Journal of ELECTRICAL ENGINEERING, VOL 63. NO 7s, 2012, 58-61

MEMS VERTICAL MOTION MODULATED FLUX CONCENTRATOR FOR MINIMIZING 1/*f* NOISE IN GMR SENSORS

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

1/f noise is one of the main noise sources of giant magnetoresistance (GMR) sensors, which will cause intrinsic detection limit at low frequency. To suppress this noise，a novel vertical motion modulated flux concentrator (VMMFC) is proposed in this paper, which has high efficiency and simple structure. The flux concentrator and modulation film of VMMFC were analyzed with numerical simulation. The simulation results show the modulation efficiency of VMMFC exceeds 21%. A preliminary prototype sensor based on the multi-layered GMR AA002 and VMMFC was fabricated and its modulation efficiency achieves 18.8%, which exceeds the efficiency of most existing sensors with other modulation schemes. Also, the magnetostatic detection ability is improved to 0.53 nT/√Hz.

Keywords: 1/*f* noise, vertical motion modulation, modulation efficiency, flux concentrator, giant magnetoresistance sensor, magnetostatic detection ability

1 INTRODUCTION

In recent years, the application of magnetic sensors has grown explosively, and various magnetic sensors were developed to meet the needs of users in medical, military, space, and information technology, etc [1-2]. At present, fluxgate magnetometers are commonly used for vectorial magnetic field measurement, which has high sensitivity but costly, bulky and power consuming. Giant magnetoresistance (GMR) sensors are the competitive candidates for the detection of weak magnetic field. However, its 1/*f* noise is a dominant limiting factor for the sensing of weak magnetic field when the frequency is less than 1 Hz [3-5].

Flux concentrator can be used to improve the sensitivity of magnetic sensor, which is often placed adjacent to the magnetic sensor to increase the field strength and signal noise ratio (SNR). It can also be used to mitigate the 1/*f* noise effect of the magnetic sensor by modulating the incoming signal to above several kHz range [6-8]. Among various modulation approaches, the flux concentrator modulation based on microelectromechanical system (MEMS) is the most promising one. Although the existing MEMS flux concentrators have demonstrated good modulation result, their modulation efficiency is low [9].

In this paper, a novel MEMS vertical motion modulated flux concentrator (VMMFC) is proposed to improve the modulation efficiency. A prototype sensor based on the multi-layered GMR sensor AA02 was fabricated and its magnetic field modulation efficiency can reach 18.8%. Also, the magnetostatic field detection ability is improved to 0.53 nT/√Hz.

2 THEORETIC AND SIMULATED ANALYSIS

2.1 Principle of VMMFC

Flux concentrators are widely used to enhance the sensitivity of the miniature magnetic sensors, and many modulation schemes are designed on the flux concentrators driven by MEMS actuators. Similarly, the VMMFC is derived from a pair of flux concentrators, as shown in Fig. 1, in which a soft magnetic film named as flux modulation film (FMF) is suspended on the air gap and driven by a vertical MEMS actuator.

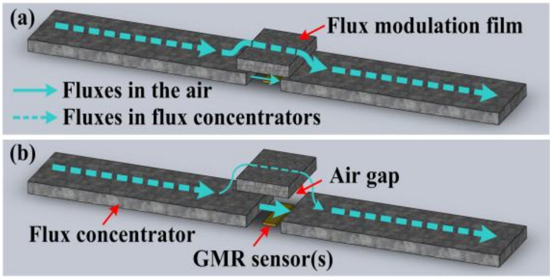

Fig. 1. Magnetic flux distributions of VMMFC flux guides: (a) FMF getting close to the air gap; (b) FMF leaving from the air gap

An electrostatic or piezoelectric micro cantilever is the preferred choice for their simplicity and effectiveness. When the FMF gets close to the flux concentrators, the magnetic fluxes in the air gap prefer to go through the flux modulation film and the gap magnetic field is weakened rapidly (Fig. 1(a)). On the contrary, the leaving of FMF from the air gap will restore the gap magnetic field (Fig. 1(b)). As a result, the gap magnetic flux density can reach the maximum and minimum values alternately when the FMF vibrates up and down, and the magnetic field to be measured is partly transferred to a higher frequency domain where the 1/f noise is much lower. Finally, the GMR elements exposed in the air gap will detect a high-frequency magnetic field with an improved signal noise ratio. Though the high-frequency signal contains a serial of harmonic components, the fundamental component can be used for sensing signals due to its largest SNR. Thus

* 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

ISSN 1335-3632 © 2012 FEI STU

the output voltage (V_o) of the GMR sensors with VMMFC can be expressed by

$$V_0 = eGV_eSB_e \sin(2\pi ft + \varphi) \quad (1)$$

Where, $\boldsymbol{e}$ is the magnetic modulation efficiency, G is the magnetic field amplification factor of flux concentrators, V_s is the excitation voltage of GMR, S is the sensitivity of GMR, B_e is the magnetic flux density of the measured field, $\boldsymbol{f}$ is vibration frequency of the vertical MEMS actuator (modulation frequency), φ is the initial phase angle. Additionally, G and E can be defined as

$$G = B_{nf} / B_e \quad (2)$$

$$e = 100\% \times (B_{max} - B_{min}) / 2B_{nf} \quad (3)$$

Here, B_{nf} is the gap magnetic flux density with flux concentrators and without FMF, B_{max} and B_{min} are the maximum and minimum gap magnetic flux density respectively.

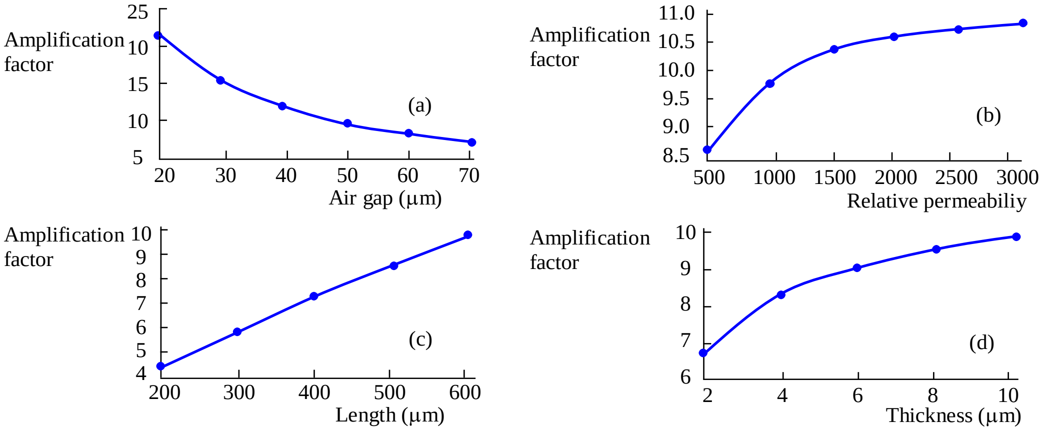

Fig. 2. Simulation results of flux concentrators: (a) - amplification factor versus air gap; (b) - amplification factor versus the relative magnetic permeability; (c) - amplification factor versus the length of concentrators; (d) - amplification factor versus the thickness of concentrators

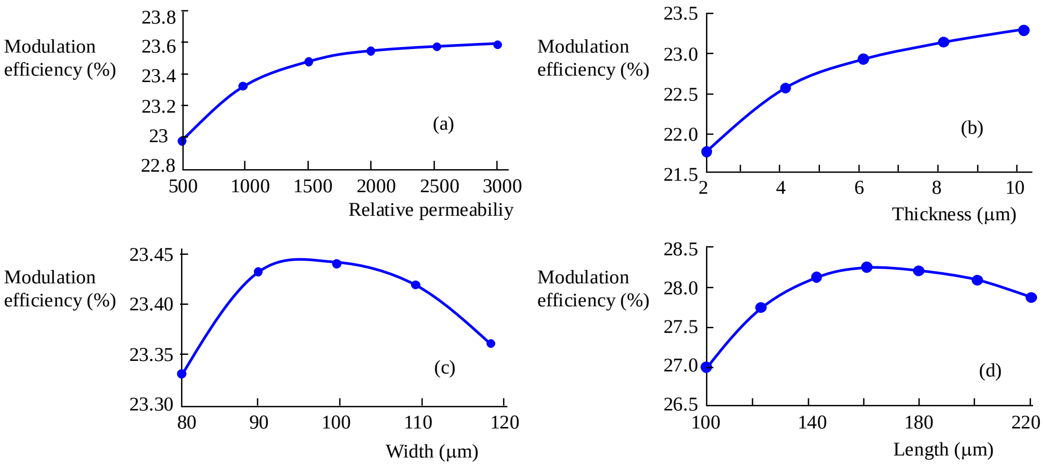

Fig. 3. Simulation results of modulation efficiency of VMMFC related with FMF: (a) - modulation efficiency versus relative magnetic permeability; (b) - modulation efficiency versus FMF thickness; (c) - modulation efficiency versus FMF width; (d) - modulation efficiency versus FMF length

2.2 Numerical simulation of VMMFC

According to Eq. (1), the magnetic field amplification factor and modulation efficiency are the most important parameters for VMMFC. Therefore, how to improve the magnetic field amplification factor and modulation efficiency is a crucial issue. These two parameters are related with the shape, size, position and magnetic permeability of the flux concentrators and FMF. Their relationship was analyzed using numerical simulation method. MAXWELL 3D software was used for the magnetic finite element analysis. Trapezoidal flux concentrators are often used, which have large amplification factor and linear working range [10]. Thus, trapezoidal flux concentrators (a short side of 80 μm and a long side of 150 μm) were taken in this research. The relation between amplification factor and main parameters of concentrators including air gap, magnetic permeability, length and thickness was analyzed. Numerical simulation results were shown in Fig. 2. It can be seen from Fig. 2(a) and (b) that the amplification factor will decrease rapidly with the air gap (20 - 70 μm) and increase with the relative magnetic permeability of concentrators (500 - 3000). Also the Amplification factor will increase almost linearly with the length of concentrators (200 - 600 μm), as shown in Fig. 2(c). Fig. 2(d) show that the amplification factor will increase with the thickness of concentrators (2 - 10 μm).

The modulation efficiency of VMMFC is related with not only the parameters of concentrators and FMF, but also the air gap. Here, concentrator parameters and air gap were assumed to be invariable. The concentrator has trapezoidal cross section, whose short side and long side are 80 μm and 150 μm individually. The relative magnetic permeability of the concentrator is 1000, and its length and thickness are 600 μm and 10 μm individually. The air gap is 50 μm. The FMC has cube structure, and it vibrates with the amplitude of 10 μm. The relation between the modulation efficiency and the relative magnetic permeability, length, width and thickness of FMF was analyzed and the simulation results were shown in Fig. 3. It can be seen from Fig. 3(a) that the modulation efficiency will increase with the relative magnetic permeability of FMF (500 - 3000). However, when the relative magnetic permeability of FMF is larger than 1000, the increment of modulation efficiency becomes slow. The modulation efficiency will increase with the thickness of FMF (2 – 10 μm), as shown in Fig. 3(b). The simulation result of Fig. 3(c) shows modulation efficiency will change very little (about 0.1) when the width of FMF varies from 80 μm to 120 μm. It can be seen from Fig. 3 that the modulation efficiency appears a maximum when the FMF length is 160μm, and it is always higher than 21% when the FMF length varies from 100 μm to 220 μm

3 DESIGN AND FABRICATION

In order to simplify the structure of VMMFC prototype sensor, the multilayer GMR chip AA002 (provided by Nonvolatile Electronics Corp. of US) is chosen, which includes a pair of internal flux concentrators. The piezoelectric silicon cantilever (PSC) serving as a vertical actuator was adopted in the design, as shown in Fig. 4(a). The four GMR elements in AA002 constitute a Wheatstone bridge, in which two GMR elements are shielded under a pair of internal flux concentrators and the other two are exposed in the air gap (60 μm width). Each flux concentrator has a size of 1000 μm (length)×300 μm (width)×18 μm (thickness) (see in Fig.4 (b)). The silicon cantilever is fabricated with photolithography and wet etching process and the piezoelectric ceramic is tightly fixed on the top surface of the silicon cantilever with a thin layer of conductive epoxy. As shown in Fig.4(c) and (d), the FMF with a composition of $Ni_{79}Fe_{21}$ is electroplated on the bottom surface of the free end of the PSC with photoresist meld method. Significantly, the FMF suspended on the air gap with approximate 12 μm static height is designed to be 600 μm (length) × 120 μm (width) × 10 μm (thickness) in dimensions for covering the air gap entirely, which is important to achieve high modulation efficiency for VMMFC The VMMFC prototype with a

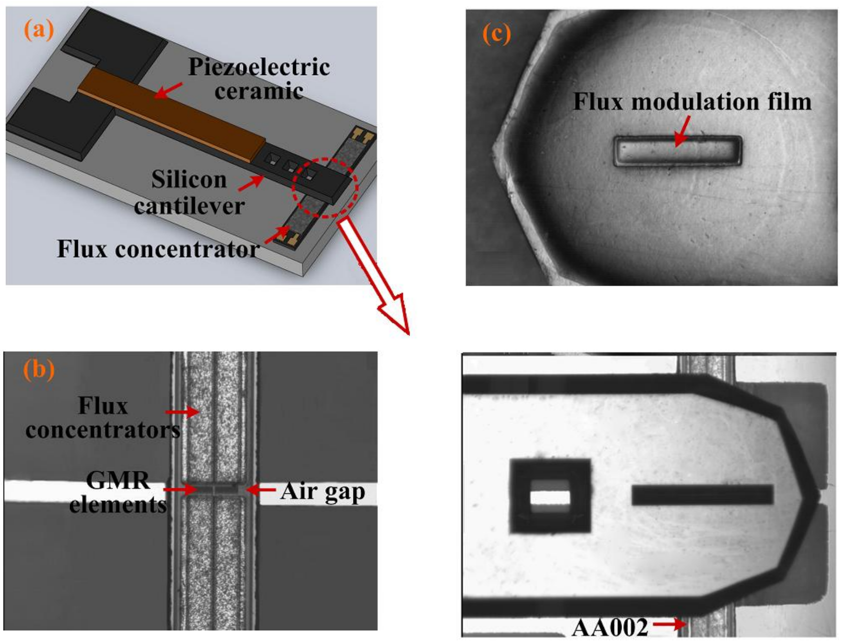

Fig. 4. Solid model and microscope photos of VMMFC prototypes: (a) - solid model; (b) - AA002 bonded on the glass substrate; (c) - free end of the silicon cantilever (bottom view); (d) - the vicinity of AA002 (top view)

pair of Helmholtz coils was placed into a three-layered magnetic shield to eliminate ambient disturbances. The SPC was self-oscillated in the atmosphere by an excitation of 10 V at 3.616 kHz, and the vibration amplitude of the FMF was 10 μm, which was measured with a laser displacement sensor (LK-G10, Keyence Corp.). The magnetic field generated with the Helmholtz coils acts on the VMMFC prototype sensor and the output voltage was amplified with a low-noise preamplifier (SR560, Stanford Research System). In addition, a real time spectrum analyzer (RSA 3303B, Tektronix Corp.) was taken to acquire the power spectrum of the amplified response.

4 EXPERIMENT RESULTS AND DISCUSSIONS

The transfer curve of the VMMFC prototype sensor was obtained when the power supply V_S is 5V and the external magnetic field B_e is within 0.1 mT (shown in Fig. 5), and its sensitivity (S_{VMMFC}) is figured out to be 4.52 mV/V/mT. Under the same conditions, the sensitivity of GMR chip AA002 (S_{AA002}) is 24.1 mV/V/mT, which was measured and calculated before the VMMFC prototype was fabricated. The modulation efficiency of VMMFC is defined as S_{VMMFC}/S_{AA002} and calculated to be 18.8%, which is higher than the efficiency of most existing sensors with other schemes and coincides with the simulation results. These results clearly show the strong ability of VMMFC on improving flux modulation efficiency with simple structures.

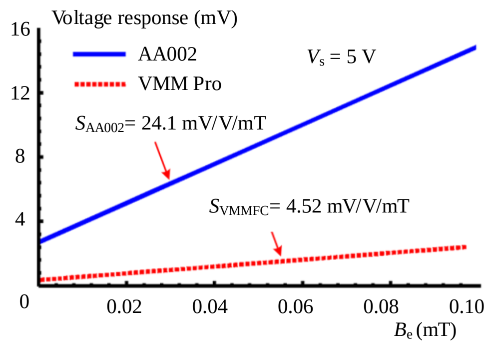

Fig. 5. Transfer curves of the VMMFC prototype sensor and AA002

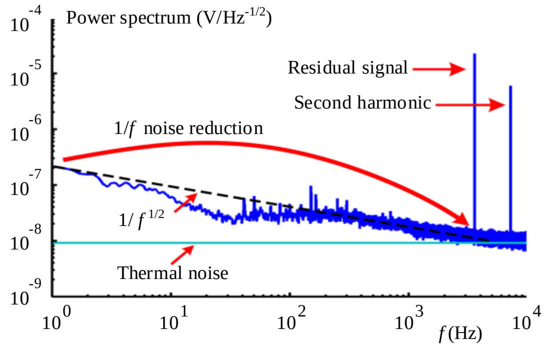

Fig. 6. Power spectrum curve of the VMMFC prototype without external magnetic field

Figure 6 shows the noise and signal power spectrum of the VMMFC prototype without external magnetic field. The noise level is about 220 nV/ √Hz at 1 Hz and 12 nV/ √Hz around 3.6 kHz while 5 V power supply acting on AA002. If the detected magnetic field is modulated from lower than 1 Hz to the sidebands of the modulation frequency, the noise level will be reduced by more than 19 times, which can verify the 1/f noise suppression of MR sensors with VMMFC. And the magnetostatic detection ability of the AA002 can be improved to 0.53 nT/ √Hz with VMMFC.

Note that a residual signal appears at the position of modulation frequency, which attributes to the remanence of the flux modulation film and/or the electric coupling between AA002 and PMSC. To decrease the remanence, the coercivity of NiFe films should better be suppressed from 160 A/m to less than 10 A/m. Also the electric coupling should be restrained by modifying the structure and size of VMMFC prototype sensors.

5 CONCLUSIONS

The VMMFC prototype sensor based on AA002 has a flux modulation efficiency of 18.8% and its magnetostatic detection ability has been improved to be 0.53 nT/√Hz, which demonstrates that VMMFC has strong ability to improve the magnetostatic detection ability of GMR sensors. It is believed that the flux modulation efficiency of VMMFC could be improved to higher than 25% through optimizing the magnetic properties of flux modulation films and the mechanical quality factor of PMSC. We expect the magnetostatic detection ability of VMMFC prototypes would be improved to a few pT/√Hz by replacing AA002 with a tunneling magnetoresistance (TMR) device which has higher sensitivity.

REFERENCES

[1] EDELSTEIN, A.S.: Advances in Magnetometry, J.Phys.:Condens. Matter. 19 (2007), 165217.

[2] EDELSTEIN, A.S. — BURNETTE, J.E. — FISCHER, G.A.: Advances in Magnetometry through Miniaturization, J. Vac. Sci. Technol. A 26 No.4 (2007), 757–762.

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

[4] INGVARSSON, S. — XIAO, G. — PARKIN, S.S.P.: Phys. Rev. Lett. 85 (2000), 3289.

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

[6] EDELSTEIN, A.S. — FISCHER, G.A.: Minimizing 1/f Noise in Magnetic Sensors Using a Microelectromechanical System Flux Concentrator, J. Appl. Phys. 91 (2002), 7795.

[7] EDELSTEIN, A.S. — FISCHER, G.A. — PEDERSEN, M.: Progress toward a Thousandfold Reduction in 1/f Noise in Magnetic Sensors Using an AC Microelectromechanical System Flux Concentrator, J. Appl. Phys. 99 (2006), 08B317.

[8] EDELSTEIN, A.S — BURNETTE, J.E. — FISCHER, G.A.: Validation of the Microelectromechanical System Flux Concentrator Concept for Minimizing the Effect of 1/*f* Noise, J. Appl. Phys. 105 (2009), 07E720.

[9] GUEDES, A. — PATIL, S.B. — CARDOSO, S.: Hybrid Magnetoresistive/ Microelectromechanical Devices for Static Field Modulation and Sensor 1/f Noise Cancellation, J. Appl. Phys. 103 (2008), 07E924.

[10] DRLJAČA, P.M. — VINCENT, F. — BESSE, P.A.: Design of Planar Magnetic Concentrators for High Sensitivity Hall Devices, Sens. Actuators A 97-98 (2002),10–14.

Received 9 September 2012

Wugang Tian, Jiafei Hu, Mengchun Pan, Dixiang Chen, Jianqiang Zhao, Guiyun Tian, for biographies see page 53 of this issue.