Silicon technology for optical MEMS

D.F. Moore[1] and R.R.A. Syms[2]
[1] *Cambridge University Engineering Department, Cambridge, UK*
[2] *Optical and Semiconductor Devices Group, Department of*
Electrical and Electronic Engineering, Imperial College, London, UK
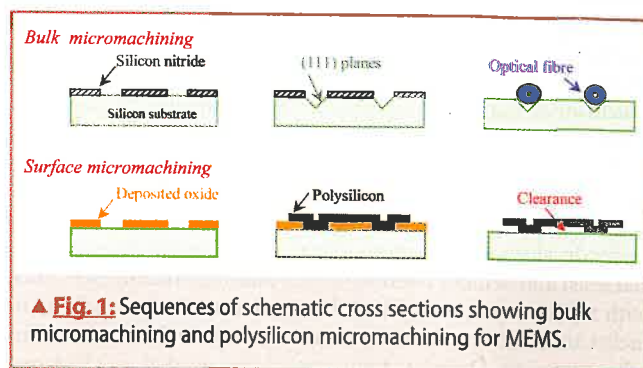
Micro-electro-mechanical systems (MEMS)

Components fabricated with the emerging technologies of micro-electro-mechanical systems (MEMS) are being incorporated in an increasing number of sensor and actuator applications [1,2]. There is rapid progress in optical systems for telecommunications to meet the needs for increased bandwidth, for optical networks with terabit capacities per fiber link, and for local area networks [3]. Some applications require precise features for optical alignment while others involve the precise movement of small optical parts to achieve advanced functionality. In the MEMS approach accurate, low-loss, optical connections are made between different guided wave optical components including fibres, waveguides and lasers. Mechanisms to allow motion and structures to provide electrical actuation are combined in micro-opto-electro-mechanical systems (MOEMS). Many MOEMS components process light in miniature free-space optical beams, and the performance scaling laws are often different from those for guided wave optical systems. This paper surveys MEMS with an emphasis on the outstanding challenges for Physicists and Engineers. The silicon and other materials and technologies used to create MEMS devices are discussed in detail, as are example applications in packaging such as fixed and demountable connectors and methods for hybrid integration.

Fabrication technologies for MEMS

The sets cross-sectional diagrams shown in Figure 1 illustrate the two main processes used for micromachining. The first established process is silicon bulk micromachining using alkaline solutions which have a much smaller etch rate of the (111) crystallographic plane in Si compared with other planes. In this process, a mask is first patterned in 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 silicon is then etched. Since the (111) planes etch the slowest, V-shaped grooves are produced by etching standard (100) oriented substrates to termination. V-grooves can be used for the precise positioning of optic fibres as shown in Figure 2. The features may be hundreds of micrometers deep and precisely defined by the initial planar lithographic process. Even grooves with diamond shape cross sections are made, although the range of possible shapes is restricted by the characteristics of the etch process. Encapsulated structures are made by fusion bonding of glass to bulk micromachined wafers, and multilayer structures are built up by bonding several silicon wafers together. Suspended structures can also be made by undercutting of etch-resistant features.
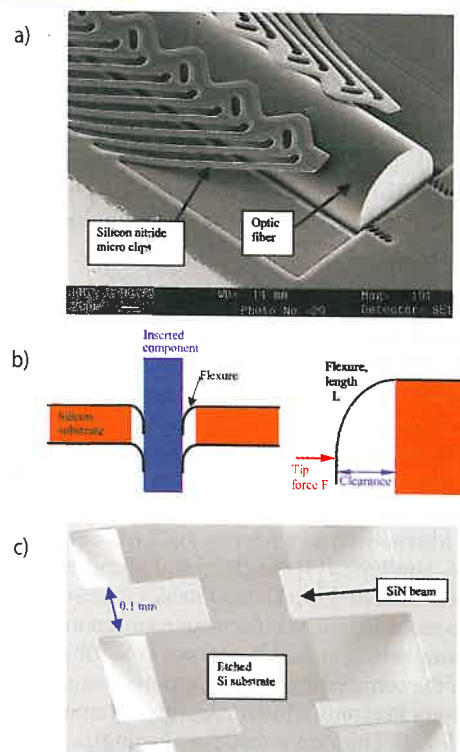
Polysilicon surface micromachining, exploits differences between deposited polysilicon and silica layers to form three-dimensional features as seen in Fig.1 row 2. The process is adapted from conventional silicon integrated circuit technology, and the chemical vapour deposited (CVD) polysilicon mechanical layer is typically 2 μm thick. The underlying silica sacrificial layer is later

▲ **Fig. 1:** Sequences of schematic cross sections showing bulk micromachining and polysilicon micromachining for MEMS.

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 such as electrostatic comb drives. 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 tens of micrometers by cost considerations, and by the mechanical and electrical properties of deposited polysilicon which 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. Foundries operate semi-standard processes with several levels of polysilicon.

Figure 3 shows more advanced micromachining processes which are under development. When the fabricated structures must be thicker than is achievable using polysilicon, an alternative surface micromachining process is to use lithographic exposure

▲ **Fig. 2:** Elastic fixtures for optical components: a) secondary electron micrograph showing silicon nitride clips holding an optic fibre in place in a silicon V-shaped groove; b) schematic of a proposed new approach to fixtures which avoids V grooves; c) silicon nitride beams made by bulk silicon micromachining.

features

of thick photoresist, followed by electroplating, to form the mechanical parts as illustrated in Fig.3 row 1. The original Lithographie, Galvanoformung, Abformung (LIGA) process uses synchrotron radiation to expose the resist. The short X-ray wavelength allows deep (up to 1 mm) resist layers to be exposed without significant diffraction effects, and high aspect ratio structures are made. The released metal layer can be used in a variety of MEMS applications including packaging. Cheaper alternatives under development use ultraviolet mask aligners to exposure special resist and achieve features several hundred micrometers thick with aspect ratios of order 15. Parts are usually electroplated in nickel and, after removal of the resist, they can be replicated in other materials. Only low temperatures are needed, so LIGA can be used as post processes to add microstructures to CMOS (Complementary Metal Oxide Semiconductor technology).
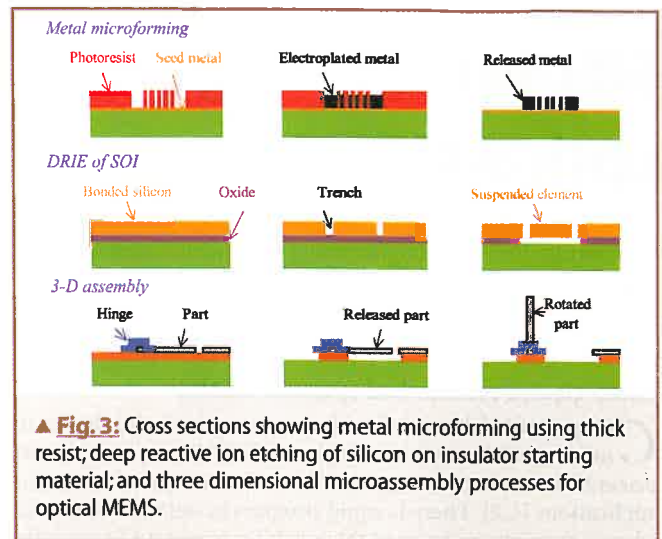
A recently developed process for forming suspended single crystal silicon structures is based upon the use of bonded silicon-on-insulator (SOI) starting material, which is available as a by-product of the high-performance silicon integrated circuit industry. As shown in Fig.3 row 2, the starting material is a silicon wafer that is thermally bonded to an oxidised silicon substrate. The bonded wafer is polished back to the desired thickness, usually in the range 5 µm - 200 µm. The bonded layer is then structured by deep reactive ion etching (DRIE) using an inductively coupled plasma etcher and specific gas chemistry to obtain high etch anisotropy. Movable structures may be made by removal of the buried oxide. There are many MEMS applications including micromechanical shutters for optical switching.

All of the above processes involve surface patterning and the resulting structures are quasi three-dimensional. Fully 3-D microstructures are made in polysilicon and in SOI by rotating surface micromachined parts out of the wafer plane, and latching them into position as seen in Fig.3 row 3. The parts are held by micromachined staple hinges. Assembly is usually manual, but mass-parallel powered assembly has been demonstrated by differential shrinkage of a polymer due to surface tension forces. Surface micromachined engines are also used to push parts out of plane. The many potential MEMS applications include components for free-space MOEMS.

MEMS packaging in optoelectronics

It is well known that passive alignment features for connecting single-mode optical fibres can be made by anisotropically etching single crystal Si. As shown in Fig.1, etching of (100) oriented Si through an appropriate mask is used to make V-shaped grooves which act as kinematic mounts for optic fibres. When two fibres are aligned in a groove and then butt-coupled together, all degrees of freedom except uniaxial motion are fixed. The assembly may then be epoxied. Alternatively, as shown in Fig.2, a fibre may be held by flexible Si_3N_4 cantilevers [4]. Single crystal silicon cantilevers have also been demonstrated [5]. Demountable connectors for ribbon optical fibres requiring the simultaneous connection of many cores are made using sets of etched V-grooves in Si substrates. 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 aligning the pins, and sliding the connector halves together. V-grooves can also be used to construct simple subsystems known as opto-hybrids such as the connection between an optical fibre and a photodiode. Systems with detectors, lasers and high speed interconnects are used as transceivers.

Precision mechanical components are also used to connect different types of waveguide. Particular attention has been given

▲ **Fig. 3:** Cross sections showing metal microforming using thick resist; deep reactive ion etching of silicon on insulator starting material; and three dimensional microassembly processes for optical MEMS.

to the optic interfaces between fibre and silica-on-silicon integrated optical components. Silica-on-silicon has several major advantages over the earlier technologies such as ion-exchanged glass, Ti : $LiNbO_3$, GaAlAs and InGaAsP. Because of this, silica-on-silicon components are likely to find widespread application in low-cost systems such as fibre-to-the-home. A typical device comprises a single-crystal Si substrate with fibre 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 may be constructed with a large number of ports.

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 silicon 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. For example, a hybrid-integrated 1.3 µm / 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 monitor photodiode.

Many new assembly techniques are under development. One proposed geometry is shown schematically in Fig.2 where a substrate carries elastic flexures on both sides to secure an inserted component in position [6]. In this arrangement the flexure length L is much greater than the clearance α and the force F acts essentially at the point of initial contact. The precision with which an optical component can be located is determined primarily by the lithography and etching technology used for 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 silicon nitride. A micrograph of chemical vapour deposited SiN beams 3 µm thick is shown in the lower part of Fig.2 where the silicon substrate has been wet etched to form a V-groove. Silicon carbide is another possible material which has the required large Young's modulus and low stress. Preliminary experiments on 5 µm thick CVD SiC carbide films and etched Si substrates indicate that the material is suitable [6]. In the longer term, active flexures would be useful to allow for the adjustment of inserted components.

An alternative alignment method exploits LIGA to construct complex components such as multi-axis flexures in Ni metal.

Several flexures soldered to a breadboard provide individual mounts for components in an optical component train. For example, Figure 4 shows a flexure for an optical fibre and a collimating lens. After assembly, the optical throughput is optimised by adjusting the position of each component in turn, using plastic deformation of the flexure by an assembly robot. Complete optical systems such as a channel monitor based on a tunable Fabry-Perot filter have been assembled.
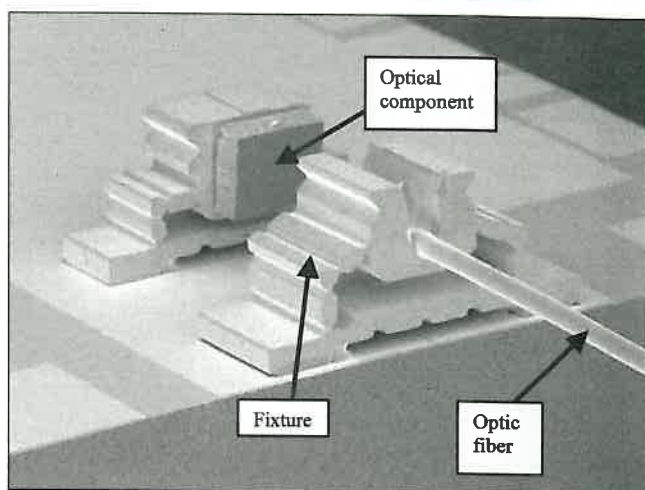
Optical breadboards are also constructed using components that are fabricated flat by surface micromachining and then rotated out-of plane. Small, free-space optic beams propagate parallel to the surface of the chip through fixed and movable lenses and gratings, and reflect off micro mirrors. The structures are hand-assembled using precision micromanipulators. Other systems have been assembled by using surface-micromachined engines to push hinged devices out of the wafer plane. A typical assembly engine is a scratch-drive actuator which acts as a controllable linear translator, allowing dynamic component positioning. Fully automatic techniques are also being developed for assembly of 3D MOEMS. One process based on surface tension force simply requires the melting of small pads of material to rotate parts out-of-plane [7], as shown in Figure 5. This method allows angular positions to be set to an accuracy of minutes of arc. Demonstrated devices again include fixed and movable mirrors, and lenses. Surface tension has been used to position and fix the parts of the bonded silicon support frame in Fig.5. The lenses are formed simultaneously by using reflow moulding of photoresist which gives optical surfaces.

MEMS optical devices

Applications for MOEMS in telecommunications were inspired by the emergence of a successful device in a different field: the digital micromirror projection display. On the display chip an array of more than a million electrostatically actuated torsion mirrors rotate to-and-fro against a system of end-stops to reject or accept individual pixels for the display. The advantages of MOEMS are small size, low cost, and the ease with which large-scale systems may be integrated. Compared with interferometric guided wave devices, the advantages are low loss, low cross talk, scalability and insensitivity to process variations. These advantages can outweigh disadvantages such as the relatively slow speed of a mechanical switch or tuning structure. Most MOEMS devices have been constructed either in polysilicon or in single-crystal silicon using bonded silicon-on-insulator, 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 multi-layer devices may be constructed. The advantages of SOI are often improvements in structural thickness (and hence the flatness of released surfaces) and low surface roughness.

Switches can be based upon the electrostatic deflection of a waveguide for integrated optics. 1 x 2 silica-on-silicon moving waveguide switches have been demonstrated with the input channel guide fabricated on a cantilever suspended over an etched cavity. Using surface electrodes, the cantilever is deflected electrostatically from side-to-side, to allow connection to either of the output waveguides. The switching time of the order of milliseconds is long compared with the data rate, but is sufficient for network reconfiguration.
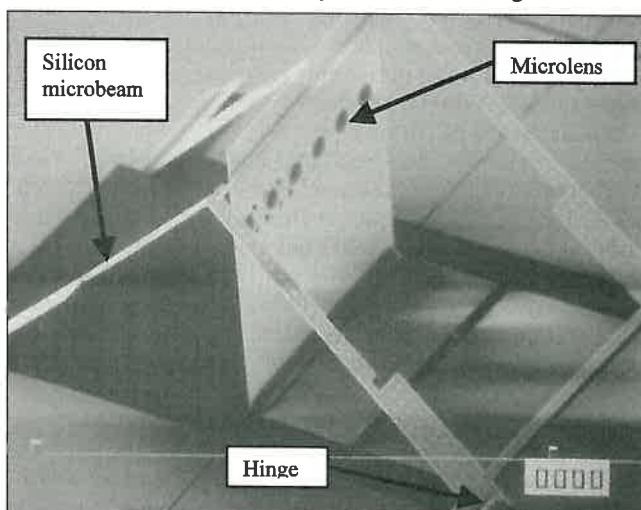
Other switches are based on the insertion of small mirrors into the nodes of a classical cross-point geometry. Suitable devices can be fabricated by deep reactive ion etching silicon. DRIE can simultaneously form vertical mirrors, fibre alignment grooves
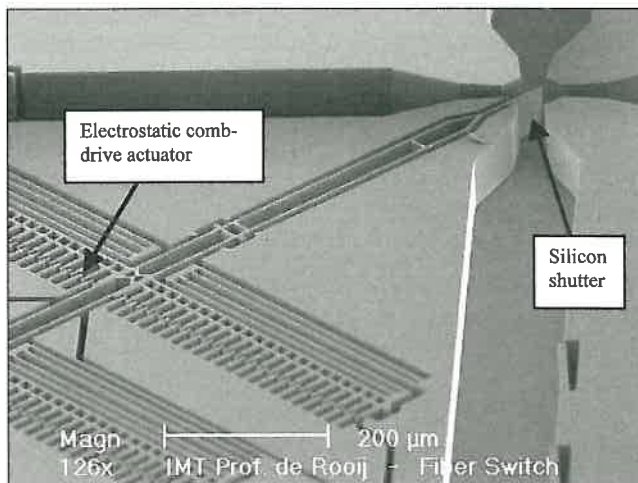

▲ **Fig. 4:** Electron micrograph showing the hybrid integration of optical components using a LIGA-type flexure (www.axsun.com).

and a simple electrostatic drive to remove or insert the mirrors into the regions where the optical axes intersect. A typical structure is shown in Figure 6. Switching times are also of the order of milliseconds, and optical isolation is excellent. However, the devices are only scalable to small-size switch arrays.

Dynamically assembled 3D MOEMS are being used to construct larger mirror insertion cross-connects. A commercially available polysilicon switch uses an 8 x 8 array of small mirrors to form a 64-node cross-point. The mirrors are driven between two states by an electrostatic drive acting through a linkage. 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. Alternative mirror plane switches with a larger number of ports are now under development. Instead of using deflection between a set of single-axis mirrors, whose positions are effectively binary, the devices operate by routing beams between two arrays of continuously adjustable, dual-axis mirrors. Using surface micromachining Lucent Technologies Inc./Bell

▲ **Fig. 5:** Scanning electron micrograph of a microlens array after surface tension self-assembly [7].

Labs have recently reported a large (238 x 238) switch fabric with a mean fiber-to-fiber insertion loss of 1.33 dB [8]. The maximum insertion loss for the 56644 possible connections was only 2.0 dB. Two fiber arrays with collimating microlenses attached are used to project and receive beams from two 2-dimensional arrays of micro-mirrors. Figure 7 shows an electrostatically actuated 2-axis tilt mirror similar to the mirrors used in the large array [8].

Mirror insertion devices are also being used as variable optical attenuators, for example for channel equalisation in dense wavelength division multiplexed systems involving erbium doped fibre amplifiers. A small mirror on a cantilever is inserted into the optical path to block part of a collimated beam, the reflected component being dumped into an absorber. Alternatively, switches may be based on a microfluidic systems and the controlled movement of gas bubbles in liquid channels.

▲ **Fig. 7:** Two axis beam steering micro-mirror built using surface micro-machined technology [8], (Lucent Technologies Inc./Bell Labs)

Linear arrays of tilt mirrors have also been used to construct ADD-DROP multiplexers. A lens is first used to collimate the output from a fibre carrying a number of different wavelengths. 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 fibre. Consequently, the spectral compositions of two output channels may be arbitrarily selected.

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 used as a modulator and filter. A more complex structure with a segmented drive electrode is used as a deformable membrane. This device has been used as a spectral plane filter, controlling the reflectivity as a con-tinuous function of wavelength to achieve spectral equalisation of the gain of a fibre amplifier.

MOEMS components have been used as the basis of tunable external cavity lasers. Gain is provided by a conventional semiconductor optical amplifier, frequency selection is achieved using 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 deep reactive ion etching of bonded silicon-on-insulator material.

Highly integrated vertical cavity semiconductor lasers with an external cavity formed by a small movable mirror are also under development. They may be optically pumped with a membrane as the external mirror. Another electrically pumped device is grown in one step and 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 altering the laser cavity length and changing the wavelength of operation.

Future prognosis

This review has considered the present technology for silicon-based MEMS and some future telecommunications applications. The key to new developments in optical MEMS is to successfully apply the underlying physics and develop cost-effective processing to make high-precision components. New materials are being used in the silicon integrated circuit industry where there is a huge on-going investment, and the much smaller MEMS activity can benefit from these developments. Examples are (i) SOI technology as seen in Fig.3 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 has promising applications in packaging as seen in Fig.2. The current MEMS product containing the largest number of micromechanical components is the mircromirror projection display.

As integrated circuit lithography and reactive ion etching techniques improve in accuracy, the necessary precision for optical MEMS can be obtained in a manufacturable way. There is a strong incentive to stay with silicon substrate technology for MEMS packaging to piggyback on this further investment, but within this paradigm there is great scope for applied physicists in both the invention of device structures and the development of materials processing.

Acknowledgements

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