BULK SILICON MICROMACHINED ELECTROSTATIC MICROACTUATORS FOR USE IN OPTICAL MEMS

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Abstract
Two concepts for electrostatic microactuators are demonstrated that are designed for use in optical MEMS devices. A parallel-plate configuration allows to deflect an optical fibre ±65 μm to realise a lensless optical 1x2 fibre switch at low voltage (30 V). A vertical comb actuator is developed for the precise and reproducible actuation of mirrors in NxN optical matrix switches. The fabrication is completely based on wet anisotropic etching of (110)-silicon.

Introduction
For many applications in optical communication networks, actuators with travel ranges from 10 to a few 100 μm are required. On the other hand, no large forces are necessary, e.g. for the movement of optical fibres or mirrors. In this case, electrostatic actuators are simple, low-power alternatives to piezoelectric or electromagnetic actuation. Parallel-plate actuators allow small devices for travel ranges below 100 μm while comb-drive concepts are used for larger deflections. They are theoretically investigated by FEM-simulation. The fabrication of both types is based on bulk silicon micromachining using wet anisotropic etching of (110)-Si in KOH. Crystalline Si has found a lot of applications in optical MEMS [1] due to a number of unique properties as it is an inherently stress-free material with no plastic deformation at room temperature. Especially components for all-optical networks require highly reliable low-power devices.

Fabrication
Both types of actuators are realised by wet anisotropic etching of single-crystalline silicon (c-Si) with high aspect ratios in a batch process. 525-μm thick (110)-wafer with a 100-nm Si₃N₄ mask are used. The boundaries of mechanical structures are extensively formed by vertical [111]-planes in (110)-silicon. This assures highly parallel and smooth electrodes with well-defined mechanical properties. The design of these actuators must take into account that the two sets of [111]-planes intersect under an angle of 109° resulting in rhombic shapes (fig. 1). An anisotropic etching process using KOH with ultrasonic agitation (at f = 130 kHz or 1 MHz) is optimised for the required deep silicon etching with aspect ratios up to 1:25 and high uniformity. The mask undercut is reduced to <0.5 % (fig. 2).

The electrode plates are isolated by PECVD-deposition of SiO₂. The bulges close to the wafer surfaces as a result of non-conformal deposition avoid sticking of the plates after switch-off (fig. 3).

Fig. 1: Layout of a parallel-plate actuator based on wet-etching of (110)-Si in KOH

Fig. 2: Wet-etched Si-plates in (110)-silicon

Fig. 3: Non-conformal isolation of the electrodes using plasma-enhanced CVD

The assembly of the actuators is performed with resin bonding (UV- or thermally curing resins). The
Parallel-plate actuators are fixed on a terraced submount and the electrodes are electrically separated by trench dicing with a wafer saw. The comb-drive actuators are assembled from 2 separate comb structures using integrated alignment structures.

**Parallel-plate actuators for moving-fibre switches**

![Figure 4: Electrostatically actuated fibre switch with parallel-plate electrodes](image)

For the reconfiguration of optical networks, 1x2 switches or rows of switches are required. A standard single-mode fibre with a diameter of 125 μm requires an alignment accuracy of below 1 μm. The simplest switch configuration is a fibre splice with butt fibre coupling (without optical elements such as lenses or mirrors). It was successfully used in magnetic [2] or thermo-mechanical switches [3, 4]. For this type of switch a bi-directional deflection of ±65 μm is required.

![Figure 5: Basic configuration of the parallel-plate actuator](image)

The electrostatic actuator design for a 1x2 moving-fibre switch (fig. 4) is shown in fig. 5. The spring that is fixed to an anchor point is deflected by the attraction force between two parallel plates. The moving electrode is fixed to the free end of the spring. By varying the length $L$ and the stiffness of the spring (width $w$) and the electrode (width $e$), a deflection of the spring at low voltage is achieved. When a voltage is applied to the electrodes, the free end of the moving electrode is attracted at first. The decreasing gap increases the force. If the voltage is high enough, the force increases more and more and finally, the electrode deflects the spring. Further details of this actuator are given in [5]. Fig. 6 shows a deflection cycle simulated with an FEM-program. Each figure a)-d) is the result of an individual iteration step as the deflection is strongly non-linear. The minimum voltage for a full deflection of the actuator with different dimensions (length of the spring $L = 25$ mm) is given in fig. 7. As an important result it is found that for electrode width $e \leq 0.5$ w the actuation voltage does not depend on the spring constant any more. It is dominated by the electrode width, only.

![Figure 6: FEM-simulation](image)

The simulation results are confirmed by measurements on fabricated actuators. Electrodes with a thickness of 60 μm show a deflection voltage of 27 V which is in good agreement with the simulation. Nevertheless the electrostatic force in parallel-plate actuators is very small and the actuator has to move the optical fibre that is from the mechanical point of view a quartz glass cylinder of 125 μm. The maximum force is achieved with electrode plates as large as possible. For this reason, the set-up uses the full thickness of a wafer (525 μm) for the electrodes and the spring. Comparing the spring constant of a silicon cantilever (100 μm thick, 525 μm high, $k = 3.1 \times 10^6$ N/μm) and an optical fibre (diameter 125 μm, $k = 2.83 \times 10^7$ N/μm) shows, that the switching voltage increases by about 6 %, only. To achieve a full deflection of the spring requires a sliding of the electrode when in contact with the...
fixed electrode. This is possible due to the electrical isolation with bulges that prevents a full contact of the electrodes. Further improvements are achieved if both electrode plates are realised with flexible cantilevers (fig. 8). The sliding between the electrodes during deflection is reduced to a minimum. It assures a reliable deflection and much less wear of the isolation.

In contrast to reconfiguration switches, optical crossconnects require compact but highly reliable NxN switch configurations (fig. 9 Bottom). Commonly, mirror devices are used. The optical path is defined by the position of the mirrors. A switched-off actuator results in a mirror that redirects the optical beam while an actuated mirror moves out of the optical path. The actuator arrays must guarantee a precise alignment and extremely high reproducibility of the mirror position for low insertion loss. Actuators realised in bulk silicon technology can fulfil these requirements due to the excellent mechanical properties of crystalline silicon. A vertically operating electrostatic comb-drive as shown in fig. 9 is realised by etching fine but deep arrays of plates in [110]-silicon. This allows a theoretical travel range of approx. 400 μm.

Measurements with a high-speed camera show a switching time of 10 ms and an optical switch achieves an insertion loss of 0.5 dB which is close to the theoretical limit for butt-coupled fibres without index matching.

Bulk comb-drive actuators for NxN mirror switch arrays

A main limiting effect for the deflection of comb drives is the side instability due to the parasitic force between the parallel plates. In a perfectly aligned actuator the forces on both sides of the moving electrode compensate each other. But if these forces exceed the lateral stability of the spring, the moving electrode is attracted by one neighbouring electrode and sticks [6]. For the simulated structure side instability occurs at approx. 110 V.
Fig. 11: FEM-simulation of an actuator with a 2-cantilever meander

![FEM-simulation of an actuator with a 2-cantilever meander](image)

Fig. 12: Deflection vs. applied voltage for an actuator according to fig. ??

It must be noted that in small actuators the springs become stiffer due to the reduced length while the force is reduced by the reduced number of comb fingers. For this reason, an optimised design for arrays with longer springs would result in much larger deflections at low voltage.

Fig. 13 is a photograph of two comb structures with different size. It shows the two complementary comb elements that are aligned against each other. The rhombic shape is a result of the wet anisotropic etching process in (110)-silicon. The actuator is assembled by adjusting the wafer with the moving comb fingers (upper half of fig. 13) against the fixed fingers (lower part of fig. 13) using alignment grooves that are visible around the rhombus. In fig. 13 the meandric spring is not yet etched. A detail of the comb fingers is shown in fig. 2.

![Two complementary comb structures with rhombic shape etched in (100)-Si before assembly](image)

Summary

Two electrostatic actuators based on bulk silicon micromachining for use in optical switches are demonstrated. The fabrication processes are suitable for batch processing and wafer level assembly. Switching voltages below 30 V are achieved for travel ranges up to 65 μm using a parallel-plate configuration. Also a vertical comb drive that is intended for optical NxN-mirror switches is presented. It allows to deflect a platform up to 300 μm with a voltage of 100 V. In this case, a significant improvement is expected with an optimisation of the spring structure.

References