GMR effect in nonhomogeneous magnetic field

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Abstract. Magnetic field sensors, based on giant magnetoresistance (GMR) effect, have a wide range of practical implementations. One of them is the use as a positioning device in different kind of actuators. Here we report on modelling of magnetoresistivity response of spin-valve (SV) based GMR structure in a various geometry of SV positioning with respect to a magnetic reference label. The model includes the magnetic label of a certain shape producing a nonhomogeneous magnetic field in 3D space and moving along a straight line in front of SV device. Different mutual label-SV positioning is considered. The reaction of micromagnetic configuration in the ferromagnetic layers and corresponding magnetoresistive effect of the SV is calculated and analyzed.

1. Introduction
The effect of giant magnetoresistance (GMR) is widely used in various industrial, informational and consumer devices [1] and has bright prospects for future use [2]. One of the applications is the positioning of the mating nodes in various kinds of actuators and manipulators. In this case, the magnetic label initiates the positioning signal in the GMR sensor. The main working element in GMR spin-valve (SV) sensors is a 4-layer structure consisting of two ferromagnetic layers (free ferromagnetic-FF and pinned ferromagnetic-FP)) separated by a nonmagnetic layer (NM) and an antiferromagnetic layer (AF) adjacent to one of the ferromagnetic layers (FP) and pinning the magnetization of the FP layer in one of the directions. The sensitive element of the GMR structures or SV sensor of the magnetic field is the FF layer. An approach of the magnetic label to the sensor causes a rotation of the magnetic moment of the FF-layer and a change in the electrical resistance in the GMR sensor. The magnitude of the initiated resistance change depends on the magnitude of the magnetic field and the relative orientation of the label magnetic field vector at the sensor location, the orientation of the SV structure and magnetic moments in the FF and FP layers.

In this paper, we consider a magnetic label, which generates a dipole-like magnetic field. We model the response of SV sensor moving along a straight line at certain distance from the label. We demonstrate that the sensor response critically depends not only on the distance but also on sensor orientation with respect to the orientation of the label.

2. Model
The simulated system consists of a magnetic label of some form (cylinder, parallelepiped) and an SV-sensor. A label with a magnetic moment \( \mathbf{M} \) creates an inhomogeneous 3D magnetic field. The method of calculating the 3D distribution of the magnetic field of the label in the space, \( \mathbf{H}(\mathbf{R}) \), was reported earlier [3]. A similar method was used in [4] to calculate the fields of permanent magnets with axial...
symmetry. In figure 1, as an illustration, the profiles of the magnetic field components \( \{H_x, H_y, H_z\} \) for a label having the shape of a parallelepiped with dimensions \( a = b = 2 \text{ mm}, c = 4 \text{ mm} \) are given. Profiles are given depending on the \( y \) coordinate for \( x_0 = 2a, z_0 = 0 \) (figure 1a), \( x_0 = 4a, z_0 = 0 \), (figure 1b), \( x_0 = 2a, c = 4 \text{ mm} \) (figure 1c), \( x_0 = 4a, z_0 = c = 4 \text{ mm} \) (figure 1d).

The label moves relative to the sensor and the task is to track the position of the label, i.e. determination of its coordinates using the sensor. In this paper, we solve the inverse problem – we place the label at the origin of Cartesian coordinates and move the sensor along the straight line. We set the magnetic moment of the label oriented along the \( z \) axis, and the sensor moves within a plane parallel to \( yz \) and located at some distance \( x_0 \) from the origin. Thus, one of the tasks is to study the dependence of the sensor signal depending on its localization relative to the label. Finally, one more task is to study the dependence of the magnetoresistance (MR) of a signal on the relative orientation of the sensor and the magnetic label. In this paper, we consider 6 sensor orientations characterized by the direction of uniaxial anisotropy in the FF layer and unidirectional anisotropy in the FP layer, defined by the direction of the magnetic field during the deposition of the layers and the orientation of the structure characterized by the normal \( \mathbf{n} \) to the plane of the multilayer structure of the sensor. Namely,

1.1: \( \mathbf{n} \parallel y, I = \{0,0,I_s\}; \)
2.1: \( \mathbf{n} \parallel z, I = \{0,0,I_s\}; \)
3.1: \( \mathbf{n} \parallel x, I = \{0,0,I_s\}; \)
1.2: \( \mathbf{n} \parallel y, I = \{I,0,0\}; \)
2.2: \( \mathbf{n} \parallel z, I = \{0,-I,0\}; \)
3.2: \( \mathbf{n} \parallel x, I = \{0,-I,0\}, \)

where \( I \) is the magnetization vector of the FF layer, \( I_s \) is the value of the magnetization in saturation. The mutual orientation of \( \mathbf{n}, I \) and \( \mathbf{M} \), is illustrated in figure 2.

The Stoner-Wohlfarth (SW) model is often used to describe the processes occurring in SV structures [5, 6]. This model allows to evaluate the reorientation of the magnetization of the
anisotropic particle under the influence of the applied field. Here we assume that the model is also valid for the magnetic film. Applying a magnetic field in a direction different from the direction of the easy axis (EA), one can cause a coherent rotation of the magnetization vector \( \mathbf{I} \) in the FF layer in the SV, as shown in figure 3. Further, the model assumes that the rotation and equilibrium state of magnetization is achieved instantly.

Figure 2. Diagram of the considered orientations of the FF-layers, with indicated by the arrows the directions of magnetization with respect to the magnetic label located at the origin of coordinates with the direction of magnetization along the z axis. The yellow arrow indicates the direction of movement of the sensor.

The angle \( \varphi \) of the magnetization rotation in the FF layer, \( \mathbf{I} \), in a field oriented at an angle \( \theta \) with respect to the EA (more precisely, to the direction of the field during deposition, giving uniaxial anisotropy in the FF layer and unidirectional anisotropy in the FP layer), can be set using energy balance \( E \), which includes the contribution of uniaxial anisotropy and Zeeman energy

\[
E = -VK_u\sin^2\varphi - V\mu_0l_S\cos(\varphi - \theta),
\]

where \( V \) is the volume of the film, \( K_u \) is the uniaxial anisotropy constant and \( \mu_0 \) is vacuum permeability. Because the equilibrium of the magnetic system occurs at the point of the total energy minimum, then to determine the angle \( \varphi \), it is necessary to solve the equation \( \partial E / \partial \varphi = 0 \), which satisfies the condition \( \partial^2 E / \partial \varphi^2 > 0 \).

\[
\frac{\partial E}{\partial \varphi} = -K_u\sin 2\varphi + H\mu_0l_S\sin(\varphi - \theta) = 0,
\]

(2)

\[
\frac{\partial E}{\partial \varphi} = -K_u\sin 2\varphi + H\mu_0l_S\left(\frac{H_y}{H}\sin\varphi - \frac{H_x}{H}\cos\varphi\right) = 0.
\]

(3)

Making the replacement \( h = (H\mu_0l_S^3)/(2K_u) \) we get

\[
1 = \frac{h}{l_S} \left(\frac{\cos\theta - \sin\varphi}{\sin\varphi}\right).
\]

(4)

Further on with replacement \( h_y = h\cos\theta \), \( h_x = h\sin\theta \), \( \cos\varphi = l_y/l_x \), \( \sin\varphi = l_x/l_y \), we obtain

\[
1 = \frac{h_y}{l_y} - \frac{h_x}{l_x}.
\]

(5)
Since, $I_x^2 + I_y^2 = I_s^2$, we come to the equation

$$I_y^4 - 2h_y I_y^3 + (h_x^2 + h_y^2 - I_s^2)I_y^2 + 2h_y I_s^2 I_y - I_s^2 h_y^2 = 0. \quad (6)$$

Solving the equations with respect to $I_y$, we find $\varphi = \arccos (I_y/I_s)$. The $\varphi$ found are limited to the domain of definition $\varphi \in [0, \pi]$ and, as mentioned above, must satisfy the condition

$$-\cos2\varphi + \frac{h}{I_s} \left( \frac{H_y}{H} \cos\varphi + \frac{H_x}{H} \sin\varphi \right) > 0. \quad (7)$$

3. Results of calculations
The numerical calculation of the rotation angle $\varphi$ was made in the Matlab environment, solving equation (6). The result of the calculation is shown in figure 4 for the sensor orientations shown in figure 2.

![Figure 4](image-url)

Figure 4. Dependence of the rotation angle $\varphi$ of the magnetization vector as a function of the sensor position along the $y$ direction with fixed coordinates $x_0, y_0$ for 6 orientations of the sensor 1.1–3.2 indicated in the inserts in figures a)–d).

It can be seen from figure 4 that the orientation of sensor 1.1, as well as 3.1, does not lead to any rotation of the magnetization $\mathbf{I}$ when scanning along the trajectory with $z = 0$, i.e. where there is only a vertical component ($H_z$), and the remaining components of the magnetic field are zero. Conversely, with such a scan, sensors with orientations 1.2 and 3.2 have a maximum angle of rotation, and at small distances from the origin of coordinates along the $x$ axis, the change can reach 90° and remain at that level in a certain range of positions, figure 4a. Due to a large demagnetization factor, this example cannot be followed by magnetization vectors in configurations 2.1 and 2.2, in which the direction of magnetization remains unchanged.

The picture can change dramatically when scanning along a path with a non-zero $z$ coordinate. In this case, non-zero components of the field $H_x$ and $H_y$ appear, and, as a result, the sensor signal appears in configuration 1.1 and 3.1, figure 4c and 4d.
Assuming, in accordance with what was said in the Introduction, that the EA direction in FF and FP coincide and \( I \) in FP does not change direction (rigid pinning in the range of exchange bias), we find that the misorientation angle of the magnetizations in FF and FP is determined by the rotation angle \( \phi \) of the FF-layer magnetization. Accordingly, the magnetoresistance, when scanning, will follow the change in the angle \( \phi \):

\[
\frac{\Delta R}{\Delta R_{\text{GMR}}} = \frac{1 - \cos(\phi)}{2}, \tag{8}
\]

where \( \Delta R = R(\phi) - R_p \), \( \Delta R_{\text{GMR}} = R_{\text{AP}} - R_{\text{P}} \), and \( R_{\text{AP}}, R_p \) are, respectively, the resistance at the anti-parallel and parallel direction of the magnetization vector in the FF- and FP-layers.

The results of MR calculations for previously selected scanning trajectories (figures 1 and 4) are presented in figure 5. These results do not introduce additional intrigue, compared with the rotation angles data, figure 4, and the conclusions that were made when discussing the results in figure 4, valid for the data obtained by MR.

![Figure 5](image)

**Figure 5.** Magnetoresistance profiles when scanning along trajectories indicated in the caption to figures 1 and 4.

### 4. Conclusion

The paper discusses the magnetoresistive response of a spin-valve sensor moving near a magnetic label, creating a non-uniform 3D magnetic field. The material presented in the paper convincingly shows that in the case of a non-uniform magnetic field, the magnitude of the magnetoresistance signal and its change along the trajectory significantly depend not only on the distance between the sensor and the label, but also on other factors. One of them is the location of the sensor scanning trajectory relative to the label. The second is the orientation of the sensor relative to the magnetic label. Both of these factors can lead to the fact that the sensor's signal will be absent even at a high magnetic field along the path of movement of the sensor. In any case, the model presented here allows optimizing the location and orientation of the sensor with respect to various types of magnetic labels in order to...
obtain the required level of the magnetoresistance signal and the accuracy of localization of the magnetic label in space.

References

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