A Three-Terminal Spin Transfer Torque Device

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Abstract:
We designed and fabricated a three-terminal spin transfer torque device in which combines a Co$_{40}$Fe$_{40}$B$_{20}$/Cu/Co$_{40}$Fe$_{40}$B$_{20}$ spin valve and a Co$_{40}$Fe$_{40}$B$_{20}$/MgO/Co$_{40}$Fe$_{40}$B$_{20}$ magnetic tunnel junction (MTJ) with a common Co$_{40}$Fe$_{40}$B$_{20}$ free layer. Conventional two-terminal devices were also studied in order to optimize the performance of our final device. Switching current density $J_s \sim 3 \times 10^7$ A/cm$^2$ in spin valve and tunneling magnetoresistance (TMR) \( \sim 140\% \) in MTJ were observed in these stand alone samples.

Summary:
Magnetic tunnel junctions (MTJ) and spin valves are two promising candidates for future magnetic random access memory (MRAM) devices that have been widely studied for the past few years [1,2]. By utilizing spin transfer torque (STT) effect, pure electrical switching of the magnetic configurations of nano-scale MTJs and spin valves can be realized with critical current density \( \sim 10^6 - 10^7 \) A/cm$^2$ [3-5]. Although STT-MTJ MRAM has the advantage of higher magneto-resistance (MR) ratio while comparing to its spin valve counterpart, dielectric breakdown of ultrathin (1-2 nm) tunnel barrier and unreliable switching caused by back-hopping of MTJs at higher applied voltages (~1V) are undesirable for industrial applications [5, 6]. In order to bypass these issues, several three-terminal devices have been proposed and studied [7,8].

Here we demonstrate the fabrication of a three-terminal spin transfer torque device which is similar to the structure in our previous work [7] but with a different nano-fabrication process and a much simpler spin valve layer design. A schematic topology of our device is shown in Figure 1. The left and the right top leads are the writing ports while the right top lead and bottom lead comprise the reading ports. The free switching ferromagnetic layer (double headed arrow in Figure 1) is shared by the spin valve and the MTJ. Both fixed ferromagnetic layers (single headed arrows) are pinned by antiferromagnetic Ir$_{20}$Mn$_{80}$ (IrMn) layers. Cu spacer and MgO tunnel barrier are used in spin valve and MTJ, respectively. All three ferromagnetic layers are Co$_{40}$Fe$_{40}$B$_{20}$ (CoFeB).

Figure 1: A schematic illustration of three-terminal STT device. Writing current is sent through top electrodes to introduce a spin transfer torque on common free layer (double-headed arrow). Reading is done by measuring the TMR between top and bottom electrodes.

Figure 2: SEM of a typical device before patterning top electrodes.
The layer stacks (in nm) bottom layers / IrMn(20) / CoFeB(5) / MgO(wedge) / CoFeB(4) / Cu(8) / CoFeB(5) / IrMn(20) / capping layers were first deposited by sputtering under 2 mTorr. The film was then fabricated into designed structure by multiple steps of aligned e-beam lithography and ion-milling. An elliptical shape pattern with dimensions ~ 80 nm x 200 nm was first defined by e-beam lithography and then milled down to the bottom IrMn layer. Second e-beam lithography was used to pattern a milling mask with its edge at the middle of the device. The right half of the device was then ion-milled to the CoFeB free layer. In order to connect top electrodes precisely out from the two ends of the device, a third aligned e-beam exposure is required. Scanning electron microscope (SEM) image of a typical device before patterning top electrodes is shown in Figure 2. Bottom lead was defined separately by photolithography afterwards. E-beam evaporated silicon oxide was used as insulating and protection layer of the device.

In order to characterize the behavior and to optimize the performance of our final design, stand-alone CoFeB/Cu/CoFeB spin valves and CoFeB/MgO/CoFeB MTJs were also fabricated and examined. Figure 3 (a) and (b) are the resistance-to-current data from DC 2-probe measurements which indicate the switching properties of a typical CoFeB/Cu/CoFeB spin valve with similar dimensions (70 nm x 200 nm) to our three-terminal device. The critical currents for switching from anti-parallel (AP) state to parallel (P) state and from P to AP are $J_{cAP} \rightarrow P \sim 2.3 \times 10^7$ A/cm$^2$ and $J_{cP} \rightarrow AP \sim 3.8 \times 10^7$ A/cm$^2$, respectively. On the other hand, as growth MTJ samples show TMR ~ 30% and reaches ~ 140% after magnetic annealing at 350°C for 30 minutes. HR loop measurement of a typical 70 nm x 200 nm MTJ sample after annealing is shown in Figure 4.

References:


