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A Magnetic Sensor Based on a Nanometric Spin Transfer Torque Magnetic Tunnel Junction Suitable for Monolithic Integration

Hugo Nicolas, Joris Pascal
HLS, FHNW, Muttenz, Switzerland

Luc Hebrard, Jean-Baptiste Kammerer
ICube, Unistra, Strasbourg, France

Ricardo C. Sousa, Ariam Mora-Hernández, Ioan-Lucian Prejbeanu
Spintec, CEA, Grenoble, France
hugo.nicolas@fhnw.ch

Abstract—This paper presents a magnetic sensor which sensing element is based on a spin transfer torque magnetic tunnel junction of less than 100 nanometers in diameter. This sensing element is to our knowledge one of the smallest ever reported. It is several orders of magnitude smaller than any other high-performance magnetometers. The design of the conditioning and signal processing electronics associated to the sensing element makes the proposed sensor suitable for monolithic integration. The sensor exhibits a resolution of 12.84 nT, a bandwidth of 400 Hz and a sensitivity of 77,830 LSB/mT. This is comparable with best in class commercially available monolithic magnetometers. Furthermore, its dynamic range up to 120 mT outperforms the typical ranges of magnetoresistive sensors. Besides offering a drastical miniaturization, the proposed sensor combines both high resolution and high dynamic range and can possibly fill a gap between Hall effect sensors and magnetoresistive sensors. Further developments are required to reduce the noise level.

Keywords—Magnetic sensor, magnetic tunnel junction, spin transfer torque, STT-MTJ, STT-MRAM, nanometer scale

I. INTRODUCTION

Magnetic sensors are ubiquitous in industrial or medical applications as well as in consumer electronics [1]. Thanks to their very large dynamic ranges, Hall sensors are among the most popular ones. On the other hand, magnetoresistive (MR) sensors are also extremely popular for their high sensitivity and resolution. However, the popularity of such sensors is also due to their availability as integrated devices with very small footprint. The typical size of these sensing elements is in the range of tens to hundreds of micrometers [2]-[5]. In this paper, we demonstrate a magnetic tunnel junction (MTJ), with a diameter of less than 100 nanometers, as a magnetic sensor. This sensing element is thousands of times smaller than any other on-chip sensing element commercially available. The next section describes the operating principle of the sensing element and its conditioning electronics. In section III, the performances of the proposed sensor are detailed and compared with commercially available high-performance magnetometers. The last section concludes on the sensor's limitations and proposes outlook to subsequent developments.

II. OPERATING PRINCIPLE

A. Magnetic Tunnel Junction

The junctions used in this work have been originally designed for magnetic random-access memory (MRAM) applications. In these devices, the free and pinned layers are made in FeCoB while the barrier is made of oxidized magnesium, MgO. The thickness of these layers is less than two nanometers. The junctions have a cylindrical shape with both diameter and height of less than 100 nm. Performing a periodic switching of the magnetization of the free layer allows one to measure the magnetic field through the detection of the junction's resistance changes. This will be detailed in section II. B. To create stable memory cells, the fabricated devices exhibit a very high coercivity and TMR (tunnel magnetoresistance). This large coercive field as high as 60 mT allows the MTJ to reach a very large dynamic range. In addition, the TMR value obtained with these junctions can reach 110 %. The typical field offset of the junctions is 14 mT, resulting in junctions with working ranges as high as +74 mT to -46 mT. Because of their extreme small size, MTJs can be used to create highly dense sensing array. Fig. 1 shows an array of MTJs for applications requiring high-density measurements. Finally, the intrinsic sensitivity of these devices is in average 4.41 mV/mT. This can be seen on Fig. 2, showing the typical phase diagrams of such MTJs as the two horizontal AP (antiparallel) to P (parallel) and P to AP slopes.

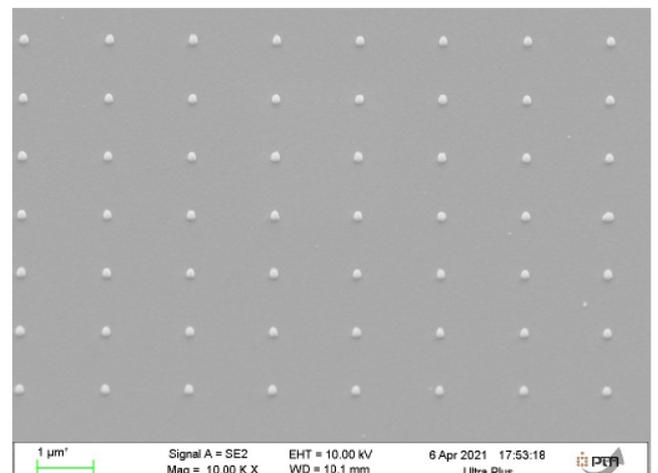


Fig. 1. SEM image of an 8 x 7 array of 100 nm MTJs. The real sized image is less than 100 μm^2 .

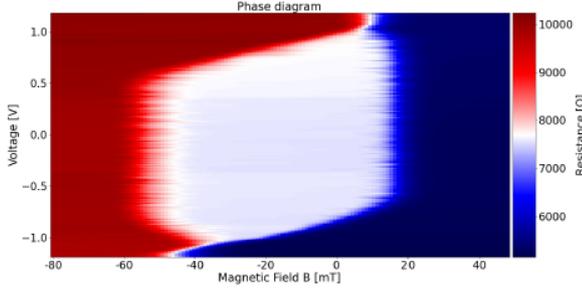


Fig. 2. Phase diagram of a standard pMTJ designed for MRAM applications. The red color indicates the AP state (high resistance) and the blue color indicates the P state (low resistance). The white color represents a virtual state where the junction can be either in the AP or P state depending on the direction of hysteresis cycle.

B. Signal processing electronics

The sensor uses the property of perpendicular MTJs (pMTJs), in which the STT (spin transfer torque) switching voltages AP to P (APP) and P to AP (PAP) change according to the external magnetic field [6]. The circuit designed to operate the MTJ is depicted in Fig. 4. The principle is to apply an input triangular signal of ± 1.6 V with a frequency of 200 kHz across the junction (In). When the voltage across the junction reaches the critical voltages, the resistance of the junction is changing. As a result of Ohm's law, the current through the MTJ undergoes a discontinuity. This current is monitored by using a shunt resistor and a differential amplifier. The resulting signal (V_0) is then passed through a 2nd order capacitor-resistor (CR) passive high-pass filter (HPF) with a cutoff frequency of 725 kHz. During the reversal events, the filter outputs very short analog pulses of 120 mV and 100 ns (V_2). These pulses are then converted to standard logical level pulses (Trig) using a comparator with a 60 mV threshold (V_1). We then use these triggers as well as the sign (Sign) and complementary sign (nSign) of the input signal to reconstruct a pulse width modulated signal (PWM). Hence, a clocked set-reset flip-flop (SR) is used with its clock input connected to the trigger, and the set and reset connected respectively to the Sign and nSign [7]. The output (V_3) of the SR as well as its complementary output are then passed through a 2nd order resistor-capacitor (RC) passive low-pass filter (LPF) with a cutoff frequency of 1325 Hz. This converts the PWM signals into dc levels. The average value of the PWM signals changes according to the external magnetic field. Using the output and complementary output allows us to create a differential signal for better noise immunity. The resulting signals are then sampled by a 24-bits sigma-delta analog-to-digital converter (ADC) with a

resolution of 149 nV/LSB and an output data rate of 400 Hz. The last two buffers can be replaced by a single differential amplifier for even higher sensitivity. The important signals obtained at different points of the circuit are shown in Fig. 3.

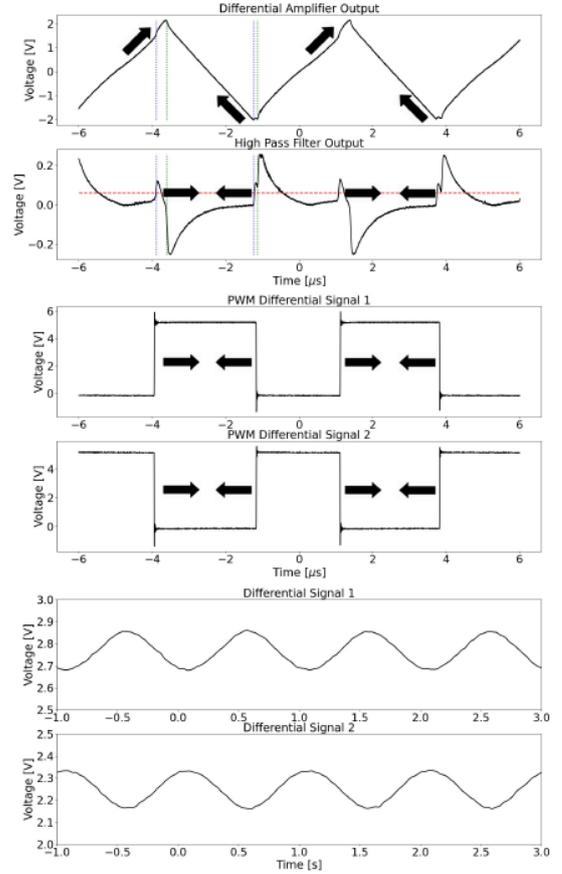


Fig. 3. Output of the differential amplifier (V_0), showing regular APP and PAP discontinuities (blue lines). HPF output (V_2), showing regular APP and PAP pulses (blue lines), with the 60 mV threshold (V_1) (red line). PWM differential outputs (V_3). The black arrows indicate how the signals are changing for an increasing external magnetic field. LPF output differential signals, sampled by the ADC during an external sine wave magnetic field measurement.

III. PERFORMANCES

Using the proposed signal processing electronics and the presented MTJs, the measured output sensitivity of the sensor reaches 77,830 LSB/mT (11.59 mV/mT) (Fig. 5). The measured integral nonlinearity error (INL) is 2.06 % of the full scale (FS). Due to the limitation of the test setup, the maximum magnetic field range which was tested is ± 8 mT. However, these MTJs have a theoretical range of up to ± 46 mT.

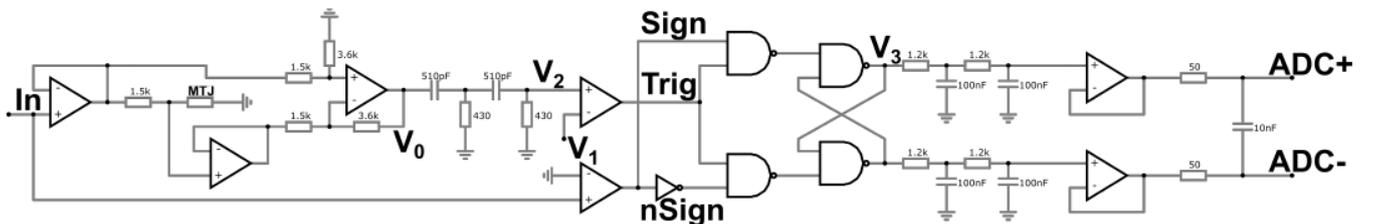


Fig. 4. Signal processing electronics

TABLE I. PERFORMANCES OF THE PRESENTED STT-MTJ SENSOR AND 3 HIGH-PERFORMANCE COMMERCIAL SENSORS

| | STT-MTJ (1 axis) | MMC MMC5603NJ (3 axis) | TI TMAG5273 (3 axis) – Z axis | Crocus CT100 (1 axis) – Vdd = 1 V |
|-------------------------|--------------------------|---------------------------|----------------------------------|--------------------------------------|
| Technology | STT-MTJ | MR (AMR) | Hall | MR (MTJ) – Analog |
| Range | $> \pm 8$ mT | ± 3 mT | ± 40 mT | ± 20 mT |
| Output data rate | 400 Hz | 75 Hz | 1200 Hz | NA |
| Resolution | 1 LSB = 12.84 nT | 1 LSB = 6.25 nT | 1 LSB = 1.2 μ T | NA |
| Noise (RMS) | 145 μ T = 11 313 LSB | 150 nT = 24 LSB | 9 μ T = 7.38 LSB | 700 nV/ \sqrt Hz |
| Sensitivity | 77 830 LSB/mT | 163 840 LSB/mT | 820 LSB/mT | 4.5 mV/mT |
| Linearity | 2.06 % FS | 0.5 % FS | 0.1 % FS | 0.5 % FS |

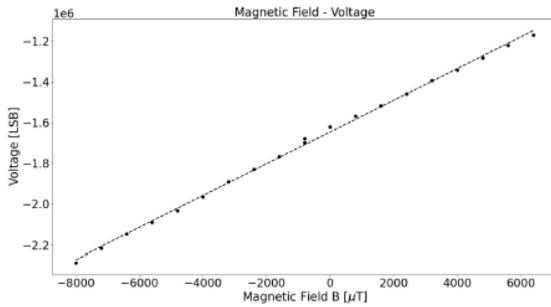
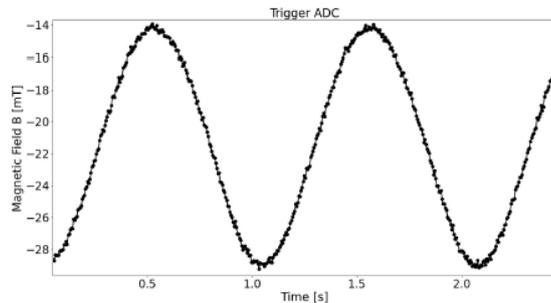


Fig. 5. Output sensitivity (each point averaged from 175 samples)

The measurement of an external magnetic field sine wave of ± 8 mT at 1 Hz shows the output signal properly oscillating with the expected frequency and amplitude of 16 mT (Fig. 6). The observed offset of -21 mT is induced by the asymmetrical critical APP and PAP voltages.


 Fig. 6. Measurement of a 1 Hz, ± 8 mT sine wave external magnetic field

The measurement of the sensor's noise shows a 1/f noise with a corner frequency of 2 Hz, followed by white noise (Fig. 7). The averaged white noise spectral density is approximately 159.7 μ V/ \sqrt Hz, corresponding to an equivalent noise of 13.7 μ T/ \sqrt Hz. The output values of the sensor exhibit a Gaussian distribution with a standard deviation σ of 11.215 LSB (1.67 mV). The measured RMS noise is 11,313 LSB (\sim 145 μ T).

The complete system, including the high-performance ADC, typically consumes 28 mW of power which could be even reduced in a fully integrated and optimized circuit. This also makes the system compatible for low power applications, including Internet of Things (IoT).

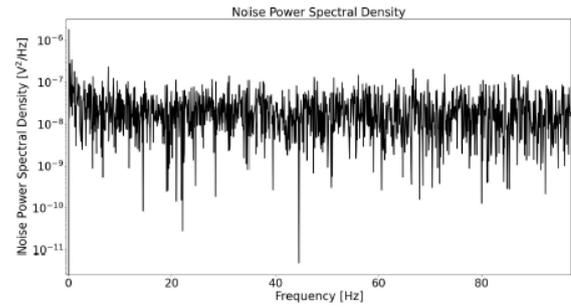


Fig. 7. Noise power spectral density showing 1/f and white noise

The proposed STT-MTJ sensor performances are compared with three other high-performance commercially available magnetic sensors in Table I. Their performances are extracted from their datasheets. These sensors are all available as surface mounted devices (SMD) with compact footprints. The MMC MMC5603NJ and the TI TMAG5273 are both outputting digital data as for the proposed STT-MTJ sensor. However, the Crocus CT100 is outputting analog signals. This often requires further signal processing such as an ADC. The CT100 sensor is based on four MTJs used as MR elements and arranged in a Wheatstone bridge configuration. It is one of the few MTJ-based magnetometers commercially available. However, MTJs used as MR elements are usually requiring larger diameters in the range of few micrometers to tens or hundreds of micrometers to reduce the noise [8].

IV. CONCLUSION

The proposed STT-MTJ sensor exhibits performances which are reaching the high-performance commercially available on-chip magnetometers. Its architecture, based on a standard nanometric spin transfer torque magnetic tunnel junction, presents a high sensitivity and a large dynamic range. The sensing element is several orders of magnitude smaller than any other magnetic sensing elements. In addition, the designed signal processing electronics allows high resolution. However, its noise level still needs to be reduced to fully outperform MR sensors. Further improvements and fine tuning on the stack of the junctions, as well as the optimization of the electronics are foreseen to reach this goal. The presented sensor device either implemented as a single sensor or as a high-density array opens the way to different applications, ranging from the medical field to industrial or physics applications.

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