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MEMS for Optical Functionality

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Abstract. We discuss key features of MEMS technology which enable new functionalities of microphotonic devices, that can by summarized as "arrayability", i.e. the ability to make massively parallel optical devices in a small form factor, "reconfigurability," the ability to change optical properties spatially and temporaly, and "nano positioning," the ability to position micro-scale devices with nanometer accuracy. We present an overview of cases where a combination of these features has led to commercial successes by creating new optical functionalities, and discuss materials-related challenges and future trends for optical MEMS research and commercialization.

Keywords: MEMS, optical functionality, arrayablity, reconfigurability, nano-positioning

1. Introduction

The field of optical micro-electro-mechanical systems (optical MEMS or MOEMS) has experienced rapid growth in the recent decade, especially in the late part of the 90's. The primary application domains, ordered by approximate precedence in embracing MEMS technology, have been: projection displays, components for optical fiber communications (sources, switches, cross-connects, routers, etc.) and optical sensing and imaging. The strong—albeit unsteady—market demand, coupled with challenging intellectual problems sparked extensive research and development activities in both academia and industry. In tune with these efforts were major funding initiatives, first by governments, and subsequently by venture capital and other private investors. Many novel designs, devices, and systems resulted, and some products are in wide commercial use today, especially in the projection display business.

One aspect of MEMS usage in optical systems is miniaturization. This is important in many cases from the point of view of footprint and materials costs. However, miniaturization alone could not have been sufficient to make optical MEMS technologies commercially successful in most cases. The key success factors of many optical MEMS products have been the new optical functionalities enabled by the use of MEMS. Among many benefits of MEMS technology that were reviewed as core success factors, the ones that stand out are:

(1) "arrayability," which is the term that we use for the ability to place tiny devices in large-scale arrays;
(2) "reconfigurability," i.e. the ability to reconfigure the optical properties, spatially and temporally, via localized micro-actuation and/or deformation; and
(3) nanoscale precision control of position and alignment for microscale devices, which we will refer to as "nano positioning."

Our goal in this paper is to review a few selected optical MEMS devices, placing emphasis on the emergence of these new functionalities and their impact on optical products. In Section 2, we begin with a historical introduction, tracing the origins of today's optical MEMS devices to solid state research in the 70's and 80's. We then present a classification of MEMS devices in Section 3. In Section 4, we describe in some detail selected MEMS product cases, and argue specifically why the three functional requirements of arrayability, reconfigurability and nano positioning result in unique system properties. We conclude with some discussion on the future promise and challenges facing optical MEMS and materials research in Section 5.

2. Historical Background

The first demonstration of a miniature ($\sim 2 \times 2$ mm) torsional mirror was by Kurt Petersen, while at IBM [1]. Quoting from this paper, Peterson predicts that "... silicon micromechanics may eventually find a practical implementation for displays (especially if silicon-driving circuitry can be integrated on the same chip, matrix addressing the two-dimensional array of mirrors-all electronically)." This statement proved to be truly prophetic, given the current success of MEMS display products such as Texas Instruments' Digital Micromirror Device (DMD) [2]. It can also be seen that micro-mirror array based displays are one of the oldest threads in optical MEMS technology [2–5]. The trend led to numerous other applications for micro-mirror arrays, as we will see later in this paper.

The key idea of a DMD based display is to provide an array of bistable micro-mirrors to intercept the light path so that one of the mirror positions directs the light onto a screen, whereas the other position directs the light onto a block where it is absorbed. Therefore, each mirror modulates a different pixel. By dithering the mirror, gray-scaling can be accomplished as well. Color displays can be obtained by standard techniques such as a color wheel (most compact and cheapest, and therefore most common) or three mirror arrays (for red-green-blue) combined with dichroic optics and projected onto the same screen. This technology is discussed in more detail in Section 4.1.

An alternative MEMS display design was proposed in 1994 by a Stanford group, led by David M. Bloom [4]. The modulation concept, as opposed to micro-mirrors, was to modulate the light via diffraction from miniature gratings, one per pixel on the screen. This concept was termed the "grating light valve" (GLV) by its inventors. The structure and micro-mechanics of the GLV are discussed in Section 2.2. In the most common GLV implementation, the light is sent through a *Schlieren* system which blocks the 0th diffraction order and lets the ± 1st diffraction orders through. So, when the grating is inactive there is no light transmitted to the screen, whereas upon actuation of the grating the corresponding pixel is illuminated by the interference pattern of the $+1$st and -1st orders. The key difference between the GLV and micro-mirror based displays is that the GLV actuators are long (~ 0.5 mm) thin ($\sim$few μm) beams alternating between two vertical positions and, hence, can be actuated faster by orders of magnitude (10 s of MHz) than the bulkier torsional micro-mirrors (typically kHz). Therefore, typically the GLV needs not be a full 2D pixel matrix, but is instead implemented as a single row, rapidly scanned in the vertical direction to produce the full display. For the same reason, the GLV row can have many more pixels than the linear dimension of a micro-mirror based display of the same generation. However, there is a caveat: since the modulation of light is based on diffraction, the efficiency is reduced, and high-power laser sources are required to obtain sufficient brightness (whereas micro-mirror based displays work with a simple light bulb.) Therefore, the GLV is naturally targeted towards high-end projection markets that can afford the price and space taken by the bulky laser sources in return for excellent resolution of thousands of pixels per dimension over a large projection area, e.g. digital cinema. On the other hand, micro-mirror displays have been successful at the lower end mass market of computer and video projectors, where XGA resolution suffices and price/footprint/weight are critical factors.

The comparison of DMDs and GLVs is interesting because it points out how the intricate relationship between optical principle (reflection vs. diffraction) and moving parts (tilting rectangular plates vs. thin beams moving vertically) can influence seemingly extraneous factors (light source selection, resolution, footprint, price) and radically change the outlook of an optical MEMS product. Interestingly, it is now public information that Texas Instruments considered alternative markets for its DMD product, such as laser printers, before discarding them in favor of the display market [5].

A natural extension of the micro-mirrors theme was what is now known as the "silicon micro-optical bench," where optical arrangements were miniaturized to the surface of a silicon chip, whereas with standard optics they would normally take several square feet on an optical table [6]. Several ingenious concepts were demonstrated for dealing with light at these small scales, including pop-up micro-mirrors, diffractive micro-lenses (Fresnel zone plates) and on-chip sources [7]. Such optical systems have great potential in a number of applications such as optical processing [8] and sensing [9]. However, the major application that emerged from these efforts was optical networking, because it was in that area that the need for miniaturization was the most pressing. Primarily, the technology driver was the desire to reduce the size of a router for a dense wavelength division multiplexing (DWDM) node from that of a large refrigerator to a briefcase, figuratively speaking. That need was important not only because such nodes were anticipated to be placed at central spots in metropolitan areas, where real estate is expensive, but also because the capacity demand was projected to increase at exponential rates.

3. Classification of Optical MEMS Devices

Walker and Nagel [10] studied and reviewed MEMS technologies for optical applications and classified them depending on the types of micro-optics used and optical functions performed, such as: sources, detectors, free space optics, wave guided optics, transmissive optics, reflective optics, diffractive optics and interferometric optics as shown in Table 1.

Micromirrors have been used to steer the optical beam path through the waveguide, in and out of optical fibers and to redirect light out of coaxial paths. Many of the reflective mode MEMS devices have been developed on bare silicon [11], metallic surfaces, and differential index multilayers. The VCSEL (vertical cavity surface emitting laser) is a typical MEMS device built on differential-index multilayers to achieve high reflectivity [12]. The mirror array has been the most successful MEMS application in optics and has been used for projection displays [2–5], free space optical switching [13] among many others. Diffractive optics has enabled planar microlenses, Fresnel zoneplate lenses and gratings. Efforts have been made to make them tunable in digital [14] or analog manners [15]. In the aforementioned devices, light propagates in free space before reaching the actuator, which deflects or diffracts it. An alternative for handling light is to confine it in a waveguide. It then becomes impossible to interact with it directly; however, one can still modify light propagation by bringing a MEMS actuator close enough to the waveguide that light from the waveguide couples evanescently with the actuator [16, 17, 23]. Typically, evanescent coupling results in phase delay, which in turn can be used for interferometric switching, etc.

Table 1. Key optical devices developed based on MEMS technology.

	Devices	Products
Reflective mode devices	Micro-mirror array for information displays, Phase correction piston arrays	Texas instrument's DMD, Daewoo's TMA
Diffractive mode optics	Fresnel zone plate Tunable Gratings	Silicon Light machine's GLV
Free space optics	3-D optical switches 2-D optical switches	Optical micro Machines, Lucent Lambda router, Xros cross-connect
Waveguide optics	Planar waveguide Fiber inline alignment	
Interference mode devices	Tunable Fabry-Perot external cavity lasers	
Detectors	Bolometer	Honeywell-bolometer array
	Micro-spectrometer	Polychromator
Transmission devices	Optical micro shutters and choppers	
Adaptive optics	Deformable mirrors for aberration correction	
Sources	VCSEL External cavity laser	

Optical MEMS research has demonstrated a large number of new devices and systems. Some of the optical MEMS devices have become great commercial successes, while many have not. Miniaturization alone is inadequate to create new markets and/or to become more competitive. The most successful optical MEMS devices commercially have been those, which combine at least two of the three functional requirements among "arrayability," "reconfigurability" and "nano positioning." Some of these successful optical MEMS cases are listed in Table 1.

4. MEMS Products: Case Studies

The study of optical MEMS technology reveals that the same basic optical MEMS technology has often been used for radically different applications, e.g. micromirrors for displays versus cross-connects in telecommunications systems. The reason this broad sharing has been possible is that the applications share at least some of the functional requirements mentioned earlier, namely arrayability, reconfigurability, and nanopositioning. In this section, we overview some optical MEMS products, which emphasize the significance of these attributes for commercial success.

4.1. Digital Micromirror Devices (DMD) for Digital Light Processing (DLP)

In the digital information era, more multimedia applications require brighter and larger-screen displays as well as compact and personalized displays.

Conventional film projectors cannot display digital multimedia information. Many electronic projection display technologies have been developed since the first CRT projection display was demonstrated by RCA in the 1940's. At present, there are two major projection display technologies competing in the rapidly growing market: DLP (Digital Light Processing) and high-temperature Poly LCD projection. DLP is very strong in the expensive large venue projector market and low-cost ultra portable projector market, while LCD projection is strong in the middle arena.

The large venue projectors can project more than 5,000 ANSI lumens on to a screen and are very expensive, heavy and bulky, and need special care for installation and maintenance. 3-chip DLP technology is dominant in this category given its ability to deliver up to 10,000 lumens of light at much lower cost than existing CRT projectors or ILA (Illuminated Light Amplifier) projectors from Hughes-JVC. The heat generation by light absorption and photo-degradation still limits the use of high-power light sources for LCD. The biggest market segment is the so-called portable projector group and about 95% of projectors in the world market fall within this category. Currently, the mainstream projection technology for this category is the one-chip DLP. The one-chip DLP engines tend to be more compact than 3-panel LCD engines, and dominate the market with the light weight mobile projectors under 3-pounds.

At the core of a digital light-processing projector is Texas Instrument's patented Digital Micromirror device (DMD) [2], a MEMS chip with an array of micromirrors mounted on its SRAM surface. Therefore, arrayability is the key optical functionality offered by the DMD device. Each of these tiny mirrors tilts in response to electrostatic charges on the mirror's mounting substrate. Depending on the degree of tilt ($+10°$, $0°$, $-10°$), individual mirrors reflect on/off control of light from the projection lamp. Controlling the duty ratio of on/off stages, 10 bit (1024) grayscales can be created digitally for each primary color. The color image is then accomplished with either rotating color wheels with one DMD chip or dichroic mirrors and combining prisms with three DMD chips for red, green and blue. Incoming video or graphic signals are turned into a digital code of binary data (0s and 1s) that tilts the DMD mirrors accordingly. By throwing the modulated light through the projection lens with precise digital signal processing, a large screen full color image is projected on to the screen.

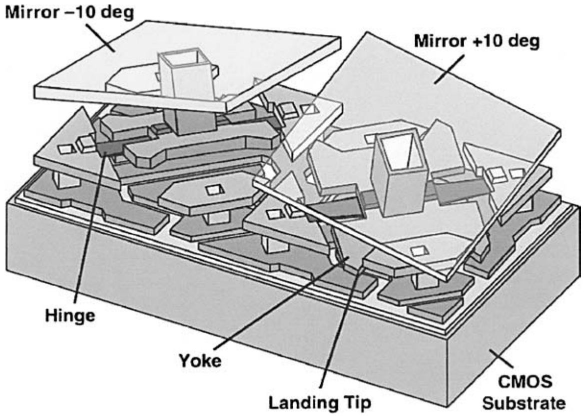

Fig. 1. Two DMD pixels (mirrors are shown as transparent) in opposite tilting states [2].

The DMD chip has micromirrors on top of a completed CMOS memory circuit as shown in Fig. 1. The DMD chip is monolithically fabricated by CMOS compatible processes. Each micromirror switch has an aluminum mirror, sized 16 μm by 16 μm. The mirror is tilted along the hinge in diagonal direction, through electrostatic attraction produced at the air gap under the mirror and on top of the CMOS. The key technical concern on the DMD chip has been the issue of mechanical reliability. Due to the high speed PWM (pulse width modulation), the torsional hinge requires reliability of more than 10^{13} cycles through its operating life. Hinge failure and hinge memory problems have been solved by continuous design improvements over the last ten years.

4.2. The Thin Film Micromirror Array (TMA)

The Thin-film Micromirror Array (TMA) is a reflective type spatial light modulator fabricated with MEMS technology [3]. Micromachined thin-film piezoelectric actuators are used to control the tilt angle of each micromirror, which defines the gray scale of the matching screen pixel. The light reflected on a mirror surface forms a rectangular shaped image on the projection stop plane and this image moves along the horizontal axis as the tilt angle changes. When a mirror does not tilt, all of the light reflected by the mirror is blocked and absorbed by the projection stop and the pixel image on the screen is in the darkest state (black). When the mirror is fully tilted, all of the light reflected by the mirror goes out through the projection stop and the pixel image is in the brightest state (white). The amount of light that passes through the projection stop is linearly proportional to the tilt angle of each mirror. The precise control of the tilt angle can generate gray levels on the screen in between the brightest and the darkest state. Therefore, the TMA shares the arrayability functional requirement with the DMD device, with the additional functional requirement of nano positioning of the miniature mirrors to control grayscale. The application of piezoelectric actuation to array MEMS technology was the key factor for achieving these functional requirements.

Each pixel consists of a dual layered structure, a mirror layer and an actuator layer. Mirror-tilting is performed by thin-film piezoelectric actuators in the form of micro-cantilevers. As shown in Fig. 2, a mirror is connected to the underlying cantilevers through a support post. The cantilevers are anchored to the underlying PMOS substrate. A cantilever consists of the non-stoichiometric silicon nitride (SiN_x) supporting layer, Pt bottom electrode, PZT layer, and top Pt electrode. When an electric field is applied between the two electrodes, the piezoelectric layer shrinks in the horizontal direction and expands in the vertical direction. Since the neutral plane of the cantilever shifts toward the bottom electrode due to the thickness of the supporting layer, the mechanical contraction of the piezoelectric layer causes an upward vertical deflection of the cantilever and, consequently, the tilting of the mirror on top of it.

The TMA chip is monolithically fabricated over a PMOS active matrix by surface micromachining techniques. The active matrix is a transistor array that addresses the video signal to each pixel. The size of each mirror is 49×49 μm for XGA format TMA chips. The mirror layer is made of aluminum and is sputter-deposited on the second sacrificial layer. The aluminum layer is patterned to make mirror shapes by a dry etching process. The sacrificial layers are removed to form the air gaps. Since two different materials are used as sacrificial layers, the release process is performed in two steps. First, the second sacrificial layer is removed through the openings between mirrors by plasma etching. After completely removing the second sacrificial layer, the first sacrificial layer is exposed to air and removed by XeF_2 vapor etch process. Both release methods show fast lateral etching rates, leave no residues, do not etch or damage the other layers such as Al and PZT. Figure 2 presents the SEM photographs of the completed VGA and XGA format TMA chips after the release process. The 800,000 finished mirrors in an XGA format TMA chip have initial tilting positions of $0^\circ \pm 0.03^\circ$. A working projector prototype of 5,400 true ANSI lumen was presented at the Asian Display 1998 with three TMA chips and a 1 kW Xenon lamp. The prototype showed overall light transmitting efficiency of 22%.

TMA's PZT microcantilever actuators have been used not only for display, but also for fast-scanning AFM tip arrays [18] and strain-tuning of photonic devices [19].

4.3. *The Grating Light Valve (GLV)*

The GLV is a unique MEMS product that acts as a dynamic, tunable grating to precisely vary the amount of laser light that is diffracted or reflected [4, 14]. The Grating Light Valve is comprised of a series of ribbons on the surface of a silicon chip as shown in Fig. 3, which

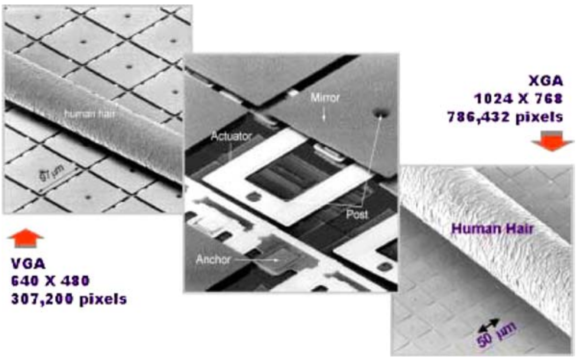

Fig. 2. Piezoelectric cantilever-actuated micromirrors for TMA display [3].

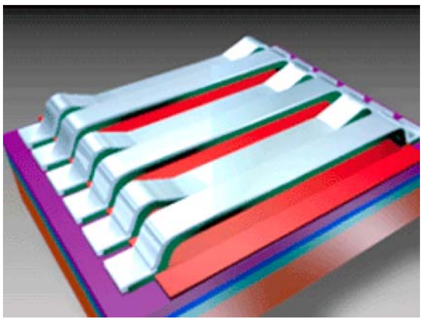

Fig. 3. Grating light valve ribbons to form a digitally tunable diffraction grating [4].

can be moved up or down over very small distances by controlling the magnitude of electrostatic forces between the ribbons and the substrate. The ribbons are arranged such that each element is capable of either reflecting or diffracting light. This allows an array of elements, when appropriately addressed by control signals, to vary the level of light reflected off the surface of the chip. This control of light can be analog (variable control of light level) or digital (switching light on or off). Because GLV devices utilize the principle of diffraction to switch, attenuate and modulate light, they are highly accurate, simple to manufacture, and have relatively high power handling capabilities. However, because the projected light is obtained from diffraction orders rather than direct reflection, some loss of incident power is inevitably incurred.

Each GLV element consists of six dual-supported parallel ribbons formed on silicon nitride and coated with a reflective top metal layer. The top is used also as an electrical conductor to create electrostatic attraction to the bottom common electrode plane, as shown in the figure. The on/off switching speed of GLV is as fast as 20 nanoseconds, which is much faster than that of existing tilting mirrors. Current GLV devices are claimed to have a diffraction efficiency near the theoretical maximum of 81%, fill factor of 95% and top layer reflectivity of 91%, with an overall device efficiency of about 70%. This optical efficiency corresponds to an insertion loss of about 1.5 dB.

The large screen projection display has been the primary target application of GLV technology. It has been demonstrated that a front projection system for a $1{,}920 \times 1{,}080$ HDTV image can be made with the scanning of a linear GLV array of 1080 pixels. However, due to the keen competition between DLP and LCD and the consequent price war in the consumer market, the need of the additional cost of scanning mechanism and the speckled image resulting from the laser beam, the commercialization of GLV projection display has been significantly delayed at the present time. However, the digital tunability of GLV has successfully introduced many reconfigurable optical devices, such as reconfigurable blocking filters, dynamic gain equalizers and GLV printers.

4.4. The Polychromator

The Polychromator is an electronically programmable, dark-field correlation spectrometer system based on a programmable MEMS diffraction grating developed in a joint effort of Honeywell, Massachusetts Institute of Technology, and Sandia National Laboratory [20]. Rather than serving as means for projecting images, the Polychromator is a newly developed sensor capable of distinguishing between a number of different gaseous species remotely by utilizing a combination of optics and MEMS. This device provides sufficient sensitivity and selectivity to detect very small amounts of gaseous species for security and biological imaging applications.

The Polychromator chip does not need a reference cell, which many conventional gas analysis techniques require. Instead, the reference spectrum for each correlection measurement is formed by modulating the Polychromator grating. The latter consists of thousands of mechanical beam elements on a silicon wafer. The beams and actuators are manufactured with standard thin film process techniques. Each grating element is 10 microns wide and one centimeter long and is designed to move up and down as shown in Fig. 4. Light from the environment (e.g., a suspicious "gas cloud") is directed onto the chip after being collected by an optical relay, such as a telescope or binoculars. The grating is then programmed to "match" the incoming spectrum with a reference spectrum. One thereby determines whether the gas cloud contains the substance that the grating was programmed to match or not. Evidently, the key functional requirement in this device is reconfigurability. The Polychromator replaces a bank of gas tanks containing the reference chemicals, which would otherwise have to be used to implement correlation spectroscopy.

4.5. Uncooled IR Bolometers

Infrared sensors allow objects to be identified and imaged according to their body temperatures. The ability to image by temperature allows for remote thermometry and the ability to see through darkness, smoke and inclement weather. Until recently, high performance cameras have required expensive cooling to cryogenic temperatures to detect photons and to suppress thermal noise. More recently, detectors operating at room temperature have been developed using micromachined bolometers and pyroelectric detectors. Uncooled infrared FPA (focal plane array) structures can image infrared scenes generated by humans and objects by transforming the induced temperature changes in the

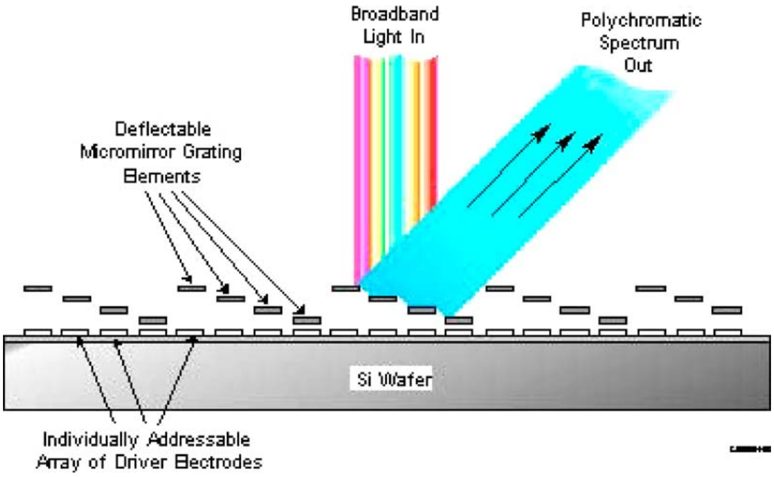

Fig. 4. Polychromator developed by MIT, Sandia and Honeywell [20].

detectors into electrical signals. Uncooled bolometers utilize the temperature-induced changes in electrical resistance, polarization, and dielectric properties of the detector materials.

Detectors on uncooled FPAs need high thermal isolation from the substrate to achieve high sensitivity. MEMS technology plays a key role in enabling the fabrication of very low thermal mass detectors with exceptionally high thermal isolation. Wood and colleagues [21] fabricated a 2-dimensional array of resistive bolometers with the thermal isolation structure as shown in Fig. 5. The silicon nitride membrane, supported by two tethers, floats above the silicon substrate. The size of the tether was adjusted to provide a thermal conductance of 8×10^{-8} W/°K. The thermal mass of the plate was 8×10^{-10} J/°K and the thermal response time was 10 msec. Operating at 30 frames per second with f/1 optics, the measured NETD (noise equivalent temperature difference) was 0.04°C with vanadium oxide as the resistive material. Honeywell has commercialized this design into products. Cole and colleagues developed a monolithic 2D array using the pyroelectric properties of lead titanate with a similar thermal isolation scheme as the one developed by Honeywell. The predicted NETD of this device was 0.01°C and has been adopted for many military applications. A tri-level design was fabricated by Kim and colleagues [22] as shown in Fig. 6. The key objectives of this design were to increase the fill factor and to minimize the thermal conductance. Kim et al. achieved a fill factor of over 92% compared to a fill factor of 62% for Honeywell's coplanar design for a similar thermal conductance.

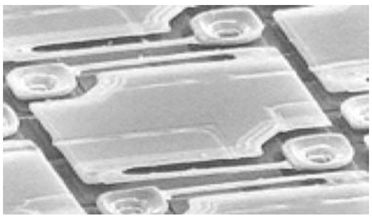

Fig. 5. Uncooled bolometer pixel (coplanar design by Honeywell) [21].

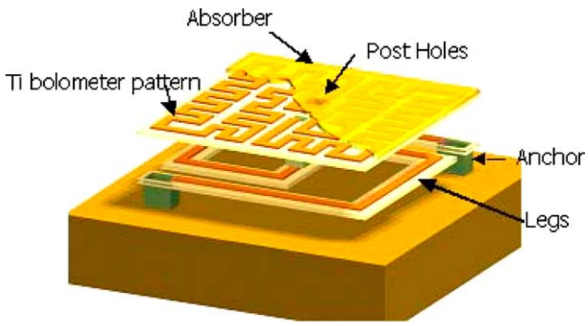

Fig. 6. Tri-level uncooled bolometer structure by Kim et al. [22].

4.6. *MEMS for Integrated Optics*

The optical MEMS examples given so far can be classified as "free space optics," since the moving structures

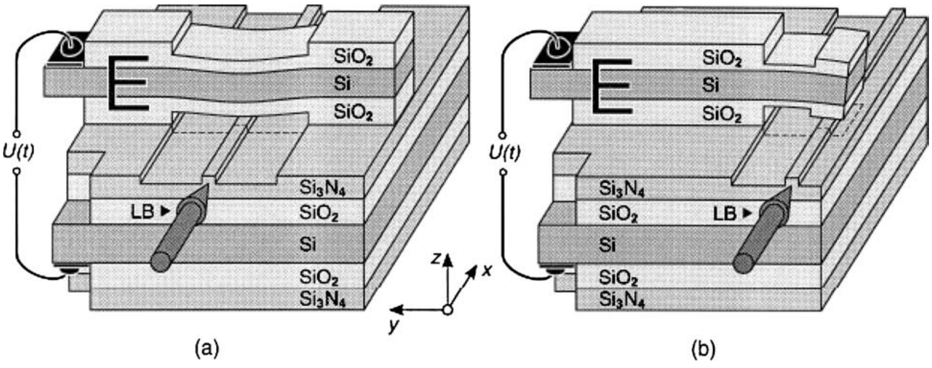

Fig. 7. MEMS for switching and tuning of integrated optics. (a) A bridge structure and (b) a cantilever suspended over an optical waveguide change the mode shape, resulting in phase shift of the guided light [23].

(mirrors, grating beams, etc.) interact with light in its free space propagation (radiation) mode. By contrast, light in integrated optics is confined to optical waveguides laid out on top of a proper optical material, as shown in Fig. 7. In this case, it is clearly difficult to control light propagation by means of mirrors or diffraction gratings in direct contact with the light beam. However, an alternative means of controlling light via mechanical structures in integrated optics still exists, based on evanescent coupling between the guided light and dielectric structures such as bridges or cantilevers suspended over the waveguide [23]. These structures are basically phase modulators, and they work by altering the effective refractive index of the waveguide and, hence, the group velocity of light. The demonstration reported in reference [23] was a 2 × 2 optical switch of the Mach-Zehnder interferometer type, where the phase delay was controlled by the MEMS device via the aforementioned phase modulation property, as opposed to the typical thermo-optic effect.

4.7. *Tunable Fabry-Perot Cavities*

The "nano positioning" functionality is critical for applications such as tunable laser cavities, where the cavity length specifies the lasing wavelength. This requirement led to a successful marriage between the positioning capabilities of MEMS and the Vertical Cavity Surface Emitting Laser (VCSEL) technology [24]. VCSELs had been invented earlier [25–27] as a means to get solid state lasers to emit light in the vertical direction with respect to the substrate, which is preferable for numerous applications in illumination, optical interconnects, etc. In the original design, the top reflector of the VCSEL device was a distributed Bragg reflector (DBR) structure. In the MEMS implementation [24], the reflector was attached to a movable cantilever structure which was capable of tuning the resonance wavelength by as much as 15 nm with a low actuation voltage, approximately 5.7 V (Fig. 8). Since these first attempts, tunability has improved to cover the entire 1530–1620 nm range of dense wavelength division multiplexing (DWDM) communications [25].

4.8. *Strain-Tunable Optical Devices*

Tunable gratings such as the GLV and the Polychromator can be described as "digital," since actuation results in change of the grating period and modulation profile by discrete amounts, equal to the size of the micromachined ribbons. Therefore, reconfigurability is limited by the smallest feature size that the available lithography can deliver in a structurally sound configuration. To cover the range of reconfigurability at ultra small scales, a new class of "analog" tunable gratings has been developed [15, 19]. Nano-positioning is an additional functionality offered by these devices, necessary for reconfiguration to be as accurate as necessary for optical applications. However, another aspect of reconfigurability is sacrificed: e.g., these analog devices cannot perform the polychromator function in a correlation spectrometer. Analog tuning of a diffractive grating is achieved by transverse actuation of the grating structure using thin-film piezoelectric actuators [15, 19] or electrostatic comb drives with flexured gratings [15], as illustrated in Fig. 9.

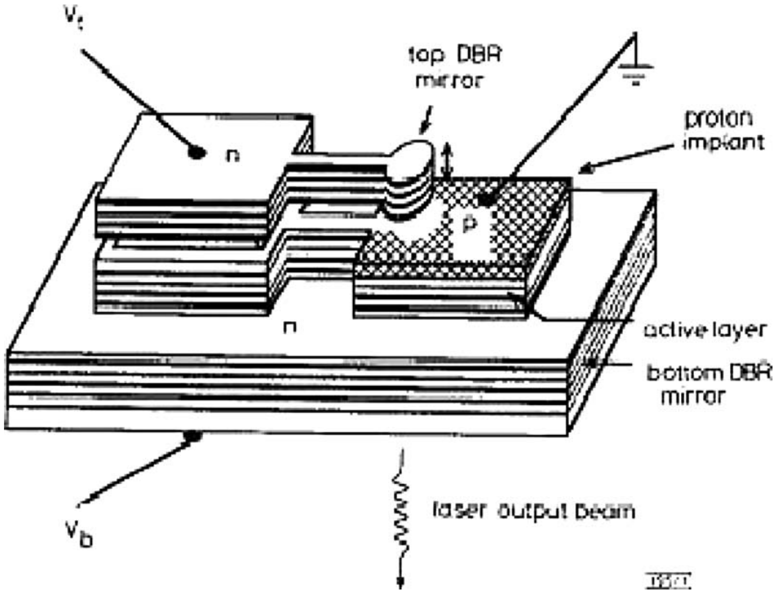

Fig. 8. Tunable VCSEL structure (after Ref. [24]).

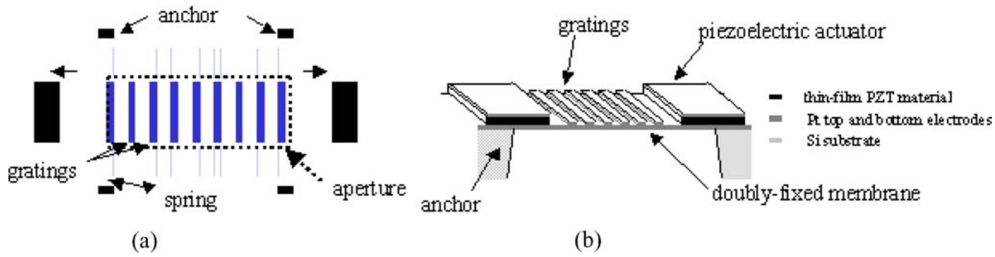

Fig. 9. Analog-tunable Gratings: (a) Electrostatic comb drive actuated grating with flexured ends [15]. (b) Piezoelectric thin film (PZT) actuated grating on a solid membrane [19].

To achieve transverse actuation, the grating grooves are defined on a floated deformable membrane. Then, the membrane is mechanically stretched by thin-film piezoelectric actuators. The piezoelectric actuators, a lead zirconate titanate (PZT) layer sandwiched between top and bottom electrodes located at both ends of the membrane, are capable of producing sufficient force to stretch the membrane up to 0.3% strain, or equivalently, 0.3% diffracted angle change. This is accomplished through the application of an electric field across the PZT film to result in its shrinkage, due to reorientation of crystallographic domains. This shrinkage on the PZT film correspondingly strains the membrane in the transverse direction. An alternative method of transverse tuning of the grating period involves using electrostatic comb-drives on a more compliant grating structure [15]. Based on the fine voltage control previously demonstrated on a thin-film piezoelectric material, the resolution of the grating period change can be better than 0.5 Å (corresponding to angular resolution better than 2.1 μ radians), although the current metrology limits the observable resolution to the order of 1 nm. Out-of-plane membrane tilt and bending, asymmetrical rotation of the membrane during actuation, thermal disturbances, modal vibrations, and optical detection techniques may limit the lowest achievable resolution. The demonstration of the tunable diffractive grating shows tuning of the first diffracted order angle up to 486 μ radians at 10 V, with minimum observable grating period displacements at approximately 0.6 nm at 1 V.

Reconfigurability combined with nano positioning leads to some interesting application capabilities for the tunable grating devices. For example, using ultra-precise tunable gratings one can compensate for thermal detuning in wavelength-sensitive optical networking elements such as wavelength multiplexers/demultiplexers and routers. Another intriguing possibility is the concept of "optical diversity," which we have developed to compensate for the aperture limitation in grating-based spectrometers. This is described in more detail in the next paragraph. It should also be noted that arrayability is possible for the grating devices, especially the piezoelectric version where the actuators occupy smaller real estate surrounding the active grating area, compared to the electrostatic version.

Optical diversity is motivated by a challenge that miniaturization often poses to optical devices: the limited optical aperture. Briefly, the problem is posed as follows: the spectral resolution in a grating spectrometer is determined by the number of periods N that the grating is composed of. Since the available area in a miniature spectrometer is, by definition, small, the acquired spectra can get "blurred." In other words, the measured value of spectral density at a given wavelength returned by the spectrometer does not correspond to the true spectral density at that wavelength of the specimen that is being tested (e.g. a potentially dangerous chemical) but also contains contributions from other neighboring wavelengths. The mathematical operation describing the blurring of the measured spectrum is a *convolution* of the true spectrum with the impulse response of the grating. The impulse response turns out to depend on N, as well as the quality of the collector optics that relay light from the specimen to the grating. The effect of the convolution can be undone by the inverse operation, namely a *deconvolution*, which can be performed digitally by post-processing the measured spectra. However, the deconvolution process is highly sensitive to noise that is unavoidably present in any measurement. It has been discovered that, by tuning the grating and repeating the spectral measurement, we can recover the blurred spectra with much less sensitivity to noise and, consequently, much higher accuracy than a single blurred measurement would allow.

Optical diversity works as follows: the grating period is first set to an initial value and a blurred measurement is taken. Then the grating is actuated so that the period changes by a small amount, and a new measurement, also blurred, is taken. The process is repeated, depending on the amount of noise present in the measurements—the lower the signal-to-noise ratio, the larger the number of necessary measurements. The ensemble of blurred measurements thus collected is subsequently processed using a class of mathematical techniques called "regularized pseudo-inverse" [29]. After this step, the final de-blurred spectrum is acquired. The quality of the spectrum de-blurring process is determined by the noise present in the measurements and also by the precision and accuracy of grating actuation. Thus, optical diversity is a good example of how reconfigurability and nano-positioning help solve a significant optical problem stemming from miniaturization of an optical spectrometer system.

5. Materials Challenges in Optical MEMS Devices

Micromachining enables the fabrication of miniature movable structures ideally suited for applications in the optical domain. Small mechanical displacements, e.g. a quarter wavelength in an interferometer can produce on-off switching or create modulation effects stronger than in conventional electrooptic or free carrier activated devices. Likewise, arrays of micromirrors can serve as the basis of displays and of optical cross-connects as discussed above. At the same time, these miniature MOEMS structures must satisfy certain dimensional and structural constraints which may be less important for other MEMS applications. For example, surface roughness determines mirror reflectivity while stressed membranes distort reflected optical images. Waveguides integrated within MOEMS must exhibit reproducible indices of refraction and optical losses. Actuators, whether electrostatic, piezoelectric or thermal-mechanical, require low voltage operation, power dissipation and chip real estate, all the while operating reproducibly over many switching cycles. Other chapters in this special issue focus, in some detail, on MEMS processing issues. In the following, we mention aspects of particular importance for MOEMS devices.

A prime example of the special materials and fabrication requirements of MOEMS is the DMD projection display chip developed by Texas Instruments (TI). Instead of utilizing the conventional surface micromachining process utilizing phosphosilicate glass for the sacrificial layers and polysilicon for the micromechanical elements, TI developed a low temperature process utilizing conventional positive photoresist and sputter deposited aluminum alloys [30]. This enables fabrication of all the underlying electronic and micromechanical components beneath the micromirrors thereby imparting a high fill factor and small mirror gaps. To insure high reliability, special attention was directed towards minimizing stiction between contacting parts, hinge memory and sensitivity to particulates. For the former, a self-assembled monolayer lubricant is applied to lower adhesion forces. In addition, feedback electronics are utilized to monitor and control the movement of the mirrors to eliminate overshoot and oscillations to further protect against stiction [31]. A low creep Al alloy was developed to minimize shifts in micromirror angle with time. Packaging was assigned to class 10 rather than class 10,000 clean rooms to eliminate failures due to foreign particles, keeping in mind that these devices contain more than one million micromechanical elements and that the eye can readily detect even a few faulty pixels within the display.

Microcantilever beams, membranes and microbridges are often stressed, particularly when thin films are deposited onto these structures. The stresses may be of an intrinsic nature (e.g. lattice mismatch) or due to thermal-mechanical stresses resulting from differences in thermal expansion coefficients. This forces structures out of plane, often at unpredictable angles. Indeed, Chen et al. [32] proposed a 2×2 optical switch based on a polysilicon microcantilever beam with attached hinged micromirror which is normally out of plane due to a Cr-Au layer which places the polysilicon under compressive stress. The switch is actuated by applying a voltage between the cantilever and the substrate thereby bringing the mirror into the optical path length of the integrated optical fibers. The micromirrors used in telecommunication for signal routing are typically coated with gold for its excellent reflecting properties in the IR. However, since Au serves as a deep trap in silicon, great care must be taken to avoid poisoning the electronic devices integrated into the structure [33].

Silicon nitride is often used to fabricate optical waveguides by a variety of techniques including sputtering, CVD, PECVD and LPCVD. Both the general method used and the detailed processing conditions contribute to variations in index of refraction n, optical loss and the magnitude and nature of residual stresses. For example, utilizing PECVD, one finds $1.9 < n < 2.2$ and stresses range from tensile to compressive depending on the Si/N ratio and the deposition conditions [32]. Thus, both the choice of materials and the processing conditions must be carefully controlled to ensure reproducible and stable structures.

In addition to passive optical materials such as Si_3N_4, active materials such as electrooptic and magnetooptic materials are of interest for optical modulation, pyroelectric materials for IR sensing and fluorescent materials as light sources. Other active materials of interest include piezoelectric materials such as PZT. The majority of such materials are complex oxides, often with the perovskite or garnet structure and normally, in the bulk state, require very high temperatures to achieve desired phase purity and microstructure. To enable integration with silicon based microelectronic and/or MEMS chips, these materials are prepared as thin films either by vapor phase techniques (e.g. sputtering, PLD, MOCVD, MBE) or chemical routes (e.g. sol gel). In general, the degree of crystallinity and orientation, microstructure, stoichiometry and built in stress depend sensitively on the deposition conditions, type and temperature of substrate during deposition and subsequent annealing conditions. In general, the films show reduced activity compared to their bulk counterparts. For example, an electrooptic modulator prepared by deposition of $BaTiO_3$ films onto an MgO single crystal substrate exhibited an effective electrooptic coefficient of 50 pm/V [34], less than an order of magnitude lower than the maximum value measured for single crystals [35]. Similar effects are often noted for piezoelectrics with reduced effective piezoelectric coefficients. These are suspected to be related to constraints imposed by the substrate, and by defects and other interfaces. Buffer layers, between silicon and the active oxides are essential to prevent interdiffussion and oxidation and also serve as seed layers to aid in the nucleation of the appropriate phases and crystallographic orientations. An excellent review of many of these issues may be found in the article by Muralt [36].

6. Conclusions and Discussion

Optical functionality offered by MEMS (MOEMS) has expanded from light emission and detection to optical amplification, switching, spatial modulation and routing, as well as basic optical signal processing [37]. The performance of optical MEMS devices has been improved significantly together with the advancements in materials for optical MEMS devices as well as a systems approach to MEMS design. However, many of the optical MEMS devices have not become commercially successful, while a few have become great successes. Miniaturization alone is insufficient to create new markets and ensure commercially competitiveness. The collection of MEMS devices discussed in this article was not meant to be exhaustive but rather indicative of the possibilities that MEMS technology offers to optical systems via the novel functionalities of "arrayability," "reconfigurability," and "nano positioning" and that the most commercially successful optical MEMS devices have been those, which combine at least two of the three functionalities.

The future information technology requires faster and smarter communication networks, which may only be obtained through all optical networking with more sophisticated optical functionalities, such as intelligent optical signal processing and adaptive optics. Integration of optical devices with MEMS technology will accomplish this goal if they are designed with well-defined optical functionality and the proper use of materials and processes.

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