Development of A 4x4 Hybrid Optical Switch

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ABSTRACT

In this paper, we present a practical approach to realize a highly accurate but low-cost hybrid optical switch. This hybrid optical switch is composed of a MEMS-based silicon micro-mirror-array structure and a mini-actuator array. The silicon micro-mirror-array structure, which includes vertical mirrors, cantilevers, and trenches for passing light beams, are fabricated by using simple KOH etching process. The wet anisotropic silicon etching technique that is employed in this work greatly reduces the complexity of the fabrication process and thus gives higher fabrication yield. The mini-actuator array consists of commercially-available electromagnetic bi-stable mini-relays and L-shape arms. When the L-shape arm does not contact the cantilever, the mirror that is under zero external force can precisely reflect the light beam. When the L-shape arm pushes up the mirror, the light beam can pass under the mirror. The main advantages of this proposed design include high precision, easy for fiber alignment, high fabrication yield as well as low cost.

Keywords: optical MEMS, optical switches, wet anisotropic etching, bi-stability, self-alignment.

1 INTRODUCTION

With the rapid growth of optical communication networks, the demand of a reliable high-capacity switching system greatly increases. Large-scale optical cross-connect switches are the key components for building complex switching systems with large-port capacities. Recently, MEMS technology has emerged to be the promising solution for developing optical cross-connect switches [1-3]. Optical switches often require the vertical smooth mirrors to reflect optical signals. Silicon mirrors fabricated by using MEMS technology are widely employed for the optical applications. Figure 1 shows the schematic of a typical MEMS optical cross-connect switch. Deep reactive ion etching (DRIE) and wet anisotropic etching are the most popular micromachining techniques to fabricate the silicon mirror. DRIE technique is usually utilized to create high-aspect-ratio structures and is not restricted by the crystal orientation of the silicon wafer. However, DRIE technique is much more expensive than wet anisotropic etching.

Vertical smooth mirrors that are formed by $\{111\}$ planes can be created on a (110) silicon wafer [4]. However, the etched shapes are strongly restricted by the crystal orientation of the silicon wafer. For example, vertical (111) mirrors and V-grooves cannot be simultaneously created on a (110) silicon wafer. Helin *et al.* [5] reported a self-aligned micromachining process that can simultaneously create vertical (100) mirrors and V-grooves on a (100) silicon wafer.

In this work, silicon micro-mirror-array structures for 4x4 hybrid optical switches are designed and fabricated by employing the concept of the self-aligned micromachining process. With our proposed approach, it is possible to simplify the fiber alignment procedure of the packaging process as well as realize an optical switch that possesses the advantages of high accuracy, low cost and high fabrication yield.

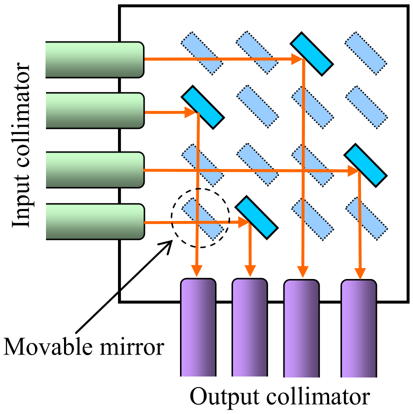


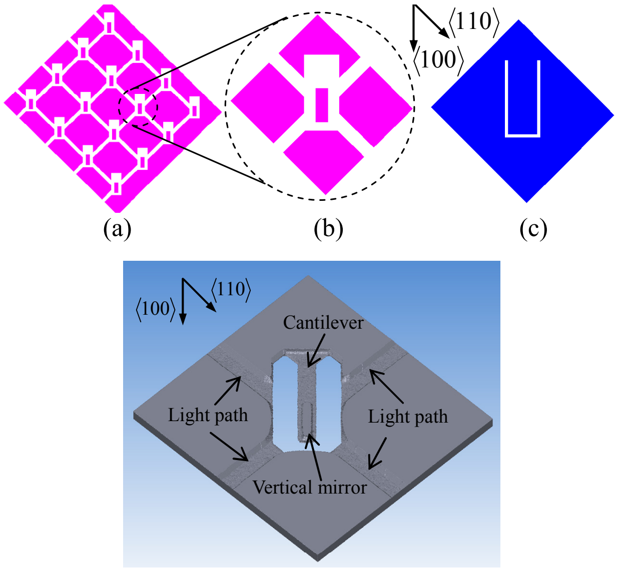
Figure 1 The typical design of the 4x4 optical switch.

2 DESIGN AND FABRICATION

Figure 2 depicts the design of the mask openings for fabricating the micro-mirror-array structures, including vertical mirrors, cantilevers, and light paths. The orientation of the silicon wafer is $<100>$ direction. As shown in Figure 2(b), because the angle between $<100>$ and $<110>$ crystallographic directions is 45^o, the mask patterns for each vertical mirror are designed to be aligned with the $<100>$ direction and mask patterns for the light paths are designed to be aligned with the $<110>$ direction. The mirror surfaces are designed to be on $\{100\}$ planes, so the lateral etching rate toward mirror surface is equal to the vertical etching rate toward the wafer surface. Therefore, the surfaces of the etched vertical mirrors are formed on $\{100\}$ planes and thus can be self-aligned with the optical paths that are along $<110>$ direction.

This etching process is also simulated by using the process simulator Etch3D®. With the mask patterns shown in Figure 2(b) and 2(c), the vertical mirror, the cantilever and the light paths can be simultaneously created on a (100) silicon wafer shown in Figure 2(d). The (100) surfaces of the fabricated mirrors are self-aligned to the light paths and thus potentially can reduce the complexity of the alignment procedure.

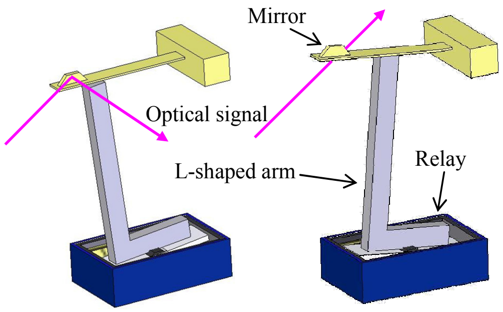
The vertical mirrors can be individually actuated by the mini-actuator array. The mini-actuator composes of the L-shape arm and the commercially-available electromagnetic bi-stable mini-relays. Each mini-actuator can retain the mirror at either one of the two stable positions without consuming any electrical power, as shown in Figure 3. At the first stable position, the L-shape arm does not contact the cantilever and thus the optical signal can be reflected by the mirror, as shown in Figure 3(a). At the second stable position, the cantilever is pushed up by the L-shape arm and therefore the optical signal can pass under the mirror, as shown in Figure 3(b). It has to be emphasized that the mirror reflects the light beam only when it is under zero external force, so that the stress-free single-crystal silicon mirror structure can precisely reflect the light beam.



(a) (b) (c)

(d)

Figure 2. (a) Mask openings for the micro-mirror-array structures. (b) Enlarged view of the mask opening for one mirror. (c) Backside mask openings for the cantilever. (d) Simulated results of the etching process.



(a) (b)

Figure 3. The operational principle of the mirror (a) The first stable position at which the L-shape arm does not contact the cantilever. (b) The second stable position at which the cantilever is pushed by the L-shape arm.

The fabrication process based on KOH etching is illustrated in Figure 4. The starting material is a (100) silicon wafer which is deposited with a silicon nitride layer on the both sides. The silicon nitride layers are used as the etching mask for the device structures. In order to achieve precise alignment with the crystal orientation of the (100) silicon wafer [6], a series of small circles are defined on the backside of the wafer and then etched by KOH etchant for a sufficient time to form pyramidal cavities. These pyramidal cavities will be used as the alignment marks for the subsequent mask patterns of the cantilevers. After the mask openings of the cantilevers are defined on the backside of the wafer, the mask patterns of the mirrors and the optical paths are defined on the front-side of the wafer using a double-side mask aligner. The wafer that is patterned on both sides is then immersed in KOH etchant. Note that the patterns exposed to KOH etching are carefully designed by considering the lateral undercutting width during the etching process. Accordingly, the desired dimensions of the micro-mirror-array structures can be created after the etching process. It has to be emphasized that our proposed process does not require back-side protection of the wafer. As a result, the complexity of the fabrication process can be reduced and the process yield can be improved.

In addition, previous study [7] indicates that high KOH concentration and high etching temperature can lead to the formation of the vertical sidewall while low KOH concentration and low etching temperature will result in the inclined sidewalls on a (100) silicon wafer. On the other hand, KOH solution added with isopropyl alcohol (IPA) can reduce the roughness of the etched surface. Therefore, the concentration of the KOH solution used in this work is 50wt% and isopropyl alcohol is added in the solution. Also, the etching temperature is 75℃.

The fabricated 4x4 micro-mirror-array structure is shown in Figure 5(a). The SEM picture of a fabricated cantilever with a vertical mirror is shown in Figure 5(b). Note that the sidewalls of the cantilever are not vertical due to the fact that the higher etching rate occurs on convex corners. After the device structures are created, the residual nitride layers are removed by using boiling phosphoric acid. Finally, a thin gold layer of about 3000Å is deposited on the device structures for improving the optical reflectivity of the mirrors. The typical dimensions of the fabricated mirrors and cantilevers are $1.5 \times 0.45 \times 0.1 mm^3$ and $6 \times 1.5 \times 0.06 mm^3$, respectively.

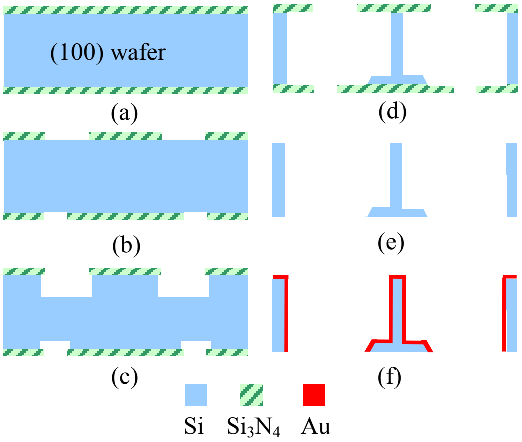
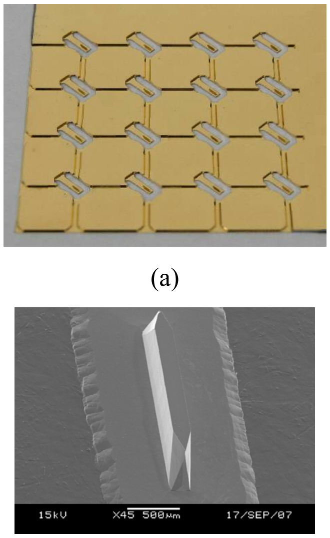


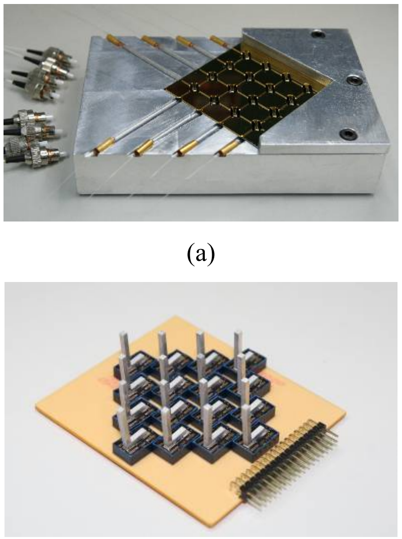
Figure 4. The fabrication process of the micro-mirror-array structures (a) The (100) silicon wafer is deposited with silicon nitride layers by LPCVD. (b) Patterns transferred. (c) The etched trenches are formed at the beginning of the KOH etching process. (d) The device structures are created after the KOH etching process. (e) The residual silicon nitride layers are removed by using boiling phosphoric acid. (f) The device structures are deposited with gold.



(a)

(b)

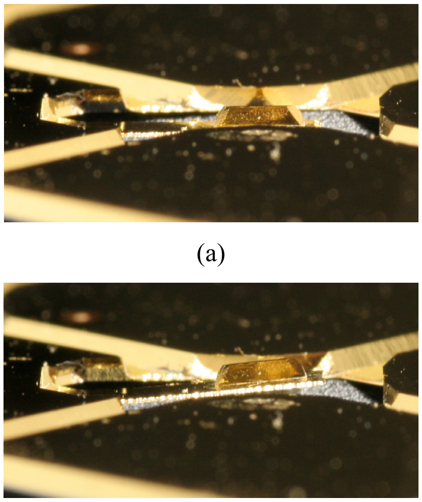
Figure 5. (a) The picture of the fabricated 4x4 micro-mirror-array structure. (b) The SEM picture of the vertical mirror and the cantilever.



(a)

(b)

Figure 6. (a)The prototype of the packaged 4x4 hybrid optical switch (b)The relay-based actuator array.



(a)

(b)

Figure 7. (a)The cantilever is not contacted by the L-shape arm and the mirror is at the first stable position. (b)The cantilever is pushed by the L-shape arm and the mirror is at the second stable position.

3 EXPERIMENTAL RESULTS

The prototype of a packaged 4x4 hybrid optical switch is shown in Figure 6(a). The silicon micro-mirror-array structure is fixed on the aluminum-made housing. The relay-based actuator array, as shown in Figure 6(b), is mounted underneath the micro-mirror-array structure. Due to the well-defined position of the vertical mirrors, the difficulty and complexity of the packaging process can be reduced. The input and output collimators pigtailed with FC/PC connectors are also assembled in the housing.

The commercially-available electromagnetic bi-stable mini-relays (TQ2-L2-5V, Panasonic) are used as the actuators in the array. The relays can be switched between the two stable states with a 5V input voltage. Figure 7(a) shows the mirror is at the first stable position, in which the L- shape arm does not contact the cantilever so that the light beam can be precisely reflected by the stress-free single-crystal silicon mirror. When the relay is in the second stable position, the mirror is pushed up by the L-shape arm, as shown in Figure 7(b). The measured displacement of the cantilever can be up to about $630\mu m$, which is large enough for the light beam to fully pass under the mirror.

The optical performance of the device is measured at the wavelength of 1550nm. The alignment of the collimator is carried out by using six-axis positioners. An infrared card is also used to detect the position of the light spot to determine the optimal position of the collimator. The output optical signal is measured by the power meter to estimate the insertion loss. Once the collimators are aligned to achieve the lowest insertion loss, the collimators are glued on the housing by using UV-glue. The measured insertion losses are about -5dB. The excess losses may be caused by the roughness of the mirrors. Thus, the further study on reducing mirror roughness is now in progress.

4 CONCLUSIONS

The development of a 4x4 hybrid optical switch is presented in this work. This hybrid switch, which consists of a MEMS-based silicon micro-mirror-array structure and a mini-actuator array, possesses the advantages of high precision, high fabrication yield and low cost. The silicon micro-mirror-array structures are realized by using a simple KOH anisotropic etching technique. The vertical mirrors, cantilevers, and optical paths can be fabricated under high etching temperature as well as high etchant concentration. The mirrors are actuated by relay-based actuators and can retain at two stable positions. When the cantilevers are not pushed by the actuators, the mirrors that are under stress-free condition are able to precisely reflect the light beams. When the cantilevers are pushed by the actuators, the mirrors are moved to the second stable position which allows light beams passing through. The maximum measured displacement of the cantilever is about $630\mu m$. The preliminary measurement results of the insertion loss is about -5dB.

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