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Fabrication and characterization of a new MEMS fluxgate sensor with nanocrystalline magnetic core

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ABSTRACT

This paper presents a new MEMS fluxgate sensor with a Fe-based nanocrystalline ribbon magnetic core and 3D micro-solenoid coils. The excitation coils were placed vertically to the sensing coil on the chip plane. Second harmonic operation principle was adopted in this fluxgate sensor. The total size of the fluxgate sensor was 6.25 mm × 4.85 mm × 120 µm. A simple testing system was established to characterize the fabricated devices. A band pass filter was used to pick up the second harmonic signals in the sensing coils. When excitation rms current of 120 mA and the operational frequency of 200 kHz were selected for the testing of the fabricated devices, the sensitivity of the developed fluxgate sensor was 1005 *V*/*T* in the linear range of −500 µT to +500 µT. Due to the combination of the 3D structure coils with the nanocrystalline core, relatively low sensor noise was achieved. The noise power density was 544 pT/Hz$^{0.5}$@1 Hz and the noise rms level was 9.68 nT in the frequency range of 25 mHz–10 Hz.

1. Introduction

Magnetic field detection and measurement has always been an essential function in many applications for years [1]. One of the most important magnetic sensing techniques is the use of the fluxgate principle [2–4]. In term of resolution of the sensor, fluxgate sensor is better than the other solid-state devices such as Hall effect and magnetostrictive sensors, and is comparable to ultrahigh sensitive but very expensive quantum-effect SQUIDs [5,6].

In recent years, there has been an urgent demand for miniature fluxgate sensors in many application fields. Miniature fluxgate sensors utilizing PCB or MEMS technology have several advantages such as small size, light weight, low cost, higher resolution and integration of the supporting electronic circuitry. Consequently, they can be applied in a series of new field such as small satellite position and attitude control, small portable GPS positioning equipment and inertial-guided missiles.

However, when the dimensions of the device decrease, the sensitivity of the sensor decreases and its noise increases [6], which limit the application of the MEMS fluxgate sensor. The application field of MEMS fluxgate sensor can be largely extended by promoting the resolution of the sensor.

Comparing with traditional magnetic core materials, such as permalloy and ferrite, amorphous alloy possesses higher permeability which will lead to larger inductance. Moreover, superior high frequency performance makes it possible for the sensor to operate in the high frequency conditions. Besides, higher resistivity can reduce the eddy current losses. So, using a fluxgate core made of amorphous alloys can further improve the sensitivity of the input–output characteristics. There are several examples in the literature using amorphous cores as the sensitive material. A compact 2D planar fluxgate sensor using a ferromagnetic amorphous metal core is described in [7]. Perez

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and Aroca et al. presented a fluxgate sensor based on PCB technology with an electrodeposited amorphous core [8].

The resolution of fluxgate sensor is affected by its noise, so decreasing the noise is the key to improve the performance of fluxgate sensor and to widen its application fields. In comparison with planar fluxgate sensor fabrication, that of 3D fluxgate sensor is more complicated because a 3D coil needs to be formed in the several planes respectively rather than a single plane. But 3D fluxgate sensors have smaller dimension and lower noise due to its solenoid coils ideally coupled with the core. So, fluxgate sensors with 3D structure are better choices than those with planar structure. Thus, 3D fluxgate sensors are attracting the attention of the researchers in the field. Some micro-fluxgate magnetic sensors composed of rectangular-ring or racetrack shaped magnetic core and solenoid coils for excitation and sensing elements was designed, fabricated and characterized [1,9,10]. A micro-fluxgate sensor using cascaded planar FeNi ring cores and a single excitation rod passing through the middle of the ring structures is described in [11].

In order to develop a new kind of fluxgate sensor with higher performance, we presented a fluxgate sensor which had a rectangle Fe-based amorphous nanocrystalline ribbon as magnetic core and simultaneously 3D solenoid coils as excitation and sensing elements on the basis of summarizing and perfecting the experiences above. The dimension of the fluxgate sensor was 6.25 mm × 4.85 mm × 120 μm, including 1 mm × 1 mm pads. Sine wave excitation current with a frequency of 200 kHz was selected in characterizing the fluxgate sensor.

2. Fabrication

The most critical element is the soft magnetic core material of which the sensor magnetic core was made. Fe-based nanocrystalline ribbon is selected as the core material of the fluxgate sensor. Fe-based nanocrystalline ribbon possesses high permeability so that the excitation current can be reduced. Moreover, high permeability can lead large inductance and high resistivity can reduce eddy current losses. So, using a Fe-based nanocrystalline ribbon as a magnetic material can further improve the sensitivity of the input–output characteristics. Fig. 1 shows the *B*–*H* loop of the Fe-based nanocrystalline ribbon core as measured by VSM.

In this work chemical wet etching was used for fabricating the magnetic core. Thick photoresist-based UV lithography and electroplating technique were adopted in the fabrication of 3D solenoid coils. Copper is selected as the material of which coils were made. The fabrication steps of the fluxgate sensor are summarized in Fig. 2. Fig. 3 shows the top view and the cross section of the fluxgate sensor.

At first, the bottom copper conductors were fabricated. The process was started with a glass wafer on the top of which chromium/copper seed layer was deposited. Then the molds with thick photoresist were made with photolithography for electroplating the bottom copper conductors. The thickness of the spun photoresist depended on the needed thickness of electroplated copper conductors. In our design, the thickness of the bottom copper conductors was 20 μm. Using electroplating techniques, copper conductors were electroplated in the molds. Likewise, vias and top conductors of the device were fabricated by the same processes as above.

After the bottom conductors were made, copper vias with a cross section of 50 μm × 50 μm and a thickness of 20 μm were created. Then the seed layer was removed by reactive ion etching. Polyimide was used to electrically insulate copper conductors and magnetic core, and to support the upper layers. It was spun on the wafer with a thickness same as the vias.

Spinning the photoresist on the top of electroplated copper conductors often leads to a nonuniform surface. This will affect the photolithography for the upper layers. Thus a hard curing step for polyimide was performed at 250 °C for 2 h in low vacuum. Then we performed a polishing process to the polyimide to acquire a uniform surface. After polishing process, the vias were exposed out so that bottom conductors and top conductors could be well interconnected with the vias.

After polishing process, 300 nm titanium protective layer was deposited for protecting the vias from being damaged by the following chemical wet etching processes. 20 μm Fe-based nanocrystalline ribbon was glued on the surface of the titanium protective layer with 5 μm epoxy

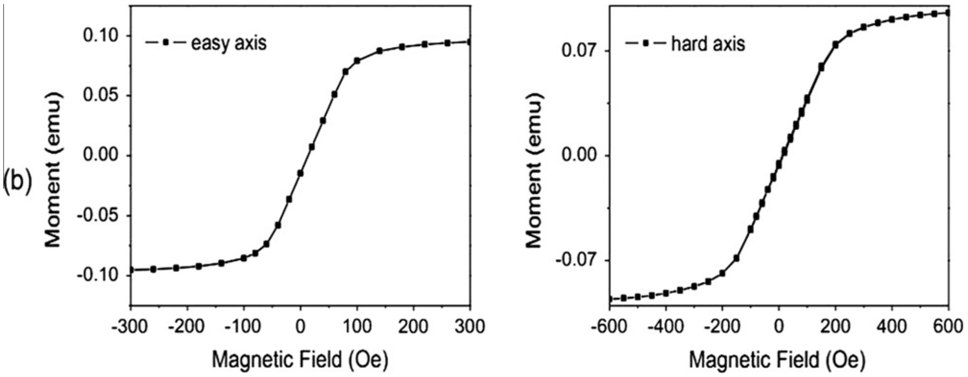

Fig. 1. *B*–*H* loop of the Fe-based nanocrystalline ribbon core.