A Model to Design Giant Magnetoresistive Sensor

Zhiqiang Cao\textsuperscript{1,2}, Weibin Chen\textsuperscript{1,3}, Hailun Zhao\textsuperscript{4}, Weisheng Zhao\textsuperscript{1,2} and Qunwen Leng\textsuperscript{1,2,*}

1 Beihang-Geortek Joint Microelectronics Institute, Qingdao Research Institute, Beihang University, Qingdao 266104, China
2 Fert Beijing Institute, BDBC, School of Microelectronics, Beihang University, Beijing 100191, China
3 School of Physics, Shandong University, Jinan 250100, China
4 Goertek Inc., Weifang 261031, China

Email: lengqw@bhqditi.com

Abstract. Giant magnetoresistive (GMR) sensor has developed rapidly in automobile, consumer electronics and current sensing areas due to its high sensitivity and low power consumption. In this work, we suggest a method to design GMR sensor based on Stoner-Wohlfarth coherent rotation model. We have investigated the influence of width of GMR sensor to its performance with the model and verified with experiments. And different pinning direction GMR elements are also researched to study Wheatstone bridge structure. The experimental results matched well with the simulation results which proved that the model is efficient in designing GMR sensor.

Keywords: GMR sensor, Stoner-Wohlfarth coherent rotation model, MATLAB, Simulation, Wheatstone bridge

1. Introduction

Giant magnetoresistive (GMR) effect has rapidly developed in theory and technology since discovered in 1988 by Albert Fert and Peter Grünberg [1, 2]. It has been successfully applied in read heads and linear applications such as e-compass, positioning control devices in robotic systems and current monitoring devices in power systems [3-5]. Even though there are other approaches have been developed in these fields, GMR based devices emerged as a promising alternative to meet the state-of-the-art application scenarios due to its high sensitivity, low power consumption and small size [6-8].

For linear applications, a Wheatstone bridge configuration based on four elements is preferred due to the null output in the absence of an external field and the minimization of temperature dependence [9]. The elements are typically designed in stripes, where the magnetization of pinned layer is fixed in the direction perpendicular to the linewidth of the stripe with an antiferromagnetic layer and synthetic antiferromagnetic structure. The key indicator of a GMR sensor is usually characterized with its sensitivity, linearity and temperature stability [10, 11]. Currently, GMR sensors have been commercialized and widely used in different field, but few researchers provide a model to design a specific sensor.

In this work, we build a model to investigate the GMR sensor performance and compared the results with experiments. In the simulation part, we studied the sensitivity and linear range of different width of GMR elements. And different pinning direction devices also simulated to compose a Wheatstone bridge structure. In the experimental part, we fabricate a series of devices as simulated
and annealed to verify the simulation results. By this method, we provide a model to design different demands sensors and this could be efficient for products developing.

2. Model and Methods

A simulation based on Stoner-Wohlfarth coherent rotation model was run on MATLAB to predict the performance of GMR sensors when changing its width and pinning directions [12, 13]. Figure 1(a) shows the schematic geometry of the magnetization in each layer of the sensor. The model considered Zeeman energy, anisotropy energy, interlayer coupling energy and exchange coupling energy. The energy per unit area can be expressed as

\[
E = E_{FL} + E_{P1} + E_{P2}, \#(1)
\]

where \(E_{FL}\) is the energy of free layer (FL), \(E_{P1}\) and \(E_{P2}\) are energy of \(P_1\) and \(P_2\), respectively. For FL, the energy is given by

\[
E_{FL} = -\overrightarrow{M}_{FL} \cdot \overrightarrow{H}_{ext} - \overrightarrow{M}_{FL} \cdot \overrightarrow{H}_{in} + 2\pi \frac{M_{FL}^2 t_{FL}}{w} \sin^2(\theta_{FL} - \theta_0) + \frac{1}{2} M_{FL} H_{kFL} \sin^2(\theta_{FL} - \theta_0) \#(2)
\]

In equation (2), the first term is Zeeman energy, second is interlayer coupling energy, third is the shape anisotropy energy and last term is induced anisotropy energy. And \(H_{ext}\) is the external field, \(H_{in}\) is interlayer coupling field, \(M_{FL}\) is the magnetization of FL, \(t_{FL}\) is the thickness of FL, \(w\) is the width of transducer, \(H_{kFL}\) is the induced anisotropy field of FL, \(\theta_{FL}\) is the angle between \(\overrightarrow{M}_{FL}\) and X direction, \(\theta_0\) is the angle between the easy axis (e.a.) of FL and X direction. In pinned layer \(P_i\) and pinning layer \(P_j\), their energy can be expressed as Eq. (3) and Eq. (4) as follows:

\[
E_{P1} = -\overrightarrow{M}_{P1} \cdot \overrightarrow{H}_{ext} - \overrightarrow{M}_{P1} \cdot \overrightarrow{H}_{ex} + 2\pi \frac{M_{P1}^2 t_{P1}}{w} \sin^2(\theta_{P1} - \theta_1) + \frac{1}{2} M_{P1} H_{kP1} \sin^2(\theta_{P1} - \theta_1) \#(3)
\]

\[
E_{P2} = -\overrightarrow{M}_{P2} \cdot \overrightarrow{H}_{ext} + 2\pi \frac{M_{P2}^2 t_{P2}}{w} \sin^2(\theta_{P2} - \theta_2) + \frac{1}{2} M_{P2} H_{kP2} \sin^2(\theta_{P2} - \theta_2) + \overrightarrow{M}_{P2} \cdot \overrightarrow{H}_{P1P2} \#(4)
\]

In Eq. (3), \(\overrightarrow{M}_{P1}\) is the magnetization of \(P_1\), \(t_{P1}\) is the thickness of \(P_1\), \(H_{kP1}\) is the induced anisotropy field of \(P_1\), \(\theta_P\) is the angle between \(\overrightarrow{M}_{P1}\) and X direction and \(\theta_1\) is the angle between e.a. of \(P_1\) and X direction. In Eq. (4), the last term is the coupling energy of \(P_1\) and \(P_2\), \(\overrightarrow{M}_{P2}\), \(t_{P2}\), \(H_{kP2}\), \(\theta_P\) and \(\theta_2\) have the same definition as that in Eq. (3) and \(\overrightarrow{H}_{P1P2}\) is the coupling field between \(P_1\) and \(P_2\). Based on the principle of energy minimization, we can deduce the \(\frac{\Delta R}{R} = \frac{1}{2} MR[1 - \cos(\theta_{FL} - \theta_{P2})]\), where MR is the maximum magnetoresistive ratio of the transducer.

Samples to verify the simulation results have a bottom-pinned multilayer structure: Ta(5.0)/NiFe19(2.0)/IrMn80(7.5)/CoFe10(2)/Ru(0.85)/CoFe30(2.1)/CuO(1.9)/CoFe30(1.0)/NiFe19(2.0)/Cu(1.0)/Ta(3.0) (thickness in nanometer) which is deposited on thermally oxidized Si substrates by a Singulus magnetron-sputtering system. It has a GMR ratio around 6.05% measured by a magneto-optical Kerr effect (MOKE) system and shows an exchange coupling field up to 300mT. The sheet resistance of full film is 21.63 \(\Omega/\square\) without external field. Then, the film was patterned into different stripes on a 6 inch wafer by lift-off and etching processes, and fabrication details can be found in other researchers works [9]. In this experiment, we designed stripes with different width (width = 0.8, 1.0, 1.2, 1.5, 2.0 \(\mu m\)) to follow the simulation size. The patterned wafer was then cut into 4 independent samples and arranged on a sample tray as shown in figure 1(b). After that, annealed in a high vacuum furnace at 270\(^o\)C under 1 T magnetic field which is set along the X axis for 1 h to define different pinning direction (PD) devices. The resistance versus external field (\(H_{ext}\)) were measured on a four-probe station which have quadrupole magnets. Every sample measured with a \(H_{ext}\) perpendicular to the stripe edge which is the easy axis of free layer.
Figure 1. (a) Film stack structure and schematic geometry of the magnetization $M$ in each layer of the GMR sensor. (b) Samples distribution during annealing process and blue stripe is the easy axis orientation of the device.

3. Results and Discussions

Figure 2. (a) MR-H curves of different width stripes in the sample of PD = 0°. (b) Sensitivity and linear range versus width changing.

Figure 2(a) shows the MR-H curves of PD = 0° samples under a Y direction $H_{\text{ext}}$ with different width. The correspondence parameters are set as follows: $MR = 6.05\%$, $M_{\text{FL}} = 1060$ emu/cm$^3$, $M_{P1} = 1580$ emu/cm$^3$, $M_{P2} = 1850$ emu/cm$^3$, $H_{\text{in}} = 2$ mT, $H_{\text{FL}} = 1$ mT, $H_{\text{P1}} = 3$ mT, $H_{\text{P2}} = 3$ mT, $H_{\text{cx}} = 200$ mT, $H_{\text{P1P2}} = 500$ mT, $t_{\text{FL}} = 3 \times 10^{-7}$ cm, $t_{P1} = 2 \times 10^{-7}$ cm, $t_{P2} = 2.1 \times 10^{-7}$ cm and $W = (0.8, 1.0, 1.2, 1.5, 2.0) \mu m$. The inset in figure 2(a) gives the directions of $H_{\text{ext}}$, pinning layer and easy axis of free layer. In figure 2(b), sensitivity and linear range of each device were extracted into a graph versus width. It shows that sensitivity growing with the stripe width and tends to be stable at a value while the linear range shows an opposite trend compare to sensitivity. In this point, we can design the sensitivity and linear range before fabricate devices.

In a full Wheatstone bridge, two of bridge elements should exhibit $dR/dH > 0$, while the remaining two exhibit $dR/dH < 0$. Thus, it could generate a differential output. In figure 3(a), we simulated the MR-H curves of different pinning direction (PD = 0°, 45°, 90°, -45°) stripes where external field is applied perpendicular to the easy axis of free layer to ensure linear output range. Composing PD = -45°
and PD = 45° into a Wheatstone bridge, it could have a sensitivity about 0.04%/Oe as shown in figure 3(b).

Figure 3. (a) The MR-H curves of four different PD elements. (b) The calculated output of the Wheatstone bridge composing of PD = 45° and -45° stripes.

To verify the simulation results, we fabricate a series of devices which parameters are according with simulation. In figure 4(a), we measured the R-H curves of 5 different width transducers with a field perpendicular to the easy axis of free layer as the same with simulations. The MR ratio of these devices are lower than full film which may caused by contact resistance or damage during process. Then we extract the sensitivity and linear range of each stripe as shown in figure 4(b). As the simulation model have not considered the influence of process, the experimental results seem a little difference compared to the calculation while they share the same trend.

Figure 4. (a) MR-H curves in different samples. (b) Sensitivity and linear range versus width of devices.

In figure 5(a), the MR-H curves of four different PD stripes with width equal to 1μm were measured. It showing a same trend with the simulation result. In figure 5(b), the output of a Wheatstone bridge composed of PD = 45° and PD = -45° stripes through wire bonding was measured. This performance matched well with the simulation result and proved the model is effective in GMR sensor design.
Figure 5. (a) MR-H curves in different PD samples. (b) The output of the Wheatstone bridge composed of PD = 45° and -45° stripes.

4. Conclusion
In conclusion, we used a Stoner-Wohlfarth coherent rotation model to simulate properties of GMR transducers. It predicts that the sensitivity can be adjusted with the width of transducers and can be calculated. We also simulated the MR-H curve of different pinning direction transducers which could be instructive for full Wheatstone bridge design. A series of devices were fabricated and measured. The experimental results showing a good matching with the simulation results in sensitivity and Wheatstone bridge output which proves it’s a feasible method to design GMR sensor by this model.

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