Optical MEMS for telecoms

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Microelectromechanical systems (MEMS) are of increasing importance in optical systems, particularly for telecommunications applications. This paper presents a review of materials, fabrication technologies, and applications in two key areas: optoelectronic packaging and functional optical devices. In packages, the advantage of MEMS are their ability to provide accurate passive alignment features or optical surfaces at low cost. In devices, the attraction is the possibility of combining mechanical, electrical, and optical features in movable components that switch, attenuate, or filter light. These free-space components can, in many cases, out-perform their counterparts in bulk or guided wave optical formats.

Components fabricated using the new discipline of MEMS are finding an increasing number of applications in sensors, devices, and actuators[1,2]. MEMS are being applied to a wide range of systems. Progress is dramatic, especially in optical telecommunications[3]. These applications may be divided roughly into two classes: i) those requiring precise features for optical alignment, and ii) those involving the small moving optical parts necessary for more advanced functionality.

In i) the advantage of using a MEMS approach is that extremely accurate, low-loss, optical connections may be made between different guided wave optical components, for example, fibers, waveguides, and lasers. These connections are made from well-characterized materials and are highly reliable with intrinsically low cost. Furthermore, the costs increase less than linearly with the number of connections, allowing the construction of complex interconnects.

In ii) the advantage is that optical components may be combined with mechanisms to allow motion and electrical structures to provide actuation. Such devices are generically known as microoptoelectromechanical systems (MOEMS). Because MOEMS components typically process light in small, free-space optical beams, their performance scaling laws[4] are often different from bulk and guided wave optical systems. In many applications, therefore, they can out perform these older technologies.

The purpose of this paper is to survey both areas with emphasis on the outstanding challenges for materials scientists and engineers.

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MEMS technologies

We begin with a short review of available micromachining processes, concentrating on those most appropriate for silicon-based MOEMS, the dominant materials system. Fig. 1 illustrates the main process variants.

The first process to be established, Si bulk micromachining, exploits the large difference in wet chemical etch rates between the (111) and other crystallographic planes in Si[5,6]. The substrate is first masked with an etch-resistant surface layer such as thermally grown SiO_2 or deposited Si_3N_4, as shown in Row 1 of Fig. 1. The Si is then etched. Since the (111) planes etch the slowest, V-shaped grooves are formed by etching (100) oriented substrates to termination. These features can be used for the precise positioning of optic fibers. Other planar structures may be used as reflectors[7,8]. Although the features may be hundreds of microns deep, the range of possible shapes is restricted. Encapsulated structures may be made by fusion bonding of glass to bulk micromachined wafers, and multilayer structures built up by bonding several wafers together[9]. Suspended structures can also be made, by undercutting etch-resistant features.

The next process to be developed, polysilicon surface micromachining, exploits differences between deposited polysilicon and silica layers to form three-dimensional features as seen in Fig. 1, Row 2. The process is adapted from conventional Si integrated circuit (IC) technology, together with a chemical vapor deposited (CVD) polysilicon mechanical layer typically 2 μm thick[10]. The underlying silica sacrificial layer is later wet etched away to produce a free standing polysilicon MEMS layer. The polysilicon layer can be incorporated into a wide variety of sensors and actuators, including electrostatic drives[1]. By careful control of the CVD process conditions, the stress in the polysilicon can be made reproducibly low. However, the thickness of the deposited layers is limited to a few microns, and the mechanical and electrical properties of the polysilicon are inferior to those of single crystal Si. The cycle of deposition, patterning, and etching of each material can be repeated several times to build up multilayer structures, and feature shapes can be arbitrary[1]. A number of foundries operating a semi-standard process with two to five levels of polysilicon exist[11,12].

Frequently, it is necessary to fabricate structures thicker than those achievable using polysilicon. An alternative surface micromachining process uses lithographic exposure of thick photoresist, followed by electroplating, to build up the

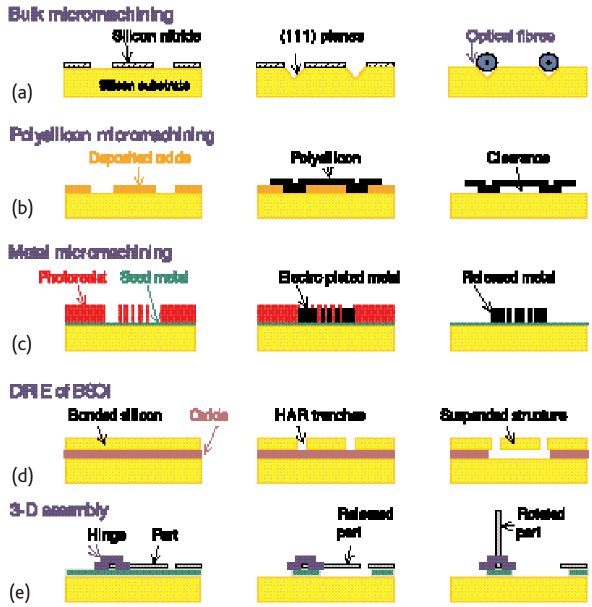

Fig. 1 Fabrication processes for optical MEMS: a) bulk micromachining, b) polysilicon micromachining, c) metal micromachining, d) DRIE of BSOI, and e) three-dimensional assembly.

mechanical parts (Fig. 1, Row 3). Originally developed in Germany, the Lithographie, Galvanoformung, Abformung (LIGA) process uses synchrotron radiation to expose the resist. The extremely short X-ray wavelength allows very deep (up to 1 mm) resist layers to be exposed without significant diffraction effects, so that very high aspect ratio structures can be made[13]. The released metal layer can be used in a wide variety of MEMS applications including optical components[14] and packaging. Cheaper alternatives use excimer lasers or UV mask aligners as exposure sources; these can achieve feature heights of around 200 μm and 20 μm, respectively. Parts are usually electroplated in Ni; after removal of the resist, these can be replicated in other materials. Only low temperatures are needed, so LIGA and its derivatives can be used as post processes to add microstructures to CMOS.

A more recent process for forming suspended single crystal Si structures uses bonded silicon-on-insulator (BSOI) as the starting material, which is available as a by-product of the Si IC industry. As shown in Fig. 1, Row 4, the start material is a Si wafer thermally bonded to an oxidized Si substrate[15]. The bonded wafer is polished back to the desired thickness, usually 5-200 μm. The bonded layer is then structured by deep reactive ion etching (DRIE)[16]. The process uses an

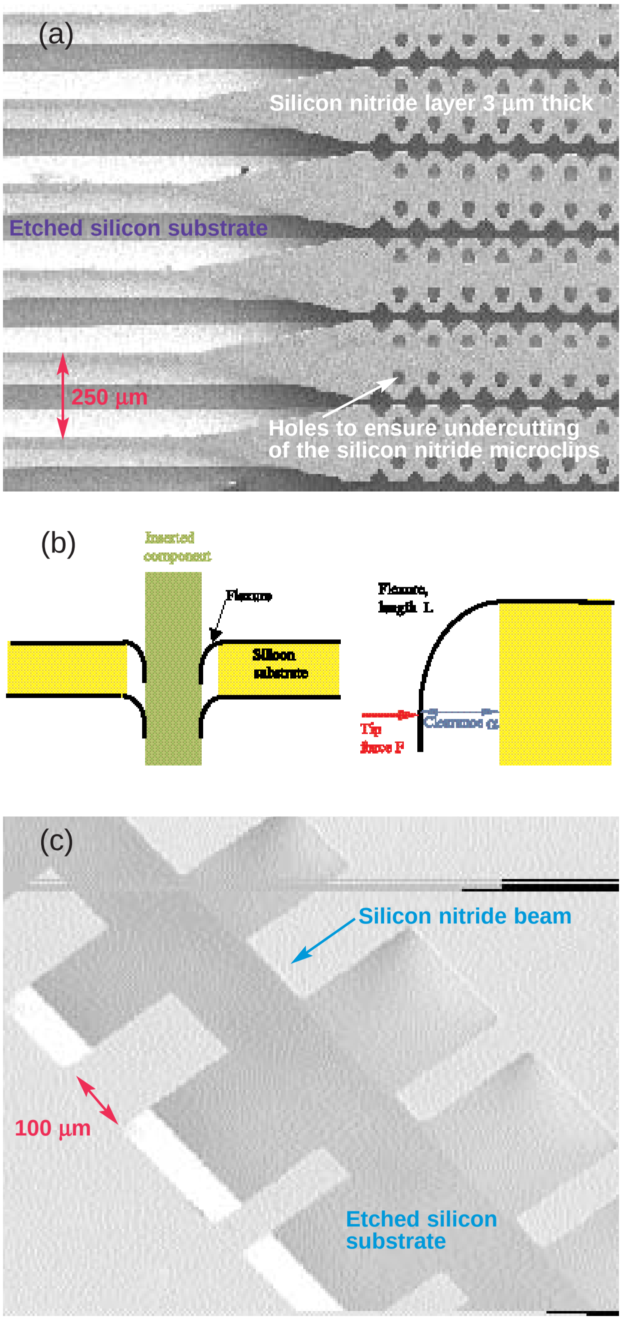

Fig. 2 Elastic component fixtures: a) Si_3N_4 clips for de-mountable fiber attachment; b) schematic of component fixture; c) component fixture in Si_3N_4.

inductively coupled plasma (ICP) etcher and specific etch gas chemistry to obtain very high etch rates and anisotropy. As with the processes described earlier, movable structures may be made by removal of the buried oxide. There are many applications, including vertical mirrors for optical switching[17]. All of the above processes involve surface patterning, so that the resulting structures are only quasi three-dimensional. Fully three-dimensional microstructures may be made in both polysilicon and BSOI by rotating surface micromachined parts out of the plane of the wafer, and latching them into position, as sketched in Fig. 1 Row 5. The parts are linked to the substrate by micromachined staple hinges[18,19]. In many cases, assembly has been manual or by a surface micromachined engine, but mass-parallel powered assembly has been demonstrated by differential shrinkage of a polymer and surface tension forces[20,21]. Potential applications include components for free-space MOEMS.

For all of the above, appropriate computer aided design (CAD) tools now exist[22]. Some CAD packages are directed explicitly at MOEMS, allowing layout, process simulation, and assembly to be linked to a final optical simulation[23].

MEMS-based optical packaging

We now consider applications, starting with optical packaging. It has long been known that precise passive alignment features suitable for low-loss connections between single-mode optical fibers[24] can be made by anisotropically etching single crystal Si[5]. As was shown in Fig. 1, etching of (100) oriented Si through rectangular mask openings can be used to make V-shaped grooves. These can act as kinematic mounts for an optic fiber. For example, V-grooves can be used directly as mechanical fiber splices. Two fibers can be aligned together by placing them both in a groove. This step eliminates all the degrees of freedom except axial motion. The fibers may then be butt-coupled, and the assembly may then be epoxied. Alternatively, the fibers may be held in the grooves by flexible Si or Si_3N_4 cantilevers[25,26]. Fig. 2a is a plan view electron micrograph showing V-grooves with U-shaped entry porches, prior to optic fibers being inserted from the left side of the figure.

Demountable connectors for ribbon optical fibers (which require the simultaneous connection of many cores) can also use etched Si substrates[27]. The two ribbon fiber ends are mounted on etched Si base-plates, so that each fiber is accurately fixed in a V-groove. On the male half of the connector, two large grooves are used to locate a pair of precision steel pins, which mate with corresponding grooves on the female half. The joint is made by first aligning the pins and then sliding the connector halves together.

Table I *Advantages of silica-on-silicon integrated optics.*

- Fabrication cheap, compatible with Si microelectronics
- Connection to single mode (SM) optical fibers cheap and low loss
- Wide range of low-loss passives, on large substrates
- Slow speed switches based on the thermo-optic effect
- Hybrid integration used to add optical sources
- Active components erbium-doped waveguide ammplifiers (EDWAs) currently being developed

V-grooves can also be used to construct simple subsystems known as opto-hybrids. For example, a single V-groove can be used to connect an optical fiber with a photodiode[28]. The diode is flip-chip bonded to the Si chip, and light is transferred from the fiber to the detector by reflection from the metallized end of the groove. More advanced systems with detectors, lasers, and high speed interconnects can act as transmitters, as shown in Fig. 3[29,30].

Precision mechanical components are also used to connect different types of waveguide. Particular attention has been given to the connection of fiber and silica-on-silicon integrated optical components[31,32]. Silica-on-silicon has several major advantages over the earlier technologies such as ion-exchanged glass, $LiNbO_3$, GaAlAs, and InGaAsP. These are summarized in Table I. Because of this, silica-on-silicon components are likely to find widespread application in low-cost systems such as fiber-to-the-home. A typical device consists of a single crystal Si substrate, carrying fiber alignment grooves, a thick buffer layer of silica to isolate the guided mode from the substrate, channel guide cores formed from doped silica, and a thick over-cladding to bury the cores. When combined with MEMS fabrication, devices with high port counts (e.g. 64-channel arrayed waveguide multiplexing filters or star components up to 256 x 256) may be built.

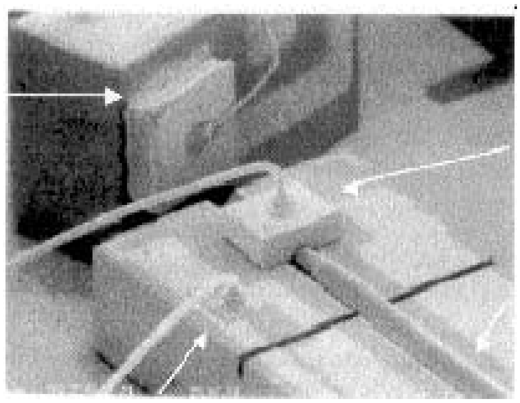

Fig. 3: Si opto-hybrid, showing passive optical alignment from laser to single mode fiber to better than 1 μm accuracy. (Courtesy Nortel Networks.)

Silica-on-silicon is also being used as a platform for the hybrid integration of optical subsystems containing components such as lasers and detectors that cannot be fabricated in the glass itself. Buried Si terraces or other precision features are used to locate the components accurately in the vertical plane, and mesas are etched into the glass to provide lateral location[33]. For example, a hybrid-integrated 1.3/1.5 μm transceiver based on a terraced silica-on-silicon platform is now available commercially. The chip contains waveguide circuitry, an embedded dielectric filter for demultiplexing, a photodiode receiver, and a laser diode source with its own monitor photodiode[34].

Many new assembly techniques are under development. One example geometry is shown in Fig. 2b, which is the

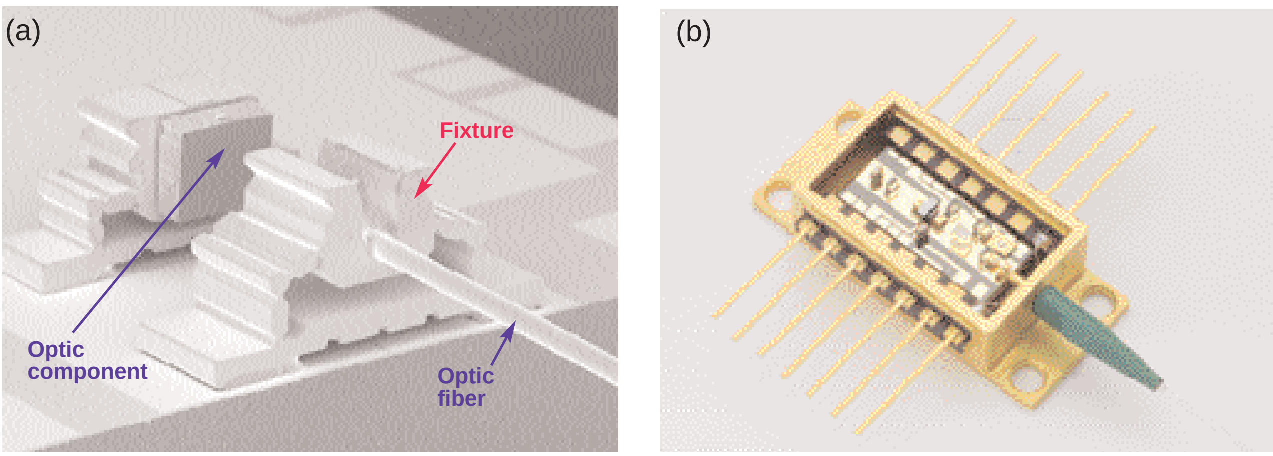

Fig. 4 Hybrid integration: a) LIGA flexure and b) MEMS channel monitor constructed as a free-space optical breadboard. (Courtesy Axsun Technologies, www.axsun.com.)

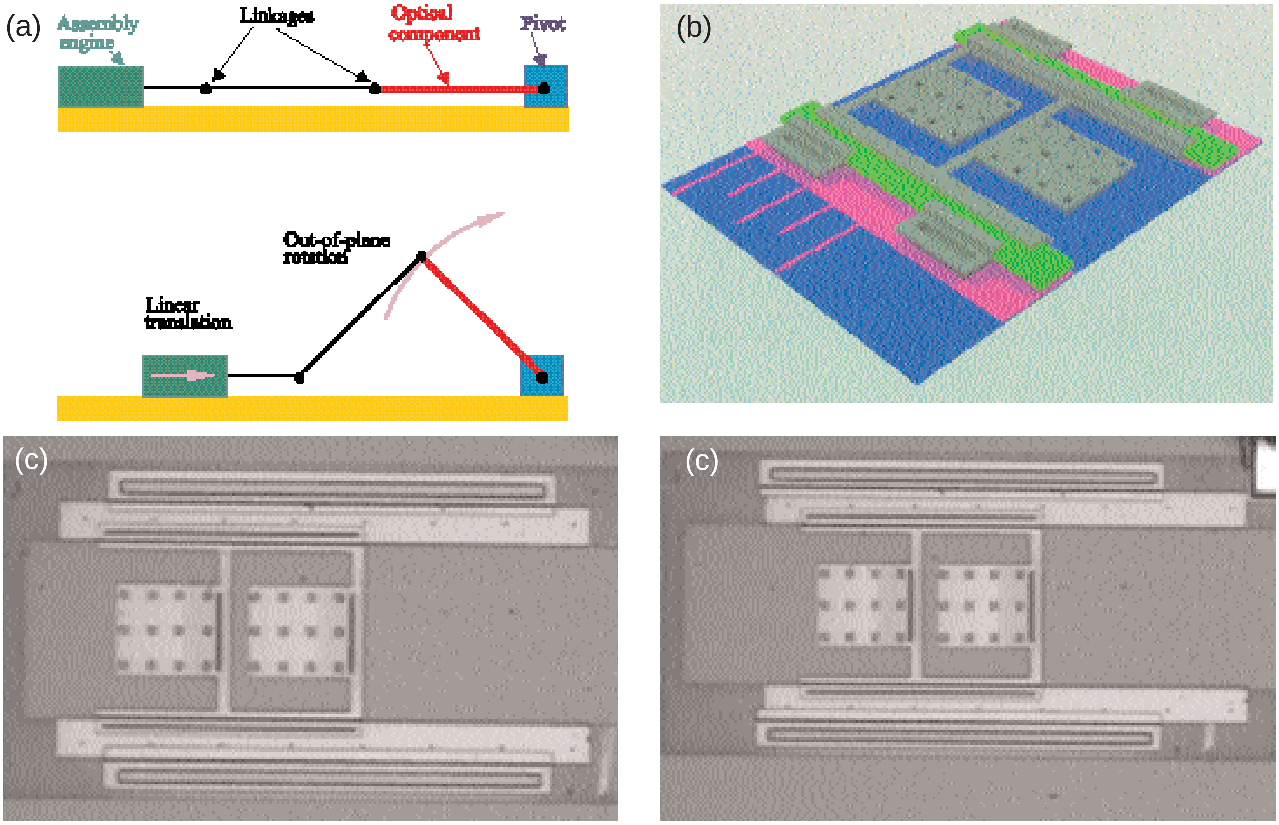

Fig. 5 Active assembly of three-dimensional micro-optics: a) mechanism; b) two-section scratch drive actuator; and c) SDA moving along a track. (Courtesy D. Uttamchandani.)

cross-section of a substrate that carries elastic flexures on both sides to secure an inserted component in position[35]. In this arrangement, where the flexure length, L, is much greater than the clearance, α, the force, F, acts at the point of initial contact. This proposed configuration has the advantage that the precision with which the optical component can be located is determined mainly by the lithography and etching technology used to pattern the deposited thin film flexures. In contrast to V-groove technology, the precise geometry of the etched substrate is of secondary importance.

A possible candidate for the microclip material is Si_3N_4. A micrograph of CVD Si_3N_4 beams 3 μm thick is shown in Fig. 2c, where the Si substrate has been wet etched to form a V-groove. SiC is another possible material, which has the required large Young's modulus as well as low stress and process compatibility[36-38]. Preliminary experiments on 5 μm thick CVD SiC films and etched Si substrates indicate that the material is suitable[35]. In the longer term, active flexures would also allow for the adjustment of inserted components.

An alternative method of alignment exploits the ability of the LIGA process to construct complex, robust components such as multi-axis flexures in Ni. A number of such flexures may be soldered to a breadboard and used to provide individual mounts for a set of components in an optical component train. This approach has been pioneered by Axsun Technologies, using LIGA processes licensed from Sandia National Laboratories[39]. For example, Fig. 4a shows an X-Y flexure for an optical fiber and collimating lens. After assembly, the optical throughput is optimized by adjusting the position of each component in turn, using plastic deformation of the flexure by an assembly robot. Fig. 4b shows a complete optical system assembled in this way, a channel monitor based on a MEMS tunable Fabry-Perot filter.

Optical breadboards are also being constructed in a different fashion, using components that are fabricated flat by surface micromachining (as shown in Fig. 1) and then rotated out-of plane to manipulate small, free-space beams traveling parallel to the surface of the chip[40,41].

Demonstrated components include fixed and movable mirrors, lenses, and gratings[42,43]. Many of these structures are hand-assembled using precision micromanipulators. Other systems have been assembled using surface-micromachined engines to push hinged devices out of the wafer plane, as shown in Fig. 5a[44,45]. Fig. 5b is a schematic of a typical assembly engine, a scratch-drive actuator. Under the control of a square-wave actuation voltage, this device acts as a highly controllable linear translator, allowing dynamic component positioning.

Fully automatic techniques are also being developed for assembly of three-dimensional MOEMS. One process based on surface tension simply requires the melting of small pads of material to rotate parts out-of-plane, as shown in Fig. 6a. This method is extremely accurate, allowing angular positions to be set to minutes of arc[21]. Demonstrated devices include fixed and movable mirrors, and lenses[46-48]. Fig. 6b shows a completed microlens array. Surface tension has been used to position and fix all the parts of the bonded Si support frame. The lenses were themselves formed simultaneously by reflow molding of photoresist, another method involving surface tension, which gives accurately spherical optical surfaces[49,50].

Functional optical devices

We now consider applications for MOEMS in functional devices. The rapid adoption of such a new technology in telecommunications has been inspired by the existence of a successful device in a different field: the Texas Instruments Digital Micromirror Device™ (DMD)[51]. The DMD consists of a large array of torsion mirrors, which rotate to-and-fro against a system of end-stops, to reject or accept individual pixels from the image in a projection TV display. The demonstration that such a complex device with about one million 16 x 16 µm mirrors could be manufactured reliably has done much to accelerate the acceptance of MOEMS.

Another major driver has been the demonstration that MOEMS can out perform their counterparts in bulk optical and guided wave form. Table II summarizes the key points. Compared with bulk optics, the advantages are small size, low cost, and the ease with which large-scale systems may be constructed by integration. Compared with guided wave devices (which are often interferometric), the advantages are low loss, low cross-talk, insensitivity to variations in process or operating conditions, and scalability. These advantages can outweigh obvious disadvantages, such as the relatively slow speed of a mechanical switching or tuning structure.

Table II *Advantages and disadvantages of MOEMS switching devices.*

Advantages	Disadvantages
Low loss	Complex manufacture
Low cross-talk	Vibration sensitive (if non-latching)
Polarization insensitive	Temperature sensitive
Wavelength sensitive	Poor power handling
Compact and scalable	Low speed
Low holding power	High voltage (if electrostatic)

MOEMS devices have been used as switches, attenuators, filters, multiplexers, and tunable sources. Most have been constructed either in polysilicon or in single crystal Si using BSOI, although III-V MOEMS are now being developed. The advantages of polysilicon surface micromachining are the existence of foundry-standard processes and the ease with which complex multilayer devices may be constructed. The advantages of BSOI are often improvements in structural thickness (and hence the flatness of released surfaces) and low surface roughness. The optimum choice of process is usually application-dependent.

We begin by considering switches. For example, electrostatic deflection of a waveguide can act as the basis of

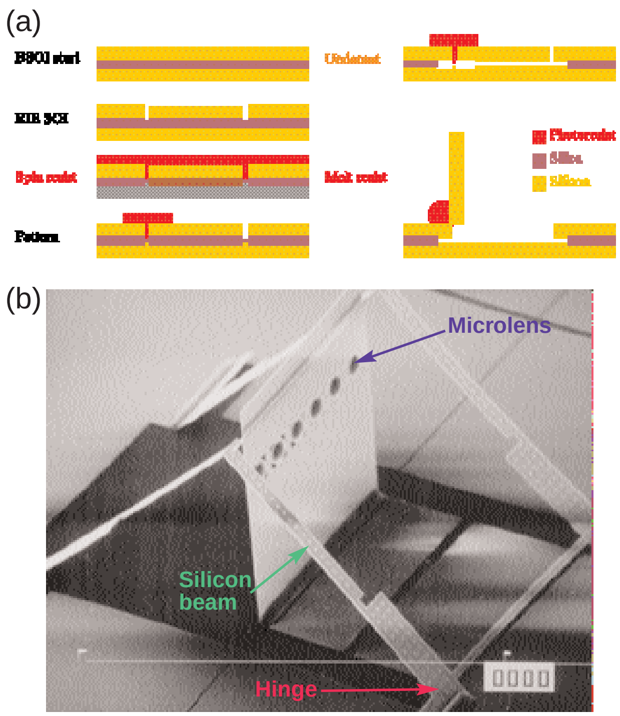

Fig. 6 Surface tension self-assembly: a) process and b) completed microlens array.

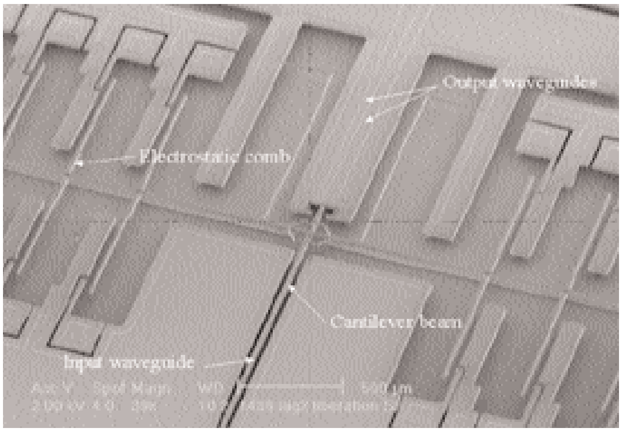

Fig. 7 MOEMS switch based on a movable optical waveguide, for optical network reconfiguration and protection. (Courtesy CEA-LETI.)

an integrated optical switch[52-54]. Mechanical actuation has the advantage of allowing switches to be made in an amorphous material that (for example) does not have an electro-optic effect. Fig. 7 shows a 1 x 2 silica-on-silicon moving waveguide switch developed by CEA-LETI. The input channel guide is fabricated on a cantilever suspended over an etched cavity. Surface electrodes deflect the cantilever from side-to-side electrostatically to allow connection to one of the two output waveguides. An additional lateral suspension minimizes out-of-plane deflections. Switching times are of the order of milliseconds, which although low compared with the data rate, is sufficient for network reconfiguration and comparable to a thermo-optic switch. Similar methods are being used to fabricate switches that operate by the direct deflection of an optical fiber[55,56].

Other switches are based on the insertion of small mirrors into the nodes of a classical cross-point geometry, as shown in Fig. 8a. Suitable devices can be fabricated by DRIE of Si. DRIE can simultaneously form vertical mirrors, fiber alignment grooves, and a simple electrostatic drive to remove or insert the mirrors into the regions where the optical axes intersect (Fig. 8b)[57]. Switching times are again of the order of milliseconds, and optical isolation is excellent. However, the devices are only scalable to small-size switch arrays.

Dynamically assembled three-dimensional MOEMS are being used to construct larger mirror insertion cross-connects known as 'mirror farms'. The mirrors pivot into position by rotating a torsional elastic suspension or hinge[58-61]. Fig. 8c shows a commercially available switch fabricated in BSOI by Onix Microsystems, which uses an 8 x 8 array of small

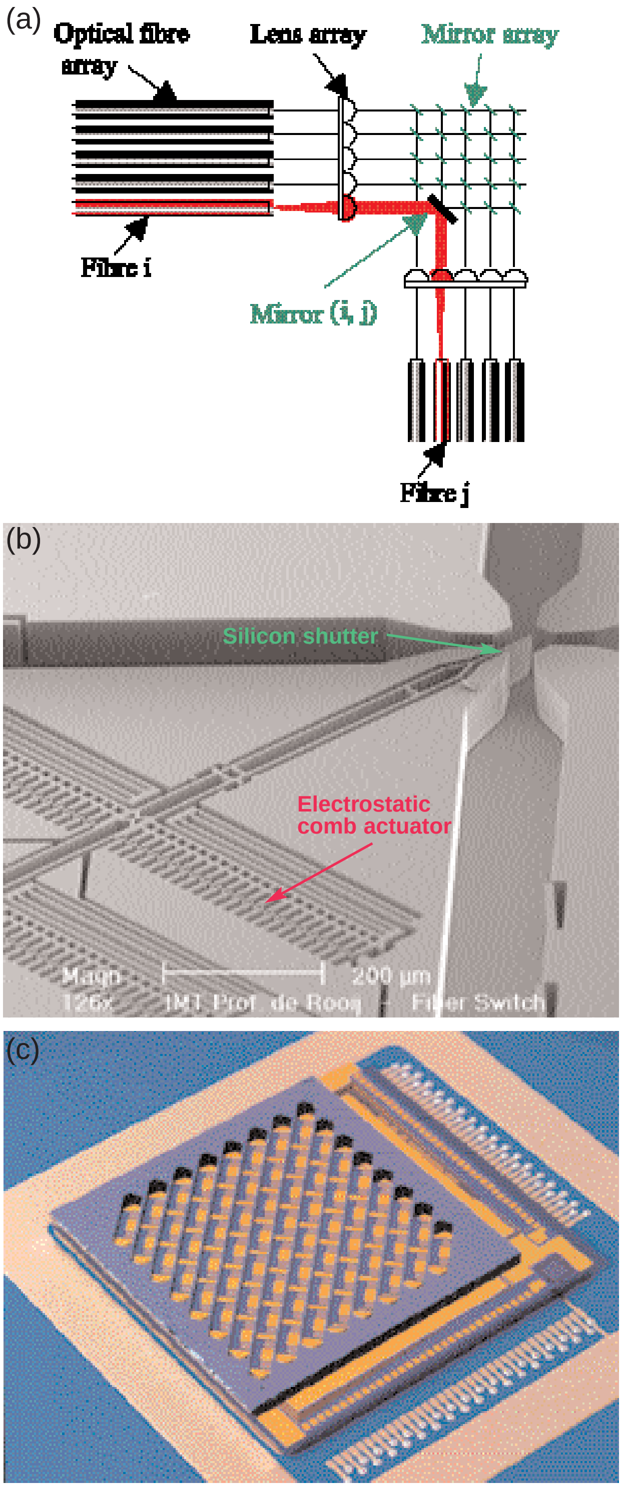

Fig. 8 Mirror insertion switch array: a) schematic; b) linear translation mirror switch fabricated by DRIE (courtesy Sercalo Microtechnology, www.sercalo.com); and c) 8 x 8 surface micromachined pop-up mirror switch (courtesy Onix Microsystems, www.onixmicrosystems.com).

mirrors to form a 64-node cross-point. The mirrors are driven between two *latchable* states (parallel and orthogonal to the substrate, respectively) by a low-voltage electromagnetic drive. Switches of this type are now well developed and reliable, despite their apparent mechanical complexity.

Two-dimensional mirror farms can suffer from increasing diffraction losses as the size of the array is increased. To achieve a very large port count (e.g. 1000 x 1000), alternative mirror plane switches are now being developed by several organizations, including Lucent Technologies[62] and Nortel. Instead of using deflection between a set of single-axis mirrors, whose positions are effectively binary, these devices operate by routing beams between two arrays of continuously adjustable, dual-axis mirrors as shown in Fig. 9a[4]. Fig. 9b shows a 2 x 2 array of tilt mirrors formed in bonded Si by Analog Devices. Key materials issues in switch arrays are the reliability of self-assembled structures[63] and the optical power handing capability of Au-coated mirror surfaces[64]. Attempts are now being made to develop methods of attaching different mirror surfaces to completed MEMS suspensions, for example using surface tension[65].

Mirror insertion devices are also being used as variable optical attenuators (VOAs)[66], for example for channel equalization in dense wavelength division multiplexed (DWDM) systems involving amplification by erbium-doped fiber amplifiers (EDFAs). In this application, a small mirror is simply inserted to block part of a collimated beam, the reflected component being dumped into an absorber.

Linear arrays of tilt mirrors have also been used to construct ADD-DROP multiplexers[67,68]. A lens is first used to collimate the output from a fiber carrying a number of different wavelengths $\lambda_1 ... \lambda_n$. A diffraction grating is used to disperse the wavelengths into a fan of beams, which are then passed through another lens to form spatially separated foci. The mirror array is placed at the focal plane, so that each wavelength falls on a separate mirror. Each mirror may then either retro reflect the light back through the multiplexer or redirect it to a second multiplexer and fiber. Consequently, the spectral compositions of two output channels may be arbitrarily selected. In fact, if the optical system is suitably folded, only a single multiplexer is required.

When an electrostatically deflectable membrane mirror is combined with a second, fixed mirror, the result is a mechanically tunable Fabry-Perot cavity. This structure forms the basis of the mechanically actuated anti-reflection switch

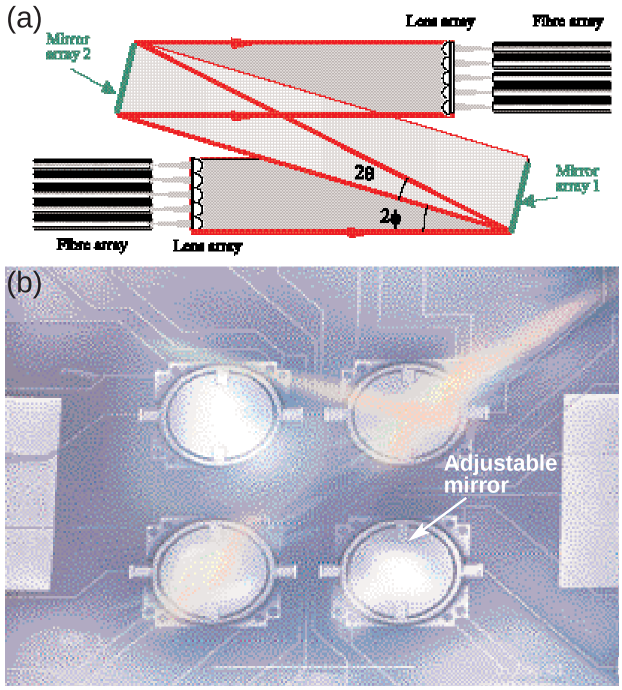

Fig. 9 Mirror plane switch: a) schematic and b) 2 x 2 electrostatically driven dual axis tilt mirror array. (Courtesy Analog Devices.)

(MARS) developed by Lucent Technologies and others, which has found application as a modulator and filter[69-71]. A more complex structure with a segmented drive electrode has also been used as a deformable membrane, as shown in Figs. 10a and 10b[72]. This device has been used as a spectral plane filter, controlling the reflectivity as a continuous function of wavelength to achieve spectral equalization of the gain of an EDFA, as shown in Fig. 10c.

Finally, MOEMS components have been used as the basis of tunable external cavity lasers[73]. For example, a hybrid-integrated Littman cavity tunable laser has been developed by Iolon[74]. Here, gain is provided by a conventional semiconductor optical amplifier, frequency selection is performed by a reflection grating, and tuning is carried out by rotating an external mirror about a remote pivot. The actuator is a comb drive structure formed by DRIE of bonded silicon-on-insulator material.

A number of companies, including Core-Tek and Bandwidth9, have developed more highly integrated vertical cavity semiconductor lasers (VCSELs) with an external cavity formed by a small movable mirror. The Core-Tek VCSEL is optically pumped and the external mirror is a membrane,

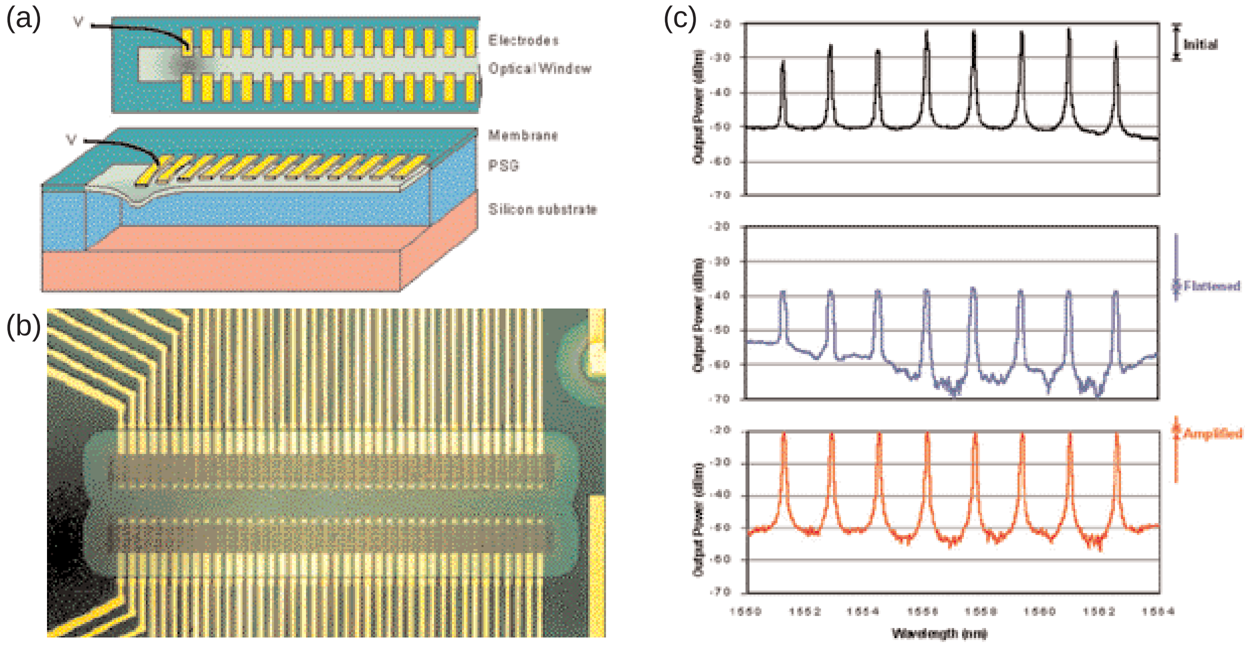

Fig. 10 MEMS spectral equalization filter: a) device schematic; b) fabricated chip; and c) spectra before, during, and after equalization and amplification. (Courtesy Jim Walker and Joe Ford.)

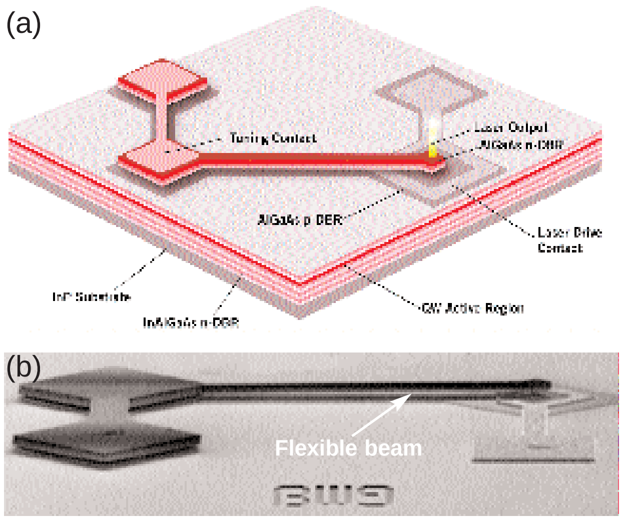

Fig. 11 Electrically pumped, directly modulated MEMS tunable VCSEL: a) schematic and b) actual device. (Courtesy Bandwidth9, www.bandwidth9.com.)

shaped by stress gradients into a spherical mirror surface to minimize diffraction losses[75]. Fig. 11 shows the Bandwidth9 laser, which is electrically pumped[76]. The device is grown entirely in one step, then etched to create a cantilevered tuning arm. Tuning is achieved by applying a small voltage to the top mirror, which causes the cantilever to move up or down. The cantilever motion alters the laser cavity length, which in turn changes the wavelength of operation. Other work is underway to integrate VSCELS, detectors, and optics[77]. The development of such compact and flexible devices (especially in array form) is certain to generate a wide range of new applications.

Future trends

This review has considered the present technology for MEMS and future applications in telecommunications. The key to new developments in optical MEMS is materials technology and cost-effective processing. New materials are being developed for the Si IC industry and the much smaller MEMS business is benefiting from this large investment. Examples are i) BSOI technology (as seen in Fig. 1), whereby low stress mirrors and other MEMS components are made with reproducible mechanical properties and excellent control of planarity and ii) low stress Si_3N_4, which has a high Young's modulus and promising applications in packaging (Fig. 2).

The most complex MEMS product currently available is Texas Instruments' DMD. However, this application is rapidly being matched by developments in telecommunications, especially in large-scale switches, variable attenuators, and tunable filters. High voltage drivers and sense electronics are now being integrated with reliable, low-loss opto-mechanical assemblies. These developments are also spreading into tunable sources, fabricated directly as III-V MOEMS.

As IC lithography and reactive ion etching techniques improve in accuracy, the necessary precision for optical MEMS manufacturing can be obtained. There is a strong incentive to stay with Si substrate technology for MEMS packaging to piggyback on this further investment, but within this paradigm there is great scope for invention in device structure, materials, and processing.

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