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Modelling and design of planar Hall effect bridge sensors for low-frequency applications

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Abstract

The applicability of miniaturized magnetic field sensors is being explored in several areas of magnetic field detection due to their integratability, low mass, and potentially low cost. In this respect, different thin-film technologies, especially those employing magnetoresistance, show great potential, being compatible with batch micro- and nanofabrication techniques. For low-frequency magnetic field detection, sensors based on the planar Hall effect, especially planar Hall effect bridge (PHEB) sensors, show promising performance given their inherent low-field linearity, limited hysteresis and moderate noise figure. In this work, the applicability of such PHEB sensors to different areas is investigated. An analytical model is constructed to estimate the performance of an arbitrary PHEB sensor geometry in terms of, e.g., sensitivity and detectivity. The model is valid for an ideal case, e.g., disregarding shape anisotropy effects, and also incorporates some approximations. To validate the results, modelled data was compared to measurements on actual PHEBs and was found to predict the measured values within 13% for the investigated geometries. Subsequently, the model was used to establish a design process for optimizing a PHEB to a particular set of requirements on the bandwidth, detectivity, compliance voltage and amplified signal-to-noise ratio. By applying this design process, the size, sensitivity, resistance, bias current and power consumption of the PHEB can be estimated. The model indicates that PHEBs can be applicable to several different areas within science including satellite attitude determination and magnetic bead detection in lab-on-a-chip applications, where detectivities down towards $1 \text{ nTHz}^{-0.5}$ at 1 Hz are required, and maybe even magnetic field measurements in scientific space missions and archaeological surveying, where the detectivity has to be less than $100 \text{ pTHz}^{-0.5}$ at 1 Hz.

Keywords: Magnetoresistance, Planar Hall effect, Low-frequency noise, Detectivity

Abbreviations¹

1. Introduction

Since the invention of the compass in 11th century China [1], magnetic field sensors have become essential in an increasing number of technology areas. Nowadays, magnetic sensor systems, or magnetometers, are employed in, e.g., electronic compasses [2, 3], archaeological surveys [4, 5], different space applications [6-8], and as bio-sensors [9, 10]. Two key features in a magnetic field sensor are the field range and the detectivity, i.e., the maximum and minimum field strength the sensor can accurately detect. The dynamic field range and detectivity of some commercial magnetic sensors are presented in Fig. 1, along with their applications.

In most of the applications requiring detectivities of less than $0.1 \text{ nTHz}^{-0.5}$ at 1 Hz, bulky instruments such as fluxgate magnetometers and different kinds of optically pumped magnetometers have been the only viable options [4-7]. However, in recent years miniaturized versions of these instruments have been developed, with a total system mass of around 0.1 kg [11, 12]. Nevertheless, reducing the mass further has proven difficult, and the interest for different thin-film magnetic field sensors, based on magnetoresistance, has therefore increased, since these sensors allow for extreme miniaturization due to their inherent compatibility with micro- and nanofabrication techniques [13].

FIG. 1. Dynamic field range and detectivity of some magnetometers and magnetic field sensors, along with their applications. Here, the examples for archaeology were a Geoscan Research FM256 Fluxgate Gradiometer, a Bartington Grad-601, a Scintrex SM-4, and a Geometrics G-858, the examples for scientific space missions were fluxgate magnetometers from the Rosetta (lander and orbiter), Themis, Cluster, Venus Express, and SMILE missions,

¹AMR – Anisotropic magnetoresistance, GMR – Giant magnetoresistance, TMR – Tunneling magnetoresistance, PHE – Planar Hall effect, PHEB – Planar Hall effect bridge, PSD – Power spectral density, SRS – Standard Research Systems

the examples for attitude control were a Billingsley TFM100S, a Lusospace AMR magnetometer, and a MEMSense AD System, and the examples for electronic compasses were an AOSI EZ-COMPASS-3AH-360, a Honeywell HMR2300 and a Honeywell HMC2003.

In space applications, magnetoresistive sensors based on anisotropic magnetoresistance (AMR) [14], giant magnetoresistance (GMR) [15], and tunnelling magnetoresistance (TMR) [16] have been proposed. However, their inherent low-frequency noise has so far limited them for use in less sensitive attitude determination systems [17, 18], Fig. 1, and radiation tolerant memory circuits [19]. Other disadvantages with magnetoresistive sensors are their relatively poor linearity and pronounced hysteresis, requiring the sensors to be biased with an external magnetic field. However, given its simple function not requiring any complicated supporting electronics, a magnetoresistive sensor with sufficient detectivity would, potentially, reduce the system mass by more than two orders of magnitudes as compared to miniaturized fluxgates. Such a magnetometer would not only allow for small satellites to be equipped with highly sensitive magnetometers, but also for completely new types of missions such as high-resolution mapping of small-scale magnetic features, e.g., Alfvénic turbulence [20], by one or many satellites equipped with hundreds of distributed magnetometers.

In the field of medicine there is a constant search for more sensitive and reliable diagnostic methods [21, 22]. In some cases only minute amounts of a target substance separate a positive from a negative sample. The presence of this target must then be translated into a measureable response. One attractive approach is to use magnetic biosensors utilizing magnetic nanoparticles. The particles become magnetized when exposed to an external magnetic field and their surface can be functionalized to react specifically with the target [23]. The biosensors detecting the presence of the target are either surface or volume based. In case of surface based detection, the sensor surface is labeled with magnetic particles. The labeling will take place in relation to the amount of target in the sample. Large amounts of target translate into a high surface coverage of particles and hence a strong signal in the sensor. Surface-based magnetic biosensing has been presented using, e.g., GMR sensors [24], Hall effect sensors [25], and GMI sensors [26]. In case of volume based detection, the particles are free to move around in the sample volume during the measurement. One method used for volume based detection is the Brownian relaxation principle. This method uses the fact that the increase of the hydrodynamic volume of a magnetic particle bound to a biological target results in a shift of the Brownian relaxation frequency relative to that for particles not bound to the biological target. This shift can be large enough to be registered by a magnetic field sensor [27, 28], Fig. 1. Typically, these kinds of measurements take place at frequencies ranging from 1 Hz to 100 kHz, which requires a sensor with low noise within this frequency interval. One way to increase the measurement sensitivity of the Brownian relaxation method could be to use a miniaturized sensor, with a size matching that of the ensemble of particles being measured upon. In order to get a proper read-out, 10^4 - 10^5 particles are measured upon simultaneously, covering a surface of approximately $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ [29, 30]. For a monodisperse iron-oxide nanoparticle ensemble with $N_p = 10^5$ particles, a particle diameter of 100 nm, and an applied AC magnetic field with amplitude $\mu_0 H = 1\text{ mT}$, the magnetic field due to the ensemble of particles that would be measured by a chip-based sensor after sedimentation is about $0.5\text{ }\mu\text{T}$ [31]. The position of a particle with respect to the sensor area is an important error factor. The effect of this is mitigated by using a large enough ensemble of particles and a sensor covering the same area as the particle ensemble in combination with a shallow microfluidic channel in which the sensor is placed. In such a case, with the particles statistically distributed over the sensor area, one may expect that the error in the measured magnetic field should scale as $N_p^{-1/2}$.

Among the magnetoresistive sensor techniques, sensors based on the planar Hall effect (PHE) have started to generate much interest. These employ the off-diagonal terms of the magnetic field-dependent resistivity tensor of an AMR sensor [32, 33]. PHE sensors have an intrinsically linear low-field response with small hysteresis, combined with a relatively moderate low-frequency noise as compared to, e.g., GMR and TMR sensors [34, 35]. Among magnetoresistive sensors, the closest analogy to PHE sensors are barber pole AMR sensors that share the moderate low-frequency noise [36], but are linearized by barber-pole shaped electrodes on top of the ferromagnetic sensor strip, rotating the current vector in the strip by 45° to its length [37]. However, only the powered part of the sensor strip will contribute to the sensitivity of the sensor, i.e., the part of the strip beneath the barber-pole electrodes will not contribute to the magnetoresistive signal. A PHE sensor, on the other hand, utilizes the whole of the ferromagnetic layer and therefore a PHE sensor can potentially be smaller than an equivalent barber pole AMR sensor. Furthermore, if structured in a Wheatstone bridge configuration, it has been shown that the sensor output of a PHE sensor can be enhanced by more than a factor of 100, as compared to the traditional cross-shaped designs [38]. In this paper, the applicability of such PHE bridge (PHEB) sensors to low-frequency magnetic field measurements is investigated by constructing an analytical model for the detectivity of an arbitrary PHEB sensor design. The model is also implemented to find the optimum design of a PHEB, given certain requirements on e.g. detectivity and bandwidth. Moreover, the modelled data is compared with results obtained from measurements on PHEB sensors to evaluate the validity of the model.

2. Theory

The PHE voltage, V_y , of a single-domain, cross-shaped PHE sensor, magnetized in-plane along the unit vector $\hat{\mathbf{m}} = (\cos \theta, \sin \theta)$, where θ is the angle between the magnetization vector and the anisotropy axis, is ideally given by

$$V_y^{\text{cross}} = I \Delta \rho \sin(2\theta) (2t_{\text{FM}})^{-1}, \quad (1)$$

where I is the uniform current through a sensor layer of thickness t_{FM} and $\Delta \rho = \rho_{\parallel} - \rho_{\perp}$ is the difference in resistivity with the magnetization parallel and perpendicular to I , respectively [34].

The PHE voltage can be increased by structuring the sensor in a Wheatstone bridge configuration, having branches at $\alpha = \pm 45^\circ$, where α is the angle between the branch current vector and the anisotropy axis [38]. The PHE voltage of a single segment PHEB is given by

$$V_y^{\text{PHEB}} = (lI \Delta \rho \sin(2\theta)) (2wt_{\text{FM}})^{-1}, \quad (2)$$

where l is the length and w is the width of each branch in the bridge [38].

To improve the signal-to-noise ratio of the bridge even further, each branch can be made up of a number of segments, cf. Fig. 2, each with length l and width w , connected in series. The PHE voltage of a PHEB with n such segments is given by

$$V_y = (nlI \Delta \rho \sin(2\theta)) (2wt_{\text{FM}})^{-1}. \quad (3)$$

Assuming the PHEB to be exchange biased along the x axis, cf. Fig. 2, the sensitivity, Σ , at small magnetic fields along the y axis, H_y , is ideally given by

$$\Sigma = \mu_0^{-1} (\partial V_y / \partial H_y) = [nIl \Delta\rho] \cdot [\mu_0 wt_{\text{FM}} (H_{\text{ex}} + H_K)]^{-1}, \quad (4)$$

where H_{ex} and H_K are the exchange-bias and anisotropy fields, respectively [38, 39].

FIG. 2. Design of a PHEB with branches consisting of n segments of length l and width w , separated by a distance p . The electrical connections were defined to give the sensors a positive sensitivity.

The two most prominent noise sources inherent to a PHEB are thermal noise and $1/f$ noise. Here, the former dominates at high frequencies and the latter at low frequencies, respectively. The two noise regimes are separated by the so called knee frequency, f_k . The power spectral density (PSD) of the thermal noise is given by the Johnson-Nyquist equation

$$S_T = 4k_B T R, \quad (5)$$

where k_B is Boltzmann's constant, T is the absolute temperature, and $R = \rho n l (wt_{\text{FM}})^{-1}$ is the resistance of each PHEB branch [40]. The PSD of the $1/f$ noise is described by the phenomenological Hooge equation

$$S_{1/f} = V^2 \gamma_H (n_C f)^{-1}, \quad (6)$$

where $V = IR$, γ_H is the dimensionless Hooge parameter, $N_C = n_C n l w t_{\text{FM}}$ is the number of charge carriers in a branch, n_C is the charge-carrier density, and f is the frequency [41].

The detectivity D_B of a PHEB sensor is given by the ratio between the voltage noise and the sensitivity according to

$$D_B = S_V^{1/2} \Sigma^{-1} = (S_T + S_{1/f})^{1/2} \Sigma^{-1}, \quad (7)$$

where S_V is the total inherent noise PSD of the PHEB [13].

It should be noted that all the above equations depict an idealized case where factors like demagnetizing effects, domain formation and current shunting through the layers of the stack are excluded. If the above expressions are used when part of the current is shunted through other layers than the ferromagnetic layer of the stack, the effect of the current shunting reduces the apparent value of $\Delta\rho$, which can then be considered an effective value.

3. Materials and methods

In this study, two sets of seven PHEB sensors each, labelled A and B, were examined. The sets differed with regard to the thickness, t_{FM} , of the ferromagnetic NiFe layer, which for set A was 30 nm and for set B was 45 nm. The design of the sets A and B can be seen in Fig. 2.

The PHEBs were structured, using UV-lithography and lift-off from a thin-film stack deposited by magnetron sputtering, on a thermally oxidized Si wafer. The thin film stack had four layers, top-down; Ta (5 nm) / Ni₈₀Fe₂₀ (30 nm or 45 nm) / Mn₈₀Ir₂₀ (20 nm) / Ta (5 nm), where subscripts denote the nominal concentration in at. % and numbers in parentheses denote the film thickness. In order to define the direction of the easy axis of the NiFe layer, and the exchange coupling between the NiFe and MnIr layers, a magnetic field of 20 mT was applied along the x axis during sputtering (Fig. 2). Each PHEB consists of n segments of length l and width w , making nl the total length of a PHEB branch. The 14 PHEBs differed with regards to either t_{FM} , l , or n according to Tab. 1.

Before being characterized, the PHEBs were attached to a printed circuit board through wire bonding. The sensitivity of a PHEB sensor was calculated from the in-phase component of the PHE voltage while sweeping the magnetic field between $\mu_0 H_y = \pm 40$ mT along the y axis, Fig. 2. The sensors were biased with an alternating current $I_{\text{p-p}} \sin(2\pi ft)$ with $I_{\text{p-p}} = 1$ mA and $f = 2.2$ kHz using a Keithley 6221 current source. The PHE voltage was amplified 40 dB by a Stanford Research Systems (SRS) SRS552 preamplifier and measured by an SRS SR830 lock-in amplifier.

TAB. 1. Thickness, length, number, and width of segments of the PHEBs of sets A and B.

<i>PHEB</i>	t_{FM} [nm]	l [μm]	n	w [μm]
A1	30	300	1	30
A2	30	450	1	30
A3	30	600	1	30
A4	30	750	1	30
A5	30	600	3	30
A6	30	600	5	30
A7	30	600	7	30
B1	45	300	1	30
B2	45	450	1	30
B3	45	600	1	30
B4	45	750	1	30
B5	45	600	3	30
B6	45	600	5	30
B7	45	600	7	30

For the noise measurements, a direct current of $I = 10$ mA, supplied from a series of lead-acid batteries, was used to bias the sensors. The noise was amplified by 40 dB using an HMS Electronics Model 565 low-noise amplifier before being recorded by an HP 35670A spectrum analyzer. The inherent Johnson noise level of the amplifier was $1.24 \text{ nVHz}^{-0.5}$. Two overlapping frequency ranges were used during the measurements; 125 mHz to 200 Hz and 8 Hz to 12.8 kHz. The noise measurement set-up is described in detail in reference [35].

4. Analytical model

It is not obvious how different parameters – length, width, thickness, bias current, etc. – influence the sensitivity and detectivity of a PHEB. For example, H_{ex} , H_K , and $\Delta\rho$ all depend on t_{FM} but in different ways. An analytical model was therefore constructed in order to visualise how the different parameters influence the performance of the bridge. The validity of the model was verified by comparing the analytical results to experimental data obtained from measurements on the PHEB sensors A1-7 and B1-7.

The dependency of $\Delta\rho$ on t_{FM} was first modelled as in reference [35] by $\Delta\rho = t_{\text{FM}} \times 0.186 \text{ } \Omega$. Of the two sets of PHEBs used to verify the model, set B had a slightly lower AMR than predicted by the model and the relation for $\Delta\rho$ was adjusted to $\Delta\rho = t_{\text{FM}} \times 0.151 \text{ } \Omega$ to account for this discrepancy. The model for $\Delta\rho$ is only valid for relatively small thicknesses, up to around 50 nm [34], since $\Delta\rho$ eventually saturates as t_{FM} increases. However, the maximum thickness of the NiFe layer was limited by the ability of the exchange bias to maintain the single domain configuration and, since this limit was in the same thickness range, the maximum thickness of this study was set to 50 nm.

The resistivity of the PHEBs was assumed to be equal to the resistivity of the NiFe layer, $\rho_{\text{Ni-Fe}} = 0.183 \text{ } \mu\Omega\text{m}$, given that $\rho_{\text{Ni-Fe}} \ll \rho_{\text{Mn-Ir}} < \rho_{\text{Ta}}$ [42]. Similarly, the charge-carrier density, n_C , of the PHEBs was estimated from the charge-carrier density of $\text{Ni}_{80}\text{Fe}_{20}$, $n_{C(\text{Ni-Fe})} = 17 \times 10^{28} \text{ m}^{-3}$ [43], assuming that the main part of the current is carried by the NiFe layer. The Hooke parameter $\gamma_H = 0.016$ was taken from reference [35].

The dependency of H_{ex} and H_K on t_{FM} was modelled as in reference [34] by curve fitting to the reported data. Both fields followed a $(t_{\text{FM}})^{-1}$ -dependence and the best curve fits were

$$\begin{aligned} \mu_0 H_{\text{ex}} [\text{T}] &= 9.3 \times 10^{-11} (t_{\text{FM}} [\text{m}])^{-1} - 4.3 \times 10^{-4} \\ \mu_0 H_K [\text{T}] &= 1.7 \times 10^{-11} (t_{\text{FM}} [\text{m}])^{-1} - 5.5 \times 10^{-5} \end{aligned} \quad (8)$$

The overall dependence of D_B on n , l , w , and t_{FM} varies depending on whether S_T or $S_{1/f}$ dominates the noise spectrum, and if the current, or the current density, $J = I/(wt_{\text{FM}})^{-1}$, is assumed to be constant. All these dependencies were calculated by curve fitting to the model, Tab. 2. The same dependencies can be found by inserting the expressions for $\Delta\rho$ and J , along with Eq. (8), into Eq. (7) confirming that the model produced well-conditioned data.

TAB. 2. Dependencies of D_B on the different parameters in the analytical model.

<i>Low f</i>		<i>High f</i>	
<i>Constant J</i>	<i>Constant I</i>	<i>Constant J</i>	<i>Constant I</i>
$(nl)^{-0.5}$	$(nl)^{-0.5}$	$(nl)^{-0.5}$	$(nl)^{-0.5}$
$w^{-0.5}$	$w^{-0.5}$	$w^{-0.5}$	$w^{0.5}$
$t_{\text{FM}}^{-2.5}$	$t_{\text{FM}}^{-2.5}$	$t_{\text{FM}}^{-2.5}$	$t_{\text{FM}}^{-1.5}$

In Tab. 2, the right side includes the fewest approximations (H_{ex} , H_K , $\Delta\rho$, and ρ) and data from this region should be more reliable than data from the left side of the table including more approximations (H_{ex} , H_K , $\Delta\rho$, ρ , n_C , and γ_H). Modelled $\mathcal{S}$ and D_B of a PHEB with t_{FM}

between 20 nm and 50 nm, nl between 100 μm and 1 mm, $w=30\text{ }\mu\text{m}$, $I=10\text{ mA}$, and $f=10\text{ Hz}$ are presented in Fig. 3.

FIG. 3. (Colour online) Predicted Σ (a) and D_B at 10 Hz (b) of a PHEB with $w=30\text{ }\mu\text{m}$ as a function of nl and t_{FM} .

5. Verification

The reliability of the analytical model was verified by comparing the modelled data with results obtained from actual measurements. The modelled detectivity of the PHEBs A1-A7 agrees well with the measurements displayed in Fig. 4. The mean deviation in D_B between the model and the measurements is 5.0% at 10 Hz.

FIG. 4. Analytical and measured results for D_B versus f of PHEBs A1-A7, A1 having the highest and A7 having the lowest D_B .

FIG. 5. Dependency of D_B at 10 Hz on nl for PHEBs A1-A7 and B1-B7 as well as corresponding data from the analytical model.

The dependence of D_B at 10 Hz on nl for PHEBs A1-A7 and B1-B7 as well as model data for PHEBs with l spanning from 0.1-4 mm and n from 2-100, and thicknesses of either $t_{FM}=30$ nm or $t_{FM}=45$ nm, are presented in Fig. 5. For set B, the model underestimates D_B as nl , or rather l , increases. This is assumed to be caused by shape anisotropy effects as the demagnetizing field of the segments become comparable to $H_{ex}+H_K$ [39]. The mean deviation between the model and the measurements for PHEBs B1-B7 is 13%.

Hence, the theoretical model will only deliver accurate predictions for, e.g., D_B , for dimensions where the effect of the shape anisotropy on the sensitivity and/or the magnetic noise are insignificant. Nevertheless, the modelled data is of the correct order of magnitude, and the model can therefore be used to estimate the performance of a certain PHEB design, or to guide the optimization of a bridge design to meet certain application requirements.

6. Design study

In an application, the PHEBs will be integrated into a system, including supporting structures (e.g. a microfluidic system for lab-on-a-chip or a boom for space applications) as well as electronics. The latter typically consists of a buffer stage and a preamplifier for isolating the signal, along with an analogue-to-digital converter, and a data acquisition unit.

When designing a PHEB for a particular magnetometer, there are a number of requirements that have to be specified before choosing its geometry. In particular, the frequency bandwidth, f_{min} - f_{max} , and the detectivity at f_{min} , $D_{B min}$, are important. Moreover, the supply voltage, V_S , and the internal noise of the buffer stage and the preamplifiers, S_{Amp} , will also affect the design. Here, the designs of three magnetometers, labelled MGM1-MGM3, are discussed. The requirement specifications of the magnetometers, presented in Tab. 3, were chosen arbitrarily, hence not relating to any particular application.

TAB. 3. Requirement specifications of MGM1-MGM3.

	$f_{min}-f_{max}$	$D_{B\ min}$	V_S	S_{Amp}
MGM1	0.1 Hz – 10 kHz	1 nTHz ^{-0.5} @0.1 Hz	5 V	1 nVHz ^{-0.5}
MGM2	1 Hz – 10 kHz	1 nTHz ^{-0.5} @1 Hz	5 V	1 nVHz ^{-0.5}
MGM3	10 Hz – 10 kHz	1 nTHz ^{-0.5} @10 Hz	5 V	1 nVHz ^{-0.5}

The first step of the design process is to define t_{FM} and, since an increase of t_{FM} is the most effective measure to suppress both $S_{1/f}$ and S_T , it should be made as thick as possible. The maximum thickness is, as already mentioned, around 50 nm.

Due to different dependencies of the detectivity on size and bias current in the high- and low-frequency regions (cf. Tab. 2), there are two ways of approaching the remaining part of the bridge design, depending on if the bridge is optimized either to minimize the chip size or the power consumption.

The smallest bridge possible fulfilling the requirement set by $D_{B\ min}$ can be found by making the $1/f$ -noise dominant at f_{min} . This implies that the frequency-independent part of the detectivity, i.e. the high-frequency region, should be suppressed by increasing I , resulting in high power consumption.

If, instead, low power consumption is required, the bias current should be kept small. The minimum current fulfilling the requirement set by $D_{B\ min}$ can in this case be found by making the thermal noise dominant at f_{min} . Contrary to the previous case of minimum size, this requires that the $1/f$ noise is suppressed by increasing the size of the bridge.

Depending on the design, the current density J is calculated at f_{min} , assuming the dominant noise source to be one order of magnitude stronger than the opponent, shifting the knee frequency of the detectivity about one decade out of the particular noise regime. Hence, $S_{1/f}(f_{min}) \geq 10S_T(f_{min})$ in the minimum size case, and $S_T(f_{min}) \geq 10S_{1/f}(f_{min})$ in the minimum power case, yielding

$$J_{size} = \sqrt{40k_B T n_c f_{min} (\rho \gamma_H)^{-1}}, \quad (8)$$

$$J_{power} = \sqrt{4k_B T n_c f_{min} (10\rho \gamma_H)^{-1}}, \quad (9)$$

where J_{size} and J_{power} are the current densities in the minimum size and minimum power cases, respectively.

With J defined as either J_{size} or J_{power} , l , w , and n can be calculated from the theoretical model. The relationship between these three parameters differs somewhat depending on the desired footprint of the sensor chip. For a 2:1 footprint (length:width), n is the largest odd integer fulfilling $n < 2^{-0.5} l(w+p)^{-1}$. The calculations below were performed for this design. Moreover, n must also fulfil $V_S > IR = J \rho n l$ to meet the requirement set by the supply voltage.

According to the requirements, D_B should be less than or equal to $D_{B,min}$ at f_{min} . Another requirement is that S_{Amp} should be smaller than S_V so that the bridge signal is not drowned by amplifier noise. A reasonable requirement is that $S_V \geq 10S_{Amp}$. Many sets of (l, w, n) fulfil these two requirements as can be seen in Fig. 6. However, it is convenient to choose the set with the

smallest l . Now, the power consumption, $P=I^2R=J^2\rho n l w t_{\text{FM}}$, and the area of the whole PHEB can be calculated. The total area of the chip containing the PHEB is approximately $4l(2^{-0.5}n(w+p)+2l)$, assuming it to be cut along the x and y axes of Fig. 2.

FIG. 6. Sets of l , w , and n that fulfil the requirements of MGM3 in the minimum size design (n varies with l and w according to $n < l(w+p)^{-1}$).

By applying this design process to the requirements of MGM1-MGM3 (Tab. 3), the size, sensitivity, resistance, bias current and power consumption of the magnetometers can be calculated (Tab. 4). The resulting D_B spectra of the magnetometers are presented in Fig. 7. For comparison to Fig. 1, the calculated values of D_B at 1 Hz in the minimum size case are $0.38 \text{ nTHz}^{-0.5}$, $1.0 \text{ nTHz}^{-0.5}$ and $3.0 \text{ nTHz}^{-0.5}$ for MGM1-MGM3, respectively.

TAB. 4. Properties of MGM1-MGM3 aiming at minimum size (top) and minimum power (bottom), all with $t_{\text{FM}}=50 \text{ nm}$.

Minimum size	J_{size} [Am ⁻²]	l [μm]	w [μm]	n	Σ [V/T]	R [Ω]	I [mA]	P [mW]	A [mm ²]
MGM1	$9.6 \cdot 10^8$	230	96	3	3.6	45	4.6	0.96	0.84
MGM2	$3.0 \cdot 10^9$	79	27	3	3.9	55	4.1	0.93	0.10
MGM3	$9.6 \cdot 10^9$	36	6.2	3	5.7	110	3.0	0.97	0.020
Minimum power	J_{power} [Am ⁻²]	l [μm]	w [μm]	n	Σ [V/T]	R [Ω]	I [mA]	P [μW]	A [mm ²]
MGM1	$9.6 \cdot 10^7$	590	65	11	3.4	620	0.31	61	5.5
MGM2	$3.0 \cdot 10^8$	210	22	9	3.1	530	0.34	60	0.69
MGM3	$9.6 \cdot 10^8$	87	7.0	7	3.2	540	0.33	62	0.12

The design process presented here, shows how system requirements, such as voltage compliance, power consumption and bandwidth, can be translated into sensor specific parameters, such as length width and number of segments, in an optimum way. Although the given examples were based on arbitrary requirements, the process could be a powerful tool for an engineer designing a PHEB sensor for, e.g., a satellite platform or a magnetic bead detection system.

It should again be noted that the model was based on an ideal case where, e.g., shape anisotropy effects are disregarded. The shape anisotropy will result in a decrease of the sensitivity and moreover it may affect the magnetic part of the $1/f$ noise [35]. Hence, shape anisotropy may have a double negative effect on the detectivity. Consequently, designs with a high length-to-width ratio, i.e. high shape anisotropy, should be used with caution.

FIG. 7. D_B versus f of MGM1-MGM3 with requirements from Tab. 3 and parameters from Tab. 4.

7. Conclusion

Summarizing, a theoretical model to estimate the detectivity of an arbitrary PHEB sensor geometry has been evaluated, and a design process to optimize the dimensions of such a PHEB, given certain requirements, has been developed. The model employs a number of estimations of material specific parameters, e.g. for the exchange bias and anisotropy fields, but it still generates predictions that compare well with available experimental data. The manufactured sensors are sensitive to variations in the fabrication process, influencing, e.g., the anisotropic magnetoresistance. Nevertheless, by improved control of the fabrication process and by employing, e.g., post-annealing of the samples [44, 45], the variation of these properties may diminish, making the model useful as a design tool for PHEB magnetometers. We have demonstrated the use of the model for optimizing the sensor geometry and driving current to minimize the sensor dimension or the power consumption given certain sensor requirements. The experimental validation of the proposed geometries is the topic of our future work.

The modelled performances of MGM1-MGM3 indicate that PHEBs are potentially applicable to a large number of science areas. Comparing with Fig. 1, they are already applicable to e.g. magnetic biodetection and satellite attitude determination, but may also have potential for archaeological surveying and for scientific space missions studying, e.g., the magnetosphere.

Biographies

Anders Persson was born in 1982. He received his MSc in Engineering Physics in 2007, and his PhD in Microsystems Technology in 2011, both from Uppsala University, Sweden. He is

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Klas Gunnarsson was born in 1962. He received his MSc degree in Engineering Physics in 1986 and his PhD degree in Solid State Physics in 1992, both at Uppsala University. Since 2001, Klas Gunnarsson is employed as a researcher at the department of Engineering Sciences, Uppsala University. His field of research comprises nanomagnetism, biomagnetism, spin dynamics and magnetic materials.

Hugo Nguyen received the M.Sc. degree in machine engineering in 1992 at Lund Institute of Technology and PhD degree in engineering physics specializing in microsystems technology in 2006 at Uppsala University, both in Sweden. He has been involved in the design of all nanosatellites proposed by the Ångström Space Technology Centre at Uppsala University and has a special interest in all kinds of interfaces between micro- and macro-systems, as well as within microsystems, for both space and non-space applications. Currently, he is conducting a project resulting in a magnetoresistive magnetometer for 3-D measurement of magnetic fields in space.

Giovanni Rizzi, born in 1986 in Milano, Italy, received his MSc degree in Engineering Physics in 2010 at Politecnico di Milano. He is currently working as a PhD student at the Technical University of Denmark. His research is focused on developing planar Hall effect sensors as a platform for biological assays. His present interests comprise lab-on-a-chip systems, biosensors and magnetic sensors.

Mikkel Fougth Hansen was born in 1971 and obtained his MSc degree in physics from University of Copenhagen in 1995 and his PhD degree in physics in 1998 from the Technical University of Denmark. He then pursued post-doctoral positions at Uppsala University and at the Center for Magnetic Recording Research at the University of California, San Diego. Since 2002 he has been associate professor at DTU Nanotech, Department of Micro- and Nanotechnology. His present research interests include magnetic lab-on-a-chip systems, magnetic nanoparticles, magnetic biosensors and applications there of.

Peter Svedlindh was born in 1956 and obtained his MSc degree en engineering physics from Uppsala University in 1980 and his PhD degree in solid state physics in 1985 from the same university. He worked as a researcher at Uppsala University and at the National Defence Research Establishment in Stockholm between 1986-2003, after which he obtained a senior lecturer position at Uppsala University. Since 2000 he is a professor in solid state physics at the Department of Engineering Sciences. His present research interests include spin dynamics, magnetic thin films, magnetic nanoparticles, magnetic biosensors and applications there of.

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