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Microelectromechanical Transducer with Optical Readout for Magnetic Flux Density Measurements

Streszczenie. *Przedstawiono mikroelektromechaniczny przetwornik z belkę krzemową i płaską cewką do pomiaru indukcji pola magnetycznego. Cewka zasilana jest ze źródła prądu stałego. Opisano system optoelektroniczny do pomiaru ugięcia belki. Zmiany natężenia pola magnetycznego powodują przemieszczenie końca belki i zmianę kąta ugięcia belki. Analizowano wpływ parametrów uzwojenia na rozkład generowanego pola magnetycznego w celu optymalizacji konstrukcji cewki.*

Abstract*The silicon cantilever with the planar coil was applied to the magnetic flux density measurements. The optoelectronic device for the measure of cantilever bending was presented and described.A coil is supplied any the direct current. The magnetic field intensity change causes the beam end displacement and changes the angle of cantilever bending. The dependence of the cantilever and external magnetic field parameters as well on the angle of the cantilever bending was investigated and analyzed. (**Mikroelektromechaniczny przetwornik indukcji pola magnetycznego na sygnał optyczny)***

Keywords:MEMS, measuring system, measurement of magneticflux density, optoelectronic system, fiber optical sensors
Słowa kluczowe: MEMS, system pomiarowy, pomiar indukcji magnetycznej, układy optoelektroniczne, czujniki światłowodowe

Introduction

The magnetic flux density measurements are essential for the monitoring of energetic transformers, generators, electric machines and at the processes of designing and construction as well.In the processes small – size sensors are used (bellow 1 mm). These sensors can also be used to the measurements at the magnetic core gapes.

For the reasons mentioned the Hall effect based sensors, coil transducers, vibration magnetometers where the solid magnet vibrations are measured, core-resonance based proton magnetometers and magneto resistance based magneto- resistors are most commonly used [1].The progress of microelectronic and micromechanic silicon technologies opened new possibilities for the designers and constructers of the magnetic field micro sensors. The micromechanical silicon structures can be applied for the microsensors.Micromachined magnetometers have been developed for some time by several authors [2, 3, 4]. The devices measure either the torque induced by the magnetic field in the magnetized material or use the Lorentz force acting on the current – carrying conductor. The Lorentz force based sensors owing to their potentially simpler fabrication and better stability seem to be a better solution [5]. Therefore, the Lorentz – force acting on a microcantilever with the planar winding has been a promising alternative for the measuring of the quasistationary and low frequency magnetic fields (50 Hz).

Construction of the magnetic microsensor

The sensor construction is shown in Fig.1. The planar coil is placed on the surface of the movingsilicon beam. The coil is supplied by the direct current. The sensor in the external magnetic field is under the influence of Lorentz's force that causes the beam deflection.
The Lorentz magnetic force $\boldsymbol{F}$ at the conducting path can be expressed as:

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B} \quad (1)$$

where: $\boldsymbol{J}$ – current density,$\boldsymbol{B}$ – magnetic flux density

Fig.1 shows the case in which $\boldsymbol{B}$ vector is parallel to the coil surface and normal regarding the current conducting paths. At the conditions described Lorentz's force is normal considering the coil and cantilever surfaces [6]. The total force that acts on the cantilever is a sum of the forces at the particular paths. The dislocation of the cantilever moving end takes place when the external magnetic field is static and cantilever current id direct. The cantilever end vibrates at the alternative external magnetic field for direct beam current. The analyses of various plane winding configurations, the mechanical cantilever construction and the winding generated magnetic field distribution as well are essential in order to optimize MEMS sensor construction.

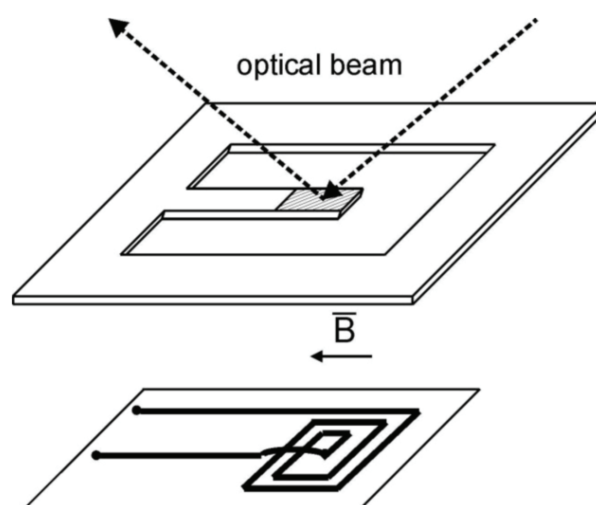

Fig. 1. Construction of the micromechanical magnetic sensorwith the silicon beam and planar coil

The measuring system

The optical methods allow to measure the beam end displacement in non-invasive way. The deflection is a measure of the magnetic flux density.

The work uses the optical processing for the beam deflection measurements.

In the method the changes of the light beam reflection angles are used. The scheme is presented in Fig.1. Considering the sizes of the optical part the system can be used at the laboratories. To minimize the optical part the opticalfibers act as a transmitter and a receiver as well. MEMS transducers with the optical fiber sensors can be

constructed in various ways, in our solution the measuring system head is equipped with one transmitting optical fibre and two optical paths consisting of several optical fibres (4-8) [7,8].

Method of optical fibre bundle displacement sensor (OFBDS) are applied of deflection measurements.

The method is considerably cheaper when compared with the other ones. The measure accuracy can be achieved by the suitable flux fibers' construction, i.e. the flux composition, fibers' number, core dimension, optical fibertype and the optical transmitting and receiving transducers as well.

The optical system with the optical flux intensity modulation due to beam deflection is presented in Fig. 2. The beam deflection angle influences the reflected light flux intensity that is subsequently sent via receivingoptical fiber.

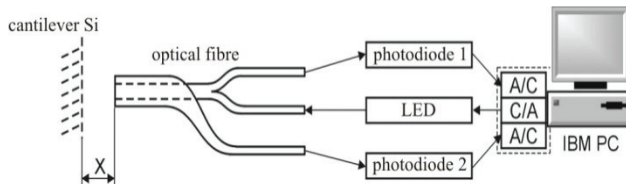

Fig.2. The block diagram of the measuring system [8]

Fig.2. presents the optical path for the multi optical fibers - opticcable system. LED diode via the central fiber illuminates the beam surface and the reflected light is sent to some receiving fibers.

The impulse mode of the transmitter work minimizes the thermal noisephotodiodes. The laser diode is supplied from generator and the impulse diode signals in the receiving system are compared with the generator signal. The shifts between the receiving signals and those between them and the transmitting signals are measured.
It allows to limit the effects of thechange laser diode radiation and the beam reflection coefficients as well.

Model of electromagnetic transducer

In modeling and simulation we used FEM method and Multiphysics 4.2 program with the electromagnetic AC/DC module. The electric and magnetic potentials can be expressed as:

$$-\nabla \cdot ((\sigma + \boldsymbol{j}\omega\varepsilon)) - \boldsymbol{J}^{e} = 0 \quad (1)$$

$$\nabla \times (\mu^{-1} \nabla \times \boldsymbol{A}) + (\sigma + \boldsymbol{j}\omega\varepsilon)\nabla \boldsymbol{V} = \boldsymbol{J}^{e} \quad (2)$$

where σ– electrical conductivity , μ -permeability, ε– permittivity , $\boldsymbol{A}$ – magnetic vector potential , V – scalar electrical potential , $\boldsymbol{J}^{e}$ – externally generated current density vector , ω– angular frequency

The relation between field and potential is given by:

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \quad (3)$$

A model was built using the 3D magnetostatic application mode and consisted of square-shaped winding on a surface of silicon wafer. The outer domain was divided into two parts- silicon wafer, aluminum windings and the air space which was large enough to avoid boundary effects. All simulations were based on the resulting magnetic field generated in system. Fig.3 shows the system geometry whereas the input parameters are collected in table 1.

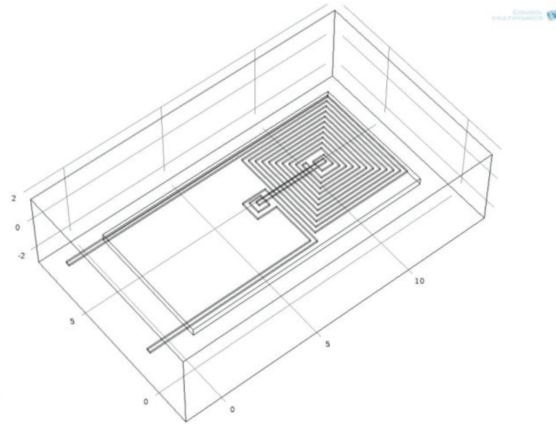

Fig.3. Model of sensor geometry (tetrahedral elements in FEM method)

Table 1. Geometric and electrical parameter description for coil

Parameter description	value	units
number of turns	5	-
turn spacing	100	μm
wire width	100	μm
wire height	10	μm
silicon relative permittivity	11,7	-
air relative permittivity	1	-
wire conductivity	35,5	$MS.m^{-1}$

Boundary conditions

The magnetic insulation for the external walls (the condition for zero magnetic flux of the aerial space), a constant electric potential of the leading out terminals and 0V (ground).

The calculations were carried out for the different beam parameters and the external magnetic field inductions in the range of 1 – 100 mT. The micro beams were constructed from <100> silicon plate, 3 inches in diameter. The sizes of the beams were following:

- the lengths in the range of 1 – 10 mm
- the widths that varied from 1 to 5 mm.

The wet anisotropic etching allowed to achieve the thicknesses of the silicon layers in the range of 10 – 50μm and thicknesses of aluminum layer in range of 1 – 10μm.
The mechanic beam parameters are collected in Table 2.

Table 2.Mechanical parameter description

Parameter description	value	units
Young's module for Si <100>	E=1.31*10^{11}	$N.m^{-2}$
Young's module for aluminium layer (Al)	E = 0,7*10^{11}	$N.m^{-2}$
Poisson's coefficient for Si <100>	ν = 0,0625	-
Poisson's coefficient for Al	ν = 0,33	-
density for Si <100>	ρ=2330	$kg.m^{-3}$
density for Al	ρ=2700	$kg.m^{-3}$

Results of simulation

The method of finished elements with the connected magnetic and mechanic fields was used in the calculations (Comsol 4.2). The number of elements varied from above 50,000 to few million depending on structure configuration 3D . In models for the numerical calculations the following material data were introduced table 1 and 2 .
The results of modeling are presented in the next figures.

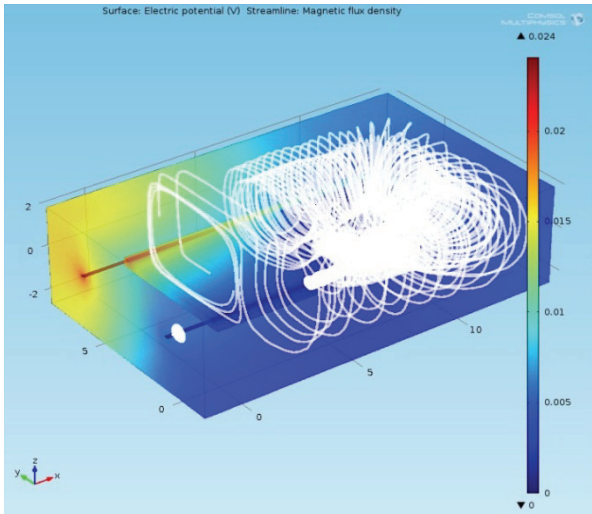

Fig.4. Distribution of streamline magnetic flux density and electrical potential DC (model in COMSOL Multiphysics 4.2)

For micro beam – the monocrystalane silicon plate with the crystallographic orientation <100> at first the density of the magnetic energy that is generated at the coil magnetic field was calculated. On that base the Lorentz's force at the individual beam tracks was evaluated. The beam deflection is caused by that force.

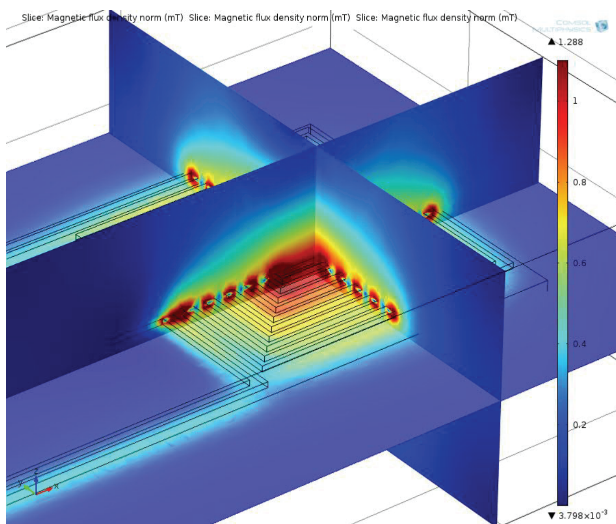

Fig.5. Distribution of magnetic flux density in spatial (DC)

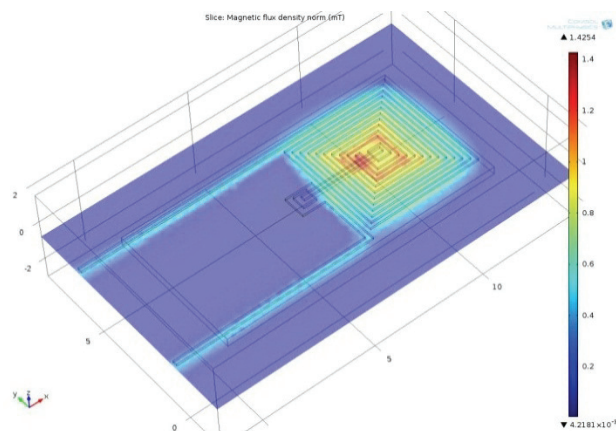

Fig.5. Distribution of magnetic flux density on surface coil (normal axis*Bz*) (DC)

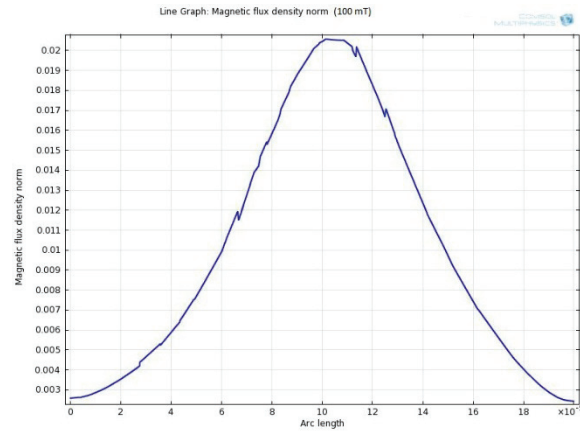

Fig.6.Cross section plot magnetic flux density *Bz* along Y axis from model of Comsol

The dependence of the beam size on the beam end displacement and its angle as well for the assumed magnetic induction was carried out. Considering the technological requirements the maximum allowable beam sizes were assumed and the influence of these parameters on the angle was analyzed.

Fig.7. shows the beam end deflection as a function of the influence of the magnetic field ***B*** for different length, width and the thicknesses of silicon cantilever.

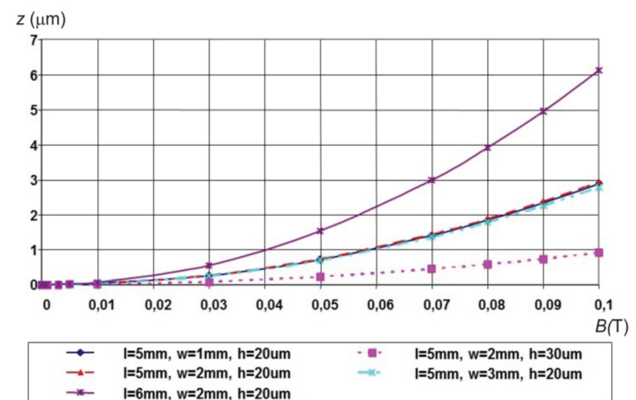

Fig.7. The dependence of external magnetic field density on the beam end deflection for different beam construction parameters and constant parameters coil

The increased beam width causes its stiffness and consequently determines the end deflection.In our transducer the measuring range, sensitivity coefficient, and the range of measured field frequency as well can be selected by the choice of construction and beam sizes. The highest transducer sensitivities were observed for the silicon beams 6 mm long and 0.5 mm wide, but the surfaces of these beams, as a consequence of higher stiffness, tend tobend at the measuring area [7]. The transducer sensitivity is mostly influenced by the silicon beam thickness. The construction with the silicon plate placed on two thin micro beams, which has considerably lower stiffness, seems to be a promising solution.

Conclusion

To design the sensor that measures the magnetic flux density the following factors should be taken into account:

- mechanical structure analysis including the size and shape of microsilicon cantilever
- planar coil parameter analysis (the square coil is more advisable than spiral coil)

- the selection of coil parameters (its sizes, shape, path width and the gap) depending on the magnetic energy values and the magnetic flux density distribution
- at the constant coil square area and constant current density the maximal values of the magnetic energy density can be achieved by increasing the coil path width (to some limited value). The same effect can be acquired via the growth of coil turns
- analysis of Lorenz forces' distribution (at every coil turn) is essential to design the sensor operating at the optimal conditions.

The micro-mechanical transducers with ferromagnetic layer or coil in a shape of planar winding seem to be an alternative for Hall's effect- and magneto-resistance based ones at the measurements of direct or slowly alternating (50 Hz) magnetic fields [9].

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