Micro-opto-electro-mechanical systems alignment stages with Vernier latch mechanisms

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Abstract

Latching alignment stages for micro-opto-mechanical systems are constructed by deep reactive-ion etching of bonded silicon on insulator. Linear, rotary and tilt stages are demonstrated. Linear stages are driven using buckling electrothermal actuators, and latching is performed by a rack-and-tooth mechanism driven by shape bimorph actuators. In-plane rotation is obtained by using a linear actuator to drive a passive rotary table, and tilt motion is achieved using an inserted mirror. Finite element modelling is used to estimate limitations in performance and propose design improvements. A rack period of 10 µm is achieved with a structural depth of 85 µm. A Vernier mechanism based on multiple rack-and-tooth latches is used to increase precision beyond the value set by pattern transfer. Two- and four-section Vernier latches are demonstrated, and difficulties with multi-section latches are identified.

Keywords: MEMS, microactuator, rotation stage, Vernier gauge

1. Introduction

Precise positioning is often required for alignment or assembly of micro-opto-electro-mechanical systems (MOEMS). Many linear microactuators have been demonstrated, based on electrostatic [1–4], electrothermal [5, 6], electromagnetic [7] and piezoelectric [8] principles. Single-axis, linear stages have been modified to allow two-axis [3, 8], out-of-plane [4], rotary [9] and tilt [10] motion. Often, it is necessary to fix the position after adjustment, and complete engines have been developed for MOEMS assembly [11]. Such systems are complex and expensive, and simpler methods of fixing have been demonstrated for fibre alignment, based on friction [12], bistability [13] and UV curing epoxy [14]. Variable optical attenuators have also been demonstrated with ratchet clamps [15].

Many devices have been constructed in thin polysilicon layers using multi-step surface micromachining such as the multi-user MEMS process [16]. As a result, they have had a small feature height ($\approx 2$ µm) and a correspondingly low load capacity. To increase out-of-plane stiffness, high-aspect-ratio micromachining is required. Several suitable methods exist. For example, the LIGA process [17] is a build-up method involving synchrotron exposure of thick layers of resist, which can form plated metal structures up to 1 mm high. Deep reactive-ion etching (DRIE) of bonded silicon on insulator (BSOI) is an etch-down process that may structure single-crystal silicon at depths of several hundred microns [18].

Recently, we developed an electrothermally operated latching linear translation stage with a high load capacity (in the milligram range) and long travel ($>100$ µm) [19]. The device was formed by single-layer DRIE of BSOI, and contained a central table suspended on a deformable suspension and latched by a rack-and-tooth mechanism. Several features contributed to the success of the design. The thick structural layer and stiff suspension raised the load capacity by orders of magnitude compared with surface micromachined devices, and the large span allowed long displacements. Although the drive powers were high (2 W), the device was suitable for one-time assembly. Resolution...
was limited to 10 \( \mu m \) by the rack spacing; however, these limits may be overcome using multiple offset latches [20], a generalization of the Vernier mechanism previously exploited in MEMS to enhance measurement accuracy [21, 22].

Here, we show how these concepts may be used to develop other stages for assembly of silicon opto-hybrids based on discrete micro-optical components, avoiding detailed thermomechanical design in favour of demonstration of functionality. In section 2, we describe the construction of linear, rotary and tilt stages by DRIE of BSOI, and identify resolution limits. In section 3, we show how the performance of the electrothermal actuator system may be modelled using finite element analysis, and propose design improvements to reduce power consumption. In section 4, we describe the principle of multi-element Vernier latches, demonstrate their operation, and discuss the improvement in resolution most likely to be achieved in practical systems. Conclusions are presented in section 5.

2. Multi-axis latching alignment stages

In this section, we review the design and construction of the linear stage in [19], and show how relatively minor layout modifications may be used to realize rotation and tilt functions. The main aim is to provide a common platform for assembly of optical component trains.

2.1. Linear stages

Latching linear stages consist of a movable table and a latching system as shown in figure 1(a). The entire structure is defined by single-layer patterning and etching. The central table is suspended at either end by buckling-mode electrothermal actuators [6]. Each actuator consists of two sets of buckling beams; the two sets are mechanically in series, to increase the achievable displacement, and several individual beams are arranged in parallel within each set to increase the available forces. Latching is provided by two rack-and-tooth mechanisms, which are operated by shape bimorph electrothermal actuators [5].

The stage is a three-terminal device, with voltages \( V_A \) used for stage actuation and \( V_L \) to open the latches. When \( V_L \) is applied, current flows through the two shape bimorph actuators, which are arranged electrically in parallel. The longer hot arms expand more than the shorter cold arms, deflecting the beams carrying the rack teeth outwards to open the two latches. When \( V_A \) is applied, current flows through both sets of buckling actuators, and through the frame, since these parts are electrically connected in series. The actuators have an initial central pre-buckle, and are made to buckle further by constrained thermal expansion arising from the electrical heating. As a result, the frame is driven forward.

Prototype devices were fabricated by DRIE, undercut and metallization of 4" diameter (100) oriented BSOI. Etching was carried out using a Surface Technology Systems inductively coupled plasma etcher, operating a cyclic etch-passivate process based on the use of SF\(_6\) and C\(_4\)F\(_8\), using a 1.8 \( \mu m \) thick photoresist hard mask. Sacrificial oxide was removed by etching in buffered HF, and wash water was removed by freeze-drying. To allow electrical contact, the wafer was sputter-coated with 300 \( \AA \) of Cr and 1000 \( \AA \) of Au. With the wafer resistivity used (5–7 \( \Omega \) cm), the majority of the current flows through the metal rather than the silicon beams.

Figure 1(b) is a scanning electron microscope view of a device fabricated in BSOI with an 85 \( \mu m \) thick bonded layer, showing part of the table and main actuator and one of the rack-and-tooth mechanisms. The table is constructed from a lattice of 50 \( \mu m \) wide beams arranged on a 100 \( \mu m \) pitch, to yield a perforated structure that can be undercut by wet etching. The frame dimensions are \( L_1 = L_2 = 5 \text{ mm} \). The frame is suspended on buckling beams of 8 \( \mu m \) width and 2.5 \( \mu m \) length, with a 10 \( \mu m \) in-plane pre-buckle. Actuators with different numbers (2–5) of buckling beams were investigated. The latches are actuated by flexures of 10 \( \mu m \) width, 10 \( \mu m \) separation, 100 \( \mu m \) cold arm length and 1 mm hot arm length.

2.2. Rotary stages

We now consider how the arrangement above may be modified to realize a latching rotary stage. The simplest approach is one in which the majority of the components are reused without alteration, using a linear stage as an actuator to drive a passive rotary table. Figure 2(a) shows a suitable layout. Here, the table is suspended by flexures from a fixed boss, so an external component mounted on the table would require a central recess. The linear stage is used as a surrounding frame to drive the table via a tangential drive pin. The contact point on the drive pin lies at a radius of \( R = 2.2 \text{ mm} \). With a
rack period of $P = 10 \mu m$, the angular precision is therefore $\Delta \theta = \tan^{-1}(P/R) = 0.26^\circ$. The table is suspended on four flexures of 5 $\mu m$ width and 920 $\mu m$ length. Figure 2(b) shows a completed device in BSOI with an 85 $\mu m$ thick bonded Si layer.

2.3. Tilt stages

The same approach may be used to allow tilt adjustment of components such as mirrors about an axis parallel to the wafer plane. However, the mirror is now provided by a separate inserted MEMS component. The component consists of a plane mirror held on a torsion bar and mounted on a frame, which is in turn inserted into a movable stage as shown in figure 3(a). To allow release by sacrificial layer etching, this part is again formed by a lattice of 50 $\mu m$ wide beams on a 100 $\mu m$ pitch, and its width and height are 4 and 2.5 mm, respectively. However, double-sided processing could be used to avoid perforation of the optical surfaces. The component mounts a torsion mirror of width and height 1 and 2 mm, respectively, on torsion bars of length 1 mm and width 5 $\mu m$.

Tilt motion is achieved by translating the linear stage so that a drive pin on the mirror contacts a fixed substrate feature. The contact point on the mirror lies at $R' \approx 1$ mm from the axis. With a period of $P = 10 \mu m$, the latched angular precision is then $\Delta \theta' = \tan^{-1}(P/R') = 0.57^\circ$. The components are attached to a surrounding handle by short sections of thin (5 $\mu m$) sprue, so that they may be held by an external manipulator, and detached after they have been inserted into an elastic clamp mounted on the linear stage. For simplicity, we formed components on the same wafer as the stage. As a result, the aspect ratio of the tabs holding the component in place is around unity; ideally, this ratio would be increased to ensure mechanical stability. Figure 3(b) shows a completed tilt stage. The mirror is tilted in its normal rest position, and is tilted in the opposite sense as the stage is driven forwards.
2.4. Performance

The performance of linear stages has been presented in [19]. As with many electrothermal devices, power consumption was high. Although the aim of this work is not to optimize power consumption, significant improvements may be made by removing the substrate from beneath the actuators in a silicon device to eliminate gas conduction cooling, or by forming the suspended parts from electroplated Ni, which has considerably improved thermo-mechanical properties. Device performance was evaluated using an optical microscope equipped with a video camera and on-screen measurement system. For the rotary stage, tangential table displacements up to 200 µm were achieved manually, without exceeding elastic limits. Figure 4(a) shows an optical view of the drive pins in their rest position, and figure 4(b) shows a similar view after a tangential displacement of the rotary table of 100 µm.

Figure 4(c) shows the displacement–power characteristics for a typical rotary device. The two latch actuators have identical performance, and 0.2 W power is needed for the 20 µm displacement involved in opening the latch. Figure 4(c) also shows the characteristics of the main frame actuator (a three-beam drive) and the corresponding tangential motion of the rotary table. Two sets of data are shown for the frame, with and without the load of the table. In the latter case, the table was displaced using an external manipulator. The effect of the table load is to reduce the displacement of the frame. A loaded displacement of 50 µm is achieved at a drive power of 1.25 W. The table displacement lags behind the frame, because of the initial separation between the drive pins. However, the loading effect is not great, and a tangential table displacement of Z = 50 µm is achieved at a drive power of 1.5 W. This value corresponds to an angular motion of θ = tan⁻¹(Z/R) = 1.3°. Displacement limits were set by the onset of thermal damage, which occurred at a power of ≈2 W. Similar performance characteristics were obtained for tilt stages.

3. Theoretical modelling

In this section, we present a simple model of the main actuator. The aim is to identify the underlying cause of the high power consumption and describe possible improvements.

3.1. Performance limitations

The performance of electrothermal actuators is in general mainly determined by the material constants k (the thermal...
conductivity) and \( \alpha \) (the coefficient of linear thermal expansion), since the former determines the power required to sustain a given temperature gradient and the latter determines the resulting thermal expansion. Compared with nickel (the most obvious alternative material), silicon has a larger \( k \) and a smaller \( \alpha \). Improvements would therefore be expected to arise simply from the adoption of an alternative fabrication route such as the LIGA process. However, there are advantages in retaining an all-silicon construction, since it offers reduced sensitivity to variations in ambient temperature in passively aligned systems. We therefore concentrate here on the possibilities offered by layout changes. In particular we note that conduction through the structural material itself is not the only form of cooling. Apart from radiative cooling (which will be significant only at very high temperatures), convection cooling and cooling by direct gas conduction through the small air gap separating the movable parts from the substrate both offer alternative energy loss paths. While the former will always be present in a simple package scheme, the latter may be reduced by selective removal of the substrate.

3.2. Finite element modelling

To illustrate this aspect, we have used the simplified layout shown in figure 5(a). Here, structural features and dimensions corresponding to the main stage actuator have been retained, while the latching system has been discarded. The movable parts are assumed fixed to ideal heat sinks at the four anchor points, and suspended above the further perfect heat sink (the substrate) with a small air-gap between. Electrothermal heating and conduction through the structural material and the air-gap are allowed in the model, and the effect of selective removal of the substrate beneath the actuators is simulated by setting the thermal conductivity of the air in the two rectangular shaded regions to zero.

Modelling was carried out using the commercial finite element package ANSYS 6.0, using element type SOLID 7.0 for 3D thermal and structural solids. The following material parameters were used. For silicon, a Young’s modulus \( E = 168 \text{ GPa} \), a Poisson’s ratio \( \nu = 0.22 \), a thermal expansion coefficient \( \alpha = 2.06 \times 10^{-6} \text{ C}^{-1} \), a thermal conductivity \( k = 150 \text{ W m}^{-1} \text{ C}^{-1} \) and a resistivity \( \rho = 10 \Omega \text{ cm} \) were assumed. For air, a thermal conductivity \( k = 0.03 \text{ W m}^{-1} \text{ C}^{-1} \) was assumed. A voltage difference was established between the two pairs of anchors, and the power consumption was estimated by integrating the product of the voltage with the current density over the cross-section of the hot arms. The actuator displacement was then obtained as a function of drive power.

Figure 5(b) shows a typical simulation result, illustrating the variation in temperature through the hot arms in the upper and lower parts of the actuator. Figure 5(c) shows the variation of displacement with power obtained in the two models, without and with substrate removal, respectively. The displacements both vary quasi-linearly with power, as expected. In the former case, around 2 W drive power is needed to achieve a displacement of 50 \( \mu \text{m} \). Given the simplicity of the model, this result is in reasonable agreement with the data previously presented. Discrepancies are most likely to have arisen from variations in the experimental air-gap following sacrificial layer etching. In the latter case, the drive power is reduced by a factor of four. This behaviour confirms the essential strategy of selective substrate removal, and further improvements are likely to result from optimization of the elastic structure.

4. Vernier latches

DRIE trials showed that it is difficult to transfer a rack pattern to the full structural depth, for small tooth periods. For example, figures 6(a) and (b) show racks with periods of 10 and 5 \( \mu \text{m} \) in an 85 \( \mu \text{m} \) thick bonded layer. In the second case, the pattern is only visible to two thirds of the structural depth. For the actuator in figure 4(c), a 10 \( \mu \text{m} \) period yields only five resolvable points over the travel range. These values are currently insufficient for accurate MOEMS assembly. The resolution may of course be increased with thinner mechanical layers, or by using a multi-layer mechanical structure such as two-layer BSOI. However, here we investigate a solution based on the Vernier coincidence principle that may always provide an increase in resolution, whatever the layer thickness.

4.1. Design

Vernier gauges are based on the alignment of two parallel periodic bar patterns of period \( P \) and \( P' \), as shown in figure 7(a). If the two patterns coincide at one particular bar (shown here in black), they will coincide again whenever \( MP = NP' \), where \( M \) and \( N \) are integers, provided \( P' = PM/N \). If \( M \) and \( N \) differ by unity, we may write \( P' = P(N - 1)/N \). In this case, shifting one of the bar patterns by a distance \( P - P' = P/N \) moves the coincidence.
points by one bar. A gauge based on the alignment of the coinciding points will therefore have a resolution of $P/N$. A Vernier gauge may be modified to form a latch as shown in figure 7(b). Here the two bar patterns are replaced by racks. The lower one is fixed, while the upper one contains a set of spring-loaded teeth. Now, the coinciding teeth can grip each other to prevent lateral movement, while the springs allow non-coinciding teeth to be forced away. For this system to operate, the springs must have small lateral play. This requirement is difficult to satisfy in the limited space available between adjacent teeth.

Fortunately, it is unnecessary to retain multiple periods of the upper rack; the latch will function correctly with one period. It is not even necessary to use teeth from the same period, as shown in figure 7(c). Now, space is created for a spring suspension, as shown in figure 7(d). Here, each tooth is mounted on a separate portal spring based on two parallel beams, so that the motion is constrained to one direction. When one half of the latch is displaced, the engaged tooth will index forwards as in figure 7(e). Mechanical stops can limit the excursion of movable teeth and facilitate disengagement as shown in figure 7(f). The springs must however be capable of resisting the return force of the movable component without buckling, as shown in figure 7(g).

In principle, the precision is improved to $P/N$ with an $N$-stage latch as described above. However, $N$ cannot be increased arbitrarily. First, the mechanism is relatively long, and it must be possible to mount the fixed or moving part on a further mechanism, so the latch may be opened and closed. Second, the force provided by this mechanism must be capable of compressing the ensemble of portal springs to engage the latch. Since this becomes more difficult as the number of portals rises, $N$ is likely to be relatively small.

Latches with $N = 2$ and $N = 4$ have been incorporated into the stages previously described. The fixed racks are mounted on the latch arm, and the sprung teeth on the frame, as shown in figure 8(a). To equalize the force needed to compress the portal springs, the stiffness of an individual spring in the case when $N = 4$ was taken to be roughly half that when $N = 2$. Stages containing Vernier latches with a 10 $\mu$m rack pitch were constructed as described earlier. Figure 8(b) shows a two-section latch. The length $L_3$ of each section was 40 $P$, or 400 $\mu$m, to allow sufficient space for portal suspensions. Each portal spring was based on beams 280 $\mu$m in length and 20 $\mu$m separation. Two-section latches used beams of 5 $\mu$m width, while four-section latches used 4 $\mu$m width. From simple bending theory, the transverse stiffness (which depends on the second moment) in the latter case was $(4/5)^3$ times that in the former case, or roughly the factor of one half previously mentioned.

4.2. Performance

Two-section latches operated essentially as expected. Figures 9(a) and (b) show a latch in two adjacent states; in figure 9(a), the left-hand movable tooth is fully engaged, and in figure 9(b) the right-hand tooth is engaged. The deflection of
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Figure 9. Two-section Vernier latch, with (a) the left-hand and (b) the right-hand element engaged; (c) latch during disengagement; (d) buckling failure of a four-section latch.

the spring supporting the displaced tooth may clearly be seen. A 5 \(\mu\)m effective linear resolution is therefore achieved from a rack of 10 \(\mu\)m pitch; this result corresponds to an angular resolution of 0.13\(^\circ\). Generally it was found that the latch arm was sufficiently stiff to deform the portal springs, and the spring compressions indexed as in figure 7(e). The Vernier mechanism operated correctly over the full range of travel, even when power was removed and the latch was required to resist the tension of the frame. However, the limiters were needed to help open the latch, as shown in figure 7(f).

Figure 9(c) shows a two-section latch being opened; the moveable tooth is clearly pulled outward by the latch arm. Slight chipping of the movable teeth was observed when opening under load, and some damage may be seen in this figure.

Four-section latches operated similarly, but less effectively. In particular, it was found that weakening the portal beams to avoid increasing the force needed to close the latch has the effect of reducing their individual Euler buckling loads. As a result, the portal springs are insufficiently rigid to withstand the return tension of the frame at large travel. For example, figure 9(d) shows a four-section latch after power has been removed from the stage drive. The inner beams (which are under axial compression as well as bending) in the two left-hand portals have buckled sequentially. The first portal (which carried the tooth that was originally engaged) has buckled, allowing the second tooth to become engaged. Its supporting portal has buckled in turn, allowing the third tooth to become engaged. Clearly, more careful design of the compression members is required to avoid this effect. Because the compression is essentially generated by the return force of the frame acting through a lever whose fulcrum is the end of the tension member, all that is required to reduce it below the buckling load is to space the two beams of the portal spring sufficiently far apart.

5. Conclusions

An electrothermal actuator and ratchet latch previously developed for linear MEMS positioning stages has been adapted for angular motion. The mechanism has been modified to allow both in-plane rotation and a tilt function based on the use of an inserted component, and a manual assembly procedure has been described. Prototypes have been fabricated using deep reactive-ion etching of bonded silicon on insulator with an 85 \(\mu\)m thick bonded layer. Because of the poor thermal properties of silicon, the power consumption of the actuators is high. This aspect may be unimportant for one-time assembly. However, electrothermal operation has been simulated using finite element analysis, and it has been demonstrated that local removal of the substrate from beneath the hot arms by backside etching provides a simple method of reducing power consumption.

Resolution is limited by difficulties with pattern transfer in a deep etched structure. A new latch mechanism based on the Vernier coincidence principle has been developed. Using a latch with two and four sets of fixed racks and sequentially offset, spring-suspended teeth, the resolution has been improved. The performance improvement is essentially provided by the ability of a typical mask-making process (e.g. electron-beam writing) to allow the relative separation of
the elements in the latch to be specified with much greater precision (e.g. 0.1 μm) than the resolution offered by the pattern transfer process. Consequently, the advantages offered are essentially independent of the precise fabrication method and layer thickness. However, difficulties with multi-section latches have been identified, and it has been shown that the resolution improvement is likely to be limited by the small number of latch elements that can be arranged to operate reliably.

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