



SMART SILICON SENSORS BASED ON VERTICAL HALL EFFECT DEVICES

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Abstract: *Future integrated systems will benefit significantly from the progress in batch manufactured silicon sensors and signal processing techniques. Silicon technologies make possible to produce sensing microdevices combining maximal sensitivity, high accuracy and minimal design complexity. Smart sensors on the base of Vertical vector Hall effect devices offer a number of advantages including reducing mass, volume and power consumption; greater redundancy of system functions and simpler architecture. In view of these characteristics, it can be expected that such smart sensors will be used extensively wide if an adequate solution is found to reduce the design cost and simplify the electrical interface. Consequently, cost effective microsystems including vector magnetic sensors, circuits and eventually actuators can be fabricated.*

This paper presents a new approach in the field of signal processing for magnetic field sensors based on vertical Hall elements. A design example is illustrated specific problems and solutions associated with data converters and signal-processing functions for smart sensors.

Keywords: *Vertical Hall effect devices, Signal Processing, Smart Sensors.*

1. INTRODUCTION

Sensors are not always suitable for applications in data-acquisition and sensor systems. There are two reasons for this: appropriate standards for the electrical output signals; and that signals show undesirable disadvantages such as offset, non-linearity (NL), cross-sensitivity (CS) etc. To apply a magnetic sensor system designers must be thoroughly familiar with its performance. Without of this knowledge they will be unable to build a manageable system of replace sensors with standard output formats.

Traditional interface function, such as analogue sensor signal conditioning, analogue to digital (A/D) conversion and the generation of reference signals, take place in smart sensors.

Smart sensors include on the same micro chip the sensing element and the interface circuit, in order to perform a suitable of the sensor signals before the transmission to the rest of the system [1-6]. There are two basic different ways to be realized smart sensors. At the first one - sensors can be fabricated directly on the silicon substrate used for the integrated circuits and the second – sensors have to

be assembled together with the interface circuit in a multi-chip module. Both approaches allow batch manufacturing of either - the integrated circuits and the sensing elements. Smart sensors typically require specific signal processing functions to match characteristics of both sensor and system.

This paper contains our recent activity in the field of signal processing for smart sensors in the base of vertical Hall microstructures. Part of new results is already presented [1]. A few design examples are reported to illustrate specific problems and solutions associated with data converters and signal processing functions for smart sensors.

2. DATA CONVERTERS

In sensor systems, after the preliminary signal processing performed by the front-end circuitry, in the most cases is necessary to convert the signals in the digital domain. This section discusses some practical implementations of analog to digital (A/D) converters for smart sensor systems based on various conversion techniques. When low power consumption and fast conversion time are required,

successive approximation A/D converters are widely used.

2.1 2-D Hall magnetic sensor in the base of incremental A/D converter

Silicon Hall magnetic sensors are generally compatible with standard IC technologies. Fig. 1 shows a functionally integrated 2-D silicon vector microsystem [7, 8]. It consists of two triple parallel-field Hall sensors replaced each other on the 90° in plane x - y [8-10].

The device contains a central square current contact C_0 and one contact on each side C_1 - C_4 symmetrically situated around C_0 . The two differential outputs generate $V_H(\mathbf{B}_x)$ and $V_H(\mathbf{B}_y)$ Hall voltages, proportionally to the x - and y - components of the magnetic field.

The measurement of the cross-sensitivity at current $I_{C_0} = \text{const.}$, after nullification of the two offsets we achieved, using the following procedure. The first step is an experimental determination of the two channels magnetosensitivities at Hall-voltage mode $V_H(\mathbf{B}_x)$ and $V_H(\mathbf{B}_y)$ of operation. The next step is applying a homogeneous variable field B parallel to one of the axis, for example B_x -axis. The other output (parasitic) signal from the y - channel is registered simultaneously. Then the dependence of the relative change of the parasitic signal from the y -direction $V_{Hy}(\mathbf{B}_x)/V_{Hy}(\mathbf{B}_y)$ is plotted in % versus the magnetic induction B_x applied to the x - axis. The

procedure described above is repeated for the remaining directions. In our case, because of the device symmetry, the relation $S_{xy} = S_{yx}$ and $S_{xz} = S_{yz}$ between respective cross-sensitivity is valid.

On Fig. 2 is presented the cross-sensitivity of the 2-D microsystem. The CS is close to a square function of the induction B . This proves the dominant role of the geometrical magnetoresistance in CS.

On Fig. 3 is presented vector Hall magnetic sensor and a biasing circuitry for measuring the internal noise.

The measurement set-up on Fig. 3 included: Hall sensor both with current biasing generator realized through accumulator, placed in a metal shielded box; Li-Ion rechargeable batteries which is also placed in a metal shielded box; wide-band low-noise operational amplifier with gain amplification coefficient non smaller than 10^4 , which is also biasing by an accumulator; oscilloscope connected with the amplifier's output to be observed output signal behavior; digital spectral analyzer with a fast Fourier transformation for the noise spectrum computation of the output sensor signal. A special attention could be paid on the sensor screening from electromagnetic disturbances, on amplifier and on the biasing circuits. The set-up used for the noise measurement is especially created for this goal instruments on the base of digital spectral analyzer Philips PM 3360.

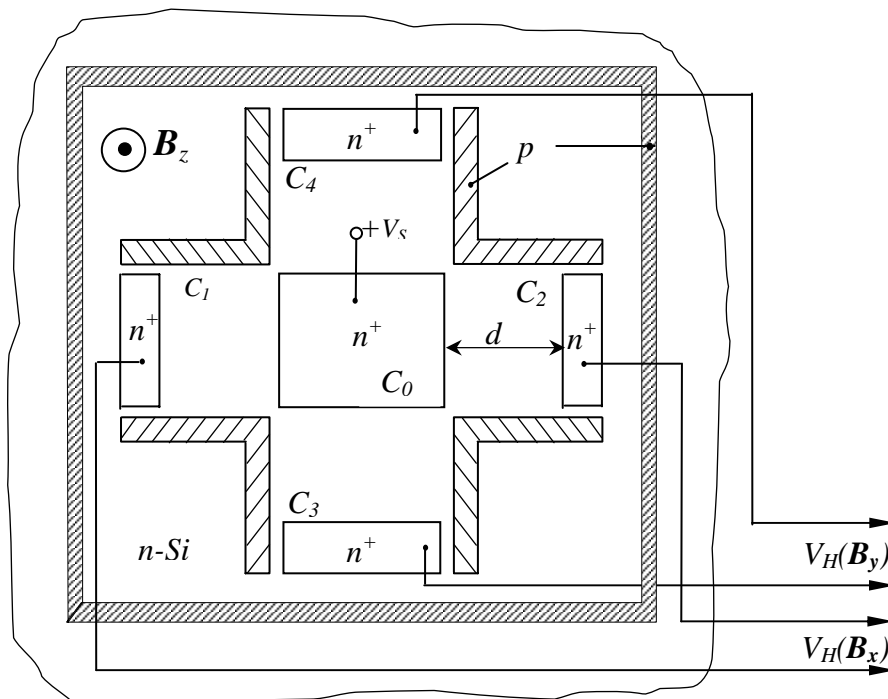


Fig. 1 - 2-D magnetic microsystem for the in-plane B_x and B_y magnetic field components.

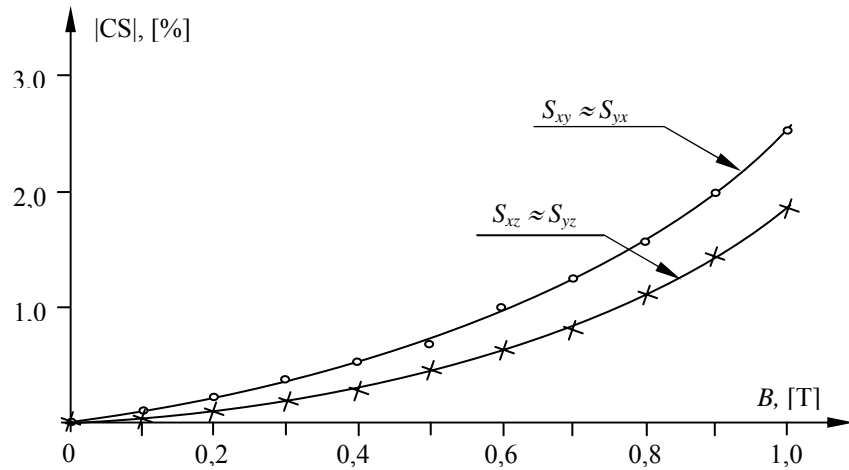


Fig. 2 - The cross-sensitivity between the x- and y- channels for $I_{C0} = 10 \text{ mA}$, $T = 300 \text{ K}$.

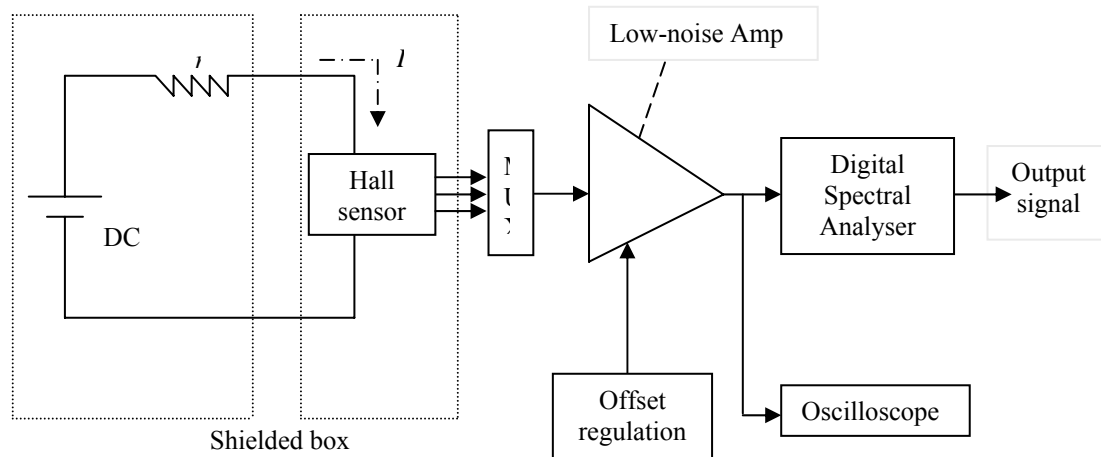


Fig. 3 - Hall magnetic sensor and a biasing circuitry for noise measurement.

In Fig. 4 is shown measured noise power spectral density for one of the sensor channels, of the microsystem of Fig. 1, in function of frequency f at magnetic field $B = 0$. There is established that the behavior of this important sensor parameter at low frequencies $f \leq 10^3 - 10^4 \text{ Hz}$ doesn't differentiate from the expected one, i.e. the $1/f$ noise (Flicker noise).

The grow up of the noise level with the increasing of the supply current I_0 is due to the increasing role of the carriers scattering, because of the higher velocity in the electric field. Among them we will consider the 2-D magnetic sensor system for angular measurements, whose scheme is shown in Fig. 5 [5-7, 10-12].

Vector 2-D Hall magnetometer [8, 11, 12] together with the front-end circuitry deliver two differential voltages proportional to B_x and B_y components of the magnetic field produced by a permanent magnet placed on top of the chip. The sensor geometry and the read out circuit have been optimized to reduce offset, temperature and noise parametric dependences and to increase sensitivity of the system as all [7 - 9]. Since the resulting front-end output voltages are in the order of few tens of mV

only, a couple of operational amplifiers are required to achieve a reasonably large signal level at the input of the subsequent A/D converter [4, 6, 7].

Differential output voltages of the operational amplifier (OA) represent alternatively the input or the reference signal of an incremental A/D converter, depending on the quadrant of the magnetic field angle α . The correct value of α is determinate by a finite state machine in the digital section [4]. When quadrant is determined, the bitstream delivered by the A/D converter is decimated by a counter, producing an output word N proportional to the ratio between the magnetic field components. Finally, a look-up table transforms N into the magnetic field angle using a Gray code representation.

In order to avoid abnormal operation of the vector probe due to the absence of the permanent magnet, in the system is included two window comparators, which check the magnetic field strength and deliver to the digital section a suitable status bit.

The measured output digital word as a function of the magnetic field angle is shown in Fig. 5.

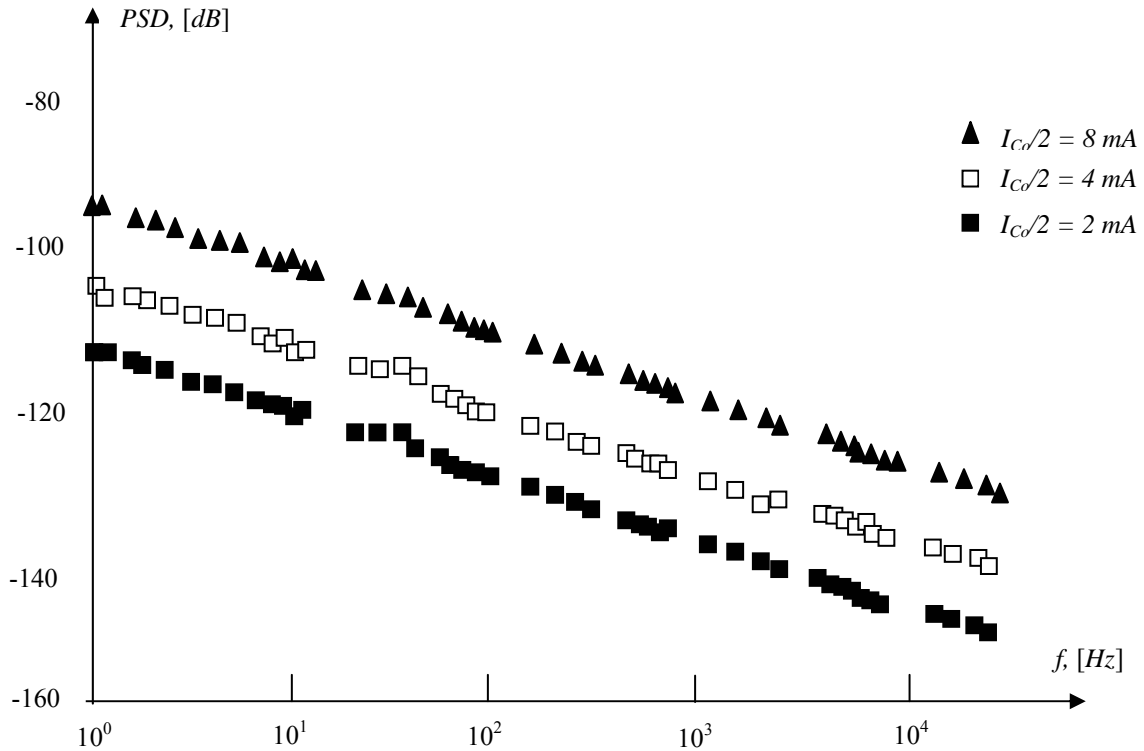


Fig. 4 - Noise power spectral density for one of the sensor channels, as a parameter is chosen the supply current $I_{C0}/2$ at temperature $T = 300$ K.

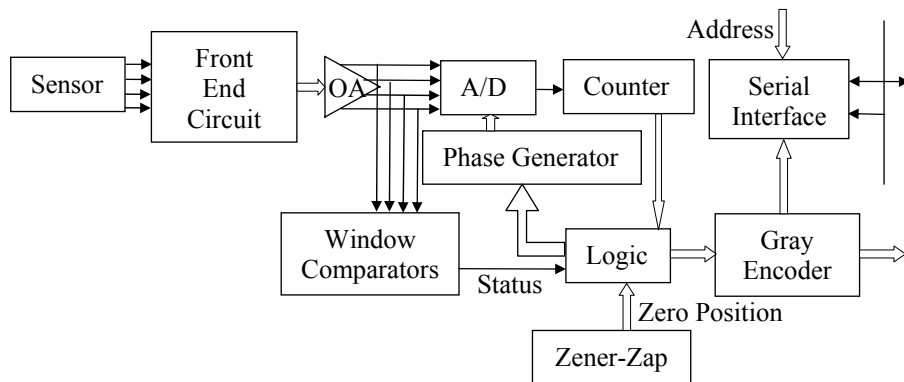


Fig. 5 - Block diagram of the rotary switch interface circuit.

2.2 Successive approximation A/D converter based on 3-D Hall magnetic sensor

Several working environments are polluted by strong low-frequency magnetic field. In order to guarantee the health of the workers, it is essential to monitor the exact integral exposure of each worker to a particular level of filed with magnetodosimeter.

The level of magnetic field which is known to be dangerous for human beings can be detected by silicon magnetic sensors fabricated in conventional CMOS technologies. However, the bias current required to be achieved the desired sensitivity.

The magnetic sensor used to detect B_x , B_y and B_z is a 3-D silicon vector sensor, completely realizable with the methods of IC technology, Fig. 6. The device contains a central current ohmic contact C_1 and one more contact on each side C_2 and C_3 symmetrically placed around C_1 . The Hall terminals are placed in following way: H_1 and H_2 – in the zone between C_1 and C_2 ; H_3 and H_4 – at either side of contact C_1 , and H_5 and H_6 – in the zone between C_1 and C_3 . Also the contacts H_1 and H_6 and, respectively, H_2 and H_5 are cross-coupled, which increase the signal for the component B_z and neutralizes the influence of the other fields B_x and B_y in this output channel [10, 13 - 15].

Fig. 7 contains the results for the parameter CS. In accordance with the experimental results a reduction of CS of about 45 % with respect to the Hall voltage mode of operation using an amperometric circuit only is achieved.

The measured noise power spectral density of the vector sensor for one of the channels is shown in

Fig. 8. For the other two channels the dependencies are the same. As can be seen, in the range 1 – 1000 Hz the internal noise is of the type $1/f$, and as the current I_{C1} increases the noise increases too.

The block-diagram of the integrated magnetodosimeter is shown in Fig. 9.

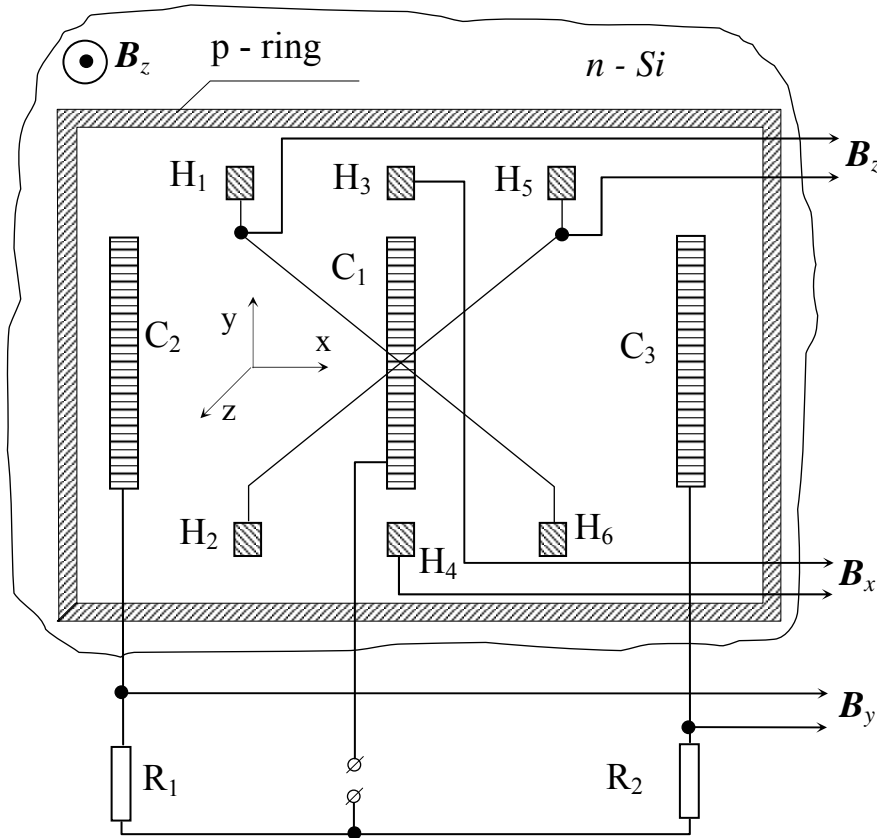


Fig. 6 - 3-D vertical Hall magnetometer for simultaneously detecting the B_x , B_y and B_z magnetic field components.

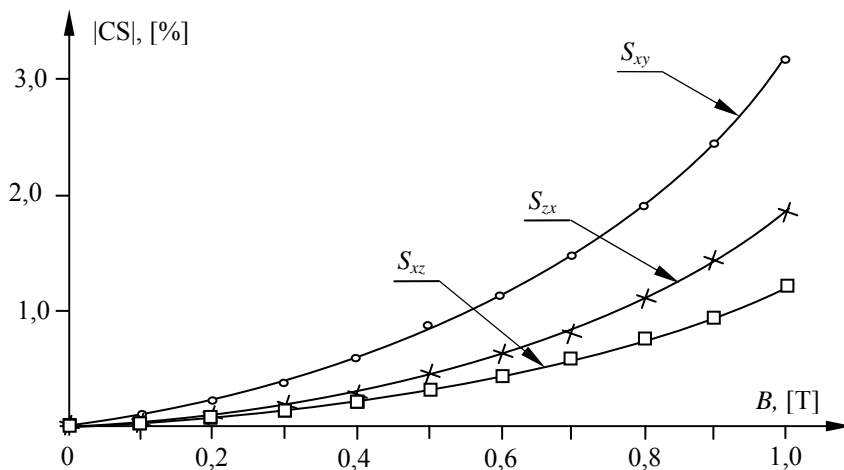


Fig. 7 - The cross-sensitivity between the x-, y-, and z- channels for $I_{C1} = 10$ mA, $T = 300$

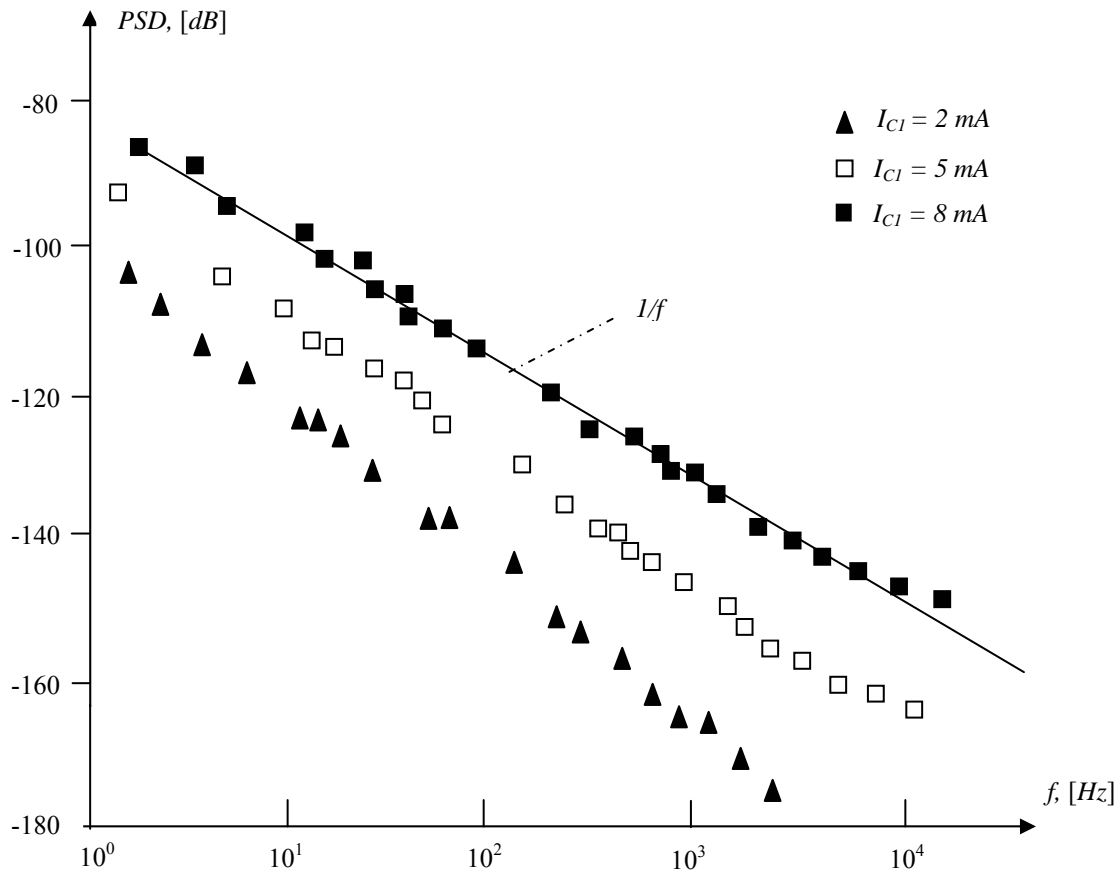


Fig. 8 - Noise power spectral density for one of the sensor channels. As a parameter is chosen the supply current I_{CI} at temperature $T = 300 \text{ K}$.

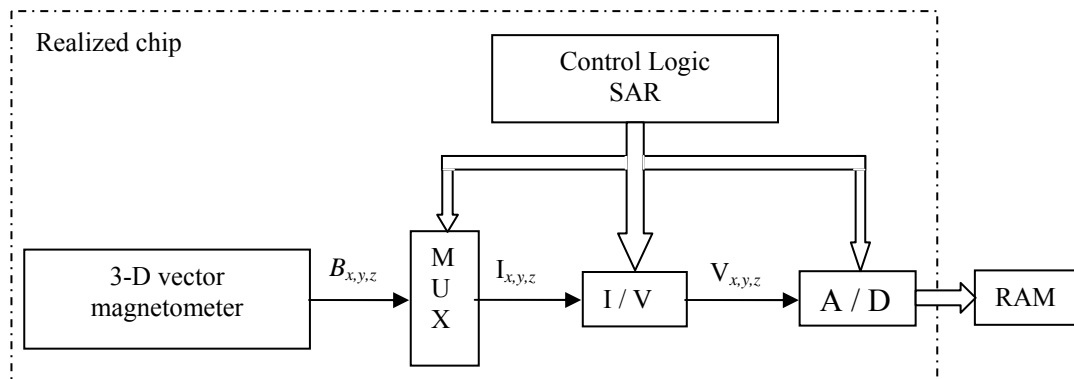


Fig. 9 - Block diagram of the integrated magnetodosimeter.

A few mA is too high to allow battery operation. This potential drawback is circumvented by choosing a particular architecture for the A/D interface, which allows pulsed operation of the sensor with a very small duty cycle. Therefore, in spite of the large power consumption of the sensors, the average power consumption of the system is kept as low as $1 \mu\text{W}$ from a 5 V power supply [7, 10].

The current signals produced by the sensor are multiplexed, transformed into voltages, equalized

and converted into the digital domain using a single A/D converter. The resulting words representing magnetic field components are delivered to the digital section, which calculates the module of the vector and stores the histogram of the magnetic field intensity during the monitored period into a RAM.

In light of the large current required to operate the magnetic sensor (2 to 10 mA), we have to keep the sensor active only during a fraction of the acquisition cycle in order to fulfill the power

consumption specifications. It is therefore necessary to use a low power sampling A/D converter, such as successive approximation architecture with two-step digital to analogue (D/A) converter.

3. CONCLUSIONS

The most important application area for Hall silicon sensors will undoubtedly be the smart sensors field. In the future, many large measurement and control systems will be bus oriented. In addition, smart Hall sensors will be a must in smart buildings and homes, smart traffic-control systems, smart cars etc. In this way of thoughts, improving and simplification of the A/D conversion and the signal processing as a section of smart Hall systems will be essential part of the future work of the smart system designer scientists.

4. ACKNOWLEDGMENT

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