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Spin torque transfer structure with new spin switching configurations

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Abstract. Spin torque transfer structures with new spin switching configurations are proposed, fabricated and investigated in this paper. The non-uniform current-induced magnetization switching is implemented based on both GMR and MTJ nano devices. The proposed new spin transfer structure has a hybrid free layer that consists of a layer with conductive channels (magnetic) and non-conductive matrix (non-magnetic) and traditional free layer(s). Two mechanisms, a higher local current density by nano-current-channels and a non-uniform magnetization switching (reversal domain nucleation and growth) by a magnetic nanocomposite structure, contribute in reducing the switching current density. The critical switching current density for the new spin transfer structure is reduced to one third of the typical value for the normal structure. It can be expected to have one order of magnitude or more reduction for the critical current density if the optimization of materials and fabrication processes could be done further. Meanwhile, the thermal stability of this new spin transfer structure is not degraded, which may solve the long-standing scaling problem for magnetic random access memory (MRAM). This spin transfer structure, with the proposed and demonstrated new spin switching configurations, not only provides a solid approach for the practical application of spin transfer devices but also forms a unique platform for researchers to explore the non-uniform current-induced switching process.

PACS. 72.25.-b Spin polarized transport – 72.25.Ba Spin polarized transport in metals – 73.63.-b Electronic transport in nanoscale materials and structures – 75.47.-m Magnetotransport phenomena; materials for magnetotransport

1 Introduction

Spin torque transfer effects in nanomagnets attract lots of attention recently [1–4]. The direction of magnetization can be changed directly by spin current instead of magnetic field. The discovery of spin torque transfer not only provides a base for "current-driven" spintronic devices and but also a new platform to study the spin flipping and precession. The mechanism of the spin torque transfer has been studied in giant magnetoresistive (GMR) or magnetic tunnel junction (MTJ) nanostructures, fixed layer/space layer/free layer, in which the magnetization switching in the free layer has been proved and treated as the single-domain uniform switching [5–11]. However, the critical switching current density in such typical sandwich structure is around 10^7 A/cm^2, which results in poor compatibilities with other integrated electronics components, which will be a challenge for any practical application. Furthermore, if there were no further change of the existing spin transfer structures that are based on the single-domain switching, from the engineering viewpoint, we would soon face the famous dilemma on the thermal stability and switching capability for high density spin transfer devices, which need a tremendous size reduction, such as MRAM and magnetic logic. The similar problem has already led to a recording areal density limit for magnetic recording media. We presented a first MTJ-based spin transfer structure that could successfully address the above challenge by inserting an innovative nano-current-channel (NCC) layer inside the free layer [12]. In this work, we will further report in details this new spin transfer structure and its integration with not only in-plane magnetization configuration but also perpendicular magnetization configuration especially focus on discussing its new spin switching configuration and related switching mechanisms.

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2 NCC type spin torque transfer structure with in-plane magnetic anisotropy

As shown in Figure 1a, this new spin transfer device has a MTJ structure with a hybrid (composite) free layer: $CoFe_{10}$(2 nm)/Fe-SiO_2(3 nm)/$CoFe_{10}$(1 nm), which

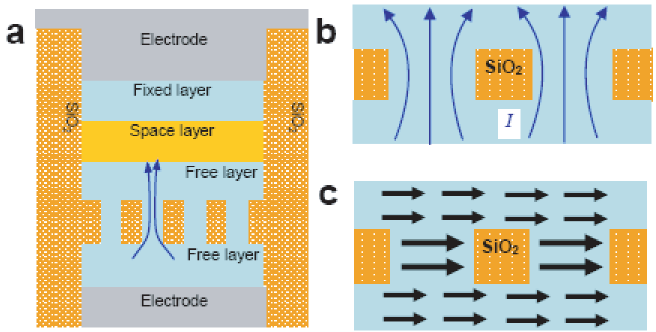

Fig. 1. The schematic spin transfer device with a novel hybrid (composite) free layer; (b) current confined effect inside the hybrid free layers; (c) new spin configuration: coupling between the sub-free layers through the magnetic nano-channels.

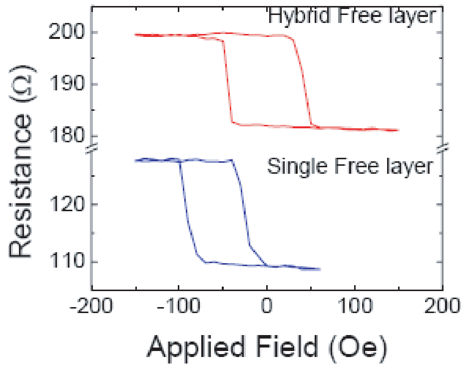

Fig. 2. MR curves for MTJ devices with a composite free layer (top) and a single free layer (bottom). MTJ device size: 180 nm × 250 nm. Structure: electrode/Ta/IrMn/CoFe/Ru/CoFe/AlO/free layer.

consists of a granular layer (NCC) with conductive channels (magnetic) and non-conductive matrix (non-magnetic) and two sub-free layers that are exchange-coupled through the NCC layer. The full MTJ stack structure is: bottom electrode/Ta 30 Å/CoFe 20 Å/FeSiO 30 Å/CoFe 10 Å/AlO_x/CoFe 30 Å/Ru 8 Å/CoFe 30 Å/IrMn 150 Å/Ta 200 Å/top electrode. We reported that the mean size of magnetic conductive channels (Fe) is 5 nm in diameter while the insulator matrix (SiO_2) boundaries thickness is around 2 nm [12,13]. The Fe conductive channels are isolated from each other by the insulator boundaries and show superparamagnetic properties at room temperature because of their ultra small sizes. The detailed properties of this nano-granular FeSiO thin film have been reported in our previous work [12–15]. Figures 1a and 1b schematically show basic functions of the hybrid free layer. First, it forces the current to concentrate and inject into the nano-size conductive channels with higher local current density that induces the local magnetization switching. If the area ratio of the conductive channels over the total free layer is less than 10% (achievable), we can increase the local current density about one order of magnitude. Second, the two sub-free layers are exchange-coupled through the magnetic conductive channels and the local reversed magnetization of the magnetic channels in NCC layer, which function as the reversal magnetic nucleus, will spread around the two sub-free layers with the continuous injection of spin current.

Figure 2 shows the magnetoresistive (MR) curves for a MTJ with a hybrid free layer ($CoFe_{10}$(2 nm)/Fe-SiO_2(3 nm)/$CoFe_{10}$(1 nm)) and a single free layer ($CoFe_{10}$ (3 nm)) respectively. In comparison with the device with single free layer, the resistance-area (RA) value increased from 4.2 Ω μm^2 to 7 Ω μm^2 while the MR ratio dropped from 16.5% to 10% for the device with a hybrid free layer by inserting a nano-current-channel layer. This extra resistance comes from the narrowed current crossing area as shown in Figures 1a and 1b. It is interesting to note that the current confined effect does not introduce a higher MR ratio as it does in the current-perpendicular-to-plane (CPP) spin valve device. For the CPP spin valve, the so-called current-confined effect will enhance the active layers' resistance ratio in the whole device, therefore, the measured MR ratio will approach its intrinsic value [16, 17]. On the other hand, for the MTJ structure, the resistance from the barrier dominates the device resistance in the CPP direction, thus the current confined layer does not contribute to the active layers' resistance ratio as much as it does in the CPP spin valve. Furthermore, the decay of the MR ratio indicates that the FeSiO layer may introduce extra resistance that does not contribute to the resistance change (ΔR). One of the possible reasons for this is that the FeSiO layer may increase the interface roughness. Further optimization of materials and deposition processes can be expected to solve this problem.

Figure 3 shows the comparison of the spin torque transfer behaviors of two devices that were introduced in former paragraph. The critical current densities required to switch the magnetizations from anti-parallel to parallel configuration and vice versus are $J^{ap-p} = 1.1\times 10^7$ A/cm^2 and $J^{p-ap} = -1.7\times 10^7$ A/cm^2, respectively for the typical MTJ structure with a single free layer. The mean J_c, defined as $(J^{ap-p} - J^{p-ap})/2$, is 1.4×10^7 A/cm^2. By inserting the current confined layer (FeSiO) inside the free layer, this value is reduced to 4.2×10^6 A/cm^2. It is noticed that the reduction of J_c in both current directions (J^{p-ap} and J^{ap-P}) is very similar. This is because the current confined layer is sandwiched by two sub-free layers (CoFe). Therefore, the current confined effect is symmetric for both current flow directions. Spin current injects through the nano-current-channels and results in a high current density due to the reduced crossing area. Such a high spin current will result in reversal domains nucleation. These reversal domains will grow and expand out by the continuously injected spin current till the whole free layer switches. The free layer switching process involves the non-uniform switching instead of single domain switching. This new spin configuration results in a huge reduction of the switching current as shown in Figure 3.

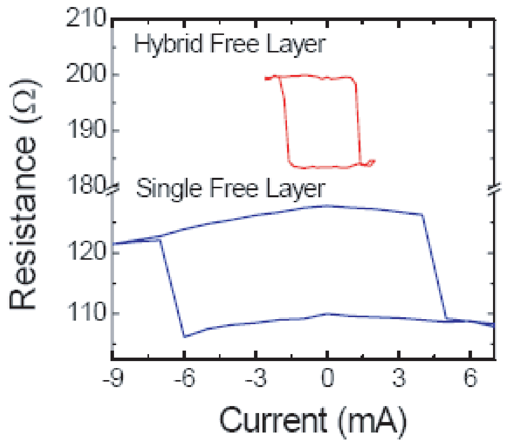

Fig. 3. Spin transfer curves for MTJ devices with a hybrid (composite) free layer (top) and a single free layer (bottom).

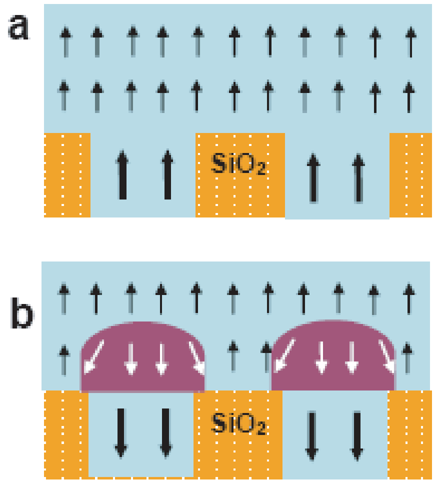

Fig. 4. Spin configurations in hybrid (composite) free layer with perpendicular anisotropy (a) remanent status (b) localized spin switching (domain nucleation) with a reversed current or field.

3 NCC type spin torque transfer structure with perpendicular magnetic anisotropy

We further integrate this new spin switching configuration in spin transfer structure with perpendicular anisotropy, which was built up by introducing CoFe/Pt multilayers. The switching field of the multilayer can be tuned by adjusting the Pt and CoFe thickness [18]. Two sets of circular GMR structure devices, 100 nm in diameter, were fabricated by electron beam lithography process. One set is with a hybrid free layer: $[CoFe/Pt]_5$ and 3 nm FeSiO nano-current-channel layer. Unlike inserting the FeSiO into the free layer as discussed in the second section, FeSiO layer was built just under the free layer in these devices. As shown in Figure 4 schematically, the magnetic nano-current-channel is perpendicularly exchange-coupled with the free layer. Spin current is confined into the nano-current-channels.

Figure 5 shows that, for the device with a single free layer, the switching field is up to 2500 Oe, while it is reduced to 1100 Oe for that with a hybrid free layer. As discussed in the above section, the nano-current-channel exhibits superparamagnetic properties alone at room temperature and is exchange-coupled with the sub-free layer. At a low magnetic field, the reversal domain nucleation appears inside the channels and the reversal domains grow and expand with further increasing the applied field till the whole free layer switches. Therefore, the hybrid free layer switching that starts from the nano-current-channel at a small field may result in lower effective switching field. This is consistent with our previous work in exchange-coupled composite perpendicular media [13–15]. However, for the in-plane magnetization configuration, there is no obvious decrease for the switching field by inserting the nano-current-channel layer. Further work should be done to fully address this point.

Figure 6 compares the spin torque transfer behaviors for these devices. The critical current densities required to switch magnetizations between anti-parallel and parallel configurations are $J^{ap-p} = 1.1 \times 10^8$ A/cm^2 and $J^{p-ap} = -1.5\times 10^8$ A/cm^2, respectively for the single free layer case. By inserting the current confined layer (FeSiO) under the free layer, J^{ap-p} value is reduced to 7.6×10^7 A/cm^2 (reduced 31%) while J^{p-ap} value is reduced to 7.2×10^7 A/cm^2 (reduced 52%). It should be noted that the reduction ratio of J_c for the two current directions (J^{p-ap} and J^{ap-p}) is very different. One possible reason is due to the different spin accumulation for the two current flow directions. Manschot [19] and Xiao [20] have reported a similar asymmetrical spin accumulation effect between the two electrodes of a spin valve structure. In our work, the inserted NCC layer formed a different interface, which resulted in asymmetrical spin accumulation and Jc reduction.

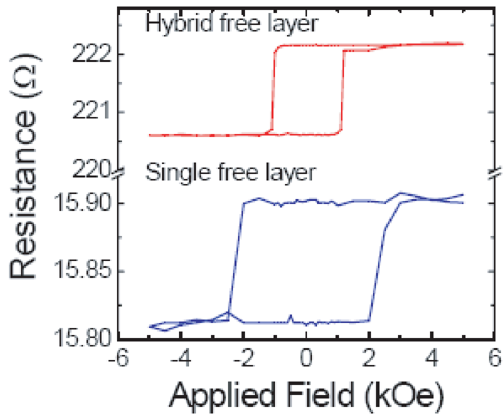

Fig. 5. MR loops for devices with a hybrid (composite) free layer (top) and a single free layer (bottom) with perpendicular anisotropy. Device size: 100 nm in diameter, circular. Structure: Ta/$[CoFe/Pt]_n$/Cu/free layer.

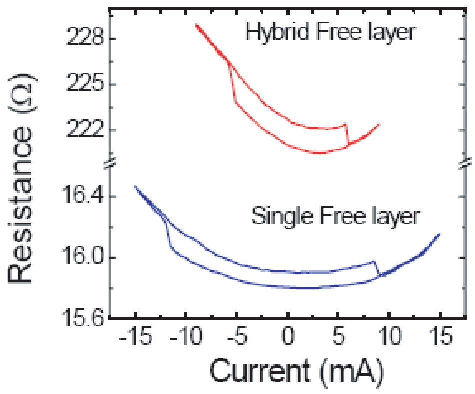

Fig. 6. Spin transfer curves for devices with a hybrid (composite) free layer (top) and a single free layer (bottom) with perpendicular anisotropy.

4 Summary

This paper presented a novel spin torque transfer structure with new spin switching configurations. By inserting a nano-current-channel layer into the free layer, the critical current density was reduced to one third of the typical current value. First, spin current is confined into the nano-current-channels, which results in a higher current density in local areas. If the area ratio of the conductive channels over total free layer is less than 10%, the local current density can be increased by one order of magnitude. Second, the magnetic nano-current-channels help switching the free layer through the magnetic exchange coupling based on a non-uniform switching mechanism. The current confined effect is more outstanding if the nano-current-channel layer is inserted in the free layer. An asymmetrical current reduction was observed for the spin torque transfer device with the NCC layer under the free layer.

The proposed and demonstrated spin torque transfer structure with new spin switching configurations not only points out a solid approach to reduce the switching current density for practical applications but also provides a unique platform to explore the fundamental aspects of non-uniform current-induced-magnetization-switching, which are still not fully addressed theoretically and experimentally.

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