



Nanoplatfroms for Neuroscience— NeuroNanotech

D1.1

First magnetic sensor with subnanoTesla resolution for low-frequency signals

Lead Beneficiary	CEA
Dissemination level	Public
Version	V1



Funded by
the European Union

Document Information

Grant Agreement Number	10116935
Project acronym	NeuroNanotech
Start date of project (Duration)	01/01/2025 (48 months)
Deliverable lead	Myriam Pannetier Lecoer
Deliverable number	D1.1
Deliverable name	First magnetic sensor with subnanoTesla resolution for low-frequency signals
WP	1-Ultimate sensing
Dissemination level	PU-Public

History of changes				
Version	Date	Author	Comments / Changes	Pages
1	28/9/26	M. Pannetier Lecoer	Creation	all

EXECUTIVE SUMMARY

This deliverable presents the latest progress achieved at SPEC-CEA and at CNRS-GREYC in the development and optimization of Giant Magnetoresistance (GMR) and Anisotropic Magnetoresistance (AMR) sensors dedicated to the detection of weak neuronal magnetic fields, respectively. The objective of this work is to improve the magnetic sensitivity of spintronic sensors while preserving their compatibility with future *in vitro* neuronal recording platforms.

We previously published in [Enger et al., ACS Appl. Electron. Mater. (2023) 5 (2): 729–739 - <https://doi.org/10.1021/acsaelm.2c01096>] that AMR sensors based on $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$ (LSMO) thin films can present sub-nT detectivity. The sensors were made of full Wheatstone bridges (WB) fabricated with 100 μm wide and 300 μm long stripes. We will present here how the demagnetizing energy could be used to optimize the design of the LSMO WB to further decrease the detectivity.

To identify the main limitations affecting sensor performance in the GMR case, a comprehensive noise model was established by combining thermal noise, flicker (1/f) noise and Random Telegraph Noise (RTN). This model was used to identify the principal design parameters governing the magnetic limit of detection (LOD), namely the electrical resistance, the sensing volume and the magnetic stability of the multilayer stack.

Based on this analysis, several generations of GMR sensors with different geometries and stack configurations were fabricated and experimentally characterized at SPEC. The results demonstrate that reducing the electrical resistance and improving magnetic domain stability significantly decrease the overall noise level while maintaining competitive magnetic sensitivity. In parallel, device miniaturization down to $50 \times 50 \mu\text{m}^2$ enables improved spatial resolution while preserving a magnetic performance compatible with neuronal sensing.

Overall, the optimized devices achieve RMS limits of detection approaching or below the nanotesla level over the frequency range relevant for neuronal activity measurements. These results represent an important step towards the integration of highly sensitive GMR sensors into future *in vitro* recording systems.

1. LSMO AMR SENSOR DESIGN OPTIMIZATION

$\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$ (LSMO) is a ferromagnetic material with a Curie temperature of about 350 K, thus allowing device operation at room temperature. To fabricate AMR sensors, we need to induce uniaxial magnetic anisotropy in the LSMO thin films. The latter can be obtained thanks to the use of vicinal substrates [Enger et al., ACS Appl. Electron. Mater. (2023) 5 (2): 729–739 - <https://doi.org/10.1021/acsaelm.2c01096>; Perna et al., Adv. Funct. Mater. 2017, 27, 1700664. <https://doi.org/10.1002/adfm.201700664>].

We present here the possible use of shape-induced anisotropy to engineer uniaxial magnetic behavior. Experiments were conducted on a 30 nm LSMO film deposited on 10° SrTiO₃ (STO) vicinal substrate at 680 °C, with 45° and 90° Wheatstone bridge (45WB and 90WB) configurations. A 10° angle was selected to induce substantial uniaxial magnetic anisotropy, facilitating the observation of geometric effects on anisotropy. In that case, we know that the expected detectivity cannot be below nT because the sensitivity is then lowered. In that case the anisotropy field (H_a) is larger than the one we can obtain with 4° but it was more interesting for the comparative study.

As shown in Figure 1, three WB geometries were designed to probe the role of demagnetizing energy:

- **Shape A:** Standard design.
- **Shape B:** Arms subdivided into two segments via trenches, enhancing demagnetizing effects while maintaining total bridge dimensions.
- **Shape C:** A surrounding LSMO body reduces shape anisotropy by promoting exchange coupling between the bridge arms and the bulk film, facilitating coherent magnetization reversal (Stoner-Wohlfarth) and lowering the saturation field.

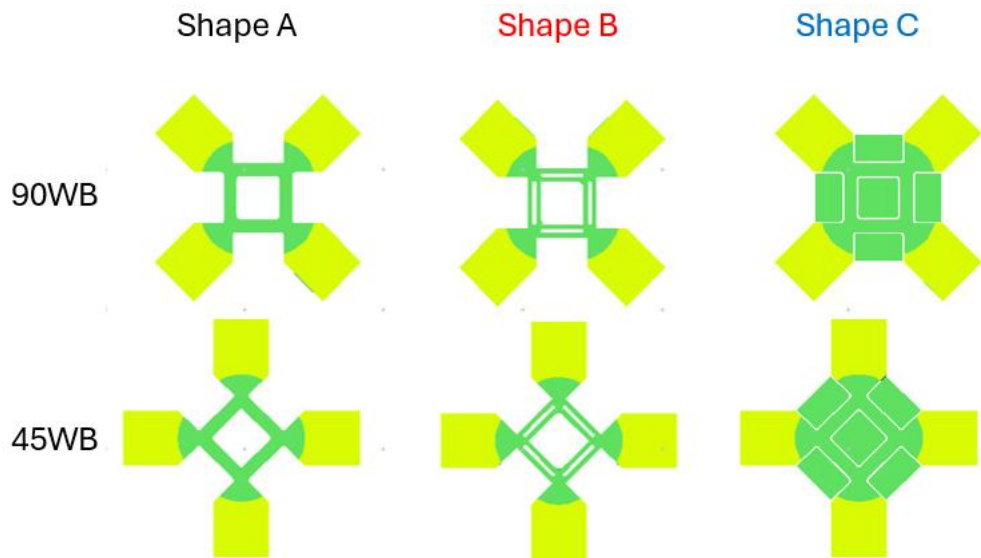


Figure 1: Schematic of the three investigated Wheatstone bridge geometries, with arms of $100\ \mu\text{m}$ width and $300\ \mu\text{m}$ length for 90° and 45° Wheatstone bridge (90WB and 45WB) configurations.

Magnetoresistance (MR) measurements are shown in Figure 2. Here we plotted the measured voltage V_{meas} at the output of the WB for a bias voltage of 5V. The slope of the curves directly gives the sensitivity in $\text{V}\cdot\text{mT}^{-1}$. They revealed that:

- Shape B exhibited higher MR ratio and H_a due to strengthened demagnetizing effects, but also increased resistance (for example, $14.0\ \text{k}\Omega$ for shape B vs. $11.9\ \text{k}\Omega$ for Shape A in 45WB)
- Shape C showed reduced MR ratio and H_a , resulting in enhanced sensitivity (nearly doubled for 90WB) due to minimized shape anisotropy effects.

Noise measurements were conducted and the resulting detectivity (also named magnetic limit of detection LOD) in $\text{T}\cdot\text{Hz}^{-1/2}$, i.e. the figure of merit for sensor performance, defined as the ratio of voltage noise in $\text{V}\cdot\text{Hz}^{-1/2}$ divided by the sensor sensitivity in $\text{V}\cdot\text{T}^{-1}$. Figure 3 shows that Shape B's trenches introduced excessive noise for 45WB. The increased gain due to in-plane magnetization alignment does not compensate the noise increase unfortunately. Shape C achieved optimal detectivity for both 45WB and 90WB structures. It thus emerges as the most promising design for optimizing AMR-based LSMO sensors, balancing sensitivity, noise, and magnetic anisotropy. It is planned to use this modified design and 4° vicinal substrates in the next generation of LSMO AMR sensors to be designed for magnetic detection of the neuronal activity.

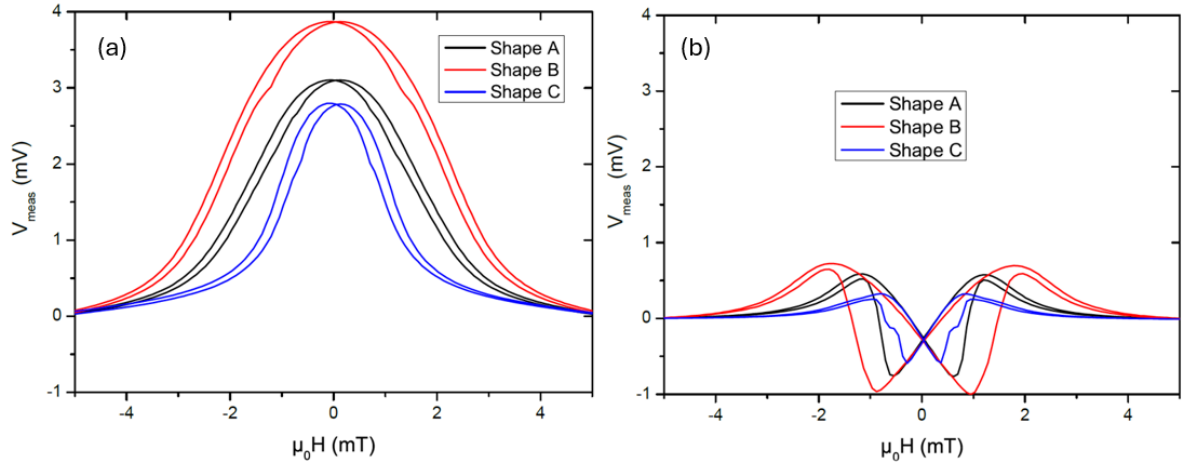


Figure 2: Measured voltage V_{meas} at the output of the Wheatstone bridges for the three different shapes (a) 90WB and (b) 45WB. Bias voltage was 5V and the temperature was 310 K.

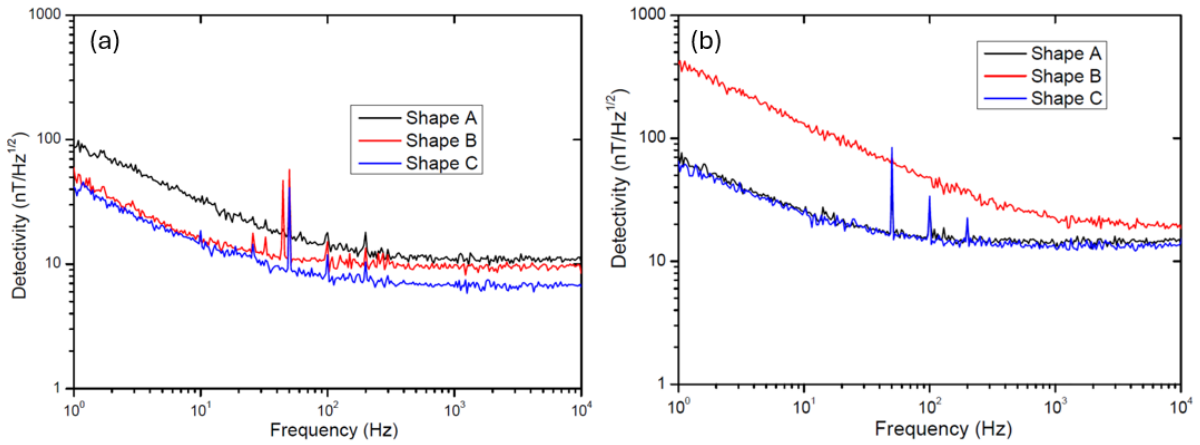


Figure 3: Measured detectivity (or magnetic limit of detection LOD) at the output of the Wheatstone bridges for the three different shapes for (a) 90WB and (b) 45WB. Bias voltage was 5V and the temperature was 310 K (30 nm LSMO thin film on a 10° vicinal SrTiO₃ substrate).

2. NOISE MODEL AND GMR SENSOR OPTIMIZATION STRATEGY

The magnetic performance of a GMR sensor is determined by its ability to detect extremely weak magnetic fields while minimizing the intrinsic electrical noise generated by the device. The sensor performance is therefore evaluated through its magnetic limit of detection (LOD), defined as the ratio between the voltage noise and the magnetic sensitivity.

The global voltage noise model combines the three dominant noise mechanisms affecting the sensors:

$$\sqrt{S_V(f)} = \sqrt{4k_B T R + \frac{\alpha(RI)^2}{n_c V f} + \frac{S_{V0}}{1 + \left(\frac{f}{f_0}\right)^2}}$$

where the first term represents the thermal (Johnson) noise, the second term describes the flicker (1/f) noise, and the third term accounts for the Random Telegraph Noise (RTN). Together, these contributions describe the overall noise behaviour over the frequency range relevant for neuronal recordings.

The magnetic limit of detection is calculated as

$$LOD(f) = \frac{\sqrt{S_V(f)}}{Sensitivity}$$

while the overall sensor performance is evaluated through the RMS limit of detection calculated over the operating bandwidth

$$LOD_{RMS} = \frac{\sqrt{\sum_{f_{min}}^{f_{max}} S_V(f)^2}}{Sensitivity}.$$

This analytical framework was used throughout the project to identify the parameters having the greatest influence on the sensor performance and to guide the optimization of the device architecture.

Three complementary optimization strategies were investigated:

- **Reduction of the electrical resistance**, to decrease the thermal noise contribution and improve the overall LOD.
- **Optimization of the sensing geometry**, by evaluating the compromise between low noise and high spatial resolution through devices ranging from $500 \times 500 \mu\text{m}^2$ to $50 \times 50 \mu\text{m}^2$.
- **Magnetic domain stabilization**, through modifications of the multilayer stack to reduce low-frequency magnetic fluctuations and improve the sensor stability.

Based on these design principles, several generations of GMR devices were fabricated and experimentally characterized.

3. GMR DEVICE DESIGN AND EXPERIMENTAL APPROACH

The experimental study was conducted on several GMR sensor configurations designed to evaluate independently the influence of resistance, sensing area and multilayer stack composition on the magnetic performance.

The reference device consists of a $500 \times 500 \mu\text{m}^2$ sensor fabricated using the initial multilayer stack. Two optimized versions were subsequently developed. The first one maintains the same sensing area while significantly reducing the electrical resistance. The second approach investigates progressively smaller sensing areas ($150 \times 150 \mu\text{m}^2$ and $50 \times 50 \mu\text{m}^2$) in order to improve spatial resolution. Finally, an optimized multilayer stack was introduced to enhance magnetic domain stability and reduce low-frequency magnetic noise.

The performance of all fabricated devices was evaluated using the same experimental methodology. For each sensor, the electrical resistance, magnetic sensitivity and RMS limit of detection were measured over the 500–5000 Hz frequency range, corresponding to the bandwidth of interest for neuronal activity detection. Measurements were performed for different bias voltages, allowing a direct comparison of the different optimization strategies.

The experimental results presented in the following section demonstrate the respective contributions of resistance reduction, device miniaturization and magnetic domain stabilization to the overall sensor performance.

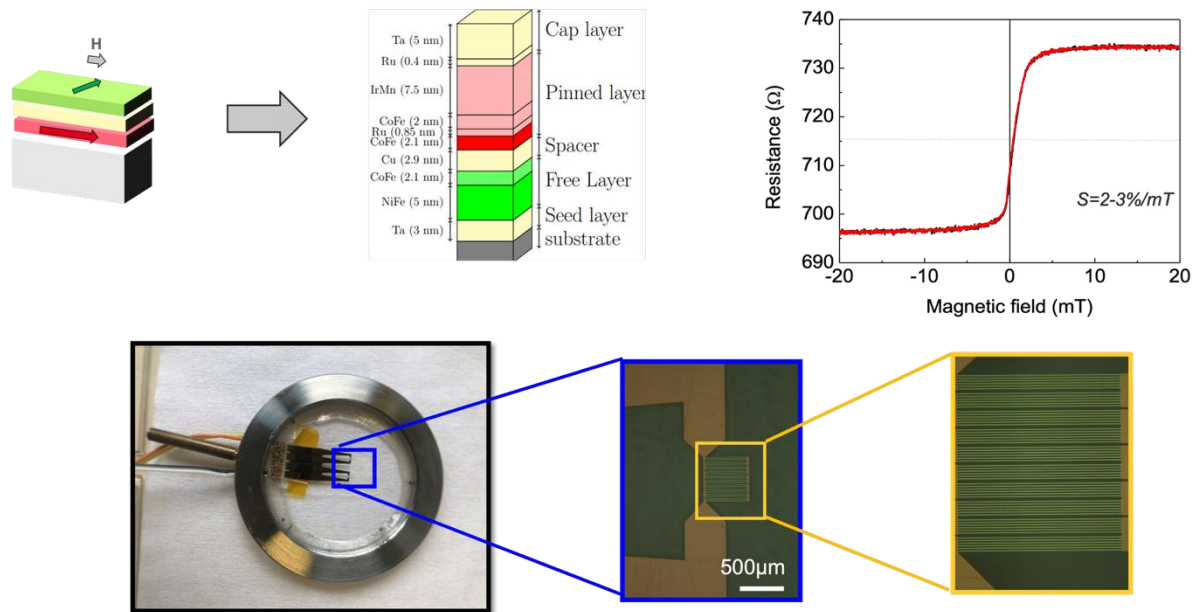


Figure 4: Top: GMR stack representation and usual magnetotransport curve; Bottom Reference GMR device fabricated on a sapphire substrate with a $500 \times 500 \mu m^2$ surface.

4. EXPERIMENTAL RESULTS ON GMR SENSORS

3.1 Effect of Electrical Resistance on Sensor Performance

The first optimization strategy focused on reducing the electrical resistance of the GMR sensors in order to decrease the thermal noise contribution predicted by the analytical noise model. A second generation of $500 \times 500 \mu m^2$ devices (V2) was therefore fabricated while preserving the same sensing geometry as the reference device.

Experimental measurements demonstrate a substantial improvement in the magnetic performance. The reduction of the electrical resistance from 5000Ω to 310Ω decreases the RMS limit of detection from 3.2 nT to 1.2 nT at a bias voltage of 1 V. When operated at 2 V, the optimized device reaches an RMS LOD of 0.93 nT, compared with 1.8 nT for the reference sensor.

These results confirm that electrical resistance is one of the dominant parameters controlling the overall noise level and validate resistance reduction as an effective strategy for improving the magnetic detection capability of GMR sensors.

Device	Resistance (ohm)	RMS LOD at 500-5000 Hz $N_{avg} = 100$	
		1V	2V
500 μm V1	5000	3.2 nT	1.8 nT
500 μm V2	310	1.2 nT	0.93 nT

3.2 Influence of Sensor Geometry

The second optimization strategy investigated the effect of the sensing area on the sensor performance. Although larger sensing elements generally provide lower intrinsic noise, smaller devices are required to improve the spatial resolution of future neuronal recording systems.

Three representative geometries were characterized experimentally. The optimized 500 μm device provides the best magnetic performance, whereas the 150 μm device exhibits higher RMS LOD values despite maintaining a comparable magnetic sensitivity. This behaviour reflects the expected trade-off between noise reduction and sensor miniaturization.

Device	Sensitivity (at 1V)	Resistance (Ohms)	RMS LOD at 500-5000 Hz $N_{avg} = 100$	
			1V	2V
Reference GMR	20 V/T	5000	3.2 nT	1.8 nT
500 μm	19.4 V/T	310	1.2 nT	0.93 nT
150 μm	20.1 V/T	315	3.7 nT	3.0 nT

The results indicate that reducing the sensing area has only a limited effect on magnetic sensitivity but increases the overall noise level. Nevertheless, the miniaturized devices remain suitable candidates for applications requiring improved spatial localization.

3.3 Magnetic Domain Stabilization

A final optimization step consisted of modifying the multilayer stack in order to improve magnetic domain stability and reduce low-frequency magnetic fluctuations. This approach was evaluated using second-generation devices fabricated with an optimized stack.

Compared with the first-generation 150 μm device, the optimized 150 μm V2 sensor achieves a significantly lower resistance together with an RMS LOD of 1.8 nT. A further reduction of the sensing area to $50 \times 50 \mu\text{m}^2$ still provides an RMS LOD of 2.6 nT, demonstrating that appropriate stack engineering can compensate for part of the performance loss associated with device miniaturization.

Device	Sensitivity (at 1V)	Resistance (Ohms)	RMS LOD at 500-5000 Hz (1V) $N_{\text{avg}} = 100$
Reference GMR	18 V/T	5000	3.2 nT
150 μm (V1)	20.1 V/T	315	3.7 nT
150 μm (V2)	12.2 V/T	135	1.8 nT
50 μm (V2)	11.5 V/T	120	2.6 nT

Overall, the combination of reduced electrical resistance and optimized multilayer stacks enables compact GMR sensors to achieve magnetic performances compatible with the requirements of neuronal magnetic recordings.

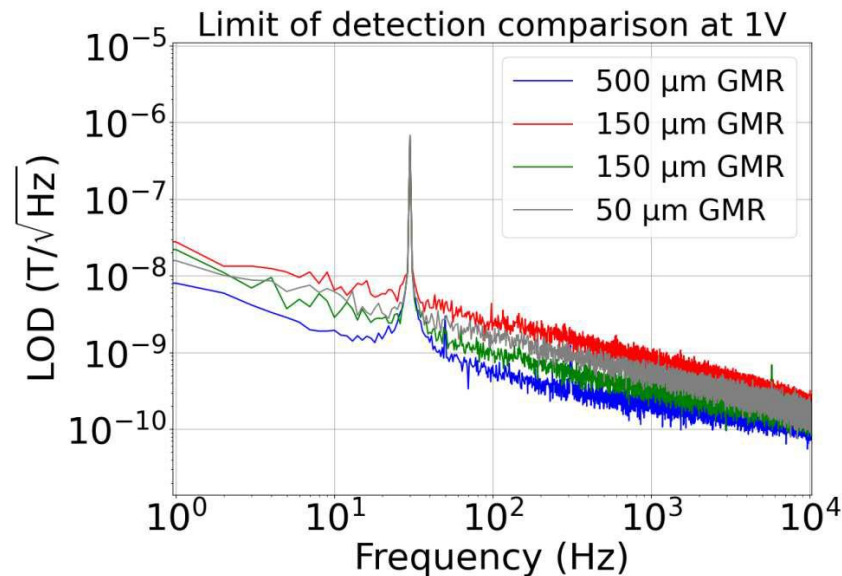


Figure 5: Limit of Detection (LOD) as a function of the frequency for a set of various surfaces GMR devices. Blue, red: stack 1; green, grey: stack 2 (optimised for magnetic domain stabilization). Note that 500-V1 and 150-V2 exhibits sub-nT range LOD for frequency down to 30Hz and 100Hz respectively. Note2: the large signal at 30Hz is the calibration field, generated by an external coil to calibrate the sensor.

5. DISCUSSION AND CONCLUSION

The work presented in this deliverable demonstrates that the performance of AMR and GMR sensors can be significantly improved through the optimization of electrical resistance, sensing geometry, shape and magnetic domain stability.

The analytical noise model successfully identified the dominant parameters affecting the magnetic limit of detection and provided a reliable framework for guiding sensor design for GMR.

Among the investigated approaches, reducing the electrical resistance produced the largest improvement in magnetic performance, enabling RMS limits of detection down to **0.93 nT** over the 500–5000 Hz frequency range. In parallel, the optimization of the multilayer stack effectively reduced low-frequency noise and allowed miniaturized devices to maintain competitive performances despite their reduced sensing area.

These results demonstrate that high magnetic sensitivity and improved spatial resolution can be achieved simultaneously through appropriate device engineering. The optimized GMR sensors therefore constitute promising candidates for future *in vitro* neuronal magnetic recording systems.

The optimized GMR devices will be used for the in-vitro recordings systems to be tested at Donders University.

The results related to GMR probes have been presented at [EMSA 2026](#) conference.

AI-assisted language editing was used in the preparation of this document. The authors remain fully responsible for its scientific content and conclusions.