ABSTRACT

Micro-opto-electro-mechanical systems (MOEMS) typically require optical surfaces with high flatness and low roughness to be combined with high quality mechanical parts and low power, high force microactuators. In the past, attention has concentrated overwhelmingly on polysilicon surface micromachining, which allows an extremely flexible approach to the design of complex optical systems. However, polysilicon components typically suffer from poor surface flatness and high roughness, and lack the strength and rigidity to support and manipulate macroscopic optical components, which often have weights in the milligram range. Bonded silicon-on-insulator (BSOI) material provides an excellent alternative, allowing high optical quality to be combined with high mechanical strength. This paper will review a number of different approaches to BSOI MEMS, including deep reactive ion etching (for in-plane devices), double-sided processing (for through-wafer devices) and surface tension self-assembly (for 3D MOEMS). Applications ranging from variable optical attenuators to tunable laser systems will be described. Methods of mounting, aligning and fixing hybrid-integrated components will also be considered, together with appropriate high-force micro-actuators.

Keywords: MEMS, MOEMS, Deep reactive ion etching, Silicon-on insulator

1. OPTICAL MEMS

Recent years have seen enormous interest in micro-opto-electro-mechanical systems (MOEMS), especially for optical fibre telecommunications [1-3]. Because MOEMS provide a simple method of combining optical components with microactuators, there are many applications for continuously adjustable devices. These include tuneable components, such as variable attenuators, tuneable filters, tuneable lasers, cross-connect switches, scanners, dispersion compensators and variable delay lines. Despite the low operating speed of mechanical systems, MOEMS can still offer a number of advantages, including wavelength and polarization insensitivity, and scalability to large port counts based on the use of miniature free-space optics [4]. In addition, passive alignment features and active alignment devices can be used to achieve the micron-scale accuracy required to assemble single-mode systems. Table I summarises the advantages and disadvantages of MOEMS.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low loss</td>
<td>Complex manufacture</td>
</tr>
<tr>
<td>Low crosstalk</td>
<td>Vibration sensitive</td>
</tr>
<tr>
<td>Polarization insensitive</td>
<td>Temperature sensitive</td>
</tr>
<tr>
<td>Wavelength insensitive</td>
<td>Poor power handling</td>
</tr>
<tr>
<td>Compact and scalable</td>
<td>Low speed</td>
</tr>
<tr>
<td>Low holding power</td>
<td>High voltage</td>
</tr>
</tbody>
</table>

Table I. Advantages and disadvantages of MEMS approaches to optical components

Several approaches can be used for MOEMS fabrication, as shown in Figure 1. These methods include anisotropic or crystal plane etching [5], polysilicon surface micromachining [1, 6], synchrotron lithography and electroplating.
known in Germany as the LIGA process [7], and deep reactive ion etching (DRIE) of bonded silicon-on-insulator (BSOI) material [8]. Self-assembly of three-dimensional structures by out-of-plane rotation of flat parts may also be used for 3D MOEMS [9].

![Figure 1. Approaches to MEMS fabrication (after [3]).](image)

Each method has its merits, as shown in Table II. For example, polysilicon MOEMS offers extreme flexibility in design, but relatively poor mechanical and optical properties, due to the use of deposited layers that are often thin, rough and curved by intrinsic stress gradients. DRIE of BSOI is a particularly promising alternative, since it allows the use of thick layers of high-quality single crystal material, of essentially arbitrary thickness. Despite limitations on process flexibility, 3D MOEMS may also be formed in BSOI by surface tension self-assembly. This paper focuses on advances in BSOI MOEMS.

<table>
<thead>
<tr>
<th>Method</th>
<th>Flexibility</th>
<th>Precision</th>
<th>In-plane surface</th>
<th>Out-of-plane surface</th>
<th>3D structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anisotropic etching</td>
<td>Poor</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>No</td>
</tr>
<tr>
<td>Surface micromachining</td>
<td>Excellent</td>
<td>Moderate</td>
<td>Excellent</td>
<td>Moderate</td>
<td>Shallow</td>
</tr>
<tr>
<td>LIGA</td>
<td>Moderate</td>
<td>Excellent</td>
<td>Rough</td>
<td>Excellent</td>
<td>No</td>
</tr>
<tr>
<td>DRIE of BSOI</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Excellent</td>
<td>Moderate</td>
<td>No</td>
</tr>
<tr>
<td>Self-assembly</td>
<td>Moderate</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table II. Relative advantages of different approaches to MOEMS fabrication.

2. DEEP REACTIVE ION ETCHING OF BONDED SILICON-ON-INSULATOR

Deep reactive ion etching is a method of near-vertical etching of silicon in a high density, fluorine-based plasma. Two methods are in common use. The first is based on the cyclic etch-passivate process originally developed by Robert Bosch GmbH [10]. In the etch step, SF₆ is used to remove silicon. Although the etching is actually isotropic, lateral erosion is prevented by deposition of a polymer (CₓFᵧ) in the passivation step. To re-initiate
etching, fluorine radicals first etch the base of the passivation, and then the silicon itself. High etch rates (4 \(\mu m/min\)) and depths of > 500 \(\mu m\) may be achieved, with wall angles of > 89°. Masking is usually performed using thick layers of photoresist or silicon dioxide, and mask selectivities of > 60 are routinely obtained. However, the result of mask erosion is that there are difficulties in transferring convex features to large structural depths. Because of the high selectivity to oxide, a buried oxide layer can act as an etch-stop; however stop-on-oxide processing requires the use of a dual frequency plasma source to avoid lateral etching [11, 12]. A number of equipment manufacturers have licensed the Bosch process, including the UK companies Surface Technology Systems (STS) and Oxford Instruments. Figure 2a shows the STS Single Chamber Multiplex inductively coupled plasma (ICP) etcher installation at Imperial College. The alternative cryogenic process offered by Alcatel achieves high wall verticality by careful control of the substrate temperature [13, 14]. Characteristic features of all DRIE processes are lag effects, which result in a reduced etching rate between closely spaced, high-aspect ratio structures [15]. As a result, these features may not bottom at the same time as more widely separated features. Loading effects, in which the average etching rate is affected by the exposed area of silicon, may also be significant. Careful design is therefore required to optimise the etching. A further feature of the cyclic DRIE process is the creation of small sidewall ‘scallops’, with a typical periodicity of 0.25 \(\mu m\).

Figure 2. a) STS DRIE Installation at Imperial College, b) comb electrostatic actuator, and c) electrothermal actuator.

Bonded silicon-on-insulator (BSOI) is a multilayer material obtained by fusing a thermally oxidised silicon wafer to another silicon wafer, which is subsequently polished back to the desired thickness [16]. The fabrication process is effectively the opposite of the SIMOX (Separation by IMplantation of OXygen) process, which uses an additional epitaxy step to regrow a single-crystal silicon layer above an implanted oxygen layer [17]. Both the oxide layer and the device layer may be much thicker in a BSOI wafer than in a SIMOX wafer, simplifying later processing and improving mechanical properties. Repetition of the oxidation, fusing and polishing steps allows the construction of multi-layer substrates [18]. After fabrication of a set of mechanical parts by deep reactive ion etching, the oxide layer may be isotropically etched using buffered HF, to free any suspended parts for motion [19]. Freeze-drying or supercritical drying may then be used to remove residual wash water without surface tension collapse [20]; however, stiction effects are much less significant in BSOI MEMS than in polysilicon MEMS, due to the larger structural thickness. Higher yields are generally obtained from dry processing. Dry process options include vapour-phase etching of the oxide layer [21], xenon difluoride etching of the silicon substrate beneath the device layer [22], and deep reactive ion etching of the substrate beneath the device.

3. BONDED SILICON MOEMS

DRIE of BSOI allows optical components and elastic supports to be combined very simply with electrostatic or electro-thermal actuation, without the need for additional functional materials. In each case, one limit to operating speed is set by the mechanical time constant of what is normally a mass-spring system. Electrostatic actuators have the advantage of not requiring a holding power; however, high (> 200 V) may be required for parallel plate operation with large electrode gaps. Parallel plate and comb electrodes may be used. The former type are simple to fabricate but complex to control, since they suffer from a pull-in instability [23]. The latter type are more stable.
[24], but are more complex to fabricate as deep structures, since they require the formation of closely-spaced interdigitated electrodes. Figure 2b shows a set of comb electrodes designed for in-plane motion and fabricated in BSOI by ICP DRIE of a 100 µm thick device layer. Out-of-plane actuators based on vertically staggered comb electrodes have also been developed [25].

Electrothermal actuators consume power continually, and have an additional limit to operating speed set by a thermal time constant; however, they typically require low drive voltages and allow larger actuation forces to be developed from a smaller, lighter structure. Material bimorphs, which operate by differential thermal expansion in a bilayered cantilever, may be used to achieve both out-of-plane [26] and in-plane [27] motion. Shape bimorphs, which operate by differential expansion between parts of different length or cross-section, may be used to achieve in-plane motion [28]. An alternative is offered by buckling mode actuators, which operate by differential thermal expansion between suspended beams and the substrate [29-31]. Figure 2c shows a four-beam buckling actuator formed by ICP DRIE of BSOI with a 100 µm thick device layer. Increasingly, actuators are being designed for bistable rather than analogue operation [32].

BSOI MOEMS have been developed in several formats, depending on the direction of the optical beam with respect to the substrate. The most common variants are shown in Figure 3. In Figure 3a, the beam travels parallel to the substrate and its propagation is controlled by optical components formed from the etched surfaces themselves. This configuration is most suitable for short optical paths, because it only allows beams with small diameters, which diffract quickly. Systems of this type may be fabricated simply by etching and undercutting the device layer. However, control of the optical quality of the etched surface is extremely important. In Figure 3b, the beam travels approximately normal to the substrate, and is acted on by components formed in the device layer surface. This configuration allows much larger beam diameters, and places few constraints on the quality of the etched surfaces. However, it may require removal of the substrate, to allow the beam to pass through, or to allow motion of a component formed in the device layer. An additional substrate carrying electrodes may also be required for actuation. In Figure 3c, the beam travels parallel to the substrate again, but is now acted by optical components formed in the surface of the device layer, which are rotated out-of-plane and fixed in position. In the following sections, we describe progress with each device format, and also give examples of newly developed optical alignment systems.

**Figure 3.** BSOI MOEMS formats: a) in plane, b) through wafer, and c) three-dimensional.

### 4. IN-PLANE COMPONENTS

DRIE was first used in MOEMS to fabricate vertically etched mirrors for use in in-plane optical systems [33, 34]. Shortly after, mirrors and shutters were combined with in-plane mechanisms and sprung fibre alignment features to form 2 x 2 [35] and 4 x 4 [36] optical switches, based on the insertion of small 45° mirrors into the crossing nodes of orthogonal optical paths. Actuation was originally based on analogue electrostatic drives, but bistable switches based on pre-buckled beams have now been developed [37]. Variable optical attenuators (VOAs) based on the partial insertion of an etched shutter into a short propagation path established between two co-linear optical fibres have also been developed [38]. Recent developments include the use of a silicon optical leaker to prevent back-reflection [39], and the use of the alternative principle of image translation by a movable mirror to improve the polarization and wavelength dependence of loss [40]. Elastic [41] and rack-and-tooth [42] clamps have also been developed, so that the attenuation may be maintained even after removal of power. For example, Figure 4a shows the schematic
of a latching VOA, which uses one shape bimorph electrothermal actuator to control the position of a small shutter, and a second actuator to operate a rack-and-tooth latch. The rack has a precision of 10 µm, which is limited by the difficulty in transferring a toothed pattern to large structural depth. A mechanical lever is therefore used to increase the precision by a factor of ten, to allow a suitable set of attenuation states to be achieved even with the small (8 µm MFD) beam obtained from a single mode fibre. Figure 4b shows a detail of the shutter and fibre alignment springs.

Other in-plane MOEMS include tuneable lasers. The most successful external cavity laser to date - the Iolon ApolloTM laser - used a hybrid-integrated mirror mounted on a deep etched electrostatically-drive rotation stage and arranged in a Littman configuration with a fixed grating [43]. More recently, vertical etching has been used to fabricate high-order blazed gratings directly [44], as shown in Figure 5a. These gratings have reasonable optical characteristics, but improvements to overall reflectivity and resolution are required to obtain competitive performance when used in lasers. Figure 5b shows the bandpass characteristic obtained from an 85 µm high, 12th order blazed grating, which has a peak reflectivity of –6 dB.

Despite these restrictions, deep-etched gratings have been combined with elastic suspensions in both the Littrow [45–47] and the Littman [48] configurations. For example, Figure 6a shows the layout of an electrostatically driven tuning actuator for a Littrow external cavity laser [46]. The grating is mounted on a compound flexure, consisting of a cantilever in series with a portal frame, allowing the linear and angular positions of the grating to be adjusted independently, for cavity initialisation and synchronous tuning, respectively. Figure 6b shows a detail of the
completed device, which uses two separate comb-drives for actuation. Single-mode output powers up to 500 µW have been obtained from fixed gratings [44]. Peak fibre-coupled powers of 100 µW have been obtained from tunable gratings, with a side-mode suppression ratio (SMSR) of > 20 dB, and electrostatic tuning over a range of 20 nm using a 50 V drive has been demonstrated. The main limitation on performance is the difficulty in increasing the height of a deep-etched structure combining a fine-period, blazed grating and comb-electrodes. This difficulty is exacerbated in the Littman configuration, which requires a longer optical path with multiple passes through an etched mirror and an etched grating. As a result, lower powers have been obtained from such devices [48].

![Image](image1.png)

Figure 6. Tuning element for a Littrow external cavity laser: a) layout and b) etched structure (after [46]).

5. OUT-OF-PLANE COMPONENTS

Out-of-plane components include variable attenuators acting on beams travelling perpendicular to the substrate. Single- [49] and twin-blade [50] devices have been constructed, together with multiple-blade irises [51], which have the potential for reduced polarization dependence. Figure 7 shows a 4-blade iris, which uses the synchronous motion of four triangular elements driven by buckling mode electrothermal actuators powered by a common electrical source (Figure 7a) and sliding together to create a variable square aperture (Figure 7b).

![Image](image2.png)

Figure 7. Iris variable attenuator: a) layout and b) device at maximum displacement (after [51]).

Alternative out-of-plane devices include Fabry-Perot filters, designed for use as channel monitors [52] and as tunable reflectors in Fabry-Perot external cavity lasers [53]. However, the majority of through-wafer devices are torsion mirror switches, originally developed from resonant mirror scanners [54, 55]. Arrays of two-axis tilt mirrors have been used in optical cross-connects with large port counts [56, 57]. Improved optical performance has
been obtained by replacing polysilicon mirrors with single crystal optical surfaces [58]. Problems of electrical drift and mechanical shock resistance have been overcome [59], and improved electromechanical performance has been obtained by replacing parallel plate electrostatic drives [23] firstly with terraced electrodes [60] and secondly with staggered comb electrodes [61-63].

6. SELF-ASSEMBLED 3D COMPONENTS

3D polysilicon MOEMS have been formed by out-of-plane rotation of flat parts mounted on micromachined hinges [64]. Assembly has either been manual or powered by a micro-engine such as a vibromotor [65] or scratch drive [66]. Buckling has also been used as a method of out-of-plane actuation [67]. Surface tension self-assembly is an alternative, in which mass-parallel rotation is powered by compact pads of meltable material. No hinge is required, and the method has been used to construct MOEMS using photoresist [68] and solder as the meltable material [69]. The fixed and movable parts are formed in the bonded layer, and linked by the meltable pad. The parts are undercut, and the pad is melted to activate the assembly sequence. Components demonstrated to date include scanners [70, 71], lens arrays [72] and corner cube reflectors [73]. For example, Figure 8a shows a torsion mirror scanner formed by the simultaneous self-assembly of two parts to form a triangular structure [70]. One part mounts a torsion mirror, actuated by a skewed electrostatic comb drive at its base. Staggered electrostatic comb drives have also been formed by self-assembly [74, 75]. Assembly angles are defined by a mechanical limiter, and are accurate to a few minutes of arc. Figure 8b shows a micro-lens array, formed by sequential assembly of three parts. Two parts first assemble to form a triangular structure, with a link bar at its apex. The third part rotates until motion is prevented by the link-bar. The upright part carries a set of refractive lenses formed by reflow of cylindrical pads of resist.

Figure 8. a) Torsion mirror and b) lens array formed by surface tension self-assembly (after [70] and [72]).

7. COMPONENTS FOR OPTICAL ALIGNMENT

Because of its relative robustness, BSOI is increasingly being used to construct alignment systems for hybrid integrated micro-optical components. Fibre-based devices include switches [76, 77], and alignment devices [78], which have been demonstrated with optical feedback [79]. A key requirement is for a high force actuator capable of deflecting a short cantilevered section of optical fibre. For example, Figure 9a shows a high-power electrothermal actuator for in-plane motion. The actuator is a folded, multiple-beam buckling mode device, which can be scaled easily to increase its stiffness [80]. The fibre is mounted in spring alignment features, and lateral motions of up to 15 µm have been achieved from devices with a cantilever length of 4 mm and a total length of 8 mm, albeit with high drive powers (7 W). This performance has sufficed to allow the device to be used in an in-line VOA operating entirely by fibre motion.
Mechanisms for aligning and fixing trains of micro-optical components such as lenses and multilayer dielectric filters during opto-hybrid assembly operations are now being developed. The mechanisms must be strong enough to support the weight of macroscopic components, which typically lie in the milligram range, so that high-aspect ratio structures are required. At present, only a restricted set of motions has been demonstrated, and further development is required to achieve true multi-axis alignment. The simplest mechanisms are manually driven [81] and electrically driven [82] latching translation stages. These methods are now being generalised to rotation stages and tilt stages [83]. Some of these exploit the possibility of forming plug-connected systems by deep reactive ion etching of additional parts in bonded silicon on insulator. For example, Figure 10 shows a latching tilt stage based on a tilt mirror. The mirror itself is fabricated as a separate component, which consists of a small reflector mounted on a torsion bar attached to a frame. The component is plug-assembled into a spring fixture on an in-plane latching translation stage. Motion of the mirror is achieved by actuating the stage with a buckling mode electrothermal drive, so that tangential motion of a drive pin attached to the mirror results in rotation. Latching is achieved using a pair of rack-and-tooth clamps operated by shape bimorph actuators. Stable latching has been demonstrated, and precision is being improved beyond the limit of pattern transfer using latches operating on the Vernier principle.

8. CONCLUSIONS

Deep reactive etching of bonded silicon-on-insulator is an extremely promising method of constructing micro-opto-electromechanical systems, since it allows high aspect ratio structures with high mechanical and optical quality to be co-integrated in a simple and flexible manner. In addition, the resulting structures are strong enough to support
and align hybrid integrated macroscopic optical components. A wide range of devices has now been demonstrated, and it is expected that improvements in performance and increases in the number of applications will continue.

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