Special Issue http://dx.doi.org/10.3786/sincs2011.30

NANO-MICRO LETTERS ARTICLE
www.nmletters.org

(Proceedings of 2011 Shanghai International Nanotechnology Cooperation Symposium, SINCS 2011, Published online 10 January 2012)

Application of Fe-based Nanocrystalline Ribbon in Improving the Performance of MEMS Fluxgate Sensor

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Abstract: In this paper, application of Fe-based nanocrystalline ribbon in fluxgate sensor based on MEMS technology is presented. A fluxgate device with magnetic core made of this material was designed, fabricated and characterized. To evaluate the improving of the magnetic field measuring performance of the device due to this new core material, a fluxgate sensor with the same structure but with permalloy core was fabricated for comparison. Experimental results showed that the fluxgate sensor with Fe-based nanocrystalline ribbon core possess notably higher sensitivity and wider linear operation range. Besides, the power consumption and noise of the sensor was relatively low.

Keywords: Nanomaterial; Nanocrystalline; Magnetic material; Fluxgate sensor; Magnetic sensor

Citation: Jian Lei, Chong Lei and Yong Zhou, "Application of Fe-based Nanocrystalline Ribbon in Improving the Performance of MEMS Fluxgate Sensor", Proceedings of Shanghai International Nanotechnology Cooperation Symposium, 126-130 (2011). http://dx.doi.org/10.3786/sincs2011.30

Introduction

Magnetic field detection and measurement have always been an essential function in many applications for years [1]. One of the most important sensing magnetic sensors is fluxgate magnetic sensor [2-4]. Fluxgate magnetic sensor is expansively used in geophysics, space application and ferromagnetic matter detection. The most crucial component determining the measuring performance of the sensor is the magnetic core.

Generally, fluxgate magnetic core materials are expected to possess high saturation induction density, high permeability and low consumption. In the selection of magnetic core material, permalloy has been used to fabricate fluxgate sensor cores widely for a long time. However,

with the development of information technology and digitalization of electronic equipment, higher demands to magnetic sensor have been raised, such as high frequency, miniaturization and low core loss. Due to poor high-frequency performance and relatively low saturation induction density, permolloy is far from being satisfactory as magnetic core materials of fluxgate sensors developed to meet the new demands mentioned above.

In order to meet the uninterrupted development of fluxgate sensors towards high frequency, miniaturization, light weight and energy-saving, core materials with more brilliant magnetic performance are requested.

Under the background of electronic information industry urgently needing soft magnetic materials having high saturation induction density, high initial permeability, low coervicity, low consumption and thermal stability, nanocrystalline soft magnetic alloys have been developed [5, 6]. Nanocrystalline alloys possess the advantages of many kinds of traditional soft magnetic materials, such as excellent high frequency performance, high permeability, high saturation induction

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density and low consumption. At present, those materials are widely applied in many fields, such as high-power transformer, switch power transformer, choke and so on. Especially as magnetic-sensing materials of sensors, they exhibit brilliant sensing performance and consume very little power. So, they can be better choices to be used in high frequency, energy-saving micro fluxgate sensors.

There are several examples in the literature using nanocrystalline alloy cores as the sensitive material. A fluxgate high-sensitivity magnetic field sensor using a nanocrystalline Fe-Ni-Zr-B alloy core is described in [7]. Stanislaw Moskowicz fabricated a fluxgate sensor with a ring-shaped core made of a nanocrystalline material of composition $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ [8]. And a fluxgate sensor using a nanocrystalline fluxgate core with transverse anisotropy is presented in [9].

According to chemical composition, nanocrystalline alloys are categorized mainly into Fe-based, Fe-Ni-based and Co-based nanocrytalline alloys. In consideration of performance and price, Fe-based nanocrystalline alloys have more extensive application than others. Thus, in this work, a micro fluxgate sensor with Fe-based nanocrystalline alloy core was fabricated and characterized for illustrating the brilliant magnetic properties of the alloys in magnetic sensors. Gluing and chemical wet etching were adopted in the fabrication of the rectangular ring-shaped Fe-based nanocrystalline alloy magnetic core. To evaluate the improving of the magnetic field measuring performance of the sensor due to this new core material, a fluxgate sensor with the same structure but with permalloy core was fabricated for comparison.

Design and Fabrication

In this work, the Fe-based nanocrystalline magnetic core was designed in the shape of a rectangular ring. The long sides and the short sides of the rectangular ring are 3750 μm and 2830 μm, respectively. Every side of the ring is 600 μm in width. Three-dimensional solenoid coils were electroplated copper winding around the sides of the rectangular core as excitation and sensing elements of the sensor. And the sensing coil was placed perpendicular to the two excitation coils and between them. Each excitation coil has 21 turns and the sensing coil has 46 turns. Both the lines of coils and the spacing between the lines are 40 μm in width. And the thickness of the copper lines is 30 μm. Four copper pads with the size of 1 mm×1 mm were included in the sensor for connection between coils and interface circuits. The dimension of the whole sensor was 6.25 mm×6 mm×130 μm.

Figure 1 shows process flow developed for the fabrication of the fluxgate sensor. The fabrication of the fluxgate sensor started with sputtering a seed layer of 100 nm on the wafer, as shown in Fig. 1(a). Then a photoresist layer of 30 μm was spun and patterned by thick photoresist-based UV-lithography for electroplating the bottom conductors of the coils. After electroplating copper in the photoresist model, another photoresist model was made on the wafer and copper was electroplated in it as the vertical conductors of the coils. Then the photoresist and seed layer were removed. To

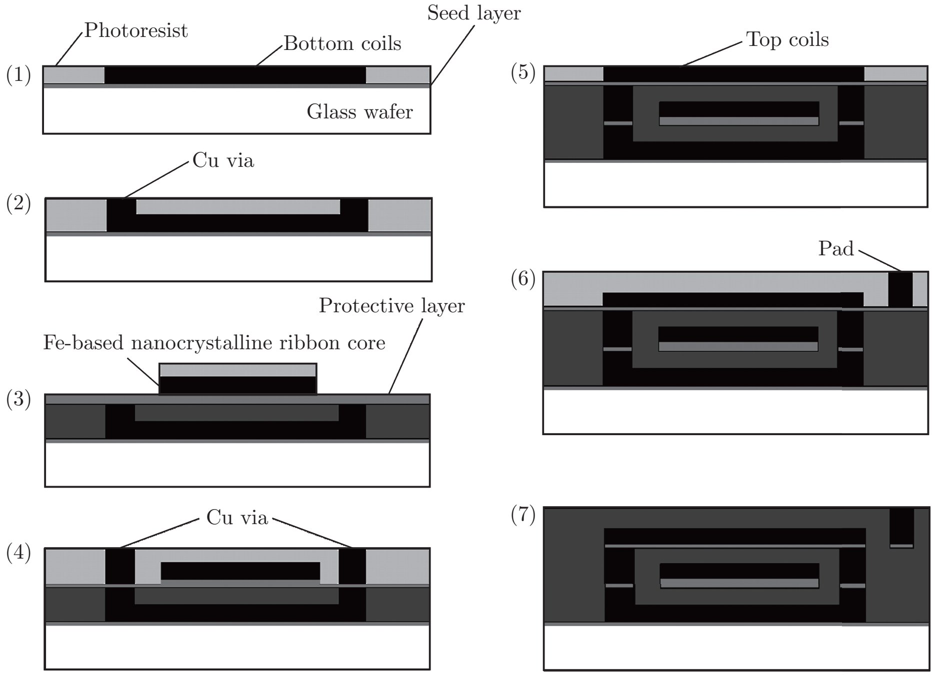

Fig. 1 Fabrication steps of the micro fluxgate sensor with Fe-based nanocrystalline alloy core.

improve the impact resistance of the sensor, polyimide with a thickness same as conductors was spun on the wafer and a hard curing step was executed to it at 250℃ for 2 h in low vacuum. Besides providing protection, polyimide also acted as the electronic insulating material between the coils and the core.

Due to the present processing technology of nanocrystalline alloy, how to fabricate a nanocrystalline core with needed size is often a difficult problem to solve. Hence, gluing and chemical wet etching were adopted in the fabrication of the Fe-based nanocrystalline magnetic core. And the Fe-based nanocrystalline material used in this work was obtained by annealing a Fe-based amorphous alloy ribbon that was acquired by purchase. The magnetic properties of this material was characterized by . . . and was compared with that of permalloy as shown in Fig. 2. The annealed ribbon was cut into pieces smaller than the wafer. Before gluing the ribbon, a titanium barrier layer of 300 nm was needed to protect the completed parts of the sensor from being damaged by the following chemical wet etching process. Then a piece of Fe-based nanocrystalline alloy ribbon was glued on the barrier layer with 5 μm epoxy resin layer and was pressed under a weight for 1 hour. For patterning the magnetic core, a photoresist model was made on the surface of the ribbon. Then the magnetic core was fabricated by chemical wet etching.

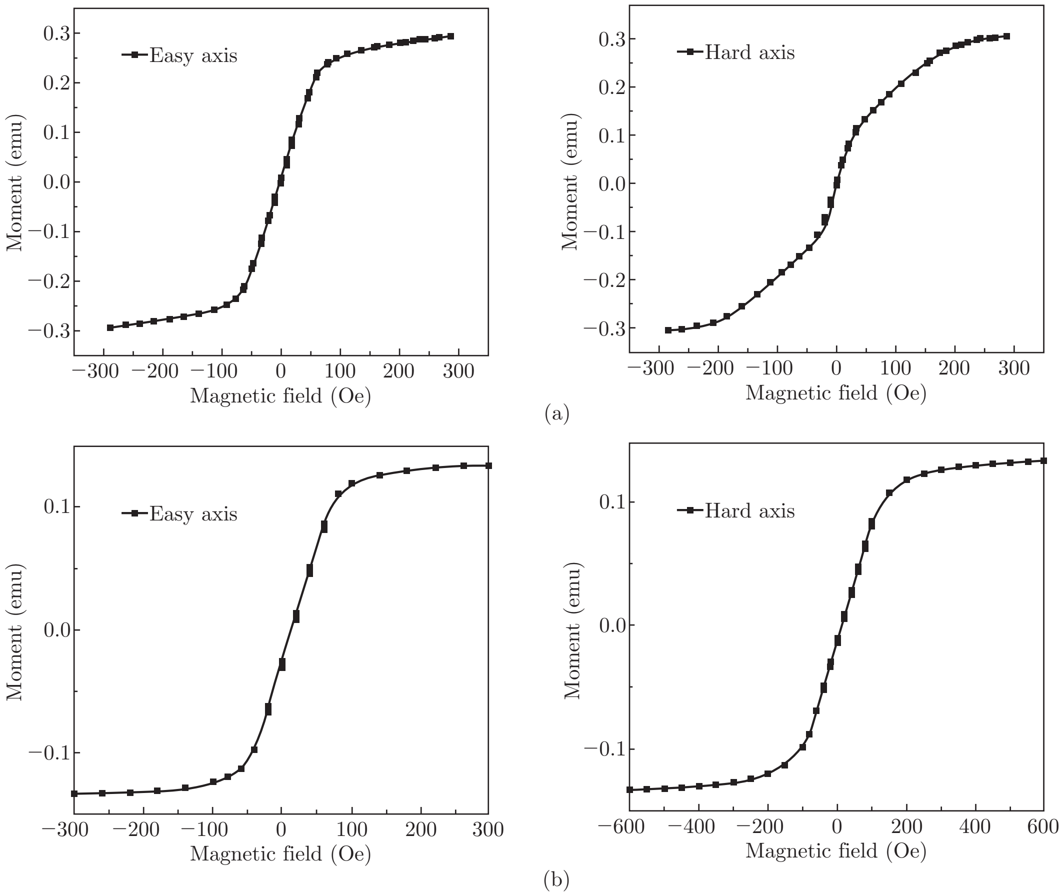

Fig. 2 (a) B-H loop of the Fe-based nanocrystalline alloy; (b) B-H loop of the permalloy.

Following the fabrication of the core, epoxy resin was eliminated by a plasma stripper and the barrier layer was removed by reactive ion etching. Then a photoresist layer was spun and patterned for electroplating the vias thicker than the core height. After electroplating the vias, the photoresist was removed and another polyimide process was performed. Using the same processes, the fabrication of the sensor ended with electroplating the top conductors. Fig. 3 shows the photograph of the fabricated fluxgate sensor with Fe-based nanocrystalline alloy core.

Testing of the sensor

To characterize the two kinds of the fluxgate sensors, a simple magnetic field measuring system based on second harmonic operation principle was established to characterize the two kinds of fluxgate sensors. The measuring system consists of excitation and sensing circuits, as shown in Fig. 4 and Fig. 5. The design of the excitation circuits must ensure that magnetic core is working in deep saturation state. Since the power of the signals provided by the function generator used as excitation source was too small to drive the fluxgate sensor, a power amplifier was needed. With the power amplifier, 100 kHz sine waveform currents with different rms values were provided to drive the excitation coils in the tests.

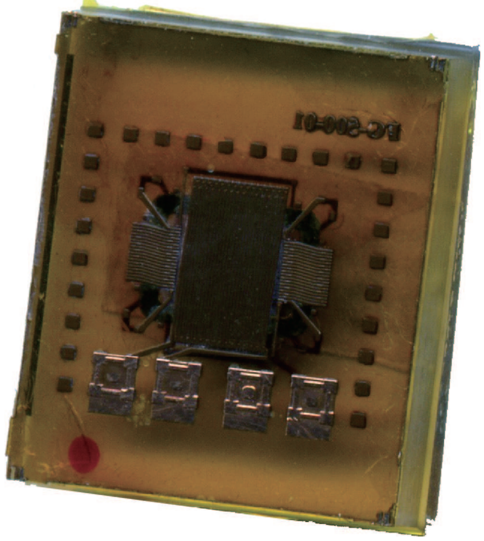

Fig. 3 Photograph of the fluxgate sensor.

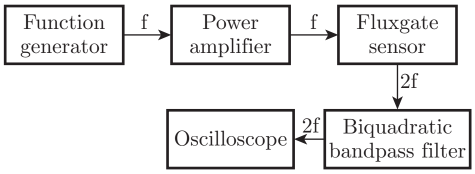

Fig. 4 Block diagram of the testing system.

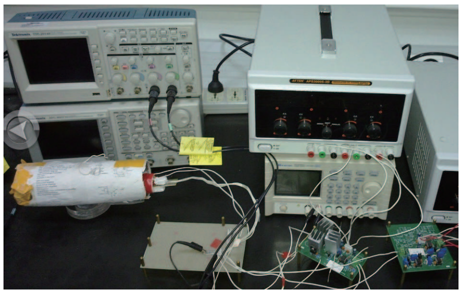

Fig. 5 Block diagram of the testing system.

According to fluxgate principle, when the fluxgate sensor is driven by a sine wave signal, second harmonic signal indicating the intensity of the magnetic field under test is generated in the sensing coil of the fluxgate sensor. With the second harmonic signal, however, some worthless signals with different frequencies adversely affecting the measuring results are output from the sensor, simultaneously. And this noise problem is very difficult to avoid only by improving the structure of the fluxgate sensor. Thus, the sensing circuits should have the function of picking out the second harmonic signal from the output of the fluxgate sensor effectively. So a biquadratic band pass filter with center frequency of 200 kHz was adopted to process the output signals of the sensing coil in the experiment. The test results were observed by an oscilloscope.

Figure 6(a) shows the curves representing the relationship between output signals and external magnetic field under different excitation currents for fluxgate sensor with Fe-based nanocrystalline ribbon core. The curves representing the sensitivity of the sensor with permalloy core was displayed in Fig. 6(b) for comparison. And Fig. 6(c) shows the comparison of the maximum sensitivity curves of the two sensors.

We can obtain from Fig. 6 that the maximum sensitivity of 653.38 V/T in the linear range of $-400\ \mu$T to $+400\ \mu$T was achieved for the sensor with nanocrystalline core when the excitation rms current was 120 mA, and that the maximum sensitivity of 172.49 V/T in the linear range of $-600\ \mu$T to $+600\ \mu$T was achieved for the one with permalloy core when the excitation rms current was 220 mA. The serial resistance of the excitation coils is around 1.7 Ω for each fluxgate sensor. Through calculation, to achieve the maximum sensitivity, the consumption of the sensor with nanocrystalline alloy core was 24.48 mW and that of the other sensor was 82.28 mW. And the noise power density of the former was 2.48 nT $/\mathrm{Hz}^{0.5}$@1Hz.

The experimental results showed that, with the same sizes and the same structures, the sensor with the nanocrystalline alloy core possesses much higher sensitivity than the one with permalloy core, while consuming less power. In other words, Fe-based nanocrystalline alloys are more advantageous as magnetic cores of fluxgate sensors than permalloy in device miniaturization and energy saving.

Conclusion

In this work, two fluxgate sensors with the same structures but with magnetic cores made by different soft magnetic materials were fabricated and characterized to evaluate the improving of the magnetic field measuring performance of the device due to Fe-based nanocrystalline alloy core. Gluing nanocrystalline alloy ribbon and chemical wet etching were adopted in the fabrication of the rectangular ring-shaped Fe-based nanocrystalline magnetic core, which solve the difficulty in the processing of nanocrystalline alloys innovatively. As the excitation frequency was 100 kHz and the excitation current was 120mA, the maximum sensitivity of 653.38 V/T in the linear range of -400 μT to +400 μT was achieved for the sensor with Fe-based nanocrystalline alloy core.

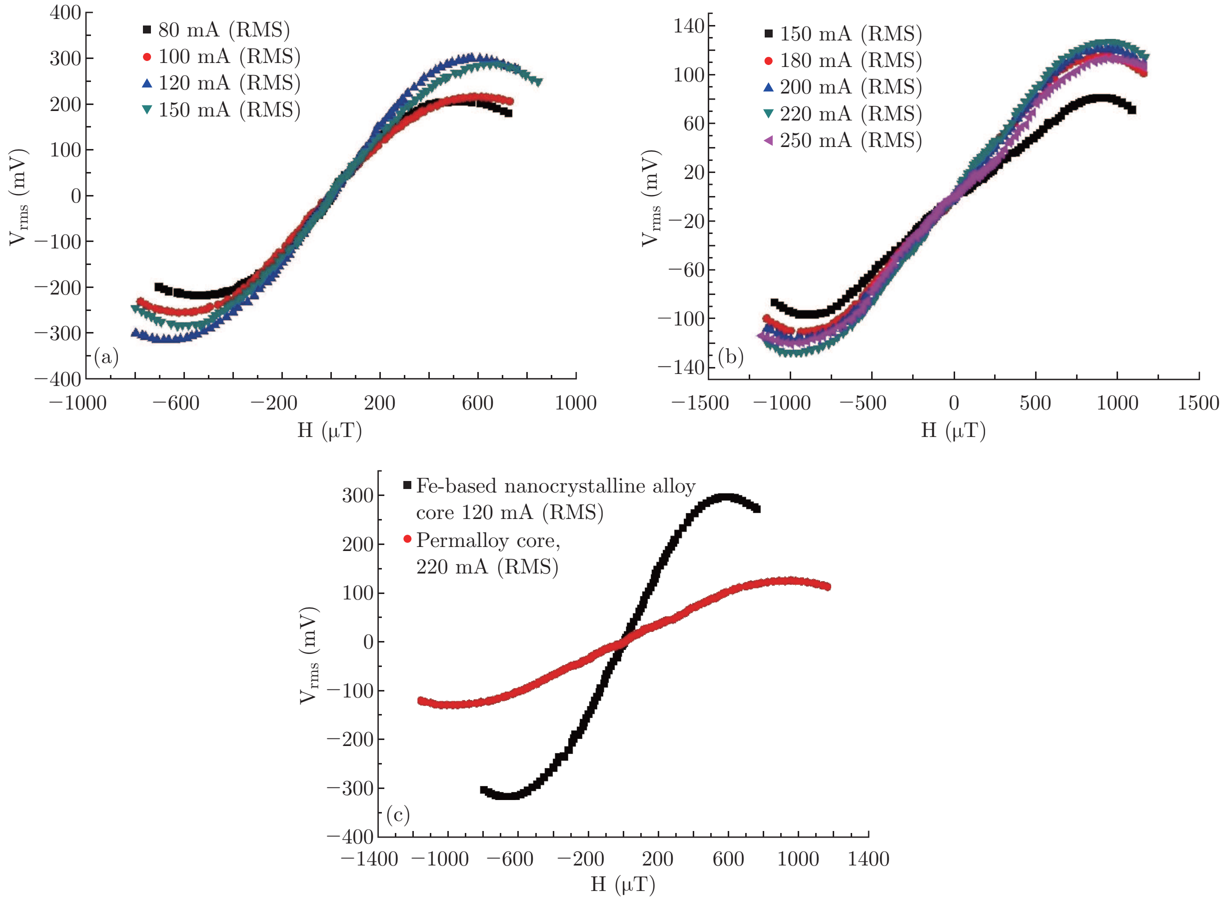

Fig. 6 (a) The sensitivity curves of the fluxgate sensor with Fe-based nanocrystalline alloy core; (b) The sensitivity of the fluxgate sensor with permalloy core; (c) The comparison of the maximum sensitivity curve of the two fluxgate sensors.

As we expected, the use of Fe-based nanocrystalline alloys as magnetic core greatly enhances the sensitivity of the fluxgate sensor, and decrease the consumption, which was due entirely to the excellent magnetic properties of this material. So, nanocrystalline alloys can be expected to be used to improve the measuring capabilities of some other magnetic sensors that need magnetic-sensing materials with high permeability, high saturation induction density and low consumption [10].

Acknowledgments

This work was supported by Basic Research Program of Science & Technology Committee of Shanghai (09JC1408600), The National Natural Science Foundation of China (No. 61074168), No-Silicon Precision Micromaching & Microfabrication Technology (D2320060098), State Key development Program of Basic Research of China (2010CB933901).

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