Giant magnetoresistance behavior of pseudo spin valve rings with magnetostatically coupled elements

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Abstract – We have investigated the giant magnetoresistance (GMR) responses of the pseudo spin valve elliptical rings placed in close proximity with individual magnetic elements. Significant modifications to the GMR responses were observed due to the effects of magnetostatic coupling between the rings and the magnetic elements. We have shown that the stability of the vortex state in the rings can be systematically controlled by varying the orientation and position of the individual magnetic elements relative to the ring structure. Our experimental observations were verified by micromagnetic simulations.

Magnetization reversal process in ring geometries has been extensively investigated recently [1–3] due to their unique properties and their potential in applications such as magnetic random access memories (MRAM) [4] and magnetic biosensors [5]. Different magnetic states have been identified experimentally in ferromagnetic rings namely, the “vortex” state in which the magnetization is circumferential and a state with two opposite head-on (180°) domain wall known as the “onion” state [6,7]. More complicated magnetic spin states have also been observed in ring structure, such as states consisting of two 360° domain walls [8] and double vortex walls in very thick rings [9]. These magnetic states come from the competition between the magnetostatic energy and exchange energy, and depend on such geometrical parameters as the film thickness, ring width and ring diameter. A transition from the onion state to the “vortex” state occurs when one of the walls unpins and traverses the structure, annihilating the other wall to generate a state in which the magnetization runs circumferentially, with no domain walls. Symmetrical rings, however, have difficulty in pinning the magnetic domain walls due to which both the magnetic “poles” of the onion state start to rotate simultaneously. The main consequence of this reversal is that the reverse onion state is formed without the intermediate flux closure state. In order to pin a domain wall, different methods have been used, including notches [10], introducing shape anisotropy into the ring [11,12], and centering the ring [13]. The stability of the vortex state has also been studied in magnetostatically coupled arrays of magnetic nanostructures using magnetometry techniques [12], magnetic imaging [14] and magneto-optical methods [15]. This is particularly important from the application point of view, where high storage density of magnetic elements is required.

In this letter, the giant magnetoresistance (GMR) responses of the pseudo spin valve elliptical rings in close proximity with individual magnetic elements have been investigated. We observed significant modifications to the GMR responses due to the effects of magnetostatic coupling between the rings and the magnetic elements. The stability of the vortex state in the rings can be systematically controlled by engineering the orientation and position of the individual magnetic elements relative to the ring structure. Polycrystalline pseudo spin valve ring-wire structures of configuration SiO$_2$/Co(10 nm)/Cu(8 nm)/Ni$_{80}$Fe$_{20}$(10 nm)/Cu(2 nm) were fabricated using multi-level lithography techniques followed by deposition and lift-off process. Elliptical ring elements of 5 μm/3 μm major/minor diameter were fabricated using electron-beam (e-beam) lithography and e-beam deposition. The width of the rings and the wires was kept constant at 300 nm and 150 nm,

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transport measurements were carried out by simultaneously evaporating Cr(10nm) and e-beam lithography. This was followed by thermal fabrication on top of the nano-wires using both optical and e-beam lithography. The ring structures are patterned in ring-wire hybrid geometry [16] and characterized using synchronous transport measurements [17], as shown in fig. 1(a), which is an efficient way of probing the entire ring structure, thus eliminating any dependence on the contact configuration of the probes. Elliptical magnetic elements of dimensions 1.5 µm × 0.7 µm were placed on the top and bottom of the ring in two configurations, as shown in fig. 1(b) and (c). These elements were patterned during the fabrication of the rings and therefore have the same pseudo spin valve film structure. They were symmetrically and asymmetrically placed ~100 nm apart from the outer diameter of the ring so as to allow both the ring and ellipse to be magnetostatically coupled. MR measurements were carried out using the standard four-point probe technique. A constant dc current of magnitude 50 µA was passed through the outer two probes, labeled as I+ and I−. Synchronous transport measurements were carried out by simultaneously probing the voltage from the two inner contact probes (labeled as V1) and the contact probes on the wire alone (labeled as V2), respectively.

Figure 2(a) shows the giant magnetoresistance (GMR) response for the elliptical ring without any biased magnetic elements for field applied along the x-direction. The open red circles corresponds to the data from the ring-wire hybrid configuration (V1) showing the switching fields of both the ring and the nano-wires, respectively. The solid blue squares correspond to the response from the section V2, which probes only the nano-wire segment. As expected, due to the synchronized transport measurements, we observed a clear superimposition of the two curves. The reversal process of elliptical ring is characterized by distinct switching states as previously discussed in ref. [17]. The Ni80Fe20 layer in the ring undergoes reversal from forward-onion state to reverse-onion state without undergoing a vortex state. The Ni80Fe20 layer in the wire segment also switches at the same switching field, which is characterized by section V2. This is shown as state E1 in fig. 2(a). Subsequently, reversal of the Co layer in the wire segment takes place at ~120 Oe bringing down the resistance to E2. The next switching process takes place at ~145 Oe, where the Co layer switches to a vortex state and decreases the resistance level to state E3. This is followed by a transition from vortex to reverse-onion state at position E4.

The GMR response obtained for an elliptical ring which is magnetostatically coupled to the magnetic elements is shown in fig. 2(b). The marked modification to the GMR response observed when compared with fig. 2(a) can be attributed to the magnetostatic interactions between the ring and the magnetic elements. The effect of symmetricly placed non-magnetic electrical contact probes were fabricated on top of the nano-wires using both optical and e-beam lithography. This was followed by thermal evaporation of Cr(10 nm)/Au(150 nm) material and lift-off processes. The ring structures are patterned in ring-wire hybrid geometry [16] and characterized using synchronous transport measurements [17], as shown in fig. 1(a), which is an efficient way of probing the entire ring structure, thus eliminating any dependence on the contact configuration of the probes. Elliptical magnetic elements of dimensions 1.5 µm × 0.7 µm were placed on the top and bottom of the ring in two configurations, as shown in fig. 1(b) and (c). These elements were patterned during the fabrication of the rings and therefore have the same pseudo spin valve film structure. They were symmetrically and asymmetrically placed ~100 nm apart from the outer diameter of the ring so as to allow both the ring and ellipse to be magnetostatically coupled. MR measurements were carried out using the standard four-point probe technique. A constant dc current of magnitude 50 µA was passed through the outer two probes, labeled as I+ and I−. Synchronous transport measurements were carried out by simultaneously probing the voltage from the two inner contact probes (labeled as V1) and the contact probes on the wire alone (labeled as V2), respectively.

Figure 2(a) shows the giant magnetoresistance (GMR) response for the elliptical ring without any biased magnetic elements for field applied along the x-direction. The open red circles corresponds to the data from the
coupling of the magnetic elements to the ring can be classified into two aspects. Firstly, the stability of the vortex state in the Co ring reduces to a smaller field range of 33 Oe (state S3) as compared to 56 Oe (state E3) for the ring without any coupled magnetic elements (fig. 2(a)). Secondly, the transition from vortex state to reverse-onion state for the Co layer of the ring takes place at a reduced switching field of 165 Oe (transition from S3 → S1) as compared to the switching field of 200 Oe (transition from E3 → E4) for elliptical ring without any coupled magnetic elements. The stray fields from the magnetic elements interact with the local region of the ring structure in close proximity. This results in the local modification of the spin state of both the sections of the ring (namely, top section and bottom section) in the direction of the spins in the magnetic elements. Therefore, the vortex state in the Co layer is stable only for a smaller field range and switches to reverse-onion state at a relatively smaller switching field. Since both the magnetic elements are symmetrically placed relative to the ring, the GMR response is symmetric in both the forward and backward loops. Moreover, the transitions from S1 → S2 and S4 → S5 correspond to the reversal of the Ni80Fe20 and the Co layers in the wire segment, respectively.

We further investigate the effect of asymmetric coupling of the magnetic element to the ring by placing one of the magnetic elements at 45° relative to the ring as shown in fig. 1(c). Shown in fig. 3(a) is the GMR response for the field applied along the x-direction. Again, the GMR response is significantly different from the responses shown in fig. 2 due to the competing local anisotropy. Understanding the switching mechanism is facilitated by micromagnetic modeling which we performed using the Object-Oriented Micromagnetic Framework (OOMMF) code from NIST [18]. The device was discretized into 10 nm × 10 nm × 4 nm cells for which the direction of the magnetocrystalline anisotropy was randomly oriented to simulate the polycrystalline nature of the sample. Standard parameters were used to characterize the properties of the Ni80Fe20 (exchange constant A = 13 × 10^-12 J m^-1, saturation moment Ms = 860 × 10^3 A m^-1, anisotropy K1 = 0) and Co (exchange constant A = 30 × 10^-12 J m^-1, saturation moment Ms = 1400 × 10^3 A m^-1, anisotropy K1 = 520 × 10^3 J m^-3) layers. The thick Cu layer suppresses exchange coupling between the ferromagnetic layers [19] and hence the RKKY interaction was ignored, leaving only the interlayer magnetostatic interactions. Considering the magnetization reversal of the structures from positive saturation field to negative saturation the top and bottom elements reverse the direction of their magnetization first as the field crosses zero corresponding to the spin state shown in fig. 3(b). The Co and Ni80Fe20 layer of the ring are in their initial forward onion states. The magnetization of the Co layer for both the top and bottom magnetic elements are pointing along their easy axis direction due to shape anisotropy. However, due to a small positive field applied, the magnetization of the Ni80Fe20 layer of the magnetic elements have switched in the opposite easy-axis direction. As the field is increased further, the Ni80Fe20 layer in the ring undergoes a transition to reverse onion state without forming an intermediate vortex state. This corresponds to position R1 in fig. 3(a). We have also mapped the different transitions (R1-R6) observed in fig. 3(a). Shown in fig. 4 are the corresponding schematics of the different spin states. On further increasing the applied field, the Ni80Fe20 layer in the wire segment also switches to the applied field direction and attains the maximum resistance value R2 in fig. 3(a) corresponding to the spin state depicted in fig. 4(b). The transitions in wire segment are facilitated by simultaneous measurement of section V2 and superimposing it on the response obtained from section V1. Therefore, this is the position when the entire ring structure is in the antiparallel state. As the applied field is further increased towards negative saturation, twisted onion states or 360° domain walls are formed in the top section of the Co layer of the ring.
due to magnetostatic interactions with the top magnetic element [15]. This intermediate metastable state corresponds to position R3 in the GMR response in fig. 3(a). Further increase in the field switches the bottom magnetic element of the Co layer along the applied field direction and correspondingly, the bottom Co layer segment of the ring, as shown by resistance level R4. The corresponding spin state is shown in fig. 4(c). As the field is increased further, the Co layer in the wire segment switches parallel to the Ni80Fe20 layer while the Co layer of the ring still maintains the vortex state, corresponding to resistance level R5. Therefore, the stability of the Co vortex state in the ring has increased to 74 Oe as compared to the 33 Oe for the ring with symmetrically placed magnetic elements, shown in fig. 2(b). With further increase in field, the magnetization of the top magnetic element also switch to the opposite easy axis direction, and therefore the ring undergoes transition from vortex state to reverse-onion state.

An expected consequence of the asymmetric coupling is also the presence of observation of non-symmetric GMR response. The switching fields of the various transitions for both the forward and backward loops are not identical. One of the major differences in the GMR response from negative saturation field to positive saturation field is the appearance of two switching fields for the Ni80Fe20 ring layer. This shows that the Ni80Fe20 layer is also undergoing a vortex state transition. The two distinct switching fields for the Ni80Fe20 ring layer can be explained by the fact that the direction of the magnetization in the top magnetic element at remanence is responsible for the kind of interactions it will experience with the ring. This argument also holds for the observed smaller vortex stability range for Co ring layer. Therefore, we have shown that by externally coupling the ring (symmetrically and asymmetrically with magnetic elements), the range of stability for Co vortex state can be controlled.

In conclusion, the GMR responses for elliptical pseudo spin valve ring structures which are magnetostatically coupled symmetrically and asymmetrically to the magnetic elements have been investigated. The GMR response of the ring structures is dominated by the magnetostatic coupling of the ring with the magnetic elements and is therefore responsible for the wide range of switching fields observed. The most prominent feature of this coupling is the extended range of stability of the Co vortex state using asymmetrically coupled magnetic elements.

**REFERENCES**


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