Linearization strategies for high sensitivity magnetoresistive sensors

Ana V. Silva¹,², Diana C. Leitão¹,², João Valadeiro¹, José Amaral¹, Paulo P. Freitas¹,³, and Susana Cardoso¹,²,a

¹ Instituto de Engenharia de Sistemas e Computadores – Microsistemas e Nanotecnologias, 1000 Lisboa, Portugal
² Instituto Superior Tecnic, Physics Department, Universidade de Lisboa, 1049 Lisboa, Portugal
³ International Iberian Nanotechnology Laboratory, 4715 Braga, Portugal

Received: 17 April 2015 / Received in final form: 28 July 2015 / Accepted: 31 August 2015
Published online: 5 October 2015 – © EDP Sciences 2015

Abstract. Ultrasensitive magnetic field sensors envisaged for applications on biomedical imaging require the detection of low-intensity and low-frequency signals. Therefore linear magnetic sensors with enhanced sensitivity low noise levels and improved field detection at low operating frequencies are necessary. Suitable devices can be designed using magnetoresistive sensors, with room temperature operation, adjustable detected field range, CMOS compatibility and cost-effective production. The advent of spintronics set the path to the technological revolution boosted by the storage industry, in particular by the development of read heads using magnetoresistive devices. New multilayered structures were engineered to yield devices with linear output. We present a detailed study of the key factors influencing MR sensor performance (materials, geometries and layout strategies) with focus on different linearization strategies available. Furthermore strategies to improve sensor detection levels are also addressed with best reported values of ∼40 pT/√Hz at 30 Hz, representing a step forward the low field detection at room temperature.

1 Introduction

Currently available sensing techniques include induction, fluxgate, SQUID (superconducting quantum interference device), nuclear precession, Hall-effect, magnetoresistance, magnetostrictive/piezoelectric composite, magnetotransistor, magneto-impedance, magneto-optics and MEMS (microelectromechanical systems) based magnetic sensors [1]. Their application to fields with stronger industrial penetration determines their development and maturity; thus five main technological families are dominant: SQUID sensors applied to magneto-encephalography is the prevalent technique for neuroimaging, NMR (nuclear magnetic resonance) is a powerful tool for medical diagnosis and chemical spectroscopy, resonance fluxgate sensors are predominant in the military industry, inductive sensors in geomagnetic research and magnetoresistive sensors govern the data storage industry [2]. When choosing a magnetic sensing technology different parameters need to be considered, e.g., sensitivity, linearity, field range, frequency bandwidth, operating temperature, dimensions.

The evolution in the fabrication of thin films with well controlled thickness (as low as few Å), driven by the semi-conductor industry, allowed the development of nanostructured devices. In the recent decades, the generation and manipulation of spin-polarized electrons in magnetic multilayered thin-film structures gave birth to spintronics, with the discovery of giant magnetoresistance by Fert et al. and Grunberg et al. in 1988 (2007 physics Nobel prize) paving the way to the digital information revolution [3]. These spintronic materials can act as extremely sensitive magnetic field sensors, because their electrical resistance can change in the presence of magnetic fields at room temperature by factors much larger than are possible with conventional magnetic materials.

Magnetoresistive (MR) sensors, with their tunable response and adjustable operation range [4], are the ideal candidates for room temperature, small footprint and cost effective applications at the pico to mili tesla (T) range (10⁻¹² to 10⁻³ T). Field sensing can be done in an extremely small, lithographically patterned area, reducing size and power consumption requirements and thus being suitable for array applications. Multiple MR sensors can be electronically addressed and multiplexed with on-board electronics. This thin film technology is compatible with standard silicon integrated circuit (IC) technology [5,6], allowing for large scale fabrication and closed packed implementations, ideal for portable solutions. Nowadays several commercial products using MR sensors provide high performance at reasonable cost [7]. Steering angle, mechanical torque and position sensors are used in automation applications, at assembly machines and industrial robots [8]. Magnetometers used as digital compasses to detect the earth’s magnetic field [9] are used in the automotive industry as well as personal electronic devices.
Magneto resistive sensors have been successfully applied to industrial sensing as electrical current sensors in power systems [10,11] or spindle high-speed measurements. Non destructive testing, either for flux leakage detection for packaging control [12] or metal surface cracks scanning [13,14], is another relevant area where MR sensors are used. Magnetic biosensors based on MR technology used to detect surface binding reactions of biological molecules labelled with magnetic particles, is an emerging field providing key advantages for both research and clinical settings, as sensors can be arrayed and multiplexed to perform complex protein or nucleic acid analysis in a single assay with full scalable IC integration capability, making it appealing for point-of-care (POC) applications along with lab-on-chip systems [15–21].

One of the most challenging MR detection areas is brain activity sensing, where field signals are of very low intensity and at low-frequency (pT range below 100 Hz), requiring sensing devices with challenging detectivity limits, at room temperature. Some major breakthroughs have already been achieved, leading the way to portable neural activity sensing [22–24].

1.1 Magneto resistive mechanism

A magneto resistive device is a solid-state transducer which directly converts an external magnetic field ($H_{\text{ext}}$) into a resistance, given a dc bias current supply:

$$R = f(H_{\text{ext}}). \quad (1)$$

These devices are composed of a combination of magneto resistive materials, whose magnetization will tend to align with the external field and are optimized to maximize their resistance variation [26]. The devices will have a minimum ($R_{\text{min}}$) and a maximum ($R_{\text{max}}$) resistance plateau and the path from one level to other can be engineered to be a linear one, allowing them to work as magnetic field sensors. The magnitude of the magnetoresistance effect (MR) can be expressed as a percentage and is defined as follows:

$$\text{MR(\%)} = \frac{R_{\text{max}} - R_{\text{min}}}{R_{\text{min}}} \times 100. \quad (2)$$

Three main thin film magnetic sensor technologies are based in MR: anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR).

1.1.1 Anisotropic magnetoresistance

The AMR effect is characteristic of transition ferromagnetic materials (and their alloys), where their electrical resistance is a function of the angle between the material magnetization and the direction of the electrical current flowing trough it. This phenomenon arises from spin-orbit coupling, reflecting the interaction between the spin of the conduction electrons and the crystal lattice [27]. An increase in the resistance of the system occurs as the majority $s$-electrons are scattered into (minority) $d$-orbital states. The anisotropic scattering probability of the $d$-bands depends on the orientation of the magnetization relative to the flowing current, being higher when these orbitals are parallel to the current direction and lower when they are perpendicular.

Typical AMR values at room temperature are $\sim 5\%$ for NiFe and CoFe bulk alloys [27] and lower for patterned thin films ($\sim 2\%$) [28], due to additional scattering (e.g., grain boundaries, film interfaces). These low MR values are the main reason why these sensors have been gradually replaced by GMR and TMR devices.

1.1.2 Giant magnetoresistance

Advances in thin film deposition techniques led to the development of a new class of devices. Giant magnetoresistance is observed in thin film multilayered structures composed of alternating ferromagnetic and non magnetic layers. The observed effect is significant change in the electrical resistance of such structures depending on whether the magnetization of consecutive ferromagnetic layers are parallel or anti-parallel [29]. The origin of this effect is the (diffusive) electron spin dependent scattering within the ferromagnetic layers and at their interfaces. Depending on the magnetization direction of the ferromagnetic layers, there is an electron scattering asymmetry which results in different resistances for each spin dependent current.

The maximum resistance value is achieved when the magnetization of the ferromagnetic (FM) layers have an antiparallel configuration, while the minimum occurs for a parallel one. The existence of the GMR effect is independent of the current direction through the multilayer. Two current modes are possible: current-in-plane (CIP) and current-perpendicular-to-plane (CPP). The largest MR values are observed in CPP mode, because all conduction electrons must pass through all layers and all spin-filter interfaces of the structure. The highest GMR values reported are up to $\sim 65\%$ at room temperature in CPP-GMR multilayers [30]. However, because the active length of these structures is the multilayer thickness, usually much smaller than the typical device lateral dimensions, these structures exhibit very small resistances that would require either sub-micron fabrication or extremely sensitive electrical measurements and thus are not normally used as sensing devices.

In the beginning of the 90s, Grunberg devised a sensor system scheme based on the essential structure for the GMR effect (two ferromagnetic layers, separated by a non magnetic metallic layer, FM1/metallic spacer/FM2) [31] being readily followed by IBM’s introduction of the spin valve (SV) system [32]. In the SV one of the FM electrodes is replaced by GMR and TMR devices.

In the SV one of the FM electrodes is replaced by GMR and TMR devices.
coupling between the two FM layers. State of the art specular SVs reach MR values of the order of $\sim 20\%$. In this case the introduction of a small oxide layer next to the FMs induces specular reflection at the interface increasing electron scattering [34].

1.1.3 Tunnel magnetoresistance

Before the discovery of the GMR effect, it was already known that the electrical resistance of magnetic tunnel junctions (MTJ) depends on the relative orientation of its ferromagnetic layers, similarly to GMR [35]. This effect is called tunnel magnetoresistance (TMR) and has a different physical origin of the GMR effect. It occurs in multilayered structures in which the electrons tunnel across a thin (5–20 Å) insulating barrier (I) sandwiched between two ferromagnetic layers in a FM1/I/FM2 like structure. In these structures the electric current flows perpendicularly to the layers plane (CPP configuration). The TMR effect is a result of the (non-diffusive) spin dependent tunneling probability. Upon applying a voltage, the electrons at the Fermi level of FM1, tunnel into free equivalent spin states at the Fermi level of FM2 and vice-versa. In ferromagnetic materials there is an imbalance at the density of states of the spin up and spin down electrons near the Fermi level, which orientates the magnetization of the layer to a certain direction. As a consequence, the tunneling of electrons is different according to their spins [36]. The conductance across the insulating barrier is dependent on the voltage at its surfaces (bias voltage) and on the ferromagnets magnetization configuration, with the largest resistance value achieved when the FM layers have an antiparallel orientation, while the lowest value occurs for the parallel configuration.

Overall, TMR yields a resistance variation one-two orders of magnitude higher than GMR technology, and thus is steadily replacing the other MR technologies in most applications. Initially, amorphous aluminum oxide (AlOx) tunnel barriers exhibited TMR values as high as $\sim 70\%$ at room temperature [37]. Major improvements were achieved upon the inclusion of crystalline MgO barriers and textured MTJ stacks. TMR values up to $\sim 600\%$ were reported at room temperature for simple CoFeB/MgO/CoFeB structures [38], and optimum values decrease to $\sim 250\%$ for complex engineered stacks developed for device applications [9,39–42]. The reported high TMR values are a consequence of coherent spin polarized tunneling. In fact, the physics of spin filtering has been extensively addressed for single crystalline MTJs, where the electron wave functions and its attenuation rates are symmetry dependent, hence playing a major role in setting the tunneling probability [43–45]. As stated by Tiusan et al. this picture can also be extended to sputtered MTJ stacks [45].

Driven by the magnetic recording industry, many other sensing applications have benefited from its technological developments. Figure 1 summarizes the technological evolution for this field. A wide range of other applications for MR sensors exists, that has been breached by AMR and SV based sensors, but where MTJ based sensors appear when their specifications surpass those of AMR or GMR. These include various types of field sensors (from nT to 1 T fields) used in several electronic and industrial applications [10] along with biosensing systems [15], whose specific requirements will define which of the technologies to use. Key properties such as operational linear range, thermal stability, materials cost, thermal treatments required or electrical robustness against electrostatic discharge need to be evaluated together while selecting the best type of MR technology for a particular application (Fig. 2).

1.2 Typical sensor structure

From a merely structural point of view, MTJs are very similar to SVs, both consisting of two ferromagnetic electrodes separated by a non-magnetic spacer (metallic for SVs and insulator in MTJs case). As device applications require a stable fixed reference electrode, several strategies can be considered: one can either resort to FM layers with different coercivities (using different materials and/or different thicknesses) or, as first introduced by
IBM [33], one can deposit an antiferromagnetic (AFM) layer adjacent to one of the FM layers, fixing its magnetization direction through exchange bias coupling at the interface. This creates a reference direction, while the other FM layer is free to rotate in response to a low external field, acting as a sensing electrode. Commonly used antiferromagnetic materials include FeMn [47], NiO [48], MnIr [28] and PtMn [49]. The magnetization direction of this fixed layer can only be reversed at fields above the exchange bias field ($\mu_0 H_\text{exch}$), which can be as high as 85 mT ($H_\text{exch} = 850 \text{ Oe}$) [50], but typically is $\sim 30–40$ mT.

The strength of the reference direction can be further enhanced by replacing the single fixed layer by a synthetic anti-ferromagnetic (SAF) structure, which is composed of two ferromagnets separated by a thin spacer layer (most common Ru, thinner than 1 nm), with thickness tuned to have anti-ferromagnetic coupling, as described by the RKKY theory [51]. One of the ferromagnetic layers is exchange biased by an AFM. As a consequence, pinning fields in the order of several hundreds of kOe are obtained [52]. SAF structures have a null net magnetization at low fields, being also advantageous for patterned structures leading to a reduced magnetostatic coupling between reference and sensing layers [53]. These types of structure also improve thermal stability and lead to a lower distribution of blocking temperatures [54]. Figure 3 illustrates a typical structure of such devices, comprised of /seed layers/AFM/pinned FM/Ru spacer/reference FM/spacer/sensing FM/cap layers. The bottom films generically represent the underlayers commonly used to enhance electrical properties (e.g., CuN, Ta as buffer layers) or to promote the correct crystallinity (e.g., Ta, Ru, NiFeCr as seed layers).

1.3 Sensor transfer curve

The sensor behavior is characterized by its transfer curve, which represents directly the output resistance dependence on field signal. For an ideal magnetic sensor, the resistance changes linearly with field (Fig. 4a). The curve possesses two stable resistance plateaus and a linear reversible path between them. Saturation fields ($H_\text{sat}$) define the ideal linear range ($2H_\text{sat}$) of the device, where a $dR$ variation corresponds to a single $dH$ value. The key feature of a magnetic sensor response is its field sensitivity, which represents how reactive a sensor is to a field variation, and can be measured experimentally from the slope of the transfer curve. Commonly the sensitivity is presented normalized as in:

$$S = \frac{1}{R_{\text{min}} \left(\frac{\Delta R}{\Delta H}\right)_\text{linear}} = \frac{\text{MR}}{(\Delta H)_{\text{linear}}}. \quad (3)$$

The linear range depends on material and device geometry (shape and dimensions), while MR is intrinsic of the FM/spacer/FM structure and interfaces. For MTJs, the maximum resistance variation is defined as in equation (4), valid in a first approximation [55], where $W$ and $h$ are the lateral dimensions of the sensor, $RA$ is the resistance-area product, which is an intrinsic property of the tunnelling barrier and $\langle \cos \alpha \rangle$ is the cosine average of the angle ($\alpha$) between reference and sensing layers magnetization directions:

$$\Delta R_{\text{MTJ}} = \frac{1}{2} \frac{\text{MR}}{W \times h} (\cos \alpha). \quad (4)$$

Magnetoresistive devices will have a linear response to an external field only if the sensing layer magnetization changes its direction through coherent rotation. To achieve this behavior, sensing and reference layer magnetizations are set orthogonal (by every interplay) to each other and the external magnetic field is applied perpendicular to the sensing layer but parallel to the reference one (Fig. 4b).

1.4 Macrospin model for coherent rotation

The Stoner-Wohlfarth model [56] provides a good estimation of the required conditions for the linearization of MR
sensors with micrometric dimensions, when layers can be considered to have a magnetic single-domain like behavior and edge effects can be neglected. Under these assumptions the magnetization of a single ferromagnetic layer \( (\mathbf{M}) \) is described as a single collective vector, whose magnitude (saturation magnetization – \( M_s \)) remains constant and orientation may vary in space and time, being defined by the system energy minima. The total energy associated with the sensing layer has two types of contributions:

\[
E_{\text{sen}} = E_{\text{app}} + E_k,
\]

where \( E_{\text{app}} \) is the energy term associated with all magnetic fields sources external to the ferromagnetic layer, defined by unit of magnetic material volume \((V_{\text{sen}})\) as:

\[
E_{\text{app}} = -\mu_0 \mathbf{H}_{\text{app}} \times M_{\text{sen}}^2,
\]

and where \( E_k \) represents the internal anisotropy energy terms. This term has several sources, which can be divided in two families, one that represents all sources intrinsic to the deposition of the ferromagnetic material, namely of magneto-crystalline and magnetostrictive natures and another family of magnetostatic nature, that represents the anisotropy created by the self-demagnetizing field of the ferromagnetic layer. In this work for the intrinsic anisotropy term is only considered the uniaxial anisotropy induced by an applied magnetic field during deposition, defined as:

\[
E_k = -K_u \sin^2 \phi,
\]

where \( K_u \) is the uniaxial anisotropy constant and \( \phi \) is the angle between the ferromagnetic layer magnetization direction and its deposition induced easy axis (e.a.), corresponding to a field of strength \( H_k = \frac{2K_u}{\mu_0 M_s} \).

The self-demagnetizing term depends on shape anisotropy. For most geometries the exact self-demagnetizing field can only be calculated numerically. For thin films ferromagnets of micrometric lateral dimensions where \( t << h < W \), the demagnetizing field can be maximized by:

\[
-N_h M_s \cos \varphi,
\]

where \( N_h \) is the principal component of the demagnetizing tensor \( \mathbf{N} \) [57] along the axis parallel to \( h \) and \( \varphi \) is the angle between the magnetization and that axis. The energy term associated with this field is given by:

\[
E_{\text{self-demag}} = \frac{\mu_0}{2} N_h (M_{\text{sen}}^2) \cos^2 \varphi.
\]

To understand the conditions required for a MR device to have a linear behavior, one can consider the energy balance of the sensing layer composing the following structure: reference layer/spacer/sensing layer, where the system is considered to be under the influence of an external field low enough for the reference layer to have its magnetization fixed. In this situation one can consider in addition to \( E_k \) terms three applied field contributions: (i) the applied external field \( (\mathbf{H}_\text{ext}) \), (ii) the Neel coupling field \( (\mathbf{H}_\text{N}) \) (induced by correlated interface roughness at the spacer interfaces with the ferromagnets) and (iii) the field created at the sensing layer by the demagnetizing field of the reference \( (\mathbf{H}_\text{d}^{\text{ref}}) \).

Upon material deposition, two different configurations of sensing and reference layers can be considered (Fig. 5) one where their uniaxial induced anisotropy axes are parallel (parallel anisotropies) and one where they are perpendicular (crossed anisotropies). The MR device is always aligned such that the external field to be sensed is parallel to the e.a. of the reference layer.

In the first configuration (Fig. 5a), the energy of the sensing layer (expressed relative to \( \theta \), the angle between the sensing layer magnetization and external field) is given by equation (5):

\[
E_{\text{sen}} = \mu_0 M_{\text{sen}}^2 \left[ \frac{\sin^2 \theta}{2} (H_k - N_h M_{\text{sen}}^2) + \frac{N_h M_{\text{sen}}^2}{2} \right] - \cos \theta (H_{\text{ext}} - H_{\text{d}^{\text{ref}}} + H_N).
\]

For a given range of \( H_{\text{ext}} \) the minimization of equation (5) yields a minimum corresponding to \( \theta = \pi \), as long as \( H_{\text{ext}} \) is negative enough for \( |H_{\text{ext}} - H_{\text{d}^{\text{ref}}} + H_N < -|H_k - N_h M_{\text{sen}}^2| \) and similarly a minimum corresponding to \( \theta = 0 \) is always present, as long as \( |H_{\text{ext}} - H_{\text{d}^{\text{ref}}} + H_N > |H_k - N_h M_{\text{sen}}^2| \).

When \( |H_{\text{ext}} - H_{\text{d}^{\text{ref}}} + H_N < |H_k - N_h M_{\text{sen}}^2| \) (moderate fields) two distinct situations can occur. When the induced anisotropy term is higher than the self demagnetizing one \( (H_k > N_h M_{\text{sen}}^2) \) a hysteretic curve is present (Fig. 6), corresponding to two possible minima \((\cos \theta = 1 \text{ and } \cos \theta = -1)\). The point where \( \cos \theta = 0 \) is denominated coercive field \( (H_c) \) and is defined by:

\[
H_c = H_k - N_h M_{\text{sen}}^2.
\]
while \( H_{\text{f}} = H_{\text{ref}} - H_N \) is the curve off-centre.

A linear magnetic response is obtained if the induced anisotropy term is lower than the self demagnetizing one \((H_k < N_hM_s^\text{sen})\) (Fig. 7). In this case only one energy minimum exists corresponding to:

\[
\cos \theta = \frac{H_{\text{ext}} - H_{\text{ref}} + H_N}{N_hM_s^\text{sen} - H_k}.
\]

The saturation fields which define the linear range are defined by:

\[
[H_d^\text{ref} - H_N \pm (H_k - N_hM_s^\text{sen})].
\]

The sensitivity of sensor will then be proportional to the curve slope:

\[
\frac{1}{N_hM_s^\text{sen} - H_k}.
\]

The highest sensitivity is reached when \(N_hM_s^\text{sen}\) balances \(H_k\).

In the configuration where reference and sensing layers have perpendicular induced uniaxial easy axes (Fig. 5b) the energy balance is given by equation (7). In this condition, there is only one possible behavior of the sensing layer, i.e., a linear magnetic response (Fig. 8).

\[
E^\text{sen} = \frac{\mu_0M_s\cos^2\theta}{2} \left( H_k + N_hM_s^\text{sen} \right) - \cos \theta \left( H_{\text{ext}} - H^\text{ref}_d + H_N \right).
\]

Saturation fields for this type of magnetic response are given by:

\[
[H_d^\text{ref} - H_N \pm (H_k + N_hM_s^\text{sen})],
\]

and its slope

\[
\frac{1}{N_hM_s^\text{sen} + H_k},
\]

meaning that the self demagnetizing field will not concur with the uniaxial anisotropy and that sensor sensitivity is increased by minimizing the induced anisotropy and demagnetizing field.

Both situations yielding a linear sensor response have, at zero external field, a perpendicular configuration of reference and sensing layers magnetization directions \((\alpha = \frac{\pi}{2})\) and thus the resistance output of a MTJ device (Eq. (4)) with a linear behavior is given by:

\[
\Delta R_{\text{MTJ}} = \frac{1}{2}MR \frac{RA}{W \times h} \frac{H_{\text{ext}} - H^\text{ref}_d + H_N}{2H_{\text{sat}}},
\]

where \(2H_{\text{sat}} = H_k \pm N_hM_s^\text{sen}\).

1.5 Choice of electrode material for TMR sensors

Adequate choosing of materials is the starting point to design solid MR sensors. Figure 9 presents a summary of coercive field for CoFe alloys used as ferromagnetic electrodes in MTJs. The values correspond to unpatterned films, being the main source of coercivity the intrinsic anisotropy. For the parallel anisotropy configuration, the higher the \(H_k\) the higher the sensitivity, as long as the demagnetizing \((H^\text{sen}_d)\) field is strong enough to fulfill the linear response condition: \(H_k < H^\text{ref}_d\), whereas for the crossed configuration lower \(H_k\) yields higher sensitivity.
AlOx barriers are relatively simple to fabricate, typically grown by depositing elemental aluminum and subsequent oxidation [63–70]. For sensing applications AlOx-MTJs present TMR values up to ~50% [8,71,72], being five times lower than values obtained for state-of-the-art MgO-MTJ stacks engineered for devices (Sect. 1.1.3). In this type of junctions the only condition required for a good quality barrier is that it be sufficiently non-conductive. In contrast, MgO-based junctions rely on coherent tunnelling processes to achieve high TMR values and therefore a particular crystallographic orientation is necessary, requiring tight control of deposition and annealing parameters and a more restrict choice of electrode materials. Consequently in applications that can cope with TMR ~50%, AlOx MTJs become advantageous for sensor engineering since the use of several electrodes such as Fe, CoFe, CoFeB, NiFe and their combinations already have been successfully demonstrated. Since no crystallization is required, annealing temperatures as low as 200–250 ºC are employed only to set $H_{exch}$.

Adding a soft magnetic NiFe layer after CoFeB (ferromagnetically coupled) results in a sensing performance improvement by presenting lower ferromagnetic coupling trough the barrier ($H_f$) and reducing coercivity, thus having a better reversibility and linearity around zero magnetic field, while maintaining the large TMR characteristic of thick CoFeB within CoFeB/MgO/CoFeB stacks, as exemplified for patterned structures in Figure 10. The inclusion of NiFe directly after CoFeB strongly reduces TMR due to the texture propagation from NiFe (fcc 1 1 1) to CoFeB (bcc 1 0 0) [61]. Correct crystallography can be assured introducing a thin Ta dusting layer (~0.21 nm) between these layers. This inclusion does not destroy the ferromagnetic coupling between CoFeB and NiFe, but causes a strong reduction of $H_c$ and $H_f$ (Fig. 11) while enhancing the sensing layer magnetic moment (Fig. 11 inset) and while maintaining the characteristic large MR values [9,62]. In contrast AlOx MTJs do not require dusting layers when including soft magnetic layers to the sensing electrodes to reduce coercivity [73], thus simplifying the composition of material stacks. Instead if MR ratio is crucial for the detection level MgO-MTJ should be considered. State-of-the-art complex MgO-MTJs stacks proper for robust sensing applications show TMR ~250% (Sect. 1.1.3). Such large values result from the strong spin polarization induced by the crystalline structure of the ferromagnetic CoFeB electrodes together with the MgO barrier, translating into coherent tunneling through the barrier [74]. These large values are obtained only when both electrodes in contact with the MgO barrier show bcc crystalline structure with (1 0 0) out-of-plane texture, promoted in as-deposited amorphous-CoFeB upon annealing at 270–350 ºC [75].

### 2 Linearization strategies

Usually and as deposited MTJs display a squared output signal, due to the parallel configuration of reference and sensing electrodes and thus cannot be straightforwardly used as magnetic field sensors. The reference electrode magnetization direction is defined by setting the exchange coupling direction trough annealing in a uniformly strong magnetic field (> few hundred mT) and several
Fig. 11. Easy axis direction, small field VSM loops for MTJ unpatterned stacks, showing the sensing layers magnetic response for samples with and without NiFe in the sensing electrode structure. Inset: full range VSM loops for the same two samples. Current in plane tunneling (CIPT) measurements indicate that TMR remains unaffected at 200% in both types of stacks. ©[2012] IEEE. Reprinted with permission from reference [62].

strategies can be used to set the magnetization of sensing layer orthogonal, yielding a linear response (Fig. 12). Some deposition systems allow a crossed configuration to be set during deposition (Sect. 1.4 and Fig. 12a). Alternatively one can either resort to:

i. use of the self-demagnetizing field of the sensing layer [76] (Fig. 12b, Sect. 2.1):

\[ H_d(r) \equiv \frac{\int_V \nabla \cdot M(r)(r-r')}{|r-r'|^3} + \frac{\int_S n \cdot M(r)(r-r')}{|r-r'|^3}. \]  

The self-demagnetizing field of the sensing layer is a key factor in the linearization of a magnetoresistive sensor, being therefore important to understand which are the best sensor geometries. The demagnetizing field \( H_d \) of a magnetic layer is given by the following expression:

The first integral is over the entire volume \( V \) of the magnetic layer while the second integral is over its boundary surface \( S \) where the magnetic poles distribute, with \( (n) \) the unitary vector normal to each surface. In the
macrospin case: \( \nabla \cdot \mathbf{M}(r) = 0 \). Assuming that the layer’s magnetization is always in the sensor plane, its demagnetizing field is also in-plane and magnetic poles are distributed only along its lateral dimensions (width and height). This self-demagnetizing field, at mid-thickness, can be decomposed in components along those two directions \( H_d = H_d^x e_x + H_d^y e_y \), which can be expressed along the layer’s half-width and half-height respectively as follows:

\[
\begin{align*}
H_d^x &\equiv -\frac{2M_s}{4\pi} \int_{-\frac{h}{2}}^{\frac{h}{2}} \cos \theta \frac{y}{\sqrt{\left(\frac{h}{2}\right)^2 + y^2 + z^2}} \, dz \, dy, \\
H_d^y &\equiv -\frac{2M_s}{4\pi} \int_{-\frac{h}{2}}^{\frac{h}{2}} \sin \theta \frac{w}{\sqrt{x^2 + \left(\frac{h}{2}\right)^2 + z^2}} \, dz \, dx.
\end{align*}
\]

An analytical solution for these integrals, as a function of sensor’s dimensions was introduced by [84] assuming a macrospin behavior and \( W, h \gg t \):

\[
\begin{align*}
H_d^x &\equiv -\frac{8M_s}{4\pi} \frac{t}{\sqrt{w^2 + h^2}} \frac{w}{h} \cos \theta, \\
H_d^y &\equiv -\frac{8M_s}{4\pi} \frac{t}{\sqrt{w^2 + h^2}} \frac{h}{w} \sin \theta.
\end{align*}
\] (10)

Sensor designing typically takes advantage of shape anisotropy as the sensing layer is patterned in a rectangular shape, with its longest dimension (width) orthogonal to the reference fixed direction. The higher the aspect ratio of the sensing layer dimensions (width to height: \( w/h \)) the more dominant is \( H_d^x \), with larger \( w/h \) enhancing the sensor’s linear operating range and lowering its field sensitivity (Fig. 13). The macrospin model becomes advantageous for the estimation of the best device dimensions afore microfabrication. Figure 14 presents an example of such estimation, where a systematic size analysis allows the determination of the aspect ratio value at which the demagnetizing field surpasses \( H_k \), linearizing the magnetic response (\( w/h \leq 50/3 \)) from \( \mu_0 H_{sat} = 0.66 \) mT to 3.33 mT for \( h = 3 \) µm to 1 µm, respectively.

The self-demagnetizing field is also proportional to the saturation magnetization \( M_s \) and thickness of the sensing layer \( t \) (Eq. (10)). For aspect ratios above 10/1 the demagnetizing field is maximized by \(-\frac{8M_s}{4\pi H_k} t\) and the condition of no coercivity (Eq. (6)) yields:

\[
h < h_{\text{threshold}} = \frac{8M_s}{4\pi H_k} t.
\] (11)

Figure 15 presents the evolution of \( M_s \) and \( H_k \) for CoFeB ((CoFe)30B70) thin films as a function of layer thickness \( t \) from where, using the macrospin model, the threshold height \( h_{\text{threshold}} \) at which a sensor curve changes from square to linear, was estimated (Eq. (11)). For example, sensors using 5 nm thick (CoFe)30B70 sensing layers can only have linear curves upon patterning with \( h \) values below 1.2 µm, while 10 nm thick are linear even with \( h = 2.8 \) µm heights.

2.2 External biasing

Manipulating the self-demagnetizing field can be insufficient to promote a linear sensor behavior, in particular when the microfabrication process is not suitable for small dimensions (\( h \sim 1 \) µm). Moreover, if sensor area is considerably large (requirement of some low noise applications) [41], the transfer curve often presents discontinuities. On the other hand, if the sensor area is significantly small, edge roughness and other local defects act as low anisotropy sites favoring the creation of localized inverted magnetization volumes which can lead to jumps in the transfer curve. Applying an external field bias \( H_{bias} \), transversal to the sensing direction can suppress...
Fig. 15. $M_s$ and $H_k$ experimental values for unpatterned samples of Ta/CoFeB/Ta thin films, annealed for 15 min at 250 °C under a 1 T field, as a function of layer thickness and corresponding calculated $H_{\text{threshold}}$ from the macrospin model. Value marked with * taken from a MgO-MTJ full stack annealed for 1 h at 280 °C under 1 T.

these effects [87–89] and promote a hysteresis-free curve. This can either be achieved with an external field or a local field (on-chip integrated) and can be implemented with a permanent magnet (PM) or a current line loop. External field creation is a bulky solution regularly used for experiments optimization toward a final monolithic solution. For example, on-chip permanent magnet biasing is widely used in MR read heads. Thin film permanent magnet integration allows for strict control of its dimensions and hence the magnitude of the created bias field. In contrast line loops present the disadvantage of needing electrical feeding and could require extra powering electronics and thus being scarcely employed.

Figure 16 exemplifies MTJ based sensors with on-chip PM biasing strategy, where a reduction in $H_c$ from 0.4 mT to 0.05 mT is visible for an isolated sensor (Fig. 16a). Magnet efficiency depends on the gap spacing, therefore is not unexpected to see a smaller impact (still, important) in larger sensors, or when arrays of sensors are used instead of single elements. Figure 16b shows the impact of PM biasing in arrays of 82 sensors connected in series, through reducing the $(H_c)$ from 0.63 mT to 0.19 mT.

For current-perpendicular-to-plane configurations, the PM elements can be placed above the top electrode, after top metallization deposition (Fig. 17a), avoiding an extra lithography step. This strategy was successfully validated in reference [78]. To ensure the best field uniformity, dimensions should be considerably larger than the sensing layer size. Alternatively a pair of PMs can be defined side by side the top metallization (Fig. 17b). While this last method requires extra lithography and lift-off steps, it provides a far better field uniformity (created at gap) than the single PM or a loop line. The field created by the PM at the sensing layer can be calculated by equation (9), dependent on the PM magnetization, dimensions and gap. Although somehow difficult to achieve precise values for the PM field strength at sensors with large area, Figure 18 illustrates the clear impact of PM in the sensor coercivity.
The linearization effect of $H_{\text{bias}}$ can be studied by energy minimization analysis, adding an extra energy term:

$$E_{\text{sen bias}} = \mu_0 M_s^\text{sen} H_{\text{bias}} \sin \theta,$$

to equations (5) and (7) of the macrospin model (Sect. 1.4). Figure 19b presents a systematic study on sensor curve coercivity with increasing external field bias, transversal to sensing direction, where above $\mu_0 H_{\text{bias}} = 0.9 \text{ mT}$ a linear curve is achieved. Chaves et al. have also showed that a further increase in the bias strength can in particular cases lead to lower noise density at low-frequencies [90]. However this noise reduction happens at the cost of sensitivity (Figs. 16 and 19a) and the net effect will be an increase in the sensors detection limit. When the MR sensor application targets low field detection the best compromise is the lowest bias field possible, strong enough to linearize the MTJ and stabilize the sensing layer magnetic configuration.

### 2.3 Ultrathin sensing layer

On-chip biasing enlarges the final device dimensions, so if small footprint is a requirement other strategies should be considered. A different approach uses a CoFeB sensing layer thin enough to have granular film structures that in the limit present a superparamagnetic (SPM) like behavior. These structures can be used to achieve linear hysteresis-free responses, with simple designs and low power consumption (no external biasing element), without the requirement of large aspect ratios.

In ultra-thin sensing layers at CoFeB/MgO/CoFeB stacks the perpendicular anisotropy at the sensing layer/tunnel barrier interface leads to an out-of-plane anisotropy component which will compete with the existent in-plane
The European Physical Journal Applied Physics

anisotropies \cite{79}. The latter can result in a linear response to in-plane magnetic fields \cite{80,81}. Figure 20a shows the progress of patterned MTJ transfer curves with decreasing sensing layer thickness. The latter presents simultaneously both types of responses, sharp hysteretic ones with TMR values up to $\sim 200\%$ ($t > t_{\text{critical}}$) and linear responses with TMR values down to 40\%, translating the thin CoFeB evolution from the ferromagnetic to the SPM-like regime ($t \leq t_{\text{critical}}$). This transition is also illustrated in the inset of Figure 20a with the abrupt drop in coercive field at $t_{\text{critical}} \sim 1.45$ nm which is in accordance with other reported values \cite{79–81,92–94}. Tsai et al. estimated $\sim 23$ nm as the average lateral size of the ferromagnetic particles at the sensing layer \cite{94} while Shen et al. obtained 40–120 nm \cite{95} which for the given $t_{\text{critical}}$ implies that the clusters have a pancake-like shape. For $t \leq t_{\text{critical}}$ a linear response is always present, independent of junction area (Fig. 20b) \cite{92}. The dramatic decrease in TMR is attributed to weakening of ferromagnetic order in the sensing layer, as the barrier conductance is proportional to the magnetization component along the applied field, being the magnetic moment of the clusters and the layer thickness highly correlated \cite{95}.

When sensitivity is a key factor for the sensing application at hands the best thickness choice is the closer to $t_{\text{critical}}$ possible ($t \sim 1.5$ nm), since it combines a linear hysteresis free response with the best sensitivity attainable: $103\%/\text{mT}$ and linear range of $\mu_0 \Delta H_{\text{linear}} = 0.4$ mT (Fig. 20a). On the other hand, when the sensor key factor is a large linear range, a smaller thickness is required ($t < t_{\text{critical}}$), e.g., for $t = 1.4$ nm a $\mu_0 \Delta H_{\text{linear}} = 6$ mT with $4\%/\text{mT}$ is obtained (Fig. 20a). Zeng et al. reports wider ranges obtained with nano MTJs, with optimum values of $\mu_0 \Delta H_{\text{linear}} = 60$ mT and $0.2\%/\text{mT}$ \cite{80}.

In this ultra thin CoFeB layers, even for temperatures below the blocking temperature the thermal ambient energy is sufficient to change the magnetization direction of the grains \cite{94}. The resulting relaxation of magnetization orientation causes the magnetic moment of the entire grain to align with any applied magnetic field. This strategy is therefore advantageous when both in-plane and out-of-plane field sensing is required. Teixeira et al. showed $35\%/\text{mT}$ of sensitivity and linear range of $\mu_0 \Delta H_{\text{linear}} = 0.75$ mT for in-plane detection and $\mu_0 \Delta H_{\text{linear}} = 1.6$ mT and $4\%/\text{mT}$ for out-of-plane fields, employing micrometric MTJs.

Moreover noise measurements showed negligible magnetic noise in the sensitive region for SPM-like thicknesses which partially compensates the associated sensitivity loss for lower frequency signals. However at higher frequency ones, the sensitivity decrease causes significant reduction in the signal-to-noise ratio of the devices \cite{92}, and thus distinct strategies to recover the sensitivity are necessary (Sect. 3.1).

2.4 Soft exchange biasing of the sensing layer

MTJ with stack incorporated sensing layer biasing, usually consisting of a soft pinned sensing layer, have the advantage of providing linear MR devices, without resorting to shape anisotropy or external biasing. This strategy is capable of yielding competitive sensitivity values, allowing a device footprint controlled only by the area of the MTJ (no additional structures), which can also be crucial for low detectivity applications (large area sensors; Sect. 3.2).

These multilayer stacks include two AFM films: one next to the pinned layer and another adjacent to the sensing layer. Both AFM layers set the magnetization of the FM layers in a fixed direction by exchange bias (Fig. 21). However the exchange field ($H_{\text{exch}}$) of the sensing layer must be small as it will define the sensor saturation field and consequently its sensitivity. The exchange

---

Fig. 20. Magneto-transport characterization for $100 \times 100 \mu m^2$ patterned MTJ circles with varying sensing layer thickness ($t$). (a) Transfer curves. Inset: Corresponding coercive fields as function of $t$. (b) TMR as function of $t$. Reprinted with permission from reference \cite{91}. © [2008], AIP Publishing LLC.
coupling strength is set by an adequate choice of antiferromagnet and adjacent ferromagnetic layer [96].

In order to set the sensing and reference electrodes magnetization orthogonally it is required that both exchange coupled interfaces have different temperature stabilities. The exchange bias vanishes above the blocking temperature \(T_b\), being close to the Neel temperature \(T_N\) for thick AFM films with large grain sizes, while for thin films \(T_b << T_N\) due to finite size effects [97]. Therefore, the \(T_b\) value is not characteristic of the material but depends on the AFM thickness [62,97]. To have different \(T_b\) values for bottom reference \(T_{RLb}\) and sensing electrode \(T_{SLb}\), such that \(T_{RLb} > T_{SLb}\), one can either resort to different AFM materials or use the same material with different thickness.

Through consecutive annealing steps under orthogonal in-plane magnetic fields at different temperatures, the crossed configuration between the magnetization of reference and sensing layers is then defined [62,82,83,98]. The first annealing, performed at higher temperature, sets both AFM fixed layers magnetization in the same direction, while the second annealing step at a lower temperature sets the soft pinned sensing layer magnetization at a perpendicular direction to the bottom one (Fig. 22).

Since the linear operation range (defined by saturation fields) is dominated by \(H_{\text{exch}}\), for applications requiring high sensitivity a reduction in \(H_{\text{exch}}\) can be achieved by increasing the distance between the coupled layers, by inserting a thin non magnetic metallic layer between the FM and AFM. As its thickness increases, the linear operating range decreases [62,83], allowing a sensitivity improvement. The sensing layer is thereby weakly pinned when compared with the reference one.

Figure 23 shows data for a stack with 2 Å thick Ru layer between sensing layer and AFM where an average of \(\mu_0 \Delta H_{\text{linear}} \sim 0.6\) mT and a sensitivity of 28%/mT is obtained, being mostly independent of sensor area. The difference in exchange bias strength between reference and sensing electrodes was achieved by employing different adjacent ferromagnetic layers, IrMn/CoFe for the bottom pinned layer and NiFe/Ru/ IrMn for the sensing layer. Orthogonality between electrodes was created with consecutive annealings, the first at 330 °C under 1 T during 2 h and a second at 150 °C, 20 mT for 1 h. All patterned MTJs had circular symmetry and areas as high as 4072 \(\mu m^2\) fabricated without loss of linearity nor sensitivity, which is advantageous for low field detection applications (Sect. 3).

This double exchange stacks have also been demonstrated as a successfully approach for nanosensors, where the effect of the stray fields dramatically increases. Nanometric circular MTJs with \(\mu_0 \Delta H_{\text{linear}} \sim 40\) mT and sensitivities of \((\sim 3\%) / mT\) were obtained with the use of a CoFe/CoFeB/Ta/NiFe/MnIr sensing layer. Their sensitivity is almost size independent consistent with a linear operation range dominated by the exchange field strength [42].

3 Towards pTesla detection with MTJ sensors

3.1 Sensitivity control using magnetic flux concentrators

Particular applications require enhanced sensitivity alongside low field detection at low operating frequencies.
The effective MFC gain \( G \) in magnetic field corresponds to the ratio of the magnetic field measured at the gap \( B_{\text{gap}} \) and the external applied field \( B_{\text{ext}} \):

\[
G = \frac{B_{\text{gap}}}{B_{\text{ext}}}.
\]  

\( G \) depends on the intrinsic magnetic properties of the MFCs (e.g., permeability), and also on its geometric parameters. It increases linearly with the longitudinal length \( L \) of concentrators, depends on the yoke and pole cross-section ratio and is inversely proportional to the gap \( g \). Therefore an optimization of geometry and material characteristics is required to control the final full device footprint yielding optimized detectivity.

Figure 25 presents data for Co$_3$Zr$_4$Nb$_4$ (CZN) \( \sim 8600 \) Å thick films, patterned with a funnel shape separated by a gap where the MTJ is placed (Fig. 24b). The sensor – MFC pole separation is fixed at 1.5 \( \mu \text{m} \) and pole dimension is equal to pillar diameter. The CZN films are deposited under 10 mT to set the magnetic easy axis perpendicular to the measurement direction, leading to a linear \( B(H) \) dependence (\( \mu_0 H_c \sim 0.1 \text{ mT} \)) with linear range of \((\pm 2 \text{ mT})\) and \( \mu_e = 841 \) (hard axis). MFC with four different dimensions were adopted (inset of Fig. 25a).

The effect of MFC1 in the magnetotransport curve of a 15 \( \mu \text{m} \) radius MgO-MTJ pillar, with soft-pinned sensing layer is presented in Figure 25a, where the reduction of \( 2\mu_0 H_{\text{sat}} \) from 7.2 mT to 1.3 mT is clear, causing a sensitivity enhancement with a gain factor of 5.1, reaching the maximum value of 155.2%/mT. Upon MFC inclusion an evident sensitivity decrease was continuously observed when the sensor area increases, with MFC gain decreasing from 6.7 (radius = 10 \( \mu \text{m} \), sensitivity of 180.4%/mT) to 3.0 (radius = 36 \( \mu \text{m} \), sensitivity of 84.5%/mT), corresponding to a reduction of \( \sim 54\% \). The gain reduction can be mainly explained by the increasing gap distance with sensor dimensions, leading to an accentuated dispersion of the field lines hence less efficient concentration.

Figure 25b compares the sensitivity evolution of fabricated sensors upon integration in the four different sizes of MFC. For all MFC dimensions a decrease in gain with increasing gap dimension is observed, yielding the expected reduction in sensor sensitivity. For all the characterized sensors the MFCs do not increase sensor coercivity. The integration of MFC with larger dimensions yields larger sensitivities: 84.5%/mT \( (G = 3.0) \) for MFC1, 102.1%/mT \( (G = 3.7) \) for MFC2, 122.3%/mT \( (G = 4.4) \) for MFC3 and \( (G = 5.3) \) 147.4%/mT for MFC4 when compared with the value obtained for the same sensor (radius = 36 \( \mu \text{m} \)) with no MFC (27.8%/mT).

On the other hand, a distinct strategy using thick MFCs with tapered profiles led to a noticeable flux increase at the sensor level [102], further strengthening the possibility of reaching sub-nT/Hz limit in field detectivity. Nevertheless, thicker than few nm MFCs, are more prone to local fluctuations in composition [103] and stress [104], and may lead to an additional out-of-plane anisotropy contributions to the system. This effect is enhanced when microfabricated structures are considered, thus potentiating the appearance of complex magnetic domain structures at the MFCs poles, originating discontinuities and hysteresis in the sensor response [105]. To overcome these drawbacks synthetic-antiferromagnet (SAF) structures consisting of multilayers alternating a ferromagnetic material with a non-magnetic spacer, can be used as MFCs [102]. In SAF-MFCs, the antiferromagnetic coupling between layers helps stabilizing the monodomain state and leads to an almost zero net magnetic moment [102,105,106]. Such configuration promotes an improved linear response and potentiates lower magnetic contributions to the noise level of the MR sensor, with the drawback of smaller magnetic permeability and hence lower gains.
as a function of sensor area and MFC gap.

The total noise of a MTJ sensor has distinct contributions from thermal, shot, random telegraph and $1/f$ electric and magnetic components, being the overall equation given by reference [107]. The minimum detectable field ($D$) of a sensor corresponds to the minimum value of applied field which causes a voltage output equal to the sensor intrinsic noise level ($S_V$). Therefore, to detect magnetic fields in the pT range a sensor with large signal-to-noise-ratio (SNR) is required, combining high sensitivity values with low noise levels. However, in the low frequency range the sensor $S_V$ is dominated by the $1/f$ component. The latter limits the field detection level and is considered to enclose an electric and magnetic component [108]. The magnetic part arises mainly from oscillations in the magnetization of the sensing layer, resulting from domain-wall pinning and depinning at defect sites (i.e., being maximum when the magnetization state is changing) [108,109]. For low frequencies, $D$ can be expressed by [76]:

$$D = \frac{1}{S_V} \sqrt{\frac{\alpha_H}{A \times f}} = \frac{\Delta H}{TMR} \sqrt{\frac{\alpha_H}{A \times f}}$$ (13)

being $S$ the sensor sensitivity at the operating point, $A$ the magnetic area of the sensor, $f$ the operating frequency and $\alpha_H$ the phenomenological Hooge’s parameter. Thereby, the detection level improvement implies: (i) a higher sensitivity steeper magnetotransport curves, (ii) large sensing area and (iii) low $\alpha_H$ value. Figure 26 shows the reported $\alpha_H$ values dependence on the resistance-area product (RA) comparing obtained data for sensors at operating point for simple and soft pinned sensing layer stacks (textured CoFeB/MgO/CoFeB structures including a pinned reference layer). Overall, and for similar RA values, lower $\alpha_H$ values are obtained for stacks with simple sensing layers when compared with soft pinned sensing layer stacks. This difference translates into lower noise levels. These data are framed with reported values for AlOx (squares) whose noise was measured in the saturation state (i.e., in the absence of local magnetization fluctuations), giving a baseline for electric noise in MTJs. For additional reference, $\alpha_H$ values for devices optimized for memory applications, employing different strategies for noise level reduction, are addressed. In all cases only saturated states of hysteretic curves are studied. For micron sized MgO memories, Stearret et al. reported $\alpha_H = 1.3 \times 10^{-10}$µm² higher then our typical values of $\sim 10^{-5}$µm² for RA $\sim$ tens of kΩ µm² [110]. For nanometric memories, Herranz et al. obtained a $\alpha_H \sim 6 \times 10^{-11}$µm² [111], increasing to $\alpha_H = 3 \times 10^{-2}$µm² [112] when a soft pinned sensing layer was used, in line with our presented results [113]. Interestingly, Yu et al. showed that a double barrier of CoFeB-MgO MTJ presents slightly lower hooge values ($\alpha_H = 1.2 \times 10^{-10}$µm² with $RA = 150$ kΩ µm²) than single barrier MgO-MTJs, resembling two single MTJ in series, hence providing improved signal to noise ratio under lower bias voltage [114]. Overall, lower $\alpha_H \sim 10^{-10}$µm² ($\sim 40$ kΩ µm²) values are achieved with single crystalline Fe/MgO/Fe MTJs [115], although for 12 monolayers of MgO a similar increase of $\alpha_H$ to $10^{-9}$µm² was reported [116]. In the latter case, where MgO thickness reaches or overcomes the critical value of Fe lattice matching, C-doping is effective in decreasing $\alpha_H$ to $10^9 \sim 10^{10}$µm², hence decreasing the low frequency noise. This can give an alternative tool to tune MgO junctions for low frequency applications [116,117].

Figure 27 compares the detection levels as function of the sensing area obtained with different sensor layouts (single isolated sensors, arrays of sensors in series, or including MFCs) and also considering distinct types of MTJ stacks namely enclosing simple, SPM-like and soft-pinned sensing layers. Although the use of a soft-pinned sensing layer is an effective strategy to linearize sensors without increasing device footprint, detectivity values two orders of magnitude higher than those achieved using single sensors with simple sensing layers ($\sim$ tens of pTesla) [85,90]
The European Physical Journal Applied Physics

Fig. 26. Hooge parameter for MTJ sensors as a function of RA. Comparison between MgO and AlOx barrier structures. AlOx-MTJ data obtained with devices at saturation from references [119–122]. CoFeB/MgO/CoFeB-MTJ data obtained at operation point. Data marked with i from references [119,123,124] and ii is unpublished data from INESC-MN; α from reference [90]; + from reference [85]; & from reference [42]; δ is unpublished data from INESC-MN; σ from reference [41]; γ from reference [83].

Fig. 27. Detectivity levels for soft-pinned sensing layer MTJ sensors as function of sensing area (at 30 Hz) framed with reported values for simple and SPM-like sensing layer structures. Comparison between single sensors (solid shapes) and sensors with integrated MFCs (half-right shapes). Square shapes represent data for micrometric structures from reference [41], either individual circular sensors (radius of 10, 28 and 36 µm) or series of 952 square sensors (50 × 50 µm² each); pentagonal shape from reference [83] measured at 10 Hz; left-triangle shape from reference [125]; right triangle shape from reference [118] whereas star shape represents data for nanometric circular MTJ pillars (radius 200 nm) from reference [42]. Simple sensing layer data from reference [90] (upward triangle) and [85] (downward triangle), and SPM-like sensing layer results from reference [92].

were systematically obtained by different authors. The limitations in decreasing further the minimum detected field of soft-pinned stacks is most probably a consequence of higher intrinsic noise present in these stacks, resulting from magnetic fluctuations at the sensing layer, due to the adjacent antiferromagnet [113]. In fact, a consistently higher noise level was also measured at the pinned layer inversion point when compared to the sensing layer in MTJ stacks [83,113].

To effectively decrease the detection level of sensors, one can also work on increasing the sensor sensitivity. In this case, when MFCs are incorporated at the sides of single sensors, a detection level enhancement is observed, resulting from the linear operating range reduction (Sect. 3.1). Alternatively, using sensors connected in series, the detection level improves (compared to a single sensor), since the noise level increases by a factor \( \sqrt{N} \) and the sensitivity improves by a factor \( N \), resulting in a final total improvement proportional to \( \sqrt{N} \) [118]. Both strategies have the drawback of increasing the final device footprint, but can be very effective in the detection level enhancement.

4 Conclusions

This paper reviews the different linearization strategies available for TMR sensing applications discussing in detail their implications on the final sensor performance with particular emphasis on sensitivity and detection levels. The linear behavior of MTJs can be engineered with shape anisotropy providing high aspect ratios can be employed and yielding coercive fields lower than 0.1 mT (e.g., for a 20 × 2 µm sensor). In specific applications an external bias field transverse to the sensing direction can promote an hysteresis free curve. Alternatively, ultrathin CoFeB sensing layers close to a SPM-like magnetic behavior can also result in a linear response to in-plane magnetic fields. In this case, sensitivity values of \( \sim 100\%/\text{mT} \) were achieved combined with linear ranges of 0.4 mT but at the cost of considerable TMR loss. On the other hand, MTJs with a soft pinned sensing layer have the advantage of providing linear devices without resorting to shape anisotropy nor external permanent magnets biasing. This route allows a small device footprint or large sensing areas still displaying a linear behavior. An average sensitivity value of 30%/mT was obtained for MTJ pillars with a wide range of dimensions (radius from 10 µm to 36 µm) without TMR loss.

To further strengthen the advantages of TMR sensors we focus on their applications to pTesla detection where linear behaviors with enhanced sensitivity and low noise levels at low frequencies are necessary. To achieve these challenging performances, additional structures such as soft ferromagnetic flux concentrators are included in the chip design. For very large area sensors (1530 µm²) 5 times amplified sensitivities with the lowest detection levels of \( \sim 40\, \text{pT/} \sqrt{\text{Hz}} \) at 30 Hz were reported for CoFeB/NiFe free
layer MTJs. These results outlook MTJ sensors application to biomedical imaging at room temperature and reinforce the position and versatility of magnetoresistive sensors.

The authors would like to thank R.M. Pinto for his contribution in the graphical editing of the document. A.V. Silva and D.C. Leitao thank FCT for grants SFRH/BD/171975/2010 and SFRH/BPD/72359/2010. Work partially supported by projects MAGNETRODES (EU-FP7-ICT-600730), EXCL/CTM-NAN/0441/2012 and PTDC/EII-PRO/3219/2012.

References

Ana V. Silva (born 1980) received her M.Sc. degree in Engineering Physics from Instituto Superior Técnico (IST) of Universidade de Lisboa in 2010, with topic “Analytical modeling of the stress-strain distribution in a multilayer structure with applied bending”, in collaboration with ECTM (TuDelft – Netherlands). She is currently a PhD student at INESC-MN and IST. Her work focus on Nano Magnetic Oscillators, based on low resistance MgO tunnel junctions. Main research areas include magnetoresistive devices for sensing and high frequency applications, device modelling, micro and nanofabrication in IC technology.

Dr. Diana C. Leitao (born 1983) graduated in Applied Physics from Universidade do Porto in 2005, and received her Ph.D. in Physics by the same institution in 2010, on the topic of “Fabrication and characterization of magnetic nanowires and antidots grown using nanoporous alumina templates”. Currently she is a post-doctoral fellow at INESC-MN and an invited assistant professor at the Physics Department of IST, being the co-author of more than 40 papers (researcher ID: C-5125-2009). Her research interests include the development and optimization of nanofabrication processes, electron beam lithography, the fabrication of nanoscale magnetoresistive sensors, and magnetic and magnetotransport characterization of nanostructures and nanodevices.

Prof. Paulo P. Freitas (born 1958) received his Ph.D. in Solid State Physics from Carnegie Mellon University in 1986, followed a postdoctoral stay at IBM Watson Research Labs. He has been a Full Professor at the Physics Department of IST, the leader of the Magnetics & Spintronics group and Director of INESC-MN. Since 2009 he joined the International Iberian Nanotechnology Laboratory (INL – Braga) where he is a deputy director. He received several awards and distinctions related to his work on magnetoresistive biochips and bioelectronics, magnetoresistive sensors, MRAMS, and read heads for ultra high density recording. He is author of more than 350 scientific articles, two patents and inventor of a bioelectronic device. Prof. Freitas supervised 17 Ph.D. students, more than 20 post-doctoral fellows, and develops an intense educational mission to train and coach new scientists and engineers.

Prof. Susana Cardoso de Freitas (born 1973) is a senior researcher at INESC-MN and the co-leader of the Magnetics & Spintronics group at INESC-MN and also an Associated professor at the Physics Department of IST. She is co-author of over 200 publications (researcher ID: B-6199-2013). Since her PhD defence in 2002, she has coordinated several national projects and participated in several EU projects. She is responsible for student training and for services provided by INESC-MN to external partners. Her research interests include advanced thin films in large area wafers and optimization of magnetoresistive sensors for challenging applications.