Study on Micro Fluxgate Magnetic Sensor

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ABSTRACT

Based on MEMS technology, a novel type of micro fluxgate magnetic sensor (MFGM), which exploits magnetic fluxgate principle, has been designed. It has symmetrical geometry, and is flexible for electrical connection, easy to form as a two-axis or a one-axes vector sensor. MFGM is easily assembled into a 3-axis subminiature magnetometer and can be applied to measure vector of the weak geomagnetic field. The microfabrication process has been developed. The UV lithography technology in combination with thick negative and positive photoresists is exploited in the microfabrication. The original samples have been produced with the dimension of $1\,cm \times 1\,cm \times 100\,um$. MFGM can be widely applied in the conventional and potential fields, for examples, scientific research, automation, process control of industry, mineral prospecting, medical appliance, especially in micro-satellite (including nano-satellite and pico-satellite) missions. It is a important part of Attitude Determination and Control System (ADCS) subsystem of MEMSSat-1 pico-satellite (researched by Tsinghua Univ.), used to obtain information about the attitude of the satellite individually or in combination with other parts such as Micro Inertial Measurement Unit (MIMU).

KEYWORDS: Fluxgate Magnetic Sensor, Magnetometers, MEMS, Pico-satellite

INTRODUCTION

Fluxgate magnetic sensors are widely applied since it appeared in early 1930s. They are vector devices which are used to measure the components of magnetic fluxes density vector at one certain point of the dc or low-frequency ac magnetic fields up to 1mT [1]. The theory exploited is based on the saturation of ferromagnetic materials [2]. They have the resolution of 0.1-10nT [3], even up to 10pT, and the absolute precision of 1nT to 100nT [4]. Compared with recent anisotropy magnetoresistance (AMR) and giant magnetoresistance (GMR) solid-state magnetic sensors, they have higher temperature stability and better long-term stability as the most primary reasons for their extensive application in satellites and other space vehicles.

Micro fluxgate magnetometers (MFGM), which are based on CMOS or MEMS technology, appeared in 1990s. By compared with traditional fluxgate magnetic sensor, MFGM has some advanced features, such as less mass, smaller size, less power consumption, better performance and batch production. The original goal is to apply of them to hand-held and portable equipments. In addition, there are broad applications in many fields, such as to geomagnetic detection, scientific research, automation, process control of industry, mineral prospecting, and medical appliance, particularly nano satellites and pico satellites. It is our primary objective to design and microfabricate MFGM as a necessary part of Attitude Determination and Control Subsystem (ADCS) of MEMSSat-1 (researched by Tsinghua Univ.), used to obtain information about the attitude of the satellite individually or in combination with other parts such as Micro Inertial Measurement Unit (MIMU).

Different types of micro fluxgate sensors have been researched according to the publications. The one-axes magnetic sensors with unenclosed magnetic core on top of planar spiral coils were researched by Almazan[5] and Choi[6]. The sensors with closed core were also developed by Ripka[3]. The two-axis planar ones with unenclosed core were designed by Kejik [7]. Gottfried-Gottfried tried to invent one-axes sensors with toroidal coils and unenclosed core [8], while Park [9] and Liakopoulos [10] researched the micro magnetometers based on enclosed core with toroidal coils and with solenoid coils, respectively.

The sensor, MEMS Magnetometer (MEMSMag), which has been designed in our work, presents the concept of solenoid coils and enclosed magnetic core, and it can be applied as a two-axis vector device. Thus it differs from those mentioned above. The related microfabrication process is also described in this paper which exhibits the means of UV-LIGA multilayer fabrication using both thick positive and thick negative photoresists.

Table 1. The performance design of MEMSMag.

Rang	-100uT~+100uT	Linearity	±1% FS
Sensitivity	20~40mV/uT	Mass	<30g (System)
Resolution	1nT~10nT	Power	±5 V DC / ± 10 mA
Operating Temp.	-20－60˚C	Size	20×20×50mm(System),5×5×2mm(Dies)
Orthogonality Between Axis	±1°	Frequency Response	DC to 300 Hz (-3 db)

SENSOR CONSTRUCTION

The fluxgate sensor exploits the fluxgate principle which was expatiated on by Primdahl[2]. When the ferromagnetic core is driven periodically into saturation by the exciting coil, the inductive electromotive force is generated in the pick-up coil located on the same core. Due to the nonlinear behaviour of magnetic material, harmonic components of the exciting frequency appear in the faradic signal. The even harmonics have relationships in quantity with the applied magnetic field.

According to this effect, a new type of two-axis micro-fluxgate magnetic sensor, MEMSMag has been designed based on MEMS technology. The design of MEMSMag exhibits the requirements of MEMSSat-1 about the performance parameters, as shown in Table 1. Fig. 1 depicts a schematic view of the sensor. It has three components with respect of functionality: the coils, the insulation and the ferromagnetic core. As the view of microfabrication, it has five layers: the insulation layers, the bottom and top conductor layers; the core layers, and the stand-up layers.

An enclosed ferromagnetic core, with the form of square-shaped ring filleted at corners, is enwrapped with negative photoresist, SU-8, as its insulating and supporting layer. The twelve coils (3 coils for each side and 38 turns for each coil) are wound solenoidally around the isolated core, acting as the roles of exciting, pick-up and compensation.

The coils have symmetries with respective to the centre and the two axis. The length of each side of core is 5000 um and the section is 400 um long and about 20 um thick. The gap between the core and the coils is 20 um wide and 10 um thick. The dimensions of original chip have been designed are $1cm \times 1cm \times 100um$. The geometry is shown in Fig. 2.

This sensor has difference form which can inherently suppress odd harmonics and increase the sensitivity and the ratio of signal to noise. On the other hand, the arrangement of coils is flexible in structure. Different electronical connections of coil pairs, different forms of sensor with different features can be formed. For an instance, connecting Coil X1 and X1'(Coil Y1 and Y1') serially as exciting coil pair, Coil X3 and X3'(Coil Y3 and Y3') serially as compensation coil pair, and Coil X2 and X2'(Coil Y2 and Y2') antiserially as pick-up coil pair, a one-axes fluxgate sensor is implemented which can detect the signal in Y direction(in X direction), and an integrated two-axis fluxgate sensor is made. However, the functionality of compensation is not complete because of the coupled field, which means that the signal of pick-up coil pair in X axes can be interfered if the compensation is utilized in Y axes, vice versa. If Coil X1, Y1, X1' and Y1'

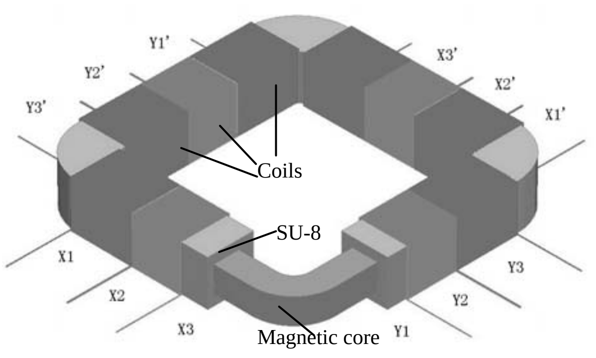

Fig. 1 Schematic diagram of the sensor

(Two coils, Coil X3 and Coil Y1, are hidden in order to show the details of insulation and core)

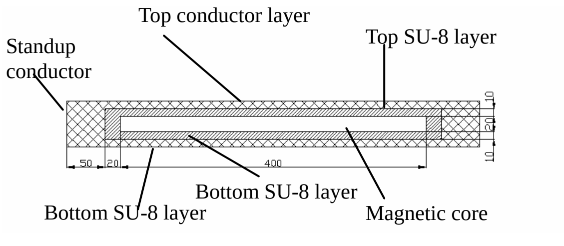

Fig. 2 The cross section geometry of sensor

Table 2: Some forms of MEMSMag by different electrical connections.

No.	Exciting pair	Pick-up pair	Compensation pair	Ratio	Description
1	X1+X1'+ Y1+Y1'	X2-X2', Y2-Y2'	X3+X3' Y3+Y3'	2:1:1	Two-axis, have compensation
2	X1+X1'+ Y1+Y1'	(X2+X3)-(X2'+X3'), (Y2+Y3)-(Y2'+Y3')		1:1	Two-axis, no compensation
3	X1+X2+X3+ X1'+X2'+X3'	(Y1+Y2+Y3)- (Y1'+Y2'+Y3')		1:1	One-axes, no compensation
4	X1+X2+X3+ X1'+X2'+X3'	(Y1+Y2)- (Y1'+Y2')	Y3+Y3'	3:2:1	One-axes, have compensation

Note: 1. the symbol "+" explicates connection in series, while "-" means in antiseries; 2. ratio is the turn number ratio of exciting : pick-up :compensation(if compensation exists).

are conductive in series, and Coil X2 and X3 contact in series then connect antiserially with the serial coil pair of X2'and X3(the same way to Coil Y2, Y3, Y2' and Y3'), a two-axis magnetic sensor without feedback loops of compensation is formed. Its sensitivity is double than the former connection form.

Furthermore, different one-axes fluxgate sensors can also be formed by different connections, as shown in Table 2. for example, a single axe device, which has feedback loop of compensation and the turn number ratio of 3:2:1(exciting: pick-up: compensation), can be formed by connecting the Coil X1, X2, X3, X1', X2' and X3' in series as exciting coil pair, concatenating the pick-up coil pair Y1-Y2 and Y1'-Y2' in antiseries after serially connection of Coil Y1 and Y2 and Coil Y1' and Y2', and contacting electrically Coil Y3 and Y3' as feedback loop. Many other types of one-axes magnetometer can be construct for different structural features and electrical parameters.

FABRICATION PROCESS

MEMSMag has a real 3-D structure compared with the other micro fluxgate magnetic sensors reported[1][3]-[9]. And it is difficult to be fabricated by standard CMOS process. Thus, the UltraViolet Lithography Galvanoformug Abform-technik (UV-LIGA) multilayer microfabrication process was developed based on MEMS technology. Simultaneously, not only thick positive photoresists are used as molds for magnetic core and conductors, but also thick negative photoresists are used too, as insulation layer and supporting structure. Fig. 3 briefly shows the fabrication processes of the micro-fluxgate device.

The process starts with oxidized silicon as substrate. The Titanium/copper/Titanium (with width of $50/100/100\,nm$) layers are deposited to form a seed layer for electroplating using iron-beam sputtering. This seed layer is patterned to form the conductive network for electroplating the bottom conductor layer which is the bottom component of coils. The thick positive photoresist, AZ 9260, is spun on the top of seed layer to construct electroplating molds for the bottom conductors. Then copper is electroplated with width of about $10\,um$. After removing the thick film, a thicker negative photoresist, SU-8, is spun to enwrap the bottom conductor layer, about $20\,um$ thick, as the insulation material between magnetic core and coils. Furthermore, SU-8 acts as the underlayment for the core. This layer is etched to open the vias, as the molds of the stand-up conductors, forming the path to connect with the bottom conductors. And then gold is sputtered, about $150\,nm$ thick, as the second seed layer. On top of the gold layer, a multi-coating positive photoresist is spun. The technology of thick positive photoresist with high aspect ratio is utilized [11]. The positive layer, using AZ 9260, is coated for two or three times to form a thick multilayer membrane, with the thickness about 30~40 um, which is patterned to form the mold for the core. The ferromagnetic film, with squared ring form filleted at corners, is electroplated. The film supplies an enclosed path for magnetic flux. Then the mold and the redundant seed layer are removed before the negative photoresist is spun. The stand-up conductors are electroplated after photolithograph and opening the vias. Following that, A third seed layer is deposited on the top of SU-8 for electroplating the top conductors. AZ 9260 is coated and patterned to form the molds. The top conductors are electroplated, connecting their corresponding stand-up ones and making up the coils. After removing the positive photoresist, SU-8 is coated and cured to encapsulate the whole coils, making no conductive contacts with ambience, except the pads.

The experiments on each process have been completed and validated the fabrication. Electroplating the thick ferromagnetic core is the key step. Thick positive photoresist is exploited as the molds, because they have good adhesion to the seed layer and can be stripped easily. In the early work, another fabrication process was developed.

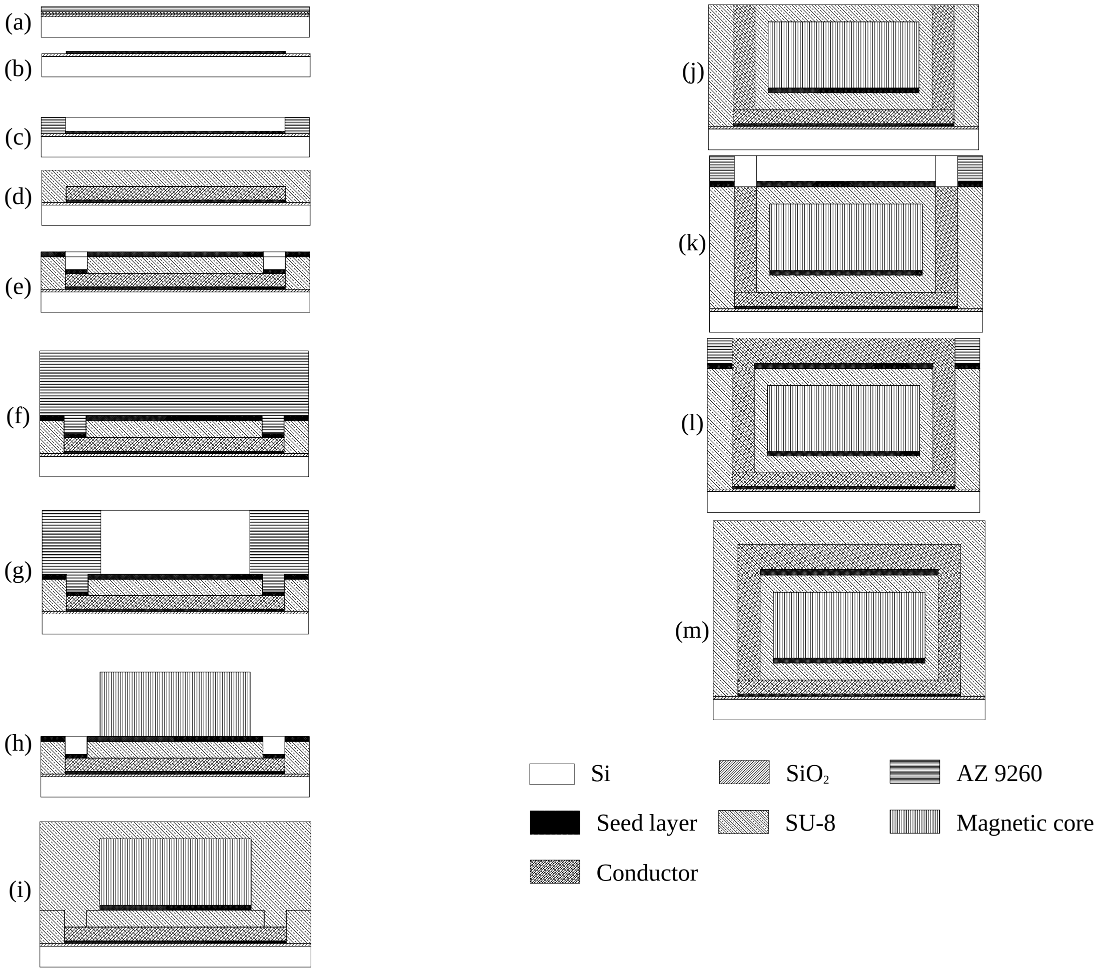

Fig. 3 Fabrication process of MEMSMag:
(a) spinning AZ 9260 on the top of the Ti/Cu/Ti seed layer, (b) obtaining the pattern of the bottom conductors, (c) preparing the molds in AZ 9260 for electroplating the bottom conductive lines, (d) coating SU-8 after removing the positive photoresist, (e) photolithograph of vias and depositing the seed layer for electroplating magnetic core, (f) multi-coating the thick positive photoresist, (g) photolithograph and etching to form the mold for NiFe ferromagnetic layer, (h) electroplating the ferromagnetic core and removing the AZ9260, (i) coating thick SU-8 photoresist to insulate the magnetic layer, (j) electroplating the vias(stand-up conductors), (k) depositing the third seed layer then coating and patterning positive photoresist for the top conductors, (l) electroplating the top conductor layer to make the coils conductive, (m) coating SU-8 and curing it after removing AZ9260, and some postprocess.

To protect the vias before depositing the second seed layer for electroplating magnetic core, positive photoresist was coated as the sacrificed layer on top of the SU-8 layer (the abandoned process was before the step as shown in Fig. 3(e)), and the negative photoresist, SU-8, was coated as the mold for the core electroplating (after the step as shown in Fig. 3(e)). However, it is actually difficult to remove the negative mold layer, the metalized seed layer and the positive sacrificed layer without destruction of the core and the underlayment after electroplating. Au, which substituted Ti/Cu/Ti, was directly sputtered as a seed layer on the top of negative underlayment layer, and thick multi-coating positive layer was used instead of negative one, that handily solved the problem and substantially degraded the complexity of fabrication.

CONCLUSIONS

A novel micro fluxgate magnetic sensor is studied. The design and fabrication are based on the MEMS technology. Compared with other micro fluxgate magnetometers reported, MEMSMag has a 3-D symmetrical structure which has the bigger effective area of across section, and consequently increases the sensitivity. In addition, MEMSMag has an enclosed path for magnetic fluxes which make it easier to saturation. This feature equivalently increases the effective permeability. The same geometry of the twelve coils has more flexibility and some types of device can be implemented with different performance. An available microfabrication process has been developed based on UV-LIGA technology. Both positive and negative photoresists are used for special functionality. Simultaneously, the technology of multi-coating positive photoresist is exploited here. By this fabrication process, some micro devices can be fabricated which have the similar geometries such as micro motor, micro inductor and RF devices.

The whole work has not completed. Up to now, the bottom and stand-up conductors had been electroplated easily. The ferromagnetic core had been molded successfully too. But the top conductors have not been micromachined yet. The works about experiment have been done synchronously.

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