High Sensitivity Micro-fabricated Fluxgate Sensor with a Racetrack Shaped Magnetic Core

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We present a micro fluxgate magnetic sensor having solenoid coils and racetrack shaped magnetic core, which was designed to decrease the operating power and magnetic flux leakage. Electroplated copper coils of 6 μm thickness and the core of 3 μm thickness were separated by benzocyclobutane (BCB) having a high insulation and good planarization characters. Permalloy ($Ni_{0.8}Fe_{0.2}$) as a magnetic core was also electroplated under 2000 gauss to induce the magnetic anisotropy. The core had the high DC effective permeability of ~1,300 and coercive field of ~0.1 Oe. The fabricated fluxgate sensor had the very small actual size of 3.0 × 1.7 mm^2. The fluxgate sensor with a racetrack shaped core had the high sensitivity of ~350 V/T at excitation condition of 3 V_{P-P} and 2 MHz square wave. When two fluxgates were perpendicularly aligned in terrestrial field, their two-axis output signals were very useful to commercialize an electronic azimuth compass for the portable navigation system.

Keywords : Magnetic, Fluxgate, Sensor, Micromachining

1. INTRODUCTION

The sensing and measuring of low magnetic field have always been an essential function for numerous applications. Various techniques and sensors have been developed to measure the low magnetic fields from 0.1 nT to 1 mT. One of the most sensitive magnetic sensors is the fluxgate sensor[1,2]. Traditional fluxgate sensor serves for the measurement of the magnetic field in the range of 1nT to 1 mT. They can reach better than 0.1 nT resolution and high precision of 10 ppm linearity error. They have broad application range from precise geophysical instruments to rugged detection sensors for security and military applications. The latest competitors of fluxgate sensor are AMR and newly developed GMR magnetoresistors[3}. The main advantage of fluxgate sensor is its high temperature stability : 30 ppm/℃ temperature coefficient of sensitivity are easily achievable, while the same parameters for any other solid-state vectorial magnetic sensors (including semiconductors and magnetoresistors) are at least 10 times worse. However the conventional fluxgate sensor utilizes bulk or ribbon core, bobbins for the excitation and the pick-up, and electronic circuits for the core excitation and signal processing. They should be hand-made, manually adjusted and individually calibrated. These result in the disadvantages of large volume, large weight, and high cost. If the fluxgate sensor is developed by silicon micromachining, we can expect various fascinating application because of the attractive features of small size, light weight, high sensitivity, high resolution, integration of signal processing circuits and so on.

Recently the fluxgate sensor by silicon micro-machining has been studied in Toyohashi University[4,5], Fraunhofer IMS[6], University of Cincinnati[7] Cambridge University[8], and Samsung Electronics [9,10]. To get a high sensitive and small size fluxgate sensor, we have also developed the micro fluxgate with a racetrack shaped magnetic core using silicon micro-machining. Racetrack shaped core will decrease the magnetic flux leakage and the operating power. It will be high sensitive and applied to micro electronic azimuth compass in mobile system to obtain real time pose and trajectory data.

2. DEVICE STRUCTURE

The fluxgate sensor conventionally consists of the soft magnetic core, excitation coil, and pick-up coil. The performance of the micro fluxgate sensor depends on the effective permeability of the magnetic core, excitation frequency, and the coil and core structures. The working principle of the traditional fluxgate sensor was given in an idealized mathematical model[11]. A fluxgate sensor with differential sensing is very attractive because of some advantages in signal processing. Figure 1 shows the working principle of the differential fluxgate sensor. The core with magnetic characteristic B(H), ignoring the hysteresis, is periodically saturated by triangular function H(t) from the excitation coil in Fig. 1(a). The resulting functions B(t) and u(t) are given in Fig. 1(b). Without external field (H_e=0), the situation would be symmetrical (full line) and the pulse voltage of the pick-up coil is cancelled due to opposite excitation. When an external magnetic field is applied parallel to the core-axis direction, the external field ($H_e \neq 0$) causes asymmetry of the curve B(H), B(t), and u(t) (dash line).

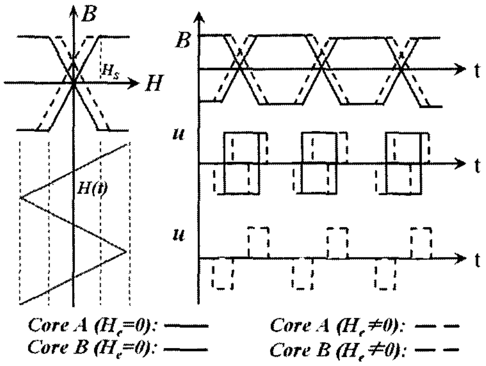

Fig. 1. Working principle of the differential fluxgate sensor.

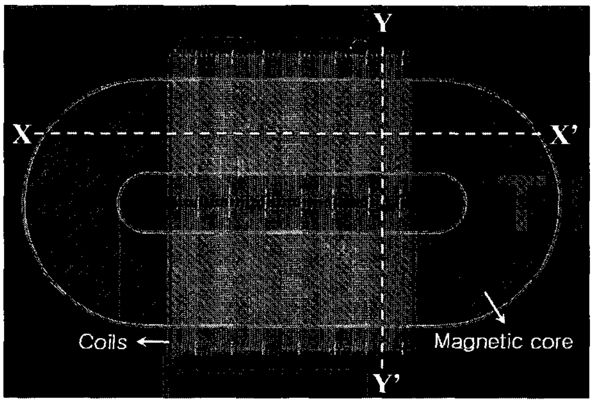

Fig. 2. Structure of the differential fluxgate sensor fabricated using silicon micromachining.

The pulse voltage appears at the pick-up coil due to the phase shift of the induced pulse. It makes the even harmonics, especially the second harmonic, in spectrogram. The sensitivity (S_B) of the fluxgate sensor using second harmonic detection is given as follows [4]:

$$S_B = 8NA\mu_{eff} f_{exc} \sin\left(\frac{\pi H_s}{H_m}\right) \tag{1}$$

where N is number of pick-up coil turns, A is the core cross-sectional area, μ_{eff} is the effective permeability of the core, f_{exc} is the excitation frequency, H_s is the saturation magnetic field of the core, and H_m is the peak excitation magnetic field. In case of $H_m = 2H_s$, the best condition to maximize the sensitivity is obtained.

Figure 2 shows the structure of the differential fluxgate sensor fabricated by silicon micromachining. The fluxgate sensor described here had the closely coupled excitation and pick-up solenoid coils and racetrack shaped core. The excitation and pick-up coils were alternately wound as an order of one turn excitation coil and one turn pick-up coil. The excitation and pick-up coils had 49 turns and 46 turns, respectively. Copper was used as the coil wire materials due to its high electrical conductivity. To decrease the magnetic flux leakage, the magnetic core with 500µ m width was designed as a racetrack shape for a closed magnetic flux path. The core was formed by $Ni_{0.8}Fe_{0.2}$ (permalloy) electroplating. The permalloy in soft magnetic materials was selected due to its high permeability, low coercive field, and stability with frequency variation.

3. FABRICATION

Figure 3 shows the fabrication process with X-X' line and Y-Y' line in Fig. 2. The insulating silicon oxide film between the copper coils and silicon substrate was grown by wet oxidation. Ti (300 Å)/Au (1500 Å) seed layers for electroplating were deposited by DC sputtering. The lower copper layer of excitation and pick-up coils were electroplated with a closely coupled structure and the seed layers were removed by Ion Beam Etching (IBE) process. Benzocyclobutane (BCB) having a high electrical resistance and good planarizing characteristics was coated as an insulating layer. The $Ni_{0.8}Fe_{0.2}$ (permalloy) magnetic core layer on permalloy seed layer was also electroplated with photoresist (AZ4260) frame. The racetrack shaped core was patterned by photolithography and etched by dilute sulfuric acid. BCB was coated again with via holes and upper copper layer was also electroplated with the same process as lower one.

Figure 4 shows the microscope photographs of the micro fluxgate sensor fabricated by silicon micromachining. Figure 4(a) and (b) show the cross-sectional with the X-X' line in Fig. 2 and top view, respectively. The pitch size of the lower and upper copper layers is 14 μm of 10 μm width and 4 μm space. The 6 μm thick copper layers with high electrical conductivity can result in decrease of the power consumption. The permalloy film with 3 μm thickness was also electroplated under 2000 gauss to induce magnetic anisotropy. The fabricated fluxgate sensor had the very small actual size of 3.0 × 1.7 mm^2.

To measure the performance of the fluxgate sensor, the excitation current to saturate the magnetic core was provided by a function generator (HP 33120A). A spectrum analyzer (Agilent 4395A) measured the second harmonic voltage generated by external magnetic field. To control external magnetic field, a magnetic shield box and DC power supply (Agilent E3642A) were used. The variation of the magnetic field generated by magnetic shield box was linear with the applied DC voltage.

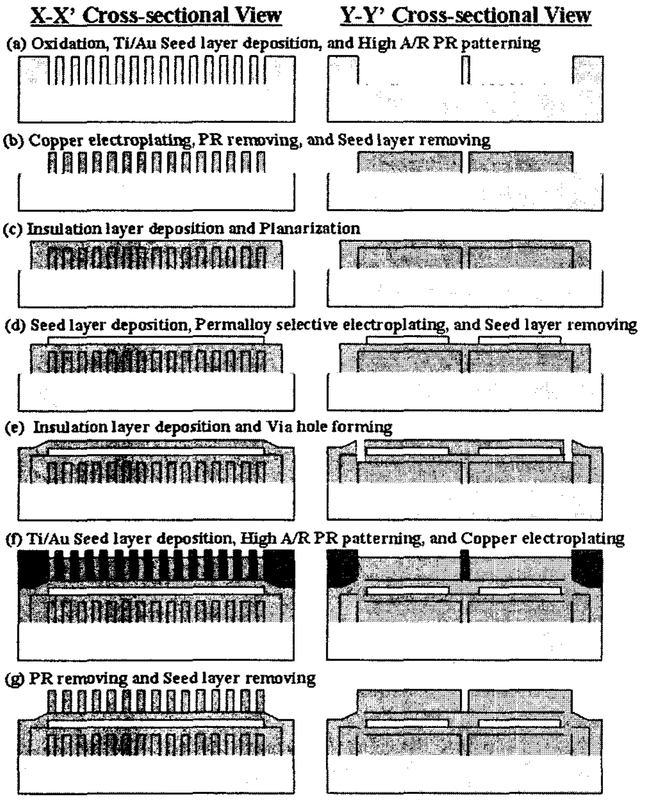

Fig. 3. The fabrication process.

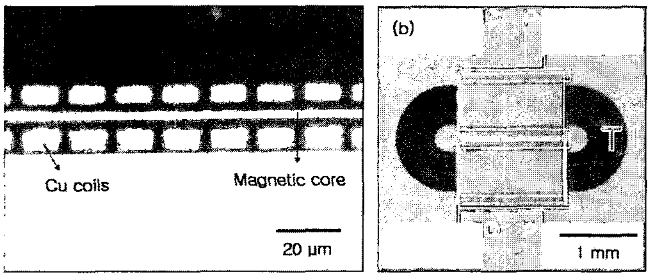

Fig. 4. Microscope photographs of the micro fluxgate sensor. (a) cross-sectional and (b) top view.

4. RESULTS AND DISCUSSION

The permalloy magnetic core had the high DC effective permeability of ~1,300 and coercive field of ~0.1 Oe. The racetrack shaped magnetic core was easily saturated due to the low coercive field and closed magnetic path for the excitation field. The induced second harmonic voltage as a function of frequency is shown in Fig. 5. The excitation voltage of $3V_{P-P}$ square wave was used under 1gauss external magnetic field. The induced second harmonic voltage increased with increasing excitation frequency and these results corresponded to Eq. (1). The maximum value of 39.5 mV was obtained at 2.5 MHz.

Figure 6 shows the linear characteristics of the induced second harmonic voltage measured at the excitation condition of 3 V_{P-P} square wave and 2 MHz. The magnetic field was applied to the fluxgate sensor as an order of A-B-C-D-A and there was no hysteretic property. The output signal as a function of external magnetic field was very linear over the range of -1 gauss (-100μ T) to +1 gauss (+100μ T). From this excellent linear response, the sensitivity of ~350 V/T was obtained at excitation square wave of $3V_{P-P}$ and 2 MHz. The power consumption of ~14 mW was measured.

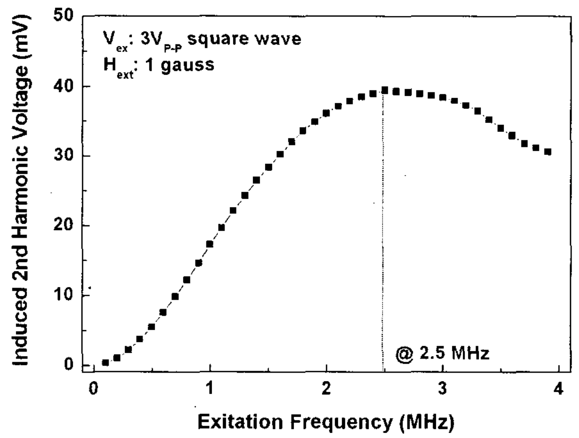

Fig. 5. Induced second harmonic voltage as a function of excitation frequency.

To measure the terrestrial fields of X- and Y-axis, two fluxgate sensors were perpendicularly aligned and rotated from 0 to 360 degree. Figure 7(a) represents the output signals of X- and Y-axis, which were sine and cosine wave, respectively. Figure 7(b) shows the X-Y plot of the sine and cosine signals of Fig. 7(a). It showed a good function of electronic azimuth compass for the portable navigation system including north-up and map data scrolling.

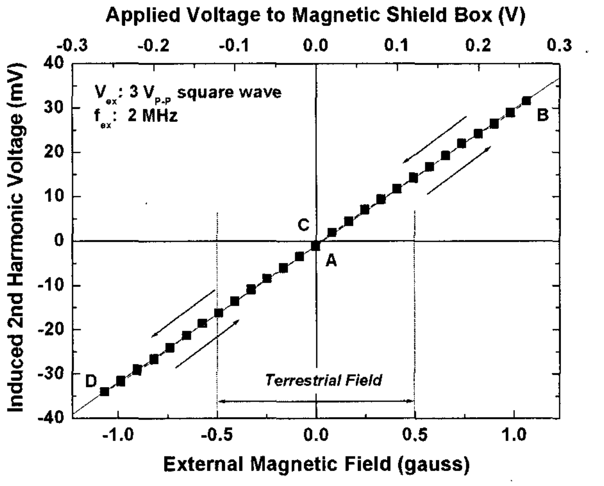

Fig. 6. Induced second harmonic voltage as a function of external magnetic field.

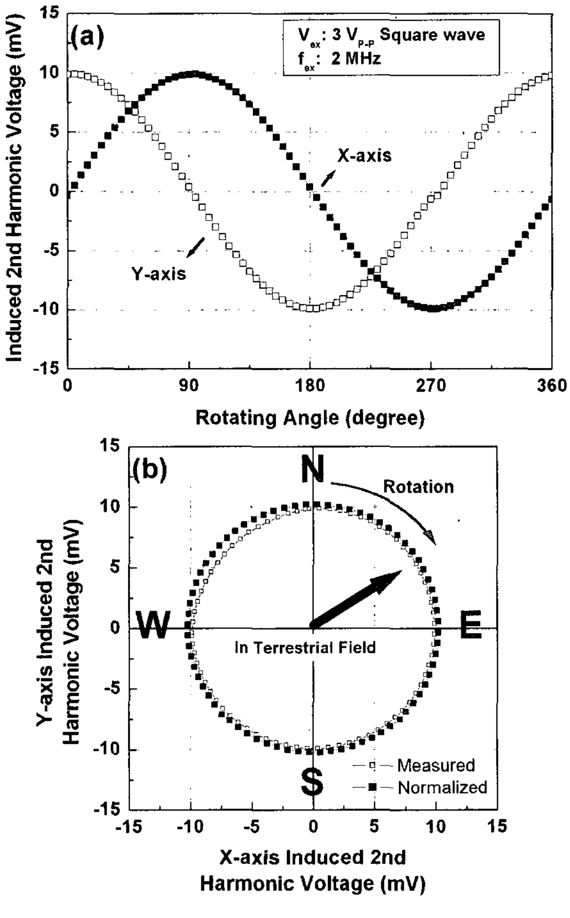

Fig. 7. (a) Induced second harmonic voltage from X- and Y-axis fluxgate and (b) X-Y plot.

5. CONCLUSION

A micro differential sensing fluxgate sensor having a racetrack shaped magnetic core and solenoid coils was fabricated by silicon micromachining. The magnetic core was easily saturated by low excitation voltage because of the racetrack shaped core and small excitation coil pitch of 28 μm. The maximum induced second harmonic voltage of 39.5 mV was obtained at 2.5 MHz. Excellent linear response over the range of -100 μT to +100 μT was obtained with 350 V/T sensitivity at excitation condition of 3 V_{P-P} and 2 MHz square wave. The power consumption of ~14 mW was measured. Although the sensor had a very small chip size of 3.0 × 1.7 mm^2, the good performance was observed in a low magnetic field range. When two fluxgates, which were perpendicularly aligned, were rotated in terrestrial field, the output signals of sine and cosine wave were obtained and their X-Y plot had a good function of the electronic azimuth compass. It is very useful for various applications such as: portable navigation systems including north-up and map data scrolling, military research, medical research, and space research.

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