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Invited Paper

New monolithic three dimensional field sensors with high sensitivity

E. HRISTOFOROU
Laboratory of Physical Metallurgy, National Technical University of Athens, Athens 15780, Greece

In this paper, a new family of field sensors is presented, able to be integrated into a single integrated circuit, illustrating quite high sensitivity and accuracy. These sensors are based on the inductive or galvanic response of soft magnetic thin films or ribbons as sensing elements, subjected to on-plane or out-of-plane rotation of magnetization. The sensing cores are magnetized by rotating field on their surface, with amplitude significantly larger than the anisotropy field of the thin film or ribbon. Thus, they illustrate pseudo-super-paramagnetic behavior by means of circular magnetization, exhibiting no discontinuities on the magnetization rotation and therefore no magnetic noise due to absence of Barkhausen jumps. The two on plane under measurement field components may be determined by the modulation of the rotating field response, by means of phase shift and amplitude modulation of the second harmonic. Such phase shift and amplitude modulation is measured either by inductive means like on-chip Hall elements, or by galvanic techniques using on-chip VIAS connections. Absence of Barkhausen noise can result in sensitivity of the order of pT of the galvanic mode of operation, while use of Hall effect devices resulted in a sensitivity of the order of nT. These sensors may serve as single chip gyroscopes and electronic compasses for various applications like mobile telecommunications, driverless driving and precise GPS systems.

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1. Introduction

Field sensing is probably the largest percentage in the magnetic sensors market. The most frequently used field sensors are the ones used for small field variations or field gradient or magnetic anomaly detection (MAD) [1]. The most important techniques and effects used to develop such field sensors based on magnetic materials are the magneto-resistance effect, the magneto-impedance effect and inductive techniques like fluxgates [2]. Magnetostriction has also been used in field sensing but only in special applications, where large scale field distribution measurement is required.

The primary standard in magnetic field sensors is the superconducting quantum interference device (SQUID) based on the Josephson junction effect [3, 4]. This sensor is made of a closed loop of superconducting material separated by a thin insulating layer. Such a thin insulator may operate as single electron transport tunnel when it is properly biased. Transmitting the smallest possible magnetic quantity, the Bohr's magneton along the Josephson junction, can result in a pulsed voltage output increment across the two ends of the superconducting materials. The lowest noise level of SQUID sensors has been found to be 0.1 fT ≅ 1 Hz, concerning high purity single superconducting crystals of low T_c (critical transition temperature), concerning liquid helium monocrystal superconductors, tested in very well magnetically isolated champers. The SQUID noise level increases with the critical transition temperature of the superconducting element as well as the magnetic shielding ability of the testing room. Concerning high T_c SQUID sensing elements (liquid nitrogen superconductors), the noise level cannot be better than 1 fT ≅ 1 Hz, while most of the measurements report noise levels of the order of 10 fT ≅ 1 Hz. The main disadvantage of these sensors is that they require helium or nitrogen cooling systems to operate. Therefore, their cost and cost of operation are quite high, allowing their use in special cases only, like primary level calibration facilities and biomedical applications.

Before the appearance of SQUID sensors, the standard in magnetic field measurements used to be the proton and gas field sensors [5]. These sensors, which currently serve as very sensitive magnetometers mainly dedicated for military sensing applications and mapping, are based on the Zeeman effect. According to this effect, when a specific gas of a low electron element is excited, its electrons are moved to a higher energy level. When de-energized, electrons drop down to their previous state, but the new "steady state" level is one of the two hyperfine states, separating the spin up and spin down stage. So, the energy state level of the electron depends on the ambient magnetic field. The noise level of this sensing element depends on the purity of the sensing gas and the conditions of the measuring operation. The lowest ever measured noise level has been 1 fT ≅ 1 Hz, while common measurements are of the order of 10 fT to 100 fT ≅ 1 Hz. They may be less noisy in the presence of ambient field compared to high T_c SQUID devices.

The second best sensors in terms of sensitivity and noise level are the fluxgate sensors [6-8]. The evolution of soft magnetic materials in terms of manufacturing and post-cast treatment, offered B-H loops with negligible hysteresis, exhibiting either sharp and bistable behaviour or linear suddenly saturated B-H loop. These materials, may exhibit magnetic hysteresis as low as a few A/m with very low Barkhausen noise. Hence, the best sensitivity of these elements has been determined to be in the order of 10 pT ≅ 1 Hz. These devices are not as spacious as the proton – gas sensors and do not require any special systems to operate, like the cryogenic demands of the superconducting SQUIDs. But they are still far from meeting the current demands for miniaturization. Any attempt to decrease their size has resulted in a decrease of the noise sensitivity, since hysteresis becomes significant and Barkhausen jumps are present. For fluxgate sensors in the size of several mm, the noise level increases up to 100 pT-1 nT ≅ 1 Hz.

In order to overcome the problem of the size, the recently developed GMI technique has been employed in field sensing development [9-15]. Sensitivity levels in the order of 100 or even 10 pT ≅ 1 Hz have been reported in some special magnetic core materials. In the same way, a combination of the fluxgate and the magneto-inductive principle has been employed to realize smaller and low noise field sensors [16].

Magneto-transport sensors are very common in the sensor market. The most well known elements are the classic magnetoresistive or anisotropic magnetoresistive heads [17-19]. These devices exhibit in plane anisotropy and despite the fact that the MR ratio is of a few %, their noise resistivity is of the order of 10 nT ≅ 1 Hz. Another family of magneto-transport field sensors concerns devices based on GMR multilayers, a stack of repeated bilayers made of a magnetic and a non-magnetic conducting film [20,21]. In this case, the resistance is measured across the multilayer and the effect of the Lorentz force altering the path of conducting electrons due to the perpendicular magnetic field is practically amplified due to the several MR layers. Special structures of GMR elements utilize multiple layers of a basic tri-layer cell made of a hard magnetic film, a soft magnetic film and a non-magnetic film all of them being conducting [22]. Spin valves, spin tunnelling devices (like TMR sensors) have also been developed for field sensing [23,24] based on the tunnelling principle.

Another magnetic technique takes advantage of the magnetostriction effect and the generated magneto-elastic waves in order to realize a distribution field sensor for non destructive evaluation of magnetic surfaces [25,26] offering noise level of ~ 10 nT ≅ 1 Hz.

The most traditional integrated magnetic field sensors, the Hall effect devices [27, 28], are still in the market despite the poor noise level characteristics but thanks to their low cost, miniaturization capabilities and inherent compatibility with CMOS technologies. Their noise level is of the order of 0.1 to 1 mT ≅ 1 Hz and their cost ranges from 2 to 20 Euros per sensor concerning field switches and magnetometers respectively.

All the described magnetic field sensors refer to dc or quasistatic field detection. If high frequency fields are to be measured, coil sensors or antennas are used, their response being extracted from the Maxwell equations. Usually, they are used without magnetic sensing core. This way their sensitivity is by definition smaller, but noise level is negligible due to the $1/\sqrt{f}$ law. If higher sensitivity is required, high frequency soft ferrites are use. There is also an open question at this point, namely the development of linear, non-hysteretic and low Barkhausen noise high frequency magnetic sensing cores.

It can be said that at this moment there still is a need for further research and development of magnetic field sensors concerning the realization of miniaturized field sensors integrated with CMOS technology, to offer sensitivity of the order of 0.1 pT to 1 pT ≅ 1 Hz. In fact, this was the motivation of a research project in our Laboratory, namely the development of a technique to increase the sensitivity by eliminating the Barkhausen noise [29,30]. The sensors presented in this paper can be realized in a CMOS compatible integrated circuit and can exhibit very low magnetic noise and repeatability error, with a by design three-dimensional field measuring ability.

2. The rotating principle

Taking into account the fact that the most significant problem in field sensors based on magnetic materials and techniques is the magnetic noise, which is mainly dependent on the Barkhausen noise, we have conceived a simple technique to overcome this barrier. A way to eliminate the Barkhausen noise, apart from minimizing pinning defects, is to keep the material in deep saturation state. Targeting time varying magnetization and Barkhausen noise elimination in a film, one can use a rotating magnetic field vector on the surface of the film as excitation field with an angular speed ω. Rotating magnetic field vector can be obtained by transmitting two orthogonal fields of $H_x(t) = H_o \sin \omega t$ and $H_y(t) = H_o \cos \omega t$ respectively. The amplitude of the magnetic vector H_o must be significantly larger than the anisotropy field H_k of the material ($H_o >> H_k$) in order to keep it far in the saturation state which in fact corresponds to the reversible rotation process of magnetic domains.

The film magnetization M rotates under the influence of the excitation field, as shown in Fig. 1. Thus the film behaves as a pseudo-isotropic-super-paramagnetic material and the magnetic noise is narrowed down to theoretically zero and the noise – sensitivity limitations are only due to circuit electronics. The magnetization of the material is continuously rotating and on each 360^o turn any offset that would be produced because of the remanent magnetization by the external field is zeroed. The parametric control of the setup (film geometry, stoichiometry, material structure and micro-structure) can lead to the minimization of the anisotropic field H_k and the magnetic noise and increase the sensitivity of the measurement.

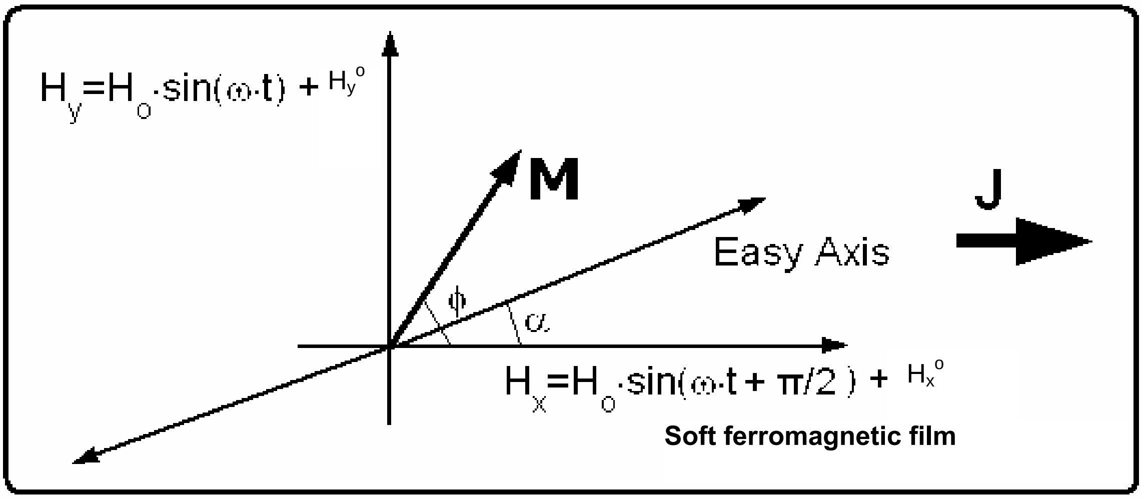


Fig. 1. Analysis of the rotating excitation field.

Angle φ is modulated by the axial components H_x^o and H_y^o of the ambient magnetic field and, thus, the film resistance and the inductive response of the arrangement become second harmonic phase and amplitude modulated waveforms.

As above described, for amplitudes of the rotating excitation field H_o significantly larger than the anisotropic field H_k, the magnetization of the material follows adequately the rotating external field and the output is a sinusoidal function. When the excitation field is reduced in amplitude and its value approaches H_k, harmonics are added in the previously mentioned sinusoidal function, as shown in Fig. 2a, due to the difficulty in magnetic domain rotation. The series of these harmonics are related to the difficulty of the magnetization vector of a mono-magnetic or quasi-mono-magnetic area to turn from one easy axis to another. The number of the Barkhausen jumps in a given period of the external field is equal to the number of the easy axes that the material has on the surface of the rotating field. Every term of the series is periodical with the same period but phase difference, which is an unambiguous function of the orientation of each grain or magnetic domain. The parametric control of the angular speed of the rotating external magnetic field can zero the "dead" time between the Barkhausen jumps in the output voltage, as shown in Fig. 2b, under the assumption that there are no pinning points in magnetic domain wall motion. Thus, changing the angular speed ω, one can obtain a quasi-sinusoidal output signal of the same angular speed.

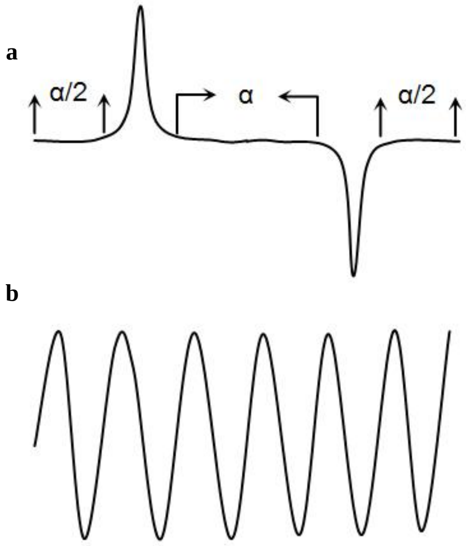


Fig. 2. Theoretical sensor output response. (a) "Dead" time between the Barkhausen jumps of the material magnetization from one easy axis to another, (b) Elimination of the "dead" time by synchronization of the angular speed of the external field to the magnetization rotation.

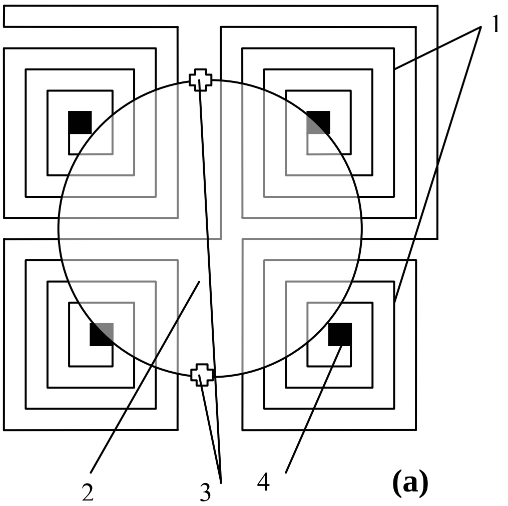
For a film of cubic bcc or fcc symmetry and with the proper selection of the angular speed of the excitation field, so that the output signal be a quasi-sinusoidal function, the frequency of the harmonic addition or noise of each magnetic grain will be 2ω for in plane anisotropy and 3ω for out of plane anisotropy. Thus, all the waveforms that are added to the signal as sinusoidal signals of the same frequency and different phase are obliged not to be random signals, but 2nd and 3rd harmonics. Thus, by placing in the setup digital band pass filters for 2ω and 3ω, magnetic noise could be removed and sensitivity could be optimized.

As it will be illustrated in the next two chapters, two main techniques are used for field detection, one being inductive and the other galvanic. Although the same property of small anisotropy field is required for both cases, suggesting as soft as possible magnetic sensing cores, the specifications of the sensing cores in these two different sensing methods are quite different. Concerning the inductive response, a large magnetic mass is required to allow acceptable sensitivity. Thus, small magnetostriction λ, high magnetic permeability μ and thick magnetic material, in the form of film or ribbon are required. Concerning the case of galvanic response, due to the large initial resistance requirement, a very thin film with small λ and high μ is required. The small magnetostriction and high permeability requirement can be satisfied by using either heat treated amorphous FeCoSiB alloy ribbons or polycrystalline Ni_3Fe films for inductive and galvanic mode of measurement respectively.

3. The field sensors

Two types of sensors have been developed. Both of them were based on the same rotating excitation technique, using a circular magnetic strip in the form of amorphous non-magnetostrictive ribbon or film, as described in the previous chapter. The main difference of the two sensors was the method of the actual measuring principle.

A schematic of the two sensors is presented in Fig. 3. The Hall effect sensing element (HE) is depicted in Figure 3a and the magneto-resistive sensing element (MR) in Fig. 3b. In both implementations, the sensing core was excited with a rotating magnetic field, generated by four planar coils: every two diagonal coils were connected in series and sinusoidal current $I_o \sin\omega t$ and $I_o \cos\omega t$ was applied in the two pairs of coils. Thus two orthogonal magnetic fields $H_o \sin\omega t$ and $H_o \cos\omega t$ were applied on the sensing core. The sensing core in the HE sensing element had on-plane magnetic anisotropy and the sensing core in the MR variation could have on-plane or out-of-plane or perpendicular magnetic anisotropy. The result of the technical field was the on-plane rotation of magnetization for the HE and the on-plane MR sensing element, with angular velocity ω. For the out-of-plane or perpendicular magnetic anisotropy films conical motion of the magnetization vector with angular velocity ω could be obtained.



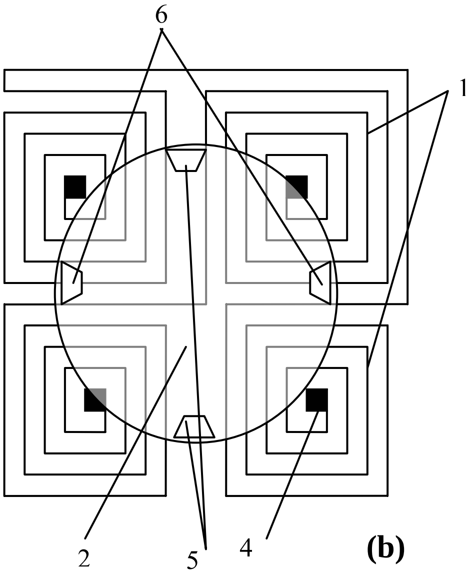


Fig. 3. The schematic of the two sensors. (a) The Hall effect sensing element (HE), (b) the magneto-resistive sensing element (MR): (1) Excitation coils, (2) Magnetic sensing core, (3) Hall elements, (4) Coil conducts, (5) Pair of ohmic contacts for the one axis of the MR sensing element, (6) pair of ohmic contacts orthogonal to (5).

Concerning the HE sensing element, phase shift and amplitude modulation of the second harmonic of any Hall element set at the vicinity of the magnetic sensing core, are the indication of the radial and circumferential on-plane magnetic field component respectively, while the offset response of any Hall element corresponds to the vertical field component. For this type of sensor, only one Hall element is required to perform the measurement, while using more than one may help in applying averaging techniques and increase the sensor sensitivity. The expected output waveforms ideally look like the ones illustrated in Fig. 4, while in practice noise is added in these waveforms. It can be seen that they include a phase modulated second harmonic.

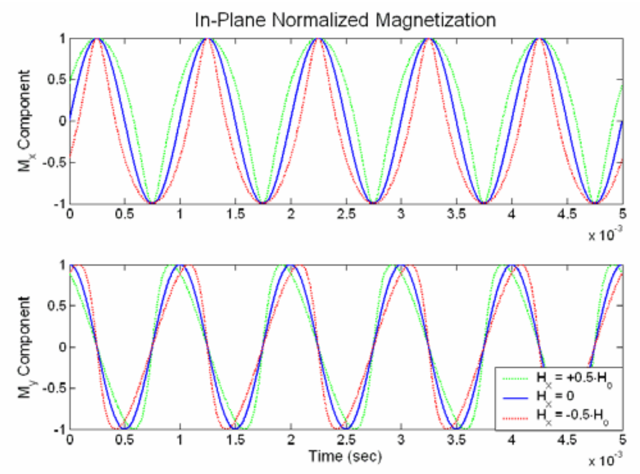


Fig. 4. The theoretical outputs of the magnetic field sensor under the influence of the x-component of the DC external field (a) and under the influence of the y-component of the DC external field (b).

The Hall element sensor version was realized by using a 25 μm thick FeCoSiB ribbon as rotating magnetization element, used after field annealing to allow small magnetostriction coefficient. Discrete Hall components were used to proof the principle of operation. The dependence of the phase and amplitude modulation of the second harmonic of the output of the Hall element demonstrated a worse-case sensitivity of 1 nT ≅ 1 Hz. Using more Hall elements, such sensitivity may be improved. The perpendicular field component is measured by the offset of the Hall element, as illustrated in Fig. 5.

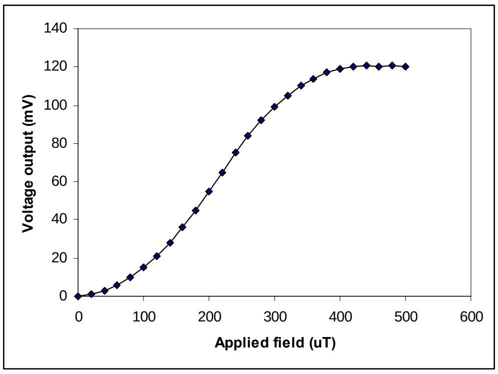


Fig. 5. The dependence of the Hall element output on H_z, the field component perpendicular to the Hall element.

Concerning the MR sensing element, the second harmonic of the magneto-resistive voltage output across two diagonal sensing points is phase modulated by the corresponding component of the ambient magnetic field. Thus, two pairs of diagonally set ohmic conducts are at least required to measure H_x^o and H_y^o. The H_z^o component of the ambient magnetic field may be measured by amplitude modulation of the second harmonic in a diagonally set pair of ohmic conducts, only when the magnetic anisotropy is out-of-plane or perpendicular to the film plane.

The MR sensor version was realized by using high resistance 4 nm Permalloy thin-film core that has been manufactured by means of DC sputtering deposition and thermal post-annealing. Such a film had by-design on-plane anisotropy. Thus, a two-dimensional field measurement was targeted to prove the principle of operation of this sensor.

Measurements obtained by Kerr microscopy showed coercive and anisotropy fields smaller than 120 A/m and 320 A/m respectively as illustrated in Fig. 6. The resistance change was also smooth, without magnetic noise. This derives from the fact that the in plane anisotropy is small and the magnetization of the core follows the rotating excitation field when it functions as an active element of the magnetic field sensor. This decreases the magnetic field noise that appears in field sensors because of the large Barkhausen jumps.

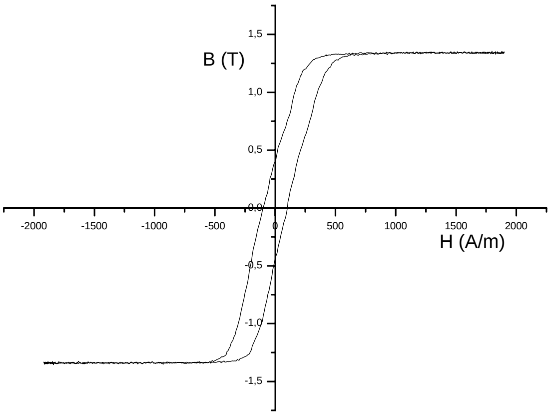


Fig. 6. Permalloy hysteresis loop obtained by Kerr microscopy.

Magnetoresistance measurements were taken by the 4-point technique with 1 μOhm resolution. As seen in Figs. 7a and 7b, the permalloy thin film reaches saturation at 320 A/m. The abnormality noticed at 180 A/m before the element reaches saturation was caused from magnetization remanence, which was vanished as field gets larger. Taken these into account, a rotating field over ~500 A/m would be enough to keep it in constant saturation and to exhibit the desired pseudo-super-paramagnetic behavior.

The rotating frequency of the sensor was set at 1 KHz. Excitation field amplitude H_o was set to 800 A/m, thus forcing magnetization to complete saturation. The whole setup was placed in a Faraday chamber for magnetic shielding, to ensure that no other magnetic field like the earths' field may affect the measurements. In this way the magnetization vector in the film plane rotated smoothly generating no magnetic noise and repeatability error, within the limits of our experimental measuring instruments.

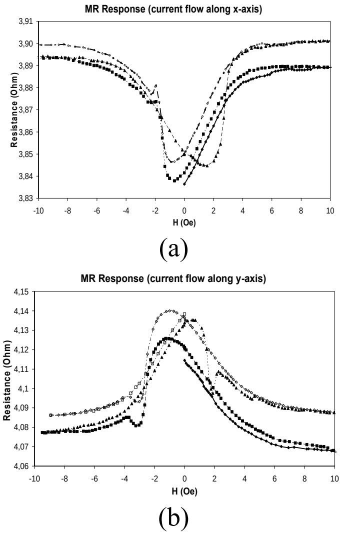


Fig. 7. MR response. (a) Current flow along x-axis, (b) Current flow along y-axis.

The x- and y- components of the external magnetic field applied on the sensor effected the even and odd passes through zero of the sensor output within the period of the excitation field. Thus, by locking-in different zero points of the sine wave, the H_x^o and H_y^o components of the ambient magnetic field were measured, by monitoring the phase changes. Actually, the locking points of interest were the zero and peaks of the excitation sinus waveform. Using the lock-in amplifier to measure phase differences between excitation field and voltage output signals, precise magnetic field sensing was realized as illustrated in Fig. 8. As expected, the sensor exhibits negligible repeatability error, despite the fact that the MR response of the employed thin-film is quite hysteretic as presented in Figs. 7a and 7b: the forced magnetization rotation suppresses both magnetic noise and repeatability error.

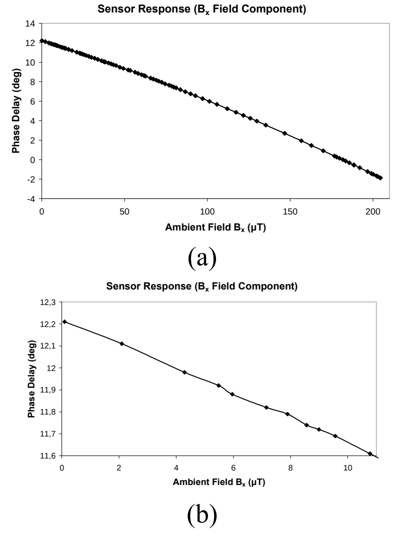


Fig. 8. MR sensor response (B_x field component). (a) High field range, (b) low field range.

4. Discussion

The Hall element – rotating magnetization magnetic field sensor offers the following advantages with respect to the given state of the art: at the first place it is able to measure 3-d ambient field by design, using a two dimensional arrangement. The two on-plane components are measured by means of measuring phase and amplitude modulation of the second harmonic, requiring only one Hall transducing element, while the vertical component is measured by using the mentioned Hall element offset amplitude modulation. Up to this moment the sensor was realized by using a discrete Hall effect device, suggesting increased levels of error in the accuracy of measurement, which is expected to decrease in the case of a miniaturized integrated circuit. The second is that it is fully compatible with CMOS techniques, using only post-processing deposition of the magnetic layer. This sensor approach requires no contact from the substrate to the sensing core, thus allowing for a simple process of adhering the magnetic ribbon on top of the silicon wafer, or depositing a magnetic layer on top of the production wafer, having the drawback of a lower sensitivity and accuracy, mainly due to the Hall effect sensor noise level. Thus, the cost of the device is limited to a cost close to that of an integrated circuit. Using ultra-soft Yttrium Iron Garnets may result in an improvement of sensitivity. Possible use can be domestic applications, like 3-d electronic compass for mobile phones, vehicle navigation and GPS aid tool, industrial and transportation applications like magnetic signature as well as other applications like anti-mining control.

The galvanic – rotating magnetization magnetic field sensor exhibits high sensitivity, low magnetic noise, and negligible repeatability error. Moreover, compared with standard fluxgates, it does not require a receiving coil to function. The sensing element design is compact and robust and its miniaturization is straight forward by means of standard microelectronic technologies. This sensor has significantly better characteristics than the Hall – rotating magnetization based sensor: the MR approach has better sensitivity and accuracy with the drawback of difficult CMOS implementation. That is because it requires VIAS technology from the silicon substrate to the sensing core, and a sensing material with out-of- plane or perpendicular anisotropy, obtained only by PVD post-processing on the silicon wafer. We estimate that, after achieving repeatable VIAS technology for integrated circuit development, the sensitivity of the device can beat the 1 pT barrier with a cost quite significantly less than the cost of the accurate fluxgate magnetometers. The measurement of the field perpendicular to the plane may be determined by means of amplitude modulation of the galvanic output: provided that the sensing core exhibit out-of-plane or perpendicular anisotropy, the rotation of magnetization has a conical mode, thus resulting in amplitude modulation measurement of the perpendicular component. Similarly, in case these films or ribbons exhibit on-plane anisotropy, the conical magnetization rotation may be achieved by using thin film permanent magnet for out-of-plane forced magnetization orientation.

The sensitivity of both sensors was increased when the excitation field intensity was set to 800 A/m. Excitation field below 400 A/m increased significantly the output noise levels of the sensors, proving the statement concerning elimination of the Barkhausen noise. The excitation field of the MR sensor can't be much larger than 800 A/m though, because the sensor output is hardly influenced by the magnetization of the material.

Further studies take place in order to characterize the sensor response under different sensing materials and other parameters like geometry and composition of the sensing element, as well as technical characteristics like frequency of excitation, temperature coefficient dependence etc. Optimization of the sensing core will be realized by optimizing the structure of the sensing core and the magnetic and electric properties of the device.

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References

[1] A. Parakka, D. C. Jiles, J. Magn. Magn. Mat. **140-144**, 1841 (1995).

[2] Magnetic Sensors and Magnetometers, Pavel Ripka (ed), Meas. Sci. Technol., 13 (2002).

[3] M. Tinkham, Introduction to superconductivity, 2nd ed., McGraw-Hill, Inc. (1996).

[4] P. Müller, A. V. Ustinov (Eds), V. V. Schmidt, Springer - Verlag (1997).

[5] J. Skalla, G. Wäckerle, M. Mehring, A. Pines, Physics Letters A **226**, 69 (1997). Also in: J. Avron, I. Herbst B. Simon, Physics Letters A **62**, 214 (1977).

[6] P. Ripka, J. Magn. Magn. Mat. **215-216**, 735 (2003).

[7] O. V. Nielsen, P. Brauer, F. Primdahl, J. L. Jørgensen, C. Boe, T. Risbo, M. Deyerler, S. Bauereisen, Sensors and Actuators A, **59**, 168 (1997).

[8] P. D. Dimitropoulos, J. N. Avaritsiotis, J. Optoelectron. Adv. Mater. **4**(2), 281 (2002).

[9] P. Ciureanu, G. Rudkowska, L. Clime, A. Sklyuyev, A. Yelon, J. Optoelectron. Adv. Mater. **6**(3), 905 (2004).

[10] H. Chiriac, M. Tibu, V. Dobrea, I. Murgulescu, J. Optoelectron. Adv. Mater. **6**(2), 647 (2004).

[11] M. M. Tehranchi, S. M. Mohseni, J. Optoelectron. Adv. Mater. **6**(2), 667 (2004).

[12] M. Knobel, M. Vàzquez, L. Kraus, Giant Magnetoimpedance, in Handbook of Magnetic Materials, North Holland (2002)

[13] L. Kraus, GMI modeling and material optimisation, Sensors & Actuators **A106**, 187 (2003).

[14] L. V. Panina, D. P. Makhnovskiy, K. Mohri, J. Magn. Magn. Mat. 272-276, 1452 (2004).

[15] K. Mohri, IEEE Trans. Magn. **28**, 3150 (1992).

[16] I. Sasada, T. Usui, Paper M-I.4, EMSA 2004, Cardiff, UK.

[17] J. M. Daughton, J. MAGN. Magn. Mat. **192**(2), 334 (1999).

[18] S. Andreev, J. Koprinarova, P. Dimitrova, J. Optoelectron. Adv. Mater. **7**(1), 317 (2005).

[19] M. Volmer, J. Neamtu, I. Inta, J. Optoelectron. Adv. Mater. **4**(1), 79 (2002).

[20] B. A. Gurney, D. R. Wilhoit, V. S. Speriosu, I. L. Sanders, IEEE Trans. Magn. **26**(5), 2747 (1990).

[21] J. M. Daughton, IEEE Trans. Magn. **30**(2), 364 (1994).

[22] A. Vedyayev, D. Bagrets, A. Bagrets, N. Ryzhanova, N. Strelkov, B. Dieny, C. Lacroix, J. Magn. Magn. Mat. **242-245**, 453 (2002).

[23] D. D. Tang, P. K. Wang, V. S. Speriosu, S. Le, K. K. Kung, IEEE Trans. Magn. **31**(6), 3206 (1995).

[24] P. Ripka, M. Tondra, J. Stokes, R. Beech, Sensors and Actuators **76**(1-3), 225 (1999).

[25] E. Hristoforou, H. Chiriac, M. Neagu, IEEE Trans. Instr. & Meas. **46**, 632 (1997).

[26] H. Gavrila, V. Ionita, J. Optoelectron. Adv. Mater. **4**(2), 173 (2002).

[27] G. Boero, M. Demierre, P. -. A. Besse, R. S. Popovic, Sensors and Actuators **106**, 314 (2003).

[28] M. Lozovan, M. Neagu, C. Hison, J. Optoelectron. Adv. Mater. **6**(2) 651 (2004).

[29] P. D. Dimitropoulos, J. N. Avaritsiotis, Sensors and Actuators **106**(1-3), 43 (2003).

[30] P. D. Dimitropoulos, J. N. Avaritsiotis, Sensors and Actuators A, Volume **94,** 165 (2001).

Corresponding author: eh@metal.ntua.gr