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# Resolution enhancement in measuring low-frequency magnetic field of tunnel magnetoresistance sensors with AC-bias polarity technique

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ABSTRACT

The noise analysis is an indispensable investigation to find out the appropriate solutions for the enhancing resolution in the magnetic sensor developments. Especially, the tunneling magnetoresistance (TMR) sensor, which is one type of resistive sensors, is a promising candidate for biomedical applications and security detections. However, these applications have the magnetic field radiations in the dc or very low-frequency regimes, where the low-frequency noise (1/*f* noise) component is dominant. To suppress the 1/*f* noise, an AC-bias circuit for TMR-bridge sensor was investigated and implemented. The obtained experimental results and designed driving circuit showed a significant reduction of the 1/*f* noise. The intrinsic noise of TMR2102 sensor at 1 Hz (~9 nT/√Hz@1Hz) was eliminated by a factor of 5. By applying the AC-bias technique the field noise level was reduced down to ~1.7 nT/√Hz@1Hz. The angular response of the TMR sensor using the proposed read-out circuit was also demonstrated in the measuring Earth magnetic field with a magnetic deviation was less than 0.1 µT. The TMR bridge sensor driven by an AC biased voltage is a promising approach for lessening the noise disturbances. Especially, it is the 1/*f* noise component in the weak magnetic field measurements. The proposed circuit could be applied for improving the resolution of the other resistive sensor types in the measuring low-frequency applications, such as strain gauges, load cells, and pressure sensors.

## 1. Introduction

Over the last two decades, tunnel magnetoresistance (TMR) sensors have shown their crucial contributions in the life and technology with various advantages, such as high sensitivity, low cost, and high magnetoresistance value [1,2]. A theoretical estimation of TMR ratio was about thousands of percentage [3,4], and verified by an experiment that TMR ratio could be reached to over six hundred percent at room temperature and over 1000% at 5 K [5]. The TMR sensor is the most promising candidate for the development of the ultrasensitive magnetometers to detect extremely weak magnetic fields, such as biomedical applications, biosensors [6,7] and biomedical images [8,9]. However, on the itinerary to transferring the TMR to these applications, a weakness of TMR sensor is the high 1/*f* noise that arises in the low-frequency region, where the above applications are subjected. The 1/*f* noise limits the resolution of TMR in the measuring dc or low-frequency regime. Various efforts to eliminate 1/*f* noise including both intrinsic and extrinsic interventions have been introduced. For examples, the intrinsic approaches were including the optimization of the free layer (FL) thickness [10,11] or control the saturation field of the FL [11–13], the improvement of the crystalline quality of FL and the presence of ferromagnetic-ferromagnetic exchange coupling benefited a high sensitivity and low noise in the TMR sensors [14], the enhancing thermal stability of ferromagnetic layers, the field annealing temperature and improving quality of the barrier layer also helped in reducing the 1/*f* noise in TMR sensors [15,16]. However, the intrinsic strategies face the limitations of the critical thicknesses in the TMR structures and the contaminations in nanoscale fabrications. Alternatively, the extrinsic manners consisted of the improvements of the resolution by either series or parallel patterning TMR elements [17,18], the integrations of microelectromechanical (MEMs) flux concentrators (FC) [19–22], and magnetic chopping techniques [23–26]. However, the drawbacks of the extrinsic approaches were the requirements of the moving MEMs parts, e.g., FC MEMs flaps, soft magnetic cantilever or the soft magnetic shielding materials. Furthermore, the soft magnetic materials faced the danger of the saturation, itself hysteresis, and low efficiency [27]. The aims of these extrinsic techniques mentioned so far were actually to oscillate the soft magnetic cantilevers MEMs or switches on/off the permeability of the soft magnetic FC for modulating the magnetic field that exposed to the sensors. The MEMs parts were made from the soft magnetic materials combining with the piezoelectric materials in either comb-shaped FC flaps or micro-cantilevers. The TMR sensors were

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placed in the center of two FC flaps or right below the micro-cantilevers. Both of MEM flaps and cantilever were driven into oscillation by an AC voltage, while the TMR sensor was powered by a DC voltage. The external magnetic field exposed to the TMR sensor would be concentrated at high frequency leading to the operation point of sensor shifted to the high-frequency regime, where was existing only the white noise. In the modulation techniques, the free layer of TMR sensor was saturated and modulated synchronously with the excitation frequency leading to the output of TMR sensor responds similarly to the excitation waveform [28]. In the case without an external magnetic field, the response of TMR sensor was symmetric. When an external magnetic field was applied, the response curve of TMR sensor would be moved to either positive or negative direction depending on the sign of the external magnetic field. The movement of the response curve from the unsaturated state to the saturated state of the FL of the TMR induced the even harmonic components. Especially, the second harmonic was dominant. By using the phase sensitive detection technique at second harmonic mode, the measuring signal could be retrieved with an extremely low noise. It showed that the operation point of TMR was also moved to the high-frequency regime leading to reduced $1/f$ noise. This method was similar to the working principle of a typical fluxgate sensor [26]. Anyhow, in the FC magnetic modulation, the additional MEMs parts must be incorporated and the complicate manufacture leading to a high production cost and large size. This work proposed a method that there were no external MEM parts incorporating with the TMR sensor. Only a single TMR bridge sensor that was powered using an AC-bias polarity circuit. In this way, the polarities of TMR-bridge were also modulated synchronously to the excitation signal resulting in the operation point of the TMR sensor was shifted to a high-frequency regime above the $1/f$ noise corner. The derivation of the proposed technique is interpreted in details in Section 3. In general, the working principle of the proposed technique is similar to the FC modulations for the lessening $1/f$ noise purpose. The proposed technique has been called AC-bias polarity, which is simple to operate and inexpensive in comparison to the field modulation techniques, including MEMs flaps, micro-cantilevers, and chopping techniques. The brief introduction about the noise sources in TMR sensors and the possible solutions for eliminating noise are presented in the following sections.

## 2. Noise in tunnel magnetoresistance sensors

The noises in the TMR sensors are contributed from various sources. Since TMR sensor is one type of resistive sensors so that it has all kind of resistive noises, such as thermal noise, shot noise, and low-frequency noise. In addition, due to the manmade structure of the TMR sensor, the defect of the inner structure certainly exists, which also contributes to the noise of TMR sensor. The comprehensive investigations of the noise sources in TMR sensors have been summarized and reported by Lei et al., [29], Fermon et al., [30] and Valadeiro et al., [31]. This section will briefly recall some prominent noise sources in TMR sensors.

### 2.1. Thermal noise

Thermal noise or White noise is relative directly to the resistance of the sensors. Fig. 1 illustrates a typical noise spectrum of a TMR sensor. It is a frequency independence noise so that thermal noise appears in the whole range of the sensor bandwidth. Thermal noise was firstly reported by Johnson [32] and Nyquist [33] in 1928. Therefore, the thermal noise was also called either Johnson noise or Nyquist noise. Thermal noise is represented by

$$V_T(\omega) = 4 \cdot k \cdot T \cdot R \quad (1)$$

where $k = 1.3806 \cdot 10^{-23}$ ($J.K^{-1}$) is the Boltzmann's constant, $T$ is the absolute temperature ($K$), and $R$ is the resistance ($\Omega$).

Thermal noise sets a noise floor in the resistive sensors. It cannot be further reduced excluding change the resistance and control the working temperature. Nevertheless, the effect of thermal noise on the resolution of the sensor depends on the square root of the bandwidth so that thermal noise can also be eliminated by narrowing the measuring bandwidth [30]. Besides, the thermal stability (TS) of TMR sensors might contribute to noise behavior. In this work, the commercial TMR sensor has the working temperature in the wide range from −40 °C to 125 °C, and in the out of working range, the temperature coefficient of sensitivity was -1160 ppm/°C [34]. The TS of TMR is decided by the characteristics of the inner structure of the sensor, and the TS of each functional material of the TMR stack, e.g. exchange bias field [35], ferromagnetic layers [36], shape and aspect ratio of patterned cells [37]. Therefore, the TS has contributed to the thermal noise spectrum so that even with AC-bias technique the TS still contributes to the noise behavior of the TMR sensor. The further intensive investigations on the effects of the AC-bias polarity circuit to the thermal stability of the sensor are needed and shall be addressed in our future works.

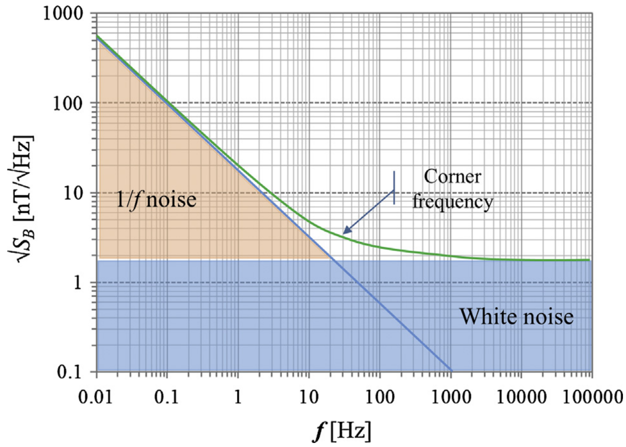


**Fig. 1.** Typical noise spectrum of a TMR sensor.

### 2.2. Shot noise

The shot noise was firstly reported by Schottky in 1918 [38]. It arises from the random fluctuations of electrical charge owing to the thermal effects. The shot noise component is contributed to the noise spectrum owing to the interruption of the charge carrier and proportional to the current passing the TMR sensors [39]. The shot noise can be given by

$$V_S(\omega) = 2 \cdot I \cdot e \quad (2)$$

where $I$ is the DC current, and $e$ is the electron charge.

The shot noise can be characterized by the Fano factor [40]. The shot noise is reduced with Fano factor is less than 1. By reducing the offset and drift of the sensor, the shot noise is also suppressed. An experimental result reported that by increasing the bias voltage and operating sensor at a low temperature the shot noise was reduced [41].

### 2.3. Low-frequency noise

Most of the resistive sensors are used in measuring the dc or low-frequency signals, e.g., $f$ less than 100 Hz. In the TMR sensor, the low-frequency noise is dominant and it is increased inversely with frequency so that it is named as $1/f$ noise. The $1/f$ noise of TMR can be expressed by

$$V_{1/f}(\omega) = \frac{\alpha}{A} \cdot \frac{V^2}{f} \quad (3)$$

where $\alpha$ is the $1/f$ Hooge parameter [42] that related to the dimension of the active surface, $A$ is the junction surface of TMR, $V$ is the biased voltage, and $f$ is the frequency. According to Eq. (3), the $1/f$ noise in

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