

A NEW LOW CONSUMPTION 3D COMPASS USING INTEGRATED MAGNETS AND PIEZORESISTIVE NANO-GAUGES

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ABSTRACT

We present for the first time a new concept for low-cost fabrication of a monolithic 3-axis MEMS compass using integrated permanent magnets and based on a technology compatible with inertial MEMS sensors. Piezoresistive gauges of nanometric scale enable to reduce the sensor size without sensitivity loss. Magnetometers were designed for sensitivities of 9V/T and resolutions less than 10nT/√Hz at a bridge current of 100μA and with an active surface of typically 200μm x 300μm. Ultra-low power consumption below 10μW can be achieved. First demonstrators have shown the good reliability of the concept and are in good agreement with design.

KEYWORDS

3D Compass, piezoresistive nano-gauges, integrated magnets

INTRODUCTION

Context

Mainly used concepts for magnetic field micro-sensors are based on Hall Effect, AMR, GMR and the fluxgate principle. Solutions to miniaturize integrated 3D magnetic field sensors have been proposed during the recent years [1, 2], but monolithic integration of a 3-axis magnetometer within a single fabrication process for these devices remains difficult, yet impossible. Fully integrated 3-axis MEMS magnetometers have recently been presented by Kyyräinen *et al.* and Thompson *et al.* [3, 4], which are based on the principle of Lorentz force and thus exhibit increased power consumption due to current biasing. As demands for enhanced performances, low energy consumption, smaller size and low fabrication costs are constantly increasing, we propose a completely new low-cost approach for a monolithic high resolution 3D magnetic field sensor for compass application. Our approach is based on the M&NEMS concept [5], which enables to maintain high sensing performances combined with drastic size reduction. In our case, we use permanent magnets instead of current biasing loops, which leads to an exceptionally low power consumption for our sensor, which can be pushed below 10μW by sampling of the polarization current. Our sensors were designed for use in compass application with a minimal angular resolution of 1° in earth's magnetic field, which corresponds to a resolution of 130nT/√Hz. An advantage is the monolithic integration of a 3 axis magnetometer within a single

surface micromachining process. The realization of inertial measurement units (IMUs) is possible as well, as the fabrication technology is also suitable for accelerometers and gyroscopes.

The concept

Permanent magnets are integrated within a surface micromachining process into mobile silicon bricks and are used for magneto-mechanical transduction. Piezoresistive silicon strain gauges of nanoscale dimensions are connected to the silicon structure (fig. 1) and are used for mechano-electrical transduction. Two different approaches have been explored for integration of magnetic material into the mobile silicon structure. In the first option, hard magnetic material (SmCo or NdFeB) is integrated into the silicon brick. Thin coupled antiferromagnetic and ferromagnetic (AF/F) multilayers ([PtMn/CoFe]_n) are deposited on top of the silicon brick in the second option.

A magnet with volume V and magnetization $\vec{M}$, exposed to an external magnetic field $\vec{B}$, is subjected to the moment

$$\vec{\Gamma} = V\vec{M} \times \vec{B}. \quad (1)$$

This moment induces a rotation of the mobile silicon structure around its flucrum, which is then intercepted by piezoresistive nano-gauges on either side of the fulcrum, in which high mechanical stresses are generated due to their small section. For this reason, the sensor size can be kept small by maintaining high sensitivity.

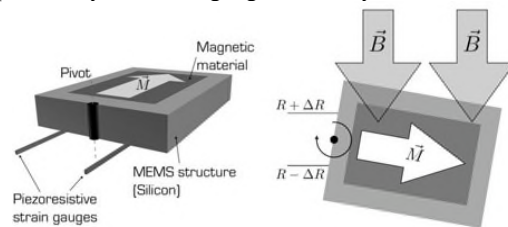


Figure 1: Magnets are integrated into a Silicon brick, which is connected to piezoresistive nano-gauges, so that a moment is generated in presence of an external magnetic field.

In order to realize a monolithic 3-axis magnetometer, three individual silicon structures for detection of the three spatial magnetic field components are used. Furthermore, at least two independent magnetization directions are required to be integrated into the dedicated silicon structures which are adapted for in-plane or out-of-plane rotation.

TECHNOLOGICAL REALIZATION

Design

According to the functional principle, the magnetometer's sensitivity is given by

$$S = i_a R \pi_{44} \frac{MV}{4d_g A_g}. \quad (2)$$

Here, an ideal hinge and a simple readout configuration as presented in fig. 2 are assumed. In equation (2), i_a is the polarization current, R the gauge resistance and π_{44} the piezoresistive coefficient for the [110]-direction lengthwise the gauges. Critical parameters for design are the gauge section A_g and the distance d_g between nano-gauges and the fulcrum.

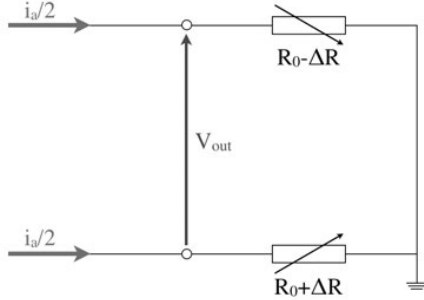


Figure 2: Basic electrical configuration for signal readout.

Resolution is mainly limited by four different noise sources: Electronic noise, arising from the amplification stage, thermo-mechanical noise [6] which is generated by thermally agitated molecules in interaction with the surface of the silicon structure, thermo-electrical noise and 1/f noise [7]. Latter two noise sources are predominant in our application and are both generated inside the nano-gauges. Hence, the conception of nano-gauges is a key issue for the design of our sensor. If thermo-electrical noise is considered to be the exclusive predominant noise source, the sensor's resolution is given by

$$R_T = \frac{4d_g}{i_a \pi_{44} MV} \sqrt{\frac{A_g^3 k_B T}{\rho_{Si} l_g}}. \quad (3)$$

If 1/f noise is considered to be the single predominant noise source, the resolution is expressed as

$$R_F = \frac{d_g}{\pi_{44} MV} \sqrt{\frac{\alpha A_g}{n_D l_g}} \sqrt{\frac{\ln \frac{f_{\max}}{f_{\min}}}{\Delta f}}. \quad (4)$$

In eqns. (3) and (4), k_B is the Boltzmann constant, T the temperature, ρ_{Si} the resistivity of silicon, l_g the gauge length, α the Hooke parameter, n_D the doping concentration, $f_{\max}$ the upper and $f_{\min}$ the lower bandwidth limit, respectively. Eqns. (3) and (4) show that in both cases, the gauge length has to be maximized and the gauge section has to be reduced in order to obtain a better

sensor resolution. However, geometrical gauge parameters cannot be chosen arbitrarily: technological constraints limit the minimum gauge section, and phenomena such as Joule heating of polarized nano-gauges and buckling in case of compressive gauge stresses impose a maximum length of the nano-gauge. Thus, A_g has been set to $250 \times 250 \text{ nm}^2$ and l_g to $5 \mu\text{m}$ in the presented case.

Besides the nano-gauges, a second design level consists in the geometrical conception of the MEMS structure. As seen from eqn. (2), a basic design rule is the maximization of integrated magnetic volume V in order to enhance the sensor's sensitivity. But also the geometric design of the structure had to be optimized so that an eventually generated moment due to acceleration forces vanishes. This was achieved by equilibrating the structure in a way that its center of gravity is situated in the sensor's rotation axis. Furthermore, the distribution of magnetic material over the sensor surface is important to be considered. In presence of a constant magnetic field gradient, a force

$$F_x = -\frac{\chi}{\mu_0} V_i B \frac{\partial B}{\partial x} \quad (5)$$

is generated on any distinct magnet with magnetic volume V_i , where χ is the magnetic susceptibility and μ_0 the magnetic permeability in vacuum. To avoid moments resulting from these magnetic forces, magnetic material is uniformly distributed over the entire MEMS structure, so that the parasitic moment is minimized.

The third important part to be designed was the suspension of the MEMS structure. For in-plane-rotating structures, bending beams were designed. Bending beams and torsion beams were used to build hinges for out-of-plane rotating structures. As the suspension cannot be considered to be an ideal hinge, an optimum position of the nano-gauges with respect to the fulcrum had to be found. A too long distance d_g between the nano-gauges and the fulcrum leads to reduced sensitivity, whereas the structure's mechanical stiffness is dominated by the gauges' stiffness. If d_g is chosen too small, the mechanical stiffness of the suspension dominates the structure's overall rigidity. Thus, there is an optimum geometry of the gauge-hinge level, for which the stress inside the nano-gauge reaches a maximum value. In our case, we found the optimum positioning of the gauges by FEM analysis using COMSOL software. In case of out-of-plane structures, d_g was determined by the given thickness of the MEMS structure, so that the suspension beam length was the parameter to be optimized.

Fig. 3 shows schemes of designed structures. Table 1 lists performances the sensors have been designed for, assuming the case of integrated NdFeB with an applied readout current of $100 \mu\text{A}$ and suspension beams with a thickness of $3 \mu\text{m}$.

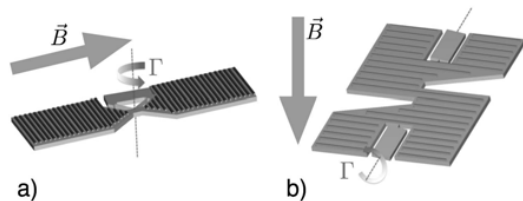


Figure 3: Scheme of designed structures for a) in-plane and b) out-of-plane rotation.

Table 1: Sensor performances.

	in-plane magnetometer	out-of-plane magnetometer
Sensitivity [V/T]	9.1	8.3
Resolution [nT/√Hz]	9.7	7.2

Fabrication

The fabrication process consists of two important process levels. A first level serves to build the silicon MEMS structure with the connected nano-gauges, while magnetic material is integrated into the structures during the second process level. The process is started on a SOI substrate (fig. 5-1). Nano-gauges are defined in the crystalline silicon layer by a lithography and etching step (fig. 5-2). After deposition of a protective SiO₂ layer (fig. 5-3), a 10μm thick silicon layer is grown by epitaxy (fig. 5-4). Ion beam deposition (IBD) was used to deposit thin coupled AF/F multilayers as narrow stripes upon the MEMS structures (fig. 5-5a)), while sputtered and then planarized hard magnetic material was embedded into 1μm deep trenches which were etched into the silicon bricks (fig. 5-5b)). The technological realization of integrated magnetic material is shown in fig. 4.

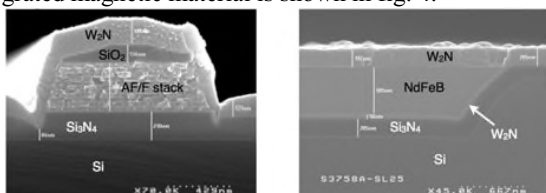


Figure 4: Deposited coupled AF/F multilayers (left) and integrated hard magnetic material (right).

After deep reactive ion etching (DRIE) of the thick Silicon layer (fig. 5-6), the structures are released by HF etching (fig. 5-7). As the integration of two perpendicular magnetization directions within a single chip is required in order to achieve 3-axis field sensing, a magnetic field was applied at an angle of 45° with respect to the long directions of the stripes of deposited AF/F layers. This critical technological step has successfully been validated by measurement on a vibrating sample magnetometer (fig. 6). In order to achieve the integration of two perpendicular magnetization directions in the hard magnetic layer, thermo-magnetic-patterning (TMP) is used [8].

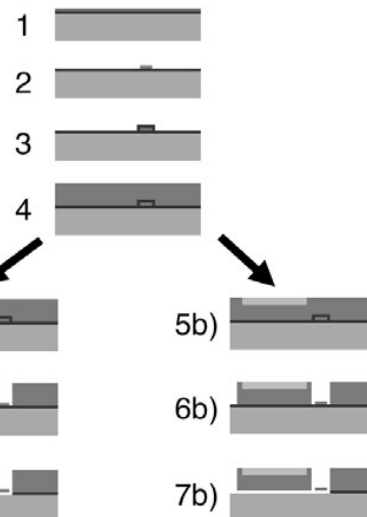


Figure 5: Basic process flow.

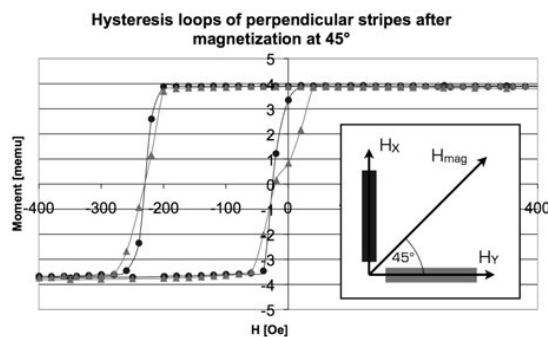


Figure 6: Experimental validation of the integration of two perpendicular magnetization directions in a single chip within a single technological step.

The silicon MEMS structure with the connected nano-gauges is shown in fig. 7. A view of an integrated 3 axis magnetometer using coupled AF/F layers is given in fig. 8.

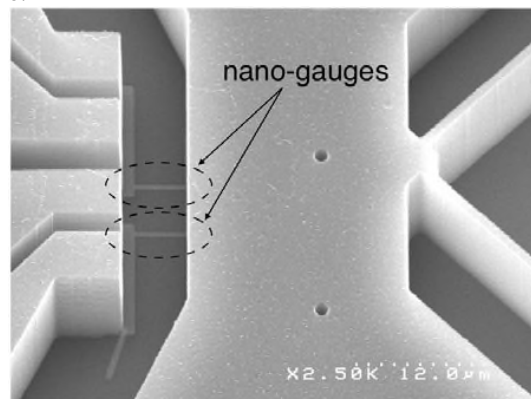


Figure 7: suspended MEMS structure with connected nano-gauges.

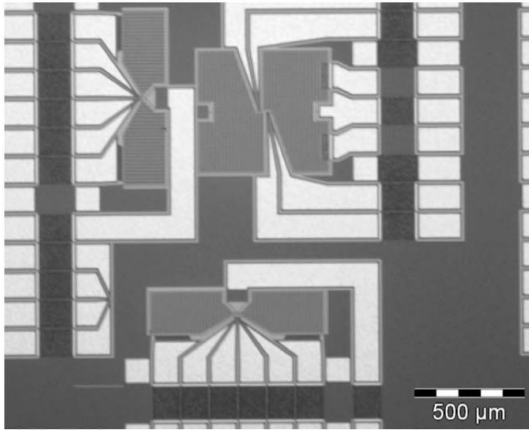


Figure 8: View of a fully integrated 3 axis magnetometer with coupled AF/F multilayers.

CHARACTERIZATION RESULTS

First sensitivity curves have been measured using coils for generation of a magnetic field. The coil current was varied between -1A and +1A during three cycles in order to achieve magnetic fields up to a range of several mT. Measurements show good reproducibility and linear dependency of the output voltage on the excitation field, so that they serve as experimental proof of our proposed concept (figs. 9 and 10). For a bias current of 100μA, the sensitivity of out-of-plane magnetometers was 170mV/T and 1.8V/T for in-plane magnetometers, respectively. Sensitivities of tested in-plane magnetometers, which were built with 10μm thick suspension beams, were in very good agreement with design.

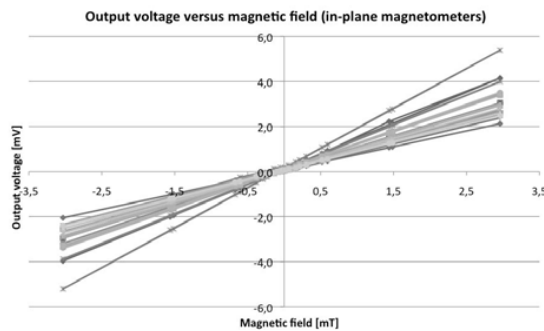


Figure 9: Experimental proof of concept for in-plane magnetometers using AF/F multilayers.

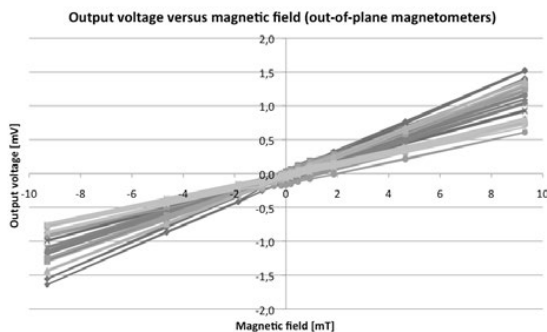


Figure 10: Experimental proof of concept for out-of-plane magnetometers using AF/F multilayers.

CONCLUSION

We have presented and experimentally validated a new concept for a fully integrated 3 axis MEMS compass using piezoresistive strain gauges at nanometric scale and integrated coupled antiferromagnetic and ferromagnetic thin multilayers. According to the design, sensitivities of over 9V/T and resolutions less than 10nT/√Hz are expected for magnetometers with integrated NdFeB and a readout current of 100μA. Sampled biasing enables to push the power consumption below 10μW. The technological approach is suitable for the fabrication of inertial sensors and is very promising regarding its use for monolithic integration of inertial measurement units (IMUs) within a single fabrication process and a single technological platform.

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