*Journal of* ELECTRICAL ENGINEERING, VOL 63. NO 7s, 2012, 50-53

# SUPPRESSING IMPACTS OF DOMAIN HOPPINGS FOR MAGNETORESISTIVE SENSORS

**Mengchun Pan*, ** — Jiafei Hu* — Dixiang Chen* — Wugang Tian* — Jianqiang Zhao* — Guiyun Tian****

Domain hoppings result in magnetic hysteresis and 1/*f* resistance noise for MR sensors, which degrade response linearity and low-frequency detection ability of MR sensors. In this paper, the solution of vertical motion flux modulation with constant magnetic excitation has been proposed. The response linearity of the prototype sensors is improved from 0.8 % to 0.12 %. The noise level is reduced near to the thermal noise level, and the low-frequency detection ability of the prototype sensor is enhanced with a factor of ~ 83.

Keywords: domain hopping, 1/*f* resistance noise, magnetic hysteresis, vertical motion flux modulation, compensation field

## 1 INTRODUCTION

Magnetoresistive (MR) sensors have many applications in magnetic field based sensing such as ferromagnetic target detection, current sensing, geomagnetic compass, reading heads and etc, owing to their high sensitivity, small bulk, and low cost [1]. But thermally excited domain hoppings widely exist in magnetic devices and typically result in magnetic hysteresis and 1/*f* resistance noise in MR sensors [2-3], which will severely degrade the response linearity and low-frequency detection ability of MR sensors.

It is well known that magnetic hysteresis will cause response discrepancy to MR sensors under the same external magnetic field, which mainly attributes to the different magnetization states under variable magnetic excitation. Thus, keeping the same magnetization state is the key to deal with magnetic hysteresis.

Unlike the common electrical 1/*f* noise, 1/*f* resistance noise is primarily related to the mechanism of magnetoresistive effect with magnetization fluctuations and can not be suppressed by the source supply modulation of MR sensors [4]. In recent years, A. S. Edelstein et al. demonstrated that the flux modulation method based on the micro-electromechanical-system (MEMS) flux concentrators can reduce the 1/*f* resistance noise by almost one thousand times [5-6]. Nevertheless, the poor modulation efficiency has hampered the further improvement of the MR sensors with flux modulation on magnetic detection ability.

In this paper, we will present the vertical motion flux modulation (VMFM) with constant magnetic excitation. It has been verified to be the powerful solution for both magnetic hysteresis and 1/*f* resistance noise.

## 2 PRINCIPLES

### 2.1 Constant magnetic excitation

Because the variable external magnetic field will induce the response hysteresis with stochastic magnetization states to MR sensors, the suppression of sensor response hysteresis needs a constant magnetic excitation. To solve this problem, tracking and compensating the external magnetic field is a feasible choice (shown in figure 1).

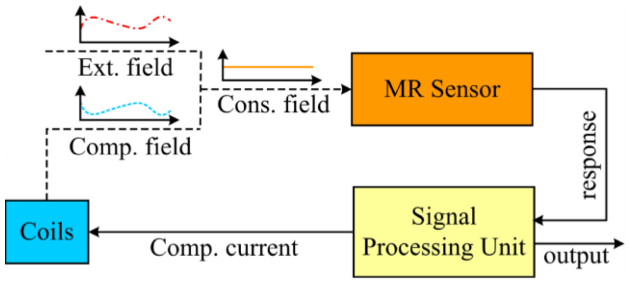


**Fig. 1.** Scheme illustration of the constant magnetic excitation with compensation coils (Ext.: external, Comp.: compensation, Cons.: constant).

It can be seen from figure 1 that the composite field (including the external field and the compensation field) applied on the MR sensor can be kept at constant by tracking the response of the MR sensor and regulating the compensation current in the coils with signal processing unit, thus the magnitude of external magnetic field can be figured out according to the compensation current.

### 2.2 Vertical motion flux modulation

Vertical motion flux modulation derives from the conventional flux concentrators, and a soft magnetic film named as flux modulation film plays the critical role in VMFM (shown in figure 2). The flux modulation film (FMF) vibrates up and down with a vertical MEMS resonator (unshown). When the flux modulation film gets close to the air gap, the magnetic fluxes prefer to go through the flux modulation film and the magnetic field intensity in the air gap drops rapidly. On the contrary, as the flux modulation film leaves away from the air gap, the magnetic field intensity is restored. Thus, the MR elements in the air gap can detect an alternating magnetic

* National University of Defense Technology, College of Mechatronics Engineering and Automation, Department of Instrument Science and Technology, No.47 Yanwachi street, 410073 Changsha, China
** Newcastle University, School of electrical, Electronic and Computer Engineering, UK, g.y.tian@ncl.ac.uk.

signal with the flux modulation film vibrating periodically, and the frequency of this magnetic signal is identical with the vibration frequency of the MEMS resonator. By this means, the external magnetic field at low frequency is transformed to be a high-frequency resistance signal via MR effect. Naturally, the low-frequency detection ability of MR sensors will be significantly improved by VMFM, due to the tens or hundreds of times reduction of 1/*f* resistance noise in high-frequency region [7-8].

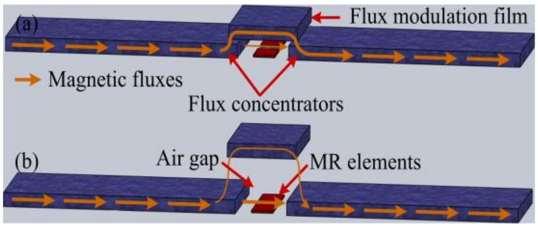


**Fig. 2.** Scheme illustration of vertical motion flux modulation: (a) - flux modulation film getting close to air gap; (b) - flux modulation film leaving away from air gap.

## 3 EXPERIMENTS

### 3.1 Prototype sensors

In order to simplify the sensor structure, the AA002 giant magnetoresistive dies (provided by Nonvolatile Electronics Corp.) were used as the sensing device in the prototype sensors of VMFM. Each AA002 die contains a pair of flux concentrators with 60 μm air gap and a Wheatstone bridge consisting of four MR elements. Two MR elements are disposed in the air gap, and the other two are respectively buried under each flux concentrator.

In the prototype sensor (shown in figure 3), the AA002 die was fixed on a pair of planar coils etched from the multilayered metal film [Cr (150 nm)/ Cu (2000 nm)/ Cr (150 nm)] on the glass substrate. By setting the current through the planar coils, a transverse compensation field will occur in the air gap. The silicon cantilever (8.0 mm × 1.0 mm × 0.3 mm) with a glued piezoelectric slice (PZT: 8.0 mm × 1.0 mm × 0.2 mm) functions as the vertical MEMS resonator. The flux modulation film (500 μm × 90 μm × 16 μm) on the tip of the silicon cantilever and the auxiliary flux concentrators on the frame were both electroplated in sulphate bath with a composition of $Ni_{79}$ $Fe_{21}$. According to the results of vibration sample magnetometer tests, the relative permeability of these $Ni_{79}$ $Fe_{21}$ films is higher than 1000. A height adjustment frame was mounted on the glass substrate after its thickness was reduced to a suitable value by timed etching. Then the frame of the silicon cantilever was bonded onto the height adjustment frame and the flux modulation film with the auxiliary flux concentrators suspends above the AA002 die with 10-μm height.

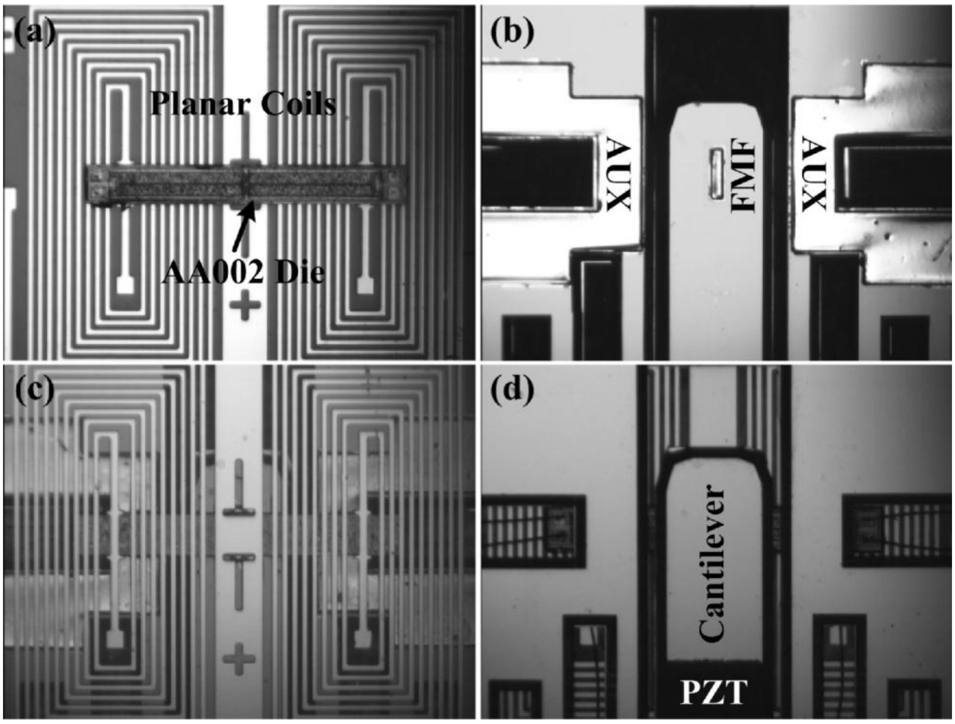


**Fig. 3.** Microscope photos of a prototype sensor: (a) - AA002 die on the planar coils; (b) - flux modulation film (FMF) on the silicon cantilever and a pair of auxiliary flux concentrators (AUX) on the frame; (c) -bottom view of the complete prototype sensor through the transparent glass substrate; (d) - top view of the complete prototype sensor

### 3.2 Sensor tests

All the tested sensors with a pair of Helmholtz coils were placed in a three-layered magnetic shielding barrel to eliminate the ambient disturbances. The adjustable test field ranging from -24 Oe to 24 Oe was produced by the precise control of the current in the Helmholtz coils.

Each prototype sensor was supplied under a DC voltage of 5.0 V, and its piezoelectric slice was driven by a square-wave voltage of 24 V (peak-peak) at resonant frequency, in the atmosphere. As a result, the flux modulation film vibrates with the silicon cantilever and the vibration amplitude can reach 9 μm, which was measured with a laser displacement sensor (LK-G5000, Keyence Corp.). The response voltage of each prototype sensor was amplified with a factor of ~330, and then acquired with a digital signal processing (DSP) system which can track the response and control a current module to produce the compensation current flowing through the planar coils. Moreover, the noise spectrum of the response voltage was obtained with a spectrum analyzer (RSA 3303B, Tektronix Corp.).

For contrast, the response curve and noise spectrum of each AA002 die was measured under the same source supply (DC 5.0 V) before the silicon cantilever was fixed. Combining the response curve of a special prototype sensor without flux modulation film, we can figure out the amplification factor of the auxiliary flux concentrators. Also the magnitude of constant field can be determined according to the response curve of each prototype sensor when the compensation field is not applied.

## 4 RESULTS AND DISCUSSIONS

Figure 4 shows the response curves of two prototype sensors without compensation field. By comparing $S_{AA002}$ with $S_{AUX}$, it can be found that the sensitivity of AA002 die was improved by the auxiliary flux concentrators and the amplification factor approximately reaches 2.6. In each positive branch of the response curve of the VMFM prototype sensor, the linear range shrinks within ~0.6 Oe to ~6.6 Oe, which is similar with that in the negative branches. Considering the sensitivity and power dissipation, the constant field was therefore designated to be ~3.6 Oe.

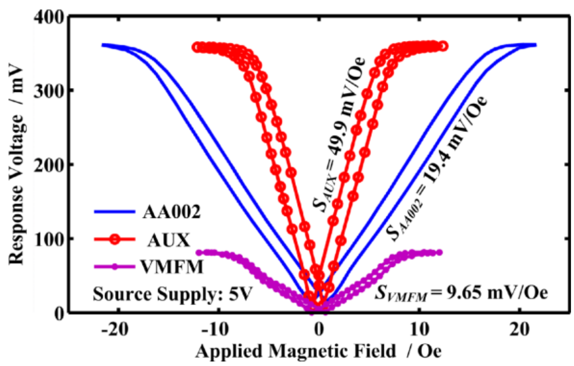


**Fig. 4.** Response curves of two prototype sensors without compensation field (**AUX** denotes the special prototype sensor with a pair of auxiliary flux concentrators but without flux modulation film; **AA002** is the AA002 die of AUX; **VMFM** stands for a normal prototype sensor of VMFM)

According to figure 4, the flux modulation efficiency of VMFM can be figured out to be approximately 19.3 % with the definition of 100%×($S_{VMFM}$ / $S_{AUX}$), which is a little higher than that reported in the literature [8]. Here, the sensitivity of the AA002 die in the VMFM prototype sensor is nearly identical with $S_{AA002}$. Although the sensitivity of the VMFM prototype sensor drops almost by half, its low-frequency detection ability (noise level/ sensitivity) has been enhanced due to a large reduction of 1/*f* resistance noise at modulation frequency.

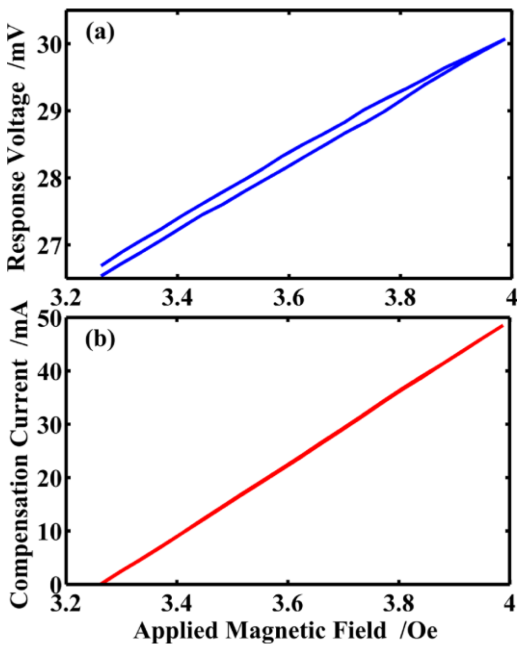


**Fig. 5.** Local curves of a VMFM prototype sensor: (a) without compensation field; (b) with constant magnetic excitation at ~3.6 Oe

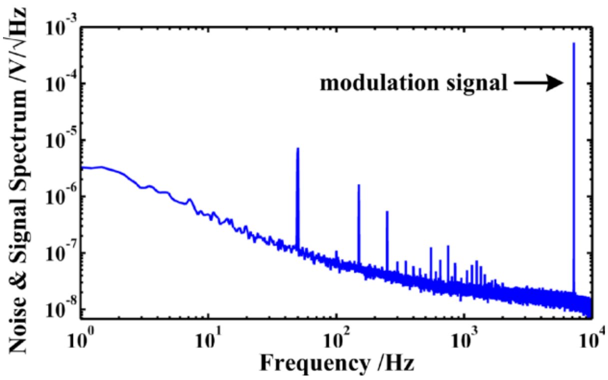


**Fig 6.** Noise and signal spectrum of a VMFM prototype sensor

Figure 5 (a) and (b) show the local curves (3.2 Oe to 4.0 Oe) of the VMFM prototype sensor without and with compensation field individually. Its response linearity and response hysteresis have been improved from 0.8 % to 0.12 % and 2.9 % to 0.26 % respectively under constant magnetic excitation of 3.6 Oe. It can be seen that constant magnetic excitation is a powerful means to suppress the magnetic hysteresis of MR sensors.

Figure 6 exhibits the noise spectrum of the VMFM prototype sensor within 1 Hz-10 kHz. The noise level is ~2000 nV/√Hz at 1Hz and 12 nV/√Hz in the vicinity of modulation frequency of 7.15 kHz. Thus, when a magnetic signal below 1 Hz is transferred to the modulation frequency, the noise level of the VMFM prototype sensor can be reduced by more than 166 times, and approaches to the thermal noise level (~9 nV/√Hz for the 5 kΩ resistance of a AA002 die). The detection ability of the VMFM prototype sensor is improved to 1.24 μOe/√Hz and 1 Hz), which is about 83 times higher than the detection ability of AA002 dies (~103.1 μOe/√Hz).

## 5 CONCLUSIONS

Domain hoppings have remarkable impacts on the response linearity and low-frequency detection ability of MR sensors. Constant magnetic excitation can be used to suppress the response hysteresis of MR sensors, and its response linearity is improved to 0.12 %. Vertical motion flux modulation can reduce the 1/*f* noise of MR sensor to near the thermal noise level, and the low-frequency detection ability of the prototype sensor can be improved to 1.24 μOe/√Hz (@ 1 Hz). In conclusion, we believe that the solution of vertical motion flux modulation with constant magnetic excitation is promising for suppressing the impacts of domain hoppings.

## REFERENCES

[1] LENZ, J. — EDELSTEIN, A.S.: Magnetic Sensors and Their Applications, IEEE Sens. J 6 No. 3 (2006), 631-649.

[2] JIANG, L. — NOWAK, E.R. — SCOTT, P.E. — JOHNSON, J.: Low-frequency Magnetic and Resistance Noise in Magnetic Tunnel Junctions, Phys. Rev. B 69 (2004), 054407.

[3] OZBAY, A. — GOKCE, A. — FLANAGAN, T. — STEARRETT, R.A. — NOWAK, E.R. — NORDMAN, C. A.: Low Frequency Magnetoresistive Noise in Spin-valve Structures, Appl. Phys. Lett. 94 (2009), 202506.

[4] STUTZKE, N.A. — RUSSEK, S.E. — PAPPAS, D.P.: Low-frequency Noise Measurements on Commercial Magnetoresistive Magnetic Field Sensors, J. Appl. Phys. 97 (2005), 10Q107.

[5] EDELSTEIN, A.S. — FISCHER, G.A. — PEDERSEN, M. — NOWAK, E.R. — CHENG, S.F. — NORDMAN, C.A.: Progress Toward a Thousandfold Reduction of 1/*f* Noise in Magnetic Sensors Using an AC Microelectromechanical System Flux Concentrator, J. Appl. Phys. 99 (2006), 08B317.

[6] EDELSTEIN, A.S. — BURNETTE, J.E. — FISCHER, G.A. — OLVER, K. — EGELHOFF, W.M. — NOWAK, E.R. — CHENG, S.F.: Validation of the Microelectromechanical System Flux Concentrator Concept for Minimizing the Effect of 1/*f* Noise, J. Appl. Phys. 105 (2009), 07E720.

[7] PAN, M. — HU, J. — TIAN, W. — CHEN, D. — ZHAO, J.: Magnetic Flux Vertical Motion Modulation for 1/*f* Noise Reduction of Magnetic Tunnel Junctions, Sens. Actuators A 179 (2012), 92-97.

[8] HU, J. — PAN, M. — TIAN, W. — CHEN, D. — ZHAO, J. — LUO, F.: 1/*f* Noise Suppression of Giant Magnetoresistive Sensors with Vertical Motion Flux Modulation, Appl. Phys. Lett. 100 (2012), 244102.

Received 8 September 2012

**Mengchun Pan** (Prof, PhD) received the PhD in electromagnetic field theory, from National University of Defense Technology, Changsha, China. Now he is the director of Department of Instrument Science & Technology, in the same university. He has published over 100 scientific papers. His main research interests include sensors, intelligent instruments and NDT.

**Jiafei Hu** graduated from Wuhan University, China, in 2006, and received MSc from National University of Defense Technology, Changsha, China, in 2008. Now he is studying for the PhD in electromagnetic sensing theory, in National University of Defense Technology. His main research interest is magnetic sensors.

**Dixiang Chen** (PhD) received BEng, MSc and PhD in 1992, 1995 and 2005 from National University of Defense Technology, Changsha, China. Now he is an associate professor in the same university. He has published over 70 scientific papers. His main research interests include sensors, intelligent instruments and NDT.

**Wugang Tian** (PhD) received BEng, MSc and PhD in 2001, 2003 and 2009 from National University of Defense Technology, Changsha, China. Now he is an instructor in the same university. He has published over 30 scientific papers. His main research interests include sensors, intelligent instruments and NDT.

**Jianqiang Zhao** graduated from Xi'an Jiaotong University, China, in 2009, and received MSc from National University of Defense Technology, Changsha, China, in 2011. Now he is studying for PhD in National University of Defense Technology. His main research interest is magnetic sensors.

**Guiyun Tian** obtained his BSc in metrology and instrumentation and M.Sc. in precision engineering at the University of Sichuan (Chengdu, PR China) in 1985 and 1988, respectively. Currently, he is Chair professor in Sensor Technologies at the School of Electrical and Electronic Engineering, Newcastle University. He has joint background in engineering and computer science. His research interests are broadly in the areas of sensor and instrumentation, signal processing, Electromagnetic non-destructive evaluation and structural Health Monitoring in particular. He has published over 150 books and papers in English and Chinese in the above areas. He is a regular reviewer for international journals and conferences.