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Design and Fabrication of Low Power Consumption Micro Fluxgate Sensor

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Abstract: The soft magnetic characteristic of core is a critical factor to performance of the micro fluxgate. Porous thin film core can be effectively used to decrease the value of saturation magnetic field strength (Hs) and improve soft magnetic behavior. It is conducive to impelling the micro fluxgate toward the direction of low power consumption. In this work, a micro fluxgate with porous core is fabricated by MEMS technology. The experiment result complies with the anticipation and indicates that this structure can be applied to decrease the power consumption and improve characteristic of micro fluxgate. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Low power, Thin film core, MEMS process, Porous structure, Micro fluxgate.

1. Introduction

As a classical weak magnetic field sensor, fluxgate have been widely used for its high measurement accuracy and excellent thermal stability. Micro fluxgate sensors are based on MEMS (Micro-Electro-Mechanical Systems) technology. By compared with traditional fluxgate magnetic sensor, Micro fluxgate sensors 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 portable equipments. In addition, there are broad applications in many fields, such as to mineral prospecting, geomagnetic detection, automation, scientific research, and process control of industry, particularly nano satellites and pico satellites.

In recent decades, silicon-based micro fluxgate sensors developed quickly with the application of MEMS technology. Now, micro fluxgate sensors show more application potential in many areas due to its attractive features of small size, light weight, high sensitivity, high resolution, integration of signal processing circuits and so on [1].

However, there is still a problem about the power consumption, which does not decrease along the reduction of the sensor dimension due to saturation magnetizing principle, even causing the more serious cooling problem, which would influence the stability and the work life, and bring great thermal noise [2]. Attempts to reduce power consumption of the micro fluxgate have been done, such as contracted structure core [3-4], short pulse excitation [5-6] and so on.

How to get a saturation magnetic field (Hs) as low as possible while ensuring high magnetic permeability and low magnetic coercive force is a major requirement to lower power consumption of micro fluxgate. In other word, what we focus on is how to make a core excited by small current can reach saturation quickly [7-8].

The core was chosen as a compromise between the sensitivity and power consumption. The thicker

core required higher current to bring it into saturation. High permeability and low coercivity, but non-rectangular shape of the magnetization curve is preferred for the core. Low saturation magnetization (for low-power) and high electrical resistivity (for low eddy current losses) are advantageous. Materials suitable for fluxgate cores are permalloys (with 78 – 81 % of nickel) and amorphous alloys.

The relevant studies have shown that porous structure with pinholes may be a good magnetic softening method for the alloy film. And the porous thin film core can better meet the above mentioned requirements. So fabrication of high quality porous core will allow micro fluxgate to maintain high performance in spite of power consumption reduction.

In this work, we reported fabrication process of low power thin film core for micro fluxgate. A silicon-based porous Fe-Ni thin film was fabricated by MEMS process. The experiment result complies with the anticipation and indicates that this MEMS technique can be applied to improve the characteristic of thin film core and decrease power consumption of micro fluxgate sensor.

2. Experiment

The diagram of micro fluxgate sensor is show in Fig. 1. We designed and fabricated three configurations for the permalloy core to compare the influence of the core structure, including common structure (racetrack), contracted structure, porous structure.

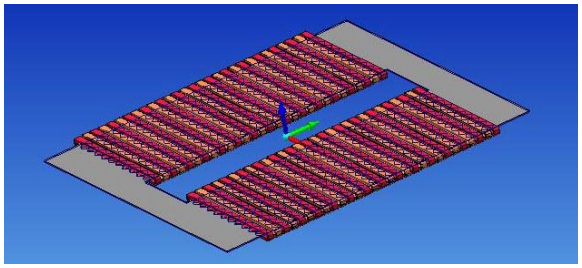


Fig. 1. The diagram of micro fluxgate sensor.

2.1. Fabrication Process

Fabrication of the micro fluxgate sensor by the MEMS technologies has been mature with continual development. Thick photoresist-based UV lithography and electroplating techniques have been adopted in the fabrication of the fluxgate sensor. The simplified micro-fabrication steps of the fluxgate sensor are summarized in Fig. 2. The fabrication started on one side of the Si wafer by making the double-side alignment symbols with chromium of 100 nm in thickness, which is important for each layer of the 3D micro fluxgate sensor to be contacted accurately in the complicated process.

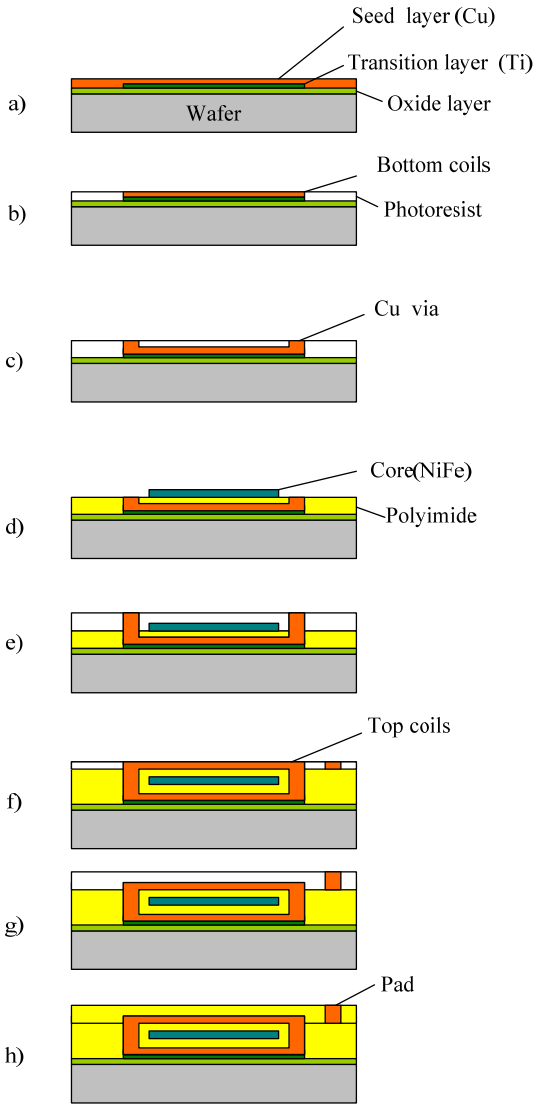


Fig. 2. Simplified micro-fabrication steps of the micro fluxgate sensor.

The solenoid coils comprise two layers of copper, patterned by photolithography to form tracks and electroplated onto the Si substrate with an insulating oxide layer, which connect together to comprise a solenoid coil. Inside the coil is a FeNi core of high permeability.

At first, the seed layer and transition layer are fabricated by sputtering deposition (Fig. 2 a). By electroplating process, the bottom copper conductors (Fig. 2 b) and vias (Fig. 2 c) are fabricated. Then a polyimide process, including spinning, curing and polishing, is performed to electrically insulate the copper conductor line and the magnetic core, and also afford a planar layer to provide a relatively smooth surface. The vias have a cross section of 40 μm×40 μm and a thickness of 20 μm. Then the magnetic cores are processed (Fig. 2d). Vias higher than magnetic core are fabricated (Fig. 2e) and a polyimide process is performed again. Finally, the top copper conductors are fabricated to form the excitation and detection coils (Fig. 2f), then the pads

are fabricated (Fig. 2g). Polyimide process is performed again and only pads are exposed out after polished (Fig. 2h), which can protect the sensor to avoid damage.

After the fabrication completion, samples are diced and tested. The excitation coils have 20 turns and the detection coils have 14 turns. Both the coil line width and the line space are 40 μm, and thickness is 30 μm. Permalloy cores fabricated in this work have same thickness of 30 μm.

2.2. Process Parameters and Main Points

2.2.1. Copper Sputtering

Copper film (300 nm thickness) was prepared on the silicon wafers substrate as seed layer by magnetron sputtering. The process is finished in JGP450 high vacuum multifunctional magnetron sputtering instrument. Film is deposited with pure Ar sputtering gas [9]. Experimental parameters are as follow:

Background pressure: 4.5×10^{-4} Pa,
Working pressure: 2.6 Pa,
Argon gas flow rate: 50 sccm (mL/min),
Power: 180 W,
Self-bias voltage: 40 V,
Deposition time: 30 min,
Substrate temperature: 200ºC,
Film thickness: 300 nm

2.2.2. Softbake, Exposure and Development

SU8 photoresist (PR) was used to fabricate the micro fluxgate sensor. The series of SU8 is chosen in this study because it can be coated with a wide coverage of microstructure thickness. And the baking time of this series is shorter than that of traditional one. Spin coating was done using a spin coater.

For porous core, a thickness of 30 μm of SU8 PR is coated onto copper seed layer. In order to reduce the thermal stress in PR, the baking process with ramping is used. Fig. 3 shows the temperature variations in this process. The temperature of the hotplate rises from room temperature until it reaches 50°C and it stays at this temperature for 2 min, then it rises to 90°C and stays there for 2 min, again it rises to 95°C and stays there for 30 min, finally the hotplate is shut to cool down the temperature to room temperature.

UV exposure was used with a mask aligner in which the main wavelength and wave energy are 365 nm and 15 mW/cm^2, respectively. The process of porous core was carried out in two steps on a heating hotplate. The temperature in the first step was 65°C for 2 min and that in the second step was 95°C for 6 min, and then the hotplate was left to cool down to room temperature. After the process, the substrate with photoresist was developed using pure propylene glycol methyl ether acetate (PGMEA) with mild ultrasonic agitation, and then spun dry to remove the residual organic solvent [10]. After the lithography process, the substrate with PR cylindrical array structure was obtained.

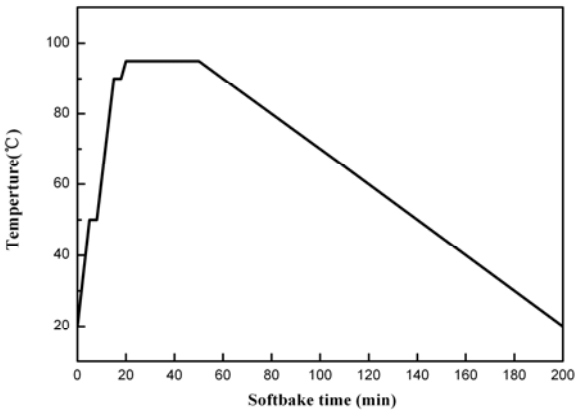


Fig. 3. Temperature variations in softbake process.

2.2.3. Electroplating

The porous Fe-Ni film is fabricated on the cylindrical array substrate by electrodeposition in plating bath. The base electrolyte of the plating bath contained the following: $NiSO_4\cdot7H_2O$ (150 g/L), $FeSO_4\cdot7H_2O$ (15 g/L), $NiCl_2\cdot6H_2O$ (75 g/L), H_3BO_3 (45 g/L) and $C_7H_4NNaO_3S\cdot2H_2O$ (2.5 g/L). PH in the bath is adjusted to approximately 3.3. The deposition is typically performed under a dc current density of 10.0 mA/mm^2 for a deposition time of 40 min. The bath temperature is 60 ºC [11-12]. When permalloy cores are electroplated in molds, magnetic field is applied on the core along the detection core in the electroplating process to improve the soft magnetic performance of the cores.

Then, the samples are thoroughly rinsed with distilled water and subsequently dried in nitrogen. We could obtain Fe-Ni thin film cores with porous structure.

The coils of sensor are fabricated by copper electroplating. The deposition is carried out in a plating bath under the room temperature. The samples are electroplated for 30 min in a mixture of CuSO4 (200 g/L), H2SO4 (60 g/L), NaCl (100 mg/L) and AuC6H5O7 (4 mL/L), with a current density of 3 A/dm^2 and air agitating.

3. Results and Discussion

After a series of procedures, micro fluxgate sensors are fabricated by MEMS process. The structural properties were characterized by microscope. Fig. 4 shows the image of the micro fluxgate sensors.

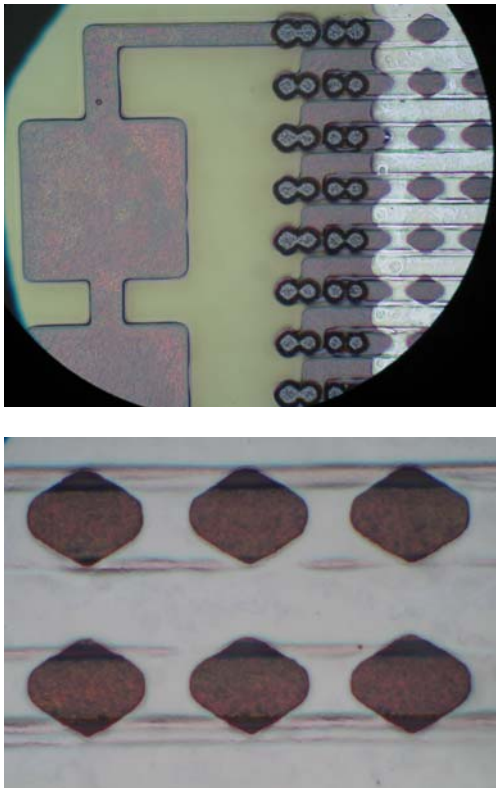


Fig. 4. The image of micro fluxgate sensor with porous core.

From above images observation, the pore shape and distribution of porous thin film has agreement with the design.

The exposure dose can affect the steepness of the cylindrical array structure. In this study, the optimal exposure dose is 400 mJ/cm^2. During soft bake, the conditions of temperature rise and fall are very important. Without heating in two steps, the abrupt temperature rise causes great thermal stress which form some cracks at the PR structure. Part of the cylinders of PR will break. This will affect the uniformity of Fe-Ni thin film. In the SU8 PR development process, mild ultrasonic agitation was used to shorten the procedure.

The electroplate Fe-Ni alloys exhibit the well known anomalous codeposition phenomenon, where preferential deposition of Fe results in a larger Fe content in the deposit, than directly given by the content of Ni and Fe in the electrolyte. The Ni and Fe content as a function of current density is presented in Fig. 5.

The residual stress in the electroplated Fe-Ni films was found to decrease with increasing current density. Typically, stress level of 150-170 MPa was obtained for films deposited at 10.0 mA/mm^2. The current efficiency of the Fe-Ni electroplating processes varied from 60 to 80 %, which is rather low, but in agreement with existing results published on electroplating of Fe-Ni. The current efficiency was found to increase with increasing current density in the investigated region 2.5-10.0 mA/mm^2. The decreasing stress as a function of current density is believed to be related to the increasing current efficiency. At lower current efficiencies secondary cathode reactions, such as evolution of hydrogen may contribute significantly to the formation of stress due to diffusion of hydrogen into the electroplated alloy.

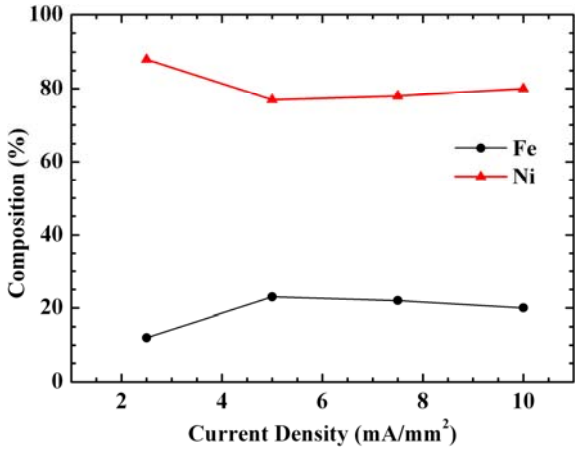


Fig. 5. Composition of Fe-Ni vs. plating current density.

The core materials are analyzed in detail to ensure the performance of the sensors. The composition of the electroplated Fe-Ni permalloy magnetic core is 78 % nickel and 22 % iron as measured by inductively coupled plasma (ICP) spectrometry.

The measured resistance of the excitation and detection coils is 2 Ω and 4 Ω, which agrees with the calculated result, considering connecting conductor lines and electro-deposition defections. In order to test the performance of sensor with porous core, a simple testing system is established which includes function signal generator, power amplifier, and oscilloscope. The solenoid with turns Ns = 1150 and length Ls = 0.3 m has been used to produce the tested dc magnetic field necessary for the sensor characterization which has been calibrated carefully with magnetometer. The tested magnetic field is controlled through the current by a DC power supply. Further, the solenoid and the sensor have been placed inside a magnetic shield.

Excitation frequency is selected as 100 kHz. Sine wave as a conventional excitation waveform is chosen because it leads to high excitation efficiency and a stable signal, while induces low level of high-frequency noise at the detection coils.

To reduce power consumption, less excitation current in excitation coils is always the first choice. Due to magnetic saturation operation principle, relatively high excitation current is required to operate the fluxgate sensor, that leading high power consumption naturally. The sensors have been tested under different excitation currents. The curves of second harmonic output voltage of sensors with different cores are plotted in Fig. 6.

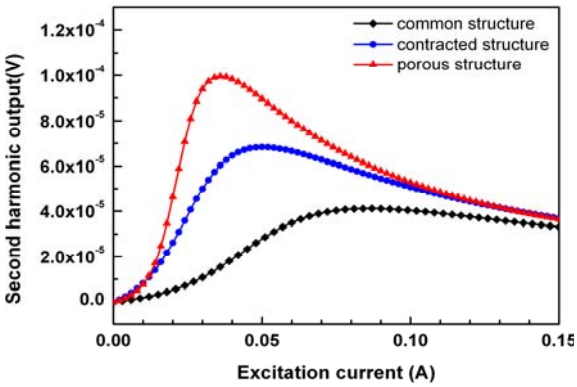


Fig. 6. Contrast of optimum excitation currents of the fluxgates with different cores.

The curves show the relation between the amplitude of the second harmonic voltage in detection coil and the excitation current. The amplitude of the second harmonic voltage varied with the changes of the excitation current in 5 A/m magnetic field.

With elevation of excitation current, the second harmonic voltage first increased to a relatively high peak value and then followed by a decrease.

In the peak of curve, the output sensitivity reach maximum value and the corresponding current is termed optimum excitation current. The smaller the optimum excitation current is, the lower the power consumption will be.

As shown in Fig. 6, the optimum excitation current of porous core is 38 mA, while the values of contract core and common core are 51 mA and 85 mA. Contrasting two results, porous magnetic core decreases the excitation current appreciably.

Fig. 7 exhibits the time variations of output voltages of detection coil under 38 mA Sinusoidal excitation current in 5 A/m magnetic field. As shown in figure, the output voltage of porous core is much higher than that of common structure core excited by the same excitation current.

So this porous core structure can reduce power consumption significantly while increasing output sensitivity. The performances of the fluxgate sensors obtain an overall improvement.

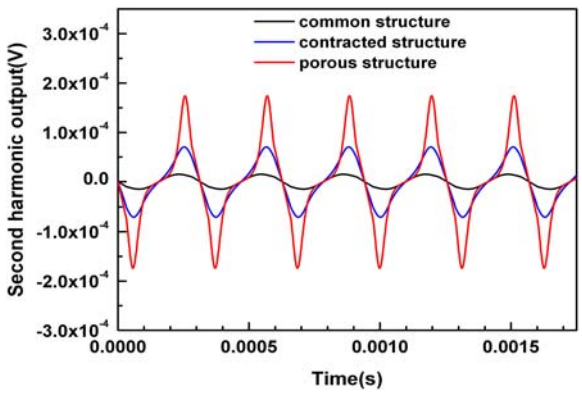


Fig. 7. Output signals of the fluxgates with different cores variation with time.

4. Conclusions

In this study, a novel technique is investigated for the fabrication of micro fluxgate porous with thin film core. Porous Fe-Ni core is fabricated onto the silicon wafer successfully using the MEMS technique. The pore diameter and distribution of core has agreement with the design. In fabrication process, the exposure dose can affect the accuracy of the pattern transfer. And the temperature and time of soft bake is also key influences of good morphology to the thin film core. The experiment result complies with the anticipation and indicates that this structure can be applied to improve the characteristic of micro fluxgate.

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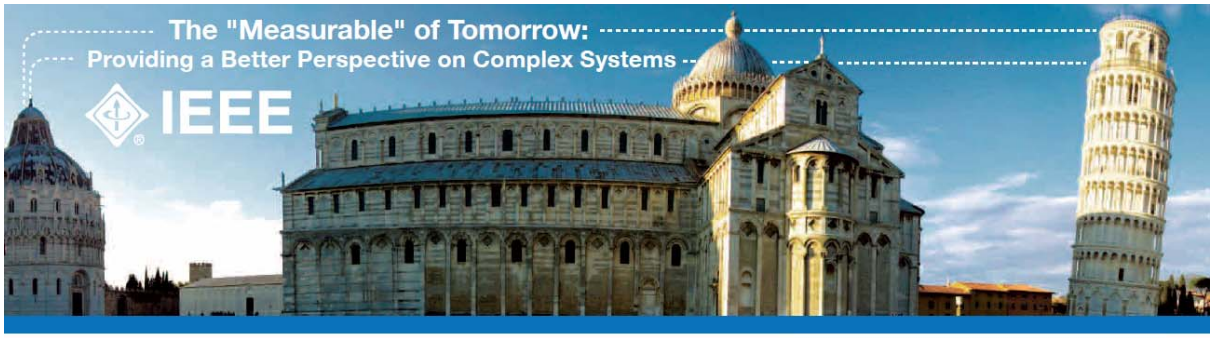
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