallel configuration at zero field due to the dipolar coupling from the uncompensated field from the RL. In this uncompensated device, we show that at ± 150 mT, the RL switches into a parallel alignment with the FL. The minor hysteresis loop of the FL is shifted by 50 mT due to the dipolar coupling field from the uncompensated CoFe RL. The remainder of this study focuses on switching behavior of OST-PSV devices, in which we compensate the dipolar field from the RL by applying an external field of $\mu_0H = 50$ mT that places the FL at the center of its hysteresis loop. Three 50 nm × 100 nm ellipse shaped OST-PSV devices were studied in detail and all of them showed similar characteristics. Here, we present representative data obtained on one of these three devices.

In quasi-static current sweep measurements, we started out from a well-defined AP or P state in the bistable region set by field [see Fig. 1(b)], then sweep current up from zero to ±3 mA and then return to zero. In our convention, positive currents correspond to electrons flowing from bottom to top of the layer stack, i.e., from the perpendicular to the free and reference layer. As shown in Fig. 1(c), $P \rightarrow AP$ switching occurs at 2.7 mA (6.9 $\times$ 10^7 A/cm^2) and $AP \rightarrow P$ switching occurs at −1.9 mA (−4.9 $\times$ 10^7 A/cm^2). The critical currents observed at 12 K are somewhat higher than the room temperature values of 2.3 mA ($P \rightarrow AP$) and −1.1 mA ($AP \rightarrow P$), which may reflect thermal activation and temperature-dependent changes to layer magnetic properties (e.g., the saturation magnetization and Gilbert damping).

We present the short-time pulsed switching probability (SP) results. Measurements are conducted by applying a sequence of current pulses of a given amplitude, duration and polarity after initializing our device into a AP or P state. We use the OST-PSV magnetoresistance signal before and after the pulse to infer whether a switching event has occurred. In the cases when a switching event occurred, we use an external field to reset the device into an initial state and repeat the procedure. Otherwise, we immediately apply the subsequent pulses until a switch event is registered. We accumulate statistics on 100 pulse trials for a desired set of amplitude and duration pairs. The ratio of the number of switching events out of one hundred represents an estimate of mean probability of switching under a given pulse amplitude and duration.

Figures 2(a) and 2(c) show the switching probability versus pulse generator output voltage $V_G$ in an applied field of 47 mT for 0.6 ns pulse. For durations as short as 0.6 ns, we measure 100% switching probability for the $AP \rightarrow P$ transition with negative pulse amplitudes and 100% switching probability for the $P \rightarrow AP$ transition with a positive pulse amplitudes. This pulse polarity dependence is consistent with the quasi-static current switching in Fig. 1(c). In Figs. 2(b) and 2(d), we present the switching probability versus pulse duration in an applied field of 47 mT for ±0.3 V pulses. We measure 100% switching probability for the $AP \rightarrow P$ transition at 0.6 ns, less than the 1 ns measured for $P \rightarrow AP$ switching transitions. This time difference can be associated with the spin torque efficiencies, i.e., the larger initial spin transfer torque from the reference layer when starting in an AP configuration. A pulse polarity dependence is consistent with the quasi-static current switching in Fig. 1(c). In Figs. 2(b) and 2(d), we present the switching probability versus pulse duration in an applied field of 47 mT for ±0.3 V pulses. We measure 100% switching probability for the $AP \rightarrow P$ transition at 0.6 ns, less than the 1 ns measured for $P \rightarrow AP$ switching transitions. This time difference can be associated with the spin torque efficiencies, i.e., the larger initial spin transfer torque from the reference layer when starting in an AP configuration. An additional feature in the $P \rightarrow AP$ transitions is that although the switching probability reaches 100% for 1 ns pulses, the probability begins to decrease around 4 ns and falls below 50% for pulse durations of 10 ns. In a conventional two magnetic layer collinear spin torque device (i.e., a device that does not have a perpendicular magnetized spin polarizing layer), the torque from the reference layer leads to a monotonic increase of the probability of switching.

![FIG. 1. (a) Major and minor resistance vs. field hysteresis loops of a OST spin valve, measured at 12 K. Inset: Layer stack schematic showing the out-of-plane polarizer (OP), in plane FL and exchange biased synthetic antiferromagnet (EB-RL). (b) Same for a pseudo spin-valve OST device. Inset: Here the dipole field from the RL is not compensated and hence shifts the minor hysteresis loop of the free layer by 50 mT. (c) Current hysteresis loop of FL of the PSV device in an applied field of $\mu_0H = 50$ mT that compensates the RL dipole field. Switching from $P \rightarrow AP$ (2.7 mA) and $AP \rightarrow P$ (−1.9 mA) is observed.](image-url)
switching probability with increasing pulse amplitude (see, for example, Ref. 12). However, the perpendicular torque in an OST device can lead to a non-monotonic dependence of the switching probability on pulse duration. For instance, a perpendicularly torque alone (i.e., without a reference layer torque) is expected to lead to an oscillatory dependence of the switching probability on pulse duration.6

Figure 3 shows the switching probability versus $V_G$ and duration $\tau$ for both $AP \rightarrow P$ and $P \rightarrow AP$ transitions. Similar to the behavior in collinear devices, we observe high switching probability for positive pulse amplitudes for $P \rightarrow AP$ transitions and high switching probability for negative pulse amplitudes for $AP \rightarrow P$ transitions. The switching probability distribution generally reflects that increased pulse durations are required for switching at lower pulse amplitudes. Unique to OST devices, we observe bipolar switching for $AP \rightarrow P$ transitions, although the positive amplitude region does not reach 100% probability. Furthermore, the $P \rightarrow AP$ transition exhibits an apparently oscillatory dependence of the switching probability on pulse duration for 5–10 ns pulses.

The distinguishing features in our switching probability diagram tend to occur for the current polarity in which electrons flow from the OP into the free layer. A relevant figure of merit here is the actual current flow through the device for a given output voltage from the generator $V_G$. In order to estimate this current, we compare the quasistatic switching current with the pulse amplitude asymptote for long durations $\tau$ on the $AP \rightarrow P$ switching probability diagram shown in Fig. 3(a). We estimate that the pulse amplitude tends toward $-0.2$ V in the long-time limit, which we correlate to the $-1.9$ mA quasistatic switching current shown in Fig. 1(c), i.e., the actual voltage across the device is closer to $-25$ mV for an $-0.2$ V amplitude pulse. We use this estimated conversion factor to calibrate the pulse generator output voltages $V_G$ into currents $I$ (see second y-axis in Fig. 3). Thus, we can estimate that under typical pulses requiring an amplitude of 0.2 V, the power dissipated in switching our 13 $\Omega$ OST-PSV device over a 1.8 ns duration is estimated to be 86 fJ. The switching current is expected to scales as $\alpha V M_s^2$, where $\alpha$ is the damping coefficient, $V$ is volume, and $M_s$ is the saturation magnetization of FL.11 Therefore, possible routes to further reduce the switching energy of OST-spin valve devices include reducing the magnetization and size of FL and using superconducting electrodes to minimize device lead resistance (estimated to be several ohms in the present devices).

In summary, we have studied the switching characteristics of orthogonal spin-transfer spin valve devices at low temperatures in both the long-time quasistatic regime and the short-time pulsed regime. High probability switching occurs under current pulses as short as 600 ps and requires less than 100 fJ per switch. The pulse induced switching characteristics are promising for low-energy, high-speed switching applications that are desired for cryogenic memory applications. More importantly, significant reductions in the switching energy and switching time of these devices are possible by reducing the magnetic moment ($M_s V$) of the free layer as well as its anisotropy, as energy barriers to magnetization reversal of only $\sim 240$ K (i.e., $\sim 60$ kgT, with $T = 4.2$ K) are needed for long term magnetization stability at liquid helium temperatures. Further, devices in which the FL is bistable at zero field (i.e., the dipole field from the RL has been compensated) and low-temperature (an OST-SV) have also been demonstrated.

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