研 究 速 報

Modelling and Optimisation of an Electromagnetic Bi-Stable μSwitch

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I. 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 realisation of high quality mirrors together with a self-positioning system for the optical fibres. 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 fulfils 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 fibres positioning. In our recent work [5], an original process was proposed, in which self-aligned vertical mirrors and V-grooves were simultaneously obtained (Figure 1). This process resulted in insertion loss lower than 0.5dB with multimode fibres.

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 characterisations have shown a response time of about 2ms, a resonance frequency of 67Hz and no degradation observed after 15 million cycles.

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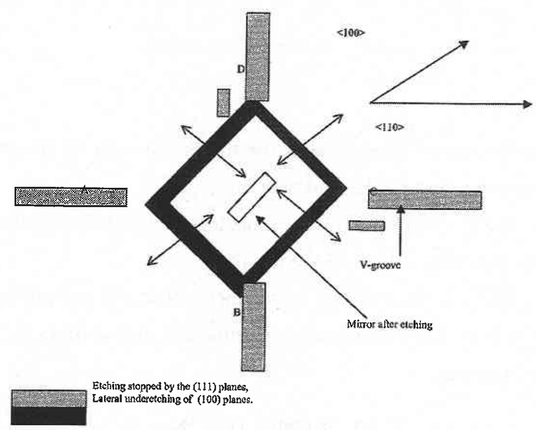

Fig. 1 Principle of the self-aligned optical structure (Arrows indicate the direction of under-etching)

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

1. FABRICATION

Optical switch with self-aligned V-grooves are fabricated in one-level mask step by bulk micro machining of (100) monocrystalline silicon with KOH. The fabrication of the 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 (Figure 2).

During the same time, (111) V-grooves are etched along the

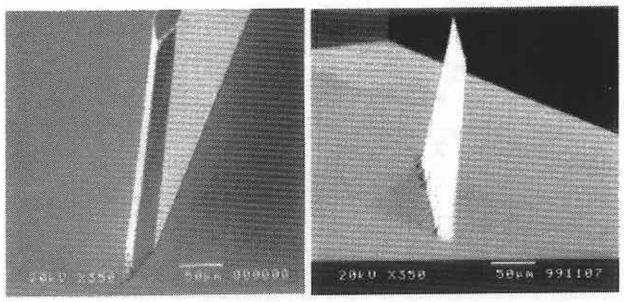

Fig. 2 Close view and side views of mirror showing the possibility to decrease thickness of mirror down to a few μm.

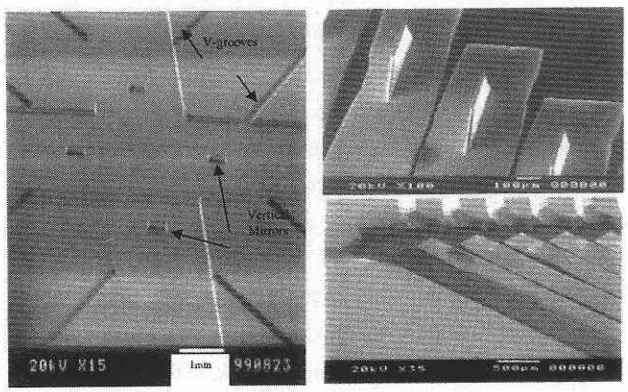

Fig. 3 Matrix-switch with V-grooves and Mirrors

<110> direction for optical fibre alignment. The well-defined 45° 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 fibres.

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].

This technology was used for a 2x2 and a 1x8 Matrix-switch as shown on Figure 3.

3. OPERATION PRINCIPLE

The switch 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 realised in conventional technology, including a yoke, a winding and a permanent magnet.

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 behaviour is obtained by a first stable mechanical position due to the cantilever stiffness. The second magnetic stable position is due to the magnet. The linear behaviour of the elastic restoring force and the non-linear behaviour of the magnetic force with respect to air gap distance allows the operation principle illustrated in Figure 6. 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. Increasing or decreasing the magnetic force by applying current in the winding provides switching operation.

Suppose the initial state corresponds to point A (ON-open). Then, if a positive current pulse is applied (so that the magnetic force is temporarily increased with no intersection with the mechanical force), then the final state is Point B (OFF-closed). Then, a significant negative pulse current allows to switch back to the starting position. In practice, to overcome the imprecision in the air-gap thickness in the closed position, (which could result in a very un-precise latch force), a given spacer is introduced.

4. MODELING AND SIMULATION

4.1 Modelling procedure

Iterative successive magnetic and mechanical Finite Element Modelling (FEM) are performed with ANSYS ® software. 2D step-by-step modelling 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 ($\pm$ 5%for instance-that is $t = 20 \pm 1\mu$m in our case) leads to a large dispersion of the mechanical characteristics ($\pm$ 15%). This implies an adjustment of the original magnetic curve (with magnet only). This is illustrated in Figure 7. Different magnetic characteristics are plotted in Figure 8. It can be seen that a solution to the problem can actually be obtained.

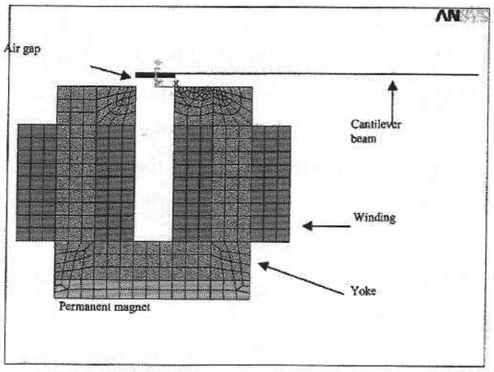

Fig. 4 Geometrical model of the bi-stable switch.

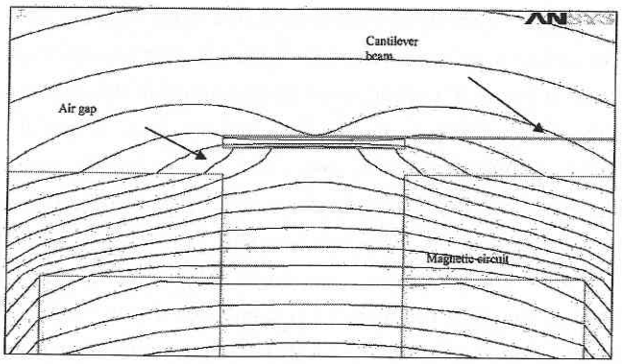

Fig. 5 Zoom in the gap region (induction lines).

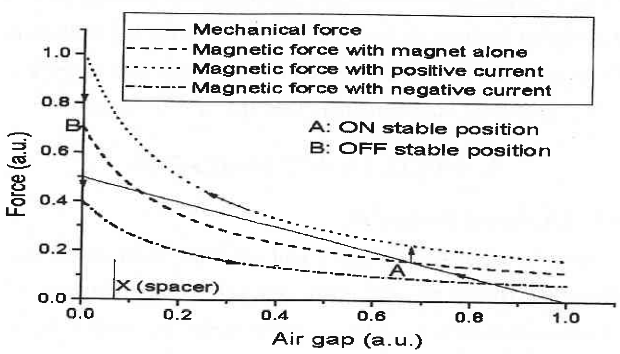

Fig. 6 Mechanical and magnetic forces vs. air gap.

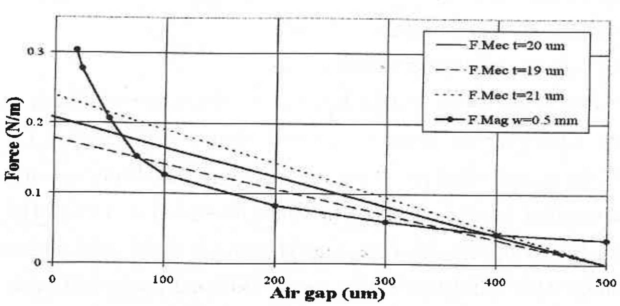

Fig. 7 Effect of dispersion in cantilever thickness on the mechanical characteristics.

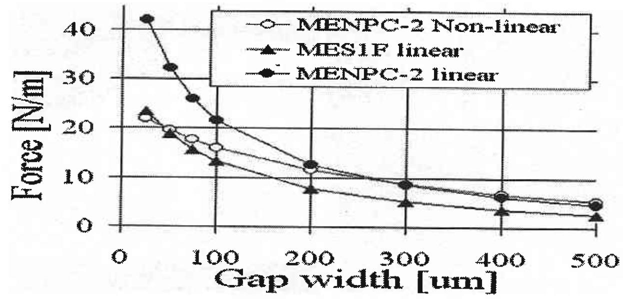

Fig. 8 Effect of magnetic properties of materials.

Indeed, different parameters allow us to optimise 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 Figure 8 correspond to two commercially available materials for the magnet (MENPC-2 and MES1F), accounting or not for the non-linear behaviour (for MENPC-2 only).

4.3 Optimisation procedure for dimensions and materials

Saturation of the magnetic yoke is necessary and must be optimised. Indeed, as the magnet is simply stuck on the yoke, the latter is a magnetic short-circuits for the magnet. Hence, if the yoke were linear, no induction would pass through the moving part. Optimisation 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 optimisation steps are the following:

Starting point: inaccuracy on dimensions of the silicon part is supposed to be known ($\pm 1\mu m$ dispersion on $20\mu m$-thick cantilevers). Given are the magnetic yoke, dimensions and magnetic characteristics of Permalloy (fig 4).

First step: optimisation of the magnet dimensions and properties (B_r) so as to obtain 2 intersections (Fig. 6), with a 'first safety margin' of 20% (switch-on current optimisation).

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 minimise the switch-off current (Figure 9).

4.4 Optimisation 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 Figure 10. 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 summarised in Table.1. It appears that the optimum value for the thickness is $W_{opt} = 0.50$mm. The corresponding mean gap position is $\hat{g} = 229\mu$m.

Furthermore, one can also deduce from Figure 10 the optimal spacer position X_{opt}, according to the procedure described in section 3.4. It is found to be $X_{opt} = 25\mu$m for $W_{opt} = 0.50$mm.

In order to calculate the switching current, one have to compare magnetic force and mechanical forces, when varying the current (Figure 11). For switch-ON, the magnetic force (at $W_{opt} =$ 0.50mm) is compared to the smallest mechanical force Fmec1 at a gap position corresponding to the spacer thickness ($g_1 = X_{opt}$), that is, $g_1 = 25\mu$m and $F_{mec1} = 0.17$N/m.

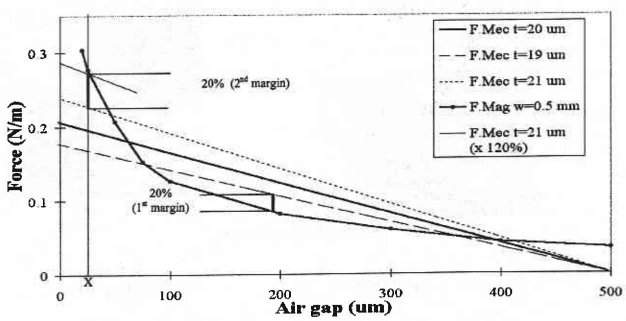

Fig. 9 Optimisation with Safety margin of 20 %

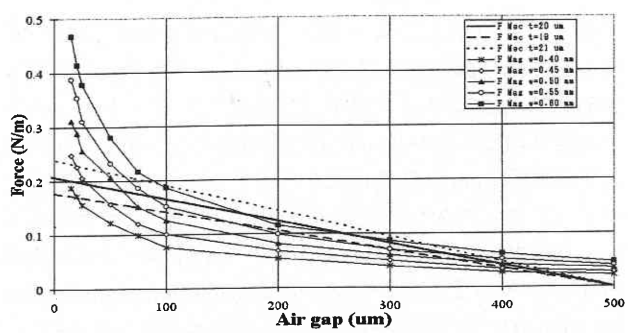

Fig. 10 Magnetic force vs. width of the permanent magnet.

Table.1 Simulation results vs. 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

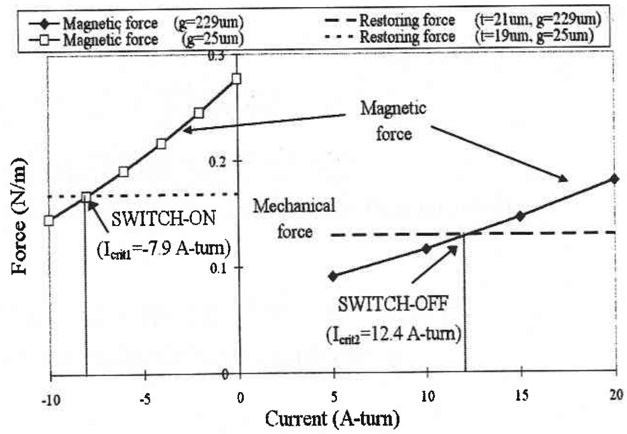

Fig. 11 Magnetic force vs. current in the windings

5. CONCLUSION AND FUTURE WORK

A Novel process was used to realise both single switches and Matrix switch 2x2 and 1x8. It allows automatic alignment of V-grooves and high quality perfectly vertical mirrors. It uses wet etching and clever use of masks and silicon lattice. The concept of electromagnetically 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 $100\mu m$ and the device performances were not affected.

Our final goal is to design and fabricate the second generation of electromagnetically actuated bi-stable optical switch, on the basis of the optimisation results presented in section 4 of this paper.

The optical switch is a case study. But the proposed modelling and optimisation procedure could be generalised and is applicable to other Microsystems, including other actuation principles involving coupled phenomena.

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