Radiation Hardness Assessment of MR sensors for Space Applications

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Abstract

As we all might know, doing space exploration is not cheap. Two factors which have a major impact on a space missions budget are related to the mass and the power consumption associated with a spacecraft. So, when we speak about any device which deals with the sensing of a magnetic field in order to perform some function, it is not acceptable not to consider magnetoresistive technology. Magnetoresistive sensors have a huge potential for space applications due to their reduced dimensions, power consumption, and the wide range of applicability. Nevertheless, one of the facts why they are still not being intensively applied, for example in magnetometers or other applications, has to do with the lack of data about radiation effects on them, among other challenges. In this work, different type of magnetoresistive sensors (spin valves, and magnetic tunnel junctions with MgO and AlOx barriers) were irradiated up to a total ionizing dose of $\sim 5$ Mrad with gamma radiation. This experiment had the objective to assess the behaviour of these sensors by inspecting if modifications induced by gamma radiation would appear or not in their characteristic parameters like transfer curve, saturated states, output signals, coercivity, transfer curve offset, and sensitivity. The irradiation was done in three steps and during these periods the sensors were unbiased. After each irradiation step, the sensors were remotely characterised. The results have shown practically no sign of degradation of the sensors’ parameters keeping, then, their performance intact.

Keywords: Magnetoresistance, Magnetoresistive sensors, Gamma irradiation, Rad-hard, Total ionizing dose

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1. Introduction

Nowadays, space and planetary assessment are starting to be supported by smaller spacecraft. The main reason for this is to lower down the costs associated with a mission. One way of doing that is through the reduction of the size and energy consumption of the components which constitute a spacecraft. Another alternative and complementary strategy is, instead of use highly qualified but expensive components in space applications, to use commercial generic ones. These have the benefits of being cheaper, to have easier access to them, lower delivery times, and the fact that their performance is not so low when compared with the ones associated with qualified components. Nevertheless, the drawback of using these components as to do with the lack of information about their behavior against the harsh environment of space. When we talk about magnetic sensors for space applications, magnetoresistance technology is naturally an option due to their features small sizes, low power consumptions and their wide range of applicability. Though, some of the magnetoresistive (MR) sensors are not yet totally mature and ready to be used in space (e.g. Magnetic tunnel junction sensors).

Other aspect why MR sensors are so desired to be used for space applications, are the fact that it is known that they present a good tolerance to radiation. In the beginning of 2000, Guo et al. (2001) [1] did the irradiation of SVs, composed by IrMn/CoFe/Cu/CoFe/NiFe, with 30 keV Ga\(^{+2}\) and observed a decrease of exchange bias and MR signal, as also the increment of resistance with the increase of ion doses. Carroll (2010) [2] shown that SVs ((Si / SiO\(_2\) 3000/ Ni\(_{80}\)Fe\(_{20}\) 100 / Cu 61 / Ni\(_{80}\)Fe\(_{20}\) 100 / Fe\(_{50}\)Mn\(_{50}\) 200 / Ge 100 , thickness in angstroms) kept their functionality, though, small changes (variations of 4 and 6 Oe were observed) in coercivity and a decrease trend of the MR signal (overall decreases of 0,15 to 0,44 % were noticed) were verified while exchange bias was observed to be rad hard, after gamma irradiations up to a dose of 50 Mrad. Conraux et al. (2003) [3] presented results from the bombardment of AlOx-based MTJs with high energetic (10 MeV/A) heavy ions, where an irreversibly small decrease in TMR amplitude with the increase of ion fluence was observed. A very good review article on radiation effect of MR sensors was presented by Lu et al. (2014) [4], where AMR sensors displayed in a Wheatstone configuration, appeared to be resistant to irradiation with gamma rays for values of TID until 200 krad. In other study [5] from the analysis of TID effects of 200 krad in AMR sensors in Wheatstone bridge configuration, it was shown that the sensors only suffered small performance degradation (with errors for the sensing field lower than 10 nT). In order to evaluated TID effects on MR sensors, biased single MgO-based MTJs were exposed to doses of gamma radiation up to 10 Mrad [6]. No signs of device’s performance modifications, neither in terms of its magnetic (coercivity and TMR signal) and electric properties, were observed. Still on the evaluation of TID effects, Arias et al. (2015) [7] have irradiated MgO-based MTJs current sensors configured in a Full Wheatstone bridge with X-rays up to a dose of 43 krad. They noticed that neither the MR signal nor bridge resistance were affected. Nevertheless, during irradiation, sensitivity and hysteresis suffered small decreases. Sensitivity was recovered, while hysteresis has reached higher values in a post-irradiation period.

To start, a brief introduction of the magnetoresistive phenomena and the space radiation environment and its effects will be presented. Next, the three types of magnetoresistive sensors which were evaluated will be identified. Also, the fabrication process of one of the types will be mentioned. Then, the method by which the sensors were characterisations and the irradiation experiment are introduced. After knowing the methodology, the results of the irradiation will be presented and discussed. In the end, some conclusions are made.

2. Background

Magnetoresistance effect

Magnetoresistance (MR) effect may be defined as the change of an electrical resistance, when a current flow through a material, due to the application of a magnetic field, \( R = f(H) \). According to the mechanism behind MR phenomenon, it is possible to categorise them in three main types: anisotropic [8], giant [9], and tunnel magnetoresistance effect [10]. One common parameter to all of MR mechanisms is the MR signal, which may be quantified as the maximum variation of the resistance, and can be represented in the following ratio form:

\[
MR(\%) = \frac{R_{\text{max}} - R_{\text{min}}}{R_{\text{min}}} \times 100. \tag{1}
\]

Depending on the type and requirements of an application, one of the three MR’s mechanisms mentioned above is typically among the elected choice. On the Table 1 it is shown some of the main features of the sensors employing the different kind of MR mechanisms. MR effect has been extensively used for a while in magnetic recording, magnetic field sensors, non-volatile memories, among many others.

Space radiation environment

It is important to know very well what will be the radiation environment that some components or
Table 1: Key features of sensors implementing MR effect. Adapted from: [11, 12]

<table>
<thead>
<tr>
<th>Physical principle</th>
<th>AMR</th>
<th>GMR - Spinvalves (SV)</th>
<th>TMR - Magnetic tunnel junctions (MTJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin film structure</td>
<td>Simple Buffer/free/cap</td>
<td>Multilayers composed by diverse materials Buffer/pinning/reference/spacer/free/cap</td>
<td>Complex multilayers composed by diverse materials Buffer/pinning/reference/barrier/free/cap</td>
</tr>
<tr>
<td>MR ratio (%)</td>
<td>2 - 6</td>
<td>6 - 20</td>
<td>50% (Al₂O₃ amorphous barrier) 300% (MgO crystalline barrier)</td>
</tr>
<tr>
<td>Thermal stability</td>
<td>up to 250 °C</td>
<td>up to 320 °C</td>
<td>up to 360 °C</td>
</tr>
<tr>
<td>Magnetic anneal treatment (°C)</td>
<td>not required</td>
<td>10 - 50</td>
<td>20 - 100</td>
</tr>
<tr>
<td>Sensor linear range (Oe)</td>
<td>1 - 100</td>
<td>~ 250</td>
<td>~ 350</td>
</tr>
<tr>
<td>Electrostatic discharge protection (robustness)</td>
<td>very good</td>
<td>good</td>
<td>fair</td>
</tr>
<tr>
<td>Materials cost</td>
<td>cheap</td>
<td>expensive</td>
<td>expensive</td>
</tr>
</tbody>
</table>

even Humans will be subjected, for example, during the execution of a space mission. The radiation issues are considered one of the most dangerous hazards found in space. Space radiation may be categorized, mainly, by three types according to their origin: cosmic galactic rays (CGRs), solar particle events (SPE), and particles trapped in radiation belts.

**Space radiation sources**

GCRs are mainly composed of charged particles where 98% are protons and heavier ions. The remain 2% are electrons and positrons. GCRs are very well known for having the highest energies in the cosmos. Within our solar system, they can have some tens of MeV up to 10^{12} MeV. Comparatively with the other two sources, GCRs are also known by having the lowest flux of particles. An important aspect of GCRs fluxes is that they are modulated by the solar activity.

Solar particles like electrons, protons, and heavier ions (from He to U) can be found anywhere in the interplanetary space and may present energies from 10 till 10^6 MeV. These particles may be produced by two types of solar events namely Solar Flares (SFs) and Coronal Mass Ejections (CMEs). This type of radiation affects predominantly missions at high planetary orbits as well as missions outer of space since there is no natural magnetic shielding out there.

Around the Earth, at altitudes from 100 to 10^6 of kilometres, there are two separated main regions where numerous electrons and protons are confined within the geomagnetic field lines, as we can see in the Figure 1. These regions are known as the Van Allan radiation belts. The electrons and protons that reside in these regions can have energies from ~ 0.1 to 10 MeV and ~ 0.1 up to 10^3 MeV, respectively. In the slot region, which separates the two belts, plasma populations with energies smaller than 0.1 MeV may be found.

**Space radiation effects**

Depending on diverse factors associated to radiation-matter interaction (as radiation source, energy, dose, and materials features like lattice atoms organization, composition and grain size), different mechanisms may occur leading to the appearing of different effects. Radiations interactions may be pronounced mainly through the following effects: total ionizing dose effects (TID), displacement damage (DD), single event effects (SEE), and electrostatic discharges (ESDs).

TID was assessed within this project. This, represents the effects associated with the accumulated dose of ionizing radiation deposited in some material. So, TID can be seen as the long-term effect of radiation, being also possible to infer the amounts of ionizing doses for which a device may withstand. This type of assessment can be done by subjecting materials to a Cobalt-60 source which are considered a standard radiation source for testing.

### 3. Sensors fabrication

Magnetic tunnel junctions with AlOx barrier were fabricated from the scratch in order to assess the gamma radiation effects on them.

Six main processes were done in order to have the final sensor. First, a two deposition step process with the same MTJ stack (Ta 50 / [Ru 150 / Ta50]x3 / NiFe 30 / CoFeB 30 / Al 8 (Ox 30") / CoFeB 30 / Ru 6 / NiFe 30 / MnIr 180 / Ru 150 / Ta 50, where the numbers represent the thickness of each layer given in angstroms) was done. The e.a. (easy
(axis) of the stack deposited in the second step was rotated about 180° relatively to the e.a. of the first stack. This strategy allowed the fabrication of full Wheatstone bridge. The deposition was done in an ion beam system (Nordiko 3000). After having the stacks deposited on top of the substrate (Si / SiO$_2$ 1000), the bottom electrodes were patterned by photolithography technique implemented by a direct write laser system (DWL), and then defined by an ion milling process (in Nordiko 3000).

Next, the main part of the sensor (MTJ pillar) was defined. The pillar was defined with dimensions of 2 $\mu$m by 40 $\mu$m. After the ion milling of the pillars, a passivation of 1214 Å with alumina was performed by a RF magnetron sputtering system (UHV2). After passivation was finished, a lift-off process was done (8 hours duration) in order to uncover the MTJ pillars from the photoresist layer which patterned the pillars and protect them from the ion milling process. After this, the top electrodes were patterned and a thick layer of AlSiCu (1,2 $\mu$m) plus a TiWN$_2$ were deposited in a magnetron sputtering system (Nordiko 7000). The last process of fabrication was to open vias (through a lift-off process) to the contact pads in order to access to the sensors, after a final passivation of 1500 Å of alumina.

After fabrication, the sensors were implemented on chip-carriers, as we observe in Figure 3.

4. Characterisation method and irradiation experiment

• Sensors characterisation

After finishing the fabrication of the sensors, I proceeded to their characterisation. Two more types of MR sensors, spin valves and MgO-based MTJs, were also characterised and subjected to the rest of the experiment. Parameters like output signal, saturated resistance, coercivity, effective coupling field were obtained. These parameters were obtained from their magnetotransport curves which were measured by using a manual setup - 140 Oe setup. The varying magnetic field is created by the change of intensity and direction (±4 A) of a current, generated by a bipolar DC current source system (Kepco), flowing through two Helmholtz coils. For the characterisations of the sensors, we should bias first then with a current (power source) or a voltage (sourcemeter), depending on the configuration of the sensors. When the application of the varying field is turn on, for each point of it, a potential difference is measured with a multimeter. All the three instruments are connected to a computer, through a GIPB connection in order to display the obtained data.

Before the implementation of the sensors on the chip-carriers, they were biased and measured with a two or four probes, composed by tungsten needles in their extremities, moved by micropositioners. After implementation, sensors characterisations were carried on in a proper chip-carrier connector linked to a pins selector board.

All of the sensor characterisations were done at INESC-MN facility in Lisbon.

• Irradiation experiment

In order predict how the magnetoresistive sensors would behave in space environment, inspections of the radiation effects on their performance were done through an irradiation experiment.

The irradiation was done with gamma radiation resulting from the decay of a Cobalt-60 source, with a half time of ~ 5 years. Gamma radiation is known by being one of the most penetrating and energetic electromagnetic radiation. Irradiation tests using this kind of sources for inspections of the long-term effects of ionizing doses and qualification of components are very frequent, since represents a worst-case scenario, for example, in the case if the components were supposed to be launched in a spacecraft to space.

The sensors were exposed to radiations with energies between ~ 1.1 and ~ 1.3 MeV. The irradiation was performed up to a total ionizing dose of ~ 5 MRad (50 kGy). This dose was delivered to the sensors in three steps of ~ 1h. In order to reach
the desired level of interest, the sensors were positioned in a specific slot with a specific distance from the source of Co-60 with a dose rate of \( \sim 1.688 \) MRad/h (16.88 kGy/h). During the irradiations, the sensors were always unbiased. In order to inspect if some changes would appear or not along the irradiations, once an irradiation step was finished the sensors were taken to INESC-MN in order to be (remotely) characterised. Still, during irradiations, sensors were irradiated unbiased. A group of sensors were not irradiated, nevertheless, they also suffered from the same handling and external conditions (except the irradiation) which the irradiated ones suffered (e.g. transport between facilities). So, during the irradiation experiment, the sensors were characterised in three different periods: before irradiations, between irradiation steps (done after each step), and after irradiations. The characterisations for each period were done in different days.

The irradiations took place at the Technological Unit of Radiosterilization at Campus Tecnológico e Nuclear - Instituto Superior Técnico (CTN-IST) -Sacavém.

5. Results

Rightly after the fabrication process, described on the section 3, characterisations were performed outside of the chip-carrier and in. These first characterisations were essential in order to make it possible the comparison between the initial state of the sensor to its response after some stage of irradiation.

Measurement conditions

Different initial conditions were used for each type of sensor during the measurements. Bias currents of 1 mA, 1.5 mA were applied to the individual SV sensors, series of MTJs with MgO barrier, respectively. On the other hand, the full Wheatstone bridge constituted with AlOx-based MTJs was bias with a constant voltage of 1.5 V with the sourcemeter.

About the software parameters, the data were obtained for a range of magnetic field between -141 to 141 Oe. Inside of this interval, different variation steps (in Oe) of the field were used: 20, 4, 2, 1. The dependent parameter, was measured 5 times for each value of the field. These points were taken after 0.5 s of the stabilization of the field.

Transfer curves, saturated levels, coercivities, and sensitivity were some of the evaluated parameters.

Transfer curves

The transfer curves, associated to the different phases of the experiment, from one sample of each group of the evaluated MR sensors are represented in Figures 4, 5 and 6. From the transfer curves, we see that, though the small variations in resistance and hysteresis, which were reversed along the experiment, the sensors kept their functionality after the exposition to 5 Mrad.

Many of the variations observed in the irradiated sensors were also observed in the un-irradiated ones, having, so, these variations anything to do with irradiation. These were thought to be linked to handling effects, since the sensors were characterised remotely. So, in order to obtain the intervals where variations have occurred, we assumed the maximum absolute deviation from the mean values of the saturated parameters (voltage and resistance), and we observed that the amplitude of these intervals were similar (about the same order) for each sensor of the same type.

Figure 4: Evolution transfer curves of the MgO-based MTJs sensors (sample MTJ2.2) along the irradiation experiment.

Figure 5: Evolution transfer curves of the SV sensor (sample SV 2.1) along the irradiation experiment.

Saturated states

Saturated states occur when magnetisations of the FL and the RL are parallel or anti-parallel to each other, translating in a minimum or maximum of
Figure 6: Evolution transfer curves of the WB sensor (sample WB 10) along the irradiation experiment.

electrical resistance identified by the plateaus in the transport curves. The saturated states of the sensors are presented in Figures 7, 8, and 9. From the inspection of these we observe that:

- for the tree type of sensors evaluated, we see that the parameters correspondent to the saturated states, resistance for the SVs and series of MgO-based MTJs, vary practically within the same interval (band) used to account for the handling effects, with maximum absolute deviations about their mean values of $R_p$ and $R_{ap}$ about: $\sim 2$ and $\sim 1.5 \, \Omega$, $\sim 0.3$ and $\sim 0.8 \, \Omega$, respectively. These variations are $< 1\%$ relative to the respective $R_p$ and $R_{ap}$ mean values;

- for the irradiated WBs we noticed that the intervals were variations have occurred along the experiment was insignificant compared with the one associated to the un-irradiated sample which had a maximum absolute deviation of $\sim 6 \, \mV$ for the $V_{max}$ and $V_{min}$, considering, so, variations in the irradiated samples (one order bellow) insignificant;

- for the sample MTJ 2.2 we noticed a distinguishable superior value of $R_{ap}$ for the 3rd irradiation phase relative to the values in other phases. Nevertheless, after this phase, the resistance has decreased and remained at the same level during the remain characterisations. This bump in resistance was not verified in any other MTJ sample.

MR signal and WB output difference

The output signals of the sensors were also evaluated and are given by the MR ratios of the MTJs and SVs, and by the output difference of the WBs, presented in Figures 10, 11, and 12. Using the same treatment done as before in order to account the effects of handling for the resistances, an interval where the values for the output signals of the irradiated sensors may vary was obtained. Again, in order to obtain the interval where variations occurred, the maximum absolute deviation relative to the mean value of the output signal for each sample was used.

Like for the saturated states, as we expected, the interval where MR signal variations for the irradiated sensors occurred are practically the same associated to the one observed for the un-irradiated sample, as we may see in the Figures 10 and 11.

Coercivity

Coercivity of a sensors can be defined as the hysteretic behaviour close to zero field. The MgO-based MTJ and SV irradiated sensors presented, practically, no coercivity. For the WBs we saw that some 1.5 Oe variations for the WB 1 and 13, as we can see in Figure 13. Nevertheless, for the three evaluated sensors no trend associated to irradiation was verified, what suggest us that, probably, these variations are not related with irradiations, but maybe with some intrinsic behaviour.

Transfer curve offset

The curves offset relative to zero field (which corresponds to the field of the middle-point of a curve) was another evaluated parameter and the results are presented in Figures 14. Shifts in transfer curves may result from an effective coupling field consequence from the interactions between the magnetic layers, like, ferromagnetic Nel coupling between the FM layers separated by a spacer (FM / spacer / FM) induced from interface interactions, the coupling of the demagnetizing field of both FM layers, and the exchange bias coupling across the spacer described by RKKY-theory (where depending on the spacer thickness a ferromagnetic/antiferromagnetic exchange bias coupling between the FM layers may occur).

From the inspection of this parameter, we may also consider that gamma irradiation did not have any relevant effect, since the variations occurred in the irradiated samples have practically the same magnitude as the uncertainty associated to the field (0.5 Oe for the 1 Oe step field).

Sensitivity

In order to evaluate the sensitivity of the sensors, linear fittings of the transfer curves in a region close to zero field (field range between -10 Oe to 10 Oe) where the data were more precisely obtained (with field steps of 1 Oe) were done. Sensitivities are presented in Figures 15, 16, and 17, and they reflect the rotation of the free layer as the field is changing. The sensitivities were obtained for the two directions which the field varied, and are denominated
For sensitivity, the results practically do not show any significant variations or trend indicative of irradiations effects. The small variations observed (of the order of 0.01 mV/Oe) are due other external factors like the handling of the sensors.

Here, we used the standard errors from the fits as the uncertainty for each sensitivity. We notice, from the figures with the sensitivities, that along the irradiation experiment there are some values that are not inserted in the uncertainties of the remains sensitivities. Nevertheless, since no significant variations, as well as any trend associated to a possible vision of radiation effects, were observed during the experiment, it suggested that maybe other external factor had affected may have caused the small deviations observed in the sensitivities.
Figure 10: Evolution of the MR signal associated to the MgO-based MTJs along the irradiation stages. The bands represented the interval where the variations occurred. For this case, these intervals bands are associated to a maximum absolute deviations close to $\sim 1.1\%$.

Figure 11: Evolution of the MR signal for the SVs along the irradiation stages. For the SVs the intervals where variations were observed, are associated to maximum absolute deviations close to $\sim 0.1\%$.

Figure 12: Evolution of the output signal, $\Delta V_0 = V_{\text{max}} - V_{\text{min}}$, for the WBs along the irradiation stages.

Figure 13: Coercivity evolution for the WBs (un-irradiated WB, WB 1, 10 and 13) along the irradiation stages.

6. Conclusion

From the analysis of the data presented in section 5, no tested sample was found to suffer any relevant degradation due to irradiation with $^{60}$Co gammas. The sensors kept their global performance intact, like we observed in the transfer curves, during the irradiation experiment. Some of these curves have shown some changes, like variations of resistance and, also, the appearance of the hysteresis-like behaviour. Nevertheless, these changes were reversed. About the origin of these changes, it was conclude that they did not have anything to do with the irradiation since:

- through the inspection of the magneto-transport and sensor parameters (coercivity, curve offset, MR signal, saturated states, and sensitivity) we observed that, for the three types of evaluated sensors, though some of the them had felt small variations, no explicit trend showing any sign of potential gamma irradiation damage during the characterisations was observed neither within each group of sensors nor among the four types;
Figure 14: Evolution of the transfer curve offset for (left) MgO-based MTJs, (middle) SVs, and (right) WBs along the irradiation stages.

Figure 15: Evolution of the sensitivity of the MgO-based MTJs along the irradiation stages.

Figure 16: Evolution of the sensitivity of the SVs along the irradiation stages.

Figure 17: Evolution of the sensitivities of the WBs along the irradiation stages.

• another aspect that may support the conclusion that the sensors did not suffer measurable damage, comes from the comparison of the irradiated sensors with the non-irradiated ones (reference samples). The small changes which were verified in the irradiated sensors were also equally verified in the reference samples, being in some cases even higher in these sensors;

From these two main points, we conclude that many of these changes have resulted from other external factors (mainly the handling of the sensors) which were not related with the irradiations, factors that were felt by the irradiated and non-irradiated samples. The fact that the sensors were not measured at the same place where they were irradiated played an important role in the observed changes.

So, due to these facts and also due to the fact that no concrete and well distinguishable signal of radiation effect was actually noticed, we observed that for the inspected range, the evaluated mag-
netoresistive sensors (SVs, MgO-based MTJs and AlOx-based MTJs in a Wheatstone bridge configuration) are resistant to high total ionizing doses as expected and also showed in previous works [7, 6], which make these type of magnetic sensors desired to be used for space applications, at least in terms of radiation tolerance. This high tolerance to radiation comes from the fact that the gammas have so high energies that they may pass through the materials without interacting with them, and/or, because ionizing radiation will not affect the mechanism which these sensors are based on which is related with spin transport (which seems not to be influenced by the radiation) when not only a voltage, but also a magnetic field are applied.

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