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Novel Integr Ated Magnetic Sensor Based on Hall Element Array

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Abstract: Recent studies confirm a steady growth of the market for magnetic sensors based on Hall element primarily integrated into ASICs used for position and motion control. They are mostly used for automotive, and robots markets. The key advantage of Hall element is its robustness and ease of integration in the integrated circuits without any technology modification. On the other hand the disadvantage of Hall element is its relatively low sensitivity, high offset voltage and noise and relatively high power consumption. Any improvement in this area will further boost the application of Hall elements.

In this paper we are presenting the new magnetic sensor, based on Hall elements which will potentially dramatically change the share of Hall element based magnetic sensors over the competing techniques. The sensor has been presented at the conference SEIA 2019 [1].

The proposed structure of the magnetic sensor addresses mentioned deficiencies of a single Hall element.

The low sensitivity of single Hall element is improved by parallel operation of an array of Hall elements containing N Hall elements. This approach directly multiplies the sensitivity by N times.

However a parallel operation of Hall elements implies a non-desirable increase of power consumption. Power consumption management is therefore critical. In the paper the proposed power consumption management is discussed in detail showing the dramatic reduction of power consumption which can reduce the consumption of the sensor to a fraction of the single Hall element.

In the paper the block diagram of the proposed sensor is shown. It consists of an improved single Hall element cell where the electronic circuit is added which allows the array to be simply concatenated in an expandable array. This resulting sub-cell is described in the paper and is patent pending.

The idea of the new sensor is to create a sensor cell with an array of Hall elements, but with simplified external electronic compared to the external electronic of a single Hall element. The structure of the proposed sensor is such that it allows simpler layout with less connections and that the total sensor size allows a single pixel dimensions of less than 50 µm × 175 µm, which is small enough to be implemented into any existing position measurement ASICs.

Keywords: Hall element array, New magnetic sensor, Virtual spinning.

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1. Introduction

Recent studies confirm a steady growth of the market for magnetic sensors based on Hall element primarily integrated into ASICs used for position and motion control. They are mostly used for automotive and for robots markets. The key advantage of Hall element is its robustness and ease of integration in the integrated circuits without any technology modification. On the other hand the disadvantage of Hall element is its relatively low sensitivity, high offset voltage and noise and relatively high power consumption. Any improvement in this area will further boost the application of Hall elements.

In the recently published market research presented in Fig. 1 demonstrates the prediction of how the automotive market will share different magnetic sensors.

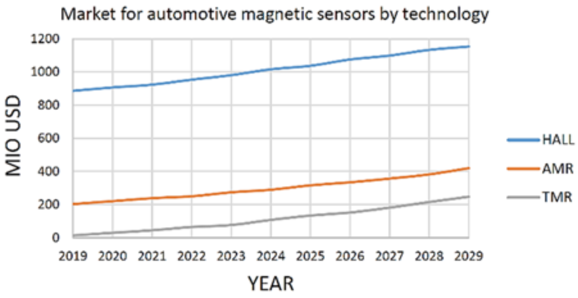

Fig. 1. Market production for various types of magnetic sensors for automotive magnetic sensors ASICs.

In this paper we are presenting the new magnetic sensor, based on Hall elements which will potentially dramatically change the share of Hall element based magnetic sensors over the competing techniques. The proposed structure of the magnetic sensor addresses all mentioned deficiencies of a single Hall element. The low sensitivity of single Hall element is improved by parallel operation of an array of Hall elements containing N Hall elements. This approach directly multiplies the sensitivity by N times.

In Fig. 2 the block diagram of the proposed sensor is shown. It consists of an improved single Hall element cell where the electronic circuit is added which allows the array to be simply concatenated in an expandable array. This resulting sub-cell is described in the paper and is patent pending [2].

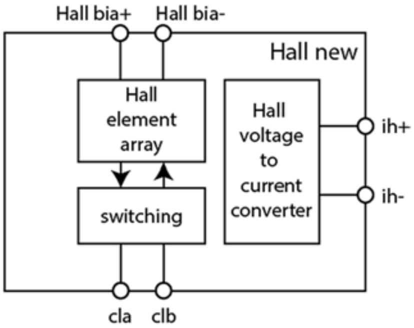

Fig. 2. Block diagram of the proposed magnetic sensor.

The idea of the new sensor is to create a sensor cell with an array of Hall elements, but with simplified external electronic compared to the external electronic of a single Hall element. The structure of the proposed sensor is such that it allows simpler layout with less connections and that the total sensor size allows a single pixel dimensions of less than 50 µm × 175 µm, which is small enough to be implemented into any existing position measurement ASICs. The sensor described has additional advantage over single Hall element, as the offset reduction is for many applications good enough not requiring the spinning technique normally used for ASICs with single Hall element as a ‘’virtual’’ spinning of Hall elements in the array is employed. When additional spinning is employed, the resulted offset is further minimized.

1.1. Advantages of Integrated Hall Element

Some of the most important advantages of integrated Hall element are as follows:

1. Low cost of fabrication due to its compatibility with Integrated ASIC standard process technology. The most widely used technologies for the Hall element plate are CMOS technologies. The best results are achieved when using N-well plate.

2. Ease of creating a ’’smart’’ magnetic microsystem with a possibility to integrate the Hall element biasing circuits, Analog Front End for Hall element signal amplification and a digital circuitry to implement ‘’smart’’ signal processing on the same die working together with other functions of the ASIC. Such so called System on Chip (SoC) is widely used in many functions in automotive industry providing sensing data for safe driving, allowing better passenger comfort etc.

3. Robustness. The integrated Hall element is very robust as it operates in a wide range of magnetic field. The robustness is improved also by the fact that integrated Hall element does not suffer from contact wiring reliability as it operates contactless.

4. The integrated Hall element is less sensitive to environment condition of dust and dirt, which hurt optical sensors, therefore in many applications integrated Hall element took over the role of optical sensor in the area of position and motion control, providing a large market especially in robotic systems.

5. One of important feature is the introduction of micro Hall element’’, which allows reduction of pixel size below 20 µm × 20 µm. This is particularly important for position and movement control.

6. The Hall element offers a function of accurate analog multiplier as the resulting output signal is the product of magnetic field density and bias current. This function has been used for electronic electricity meters.

1.2. Disadvantages of Integrated Hall Element

1. The sensitivity of Hall element is about 100 V/TA, which is a low compared to competitive integrated magnetic sensors.

2. In addition the realized offset voltage is relatively high and is a function of the Hall element structure symmetry mainly a consequence of the geometry accuracy of the production process.

3. The highest disadvantage of integrated magnetic sensor is high power consumption compared to competitive sensors. This power consumption is due to large bias current, which needs to be as large as possible. For typical ASIC supply voltage of 3.3 V this current is in the range of 1 mA, this means that the power consumption is 3.3 mW. Consequently for an ASIC with an array of 64 Hall elements as shown in Fig. 3 the power consumption rises to about 200 mW which is not negligible.

4. Low sensitivity and low signal to noise ratio.

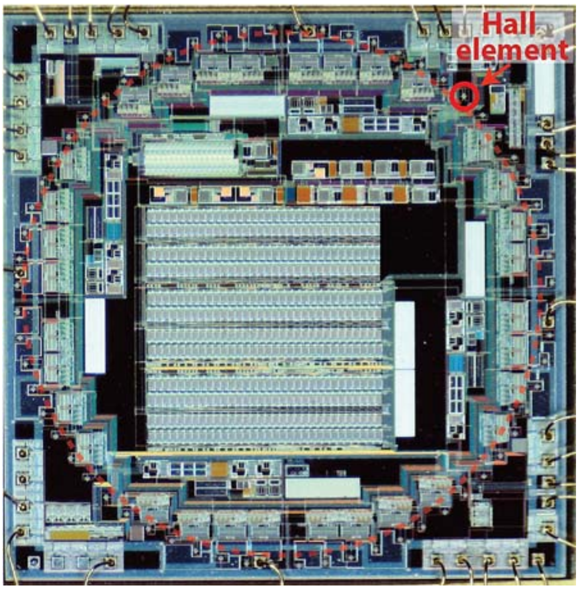

Fig. 3. ASIC with an array of 64 Hall elements.

2. Methods to Mitigate the Disadvantages of Integrated Hall Elements

For sensitivity improvement the concept of an array of Hall elements has been proposed as shown in Fig. 4.

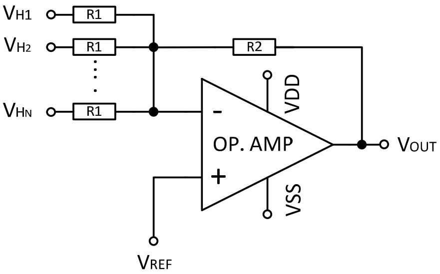

Fig. 4. The analog summing circuit.

In the array the output signal of N Hall elements are summed with the analog summer as schematically presented in Fig. 4 and shown in the Eq. 1 and Eq. 2. With this approach not only the sensitivity has been increased but also the signal to noise ratio is improved as shown in Eq. 3 and Eq. 4.

$$V_{OUT} = V_H \frac{R_2}{R_1} \cdot N \tag{1}$$

$$V_{OUT} = \sum_{i=1}^{N} V_{Hi} = N \cdot V_H \tag{2}$$

$$P_{noise_{HN}} = P_{noise_{H1}} + P_{noise_{H2}} + \dots P_{noise_{HI}} = N \cdot P_{noise_H} \tag{3}$$

$$V_{noise} = V_{noise}\sqrt{N} \tag{4}$$

Unfortunately this concept at the same time increases also the power consumption as the bias current is increased N-times. The improvement is therefore a bit questionable. Nevertheless the signal to noise improvement by a factor of √N is a good improvement.

In addition, also the improvement of the offset voltage is noticeable as the offset voltage, which has a random nature is portion reduced by √N, however this is not true for the offset voltage caused by a systematic mask error or any other systematic error. This can be annulated by clever orientation of the Hall elements in the array.

The problem of the offset voltage has been very effectively reduced by the method called ''spinning of the Hall element''. This means that electrical rotation of the Hall element is performed by switching the symmetrical structure of the Hall element as shown in Fig. 5, where a simplified two phase spinning effect dramatically reduces the offset voltage.

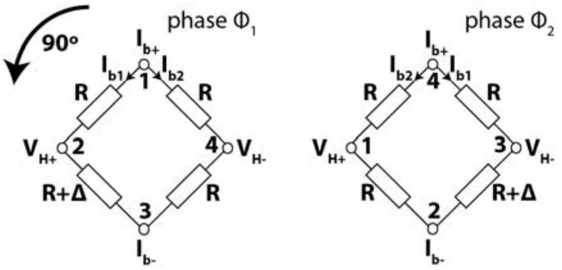

Fig. 5. Simplified explanation of two phase spinning effect on offset voltage.

The offset voltage caused by asymmetry is simulated by using a resistor bridge representation of the Hall element. The ideal geometry where all four resistors R are identical, is replaced with the bridge where the resistor connected between node 2 and the node 3 is different by a small value Δ, which is usually around of 1 % of R. The simplified explanation of the spinning effect is shown in Fig. 5.

In Fig. 5 the two phase spinning shows the situation of phase 1, Φ1, where the offset voltage is Ib1 · Δ as shown in Eq. 3 and Eq. 4, where Ib is Hall element bias current and Ib1 and Ib2 are in the first approximation equal, as the asymmetry Δ of the bridge is close to zero. In this case the offset voltage is equal Ib1 · Δ, Eq. 5 and Eq. 6.

In the phase 2, Φ2, the situation is similar, but in this case the offset voltage changes its sign as shown in Eq. 6.

$$I_b = I_{b1} + I_{b2}, \quad I_{b1} \approx I_{b2} \tag{5}$$

$$V_{off1} \approx \frac{I_b}{2} \cdot \Delta \approx V_{off} \tag{6}$$

$$\begin{gathered} V_{off2} \approx -\frac{I_b}{2} \cdot \Delta \approx -V_{off} \\ \Phi_1 = V_H + V_{off} \\ \Phi_2 = V_H - V_{off} \\ \Phi_1 + \Phi_2 = 2 \cdot V_H \end{gathered} \tag{7}$$

There is an additional benefit of spinning. The effect of switching of the signal acts as chopping. The result is therefore the shift in the frequency specter around the spinning frequency, which significantly reduces the 1/f noise. The negative side of this is the limitation of the system bandwidth according to Nyquist frequency.

The bandwidth of the magnetic microsystem has been improved by the idea of combining two types of magnetic sensors, Hall elements array and a microcoil on the same ASIC. The resulting microsystem works on the principle of adding the Hall element signal at low frequency and the microcoil signal at high frequency [3].

The resulting response of the approach is shown in Fig. 6.

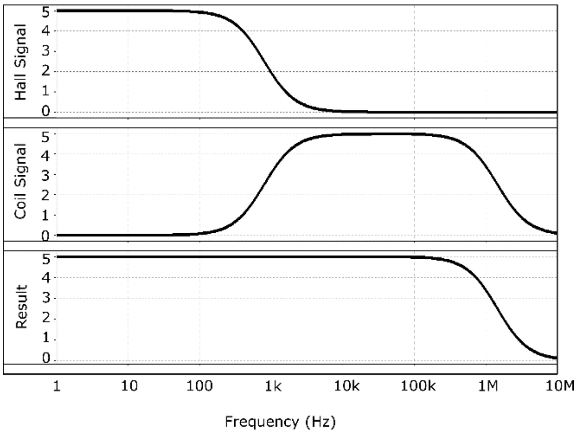

Fig. 6. The microsystem response with Hall element array and microcoil.

In Fig. 7 the photo of the ASIC layout based on the principle of Hall element and microcoil is shown. The resulting microsystem has been used for precise open loop current measurement up to cut-off frequency fm 940 kHz. As the fn cut-off frequency for Hall element has been selected at 517 Hz the overall signal to noise ratio has been reduced by √fm/fn = 42.6 times.

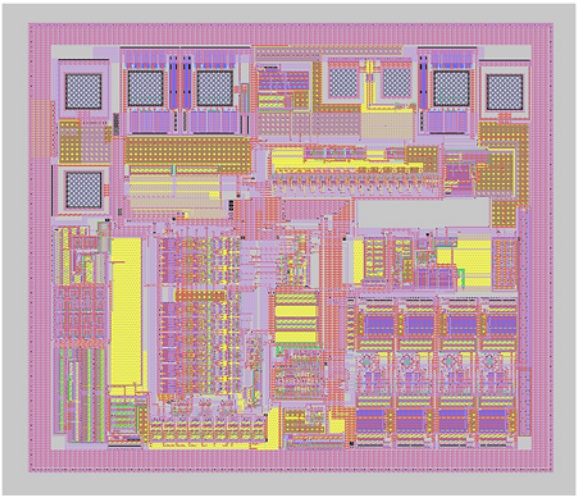

Fig. 7. Photo of the ASIC layout based on the principle of Hall element and microcoil.

3. Structure of the Proposed Magnetic Sensor

The layout of the designed sensor is shown in the Fig. 8. It consists of an array of 4 Hall elements occupying the area of 50 μm × 175 μm in 0.35 CMOS technology.

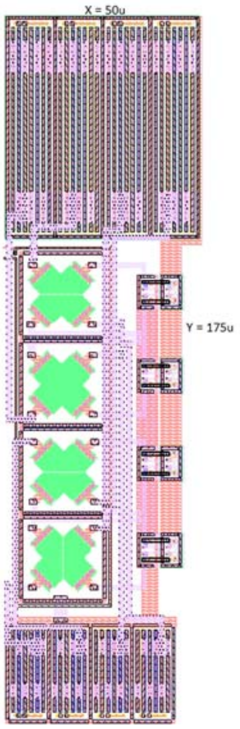

Fig. 8. Layout of the proposed magnetic sensor call in 0.35 μm CMOS technology.

The required analog switches to switch the bias current are included in this area. Such area is small enough to create dense pixel array needed for accurate position measurement.

There are various modes of operation available as shown in Fig. 9, Fig. 10 and Fig. 11.

Fig. 9 presents the situation M1, where the bias current of each four Hall elements is switched on after the previous one. This means that the total bias current for all elements is equal to the situation of single Hall element. However the sensitivity of the array is improved by four times.

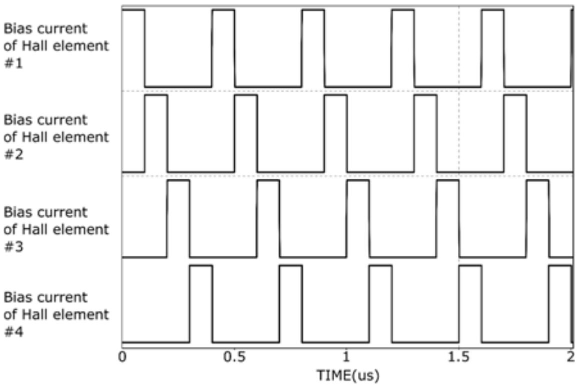

Fig. 9. Total bias current for situation M=1 equals to the bias current of a single Hall element.

Fig. 10 shows the situation M2, where the total bias current is reduced further to 50 % of M1, but the amplitude of each Hall element current remains the same. So the sensitivity also remains as for M1.

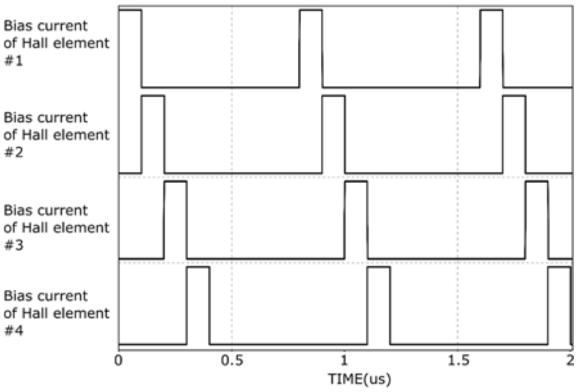

Fig. 10. Total bias current for situation M=2 equals to 50 % of a single Hall element.

Fig. 11 shows the situation when the total bias current is reduced additionally to 25 % of M1, with the same sensitivity. The down side of this approach is bandwidth reduction according to the Nyquist frequency limit. Nevertheless, this has been compensated by the conversion the Hall element voltage to current allowing to much higher frequency of bias current switching.

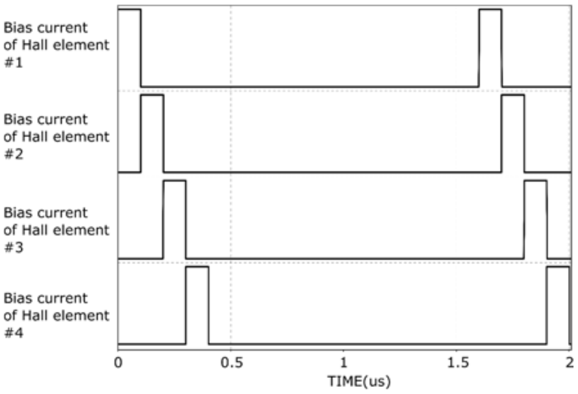

Fig. 11. Total bias current for situation M=4 equals to 25% of a single Hall element.

Fig. 12 presents the microphotograph of the test ASIC built in 0.35 μm CMOS technology. As it can be seen the novel Hall element is very small compared to tiny test ASIC.

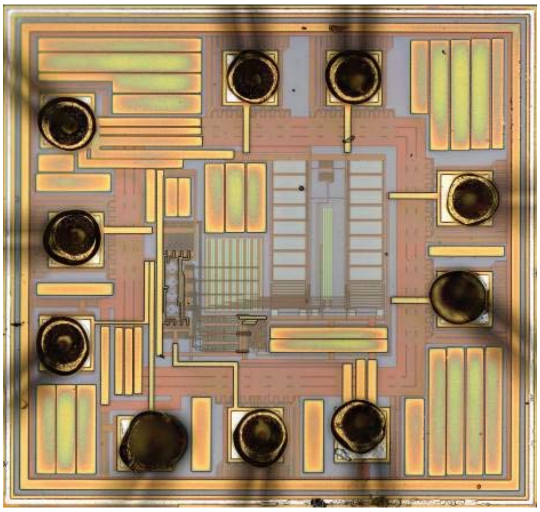

Fig. 12. Photomicrograph of the test ASIC. Die size is 772 μm x 724 μm.

4. Measured Results of the Designed and Fabricated Sensor

Fig. 13 shows the pulse response of fast 10 kHz magnetic field generated with on-chip micro coil.

Fig. 14 demonstrates the high frequency bandwidth of the test ASIC.

Fig. 15 shows the sine-wave response of 1 MHz magnetic field.

5. Conclusions

The proposed sensor proved to optimize key features of integrated Hall element sensor. The advantages of Hall element remain unchanged. The novel sensor has a potential to promote the leading role of Hall element for magnetic sensors.

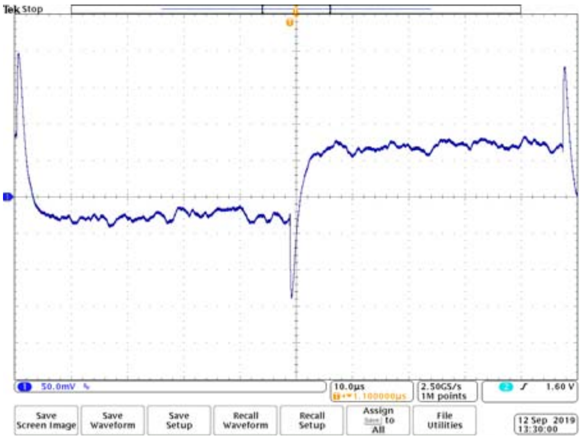

Fig. 13. Response to square wave of frequency 10 kHz.

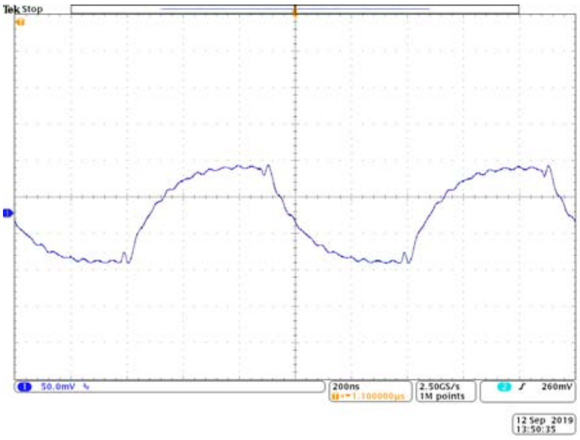

Fig. 14. Response to square wave of frequency 1 MHz.

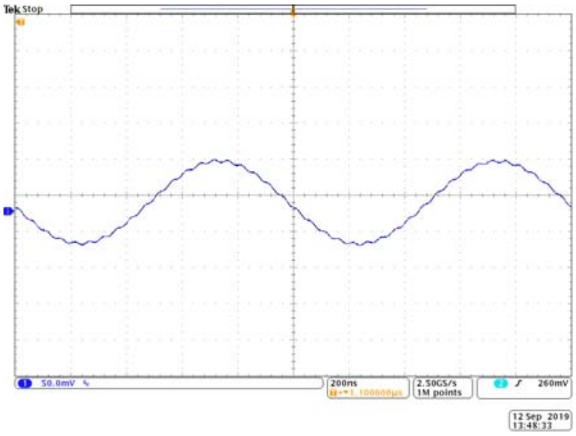

Fig. 15. Response to sine wave of 1MHz frequency.

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References

[1]. Trontelj Janez, Berčan Damjan, Gradišek Miha, Novel integrated magnetic sensor based on Hall element, in *Proceedings of the 5th International Conference on Sensors and Electronic Instrumentation Advances (SEIA'19),* Tenerife (Canary Islands), Spain, *25-27 September* 2019, pp. 57-58.

[2]. Trontelj Janez, Hallov senzor, senzorski sklop, ki vključuje Hallove senzorje in načini krmiljenja senzorrskega sklopa, 201900120, 2019.

[3]. Janez Trontelj, Vinko Kunc, 'Integrirani brezkontaktni merilnik električnega toka, patent št. 9800063, 1999.

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