# MgO Magnetic Tunnel Junction sensors in Full Wheatstone bridge configuration for Electrical current detection

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**Abstract**

Magnetoresistive (MR) electrical current sensors have been proven to hold great importance in non-stable temperature environmental places such as space applications and high power converters.In this work we fabricate a full Wheatstone bridge composed by two adjacent branches, each with two arrays of MgO-based magnetic tunnel junction (MTJ) elements connected in series, integrated with a Ru resistive element for temperature drift compensation. The measured current was driven into a U-shaped copper trace placed under a specific PCB with a 1.1 mm separation between sensor and trace. The response of the device was also monitored between -25 to 75°C, using a climate chamber.

**Keywords:** Tunneling Magnetoresistance (TMR )sensors, MgO MTJ, Wheatstone bridge, Current sensors.

## 1 Introduction

Tunneling Magnetoresistance (TMR) based sensors applications can be classified into two major groups: magnetic storage systems (hard disks read heads and magnetic random access memories) and magnetic field sensing. Focusing in the magnetic field sensing, for sensors where a linear sensor output is required, TMR elements can be arranged in a four element bridge configuration due to inherent linearity and the null output in the absence of a magnetic field. TMR based sensors are nowadays used in very different fields such as positioning control devices in robotics and related systems, geomagnetism, biotechnology applications and electrical current measurements. This work presents a Full Wheatstone bridge based on MTJ sensors, for industrial electrical current sensing where each resistive element of the bridge consists in an array of MTJ elements connected in series, in order to increase the detectivity of the device.

Even though a unique resistance can be used as a sensing element, a Wheatstone bridge setup is always a good strategy in the design of resistive sensors, since it provides a differential output as a function of the resistance variation. In fact, using MTJs as resistive elements in a Wheatstone Bridge allows to have a linear magnetic field sensor with an offset-free signal.

## 2 Sensor design and fabrication

**Device design**

Linear TMR sensors typically can be arranged in a Full Wheatstone bridge configuration with four active elements (Fig. 1). To get a full Wheatstone bridge behavior, the resistances of the bridge need to be made active in pairs: $R_1 = R_4 = R + \Delta R$ and $R_2 = R_3 = R - \Delta R$, which gives the following output:

$$V_o = \Delta R \times I_b ias \qquad (1)$$

Since the resistance elements are MTJ sensors, a full bridge behavior implies that for the same input, two sensors be in the maximum resistance state and the other two in the minimum resistance state, where maximum and minimum resistances correspond to the anti-parallel and parallel states of free and pinned magnetic layers of the structure.

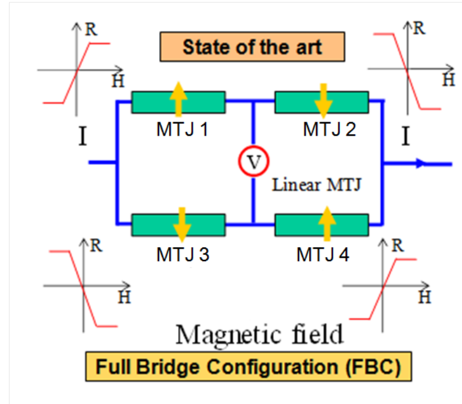


Figure 1: Full Wheatstone bridge configuration with the respective resistance states.

There are two main approaches: manipulate the reference layer to set two different and symmetric orientations in adjacent arms of the bridge, or set locally different orientations of the free layer. Concerning the second option, the one chosen for this work, a magnetic field is applied in opposite directions, which rotates the free layer locally. This can be done, for instance, by an electrical current flowing in different directions above or below the sensors, meaning that the device output can only be measured by applying an electrical current, instead of an external magnetic field.

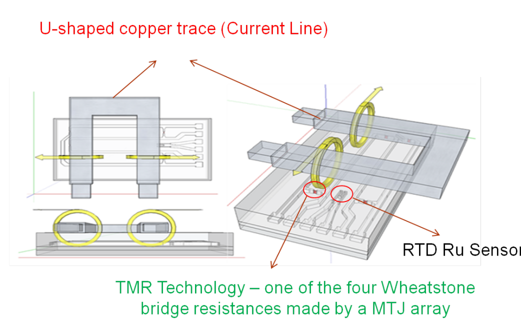


Figure 2: Sensor configuration model.

So, in the chosen configuration, a current trace is set under or on top of PCB, with the integrated sensor , where the current flows parallel to the resistances plane. The magnetic field generated by the current flow is parallel or anti-parallel to the pinned layer, respectively, so the free layer magnetization rotates accordingly to the external field orientation. A current is driven through the copper trace, increasing $R_1$ and $R_4$ values, and decreasing $R_2$ and $R_3$ values, thus obtaining a full Wheatstone behavior. In the particular case of a MR sensor a constant current source is recommended to bias the Wheatstone bridge in order to reduce its output voltage thermal drift.

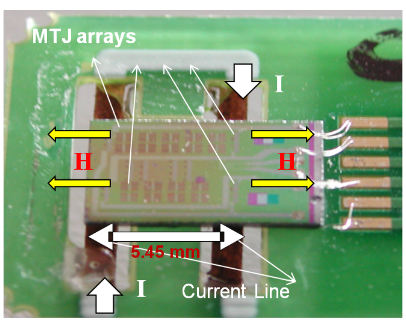


Figure 3: Sensor layout and induced magnetic field changing resistance states of the MTJ arrays.

The built-in current trace has a rectangular cross section $\omega \times h$, where $\omega = 1.18mm$ is the width, $h = 0.8mm$ is the thickness, and $l = 25mm$ is the trace's length. All this parameters are accounted for the calculation of the magnetic field created along the sensing direction of the sensors by the current flow:

$$\vec{H}(\vec{r}) = \frac{1}{4\Pi}\int_V \vec{J}(\vec{r'}) \times \frac{\vec{r}-\vec{r'}}{|\vec{r}-\vec{r'}|^3} d^3r' \qquad (2)$$

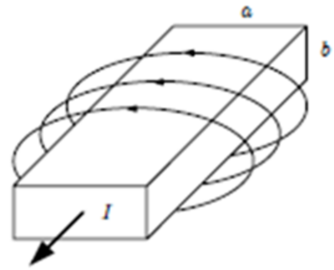


Figure 4: Current trace cross-section generating magnetic field.

where $d$ is the distance from the line. The calculated magnetic field has units of $A/m$ using SI system, and can be converted to $Oe$ multiplying by a factor of $\frac{4\pi}{1000}$.The maximum field value created by unit of current is 240 Oe/A and it's achieved at the center of the current line.

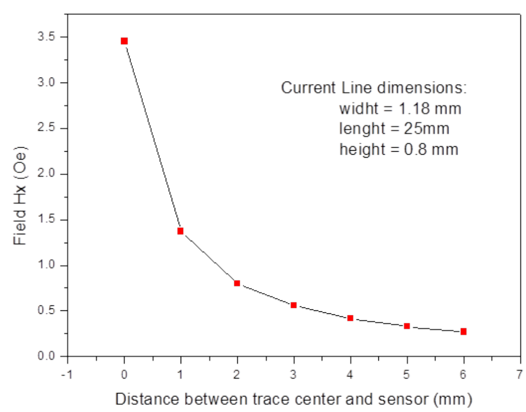


Figure 5: Magnetic field generated by a current trace along several distances.

The first series of MTJs used in this work have

390 MTJ elements each. The main reason using a large number of MTJ elements connected in series is the increased electrical robustness and detectivity when compared to a single element. Each device consists in 4 of these series connected in full Wheatstone bridge configuration, where each series corresponds to the resistance elements of the bridge. In the two processes made for the current sensor application two different areas were used: $2\times30\mu m^2$ for the 390 elements series and $3\times30\mu m^2$ for the 114 elements series.

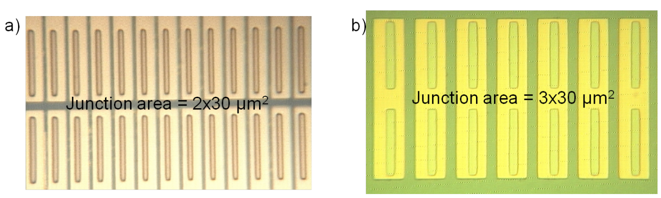


Figure 6: MTJ elements connected in series with the respective areas.

In the first mask there are also test structures: a single isolated element to compare the TMR curves with the TMR of the series; and isolated series of 390 elements. These ones are for calibration of the magnetic field created by the electrical current in the lines, since their output curve can be either get by applying an external magnetic field or by the electrical current. Matching both curves it's possible to determine the intensity of the field created by the current.

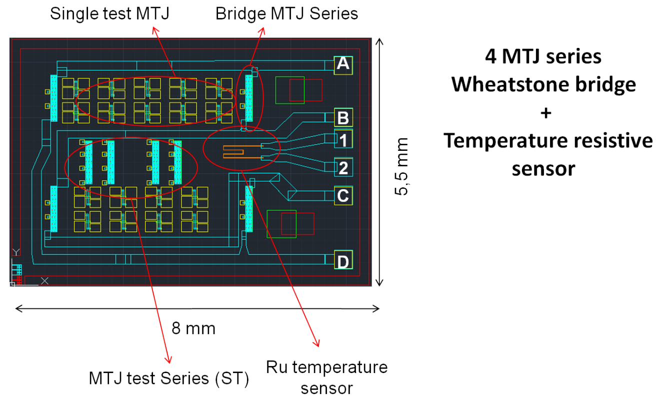


Figure 7: Mask design of different current lines configurations.

# 3 Microfabrication

The first step in this microfabrication process is to deposit the layers of the MTJ structure. The two wafers used in this work (TJ65 and TJ485) were both deposited at INL by sputtering in a Timaris tool (Singulus) by ion beam deposition, and annealed during 1 hour at 330°)C. Figure 8 shows the MTJ stacks and their respectively $R\times A$.

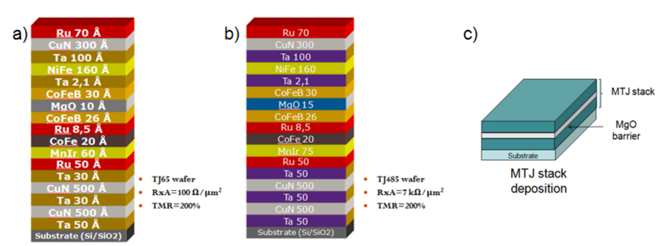


Figure 8: a) TJ65 stack sample. b)TJ485 stack sample. c) Stack deposition step.

The overall process consists in 5 steps of photolithography (six if we count the lithography of the permanent magnets on the second optimized process) by direct write laser. In the first one, the bottom contacts of the MTJs were patterned followed by ion milling. Next ($2^{nd}$ lithography) the junction pillars were defined and patterned by ion milling. In order to isolate electrically the tunnel junctions a $1200\AA$ of $Al_2O_3$ was deposited on top of the sensors. Then temperature sensor ($3^{rd}$ lithography) was defined depositing $400\AA$ of Ru by sputtering and defined by lift off. The top electrodes, $3000\AA$ of AlSiCu, were too, deposited by sputtering and defined by lift off. Finally, the sensors were passivated with 1000Åof $Al_2O_3$, opening the contacts by photolithography before the oxide deposition.

# 4 Characterization

## 4.1 DC Characterization

The MR curves for each resistive element of a bridge were obtained biasing the sensors with $I_bias = 1mA$ and varying the external field in the range of $\pm 140Oe$. The measurements were performed taking the output between the terminals of the MTJ arrays. Since the resistive elements are fabricated already in bridge configuration, it's not possible to measure one element alone. So the MR curves are in fact of the parallel of one resistive element with the other three elements. The elements show a linear range of about 65 Oe and a sensitivity of 9.2 Ω/Oe. In order to get the resistance of each element alone, it's necessary to solve a system of equations taken from the resistances parallel for each measurement. Due to its complexity, this system was solved numerically using the software Mathematica. The equivalent resistances of each different resistive parallel can be extracted from the plots in Fig. 9: $R_{eq1//(2+3+4)} = 683.24\Omega$, $R_{eq2//(1+3+4)} = 713.91\Omega$, $R_{eq3//(1+2+4)} = 731.98\Omega$ and $R_{eq4//(1+2+3)} = 746.86\Omega$. Solving the system for these values, each element's resistance is then: $R_1 = 1073.90\Omega$, $R_2 = 1143.45\Omega$, $R_3 = 1157.46\Omega$ and $R_4 = 1231.73\Omega$.

The equivalent resistance of a bridge is given by:

$$R_{bridge} = \frac{(R_1 + R_3)(R_2 + R_4)}{R_1 + R_2 + R_3 + R_4} \tag{3}$$

Using the values determined above, it's now possible to get the bridge resistance:

$$R_{bridge} = 1148.16\Omega \tag{4}$$

If the resistance of all elements were equal, the resistance of the bridge would be simply given by $R$, the resistance of one element. Also, given the fact that the resistances are not all equal, which implies an offset voltage in the bridge's output.

For a bridge with 390 MTJ elements as resistances, it was measured its output using a bias current of $1mA$, and sweeping the current between $-10A$ to $+10A$. The bridge presents a sensitivity of $9.69\frac{mV}{A} = 7.23\frac{V}{Oe.I_bias}$, and a linear output in the range of $\pm 10A$ is obtained. The $R \times A$ is $100\Omega \cdot \mu m^2$. The offset voltage of the transfer curve is $35mV$ and the offset ratio is 0.7%.

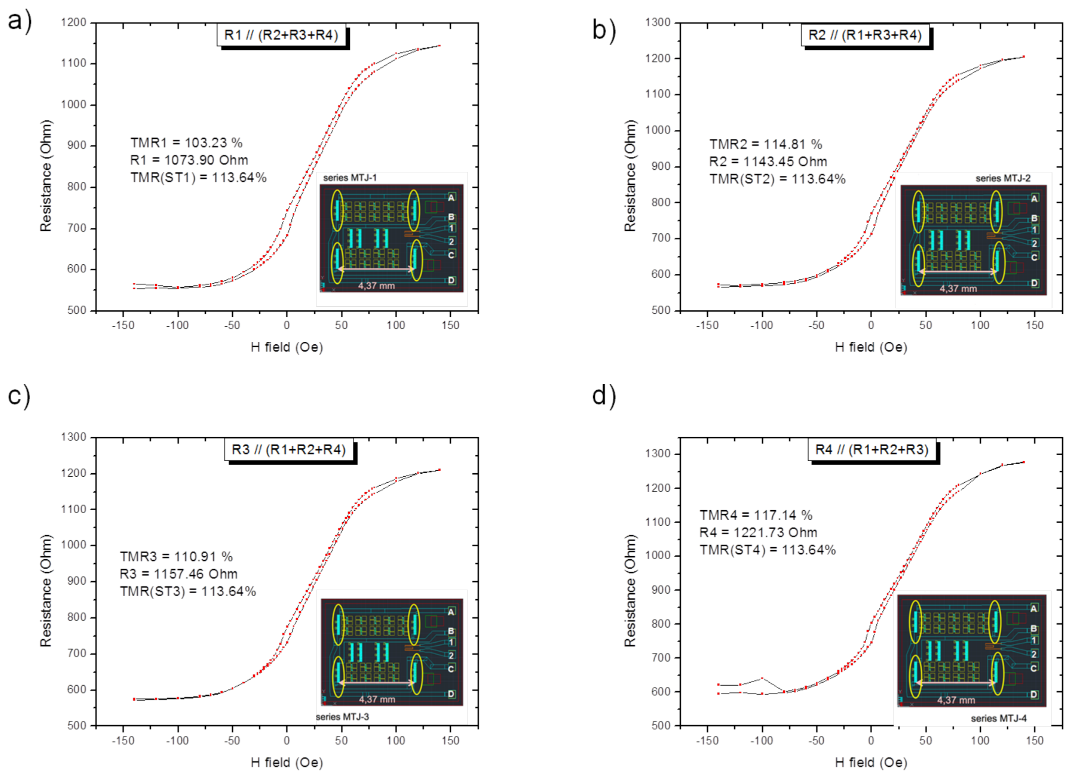


Figure 9: MR transfer curves for the 4 resistive elements of one bridge.

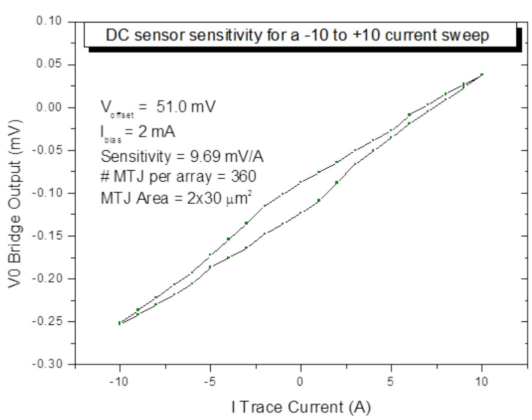


Figure 10: I-V transfer curve of a 390 MTJ elements bridge

Since the aim of bridges is to have an offset-free signal and in order to be able to use this device it's possible to correct the offset, using for instance an operational amplifier summer circuit. This asymmetry in the device output is probably due to a slightly different shape of one of the junction pillars or a shorted junction.

The use of an array of MTJ as resistive element has the difficulty of not knowing exactly how many sensors are working in each array, and it's sufficient that only one sensor is not working, to result in a non null offset voltage.

## 4.2 AC Characterization

In the AC measurements (also performed in the Department of Electronic Engineering, University of Valencia), we measured the AC sensor response for the frequencies of 500 Hz, 1 kHz, 5 kHz, 10 kHz, 50 kHz, 100 kHz, and 200 kHz. The sinusoidal current amplitude was in all cases from 0.8 to $7.5A_rms$ except for the 500 Hz and 200 kHz values. For these frequencies the maximum current amplitude was limited to 3.2 and $4.3A_rms$ due to saturation and power limits requirements respectively. Fig. 11 shows the experimental AC frequency response obtained. The values in dB where calculated referring the sensor output voltage to the initial output for each current value and for all the frequencies. In all the cases the -3 dB decay corresponds to a frequency close to 200 kHz. But this is the frequency region where there was a limitation imposed by the power output voltage amplifier. Again, as far as the experimental set-up reaches the MTJ current sensor presents a high AC frequency response.

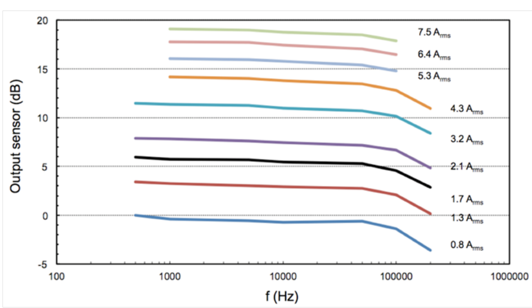


Figure 11: AC frequency response using high current level ($7.5A_rms$).

### 4.3 Thermal Characterization

We submitted the sensor to a DC current excursion from -10 A to +10 A under temperatures of $-25°C$ to $75°C$ using a climate chamber. The tests carried out showed a 2.24 $\Omega/°C$ sensitivity temperature coefficient TC(S) rather lower compared with the spin-valve technology. Additionally we measured the resistance drift of the bridge TC(RB) considering the same temperature interval, we obtained the value of $0.29\Omega/°C$. Both drifts are quite small compared with spin-valve technology.

## 5 Conclusion

The main objective of this work was to present a MgO-MTJ based electrical current sensor. This Wheatstone Bridge device was designed to use MTJ elements connected in series as the four characteristic resistances of the bridge. Two types of MTJ wafers were used (TJ65 and TJ485 with different MgO thickness) in order to test and optimize the sensor's output signal voltage and therefore it's sensitivity towards the induced magnetic fields. A 160 % of tunnel magnetoresistance effect in a single junction and a 120 % in its corresponding series elements connection has been achieved with a sensitivity of 9.2 $\Omega/Oe$ in a 65 Oe linear range.

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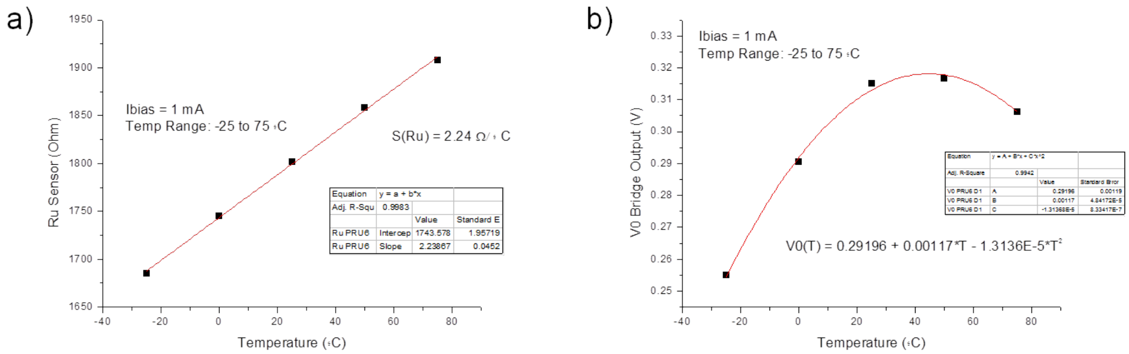


Figure 12: Sensitivity versus Temperature for the ruthenium and bridge sensors.

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