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Ultra-Low Offset Vertical Hall Sensor in CMOS Technology

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Abstract

This paper reports on a novel vertical Hall sensor with ultra-low offset (ULOVHS) for the measurement of an in-plane magnetic field component. The sensor consists of four parallel coupled fully symmetric vertical Hall sensors (FSVHS). Each FSVHS is formed by the connection of four identical three-contact vertical Hall elements (3CVHE). As a result, with a bias current of 0.5 mA and after current switching, a mean residual offset of 0.27 µV with a standard deviation of 0.29 µV has been achieved among 40 samples on an 8-inch wafer, which is an improvement of a factor of 16 compared to the FSVHS (4.2±14 µV). Furthermore, the measured current related sensitivity of the novel device is S_I = 12.65 V/AT, allowing the detection of magnetic fields down to B_{min} = 40 µT without any additional electrical compensation circuitry. This represents the best results to date achieved by a stand-alone VHS in standard CMOS technology.

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Keywords: CMOS Hall sensor; vertical Hall sensor; offset compensation; spinning-current; parallel coupling

1. Introduction

Among the various sensing methods to detect magnetic fields, the Hall-effect is probably the most widely used. A promising approach for implementing low-cost three dimensional (3D) magnetometers is the combination of Hall plates with vertical Hall sensors (VHS) using standard integrated circuit (IC) processes. Thereby, planar Hall plates are sensitive to the magnetic field component perpendicular to the chip surface, while VHS transduce the magnetic field in the plane of the chip [1,2]. In general, the output voltage of Hall-effect devices can be written as

$$V_{out}(B) = V_{Hall}(B) + V_{off} = S_V V_{in} B + V_{off} \quad (1)$$

where $S_V = V_{in}^{-1} dV_{out} / dB$, V_{Hall}, V_{in} and $V_{off} = V_{out}(0)$ denote the voltage related sensitivity, the Hall voltage, the bias voltage and the offset of the device in the absence of a magnetic field, respectively.

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Whereas planar Hall plates show a respectable offset performance, conventional vertical Hall sensors (VHS) are subjected to higher offsets at, generally, lower sensitivities. Further, offset compensation techniques like hard-wiring [3] and current spinning [4] are less efficient. State-of-the-art VHS with four, five or six contacts suffer from either large initial offsets or high residual offsets after current spinning [5]. In both cases a pre- or post-compensation of the sensor offset is necessary, which increases the chip area for signal conditioning circuitry and the packaging cost.

Recently, we proposed the first fully symmetric vertical Hall sensor (FSVHS) with an electrical symmetry equivalent to planar Hall devices [6]. The inherent symmetry of the FSVHS results in an equivalent magnetic offset field in the range of a few hundreds of µT. However, for highly precise applications a calibration of the offset voltage of each sensor is still necessary. The rationale of this paper is the expectation that the conventional parallel coupling of FSVHS is able to improve the electrical symmetry of the device and its offset characteristic even further.

In this work, we present a novel ultra-low offset VHS (ULOVHS) with a residual magnetic offset field of tens of µT. In Section 2, the concept and the CMOS design are introduced. The experimental examination of the offset, sensitivity and noise characteristic of the novel device and corresponding FSVHS are described in Section 3.

2. Device Structure

In [7] it has been concluded that the ideal VHS is a four-contact device benefiting from equivalent current flow distributions in all operating modes. The FSVHS is the first device to meet those demands [6]. As shown in Fig. 1(a), it consists of four three-contact vertical Hall elements (3CVHE) connected by metal lines of identical resistance. The center contacts C1 to C4 serve for biasing and sensing, enabling the device to be operated in four different modes [see Fig. 1(b)]. However, the symmetry of the device is affected by resistive mismatches introduced by the fabrication process. Due to the strong suppression of non-linear effects caused by the junction field effect (JFE), residual offsets in the range of tens of µV are the result. Besides current-spinning, hard wiring, or orthogonally coupling of two or more identical Hall sensor is known to effectively reduce the offset. Thereby, parallel coupling suppresses the influence of systematic fabrication errors. Current-spinning combined with orthogonal coupling have resulted in residual offset fields down to several µT for state-of-the-art planar Hall plates [8].

The new ULOVHS consists of four parallel FSVHS coupled as schematically shown in Fig. 2(a). Each FSVHS and thus the entire ULOVHS are composed of 3CVHE. The schematic cross-section and a photograph of the 3CVHE realized in sub-micron CMOS technology are shown in Figs. 2(b) and (c). It consists of a deep n-well diffused into a p-doped substrate. Its three n^+-diffusions serve to interconnect the elements and operate the device.

3. Experimental Results

The offset characterization of the ULOVHS and corresponding FSVHS were performed at the wafer level using the semi-automatic wafer prober PA200 from Süss combined with the parameter analyzer B1500 from Agilent. For this measurement the bias current I_{in} is swept between 0 and 1 mA and V_{off} is extracted for each mode of operation. The typical offset voltage of an ULOVHS is illustrated in Fig. 3. All modes show a dominantly linear behavior. Due

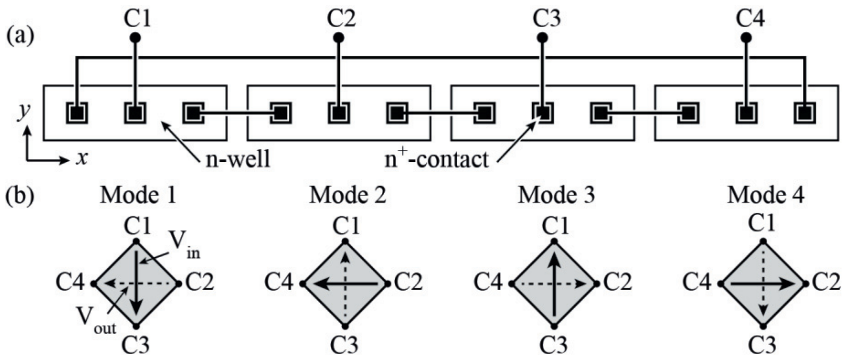

Figure 1. Schematic of (a) a FSVHS and (b) its four modes of operation.

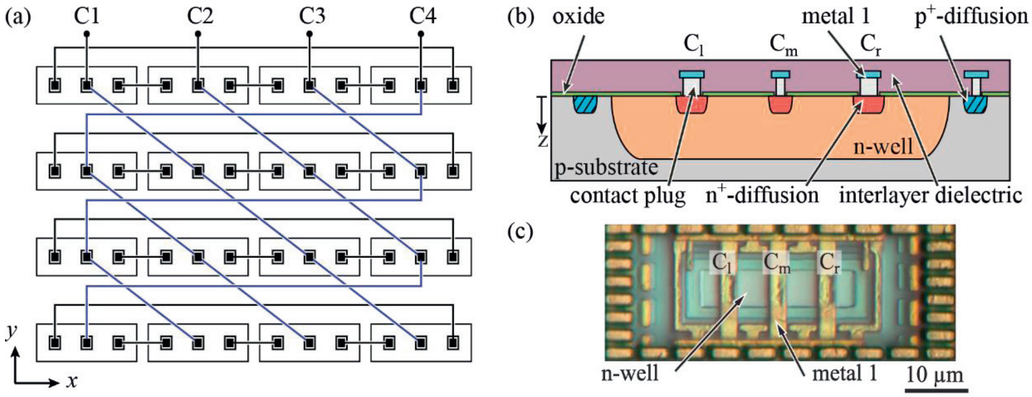

Figure 2. (a) Schematic of the parallel coupling of four FSVHS resulting in an ULOVHS, (b) schematic cross-section of the fabricated 3CVHE and (c) optical micrograph of a 3CVHE fabricated using sub-micron CMOS technology.

to fabrication imperfections the single mode offset of this sample is 260 μV at a drive current of I_{in} = 1 mA. By additionally applying current spinning, the residual offset is reduced by a factor of 480 to V_{res} = 0.54 μV. The distribution of V_{res} at I_{in} = 0.5 mA over 40 positions on an 8-inch wafer is shown in Fig. 4. The mean residual offset and its standard deviation is only 0.27±0.29 μV. Since V_{res} varies randomly, a systematic offset due to the technology is unlikely.

The sensitivity measurements were performed with individual chips wire bonded to a standard ceramic chip carrier. The carrier was mounted in the center of a Helmholtz coil setup. The response of a representative ULOVHS to an in-plane magnetic field B up to 6.8 mT at a bias current of I_{in} = 0.5 mA is shown in Fig. 5. A linear behavior with a voltage and current related sensitivities S_V = 11.5 mv/VT and $S_I = S_V R_{in}$ = 12.65 V/AT, respectively, is extracted.

The noise measurements were done on individual chips using the spectrum analyzer A4395 from Agilent. A typical noise spectrum for a FSVHS and novel ULOVHS for a constant voltage supply of V_{in} = 3 V is shown in Fig. 6. The 1/f noise of the ULOVHS is reduced by a factor of about 3 compared to the FSVHS. The white noise levels are extracted to be 4.49 V/$\sqrt{\text{Hz}}$ and 9.72 V/$\sqrt{\text{Hz}}$ for the ULOVHS and FSVHS, respectively. Further, the corner frequencies f_c are calculated to be $f_{c,ULO}$ = 170.7 Hz and $f_{c,FS}$ = 126.3 Hz, respectively.

The main figures of merit of the FSVHS and ULOVHS extracted over an 8-inch wafer are listed in Table 1. Due to the parallel coupling of four FSVHS, the input resistance R_{in} of the ULOVHS is reduced by about a factor of four compared to a single FSVHS, leading to a similar reduction of S_I. Further, the initial single mode offset of the ULOVHS, V_{off} = 0.13 mV, is 23 times smaller than that of the FSVHS (V_{off} = 3.02 mV). Moreover, the standard

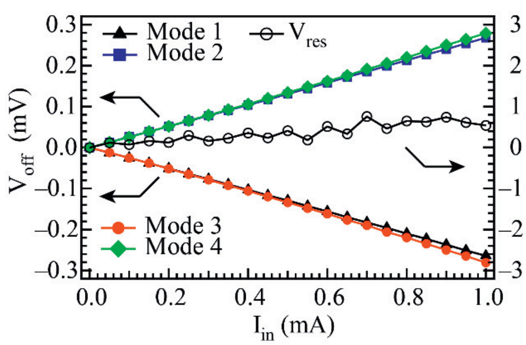

Figure 3. Offset voltage V_{off} and residual offset V_{res} after current-spinning as a function of the bias current I_{in} for a representative ULOVHS sample.

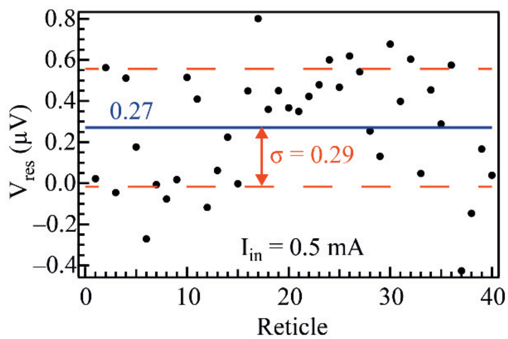

Figure 4. Residual offset distribution of the ULOVHS over the wafer at a bias current of I_{in} = 0.5 mA. The mean value and the standard deviation σ are indicated.

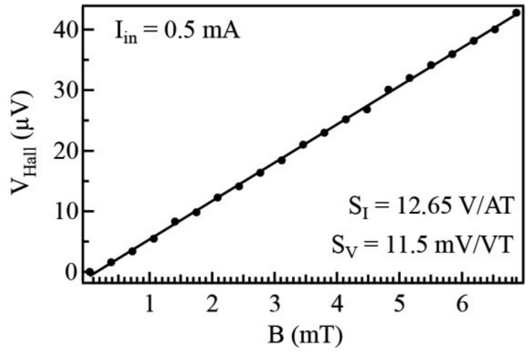

Figure 5. Hall voltage as a function of the magnetic field for a representative ULOVHS.

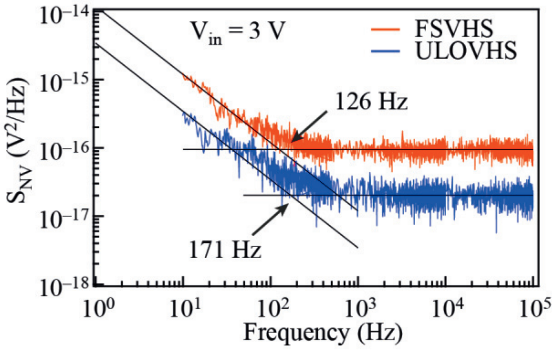

Figure 6. Noise spectral density S_{NV} as a function of the frequency for both VHS variants.

Table 1: Technical data and figures of merit of the ULOVHS and FSVHS

I_{in} = 0.5 mA	R_{in} (Ω)	V_{off} (mV)	V_{res} (μV)	S_I (V/AT)	S_V (mV/VT)	B_{off} (mT)	B_{noise} (μT/√HZ)
ULOVHS	1098±38	0.13±0.08	0.27±0.29	12.65	11.5	0.04±0.05	0.13
FSVHS	4870±62	3.02±1.61	4.20±14.0	58.7	12.1	0.14±0.48	0.29

deviation of the equivalent magnetic offset field B_{off} of the ULOVHS of ±0.05 mT is reduced tenfold compared to that of the FSVHS (±0.48 mT). The equivalent magnetic noise field B_{noise} above the corner frequency is 0.13 μT/√Hz and 0.29 μT/√Hz for the ULOVHS and FSVHS, respectively. Even for high bandwidth applications up to 100 kHz the noise equivalent magnetic field is in the range of the residual offset field.

4. Conclusion

The presented ULOVHS inherently benefits from low offset and noise. A magnetic offset field in the range of the earth's magnetic field represents the best performance to date achieved with a CMOS fabricated VHS. Further, the variation of B_{off} over the wafer is small enough so that a single chip offset calibration can be avoided in the likely case that the input referred noise voltage of the signal conditioning circuitry is larger than the residual offset of the sensor.

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