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COMPACT CURRENT-SPUN 3D MAGNETIC FIELD SENSING MODES FOR AN INVERTED PYRAMID HALL-EFFECT SENSOR

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ABSTRACT

This paper reports two novel sensing modes for the 3-axis Hall-effect sensor based on an inverted pyramid structure. The proposed current-spinning schemes enable 3-axis magnetic field measurements with reduced readout complexity (6 less switching phases for 3D1) while preserving sensitivity and offset. Residual offsets in the millitesla range at 1 V supply voltage were measured on three identical samples using 6- or 12-phase current spinning sequences, with in-plane voltage and current-related sensitivities up to 16.7 mV/V/T and 86.1 V/A/T, respectively. These modes represent a more efficient and simpler readout method for the pyramid sensor, while remaining competitive with the state-of-the-art.

KEYWORDS

3D Magnetic Sensor, Hall Effect, Current Spinning, Inverted Pyramid, 3-Axis Measurements

INTRODUCTION

Hall-effect sensors remain the dominant technology in the magnetic sensor market due to their simplicity, reliability, and CMOS-compatibility. These benefits extend to 3-axis sensing implementations, increasingly relevant for commercial applications such as joysticks and contactless current/power sensors.

Traditional CMOS-compatible 3-axis sensors rely on a combination of lateral Hall devices (LHDs) to sense out-of-plane fields and vertical Hall devices (VHDs) to sense in-plane fields [1]. However, VHDs exhibit a trade-off between offset and sensitivity [2], limiting the performance of the in-plane axes. Alternative concepts, such as the hexagonal prism [3] and Hall sensors with integrated magnetic concentrators (IMCs) [4], solve these drawbacks, but they suffer from limited CMOS integration, larger footprints, or reduced dynamic range.

In previous work [5], we presented a novel 3-axis Hall effect device based on an inverted pyramid structure, which exhibited a low footprint, high sensitivity and isotropy. In addition, we proved that current spinning, an offset-reduction technique in which input and output ports are periodically swapped and averaged, can be applied to the pyramid sensor [6]. We applied current spinning [7] to one in-plane (X/Y) and two out-of-plane (Z1/Z2) bias-sense configurations (modes), and the measured residual offset was one to three orders of magnitude lower than the initial raw offset. These modes, however, do not allow for simultaneous sensing of the three components of the magnetic field. To sense 3-axis fields, in-plane and out-of-plane modes must be continuously swapped. Therefore, switches are required to short different terminals, but in CMOS technology these elements are generally high resistance and mismatched [8-9], which causes a higher residual offset according to experience.

In this work, we present for the first time two fully 3-axis current-spun sensing modes (3D1 and 3D2), designed for direct implementation in readout circuitry while utilizing fewer switches than our previous proposed scheme. These new modes allow for *xyz*-magnetic field sensing in a compact and straightforward fashion. In the following sections, we introduce the sensor working principle and describe the new working modes. Then, we present the characterization results, focusing on the sensitivity and residual offsets of the new 3D modes. Lastly, we compare these modes with the state-of-the-art.

SENSOR CONCEPT AND OPERATION

Sensor design and working principles

A SEM image and a schematic representation of the sensor are reported in Figure 1. The device features an inverted silicon pyramid with a base width (p) of 50 μm and sidewalls tilted at 54.74° . The sidewalls are n-type doped, with a peak concentration of approximately $5 \times 10^{16} \text{ cm}^{-3}$ and a junction depth of about 1 μm . Eight n^+ contacts, 5 μm wide at the corners (c) and 10 μm at the mid-sides (s), are formed for electrical access. The structure is passivated with 300 nm of LPCVD silicon dioxide, and vias are opened 10 μm from the pyramid base for metal interconnection. More details about the manufacturing of this device are reported in [5-6].

Figure 1 also displays the working principle of the pyramid sensor. Although the figure is a simplified representation and not fully accurate in all details, it helps to clarify the physics of the device. To sense in-plane magnetic fields two antiparallel supply currents, orthogonal to the field, must flow towards different sensing contacts. This way, the in-plane field will produce a Lorentz force that pushes the two currents in opposite directions, one closer and the other further away from the sensing contact. An electric field arises from this charge separation that counteracts the action of the Lorentz forces, generating in turn a differential Hall voltage. An out-of-

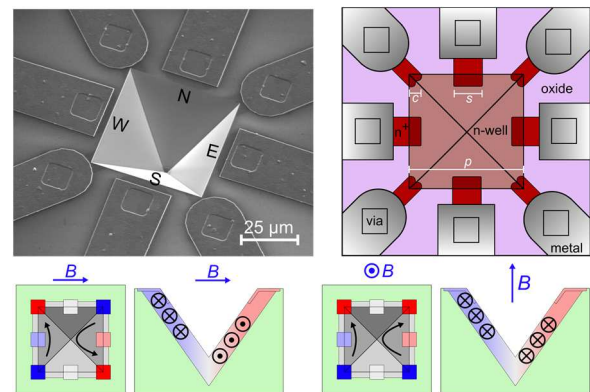


Figure 1: Top: SEM image of pyramid sensor, and sketch of main layers and geometric features. Bottom: simplified working principle.

plane field, instead, will generate a force that pushes both currents in the same direction, producing a common mode voltage that is not sensed by the differential readout. To detect out-of-plane fields, instead, parallel supply currents must be employed.

Two novel current-spun sensing modes: 3D1 and 3D2

While several modes exist to operate this device, not all of them are suitable for implementation in the pyramid Hall sensor. In fact, there is a crucial criteria that must be respected: the mode must be current-spinnable.

Current spinning is, by far, the most effective offset cancellation technique for Hall-effect sensors, allowing a three to four orders of magnitude reduction of the raw offset [10]. In addition, it modulates the flicker noise to high frequencies, improving the signal-to-noise ratio of the Hall device. In [6], we proved the existence of three modes (X/Y, Z1 and Z2) that respect this condition.

While these modes are suitable for in-plane or out-of-plane field measurements, they cannot be directly employed in 3-axis sensing since different field components require different terminals to be permanently shorted by wires. In general, it is reasonable to switch between modes by employing a benchtop or PCB switch matrix, but this is not the case for integrated circuits. In fact, the typical on-resistance (R_{on}) of a transistor in a 180-nm CMOS process is on the order of 100 Ω to 1 k Ω [8]. In addition, the R_{on} values of these switches are generally mismatched [9], which leads to larger residual offsets. To solve this issue, we developed two novel current-spun modes, 3D1 and 3D2, conceptually described in Figure 2.

Mode 3D1 is a 6-phase spinning scheme where opposite corner contacts are permanently shorted. In each phase, two different components of the magnetic field can be sensed. Specifically, Phase 1 and 4 allow the extraction of the x - and y -fields, Phase 2 and 5 of the x - and z -, while Phase 3 and 6 of the y - and z -components. It can be noticed that mode 3D1 is essentially a combination of mode X and Y from [6], where the z -field is extracted from the unused terminals of the spinning schemes. Mode 3D2, instead, can be seen as a decomposition of mode 3D1. Each sidewall, named N, S, E and W (Figure 1), is current spun separately and then reconstructed in post-processing leveraging superposition. In particular, the x -signal is obtained by summing the outputs from W and E, while the y -signal is reconstructed similarly from the N and S. The z -

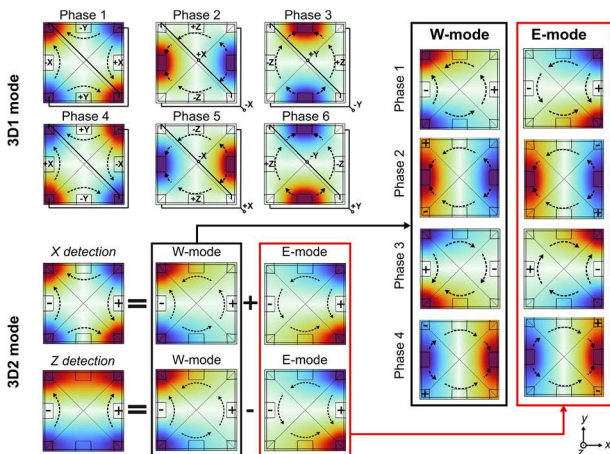


Figure 2: Spinning sequences of the two 3D modes.

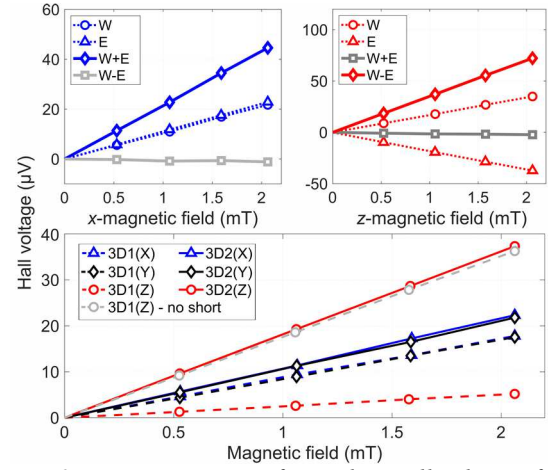


Figure 3: Top: Extraction of x - and z - Hall voltages from west (W) and east (E) pyramid-sidewall signals. Bottom: Comparison of 3D1 and 3D2 Hall voltages.

component, instead, is extracted by subtracting the W/E or N/S signals. Each sidewall is current spun similarly to 3D1, with the difference that only one couple of adjacent corner contacts is biased in Phase 1/3, and only one couple of corner contacts is sensed in Phase 2/4. To sense xyz -fields, 16 phases are required, i.e. four for each sidewall, where the z -component is redundantly obtained from W/E and N/S. However, since several phases (such as Phase 2 and 4 for modes W and E in Figure 2) share the same biasing configuration, the total number of phases can be reduced to 12 if two output stages are employed.

EXPERIMENTAL RESULTS

The sensitivities and offsets of these novel modes were measured on three identical pyramid devices. A standard benchtop setup with a Yokogawa GS200 sourcemeter, an Agilent 34401A multimeter and an Agilent U2751 switch matrix was used.

For the sensitivity measurements, a single-axis Helmholtz coil, driven by a TENMA 72-2645 power source, was employed to generate a spatially uniform magnetic field. The samples were manually aligned to the field to sense the desired component, which resulted in some slight misalignments that caused the small crosstalk in the W-E curve of Figure 3. The sensitivity extracted, however, is mostly unaffected. Four currents, equidistant in the range 50 - 125 μ A, were supplied, and the output voltage was measured for magnetic fields in the range 0 - 2 mT. The output voltage was averaged over the phases of the spinning scheme and further averaged over 20 cycles to mitigate noise. The 3D1 and 3D2 Hall voltages measured on one sample for a supply current of 125 μ A are displayed in Figure 3, together with the signals extracted from W and E sidewalls and then combined to measure either the x - or z -magnetic field. Contrarily to Figure 3, where the W and E signals were summed up for better representation, the 3D2 output signals, sensitivities and offsets are extracted by averaging the single-wall outputs. The z -component of 3D1 was also measured without short circuit, and compared to its corresponding counterpart with the corner contacts shorted. A linear regression was then applied to these curves to extract the absolute sensitivity, which was then divided by the supply current and supply voltage to

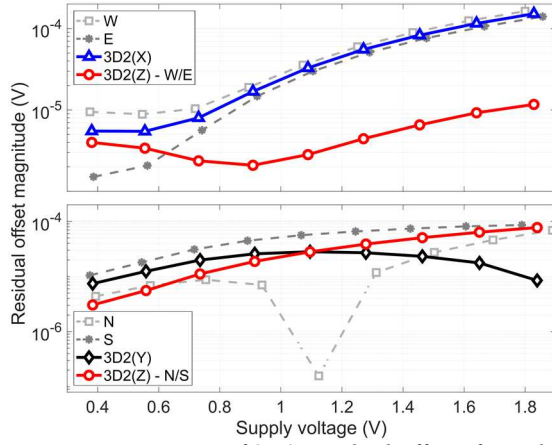


Figure 4: Extraction of 3D2 residual offsets from the single-sidewall outputs.

obtain, respectively, the voltage- (S_V) and current-related (S_I) sensitivities. Different phases have different input resistance, therefore the reported S_V is normalized with the average supply voltage measured during the spinning cycle. Specifically, the input resistance ratio between Phase 1/3 and Phase 2/4 of 3D1(X/Y) is around 1.6, while for mode 3D2's phases N/S/E/W is ~ 1.2 .

For the offset measurements, we used a zero Gauss chamber to shield the samples against external magnetic fields. The offset was measured for eight supply currents in the range 50 - 225 μ A. Each output was then averaged over the phases of the spinning scheme to extract the residual offset, and averaged over 50 cycles to reduce noise. The results, obtained from the same sample of Figure 3, are displayed in Figure 4 and Figure 5. In particular, Figure 4 reports the residual offsets (V_{off}) extracted from each sidewall, which are then combined to obtain the x -, y -, and z - V_{off} . Figure 5 reports the magnitude of the equivalent residual offset (B_{off}), i.e. the residual offset divided by the absolute sensitivity, for the two 3D modes. The z -component of 3D2 is extracted from both N/S and W/E, and these two signals are further averaged and displayed in the same graph. Since different modes and components have different input resistance, their supply voltage range is also different.

A summary of the performance of the new 3D modes is reported in Table 1, compared with the previous pyramid modes and the state-of-the-art. The reported sensitivities are averaged over the three samples and the four supplies, while reported B_{off} is the mean and 1- σ standard deviation calculated over the characterized devices. Wherever not specified, the mean offset is assumed negligible (~ 0 T).

DISCUSSION

Comparing the results obtained with the new 3D modes and the old ones, we can notice that the performance of the pyramid device is mostly preserved. In addition, the proposed modes only require a single supply current, thus simplifying the implementation of a readout interface.

Mode 3D1 presents very similar in-plane sensitivities and B_{off} to X/Y due to the identical biasing and sensing configuration employed, with a slight difference (around 5-6 % for S_V and B_{off}) related to process spread. The z - S_V is instead 4.6 mV/V/T, which is ~ 5 x lower than the average

S_V measured in [6]. This is caused by the short circuits that connect opposite corner terminals, and by removing them the S_I and S_V increase to 145.9 V/A/T and 23.3 mV/V/T. In addition, this improves B_{off} by a factor of 2.5. The presence of a short circuit is clearly harmful for the z -axis performance. Arguably, the reason for this behavior is that most of the supply current is shunted by the short circuits, following the least resistive path. Therefore, there is much less current that flows on the sidewalls where the sense terminals are located, producing in turn a much lower Hall voltage. Removing the short circuits enhances the z -axis sensitivity. However, multiple supply currents are then required to measure the in-plane components. It has not yet been demonstrated that the 3D1 spinning configuration can still effectively suppress the residual offset under these conditions. Therefore, further investigation is needed to validate this new configuration.

Mode 3D2, instead, exhibits z - S_V and B_{off} that are on-par with mode Z1 from [6], and even a higher S_I (142.0 V/A/T vs 94.8 V/A/T) which is related to the higher input resistance. The in-plane S_I is, instead, only slightly higher than mode XY (86.1 V/A/T vs 73.2 V/A/T), while the S_V is 1.3x lower which in turn results in 1.3x higher B_{off} . The reason lies again in how the supply current flows in the device. For example, let us focus on W-mode from Figure 3. From this sketch, we can observe that most of the current flows on the west sidewall, following the least resistive path. Some current, however, flows on the east sidewall. These two currents run in parallel and, under a positive x -directed field, are both deflected away from the sense terminals. If the currents on the west and east sidewalls were identical, no output voltage would be produced. However, the west-side current is larger, so a measurable Hall voltage appears. The portion of the x -signal contributed by the east (weaker) sidewall partially cancels the x -signal from the west sidewall. Clearly, this cancellation does not occur for z -sensing, where the corresponding "parasitic" current instead produces a Hall voltage that adds up to the desired z -signal.

Mode 3D2 requires 12 phases to measure the 3-axis field, where 6 phases are employed to sense xz -fields, and the remaining 6 for the yz -ones. The z -component is therefore redundantly obtained from the spinning of W/E and N/S. This introduces an extra degree of freedom for 3D2. Some applications, in fact, might require only the z -component

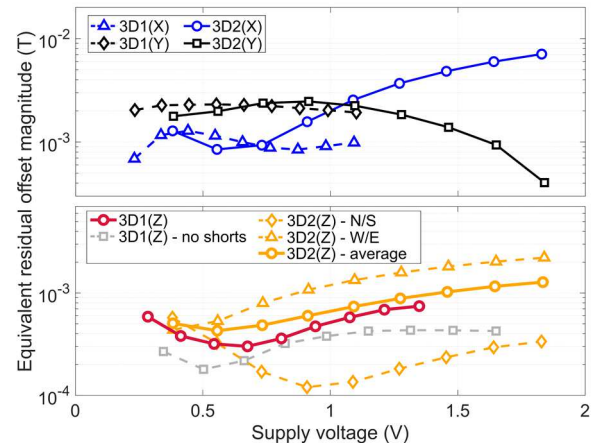


Figure 5: Equivalent residual offsets magnitudes of 3D1 and 3D2 modes.

Table 1: Summary of 3D1 and 3D2, and benchmark with the state-of-the-art

3D Sensor / Mode	S_V (mV/V/T)		S_I (V/A/T)		B_{off} @ 1 V (mT)		Footprint (μm)	Required unique spinning phases
	XY	Z	XY	Z	XY	Z		
Pyramid 3D1	16.7	4.6	70.1	23.5	1.21 ± 2.85	0.73 ± 1.86	50	6
3D1(Z) – no short	-	23.3	-	145.9	-	-0.17 ± 0.75	50	4
Pyramid 3D2	12.4	20.4	86.1	142.0	-1.41 ± 4.06	-0.12 ± 1.03	50	12 (6 for XZ/YZ)
Pyramid prior [6]	15.9	20.5	73.2	146.4	-1.35 ± 3.00	0.57 ± 1.04	50	12 (+2-4 extra switches)
LHD + VHDs [1]	15.4	15.1	161.0	378.0	$\sim 30^*$	$\sim 30^*$	> 90	1 (no spinning)
5-cont. VHD [2]	35.1	-	120.0	-	0.6	-	-	4 (for X or Y)
IMC Hall [4]	~ 300.0	50.0	~ 1500.0	250.0	~ 0.03	~ 0.03	2000	12

* values not reported, but estimated from typical raw offsets of LHDs and VHDs [2]

and either x - or y -, which means that the total number of phases can be halved. If the three axes of the magnetic field are instead required, the two z -signals can be averaged out, leading to a statistically lower residual offset.

Comparing the pyramid device with the state-of-the-art 3-axis Hall sensors, it has one of the lowest footprints found in literature, making the structure suitable in arrays where spatial resolution is required. The lower S_V (35.1 mV/V/T for VHDs [2]) is partially due to the unoptimized geometry and partially due to the doping level, which is at least 5x higher than standard Hall devices [2], which degrades mobility and, thus, sensitivity. The residual offset of the new 3D modes is at least one order of magnitude better than a standard LHD+VHDs configuration that is not current spun, but still higher than an optimized 5-contacts VHD and the IMC Hall device. This hints that the pyramid device might present some components of residual offset that are not generally present in conventional devices, either due to its structure or issues in the fabrication, which should be assessed and eventually solved in future work. Nevertheless, in its current state, the pyramid device is still suitable for applications where higher fields are involved (~ 100 mT), so that the relatively high offset of the device does not constitute an issue.

CONCLUSIONS

In this paper two novel current-spun 3D sensing modes, 3D1 and 3D2, were developed and experimentally validated for an inverted pyramid Hall-effect sensor with eight contacts. Both modes enable 3-axis magnetic field sensing within the same spinning cycle, without requiring additional switching elements to short different terminals. The modes preserve the device's sensitivity, achieving in-plane current-related sensitivities of 70.1 V/A/T (3D1) and 86.1 V/A/T (3D2), with residual offsets in the millitesla range. These new modes define a practical readout strategy for the pyramid device, laying the foundation for its future integration into a fully monolithic 3-axis Hall-sensor system. The performed analysis of their benefits and trade-offs confirms the pyramid architecture as a compact and low-footprint alternative to conventional Hall devices.

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