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Optical MEMS for Telecommunications: Some Reliability Issues

Ivanka Stanimirović and Zdravko Stanimirović

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1. Introduction

Constant demand for mobility, interconnectivity and bandwidth is causing rapid expansion of the telecommunication infrastructure across the world. World-wide installation of optical fibre-based telecommunication systems has given rise to a promising optically-related sub segment of MEMS technology called micro-opto-electro-mechanical systems (MOEMS), commonly known as optical MEMS. MEMS telecommunications applications can be roughly divided into two key classes: optoelectronic packaging and functional optical devices. When functional optical devices are in question, optical MEMS devices that integrate optical, mechanical, and electrical components on a single wafer are allowing the implementation of various key optical-network elements in a compact, low-cost form. They usually involve small moving optical parts in order to obtain more advanced functionality. In optoelectronic packaging, MEMS are providing low-cost accurate optical alignment. At the moment, fabrication of complex optical MEMS devices and micro-electro-mechanical alignment devices is based on micromachining techniques combined with IC-based processing methods. Such manufacturing techniques have enabled low cost, mass production of optical MEMS components and devices. However, successful commercialization of optical MEMS technology that is being driven by the progress in optical communications strongly depends on device reliability. Optical MEMS device reliability is significantly more complex than silicon IC reliability, partly because optical MEMS failures can be either electrical or mechanical, and partly because there is a vast diversity of device designs, materials and functions. It is of the greatest importance that design and realization of optical MEMS device must include all levels of reliability issues from the onset of the project. For that reason, this chapter focuses on the identification and understanding of main mechanisms that cause failure of optical MEMS devices that are being used in telecommunications. First, the commonly used MEMS process-

ing technologies are summarized. Then, functional optical MEMS devices for optical network infrastructure are discussed. Finally, the key issues of various MEMS device failure mechanisms and design, processing and packaging implications are presented. At the closing subsection, the brief summary of the topic is presented with an emphasis on the importance of the research of relevant reliability issues that stand in the way of successful commercialization of optical MEMS devices.

2. Optical MEMS technologies

Similar to optical MEMS devices, there is no single standard processing technology for optical MEMS fabrication. Silicon based optical MEMS is dominant materials system and different micromachining processes are being used as the most appropriate fabrication techniques. Also, conventional IC processes (lithography, depositions, implantation, dry etching, etc.) are often used in microstructure formation.

Bulk micromachining has been used for a long time for realization of 3D optomechanical structures on Si substrate for aligning optical fibres or forming optical MEMS devices. Single crystal Si has excellent mechanical properties and low-cost, high-purity Si substrates are available from IC industry. Si bulk micromachining is the process that impacts the substrate. Precise removal of the designated part of silicon substrate can be achieved by anisotropic etchants. Large difference in anisotropic etch rates between the $\langle 111 \rangle$ plane and other crystallographic planes in Si, enables pattern formation on either front-side or backside of the substrate. The etching rate of anisotropic etchants such as potassium hydroxide (KOH), aqueous solution of ethylene diamine and pyrocatechol (EDP) and tetramethylammonium hydroxide (TMAH), is much slower in $\langle 111 \rangle$ direction than in $\langle 100 \rangle$ and $\langle 110 \rangle$ directions [1]. Selectivity for such anisotropic etchants can be higher than 100 allowing creation of 3D optomechanical structures with high precision. Basic properties of commonly used anisotropic etchants are listed in Table 1.

| Etchant | Etch rate (110) $\mu\text{m}/\text{min}$ | AR {100}/{111} | Etch Masks | Etch stop | Main characteristics |
|---------|---|-------------------|--|--|---|
| KOH | 1,4 | 400 | Si_3N_4 , SiO_2 | $\text{B} > 10^{20}/\text{cm}^3$ | Fastest, greatest selectivity, makes vertical sidewalls |
| EDP | 1,25 | 35 | SiO_2 , Si_3N_4 , Ta, Au, Cr, Ag, Cu | $\text{B} \sim 7 \times 10^{19}/\text{cm}^3$ | Lots of masks, lowest Boron doping etch stop, low AR |
| TMAH | 1 | 30 | Si_3N_4 | $\text{B} \sim 4 \times 10^{20}/\text{cm}^3$ | Smooth surface, slow etch rate, low AR |

Table 1. Basic properties of common anisotropic etchants

V-shaped grooves commonly used for precision positioning of optic fibres, are an example of this processing technology. The (100) Si substrate is first masked with an etch-resistance surface layer (deposited Si_3N_4 for KOH or thermally grown SiO_2 for EDP) and then the Si is etched. Slower rate of <111> planes etch enables V-groove formation by etching <100> oriented planes. V-groove depth can be very well controlled by lithography because {111} planes are effective stop etching planes. Schematic of V-shaped groove formation is shown in Figure 1. By etching through square openings, pyramidal-shaped holes can also be formed that are being used for holding ball lenses. V-grooves and pyramidal-shaped holes are the basis of conventional microoptical benches. Bulk optical components are placed on the etched Si substrate and precisely positioned by holes of various geometries. Vertical micromirrors can be formed by anisotropic etching on a (110) Si substrate. Atomically smooth {111} planes are perpendicular to the surface of the substrate. Large-area semitransparent, optical-quality surfaces are provided. These micromirrors can be also used as beam splitters. In addition to the {111} stop etch planes, some etchants exhibit reduced etch rate in regions that are heavily doped with boron. This allows more flexibility in shapes of final structures: membranes, suspended beams, support beams for vertical micromirrors etched on (110) substrate, etc. Besides boron, other doping materials can be used but doping involves high temperatures and has side effects such as lattice shrinkage and introduction of large tensile stresses in parts formed this way [2].

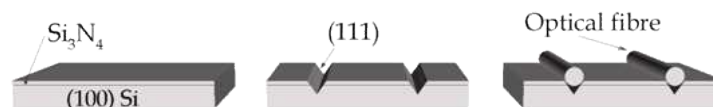


Figure 1. V-shaped grooves formed by bulk silicon etch with wet chemistry

Fusion bonding of glass to bulk micromachined Si substrates allows formation of encapsulated structures as shown in Figure 2. Also, multilayer structures may be formed by bonding Si substrates together. In this way, the range of devices that can be manufactured using bulk micromachining is greatly extended.

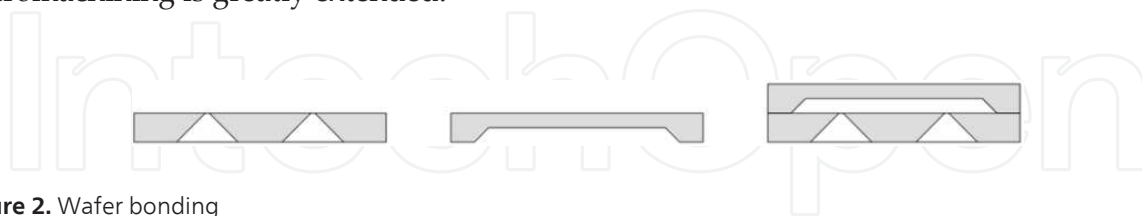


Figure 2. Wafer bonding

Another process commonly used in optical MEMS fabrication is surface micromachining. While, in bulk micromachining, substrates materials are being removed in order to create 3D structures, surface micromachined structures are constructed from deposited thin films. Alternating layers of structural and sacrificial materials are deposited and patterned on the substrate. The sacrificial layers can be selectively removed by an etchant that attacks only the sacrificial materials. In this way suspended beams, cantilevers, diaphragms and cavities can be realized. Because of its excellent mechanical properties, polysilicon is being used as structural material and SiO_2 as the sacrificial material because of the high selectivity of

sacrificial etching with hydrofluoric acid. Figure 3. illustrates polysilicon surface machining process. The complexity of the surface machining process is determined by the number of structural and sacrificial layers. Two structural layers allow formation of free moving mechanical gears, springs, sliders, etc. The main advantage of surface micromachining over bulk micromachining is that many different devices can be realized using common fabrication process. By changing patterns on the photomask layouts different devices are being fabricated simultaneously on the same substrate. For that reason, the surface micromachining process is often referred to as an IC process that allows formation of multilayer structures usually with two to five polysilicon levels.

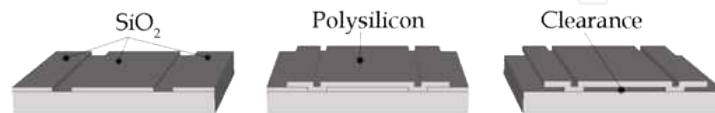


Figure 3. Polysilicon surface micromachining

Often, it is desirable to fabricate structures thicker than those achievable using polysilicon. An alternative micromachining process uses lithographic exposure of thick photoresist, followed by electroplating to build on chip high aspect ratio 3D structures. In the LIGA (lithography, electroplating and moulding) process synchrotron radiation is used as the exposure source that can achieve feature heights of the order of $500\mu\text{m}$. Cheaper alternatives use excimer lasers or UV mask aligners that achieve feature heights of the order of $200\mu\text{m}$ and $20\mu\text{m}$, respectively [2]. Parts are usually plated in nickel after removal of the resist as illustrated in Figure 4. The released metal layer can be used in various applications including optical MEMS devices.

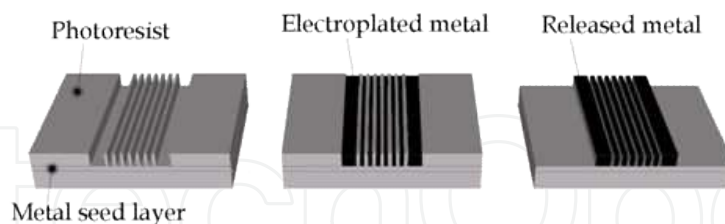


Figure 4. Metal micromachining

Suspended single crystal Si structures, with lower stress and more reproducible properties than polysilicon, are formed using process based on BSOI (bonded silicon-on-insulator). Si wafer is thermally bonded to an oxidized Si substrate. Desired thickness (usually 5 to $200\mu\text{m}$ [3]) of the bonded wafer is achieved by polishing and the bonded layer is structured by deep reactive ion etching (DRIE) that has high etch rates and anisotropy to form very deep features with almost vertical sidewalls (Figure 5.). Movable parts can be made by removal of the buried oxide and one of the typical applications of this technique is realization of vertical mirrors for optical switching.

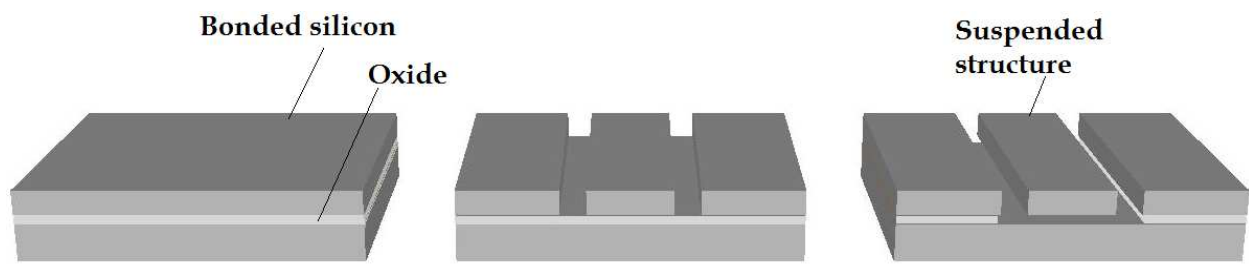


Figure 5. Deep reactive ion etching (DRIE) of bonded silicon-on-insulator (BSOI)

DRIE has also allowed Si micromolding techniques, such as HexSil process, to be developed [4]. DRIE is used to etch narrow trenches into the substrate. Trenches are fraction of a millimetre deep. After that, a sacrificial oxide layer is deposited, followed by the polysilicon structural layer that fills the trenches. As shown in Figure 6., deep suspended structures are being made by releasing the polysilicon.

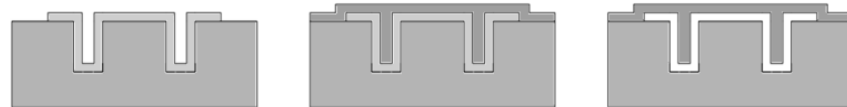


Figure 6. HexSil process

All described techniques involve surface patterning processes and therefore realized microstructures are quasi 3D. Very often out-of-plane structures with high aspect ratios are required for free-space optical systems. Anisotropic etching or deep dry etching can provide such structures but it is difficult to pattern their side walls. Fully 3D structures can be formed using microhinge technology [5]. Surface micromachined polysilicon planes are patterned by photolithography and then folded into 3D structures. Figure 7. shows schematic cross section of the microhinge that consists of hinge pin and a confining staple. After selective etching of the sacrificial SiO_2 , the polysilicon plate connected to the hinge pin is free to rotate out of the substrate plane and become perpendicular to the substrate. Polysilicon plate can also achieve other angles. This technology allows monolithic integration of 3D structures with surface micromachined actuators. It is of the special interest for fabrication of integrable free-space microoptical elements.

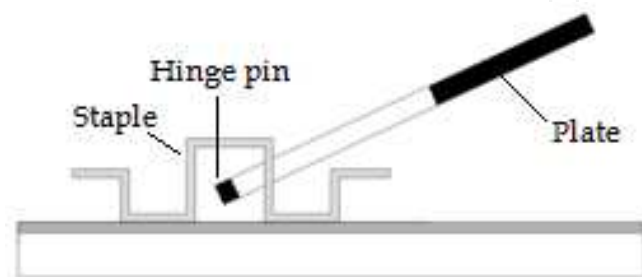


Figure 7. Schematic of surface-micromachined microhinge

The full potential of surface micromachining, bulk micromachining and wafer/chip bonding techniques is still being explored. The key activities are continued development of masks and etches that can yield high aspect ratio structures and the development of deposition techniques. Special attention is being paid to the development of techniques for creating fully 3D structures.

3. Optical MEMS devices

Components fabricated using optical MEMS devices are finding an increasing number of applications when optical side of telecommunications is in question. They can be divided in two categories: core and peripheral optical MEMS devices (Table 2.). Core optical MEMS devices incorporate fixed structures (V-grooves, gratings, etc.) and moving elements (micro-mirrors, attenuators, etc.). Peripheral optical MEMS devices are alignment components and structural components. The key area, when optical MEMS for telecommunications are in question, is related to functional optical devices - devices that involve small moving optical parts necessary for more advanced functionality. They are core optical MEMS with moving elements.

| Core optical MEMS | | Peripheral optical MEMS | |
|-------------------|-------------|-------------------------|---------------|
| Fixed Structures | V-grooves | Alignment components | Lenses |
| | Connectors | | |
| | Benches | | |
| | Gratings | | |
| Moving Elements | Mirrors | Structural components | Packaging |
| | Shutters | | Beam steering |
| | Filters | | Fiber-guides |
| | Attenuators | | |

Table 2. Optical MEMS for telecommunication applications [6]

One of the simplest functional optical MEMS devices is the variable optical attenuator (VOA) [2, 7]. Typically, a moving micro-structure is designed to either partially block or decouple the lightpath. An example of a blocking VOA is shown in Figure 8. The light from the input fiber is collimated with a lens, partially blocked or attenuated by the MEMS device and recoupled to an output fiber. The MEMS device itself could be actuated horizontally or vertically. Actuators could be electrostatic, thermal or electromagnetic. Such a device could be also used as an on-off switch.

The main goal of optical MEMS is providing a high-performance, low-cost solutions for optical switching and wavelength division multiplexing (WDM) or dense wavelength division multiplexing (DWDM). Depending on the specific application, these devices can be wavelength insensitive or wavelength selectable. Wavelength and protocol insensitive device for

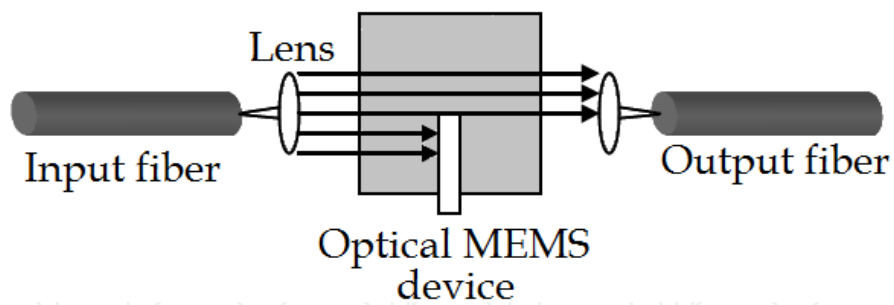


Figure 8. Schematic of variable optical attenuator (VOA)

all optical switching is optical cross connect (OXC). It replaced conventional optical-electrical-optical (OEO) switching that required conversion of optical signals to electrical ones, switching of electrical signals and conversion of electrical signals to optical ones. OEO switching solution cannot keep up with rapid data rate increase because expensive transceivers and electrical switch core will have to be replaced. However, all optical switching provide avoidance of conversion stages and core switch is independent of data rate and data protocol, making cross connect ready for data rate upgrades. This solution is also cost effective because the use of expensive power-consuming high-speed electronics, transmitters and receivers is avoided. This complexity reduction significantly improves reliability of the device. A typical MEMS OXC consists of micromirrors made of either polysilicon or crystalline silicon, using silicon-on-oxide (SOI), coated with metal for reflectivity. The actuation can be electrostatic, magnetic or combination of the two. Two MEMS approaches for optical switching can be distinguished: 2D (planar) switching and 3D free-space switching [8, 9]. In 2D MEMS the switches are digital because mirror position is bistable (Figure 9.). MEMS micromirrors are arranged in a crossbar configuration and all optical paths lie on a planar (2D) surface (Figure 10.). When a micromirror is activated it moves into the path of the beam and directs the light to one of the outputs. Light can also be passed through the matrix without hitting the micromirror allowing adding or dropping optical channels.

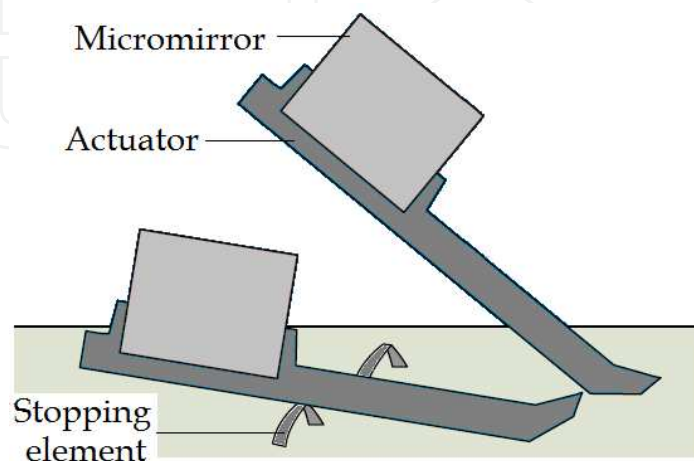


Figure 9. Schematic of basic element for 2D optical switches

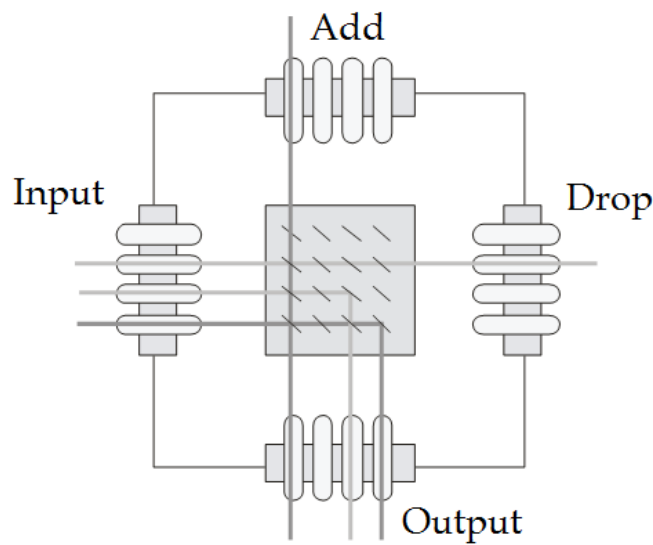


Figure 10. MEMS approach for optical cross connect switching

For switching ultra-high N networks planar switching is being replaced with more robust and cost-effective solution. 3D MEMS is a most promising technology for optical cross connect switches with >1000 input and output ports. In 3D MEMS a connection path is established by tilting two micromirrors independently to direct the light from an input port to selected output port (Figure 11.). This approach requires 2-axis mirror cells that usually consist of a gimbal and a mirror [10]. The gimbal connects to the support structure with a pair of torsional springs and another pair of torsional springs connects the mirror to the gimbal. Second pair of springs is rotated 90° with the respect to the first pair. Each pair of springs can be independently actuated and their combination enables two-directional tilt of the mirror (Figure 12.). A drawback of this approach is that a complex and expensive feedback system is required to maintain the position of the mirrors during external disturbances or drift.

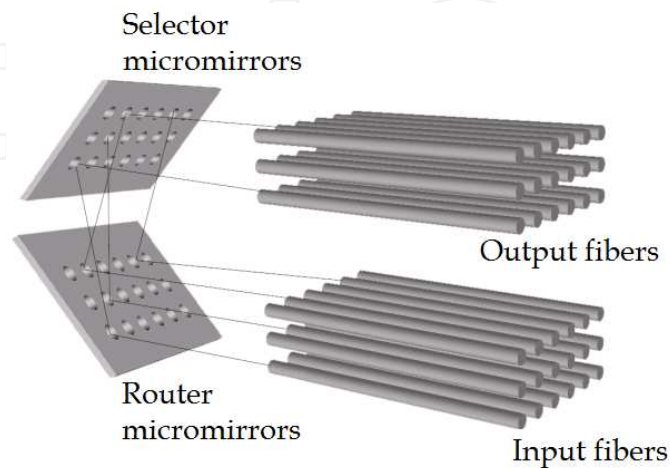


Figure 11. 3D MEMS approach for optical cross connect switching

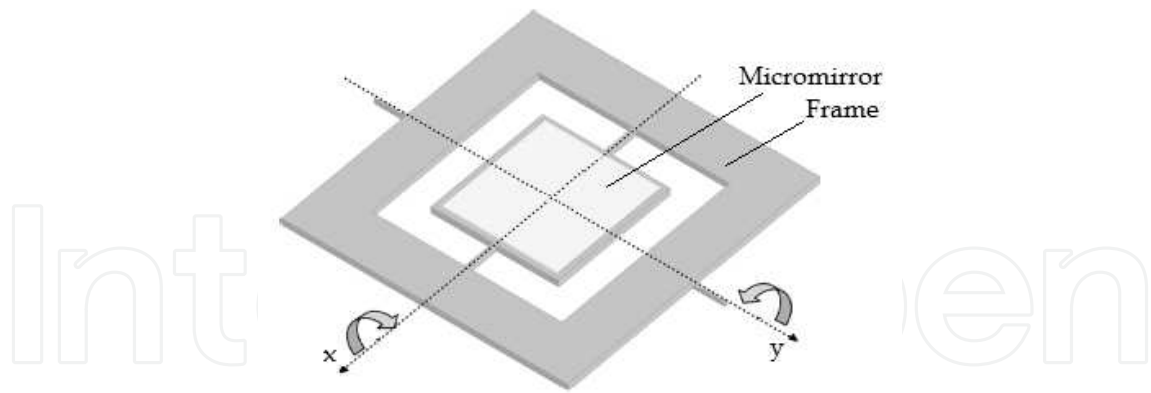


Figure 12. Schematic of two-axis single crystal silicon mirror

The output characteristics of an optical amplifier are not uniform across the laser wavelength spectrum. This is problematic for WDM because each segment of spectrum carries a data channel. For that reason, a dynamic gain equalizer (DGE) is needed to level output spectrum [10]. First, channels are separated by dispersing spectrum through assembly of lens and grating (Figure 13.). Then, they are projected onto the DGE and the output of each channel is tuned independently. The tuning can be performed by either an MEMS micromirror array (Figure 14.) or mechanical anti-reflection switch (MARS) (Figure 15.). MARS uses the strip of dielectric (usually silicon-nitride) membrane and air gap that serve as a spatially variable, tunable multi-layer dielectric mirror. When the incident signal is spectrally dispersed along the axis of the device defined by an array of strip electrodes, one obtains a simple and compact tunable spectral shaper.

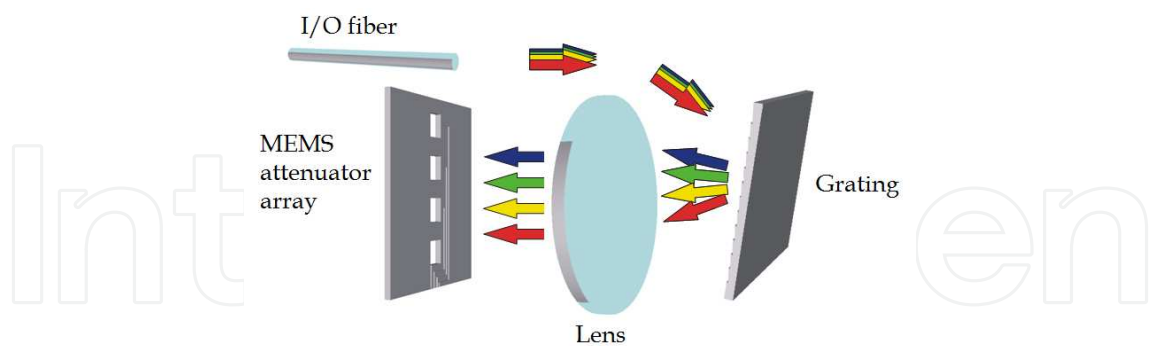


Figure 13. Schematic of WDM DGE using MEMS mirror array, lens and grating

In optical WDM provisioning, a data channel may be dropped or added. MEMS technology provides simple solution in optical add-drop multiplexer (OADM) [10]. The tilting-mirror DGE at larger tilting angles can achieve dynamic channel blocking. The full add-drop function of data channels is obtained by inserting channel blocker between an optical splitter and an optical coupler. Independent control for each channel is wavelength selectable resulting in flexibility to add/drop any combination of data channels. WDM provisioning using wave-

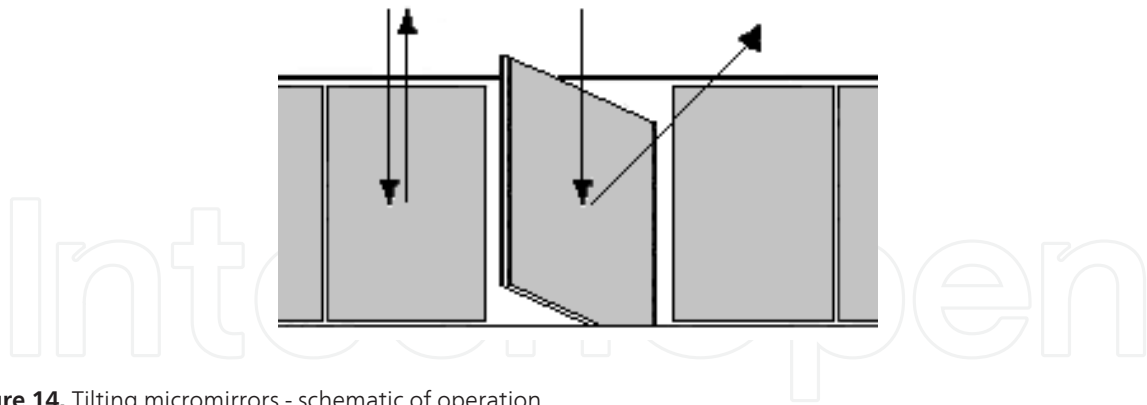


Figure 14. Tilting micromirrors - schematic of operation

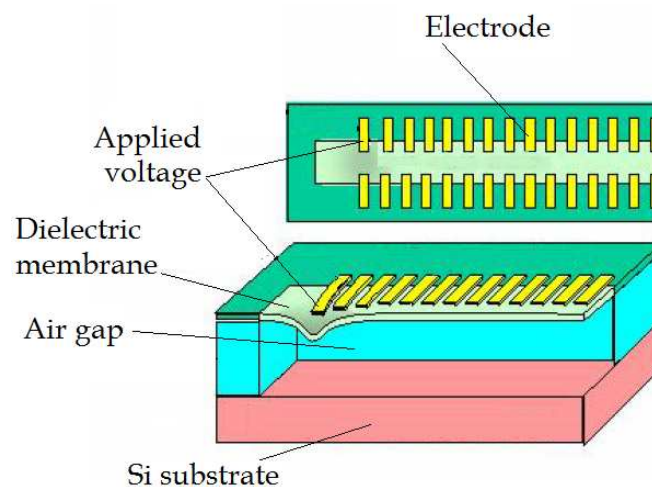


Figure 15. Schematic of MARS DGE using continuous membrane and finger electrodes [3]

length-selectable switches (WSS) is being often used. The simplest WSS is a channel blocker, with a single input and output fibre, having the capability to power equalize or completely attenuate the WDM channels. The more capable $1 \times K$ WSS has a single input and K output fibres, adding the capability to independently route the individual WDM channels among the K fibres (Figure 16.). WSS with higher K requires a large micromirror tilting angle ($>8^\circ$) and devices using vertical comb drive or double hinged angle amplification [10]. Gentler angle-bias response at large angles can be obtained by using alternative design that uses fringe electrical fields.

There are several other MEMS devices for optical networking applications such as polarization-mode dispersion (PMD) compensators, tunable laser, etc [11]. New developments in optical MEMS are based on materials technology and cost-effective processing. Optical MEMS are also benefiting from developments of IC industry such as BSOI technology that provided realization of low stress micromirrors, as well as production of other MEMS devices with reproducible mechanical properties and excellent planarity. Continuing progress results in products with better performances such as large-scale switches, variable attenuators, tunable

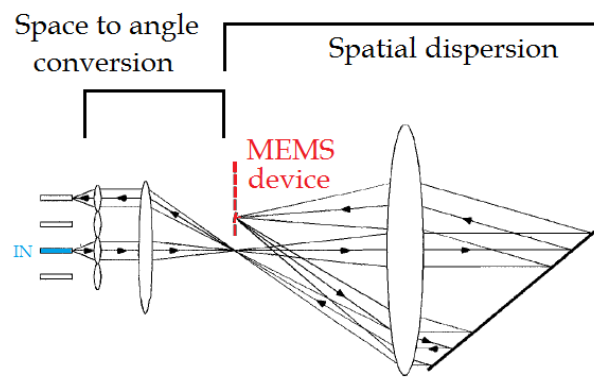


Figure 16. Schematic of MEMS 1xK WSS

filters, etc. High-voltage drivers and sense electronics are being integrated with highly reliable low-loss optical MEMS devices. Accuracy improvement of IC lithography and reactive ion etching provides necessary precision for optical MEMS production. Since there is a great scope for invention in MEMS device structure, materials and processing, optical MEMS will continue to play an increasingly important role in future of optical networks and ultra-high bandwidth communications.

It should be mentioned that besides functional optical MEMS devices, MEMS technology is also being applied in optoelectronic packaging. Ability to provide accurate passive alignment at low cost is one of the important assets of MEMS technology. MEMS approach provides accurate, low-loss optical connections between different guided wave optical components. Highly reliable connections realized using well characterized materials allow construction of complex interconnections. As an illustration, schematic of optical fibre fixed in a V-shaped groove by the triangular microclip is shown in Figure 17.



Figure 17. Schematic of optical fibre fixed in a V-groove by the triangular silicon nitride mechanical microclip

4. Reliability of optical MEMS

Reliability of optical MEMS for telecommunications is identified as the next manufacturers challenge for the forthcoming years due to a growing market and stricter requirements. Because of the vast diversity of device designs, materials and functions it is necessary to understand both technologies related variables as well as external variables such as environ-

mental and operational conditions. MEMS reliability analysis is extremely important to identify and understand the different failure mechanisms that can be electrical or/and mechanical. Optical MEMS failure mechanisms are more complicated than those in microelectronics for several reasons:

- MEMS devices are designed to interact with environment at various environmental conditions (e.g., temperatures),
- they are often hermetically sealed and they are expected to have long-term performances,
- some of the failures is impossible to predict,
- reliability testing for MEMS devices is not standardized unlike IC and microelectronics,
- for every new device new testing procedures need to be developed.

Design for test is important as well as performing parametric testing, testing during assembly, burn-in and final testing, testing during use, etc. Testing during assembly is of utmost importance for optical MEMS devices. It has two purposes. The first is to determine which devices are ready for the packaging process and the other is monitoring the yield of the packaging process. After the assembly devices are subjected to “burn-in” tests because packaged device may fail to perform due to the invasion of unwanted foreign substances such as dust particles and moisture. The main purpose of this test is to induce “infant mortality” failure on the manufacturing premises but not during operational lifetime (Figure 18). During the useful lifetime of the device the failure rate is relatively low. Failures are usually caused by external events such as vibration, shock, ESD, etc. Testing during use ensures proper functioning of the device for the intended application. Finally, device deteriorates due to intrinsic problems caused by material fatigue, frictional wear, and creep.

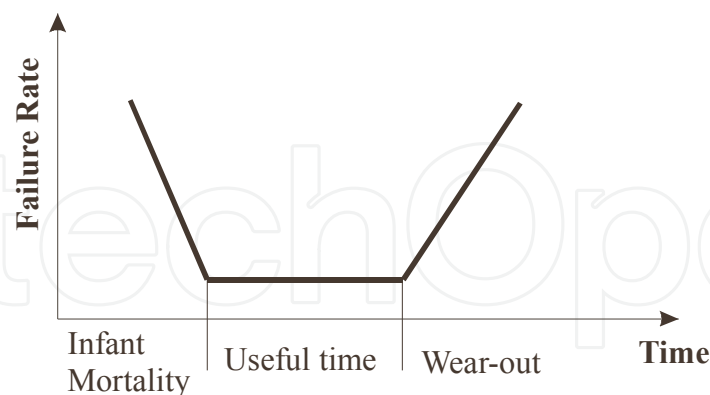


Figure 18. Failure rate as a function of time

One of the potential failure mechanisms of optical MEMS is stiction. Stiction occurs when surface adhesion at the contacting interface exceeds the restoring force. Adhesion may be driven by either capillary condensation or van der Waals forces [12]. Capillary condensation is affected by moisture and surface contamination, while van der Waals forces are affected by surface roughness. Since device dimensions are minute, gravity and other body forces do not

play a significant role. Van der Waals forces are short range forces which cause materials to be attracted at the molecular level. The vulnerability to stiction can be significantly reduced by surface passivation coatings, the use of critical point (CO₂) drying of MEMS devices and moisture free packaging [10]. Enclosure in a controlled atmosphere and robust hermetic packaging greatly reduce the presence of moisture. Also, anti-stick layers are commonly being used to lower the surface interaction energy and prevent stiction. These layers provide hydrophobic surfaces on which water cannot condense and capillary stiction will not occur. However, the reliability and reproducibility of these layers is an important issue because of the high temperatures required in MEMS packaging process steps. The best way to avoid stiction failures is to eliminate presence of contacting surfaces by using adequate design or to enhance restoring force. In case of MEMS micromirrors, excessive adhesive force between the landing tip and its landing site may lead to stiction failure of the device. When the electronic reset sequence is applied, sufficiently high adhesive force may obstruct the movement of the mirror. Capillary water condensation causes the landing tip of the mirror and adequate landing site to become stuck. A partial vacuum is produced at the interface due to the surface tension and great forces are required to pull the tip and the landing site apart. For this reason, the usually used method for MEMS micromirror stiction elimination are implementation of springs on the landing tips of the mirror (Figure 19.) [13]. When the mirror landing tip lands on its landing site the spring bends and stores energy that will assist the mirror in taking off the surface when the reset pulse is being applied and bias voltage is being removed.

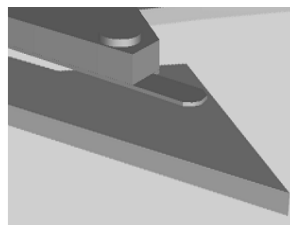


Figure 19. Stiction elimination: schematic of the spring tip and its landing site

Friction is another mechanism that impacts the lifetime of MEMS device. It is of interest when sliding/rotating optical MEMS are in question and it sets the upper limit of MEMS device lifetime. Friction occurs when two contacting surfaces move against each other. Repeated formation and breaking of contact lead to increase of the contacting stress. When the stress exceeds the material yield strength, material loss occurs. Significant wear finally causes mechanical failure. Frictional wear can be reduced by application of certain coatings (e.g. tungsten). Also, humidity can reduce wear by forming surface hydroxide but it can lead to increased stiction. However, elimination of rubbing surfaces during optical MEMS design phase is the best way to avoid friction [14]. Figure 20. shows an example of friction when optical MEMS devices are in question. A microengine in combination with the microtransmission is often used to drive a pop-up micromirror up, out of the plane. Sets of microgears provide linear motion with high degree of force. Intimately contacting surfaces repeatedly move against each other causing the augmentation of asperities that may lead to accumulation of debris and, finally, mechanical failure.



Figure 20. Schematic of the microengine affected by friction and wear

Lifetime of optical MEMS devices can also be affected by fatigue. Repeated motions can cause stress that even significantly below the crack strength, leads to crack growth and eventual failure. Crack growth can be facilitated by stress corrosion and for that reason is highly sensitive to humidity. Both silicon and polysilicon are not immune to fatigue. Stress engineering during design phase and materials selection can reduce the problem, but humidity control is the key factor to fatigue elimination. Micromirrors are often affected by fatigue. Each micromirror is hinged so it can rotate. Having in mind that each mirror will be switched thousands of times per second, hinge fatigue should be taken into consideration. In order to avoid fatigue, micromirror hinges are usually realized using thin-film technology. The fatigue properties of thin-film layers are different from those of bulk materials. Metal thin films exhibit much less fatigue than do their macroscopic counterparts since they do not have internal crystal structure because they are just a few grains thick [14]. Thin-films have less stiffness and therefore are less prone to breaking. Fatigue causes movement of dislocations to the surface of the material forming fatigue crack after enough damage has been accumulated. For that reason, not enough damage will accumulate on the thin film surface to form fatigue cracks. However, having in mind that the fatigue properties of thin films are often not known and that fatigue predictions are error prone, hinge structural materials should have material strength that far exceeds the maximum stress expected.

When strain varies with time under the constant stress, creep occurs. Movement of dislocations and diffusion of atoms trigger the deformation. It depends on the material in question, grain size, temperature and initial stress. Over the time surface flatness becomes affected by creep as well as parameters of mechanical parts. Metals are known to creep under stress, while silicon and polysilicon are more robust against creep as brittle materials. For optical MEMS devices silicon is often coated with a thin metal film. Reflective metal coatings on micromirrors are required for the desired optical performance. However, micromirrors can become deformed during annealing. After cooling, micromirrors can have significant curvature due to the CTE mismatch between silicon and metal. When single sided metallization is in question, the curvature will slowly decrease as the metal creeps and not the underlying silicon. When symmetrical mirrors are in question, where both sides are metallized using two metal films deposited under different conditions, an uncontrolled increase in mirror curvature can be

expected. By increasing silicon thickness flatter micromirrors can be obtained. However, that would affect the resonant frequency, response time and susceptibility to mechanical shock. It can also lead to very high drive voltages, with associated dielectric breakdown and dielectric charging issues [15]. When micromirror hinges are in question, unlike hinge fatigue, creep induced hinge memory poses a significant threat to MEMS micromirror device reliability. It is very significant life limiting failure mode that occurs when a micromirror operates in the same direction for a long period of time. When the bias voltage is removed the mirrors should return to a flat state. Their return to a non-flat state is known as a hinge memory effect (Figure 21.). The angle between the flat and non-flat state is called residual torque angle. As this angle increases, at one point the mirror will not be able to land to the other side. Main contributors to hinge memory failure are duty cycle and operating temperature, but the main cause of this type of failure is the creep [12]. As structural mirror beam materials high melting point compounds are being used such as Al_3Ti , AlTi , AlN because high melting point metal often has low creep. Since it is obvious that temperature affects the lifetime of the micromirror device, thermal management is very important. In order to keep temperature in the device within the acceptable range, heatsinks are being used. Adequate thermal management significantly influences lifetime of the device allowing the mirrors to be efficiently controlled over a longer period of time.

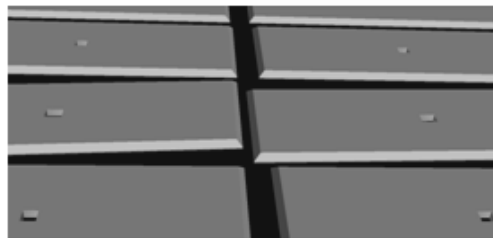


Figure 21. Schematic presentation of the hinge memory failure mode

Common cause of electrical failure when MEMS devices are in question is anodic oxidation on unpassivated silicon wiring and electrodes. Positively biased electrode oxidizes under the high humidity. Negatively biased electrode remains unaffected. In order to eliminate anodic oxidation the primary goal is moisture elimination by using hermetically sealed packages. Also, for any silicon used as conductors, passivation should be provided.

Environmental robustness is a great reliability concern for all MEMS devices. Examination of micromirror environmental robustness is based on standard semiconductor test requirements such as temperature cycling, thermal shock, moisture resistance, ESD, cold and hot storage life, etc. Similar to ICs, MEMS devices are also susceptible to ESD damage. Sudden transfer of charge that occurs between MEMS device and person or piece of equipment causes ESD damage when on-chip protection circuits are not available because of the incompatibility to IC processing or design complexity (Figure 22.). ESD proof clothing and tools are obligatory when elimination of ESD in MEMS fabrication is in question.

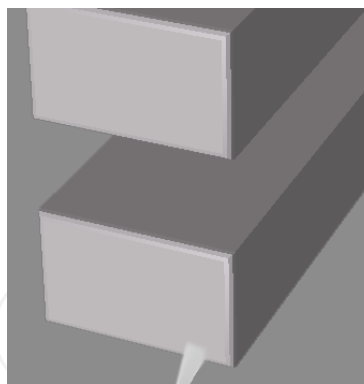


Figure 22. Schematic of ESD damage: polysilicon comb finger

Another large optical MEMS reliability concern is vibration [16, 17]. Due to the sensitivity and fragile nature of many MEMS, external vibrations can have disastrous implications. They may cause failure through inducing surface adhesion or through fracturing device support structures. Long-term vibration can also contribute to fatigue. Another issue can be shock. Shock is a single mechanical impact instead of a rhythmic event. A shock creates a direct transfer of mechanical energy across the device. Shocks can lead to both adhesion and fracture. Although optical MEMS devices seem fragile due to their small size, their size proved to be one of their greatest assets. Small size enables their robustness. They proved to be able to sustain low-frequency vibrations and mechanical shock without damage. However, besides being an asset, size may be related to another type of failure mechanism. Dimensions of MEMS devices are so small that the presence of the smallest particle during fabrication may cause non-functionality of one or more devices (Figure 23.). For that reason the source of each contaminating particle should be detected and eliminated, especially during packaging, because particles sealed in the package may affect operation of the device during its lifetime. Hermetic packaging can provide adequate protection, electronic contacts and, if necessary, interaction with the environment through the window transparent to light. Also, vacuum packaged devices eliminate effects of capillary stiction. Failure due to contaminations introduced during packaging is the most common failure mode of optical MEMS devices.

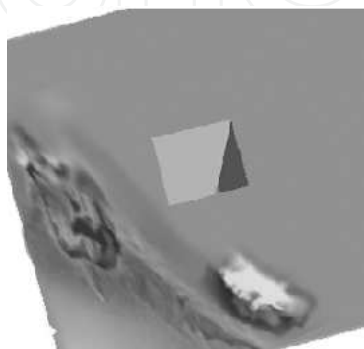


Figure 23. Schematic presentation of micromirror failure caused by particle contamination

5. Conclusion

Optical MEMS devices are still relatively unproven in telecommunications applications and the most optical MEMS devices are not yet fully qualified. A brief insight in reliability of optical MEMS devices for telecommunications applications has been presented in this chapter. Several major reliability issues have been discussed: stiction, friction, fatigue, creep, etc. However, developing reliable optical MEMS component is non-trivial. Production of reliable optical MEMS device requires sophisticated design considerations and better control of microfabrication processes that are used in realization of MEMS device. One of the challenges is providing temperature insensitive, particle free, mechanically stable environment. Usually submicron alignment tolerances are required and high port count optical MEMS require handling and packaging of large numbers of optical fibers, micromirrors, lenses and electrical control leads. Light collimation and focusing, wavelength separation, precisely controlled, large, flat and highly reflective microstructures, significant control electronics are just some of the issues. Reliable packaging is an imperative. Reliable package must not prevent mechanical action of moving parts of the structure, but it should prevent transfer of heat, moisture, outgassing, etc [18, 19]. Another issue is the need for credible testing techniques applicable during fabrication, assembly and packaging, as well as during operational lifetime of the device. As the number of ports grow testing requirements become challenging since multiple, expensive laser sources and flexible test architectures are required. Besides all that, competing technologies pose significant threat to optical MEMS applications (Table 3.) Micromotors, LCD devices, planar waveguides, solid state technologies such as Lithium Niobate and Semiconductor Optical Amplifiers (SOA) can realize various wavelength and fiber management component functions although many coincide that 3D optical MEMS is the only all optical technology that can integrate such complex switching functions in a small package. The key to successful future of optical MEMS in telecommunications market lies in improvement of device structure, materials and processing. Lower losses are required that can be obtained through flatter micromirrors and better quality lenses. More ports are required to handle the expansion of the traffic and reliable and cost-effective packaging is needed to house thousands of tiny fragile MEMS structures. It should be pointed out that industrial standardization of MEMS technology is at least several years away [17, 20] and till then optical MEMS devices will be custom made according to customer requirements. The lack of information flow, as well as reluctance in sharing experience will keep optical MEMS devices from full commercialization although there are several commercially successful applications.

| Technology | Cost | Perf. | Scale | Reliab. | Integ. | Maturity |
|------------------|--------|----------|----------|----------------|--------|----------|
| MEMS | strong | good | strong | not determined | strong | moderate |
| Micromotors | weak | strong | weak | moderate | weak | strong |
| LCD | weak | strong | moderate | weak | weak | good |
| Planar Waveguide | good | good | moderate | good | strong | moderate |
| Solid state /SOA | weak | moderate | moderate | not determined | good | weak |

Table 3. Comparison of the Technology Alternatives for Wavelength Management/Fibre Management components [21]

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Author details

Ivanka Stanimirović and Zdravko Stanimirović

IRITEL A.D., Belgrade, Republic of Serbia

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