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Exchange biased spin valve-based gating flux sensor

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ABSTRACT

A hybrid type of magnetic sensor, combining the advantages of both fluxgate sensors and giant magnetoresistance sensors (GMR), was developed in this work by applying the fluxgate principle into the GMR sensors. The well-known measuring principle of the fluxgate sensor is based on the offset of the hysteresis curve and the second harmonic characteristic using the phase sensitive detection technique. The GMR spin valve was used as the soft magnetic core and the pickup coil of the fluxgate. Based on the harmonic analysis using Fourier series, the second harmonic component of the hybrid GMR-fluxgate sensor output was found to be dominated. The sensitivity of the device was maximized by turning the amplitude and the phase of the sinusoidal excitation current. The obtained sensitivity was 1.52 mV/mT and the field noise was found to be 5.7 nT/√Hz@1Hz. The non-hysteresis of the transfer *V-B* curve was achieved, and the nonlinearity was about 2.5% within the operation range of ± 0.2 mT. The proposed sensor is an appropriate design for low field measurements and geomagnetic applications.

1. Introduction

Nowadays, the development of magnetic sensors has pursued an advanced manufacturing technique for the extension of magnetic sensor applications. Such an advanced technique that must be used to enhance the sensor resolution, reduce the sensor size, and save the energy, extend the bandwidth, lessen the production cost, etc. [1,2]. The magnetic sensors have been developed based on many kinds of effects, such as Hall effect [3], gating flux effect (fluxgate) [4,5], anisotropic magnetoresistance effect (AMR) [6], giant magnetoresistance effect (GMR) [7–9], tunnel magnetoresistance effect (TMR) [10], and so on. Although the fluxgate sensors were developed from the 1930 s, fluxgate sensor is still being considered as an ideal sensor in terms of the ultra-high sensitivity, low noise, small hysteresis, and high linearity [5]. There are many kinds of fluxgate sensors that have been developed, e.g. parallel fluxgate [11,12], orthogonal fluxgate [13], and core-less fluxgate [14,15]. In spite of these invented fluxgate sensors were manufactured using the advanced technology as CMOS-MEMS for miniature sensors, where some advantage properties of miniature fluxgate would be disappeared, i.e. low sensitivity, high noise, and high power consumption [16,17]. A potential approaching technique to solve these problems mentioned so far was the combining advantages of both the fluxgate and magnetoresistance (MR) sensors. Such a concept MR-fluxgate based on AMR effect was proposed by Dimitropoulos and et al. [18]. Its advantages were the reduction of the repeatability, improvement of the time-drift of AMR, and the temperature stability, which are the crucial criteria for the weak magnetic field, linear, and geomagnetic measurements [1]. These errors arise owing to the manmade structure of spin valves, which are synthesized by the multilayer of the functional metals including ferromagnetic (FM), non-magnetic (NM) and antiferromagnetic (AFM) materials [19]. The hysteresis of the spin valve is induced owing to the magnetic domain formation of the FM single domain layer and the interlayer coupling between each FM layers [20]. Furthermore, the shift of the operation point caused by coupling between the pinned and free layers also affects to the repeatability, time-drift, and the symmetrical polarity measurement [21,22], however, they could be well controlled by the ac-driven and constant magnetic bias techniques [6,7,23]. The temperature stability mainly depends on the properties of AFM layer materials. The MR behavior is disappeared at above Néel temperature of AFM layer [24]. Besides, the spin valve cell is patterned into a resistive bar so that its performance also depends on the thermal noise. The solutions to improve the temperature stability are the employment of the Wheatstone bridge configuration [25] and optimization of the shape, size, and aspect ratio of the sensing spin valve cells [26]. In the same year 2003, Dimitropoulos and et al. also reported another design that mentioned to both spin valve and AMR sensors. However, their obtained experimental results have only presented with AMR sensor [27]. Another invention was the TMR-fluxgate sensor that applied the working principle of fluxgate into TMR sensor. Its results showed that their device could be used to measure low-

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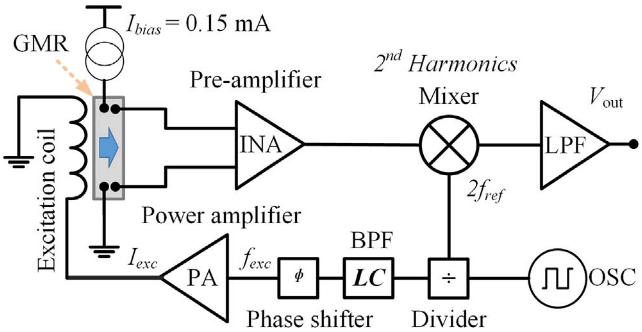

Fig. 1. Block diagram of the hybrid GMR-fluxgate sensor.

frequency magnetic field, but the noise level was not given [28]. Nonetheless, the TMR fabrication is very complicated in the barrier layer, and requirement of high-end equipment and advanced patterning technology. Among MR sensors, the GMR is relevant a simple energized sensor, robustness, low manufacturing cost and batch processes [26]. The resolution of GMR sensor can be used in a range of μT [6]. However, the limitations of GMR are nonlinear, hysteresis and noise at low-frequency [23,29]. Therefore, in this study, a GMR-fluxgate sensor was proposed to achieve both the advantages of fluxgate and GMR sensors. The transducer circuit was designed and implemented. The harmonic characteristics of the GMR-fluxgate sensor response were analyzed by Fourier series. The sensitivity and noise were also presented and discussed.

2. Experimental details

2.1. Working principle

Fig. 1 shows the block diagram of the measurement setup for the GMR-fluxgate sensor. The well-known working principle of a fluxgate sensors is based on the shift of the hysteresis curve of the magnetic core integrated inside fluxgate sensors. The core is periodically saturated in both the polarities by the excitation current, which passes through the excitation coil. The excitation current can be generated using a function generator or an oscillation source. The voltage of the pickup coil is induced by gating flux effect. Since gating event occurs twice in one cycle of the excitation signal so that the response of the fluxgate is detected in the second harmonic mode. Hence, the reference signal of a phase sensitive detector (PSD) is in double frequency to the excitation signal. The mixer multiplies the induced voltage of the pickup coil and the reference signal to retrieve the response of the fluxgate. Finally, a low pass filter extracts the dc voltage component, which is proportional to the measured external magnetic field. In this report, a new kind of hybrid magnetic sensor combining GMR spin valve and fluxgate sensors was proposed. The roles of the GMR spin valve were not only a pickup coil but also a soft magnetic core of fluxgate sensors. As the general fluxgate principle was carried out on the GMR spin valve so that a common measurement setup was similar.

Fig. 2 shows of how the hybrid GMR-Fluxgate sensor induce a second harmonic output. To illustrate the working principle of the proposed sensors, suppose, a sinusoidal excitation signal is used. In the first case, without an external magnetic field ($\boldsymbol{B}_{\mathrm{ext}} = 0$), the output of the sensor is symmetric, as shown in Fig. 2(a). The output is induced by the response of free layer to the excitation ($\boldsymbol{B}_{\mathrm{exc}}$) and external magnetic fields ($\boldsymbol{B}_{\mathrm{ext}}$). In the unbalanced cases, which are depicted in Fig. 2(b) and (c), the outputs of the sensor are shifted by the influence of an external magnetic field offset ($\boldsymbol{B}_{\mathrm{ext}} \neq 0$). The distortion of the output attributed by $\boldsymbol{B}_{\mathrm{ext}}$ that promotes the second harmonic component, which is proportional to the $\boldsymbol{B}_{\mathrm{ext}}$.

2.2. Sensor construction

The GMR sensor, in this work, was a single cell with the active area of 1.5 μm × 150 μm, while the cutting size of the GMR chip was 1.5 mm × 2.5 mm. The GMR chip was attached and connected on a printed circuit board (PCB) by aluminum wire bonding machine. The spin valve film was fabricated by RF magnetron sputtering method, with a typical spin valve structure of [Si/SiO_2]/Ta 30 Å/NiFe 30 Å/Co 10 Å/Cu 25 Å/CoFe 20 Å/IrMn 70 Å/Ta 100 Å. The magnetoresistance (MR) of the GMR films was about 6%, and the operation point was shifted of 2 mT owing to Néel biasing that is caused by the coupling between the antiferromagnetic layer and free layer [30]. The bias current was set at a small value of 0.15 mA to lessen the power consumption. The bias current could be tuned by a current source circuit using a transistor BC447, as shown in Fig. 3. The pinned axis of the active cell was defined by a post-field annealing process with an applied magnetic field along the short dimension of the patterned GMR cell. The excitation coil was formed by wrapping transversely copper wires around the pinned axis of the GMR. The copper wire had the diameter of 0.16 mm, and the number of turns was 300. The excitation coil generated the modulation field around the GMR cell. The strength of the modulated field is strong enough to saturate the free layer of the GMR cell but smaller than the limitation of the exchange bias value to ensure the spin valve be oscillating in working range [31,32]. The exchange bias of the sheet films was about 50 mT, and the coercivity of the free layer was about 0.8 mT. A macro flux concentrator was used to amplify the flux density around spin valve cell by cutting soft Co-based magnetic ribbon, which is the commercial material Metglas2714A. With the flux concentrator, the sensitivity was enhanced. The modulated magnetic field induced by excitation coil switched periodically the GMR between high and low magnetoresistance states.

2.3. Design of driving circuit

Fig. 3 shows the designed driving circuit of the GMR-fluxgate consisting of two parts; the first part was an excitation circuit and the second one is a readout chain. The circuit was designed by Eagle software and implemented on double side PCB. To measure the response voltage of GMR-Fluxgate, a 2 Mhz crystal OSC was used as a source of the excitation signal. Since the studied excitation for an ac-driven GMR is around 1 kHz to the several kHz [33]. In addition, the excitation frequency is limited by the bandwidth of the excitation coil. The bandwidth of the coil in work is about 5 kHz with an attenuation of the amplitude is −3 dB. Thus, the excitation of 1 kHz was used to ensure there is no effect on the bandwidth to the response of the sensor. Furthermore, with 1 kHz of the excitation signal, the noise of the MR sensors has been significantly reduced [10,34]. Therefore, the oscillating signal of the OSC must be divided using two counters IC (CD4024 × 2). An approximate 1 kHz (0.976 kHz) square excitation signal was converted to a sine wave by a bandpass filter (BPF) using an appropriate LC circuits. To maximize the sensitivity of the modulation voltage, the phase of the excitation signal was tuned by an analog phase shifter (OP37G). A 0.1 μF capacitor was inserted after the phase shifter to remove the DC level. Finally, the sinewave was amplified via a summing power amplifier (OPA551) in order to induce an enough excitation current and an additional DC field component for biasing operation point of the spin valve. The DC level was adjusted by turning the 2 kΩ potentiometer (offset-exc) in the circuit. The AC component was about 20 mA (4 mT) and the DC level for the biasing operation point was 10 mA (2 mT). The I_{exc} has to be controlled by the fact that if the I_{exc} generates B_{exc} is smaller than the magnetization reversal field (unsaturation), the response output of the sensor is similar to the case of $B_{\mathrm{ext}} = 0$, as depicted in Fig. 2(a). Resultantly, the second harmonic component is not enhanced. On the other hand, if the B_{exc} is higher than the field of the magnetization reversal of the spin valve, it means that the sensor is completely saturated so that the sensor does not response