INTEGRATED HALL SENSOR / FLUX CONCENTRATOR MICROSYSTEMS

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Abstract : The paper describes highly sensitive single-axis and two-axis integrated Hall magnetic sensors. They consist of an integrated combination of a CMOS Hall integrated circuit and a planar magnetic flux concentrator. The magnetic flux concentrator is made of a thick ferromagnetic layer bonded on the CMOS wafer. The CMOS part of the system contains two or more conventional Hall elements positioned under the periphery of the flux concentrator. The flux concentrator converts locally a magnetic field parallel with the chip surface into a field perpendicular to the chip surface. Therefore, a conventional Hall element can detect an external magnetic field parallel with the chip surface. The flux concentrator also provides a magnetic gain.

Integriran mikrosistem Hallov senzor / zgoščevalec magnetnega pretoka

Ključne besede: polprevodniki, mikroelektronika, CMOS tehnologije, mikrosistemi integrirani, senzorji magnetni integrirani, HALL senzorji, polja magnetna vzporedna površini chip-a, pretok magnetni zgoščeni, koncentratorji pretoka magnetnega planarni, občutljivost višja, offset magnetni ekvivalentni, šum magnetni ekvivalentni

Izvleček : V prispevku opisujemo zelo občutljive eno- in dvoosne integrirane Hallove magnetne senzorje. Dobimo jih z integrirano kombinacijo CMOS Hallovega integriranega vezja in ravninskega zgoščevalca magnetnega pretoka. Zgoščevalec magnetnega pretoka je izdelan iz debele feromagnetne plasti pritrjene na CMOS silicijevo rezino. CMOS del vsebuje dva ali nekaj konvencionalnih Hallovih elementov postavljenih pod obod zgoščevalca pretoka. Le-ta pretvori lokalno vzporedno magnetno polje v navpičnega glede na površino čipa. Zatorej lahko konvencionalni Hallov element zazna tudi zunanje magnetno polje vzporedno s površino čipa. Zgoščevalnik pretoka pa dodatno poskrbi tudi za ojačanje gostote magnetnega pretoka.

1. Introduction

The subject of this paper is a new class of magnetic sensor microsystems based on an integrated combination of Hall elements and ferro-magnetic structures. Such microsystems are members of emerging family of Hybrid Ferromagnetic - Semiconductor Structures /1/. The term "hybrid" here means: fabricated by dissimilar technologies, but the "hybridization" is now usually made at the semiconductor wafer level. Such hybrid structures are used as sensitive magnetic sensors and are also investigated as candidates for the information storage cells of novel magnetic random access memories /2/.

It is interesting to note that the idea of combining a semiconductor magnetic field sensor with ferromagnetic structures came to many researchers in the past. Probably the first report on the subject was published back in 1955 /3/. In order to amplify the magnetic field "seen" by an InSb Hall plate, the authors put the Hall plate in the air gap between two long ferromagnetic rods. In this way they considerably increased the effective sensitivity and the resolution of the Hall element and could measure quasi-static magnetic fields down to milli-gauss range. The operation of this device is based on the following well-known effect: if a ferromagnetic rod is placed in a magnetic field parallel with the long axes of the rod, the rod tends to collect the magnetic field lines in itself: it operates as a magnetic flux concentrator. Similar macroscopic systems Hall sensor - Magnetic concentrators, made of discrete components, were investigated also by other researchers /4/ - /6/. We developed a first hybrid micro-system Hall sensor - Magnetic concentrators /7/ which became a part of a commercially available product. The best reported detectivity limit of a combination Hall sensor - Magnetic concentrators is as low as 10 pT /5/.

In /5/ we find also a report of an attempt to incorporate ferromagnetic material into the package of a Hall device. This idea is also presented in /8/, and is now used in several commercially available Hall magnetic sensors.

To the best of our knowledge, the idea of using an integrated combination of a semiconductor magnetic micro-sensor and a thin ferromagnetic film was mentioned for the first time in a patent /9/.

In this paper we analyze integrated combinations of Hall elements and magnetic flux concentrators. As in the case of the conventional applications of magnetic concentrators /3/ - /7/, we use the integrated magnetic concentrators as passive magnetic amplifiers. However, the structure of our concentrators is different: it is planar, which allows an easy integration on a semiconductor wafer. We shall describe two basic structures, one with so-called twin magnetic flux concentrators and the other with a single magnetic flux concentrator. In both cases we shall estimate the relationships between the parameters of the structure and its magnetic gain and the saturation field.

2. TWIN magnetic flux concentrators

The idea of the integrated twin magnetic flux concentrators /10/ is illustrated in Figure 1. Obviously, the idea is inspired by the conventional configuration of the combination

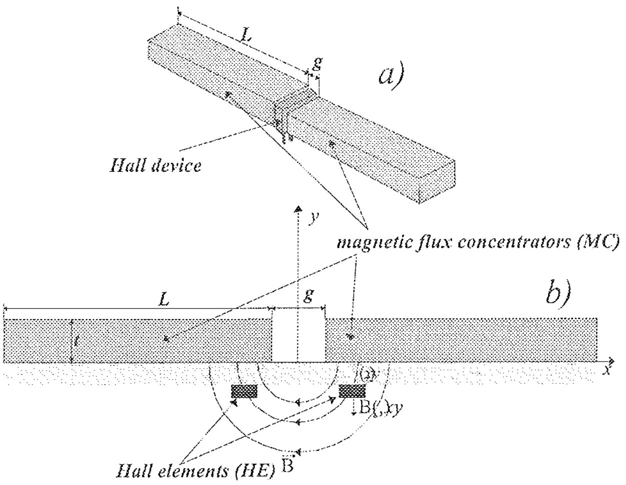

Figure 1: *Comparison of a conventional (a) and an integrated (b) combination Hall magnetic sensor - magnetic flux concentrators: a) the Hall device is placed in the air gap between the two flux concentrators; b) two Hall elements are placed under the planar magnetic concentrators /11/.*

Hall magnetic sensor - rod-like magnetic concentrators (MC). The key difference is, however, that the Hall element in (b) is placed not in, but near the air gap and under the concentrators. In this way, we can use conventional planar integrated Hall elements and we can define by photolithography the shape of MCs and the mutual positions in the system MCs - Hall elements.

The integrated magnetic flux concentrators consist of a high permeability and low coercive field (very soft) ferromagnetic layer bonded on the Hall sensor chip surface. The layer is structured so that a narrow air gap is created approximately in the middle of the chip. Figure 2 shows the distribution of the magnetic field lines around the MCs. The MCs "suck in" the magnetic field lines and convert locally the magnetic field parallel with chip surface into a magnetic field perpendicular to the chip surface. The perpendicular component of the magnetic field is the strongest near the gap. There we place the Hall elements. We use two Hall elements because two equivalent places are available and so we increase the signal to noise ratio. The Hall plates below the different concentrators see the useful magnetic field in opposite directions. So the system is insensitive to an external field component perpendicular to the chip surface /12/.

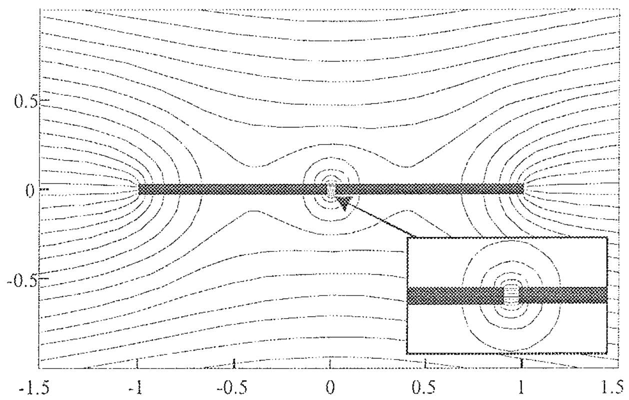

Figure 2: *The result of a two-dimensional simulation of twin planar MCs introduced into a homogenous magnetic field parallel with the MC-plane.*

In order to obtain an intuitive insight into the behavior of the magnetic concentrators, we shall perform here an appreciative two-dimensional analysis. We assume that integrated magnetic flux concentrators are layer-like (the planar dimensions of an MC are much larger than its thickness t). Moreover, since in practice we work only with very high-permeability materials, with $\mu_r > 10^5$, we assume $\mu_r \to \infty$.

2.1 Magnetic gain

We define the magnetic gain of an MC as the ratio

$$G_{XY} = B_{HE}/B_0 . \tag{1}$$

Here B_{HE} is the (perpendicular) component of the magnetic induction "seen" by the planar Hall element (HE) at a position (X, Y) (see Figure 1) and B_0 is the magnetic induction component parallel with the axis of the MC faraway from the MC.

Let us put the magnetic scalar potential difference (i.e. the equivalent excitation current I_{ex}) acting between the two adjacent MCs in the form

$$I_{ex} = KH_0(2L+g) \qquad (2)$$

Here H_0 is the magnitude of the magnetic field vector H_0 before introducing the MC, $H_0 = B_0 / \mu_0$. K is a numerical factor defined by $K = \int H_g\, dl / H_0 (2L + g)$, where H_g is the magnetic field in the gap and the integration is done over the gap. It tells which part of the theoretically available equivalent excitation current along the whole length of the MC we can rally use around the air gap. From physical arguments we estimate the limits for K in the two-dimensional case, with $L >> t$, as follows: when $g / t \to 0$, then $K \approx g / t \to 0$; when $L >> g >> t$, then $K \approx 1 / 2$. The values of K deduced from numerical simulations, Figure 3, supports these estimations.

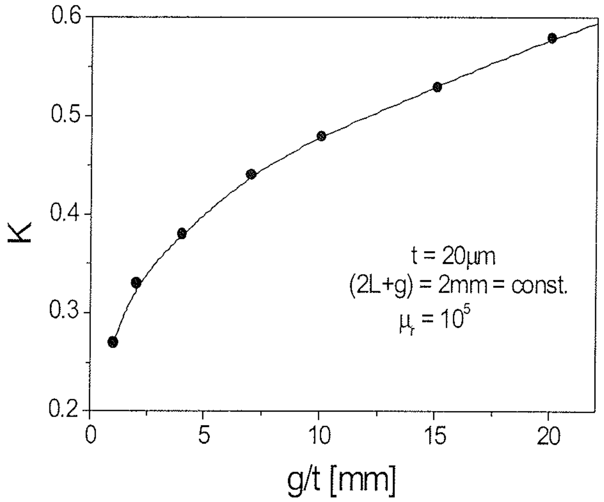

Figure 3. *The values of the factor* K *deduced from two-dimensional simulation of twin planar MCs.*

By inspecting Figure 2 we see that the magnetic field lines below the MC and close to the gap have approximately a circular form. This is always the case for high-permeability MCs and narrow gaps. Using this fact we find now the magnetic gain of a twin MC for a HE placed at (X, Y):

$$G_{XY} = \frac{K(2L+g)X}{\pi(X^2+Y^2)}$$

$$for \quad X > g/2,\ g \approx t \ and\ \mu_r >> 1 \qquad (3)$$

With an optimal layout of MC, for given t, L and g, one can increase K and so the magnetic gain G_{XY} up to a factor of 2 /13/. The realistic values of G_{XY} for an integrated sensor are between 5 and 10. But adding external MCs, this can be easily increased to about 100 /11/.

2.2 Saturation field

By inspecting Figure 2 we notice that the magnetic field lines have the highest density in the magnetic concentrators somewhere between the middle of each concentrator and the gap. We find the corresponding maximal magnetic flux density by calculating the total flux entering into an MC as follows:

$$B_{\max} \approx \mu_0 \frac{KH_0(2L+g)}{g}\left(1+\frac{2}{\pi}\frac{g}{t}\ln(L/g)\right) \qquad (4)$$

When this induction reaches the saturation induction B_{sat} of the MC material, our magnetic sensor shows a strong decrease in its magnetic sensitivity. The external magnetic field induction at the onset of the saturation is given by

$$B_{0sat} \approx B_{sat}\, g\left[K(2L+g)\left(1+\frac{2}{\pi}\frac{g}{t}\ln(L/g)\right)\right]^{-1}$$

$$for \quad g \approx t \ and\ \mu_r >> 1 \qquad (5)$$

For a sensor with the MCs of the total length $2L + g = 2$ mm, $t = g = 20$ μm and $B_{sat} = 1$ T, we obtain $B_{0sat} \approx 10$ mT. By choosing an optimal form of the MC for given t, L and g, one can increase the saturation field up to a factor of 2 /12/.

2.3 Application

By integrating twin magnetic concentrators with Hall elements, we obtain a magnetic sensor system with the following combination of features: existence of a magnetic gain, which brings a higher magnetic sensitivity, lower equivalent magnetic offset, and lower equivalent magnetic noise than those in conventional integrated Hall sensors; and sensitivity to a magnetic field parallel with the chip surface, much as in the case of magneto-resistance sensors. Figure 4 shows one example of such an integrated magnetic sensor.

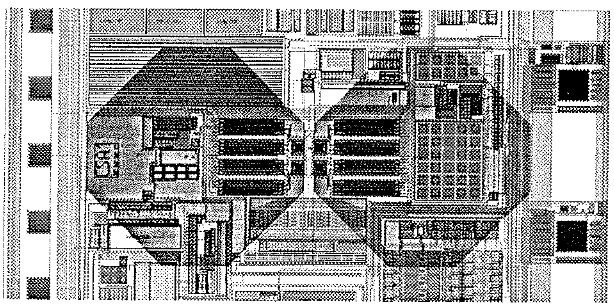

Figure 4: *The detail of the layout of an integrated magnetic sensor microsystem. The semiconductor part is a CMOS Hall ASIC. The twin magnetic concentrator has the form of the two octagons. The sensor responds to a magnetic field parallel to the in-plane symmetry axes of the two concentrators. The magnetic sensitivity is 300 V/T and the equivalent offset field is 0.05 mT. (Courtesy of SENTRON AG, Zug, Switzerland).*

3. Single magnetic FLUX concentrator

A single integrated magnetic flux concentrator is shown in Figure 5 /14/, /15/. Here again, the concentrator converts locally a magnetic field parallel with the chip surface into a magnetic field perpendicular to the chip surface. The strongest perpendicular component of the magnetic field appears under the concentrator extremities. The Hall elements are placed under the concentrator extremities and "see" this perpendicular component of the magnetic field much as in the case of twin magnetic concentrators.

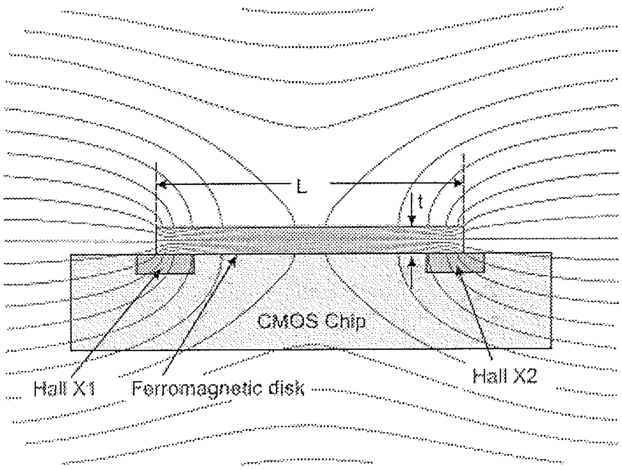

Figure 5: *Cross-section of a Hall chip combined with a single magnetic flux concentrator. The magnetic concentrator usually has the form of a disc /15/.*

3.1 Magnetic gain

We define the magnetic gain of a single magnetic field concentrator in the same way as above, Eq. (1). In order to estimate the magnetic gain, we model a disc-like magnetic concentrator with an oblate ellipsoid. For a very flat oblate ellipsoid magnetized parallel to a long axis, the demagnetization factor /16/ in our notation is

$$N \approx \frac{\pi t}{4L}\left(1-\frac{4t}{\pi L}\right) \qquad for \quad L/t >> 1 \tag{6}$$

In a very high-permeability and not very elongated structure, the internal magnetic induction is

$$B_i \approx \frac{\mu_0}{N} H_0 \tag{7}$$

Assuming that the external magnetic induction "seen" by the Hall elements $B_{HE} \approx B_i$, we obtain for the magnetic gain

$$G_E \approx 1/N \qquad for \quad \mu_r \to \infty \tag{8}$$

where N is given by Eq. (6). For a disc with L / t = 10, we calculate $G_E \approx 14.5$. Numerical simulations gave /15/ a similar value for the total magnetic gain, but only about 7 for the perpendicular field component.

3.2 Saturation field

From Eq. (7) we readily obtain

$$B_{0sat} \approx NB_{sat} \qquad for \quad \mu_r \to \infty \tag{9}$$

where B_{sat} is the saturation induction of the MC material. For a disc-like MC with L / t = 10 and B_{sat} = 1 T, this gives $B_{0sat} \approx 69$ mT.

3.3 Application

If used as a single-axes magnetic field sensor, the single MC system shown in this section may reach similar performance as the one with twin MC. The disc-like form of a single magnetic concentrator is very advantageous for contactless angular position sensing applications /15/. Figure 6 shows one example of such an integrated magnetic sensor microsystem.

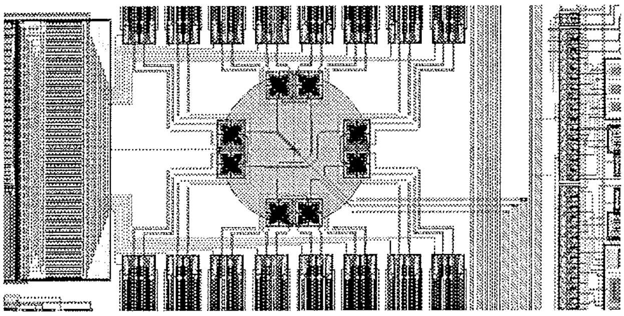

Figure 6: *Detail of the layout of an integrated 2-axes magnetic sensor microsystem. The semiconductor part is a CMOS Hall ASIC. The disc-like magnetic concentrator is deposited in a post-processing step. The sensor gives two component of an in-plane magnetic field and shall be used as an angular position sensor. (Courtesy of SENTRON AG, Zug, Switzerland).*

4. Conclusions

The Hall sensor microsystems described in this paper respond to a magnetic field parallel to the chip surface and not, as conventional Hall magnetic sensors, to a field perpendicular to the device surface. Thanks to the flux concentration effect, they also have higher magnetic sensitivity, lower equivalent magnetic offset, and lower equivalent magnetic noise than conventional Hall devices. Therefore, from the application point of view, these new integrated Hall sensors are similar to hypothetical low-offset and very linear magnetoresistive sensors (MR). Moreover, the structure of our new Hall sensors is fully compatible with conventional CMOS technology. This allows full system integration on a chip. Typical applications are sensitive position sensing and contactless angle measurement.

Assuming a state of the art realization of the CMOS part, the system performance of a magnetic sensor with a magnetic flux concentrator is determined by the characteristics of the concentrator. The magnetic gain is proportional to the ration length / thickness of the concentrator. The saturation magnetic field is inversely proportional to the magnetic gain. By and large, the maximal magnetic filed that could be concentrated on the Hall element is determined by thickness of the magnetic concentrator and the length of the sensor chip.

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