Modeling and Optimization of Bi-stable Optical Switch

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ABSTRACT

High performance silicon-based, micro-optical switch are being developed for application to optical networks. The mechanical part was fabricated in a one-level mask step by bulk micromachining of (100) monocrystalline silicon with KOH. The resulting structure was assembled with a 100µm-thick Permalloy piece and then, it was associated to a small magnetic circuit for its electromagnetic actuation. In order to avoid power consumption during ON and OFF states, a bi-stable operation principle is proposed. The bi-stable behavior is obtained thanks to a stable mechanical position due to the cantilever stiffness and a second magnetic stable position due to a magnet. Switching operation is provided by electrical currents in windings. The purpose of the present paper is to present a study on modeling and optimization of this system by means of FEM simulations using ANSYS software. Iterative magneto-mechanical simulations are performed. Optimization of dimensions and material properties is presented.

Keywords: *Optical switch, bi-stable, electro-magnetic actuation, ANSYS simulation, optimization.*

1 INTRODUCTION

Targeting a low-cost batch-fabrication for a promising market, silicon-based optical switches are intensively studied for application to optical communication networks [1-5]. The main breakthrough is the realization of high quality mirrors together with a self-positioning system for the optical fibers. Thus, very low insertion loss can be obtained without expensive handling for alignment.

Contrarily to deep RIE-based process, in which ripples on the etched walls are inevitable, wet anisotropic etching process fulfills the requirement of high surface quality on the mirrors, thus reducing optical losses. Furthermore, such process is also compatible with the well-known (111) V-grooves, which were originally dedicated to optical fibers positioning. In our recent work [5], an original process was proposed, in which self-aligned vertical mirrors and V-grooves were simultaneously obtained. This process resulted in insertion loss lower than 0.5dB with multimode fibers.

In order to avoid power consumption when holding the ON and OFF positions, a self-latching system with electromagnetic force has been developed. This system uses the above-mentioned silicon part, including the V-grooves and the (movable) mirror structure. A displacement of 100µm, high enough for switching operation, was achieved with 10mW. The operation principle of the self-latching system was successfully demonstrated on the bypass. The ON position was kept without applied current and a current of 1A was necessary to switch from ON to OFF positions. Moreover, preliminary characterizations have shown a response time of about 2ms, a resonance frequency of 67Hz and no degradation observed after 15 million cycles.

Though the bi-stable optical-switch has already shown satisfactory and promising results, it is not yet optimized. The purpose of the present paper is to present a study on modeling and optimization of this system by means of FEM simulations using ANSYS software.

2 FABRICATION

Optical switch with self-aligned V-grooves are fabricated in one-level mask step by bulk micromchining of (100) monocrystalline silicon with KOH. The fabrication of the whole structure takes advantage of some crystallographic properties.

A first set of mask patterns along the <100> direction produce a vertical under-etching of (100) sidewalls, leading to the mirror structure. During the same time, (111) V-grooves are etched along the <110> direction for optical fiber alignment. The well-defined 45^o angle between the <100> and <110> directions is exploited for the self-alignment of the vertical mirror and V-grooves. Because the mirror surface is a (100) plane, it is strictly perpendicular to the optical axes, limiting optical loss. The selectivity against the (111) planes is used to fix the V-groove depth by the corresponding width pattern in the mask. Thus, two different structural depths can be obtained for the mirror and the V-grooves, avoiding a contact of the mirror with optical fibers.

A cantilever beam is defined by etching from the backside. Typical dimensions are 11.7mm*1.4mm*60µm.

More details on the etching principle and on the fabrication process are given in ref. [5].

3 OPERATION PRINCIPLE

The optical switch is schematically depicted in Fig.1 and Fig.2. It includes two parts separated by an air gap:

- A movable monolithic silicon part. It includes a vertical mirror on top of a cantilever beam, which can be deflected out of plane. A 100µm-thick Permalloy piece is assembled with this silicon part on the bottom side of the cantilever.
- A fixed small electromagnet realized in conventional technology, including a yoke, a winding and a permanent magnet.

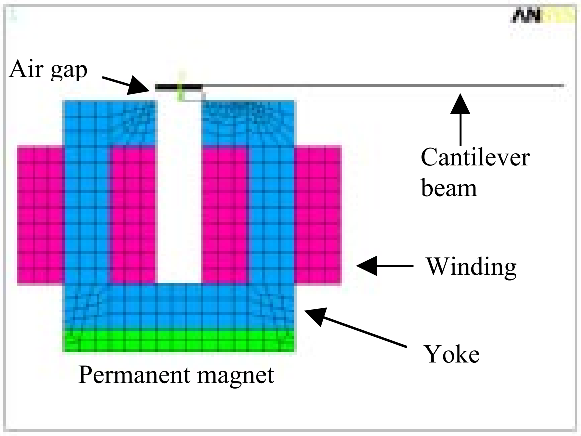

Fig.1: Geometrical model of the bi-stable switch

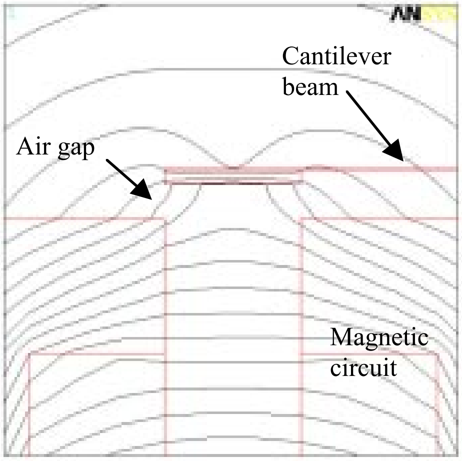

Fig.2: Zoom in the gap region showing induction lines

The role of the Permalloy piece and yoke is to provide a magnetic force on the cantilever. Currents in the windings lead to an increase or a decrease of this magnetic force depending on current direction. The current input port is the control port of the system. ON and OFF states are obtained by applying negative and positive current pulses respectively.

The bi-stable behavior is obtained by a first stable mechanical position due to the cantilever stiffness and a second magnetic stable position due to the magnet. The linear behavior of the elastic restoring force and the nonlinear behavior of the magnetic force with respect to air gap distance, allows the operation principle illustrated in Fig.3. Depending on the magnitude of the magnetic force as compared to the mechanical force, one can have three different configurations with zero, one or two stable states. Switching operation is provided by increasing or decreasing the magnetic force by means of the current in the winding (Fig.3). Suppose the initial state corresponds to ON (open) state, that is, point A in Fig.3. Then if we apply a positive current pulse, so that the magnetic force is *temporarily* increased with no intersection with the mechanical force, then the final state will be the OFF (closed), that is point B in Fig.3. Then, starting from the latter state, if a negative pulse current is applied, high enough to temporarily decrease the magnetic force in a configuration with only one intersection with the mechanical force, then the final state will be the ON state again. It is noteworthy that the magnetic force magnitudes in Fig.3 take finite and controlled values in OFF state. This is preferable to easily perform the OFF-ON transition (with a reasonable current). In practice, this can be achieved by using a spacer at an airgap position X, avoiding the vanishing air gap, which corresponds to a very high and imprecise magnetic force.

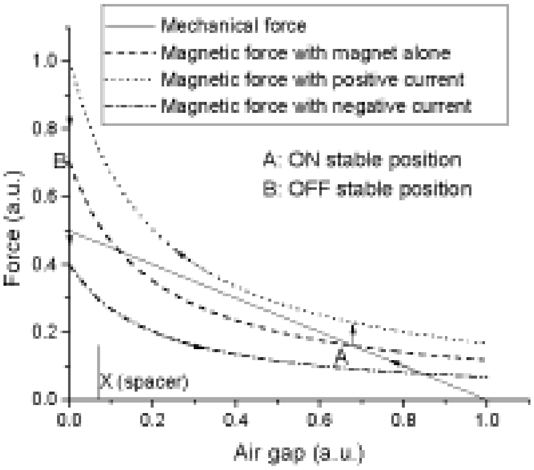

Fig.3: Mechanical and magnetic forces vs. air gap. The bi-stable operation is possible only when the curves of magnetic and mechanical forces have two intersection points. A spacer X is introduced to limit the magnetic force close to zero air gaps and so optimize the switch-off current.

4 MODELING AND SIMULATION

4.1 Modeling procedure

Iterative successive magnetic and mechanical Finite Element Modeling (FEM) are performed with ANSYS ® software. 2D step-by-step modeling is based on the mesh deformation in the gap. They heavily rely on the magnetic non-linearities. A good agreement was also obtained with strong, coupled magneto-mechanical computations.

4.2 First simulation results

Due to the strong (cubic) dependence of bending deflection on the cantilever thickness t, a small thickness inaccuracy (± 5% for instance – that is t=20 ± 1µm in our case) leads to a large dispersion of the mechanical characteristics (± 15%). This implies an adjustment of the original magnetic curve (with magnet only). This is illustrated in Fig.4. Different magnetic characteristics are plotted in Fig.5. It can be seen that a solution to the problem can actually be obtained. Indeed, different parameters allow us to optimize the magnetic characteristic. These parameters are the permanent magnet properties, type and saturation level of the magnetic material, position, dimensions and overall geometry. The simulation results in Fig.5 correspond to two commercially available materials for the magnet (MENPC-2 and MES1F), accounting or not for the nonlinear behavior (for MENPC-2 only).

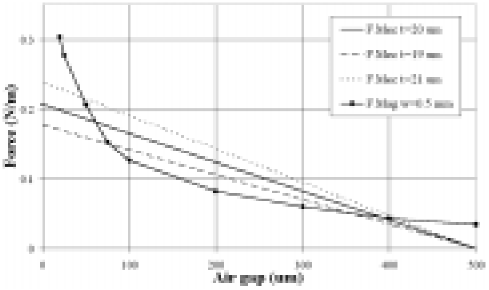

Fig.4: Effect of dispersion in cantilever thickness on the mechanical characteristics. At low air gaps, the magnetic force must overpass the highest possible mechanical force. It must be below the smallest one at intermediate air gaps, and overpass the mechanical force again at high air gaps.

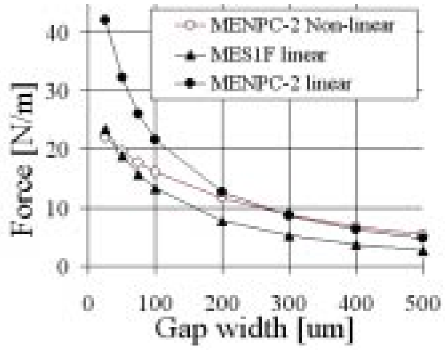

Fig.5: Effect of magnetic properties (MENPC-2 and MES1F materials) and magnetic saturation.

4.3 Optimization procedure for dimensions and materials

Saturation of the magnetic yoke is necessary and must be optimized. Indeed, as the magnet is simply stuck on the yoke, the latter is a magnetic short-circuit for the magnet. Hence, if the yoke were linear, no induction would pass through the moving part. Optimization of the saturation level (by increasing the volume of the magnet, by reducing the yoke width and choosing the most appropriate material) is crucial. The optimization steps are the following:

Starting point: inaccuracy on dimensions of the silicon part is supposed to be known (± 1µm dispersion on 20µm-thick cantilevers). Given are the magnetic yoke of Fig.1, dimensions and magnetic characteristics of Permalloy.

First step: optimization of the magnet dimensions and properties (B_r) so as to obtain 2 intersections as in Fig.4, with a 'first safety margin' of 20%. That means that there is a mean position in the gap $\hat{g}$, for which the magnetic force is 20% higher than the lowest mechanical force (see Fig.6). This optimizes the switch-on current.

Second step: verification that the yoke saturation level provides the best solution (different types of commercially available materials are tested).

Third step: the spacer thickness is chosen with a 'second safety margin' of 20%: at the spacer position, the magnetic force must be 20% higher than the highest possible mechanical force to minimize the switch-off current (Fig.6).

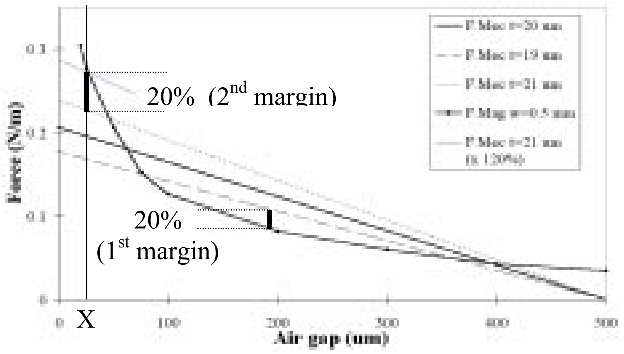

Fig.6: Optimization procedure of the magnetic characteristic and spacer thickness X, taking into account the dispersion in cantilever thickness. Safety margin of 20% are chosen to ensure correct operation of the device.

4.4 Optimization results

Because of time constraint, we have completed the analysis only for one material (MENPC-2). We have performed a set of simulations by varying the width w of the permanent magnet. This parameter is a way to tune the magnitude of the magnetic force. The corresponding characteristics are drawn together with the mechanical force in Fig.7. A dispersion of 5% in the cantilever thickness is assumed. From these curves, one can calculate the results of the first safety margins, as defined in section 4.3. They are summarized in Table.1. It appears that the optimum value for the thickness is W_{opt}=0.50mm. The corresponding mean gap position is $\hat{g} = 229\ \mu m$. Furthermore, one can also deduce from Fig.7 the optimal spacer position X_{opt}, according to the procedure described in section 3.4. It is found to be X_{opt}=25µm for W_{opt}=0.50mm.

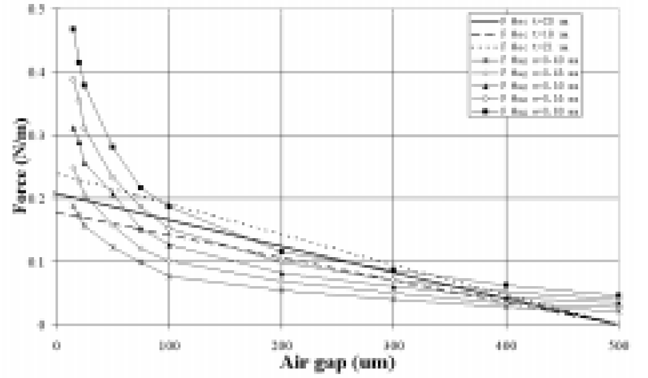

Fig.7: Characteristics of the magnetic force when varying the width of the permanent magnet.

Width of Permanent magnet	0.40	0.45	**0.50**	0.55	0.60
1st safety margin (%)	50	34	**22**	6	< 0

Table.1 Simulation results for the first safety margins (cf.4.3) when varying the width of the permanent magnet. (Optimum value in bold).

In order to calculate the switching current, one have to compare magnetic force and mechanical forces, when varying the current (Fig.8). For switch-ON, the magnetic force (at W_{opt}=0.50mm) is compared to the smallest mechanical force F_{mec1} at a gap position corresponding to the spacer thickness ($g_1=X_{opt}$), that is, g_1=25µm and F_{mec1}=0.17N/m. The intersection of these curves gives I_{ON}=-7.9A-turn. For switch-OFF, the magnetic force is compared to the highest mechanical force F_{mec2} at the mean gap position, corresponding to the 1st safety margin ($g_2 = \hat{g}$), that is g_2=229µm and F_{mec2}=0.13N/m. The intersection of these curves gives I_{OFF}=12.4A-turn. It is noteworthy that a clever way to reduce the switch-ON current further is to take advantage of the Q-factor amplification when working at resonance. This point was also checked experimentally.

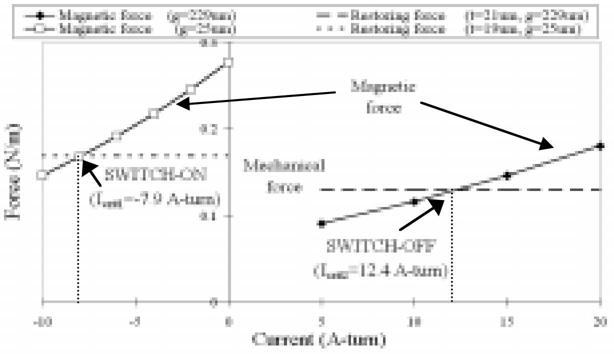

Fig.8: Magnetic force vs. current in the windings. Comparison with mechanical force at specific gap positions lead to the switching currents: I_{ON}=-7.3, I_{OFF}=12.4 (A-turn).

5 CONCLUSION AND FUTURE WORK

The concept of electro-magnetically actuated bi-stable operation has been validated on a test device. A first set of tests was performed and good operation was obtained. More than 15 million cycles were successfully measured with deflection amplitude of more than 100µm and the device performances were not affected. However, this first test device was not optimized as regards working conditions and power consumptions. In this work, we have shown a modeling and optimization procedure of this magneto-mechanical system by means of FEM simulations using ANSYS® software. Our final goal is to design and fabricate the second generation of electro-magnetically actuated bi-stable optical switch, on the basis of the optimization results presented in section 4 of this paper. The optical switch is a case study. But the proposed modeling and optimization procedure could be generalized and is applicable to other microsystems, including other actuation principles involving coupled phenomena.

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