Detection of a single synthetic antiferromagnetic nanoparticle with an AMR nanostructure: comparison between simulations and experiments

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Abstract The depinning field of a domain wall in a permalloy nanostructure can be used to detect the presence of a magnetic particle. In this device the displacement of the domain wall in a sweeping magnetic field produces a variation of the voltage drop across a corner due to the anisotropic magnetoresistance effect and hence an electrical signal. In this paper we use micromagnetic simulations to calculate the output signal of a particularly shaped device in the presence of a single synthetic antiferromagnetic nanoparticle. The calculated magnetoresistive signal is in good agreement with corresponding experimental data.

1. Introduction

Magnetic beads and nanoparticles are widely used in biology mainly as a tool for biomolecule purification or separation. The use of magnetic carriers as a label to achieve biomolecule detection with a direct electrical readout has been recently proposed and experimentally demonstrated. In this approach the particles are bound by a bioassay to the surface of a magnetic sensor that detects their presence and therefore the molecular recognition event.

Several magnetic sensors are currently being investigated, e.g., giant magnetoresistance and spin valve sensors [1], magnetic tunnel junctions [2], micro-Hall sensors [3], and planar Hall effect sensors [4].

Recently, we have proposed a new sensing principle suitable for the detection of a few magnetic beads, based on the displacement of a magnetic domain wall (DW) in a square nanosized Permalloy (Py) ring. By monitoring the position of the DW via the anisotropic magnetoresistance (AMR) effect the detection of a single magnetic bead with a diameter of 80 nm has been demonstrated [5].

In this paper we present results on a similar device, shaped as a corner with two ending disks which is designed for trapping beads only on the sensing area and with enhanced sensitivity [6]. Micromagnetic calculations of the response to a single synthetic antiferromagnetic nanoparticle (SAF), by combining the calculated spin configuration of the device with the current distribution, are shown to be in good agreement with the experimental measurements.

2. Detection principle

The device object of this study is a Py nanostructure, 25nm thick, shaped as a corner with two ending disks and four nonmagnetic Au contacts for injecting a current and measuring the voltage drop across the corner (see Fig.1). The Py structure is patterned on top of the Au contacts, and the final device is made of two segments 2 μm long, and 180 nm wide, terminated by disks of 500 nm diameter.

The micromagnetic configuration in Fig. 1(a) is obtained by applying a magnetic field of 1000 Oe directed along the bisector of the corner. A transverse head–to-head DW spin structure is positioned at the...
corner of the device; meanwhile in the two ending disks a vortex state (VS) configuration is created. This DW can be annihilated by a field $H_{1x}$ along the $x$-direction in the vortex inside one of the ending disks, leading to the configuration of Fig. 1(b). Upon application of a field in the opposite direction the DW is re-nucleated and brought back to the initial position.

Magnetoresistance measurements, i.e. the measurement of the voltage drop between the two reading contacts flanking the corner when a current is injected in the structure ($V_A$ and $V_B$ in figure 1), can be used to sense the presence of a DW in the nano-sized corner by exploiting the AMR effect. The resistance of the Py strip is higher when the magnetization is parallel to the injected current, i.e. in the state when there is no DW between the two sensing leads; this leads to the voltage drop $V_B$ in Fig 1(b). If a DW is present between the measuring leads, some of the spins are perpendicular to the current flow and hence the voltage drop is lowered ($V_A$, Fig. 1(a)).

As DWs have been demonstrated to attract magnetic nanoparticles [5], the corner-shaped configuration is particularly convenient because only one magnetic pole (the DW at the corner) can exert a force on a particle. The vortex configuration in the ending disks creates a field gradient much lower than that of DW, so that particles are essentially focused at the sensing area.

When a magnetized nanoparticle is attracted toward a corner with a DW, the dipolar interaction between the stray field generated by the DW and the magnetic moment of the particle prevents the displacement of the DW at $H_{1x}$; therefore, a higher field $H_{2x}$ is required to switch the magnetization in the horizontal segment of the structure, as sketched in Fig 1(c) and (d). By accurately measuring the switching field between the two voltage values, it is possible to detect the presence of a small number of nanoparticles trapped at the corner, and even a single nanoparticle.

This work investigates both theoretically and experimentally the effect of synthetic antiferromagnetic nanoparticles on top of the device. They are cylinders of 70nm diameter and 30nm height that contain two layers of Co$_{90}$Fe$_{20}$ separated by a layer of non magnetic material (Ru). This configuration has been chosen in order to obtain antiparallel magnetization of the two layers at low fields; thus the nanoparticles have a magnetic behavior comparable to that of a superparamagnetic bead, but with an enhanced magnetic moment [7].

2. Experiments and results

Simulations of the electrical response of the nanostructure have been performed by means of the commercial software LLG [8], which allows for the simultaneous calculation on the same mesh of the micromagnetic configuration and current distribution of a sample. The Permalloy parameters used in the simulations are: magnetization of 800 emu/cm$^3$, exchange constant of 1.05 μerg/cm, and a cell size 10 nm; two gold current pads were positioned on top of the Py strips in the same position of the real device. The contact pads are considered equipotential since the conductivity of Py is ten times lower than that of Au. The average resistivity of Py has been chosen to be 15 μΩcm and the AMR ratio equal to 2 %.

The relation between the current density $J$ and the electric field $E$ in a ferromagnetic material (neglecting the Hall effect contribution) is:

$$E = m(\vec{J} \cdot \hat{m})[\rho_\parallel - \rho_\perp] + \rho_\perp \vec{J} \cdot \hat{m}$$

(1)

where $\hat{m}$ is the magnetization unit vector and $\rho_\parallel$ and $\rho_\perp$ indicate the resistivity in direction parallel and perpendicular to $\hat{m}$, respectively. By introducing $J_m = \vec{J} \cdot \hat{m}$, the component $E_J$ of the electric field parallel to $\vec{J}$ can be obtained from (1)

$$E_J = J_m^2 [\rho_\parallel - \rho_\perp] \rho_\perp \vec{J} \cdot \hat{m}$$

(2)

where $\vec{J}$ and $\hat{m}$ are computed in every cell and $J_m$ and $m$, were taken equal to zero. The total voltage has been obtained by numerical integration of the electric field over the Py cells between the two contact pads. In the simulation, the initial state was chosen with the DW at the corner and the magnetic field, along one side of the corner; the field value has been increased from 0 to 250 Oe, then swept to -250 Oe, and finally brought back to the initial value.

The black curve in Fig 2(a) shows the output signal for a device with a DC current of 16 μA injected through the gold pads. The steps in the signal correspond to the two field values at which the DW is annihilated ($H_1$) and brought back to the initial position ($H_2$). The red curve is the calculated signal when a
single SAF nanoparticle is positioned on top of the corner at the focusing point of the stray field generated by the DW (as in Fig. 2(b)). In the calculation a spacer layer of 20 nm has been assumed, which represents the SiO\textsubscript{2} capping layer in the real device; the micromagnetic configuration of the SAF nanoparticle has also been included. For the two CoFe ferromagnetic layers the saturation magnetization was chosen to be 1600 emu/cm\textsuperscript{3} and the exchange constant 1.53 μerg/cm [9].

The calculations indicate that the positive switching field $H_1$ increases of 5 Oe in the presence of the SAF particle, whereas the negative switching field $H_2$, is not affected by the presence of nanoparticles. This confirms the validity of the device operating principle, where one switching field is used for the detection and the other as a reference.

Fig 2(c) shows the plot of the measured signal for a real device, where an AC current of 16μA is injected through the current pads and the signal is detected with a lock-in amplifier. Black squares refer to the clean device-without particles near the corner. The field loop applied to the system is the same as the one used in the simulations. A 1 μl drop of SAF nanoparticles diluted in an aqueous solution of NH\textsubscript{4}OH with pH 8 (final concentration of 2.7×10\textsuperscript{9} particles/ml) is subsequently dispensed on top of the sensor capped with 20 nm of SiO\textsubscript{2}. The distribution of particles has been measured by atomic force microscope (AFM) after drying with N\textsubscript{2} (Fig 2(d)); the red curve in Fig 2(c) is the corresponding output signal measured for the device. The variation of the $H_1$ switching field is in this case 15 Oe; from the value of the total volume of the cluster of particles, as estimated by AFM, this change is due to the presence of 5-6 SAF nanoparticles on top of the corner.

The comparison of the shape of the signal and the switching field values in Fig 1(a) and (c) confirms the validity of the model that describes the magnetoresistive behavior of the nanostructure. In particular, the convex behavior of the signal on which the jumps are superposed is due to the continuous rotation of the magnetization in the segment of the corner perpendicular to the applied field, as clearly seen in the simulations.

A quantitative comparison of the variation of the switching field between numerical calculations and experiments is prevented by the inherent difficulty in the evaluation of the exact number of SAF particles from AFM images. Furthermore, the profile analysis of Fig 2(d) shows that the particles are partially piled up on top of the sensor; this lowers the net effect of the particles at the top with respect to those at the bottom. In addition, the position of the single particle on the active area influences the magnetic behavior; in our simulations the change of the switching field slightly decreases (by 1 Oe) when a single SAF is moved from the outer edge of the corner (as in Fig 2(b)) towards the internal edge along the bisector. Finally, the interaction between the different particles in the cluster can cause a deviation of the output signal from the linear dependence on the number of particles. Nevertheless, our experimental data indicate that the variation per particle is on the order of 3 Oe; this value is comparable to the calculated 5 Oe for a single SAF on top of the corner. This supports the validity of the simulations. As we know that the vortex in the terminating disks can act as a weak attracting pole [6], we verified by simulations that the presence of particles on top of the ending disks does not affect the value of $H_1$; therefore, an influence from particles trapped by the vortex state configuration can be excluded.

In conclusion, we have successfully used micromagnetic simulation to interpret our data on the detection of SAF nanoparticles via their effect on the depinning field of domain walls in nanosized corners of permalloy. The calculation of the AMR signal from the simulated magnetic configuration and the current distribution allows for the correct modeling of the output voltage behaviour of the nanostructure. The outcome of this study is thought to provide a useful tool for the optimization of this device or other micro/nanosensor based on AMR and oriented to the detection of a few magnetic particles.
Figure 1 Device operation for detecting the presence of a magnetic nano-particle.
(a) A DW is initially positioned at the corner and a vortex state configuration is present in the ending disks (VS) giving rise to a measured voltage $V_A$. When a field $H_{1x}$ is applied, the system switches to the configuration (b) and the voltage changes to $V_B$ due to the AMR effect. When a magnetic nanoparticle is in proximity of the corner, as sketched in (c), a higher field $H_{2x} > H_{1x}$ is needed to switch the magnetic configuration to (d) due to the DW-particle dipolar interaction. Thus, the presence of the nanoparticle can be detected as a change in the switching field.
Figure 2 Comparison between simulated and measured electric response of the device.
(a) Simulated AMR signal of the clean device (squares, black curve) and with a SAF nanoparticle on the top (circles, red curve). The particle is positioned as in (b).
(c) Measured signals before and after SAF nanoparticles (NPs) are dispensed (d) Particle distribution as observed by AFM: the intense white spot at the corner indicates the presence of a cluster of SAF nanoparticles.
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