TECHNICAL NOTE

ON-LINE IRRADIATION TESTING OF A GIANT MAGNETO-RESISTIVE (GMR) SENSOR

Jeffrey Olfert*, Brian Luloff, Dan MacDonald, and Robert Lumsden

Canadian Nuclear Laboratories, Chalk River, ON K0J 1J0, Canada

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*Corresponding author: jeff.olfert@cnl.ca

Magneto-resistive sensors are rapidly gaining favour for magnetic field sensing applications owing to their high sensitivity, small size, and low cost. Their metallic, nonsemiconductor construction makes them excellent candidates for use in the harsh environments present in nuclear and space applications. In this work, a commercially available magneto-resistive sensor was irradiated up to a total gamma dose of 2 MGy (200 Mrad), and online testing was performed to monitor the sensor throughout the irradiation to detect any degradation. No significant evidence of degradation of the sensor characteristics was observed. A very small (< 1%) change in the bridge balance of the sensor as a function of accumulated dose was detected.

1. Introduction

1.1. Giant magneto-resistance

Magneto-resistance is a material property where electrical resistance is influenced by the magnetic state of the material. The Giant Magneto-Resistance (GMR) phenomenon was discovered by Albert Fert and Peter Grünberg in 1988, and for this discovery, they received the Nobel Prize for Physics in 2007 [1]. The term "Giant" used by the discoverers refers to the magnitude of the change in resistance, as opposed to the small effects of ordinary magneto-resistance (OMR) first described by William Thomson (Lord Kelvin) in 1856 [2]. GMR is a quantum mechanical effect that occurs in thin-film configurations of ferromagnetic material layers separated by layers of conducting material. The conducting layer thickness is chosen such that the 2 ferromagnetic layers are naturally antiferromagnetically coupled, with their overall electron spins in opposite directions. In this state, conduction electrons are more likely to be scattered as they attempt to pass from 1 ferromagnetic layer to another due to the difference in their spins. When an external magnetic field is applied, the spins of the electrons become aligned in the ferromagnetic layers, allowing conduction electrons to pass from 1 layer to another more easily, resulting in a lowered electrical resistance. This is illustrated in Figure 1.

The change in resistance with magnetic field is unipolar, meaning that the response does not depend on the polarity of the magnetic field. Either the top or bottom layer in Figure 1 can flip to align with an external magnetic field, which leads to this characteristic. A typical sensor response to a large-amplitude bipolar magnetic field variation is shown in Figure 2. Note that bipolar operation can be achieved by adding a constant magnetic field to bias the sensor into the linear region.

As the sensor is comprised of ferromagnetic material, there is a small amount of hysteresis in the response after the sensor is saturated in either direction, and this is illustrated by Figure 2. Starting with saturation along the positive *x* axis, the 4 individual legs of the sensor response are shown. Depending on the application, this hysteresis may or may not be important. For this testing, the hysteresis was characterized to look for any changes due to irradiation.

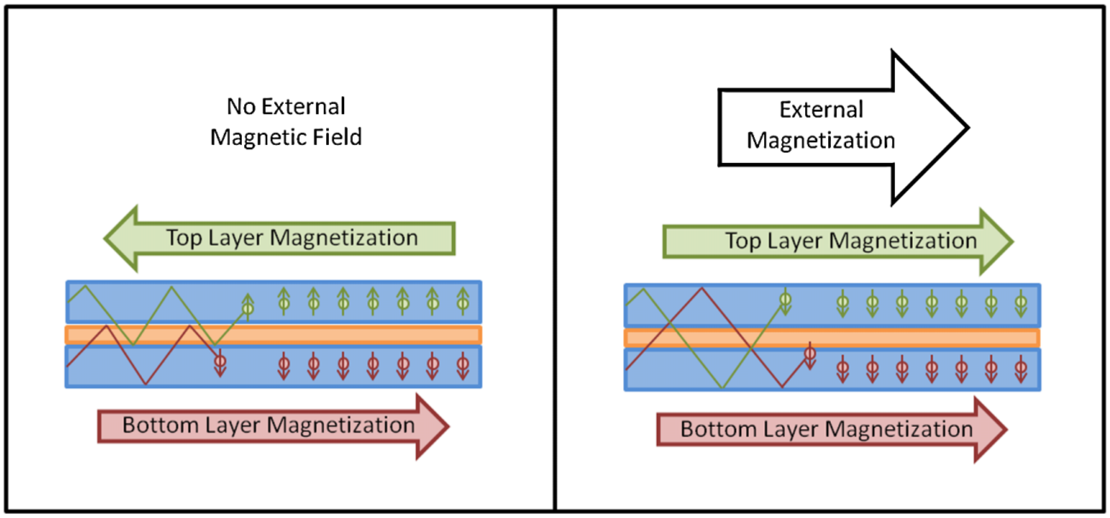

FIGURE 1. The GMR Effect. Ferromagnetic layers (blue) are separated by thin conducting layers (orange).

The GMR sensor chosen for irradiation is comprised of 4 identical sensing resistors, arranged as a Wheatstone bridge (Figure 3). The sensor is driven with a constant voltage. Two legs of the bridge are magnetically shielded, and the differential signal across the bridge is used as the sensor output.

GMR sensors are produced using advanced photolithographic manufacturing, allowing large-scale manufacturing at a very low cost per unit. A wide variety of GMR sensors are available from commercial suppliers. GMR sensors are used in many products, from automobiles to vending machines, where magnetic field sensing is required. The

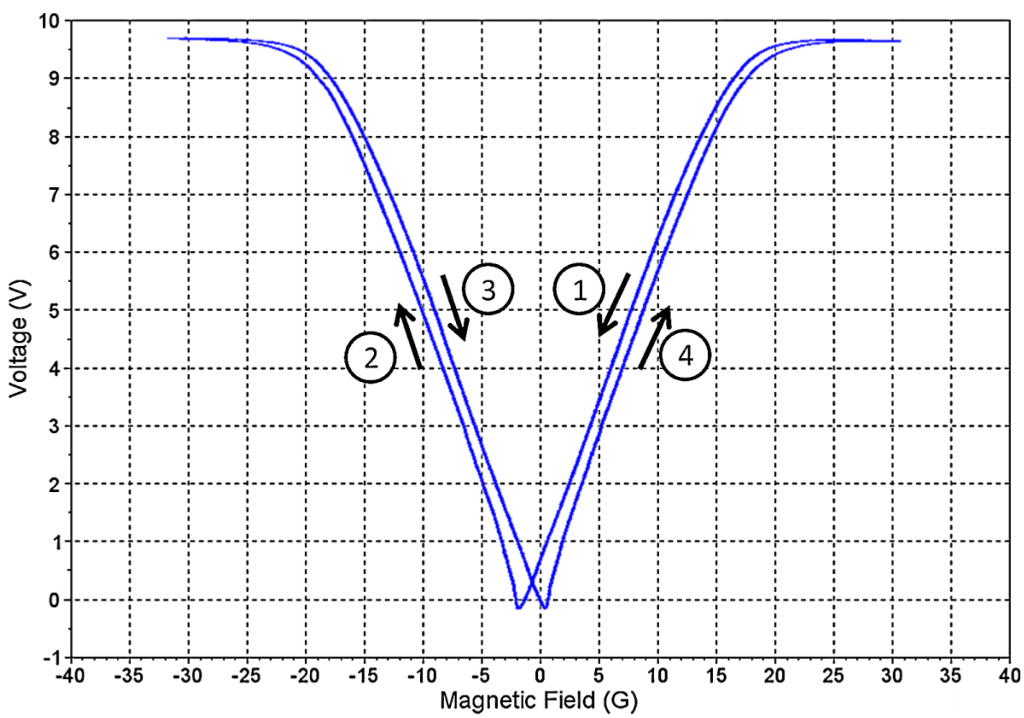

FIGURE 2. Typical GMR sensor response.

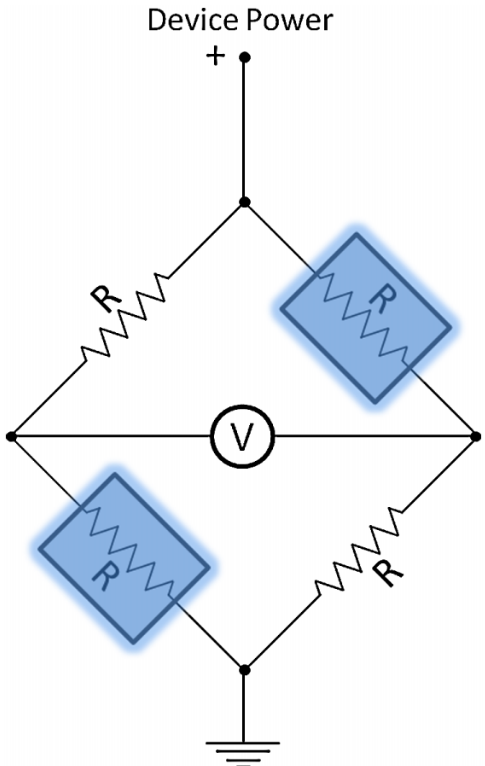

FIGURE 3. GMR sensor elements in Wheatstone bridge configuration.

sensors are also useful for electromagnetic nondestructive testing and magnetometers for compassing applications. The metallic (i.e., nonsemiconductor) nature of the sensors also makes it possible that they may operate in high gamma radiation fields in nuclear and space applications. The sensitivity to gamma radiation has been studied previously.

1.2. Summary of past irradiations

Past work on irradiation of magneto-resistive sensors has focused mainly on space applications. Commercially available OMR sensors have been irradiated in gamma cells up to 2 kGy (200 krad) [3] without any significant degradation. Laboratory-produced Tunnelling Magneto-resistive (TMR) sensors have been irradiated up to 1 kGy (100 krad) [4] without any significant degradation. The magnetic properties of GMR constituent materials were studied up to 0.5 MGy (50 Mrad) total gamma dose [5, 6], and no significant changes were observed. This work also performed neutron irradiation of GMR materials up to a total fast neutron fluence of $8*10^{11}$ n/cm^2 and found no degradation of the magnetic properties of the materials.

The use of GMR sensors for nuclear applications requires gamma radiation tolerance up to total doses in the MGy range. For example, sensors used for inspection of a

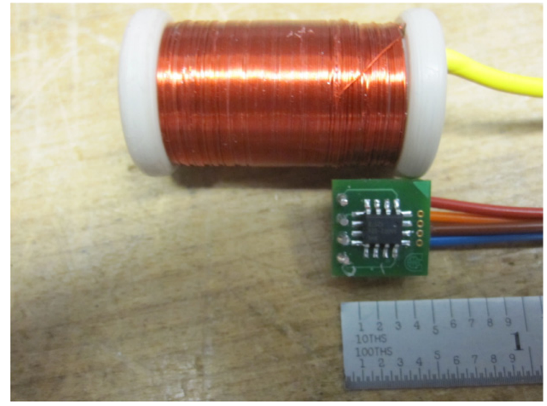

FIGURE 4. GMR sensor and excitation coil.

shutdown reactor core are typically exposed to total gamma doses of up to 2 MGy (200 Mrad). Commercially available sensors for nuclear reactor applications are expected to operate subject to gamma irradiation doses that are 3 orders of magnitude greater than that studied previously. For this reason an irradiation program has been initiated to determine the gamma irradiation response of sensors that could be used in nuclear reactor core applications. Here, and throughout the remainder of the text, radiation refers to gamma radiation only.

2. Methods

2.1. Excitation of GMR sensor

The GMR sensor under test was fixed inside an excitation coil, and the coil current was controlled to produce a magnetic field for the GMR sensor to sense (Figure 4). Three separate current profiles were used: a small-amplitude sine wave of 10 kHz, a small-amplitude sine wave of 1 kHz, and a large-amplitude slowly varying triangle wave with a period of about 11 s. The 2 sine wave profiles also had a constant bias current to operate in the linear region of the sensor. For the large-amplitude triangle wave, the coil current was driven to saturate the sensor for part of the period.

2.2. Irradiation setup

The NRU[1] Rod Bay was used for the irradiation testing. This unique facility can handle highly radioactive components and materials, and is used to store spent fuel from the NRU reactor. Underwater examinations and testing of radioactive components can also be performed in the facility. For this irradiation testing, the GMR and excitation coil were placed inside a test canister, which was placed next to 4 fuel rods that had been recently discharged from the NRU reactor.

[1]National Research Universal (heavy-water moderated and cooled test reactor), Chalk River Laboratories.

The dose rate and total dose were measured by placing a separate canister containing dosimeters in the irradiation location.

Online monitoring of the GMR sensor was performed twice daily over the course of the 33 day test. The sensor output and excitation coil current were recorded using a laptop computer with a commercially available data acquisition module. The temperature inside the canister was also recorded for each measurement, as the GMR sensor is sensitive to temperature.

3. Results

In general, there were no significant changes in the GMR sensor response during the course of the irradiation up to 2 MGy (200 Mrad). Some differences were observed in the raw measurements, but these differences were attributed to temperature variations and mostly disappeared once the manufacturer-specified temperature correction for the sensor was applied.

Overall sensor response was examined by considering the total minimum-to-maximum voltage change along leg 1 of the response curve, as visible in Figure 2, during the slow ramping of the excitation coil current. There was no significant change in sensor response, as shown in Figure 5. In addition, linear regression analysis for the linear response regions of the 4 legs in Figure 2 also showed no significant change in the slope over the course of the irradiation. This is shown in Figure 6.

A small drift in the sensor bridge balance was observed with increased radiation exposure, and this is illustrated in Figure 7. The average of the minimum and maximum voltages is plotted, and the change in this average indicates a shift in the sensor bridge balance (as the total max–min voltage remained relatively constant, Figure 5). The GMR output is a differential signal from the on-chip Wheatstone bridge, so any change in the bridge balance is due to a differential change in resistance of 2 adjacent legs of the bridge. A likely explanation for this is slightly differing irradiation effects on the different sensor elements.

No significant degradation in GMR response was observed during the 1 and 10 kHz sinusoid testing. Analysis was performed by taking the Fourier transform of the signals and comparing the amplitude response of the principal component, as well as the surrounding noise floor.

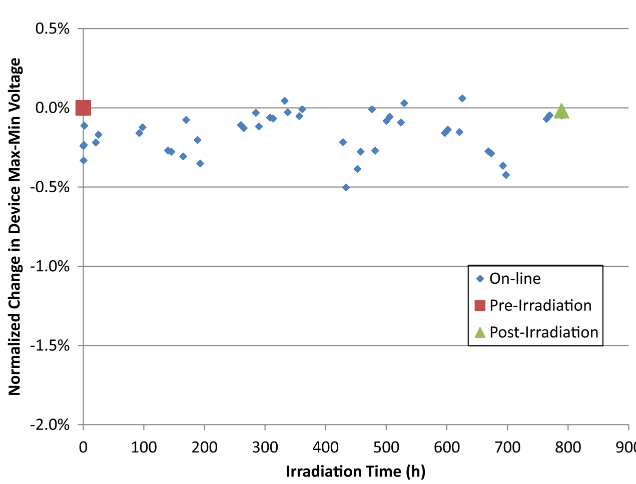

FIGURE 5. GMR sensor response during irradiation, adjusted for temperature effects.

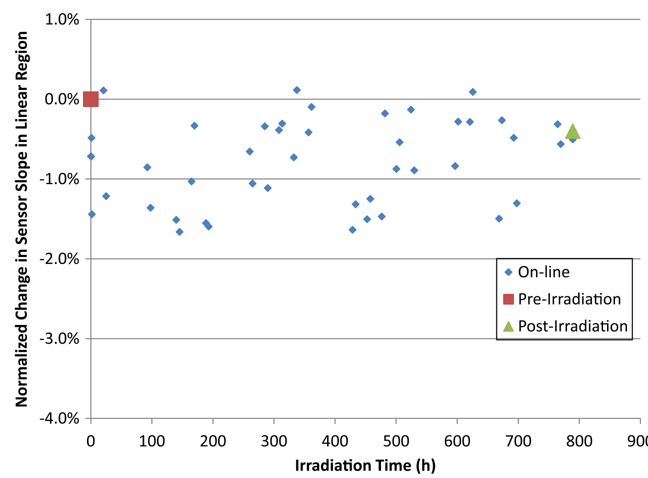

FIGURE 6. GMR sensor response during irradiation as measured by slope in linear region, adjusted for temperature effects.

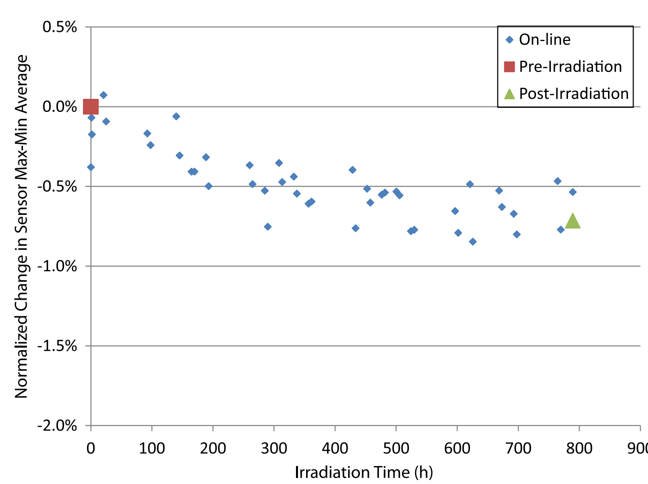

FIGURE 7. GMR sensor bridge balance during irradiation, adjusted for temperature effects.

Pre- and post-irradiation amplitude Fourier amplitude spectra for both 1 and 10 kHz are shown in Figure 8. No significant changes are visible in the response of the sensor.

A small (< 1°) shift in the phase of the principal frequency component, relative to the excitation coil current, was observed over the duration of the irradiation for both the 1 and 10 kHz sinusoids. This is consistent with a possible degradation in GMR sensor response; however, it is also consistent with a postulated degradation in the signal cable itself due to irradiation, so no conclusions should be drawn from this observation.

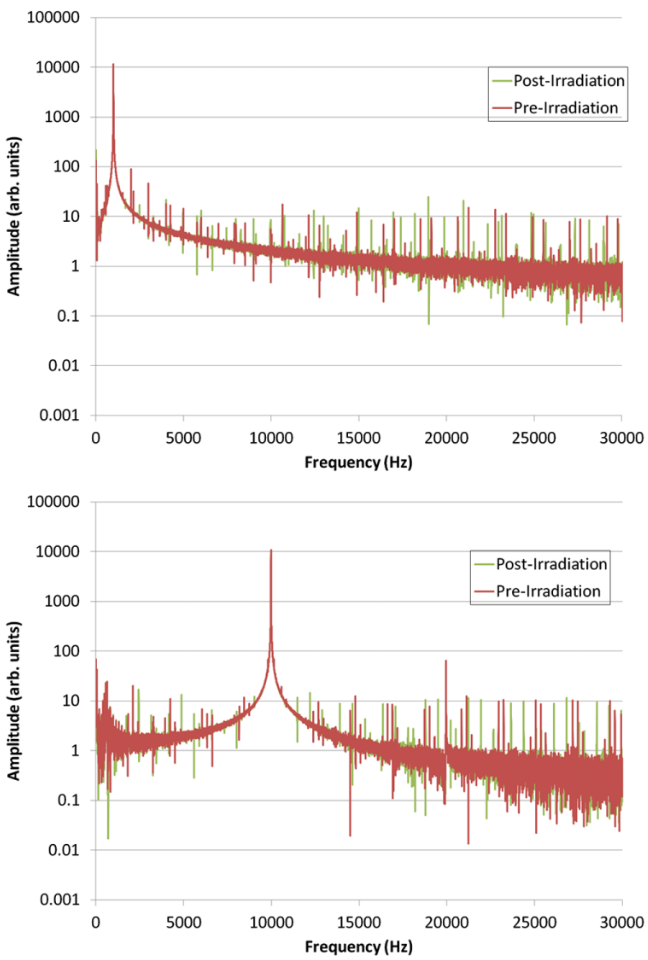

FIGURE 8. Fourier Amplitude Spectra for 1 kHz (top) and 10 kHz (bottom) coil excitation, before and after irradiation.

4. Conclusions

A commercially available GMR sensor was irradiated in the NRU Rod Bays to a total gamma dose of 2 MGy (200 Mrad). Online testing of the sensor response was performed during the irradiation to monitor the sensor's performance in high radiation fields and no significant degradation of the sensor characteristics was observed. The sensor appears to be suitable for use in high radiation fields in close proximity to spent nuclear fuel, for example, or in a shutdown reactor core.

ACKNOWLEDGEMENTS

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