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Fabrication and Electromechanical Characteristics of 2 ×2 Torsion-Mirror Optical Switch Arrays with Monolithically Integrated Fiber Self-Holding Structures *

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Abstract : Novel 2 ×2 torsion-mirror optical switch arrays are fabricated by using the mixed micromachining based on the surface and bulk silicon microelectronics, then are investigated electromechanically in applied direct and alternating electric fields. When the thickness of the elastic torsion beams suspending the aluminum coated polysilicon micro-mirrors of the switches in the arrays is about 1μm, the electrostatic yielding voltages for driving the mirrors to achieve their ON-state are in the range of 270～290V, and the minimum holding voltages for mirrors ON-state are found as 55V or so. Theoretical analysis manifests that the yielding voltage is more sensitive to beam thickness than other design parameters do about the torsion-mirror switch structures. The lifetime can reach 10^8 times. The estimated shortest switching time of the switches at least lasts for less than 2ms. The force analysis on the two kinds of new fiber self-holding structures integrated monolithically in the chip of the optical switch arrays indicates that the structures can feature self-fixing and self-aligning of optical fibers.

Key words : MEMS; optical switch; torsion-mirror; fiber self-holding structures; mixed micromachining
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1 Introduction

A surging interest in the use of silicon-based micro-electromechanical systems (MEMS) for a variety of optical networking application was found in the coming rapid and widespread deployment of optical networks. Good performance, low cost and miniaturized MEMS optical switch arrays in different scales, which can achieve small insertion loss, low cross talk, large switching contrast, and wavelength and polarization-insensitivities[1], are going to be the key considerations in the optical cross connectors (OXCs) and optical add/drop multiplexers (OADMs) for optical networking that is the only way to fill the acute need for broadband communication[2], which has been brought about by the explosion of the Internet, and thus

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have been becoming increasingly important and will have potential huge market. In the considerable variety[3~7] of MEMS optical switches that have emerged constantly up to the present, those with torsion-mirror structures, which can advoid the mechanical fatigue problems resulting from the micro-friction[5] mechanism therefore, improve the reliability (e. g. operating lifetimes), are very promising in optical networking applications. Furthermore, integrating fiber holding structures[8], which can feature self-aligning as well as self-fixing of optical fibers, together with optical switch structures in a monolithic chip is also pursued to achieve extra precise positioning of the fibers without complicated manual work and, thus, easy control of the total relevant production cost.

The fabrication and electromechanical characteristics of a new type of 2 ×2 optical switch arrays with monolithically integrated fiber self-holding structures are reported. The components were fabricated in regular silicon wafers using the mixed micromachining based on the surface and bulk silicon microelectronics. In order to get long lifetime of the switches in the arrays, torsion-mirror structures, which are micro-mirrors suspended by elastic torsion beams, were designed as the movable parts of them so that the mechanical fatigue problems resulting from the micro-friction mechanism can be avoided. Each switch regulates light beam in a free space using its electrically driven torsion mirror. Two kinds of new fiber self-holding structures were produced monolithically in the chip of the optical switch arrays by using the same etching steps for forming the relevant fiber grooves. The force analysis on the structures indicates that they can feature self-fixing and self-aligning of the optical fibers.

2　Structures and fabrication

Figure 1 depicts the schematic diagram of the 2 ×2 torsion-mirror optical switch array, the through cavities produced in a p^+ (100) silicon substrate of 400μm in thickness were arranged in a 2 ×2 matrix. A fiber groove net was formed in a square pattern on the backside of the substrate. One sidewall of each through cavity in the arrays was designed to locate exactly at the crossing of two grooves perpendicular to each other by a 45 ° inclination, meanwhile produced perpendicular strictly to the substrate surface by using inductively coupled plasma (ICP), which performs the functions of stopping the tilting movement of the micro-mirror and positioning the mirror having been ON-state. Incident and redirected lights propagate into and out of the cavities through the optical fibers mounted in the grooves or through the free space in the grooves. In the front of the substrate, the micro-mirrors in the size of 345μm ×600μm, which were made of a polysilicon film with aluminum sputtered on its surface to improve electric conductivity as well as optical reflectivity, were suspended by elastic torsion beams across each through cavity to compose the optical crossbar switches. When a large enough bias was applied between one micro-mirror and the substrate, the mirror was attracted electrically and tilted (with its torsion beam as the axis) inward its through cavity by 90 ° precisely till it touches the stopper sidewall of the cavity. Under this condition, the mirror was positioned exactly at one of the crossings of the fiber grooves by a 45 ° inclination. Therefore, the light out of one input fiber will be reflected just right to one output fiber by the mirror, which indicates that the diversion from one light path to another was carried out. The OFF-state micro-mirrors were kept almost horizontally if no bias was applied and thereby did not interfere the light beams if adequate margins were given in the design. Since the light beams can cross in a

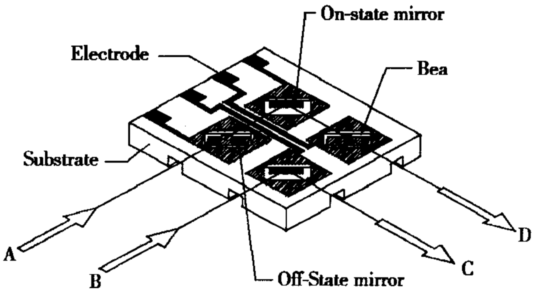

Fig. 1　Schematic structure of the 2 ×2 torsion-mirror optical switch array

free space without interfering with one another, the optical switch arrays can be produced compactly. Figure 2 (a) and (b) are the scanning electron micrograph (SEM) photographs of one of the switch arrays and one torsion-mirror switch structure in the arrays, respectively. Actually, the switch array configuration presented above can make the size of array extended to $N \times N (N > 2)$ easily without changing the structure design a lot.

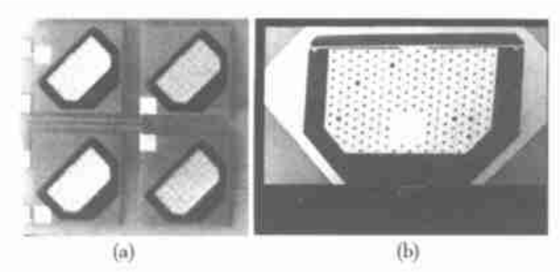

Fig. 2 SEM photographs of (a) one of the optical switch arrays and (b) one torsion-mirror optical switch structure

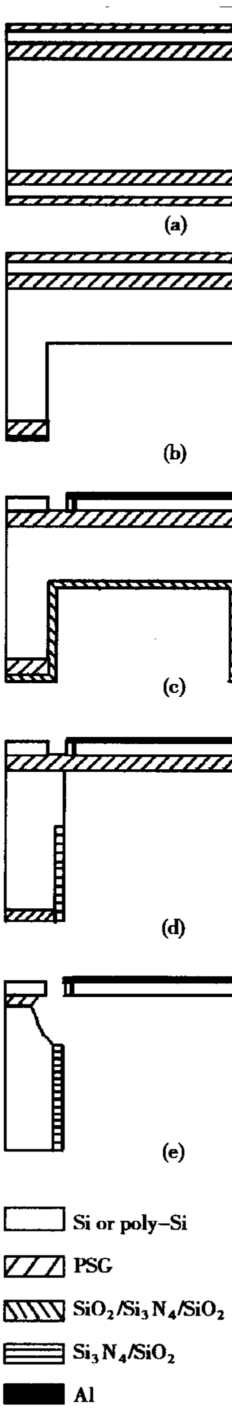

Fig. 3 Schematic sequence of the main fabrication process for the torsion-mirror optical switches

Figure 3 demonstrates the sequence of the main fabrication process, which begins with: (1) the low pressure chemical vapor deposition (LPCVD) of a phosphorus silicon glass (PSG) film as an insulating and sacrificial layer, followed by the LPCVD of a 1μm-thick implanted polysilicon and another 0.2μm-thick PSG film as the protection layer of the polysilicon surface. (2) On the backside of the substrate, the cavity and the groove mask composed of the inside PSG and an aluminum layer sputtered on the PSG were made after the outside 0.2μm-thick PSG and then the 1μm-thick polysilicon were removed. By using ICP, the silicon substrate was etched anisotropically from the backside to form the cavities and fiber grooves partially. (3) After the sandwich layer composed of $SiO_2/Si_3N_4/SiO_2$ was deposited by LPCVD, it was removed totally from the front side of the substrate. The sputtering and patterning aluminum on the top surface, which was used to produce electrodes as well as to make the aluminum as a reflective and conductive layer, was followed by patterning and then ICP-etching polysilicon. (4) The $SiO_2/Si_3N_4/SiO_2$ sandwich layer on the backside was etched but the part on the sidewalls of the cavities and grooves remained in the anisotropical reactive ion etching (RIE) step. Then, the cavities were etched from the backside using ICP till the PSG sacrificial layer interrupted the etching. At the same time, the substrate in the groove regions was also etched more. (5) Finally, the PSG sacrificial layer was removed to release the micro-mirrors fully suspended by the elastic torsion-beams over the through cavities after the silicon substrate was isotropically etched a little more from the backside. Actually, during the last isotropical RIE, the outside SiO_2 sublayer in the SiO_2/Si_3N_4/SiO_2 sandwich layer on the sidewalls of the cavities and grooves was etched but its Si_3N_4 and inside SiO_2 sublayers were remained, which was employed as an insulation film, e. g., between each ON-state mirror and the stopper sidewall of its cavity.

Two kinds of new fiber self-holding structures were formed in the sidewalls of the fiber positioning grooves by using the same etching steps for producing the grooves themselves, which manifested that the holding structures were integrated monolithically with the torsion-mirror switch structures in the array chip actually. Figure 4 (a) and (b) show the schematic diagram of one of the fiber self-holding structures and a close SEM view of one cantilever beam in the structure, respectively. The shapes of the two kinds of self-holding structures were bi-cantilever beams and two opposite bi-cantilever beams, respectively. Each cantilever beam has a “boss structure”, namely clamp paw, at its free end. The Si_3N_4 and inside SiO_2 sublayers of the SiO_2/Si_3N_4/SiO_2 sandwich layers also remain on all side surfaces of the cantilever beams. Force analysis on the fiber self-holding structures indicated that the new with bi-cantilever beams or two opposite bi-cantilever beams is more stable than the old with single-cantilever beam[5] because the former is a symmetrical structure and, thus, the resultant force put in the longitudinal direction of the fibers equals to zero. Additionally, the clamping force of the new fiber self-holding structures can be adjusted according to the actual situations[9] so that the axes of the fibers mounted in the grooves can be kept in line even though the groove width changes somewhat along the longitudinal direction of the fibers, which will benefit the self-aligning of the fibers. The structures not only can clamp the fibers but also can push them to the opposite sides or in the central lines of the grooves so that the optical fibers can be mounted to the right positions easily. In general, the new self-holding structures facilitate substantially the fiber self-fixing and, meanwhile, self-aligning functions, which implicates that a lot of extra manual manipulation is not necessary for assembling optical fibers precisely on the torsion-mirror optical switch arrays and the lowcost batch production of the components can be achieved.

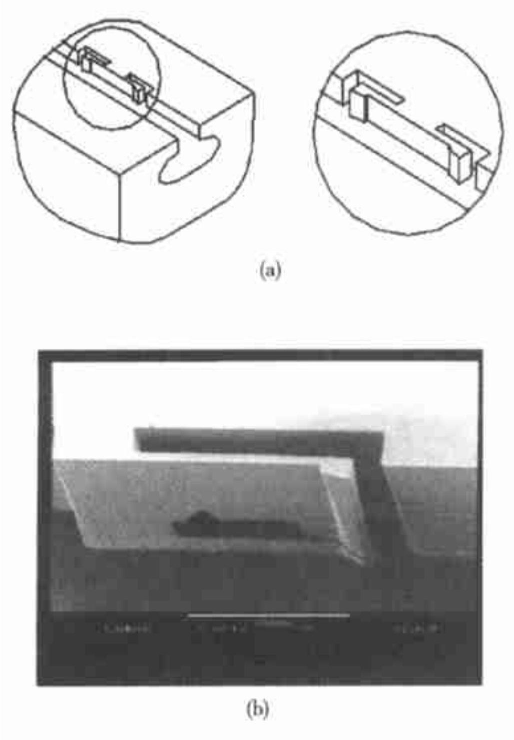

Fig. 4 (a) Schematic diagram of one of the fiber self-holding structures and (b) SEM of one cantilever beam in the structure

3 Characterization

The electromechanical characteristics of the torsion-mirror optical switches were investigated under applied DC bias, AC bias or the kind of bias in the mixed form of A_0

$+A_1\sin(\omega t)$, where A_0 is the voltage value of the DC part, A_1 ($A_1 > 0$) and ω present the amplitude and frequency of the AC part, respectively, in an atmospheric pressure with a reflected laser-beam experimental system. Figure 5, the DC bias voltage dependence of the tilting angle of the micro-mirrors with the torsion-beams of about 1μm thickness, shows that there certainly exist electrostatic yielding voltages[6] of the torsion-mirror optical switches, under which the mirrors are driven to tilt from their OFF-state inward their through cavities spontaneously till they touch the stopper sidewalls of the cavities to achieve their ON-state. In Fig. 5, the solid line with symbols of open diamond presents the measured results while the dispersed data points shown by open circle are the results of simulation by using the Intellisuit simulator. In the simulation, the designed torsion-mirror switch structure was used. As shown in Fig. 5, the results of simulation agree very well with the corresponding experimental measurements. The typical electrostatic yielding voltages of the torsion-mirror optical switches are found in the range of 270～290V, depending on the measured samples.

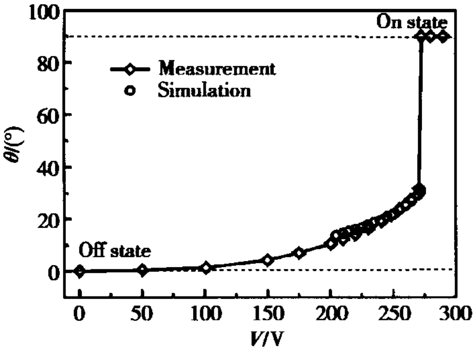

Fig. 5 Experimental characteristic of mirror tilting angle versus applied DC bias

Even under applied DC bias, the theoretical analysis on the electromechanical characteristics of the torsion-mirror switch structures, which is different from a typical electrostatic actuator composed of two parallel plates, is basically complicated because the profile of electrostatic field changes as the tilting angle of the micro-mirrors. In order to simplify the analysis, three assumptions were set: (1) Except with the stopper sidewall, a micro-mirror will have no electrostatic-field interaction with the other sidewall of its through-cavity; (2) The distribution of the electrostatic field between a micro-mirror and the stopper sidewall of its through cavity is uniform along the axis parallel to the torsion beam, and thus the micro-mirror can be considered as a part of an infinite belt; (3) The shape of the field is represented by the arc whose pivot is at the torsion beam. Taking the width W and length L of the micro-mirror; the width w, length l and thickness t of the torsion beam; and the distance l_0 between the mirror and the beam as design parameters, we obtained the equation, which can be used to estimate the value of the yielding voltage of the torsion-mirror optical switches theoretically, as follows:

$$V_{\mathrm{th}} = \sqrt{\frac{2\pi^3 G w t^3}{81\varepsilon_0\varepsilon_r W l\left[\ln\left(\frac{L}{l_0}\right) - \frac{\sqrt{2}w_g}{W}\ln\left(\frac{L}{T_s - d_g}\right)\right]}} \tag{1}$$

where G represents the Young's modulus of polysilicon, $\varepsilon_0 = 8.85\times10^{-12}$F/m is a dielectric constant of the vacuum, ε_r represents the relative dielectric constant of the air, T_s represeats the thickness of the substrate, and w_g and d_g represent the width and depth of the fiber grooves, respectively. How the existence of the fiber grooves affects the profile of the electrostatic field between a micro-mirror and the stopper sidewall of its through cavity is taken into account in Eq. (1) to a certain extent because producing the fiber grooves decreased the effective area of the stopper sidewall of a through cavity. For the torsion-mirror optical switches, the theoretical value of the yielding voltage given by Eq. (1) equals 220.80V. The discrepancy between the calculated result and the experimental result demonstrated in Fig. 5 is mainly due to the neglect of the concentration of the electric field on the mirror edges, the neglect of the electrostatic field interaction between the micro-mirror and each other sidewall (except the stopper sidewall) of its through-cavity and the value of the Young's modulus, which is selected to use, in the calculation. The Eq. (1) also indicates that the yielding voltage is most sensitive to the beam thickness among the five parameters about the dimensions of the micro-mirror and the torsion beam. The variation of only ±0.1μm in the beam thickness gives a large change of yielding voltage by ±30V or so according to Eq. (1). Therefore, the measured distribution of the yielding voltage can be explained by the thickness variation of the LPCVD deposited polysilicon for producing the micro-mirrors and the elastic torsion beams. It is more important to fabricate thinner beams if the yielding voltage of the torsion-mirror optical switches is expected to be much lower. Actually, the thickness control of the LPCVD deposited polysilicon is good because the measured distribution of the yielding voltage is only about 30V.

The minimum holding voltage that is necessary and adequate to keep the micro-mirrors to be in their ON-state was found 55V or so, much lower than the yielding voltages, which reduced the chance of a dielectric breakdown eventually. Combined with the simulation on the vibration characteristics of the torsion-mirror optical switches using the ANSYS simulator, the typical intrinsic frequency of the first-mode vibration, ω_0, of the torsion mirrors was found about 524Hz. It can be estimated that the shortest switching time of the torsion-mirror optical switches will would be less than 2ms.

The alternating electric field induced by the applied bias in the mixed form of $A_0 + A_1\sin(\omega t)$ with a proper given ω as well as the value of $|A_0| + A_1$ larger than the electrostatic yielding voltages of the torsion-mirror optical switches can also drive the micro-mirrors from their OFF-state to the ON-state. Under this condition, the micro-mirrors will be kept in their ON-state if the value of $|A_0| - A_1$ is equal to or higher than the minimum holding voltage. Otherwise, the micro-mirrors will vibrate between their OFF and ON states in the alternating electric field.

The long term vibration of the micro-mirrors between their OFF-state and ON-state was observed in a proper alternating electric field to test the lifetime of the torsion beams. No mechanical failure was found after vibrations for at least one hundred million cycles. Actually, the lifetime of the torsion beams can be expected to be semi-permanent.

One of the disadvantages of the novel 2 ×2 torsion-mirror optical switch arrays is that the light beam traveling paths in the free space within each array are relatively long and that according to the ON or OFF states of the four switches in the array, their lengths may be unavoidablly different. Therefore, some collimation technologies should be used to reduce the light diffraction from the input fiber ends and, simultaneously, to enhance the light collection into the output fiber ends in order to obtain small coupling loss. The light beam collimation technologies and the optical properties of the 2 ×2 torsion-mirror optical switch arrays are going to be reported in detail in another paper.

4 Conclusion

Novel 2 ×2 torsion-mirror optical switch arrays with monolithically integrated fiber self-holding structures were fabricated, and then characterized electromechanically under applied bias. The components demonstrated good electromechanical performances and provide an impetus to being used to develop OXCs and OADMs for optical networking.

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具有光纤自定位保持结构的 2×2 扭转微镜光开关阵列的制作和机电特性*

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摘要: 应用基于表面硅、体硅微电子工艺的混合微加工技术,制作了新型 2×2 扭转微镜光开关阵列,并研究了其在外加静电场和交变电场中的机电特性. 当该光开关中悬挂多晶硅微镜的弹性扭转梁的厚度约为 1μm 时,驱动微镜以实现其“开”状态的拐点静电电压为 270～290V,而维持微镜“开”状态的最低保持电压在 55V 左右. 理论分析表明,在关于该光开关结构的一系列设计参数中,拐点静电电压对于弹性扭转梁的厚度最敏感. 该光开关的开关寿命超过 10^8 次,而其开关时间预计小于 2ms. 对单片集成制造在该光开关阵列芯片上的两种新型光纤自定位保持结构的力学分析表明,它们具有光纤自固定、自对准的性质.

关键词: 微机电系统; 光开关; 扭转微镜; 光纤自定位保持结构; 混合微加工
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