Development of Prototype Micromechanical Optical Switch*

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A new mechanical optical switch with a latching function was fabricated on a planar lightwave circuits (PLCs) by combining three technologies: integrated optics, micromachining on silicon or silica, and surface mounted actuators. The switching function is obtained by mechanical deflection of silica cantilevers driven by electromagnetic force. A prototype switch was made and its performance was measured experimentally. The insertion loss was 4.4 dB, cross-talk was -40 dB, and switching time was 40 ms for a driving voltage of 7 V and a current of 350 mA.

Key Words: Micromechanics, Electromagnetic Actuator, Micromachine, Optical Instrument, Communication Equipment

1. Introduction

Optomechanical fiber switches are commonly used for restoring signal paths in optical communication systems and for testing optical components and systems⁽¹⁾⁻⁽⁴⁾. In this kind of switch, the usual way to perform the switching is to move the optical fiber mechanically because this is simple and achieves good performance⁽¹⁾⁻⁽³⁾. Although such devices are already commercially available, they are still very expensive and difficult to fabricate in large quantities. To overcome these problems, we made an integrated micro-mechanical optical switch by combining three technologies: integrated optics, micromachining on silica, and surface-mounted actuators. The switching function is obtained by mechanical deflection of cantilever beams driven by electromagnetic force. The use of micromachining technology enables switch tips on a wafer to be mass-produced easily through processes

such as film deposition, photolithography, and etching. A prototype switch was made for preliminary examination of its switching functions. The switch design and the first functional results are presented in this paper.

2. Experimental Procedure

2.1 Optical switch design

A schematic view of the optical switch with a silica substrate is shown in Fig. 1. The switch consists of two silica cantilevers fabricated on a silica-silicon-silica wafer. The free ends of the two silica cantilevers are fastened together and a soft magnetic block

Fig. 1 Schematic view of the optical switch

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Fig. 2 Latching function of the electromagnetic actuators

is put on them. The cantilevers themselves are movable light waveguides (LWGs), and the route of the optical signal is switched by moving these cantilevers. The signals that go through the gaps are individually transferred to the rigid LWGs in front of them. The structure of the cantilevers enables the optical switch to provide a pair of linked 1×2 switches.

Figure 2 shows the latching function of the electromagnetic actuators. They are composed of coils and permanent magnets. The cantilevers are attracted toward one of the two actuators in the direction of the current in the coils. They are held there by the force of the permanent magnet even after the current has been turned off. When the current direction is commuted, the cantilevers are attracted toward the other actuator and held there.

2.2 Fabrication process

Two fabrication processes are examined: A silicon-substrate process and a silica substrate process. Figure 3 shows cross-sections of the etching process for obtaining movable cantilevers using silicon substrate. PLCs are fabricated on the (100) silicon wafer by the following process. First, silica ($t=15\text{ }\mu\text{m}$) is deposited by electron beam (EB) evaporation. Then, Ti-doped silica ($t=8\text{ }\mu\text{m}$) is deposited onto the wafer by EB evaporation and patterned by photolithography to form LWG cores. Then silica ($t=15\text{ }\mu\text{m}$) is deposited as a cladding layer by flame hydrolysis deposition method⁽⁶⁾. After PLC formation, the wafer is dry-etched anisotropically to form the outline of the silica cantilevers (Fig. 3(a)). To produce movable cantilevers with an air gap underneath, anisotropic wet-etching is applied to the silicon substrate (Fig. 3(b), (c)). Anisotropic wet-etching was done by using 40 mass% KOH solution at the temperature of 348 K.

Figure 4 shows cross-sections of the etching process using a silica substrate. PLCs are fabricated on the silica wafer by the following process. First, silicon film ($t=2\text{ }\mu\text{m}$) is deposited by sputtering onto the silica wafer as a separator. PLCs are then fabricated on the surface of the silicon thin film by the

Table 1 Mechanical characteristics of silicon and silica

Material	Silicon	Silica
Young's modulus (Pa)	1.2×10^{11}	0.71×10^{11}
Thermal expansion coefficient (K^{-1})	3×10^{-6}	1×10^{-6}

Fig. 3 Process for fabricating the cantilevers

Fig. 4 Etching process for movable cantilevers

same process as for silicon substrate. After PLC formation, the wafer is dry-etched anisotropically to form the outline of the silica cantilevers (Fig. 4(a)). The wafer is then diced. To produce movable cantilevers with an air gap underneath, wet-etching is applied to the silicon layer under the silica cantilevers. Wet-etching was done by using 40 mass% KOH solution at the temperature of 348 K (Fig. 4(b), (c)). The design of the silica-substrate-type cantilever head was different from the silicon-substrate-type one; that is, the head width of the silica-substrate-type was decreased.

The cladding layer for both processes was formed by flame hydrolysis deposition process and treated at high temperature over 1400 K. The heat treatment caused large thermal stress in silicon and silica layers, and cracking of silicon and silica is caused by thermal stress in the layers because thermal expansion coefficient of silica is smaller than that of silicon. To clarify the thermal stress value in the silicon and silica layers, thermal stress was numerically calculated by using material dynamics for the laminated-beam method⁽⁶⁾. The mechanical characteristics of silicon and silica are shown in Table 1.

2.3 Evaluation of device characteristics

Figure 5 schematically shows the experimental equipment for evaluating characteristics of the optical

Fig. 5 Schematic view of the experimental equipment for evaluating device characteristics

switch. Lightwaves ($\lambda=1.3\mu\text{m}$) from a laser diode were coupled into a $9\text{-}\mu\text{m}$ -core single-mode optical fiber. The other end of this fiber was butt-coupled to the fixed end of the movable waveguide in order to inject the lightwaves into the cantilever waveguides. The lightwaves propagated across the gap between the input and output waveguides. Another single-mode fiber was butt-coupled to the end of the output waveguide. An optical power sensor was connected to the other end of the fiber, and the optical power of the lightwaves propagating through the switch was measured. And the total optical loss, cross talk, and switching time were evaluated.

3. Experimental Results

Figure 6 shows an optical microscope image of the cantilevers and their head on a silicon substrate after anisotropic etching of the substrate. Though the cantilevers are formed in the air, a part of the silica layer in the air near the head is broken and some cracks are observed. Observing closely, it was clarified that cracking was caused in the final period of the etching process.

Figure 7 shows the calculated thermal stress against silicon thickness in various parts of a laminated silicon/silica ($t=50\mu\text{m}$). The positive value means compressive stress, and the negative value means tensile stress. In this figure, there is a minimum value of stress in part C at a 0.1 mm thickness of silicon substrate. In part A, there is also a minimum value of stress at a $0.02\text{--}0.03\text{ mm}$ thickness of silicon substrate. In the final period of silicon etching, the substrate thickness is probably less than 0.1 mm so cracks were considerably caused by negative stress.

Figure 8 shows the effect of silica thickness on the minimum stress in parts A and C. The thickness of silica has an effect on the thermal stress in silicon, and

Fig. 6 Optical microscope image of the cantilevers and their head after silicon-substrate etching

Fig. 7 Thermal stress evaluation of silica/silicon laminated structure

Fig. 8 Minimum stress evaluation of silica/silicon laminated structure at various thicknesses of silica layer

decreasing the thickness of silica probably reduces thermal stress. In this figure, however, little change in the minimum stress value in parts A and C for the range of a $0.03\text{--}0.1\text{ mm}$ thickness of silica. Silica thickness of 0.03 mm is required for normal propagation of a light signal, and a larger thickness than 0.1 mm causes other problems in the etching process such as long processing time or reduced silica quality.

To obtain damage-free cantilevers, silica sub-

Fig. 9 SEM image of the cantilever head after silicon-separator etching

Fig. 10 Micrograph of the micromechanical optical switch with electromagnetic actuators

strate method was examined. Figure 9 shows a scanning-electron-microscope image of the cantilever head just after the etching of the silicon separator. There was an air gap between the cantilevers and the substrate. The side-etching rate of anisotropic dry-etching used in this study was smaller than the forward etching rate in silica etching. However, when the front end of the etching reached the silicon separa-

Table 2 Performance evaluation results

size (mm)	12.4 * 13
insertion loss (dB)	4.4 (*)
cross talk (dB)	-40
driving voltage (V)	7
driving current (mA)	350
switching time (ms)	40

(*) 3.1 dB for switching gap only

tor, the side-etching rate suddenly increased. The same phenomena also occurred in the etching of the switch. The gaps between the cantilever and substrate widened and the half-switching stroke became about $4\text{ }\mu\text{m}$ larger than the designed value.

Figure 10 shows a micrograph of the micro-mechanical optical switch after the electromagnetic actuators had been mounted. The switch is 12.4 mm long, 13 mm wide, and 5 mm high. The gap between the input and output waveguides was filled with refractive-index matching fluid.

The results of the performance evaluation of the switch are listed in Table 2. The insertion loss was 4.4 dB (3.1 dB for switching gap only) and the cross talk was -40 dB . The switching time was around 40 ms for each direction. The insertion loss was larger than the estimated switch loss because of the parallel decentering caused by the large side-etching of the cantilevers. Although it is not easy to reduce the side-etching rate, precision etching is indispensable to decrease the insertion loss in this type of optical switch. Improved etching or an improved cantilever structure should be examined for precision etching.

4. Conclusion

A new mechanical optical switch with a latching function was fabricated on planar lightwave circuits. A prototype of this switch was made in order to examine its switching functions. Performance evaluation results show that insertion loss is 4.4 dB, cross talk is -40 dB , and switching time is 40 ms under a driving voltage of 7 V and a driving current of 350 mA. The large insertion loss of the switch is assumed to originate in parallel decentering of the waveguides because of the large side-etching during anisotropic dry-etching of the silica layer. Precision etching is therefore indispensable to decrease the insertion loss in this type of optical switch.

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