Design and Modelling of a Silicon Optical MEMS Switch Controlled by Magnetic Field Generated by a Plain Coil

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Abstract. Optical switches can be made as a silicon cantilever with a magnetic layer. Such a structure is placed in a magnetic field of a planar coil. There is a torque deflecting the silicon beam with NiFe layer depending on a flux density of the magnetic field. The study shows an analysis of ferromagnetic layer parameters, beam’s dimensions on optical switch characteristics. Different constructions of the beams were simulated for a range of values of magnetic field strength from 100 to 1000 A/m. An influence of the actuators parameters on characteristics was analysed. The loss of stiffness of the beam caused by specific constructions effected in displacements reaching 85 nm. Comsol Multiphysics 4.3b was used for the simulations.

1. Introduction
The use of optical sensors in the industry is still expanding. A transmission of a signal from the sensors is mostly done by optical fibers. Splitters and optical switches are used to minimize the amount of elements and ease the process of collecting data from optical circuits [1,2]. Another advantage is a possibility to transmit measured data from many sensors for different wavelengths by the minimized number of optical paths. The development of the technology effects in smaller sensors and an increased amount of sensors in a single structure. Increasing a number of bistable switches will be necessary [3]. A replacement of a bistable micro-switches matrix by multi-state switches will effect in a loss of power consumption and dimensions of a whole layout, and a simplification of a controlling system. The optical switches are made as a silicon cantilever with a magnetic layer (figures 1, 2). Such a structure is placed in a magnetic field of a planar coil. There is a torque deflecting the silicon beam with NiFe layer depending on a flux density of the magnetic field [4,5].

A position of the switch is controlled by a change in an external magnetic field $H$ (a change in a current in the coil) which effects in a torque $T_H$ deflecting the beam, which can be described by the equation [6]:

$$T_H = \mu_0 V \left| M \times \vec{H} \right| = \mu_0 V \cdot M \cdot H \cdot \sin \alpha$$

(1)

Where : $M$ - magnetization vector of a the ferromagnetic layer, $\alpha$ - an angle between the magnetization vector and the external magnetic field vector $H$, $V$ - volume of the magnetic material
2. Modelling and simulation

Due to a complicated construction of MEMS (many layers of different materials), silicon anisotropy and non-linear ferromagnetic characteristics, analytical calculations are too complicated. The Comsol Multiphysics and the finite elements method were used in the study. In the models, combined mechanical and magnetic fields were used (MEMS, AC/DC modules) [7,8]. A 3D magnetic field distribution generated by the planar winding was considered [9]. With the magnetization vector it effects in the moment bending the beam. The study shows an analysis of numerical models of MEMS transducers used in silicon microactuators and controlled by magnetic field. Movable silicon cantilevers structures with a ferromagnetic layer on the surface, which were attached from one side, were considered. A mirror placed on a free end of the beam reflected transmitted light. Silicon cantilevers (Si <100>) (E=160 GPa, density 2320 kg/m$^3$, $\varepsilon_r$=4.5), thickness 10 µm, width 2-3 mm and length 4-6 mm with 10 µm ferromagnetic layer (E=152 GPa, density 7860 kg/m$^3$, $\varepsilon_r$=1) were analysed (figure 2). Further reduction of the thickness caused errors in the simulation, especially on a boundary between the silicon and ferromagnetic layer. The models were meshed using very fine free triangular mesh. Mapped meshes were also tested, but they caused serious errors on the boundaries between the used materials. The simulations were computed on Intel i7, 6 core machine with 12 GB of RAM memory. Single simulation for 3 “k” factors and range of magnetic field strength was taking from one to two hours. The k factor represented anisotropic properties of the ferromagnetic layer. In case where length/thickness and width/thickness proportion are much higher than 100 and length of the layer is bigger than its width, geometrical properties of the layer have crucial influence on the k factor. The k factors of values from 0.05 to 0.2 were calculated according to geometrical properties and magnetic properties of NiFe layer.

![Figure 1. Construction of MEMS optical switch.](image1)

![Figure 2. Model of a switch geometry in the Comsol.](image2)
Figure 3. Distribution of magnetic flux density on surface coil (normal axis $B_z$) (DC).

Figure 4 shows deflection of a 10 µm thick, 3 mm wide and 6 mm long beam, with 50% Ni 50% Fe 10 µm layer on its surface, in strong magnetic field $B=1$ mT (field direction is perpendicular to the beam’s surface). The beam’s deflection reaches almost 85 nm. However, further research was carried out for lower values of magnetic field, which generation in real planar coil-constructions is more probable. The influence of magnetic field on the beam’s deflection was further analysed.

Figure 4. Deflection of the cantilever with a ferromagnetic layer in a magnetic flux density $B=1$ mT (deflection scale factor 1000:1).
3. Results of modelling and simulation
This paragraph shows the results of modelling of different 3x6 mm 10 µm cantilever constructions: a full cantilever, a cantilever with a 2.6x2.5 mm cut-out cavity and an improved construction of cantilever with 2.8x2.5 mm cut-out cavity. Each of the beams had a 10 um ferromagnetic layer on its surface. The cantilevers were put and simulated in magnetic field varying from 100 to 1000 A/m.

Figure 5 shows results of the modelling for the most stiff construction – 3x6 mm, 10 µm thick full cantilever with 10 µm ferromagnetic layer on its surface. A maximum deflection is about 1 nm for reasonable values of magnetic field and maximum k factor equalled to 0.2. The full beam construction occurs to be too stiff in comparison to the cut-out construction, which use is much more relevant (compare figures 5, 6 and 7).

![Graph](image)

**Figure 5.** Deflection of the full 3x6 mm cantilever as a function of magnetic field for k=0.2.

Figures 6 and 7 show results of simulation for the cut-out 3x6 mm (10 µm silicon, 10 µm ferromagnetic layer) cantilevers’ constructions for different values of magnetic field and k factors. The loss of stiffness effects in much higher deflections, for reasonable magnetic fields, reaching 43 nm for the basic construction (2.6x2.5 mm cut-out cavity) and almost 85 nm for the improved construction. The second mentioned constructions has an enlarged 2.8x2.5 mm cut-out cavity, which means that a surface where ferromagnetic layer is placed is attached by two 0.1x2.5 mm silicon beams.
Figure 6. Deflection of the 2.6x2.5 mm cavity cut-out 3x6 mm cantilever construction as a function of magnetic field, for different k factors.

Figure 7. Deflection of 2.8x2.5 mm cavity cut-out 3x6 mm cantilever construction as a function of magnetic field, for different k factors.

Figure 8 shows comparison of results for the two cut-out constructions for the same k factor and varying magnetic field strengths. The increase of width of the cut-out surface effects in much higher deflections (the loss of stiffness). Figure 9 shows combined results achieved for the best construction of the cantilever and the planar coil.
Figure 8. Comparison of deflection of different 3x6 mm cavity cut-out constructions as a function of magnetic field, for k=0.2.

Figure 9. Deflection of the 3x6 mm, 2.8x2.5 mm cavity cut-out construction for k=0.2, as a function of current supplying the planar coil.

4. Conclusion
An influence of the actuators parameters on characteristics was analysed. Comsol Multiphysics 4.3b was used. The study shows the analysis of ferromagnetic layer parameters and beam’s dimensions on the optical switch characteristics. Different constructions of the beams were simulated for a range of values of magnetic field strength from 100 to 1000 A/m. The full beams occur to be too stiff to reach reasonable deflections (no more than 1 nm was observed). The loss of stiffness of whole construction, caused by cutting-out a cavity in cantilever’s surface effects in much higher displacements, reaching 85 nm for the best construction, even though the volume of the ferromagnetic layer is much smaller.
(nearly 50% smaller in comparison to the full-cantilever construction). Reducing width of the attaching beams by 50% causes a 50% growth of the whole construction’s deflection. The study was carried out for magnetic field strengths occurring in practice [10]. The beams were placed in a very small distance to the planar coil to minimize the losses in the air-gap. However, the planar coil used in the simulation, in real case was able to generate only the lower values of magnetic field strengths, due to need of high supplying currents (the currents reaching 10 mA were used during the simulations). The study proves that deflections of the beams in real-life cases are big enough to be measured by an optical transducer.

5. References
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