Micromachining for Optical and Optoelectronic Systems

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Invited Paper

Micromachining technology opens up many new opportunities for optical and optoelectronic systems. It offers unprecedented capabilities in extending the functionality of optical devices and the miniaturization of optical systems. Movable structures, microactuators, and microoptical elements can be monolithically integrated on the same substrate using batch processing technologies. In this paper, we review the recent advances in this fast-emerging field. The basic bulk- and surface-micromachining technologies applicable to optical systems are reviewed. The free-space microoptical bench and the concept of optical prealignment are introduced. Examples of micromachined optical devices are described, including optical switches with low loss and high contract ratio, low-cost modulators, micromechanical scanners, and the XYZ micropositioners with large travel distance and fine positioning accuracy. Monolithically integrated systems such as single-chip optical disk pickup heads and a femtosecond autocorrelator have also been demonstrated.

Keywords**—***Integrated optics, integrated optoelectronics, microelectromechanical devices, optical switches.*

I. INTRODUCTION

The miniaturization and integration of electronics have created a far-reaching technological revolution. The invention of integrated circuits not only allows a large number of transistors to be fabricated on the same silicon chip but also enables them to be interconnected into functional circuits. Today, the optics is at the same stage that electronics was a couple of decades ago: though high-performance optoelectronic devices have been developed, most of the optical systems are still assembled piece by piece. In 1969, Miller proposed the concept of "integrated optics" [1], in which he envisioned active optical devices interconnected by optical waveguides, similar to the way transistors are interconnected by wires in integrated circuits. Though there has been significant development of waveguide-based integrated optics (also known as photonic integrated circuit), many free-space optical systems cannot be integrated by such technology. Free-space optics can perform optical imaging and generate diffraction-limited focused spots, and is widely used in optical display, data storage, switching, and sensing systems.

The micromachining, or microelectromechanical systems (MEMS) [2], technology has opened up many new possibilities for free-space optical systems. Movable micromechanical structures as well as precision optomechanical parts can be made by micromachining—a batch-fabrication technology similar to the microfabrication process for making very large scale integrated (VLSI) circuits. The movable structures are attractive for optical applications because small mechanical displacement can often produce physical effects that are stronger than the conventional electrooptic or free carrier effects. For example, a displacement of one-quarter wavelength in an interferometer can produce an ON/OFF switching. Many new optical devices and systems based on movable structures have been reported. Compared with macroscale optomechanical devices, the micromechanical devices are smaller, lighter, faster (higher resonant frequencies), and more rugged. Very efficient light modulators, switches, broadly tunable semiconductor lasers, detectors, and filters can be realized by the optical MEMS technology [3], [4]. The optical MEMS technology is sometimes also called microoptoelectromechanical systems (MOEMS) or microoptomechanical systems (MOMS). In this paper, we will use these terms interchangeably.

Optics is an ideal application domain for the MEMS technology: photons have no mass and are much easier to actuate than other macroscale objects. Microactuators with small force and medium travel distance are useful for many optical applications. Packaging of optical MEMS devices may also be easier than that of other MEMS devices since optics provides a noncontact, nonintrusive access to the MEMS devices. Its applications include projection and head-mount display, optical data storage, printing, optical scanners, switches, modulators, sensors, and packaging of

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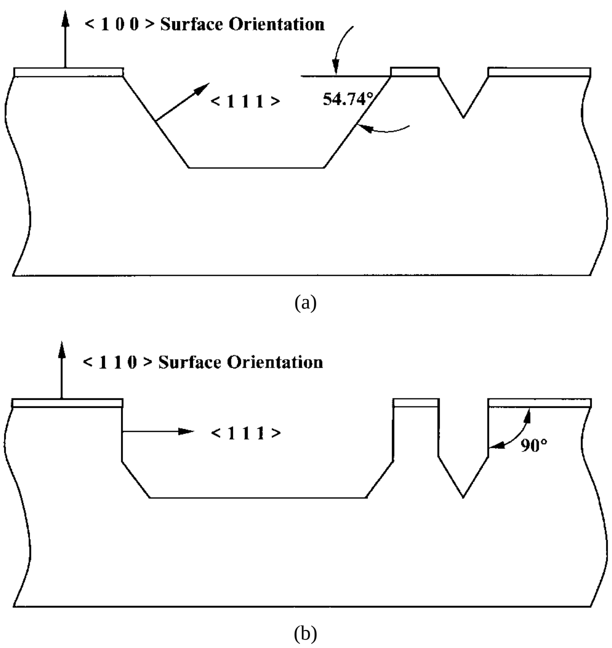

Fig. 1. Schematic diagrams illustrating the profiles of anisotropically etched silicon substrates. (a) (100). (b) (110).

optoelectronic components. The marriage of optics and MEMS has created a new class of microoptoelectromechanical devices and integrated circuits that are more efficient than macroscale devices.

II. Micromachining Technology for Optical Applications

A. Bulk Micromachining

Bulk micromachining has long been employed to create three-dimensional optomechanical structures on silicon substrate for aligning optical fibers or forming microoptical elements [5]. Single crystal silicon has excellent mechanical properties, and silicon substrates with high purity are readily available at low cost for semiconductor manufacturing. Silicon can be machined precisely by anisotropic etchants, whose etching rates depend on the crystallographic orientations [5], [6]. The etching rate of anisotropic etchants, such as ethylene diamine pyrocatechol (EDP), potassium hydroxide (KOH), and tetramethylammonium hydroxide (TMAH), is much slower in the <111> directions than in the <100> and <110> directions. Selectivity, defined as the ratio of the etch rates of the desired direction to those of the undersized one, for such anisotropic etchants can be higher than 100. This is a very powerful technique to create three-dimensional optomechanical structures with high precision.

Silicon V-grooves are now widely used in optical instruments and packaging of fiber and optoelectronic components [7], [8]. They are created by anisotropic etching of a (100) silicon substrate with stripe openings along the <110> or <1$\bar{1}$0> directions. The exposed {111} planes form a 54.74° slope with the surface of the wafer, as shown in Fig. 1(a). The depth of the V-groove can be very well controlled by lithography because {111} planes are effective stop-etching planes. Pyramidal-shaped holes that are ideal for holding ball lenses can also be formed by etching through square openings. These V-grooves and the pyramidal-shaped holes form the basis of conventional microoptical benches. As shown in Fig. 2(a), bulk optical components are dropped onto the etched silicon substrates and precisely positioned by holes of various geometry. Vertical micromirrors can be formed by anisotropic etching on a (110) silicon substrate [5], [6], as shown in Fig. 1(b). The atomically smooth {111} planes are perpendicular to the surface of the substrate and provide large-area, optical-quality surfaces. The selectivity of {110} over {111} planes is as high as 500 for some KOH solutions. Therefore, high-aspect-ratio microstructures can be produced this way. Micromirrors with 2-μm thickness and 200-μm height have been reported [9]. These vertical micromirrors are semitransparent and can be used as beam splitters. Fig. 2(b) illustrates the optical circuits consisting of such thin micromirrors, including Fabry–Pérot and Michaelson interferometer [9]. In addition to the {111} stop etch planes, some silicon etchants exhibit reduced etch rate in regions that are heavily doped with boron, adding more flexibility in defining the final shapes of the structures [5]. The boron diffusion therefore can be utilized to pattern membranes, suspended beams, or support beams for the vertical mirrors etched on (110) silicon substrate [10].

The vertical micromirrors created by anisotropic etching of (110) silicon substrates are, however, orientation dependent. Recently, there has been significant interest in three-dimensional structures created by deep reactive ion etching (DRIE) [11], [12]. DRIE allows etching of highly anisotropic, randomly shaped and located features into a single crystal silicon wafer, with only photoresist as an etch mask. Fig. 3 shows the scanning electron micrograph (SEM) of three-dimensional structures etched by DRIE [12]. Though the etched surface is rougher than the wet chemically etched (110) wafer, it is still smooth enough for many micromirror applications. Marxer *et al.* [13] and Juan *et al.* [14] have used the DRIE technique to fabricate a vertical micromirror for fiber-optic switches. The microactuators for the switch are also integrated through the same DRIE process. The mirror roughness is estimated to be 36 nm, which corresponds to a scattering loss of 6% [13].

B. Surface Micromachining

In contrast to bulk micromachining, in which substrate materials are removed to create three-dimensional structures, surface-micromachined structures are constructed entirely from deposited thin films. Alternating layers of *structural* and *sacrificial* materials are deposited and patterned on the substrate. The sacrificial materials can be selectively removed by an etchant that attacks only the sacrificial materials. Suspended beams, cantilevers, diaphragms, and cavities can be made this way. The use of sacrificial material to free micromechanical devices from the silicon

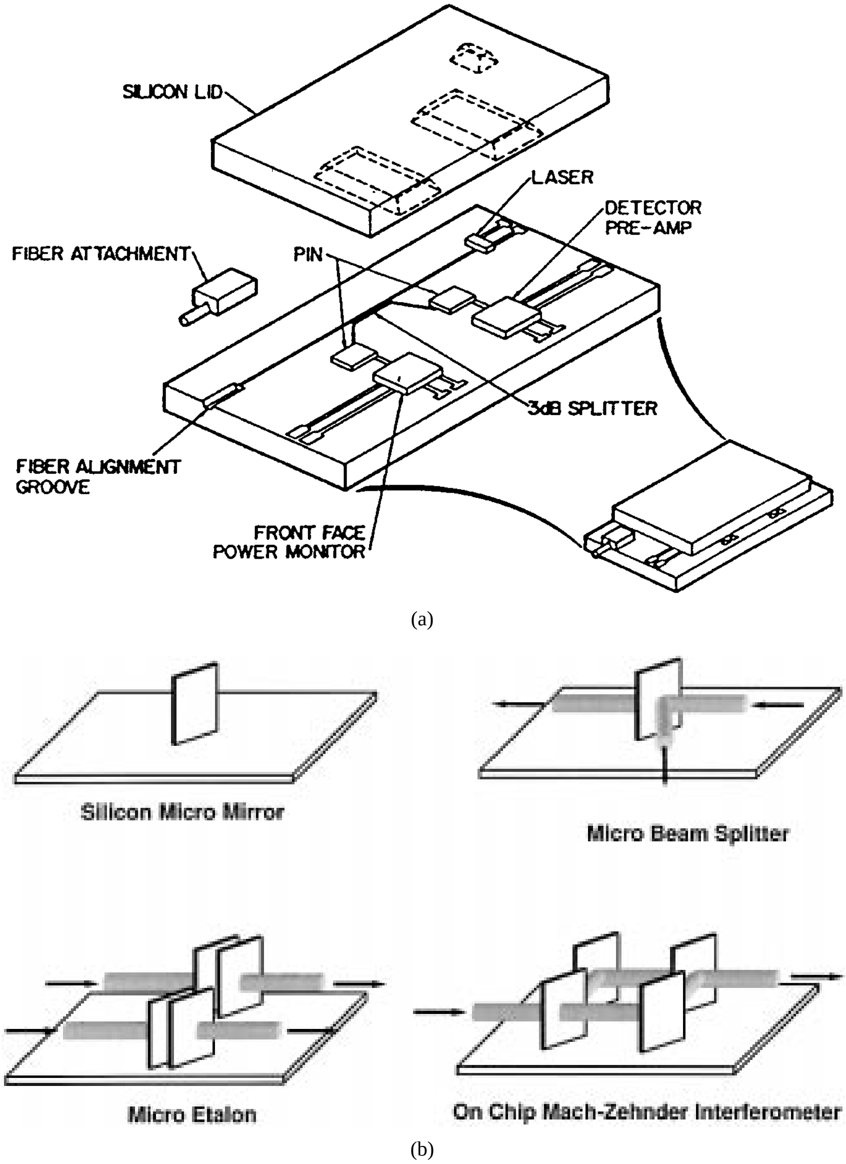

Fig. 2. Silicon optical benches on silicon substrates. (a) (100) [7]. (b) (110) (after [9]).

substrate was first demonstrated by Nathanson *et al.* [15] for fabricating a field effect transistor with a suspended resonant gate. In 1983, Howe and Muller [16] described the use of polysilicon as the structural material and silicon dioxide as the sacrificial material. Because of the excellent mechanical properties of polysilicon material and the high selectivity of sacrificial etching with hydrofluoric acid, this combination has become the most popular choice for surface micromachining.

Fig. 4 illustrates the surface-micromachining process for making cantilevers. This process requires one layer of sacrificial material and one layer of structural material. The complexity of the surface-micromachining process can be quantified by the number of structural and sacrificial materials. With two structural polysilicon layers, free-moving mechanical gears, springs, and sliders have been demonstrated [17], [18]. Micromotors [19], [20] and other microactuators were later demonstrated using similar fabrication processes. One of the main features that distinguishes the surface micromachining from the bulk micromachining is that many different devices can be fabricated using a common fabrication process. By changing the patterns on the photomask layouts, different devices such as cantilever resonators, sliders, micromotors, or comb drive actuators are fabricated simultaneously on the same substrate. This methodology is similar to that used in today's VLSI circuits. For this reason, the surface-micromachining process is often referred to as an integrated circuit (IC) process or VLSI-like process. Today, there already are two commercial foundries offering such polysilicon surface-micromachining processes.[1] Some of these processes can also be integrated

[1] MEMS Technology Applications Center, Microelectronics Center at North Carolina (MCNC), Research Triangle Park, NC, and Integrated Micro Electro Mechanical Systems, offered at Analog Devices, Cambridge, MA.

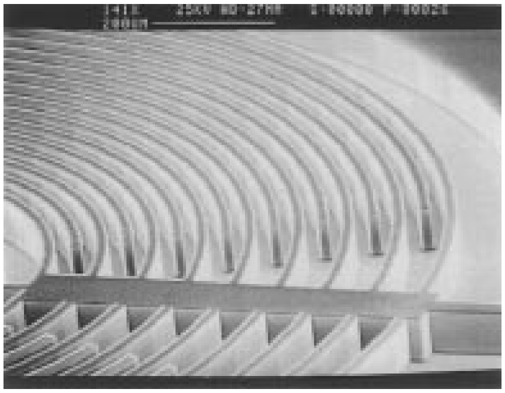

Fig. 3. The SEM micrograph of high-aspect-ratio structures created by DRIE [12].

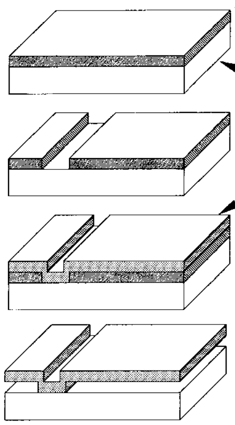

Fig. 4. Schematic of the fabrication process for surface-micromachined cantilevers.

with complementary metal–oxide–semiconductor circuits [21], [22]. Surface micromachining using other combinations of structural/sacrificial materials has also been demonstrated. For example, aluminum structure material and organic sacrificial material are used in Texas Instruments' digital micromirror devices (DMD's) [23], which will be discussed later.

C. Microhinges

Out-of-plane structures with high aspect ratios are often needed for free-space optical systems. Though they can be obtained by anisotropic etching or deep dry etching, it is difficult to pattern their side walls, as often required for free-space optical elements. In 1991, Pister and his coworkers proposed using the *microhinges* to fabricate a variety of three-dimensional structures using the surface-micromachining process [24]. This allows the surface-micromachined polysilicon plates to be patterned by photolithography and then folded into three-dimensional structures. The schematic cross section and the fabrication processes of the microhinge are illustrated in Fig. 5. It consists of a hinge pin and a confining staple. After selective etching of the sacrificial silicon dioxide, the polysilicon plate connected to the hinge pin is free to rotate out of the substrate plane and become perpendicular to the substrate. It is also possible to achieve other angles for the polysilicon plates. The microhinge technology allows the three-dimensional structures to be monolithically integrated with surface-micromachined actuators. It is particularly useful for fabricating integrable free-space microoptical elements, as will be shown in the next section.

In addition to the microhinges, alternative surface-micromachining techniques have been proposed for fabricating three-dimensional structures. The research group at the University of Tokyo proposed to use the "reshaping" technology to create complex three-dimensional structures [25]. The basic concept is to use thin flexure beams to connect polysilicon plates. The beams are then buckled or twisted by integrated microactuators to create the desired three-dimensional structures. By passing current through the polysilicon beam until plastic deformation, the three-dimensional structures are permanently fixed. Other techniques have also been proposed. Green *et al.* proposed to use the surface tension of molten solder to produce out-of-plane rotation [26]. Smela *et al.* used active polymers for controlled folding of microstructures in electrolyte liquid solution [27].

III. Free-Space Microoptical Bench

These surface-micromachining techniques have opened up the possibility of monolithically integrating free-space microoptical elements, micropositioners, and microactuators on the same substrate. This new technology, called *free-space microoptical bench* (FS-MOB), is illustrated in Fig. 6 [28]. In free-space optical systems, photons propagate between optical elements without being confined in physical media. Normally, the free-space optical systems are constructed on optical tables, with each optical element mounted on an XYZ micropositioning stage for optical alignment. With the micromachining technology, the optical system can be miniaturized and batch fabricated on a silicon substrate. Unlike the conventional systems, the optical elements can be integrally fabricated on translation or rotation stages. Microactuators for moving the optical elements can also be fabricated by the same micromachining process.

FS-MOB offers many advantages over conventional optical systems. First, the FS-MOB is made by a VLSI-like batch-fabrication process, which can significantly reduce the system cost. Conventional optical systems often need custom design and expensive assembly. Second, the optical system can be miniaturized by the FS-MOB technology. Many optical systems are limited by the sizes of micropositioning stages and optomechanical structures. Using the MEMS structures and actuators in FS-MOB, the size and weight of the optical systems can be greatly reduced. Third, the entire optical system can be monolithically integrated on a single chip. The use of out-of-plane optical elements allows multiple elements to be cascaded along the optical axes on the same substrate. Therefore, single-chip microoptical systems can be achieved. Fourth, the optics in FS-MOB can be "prealigned." Since all the microoptical

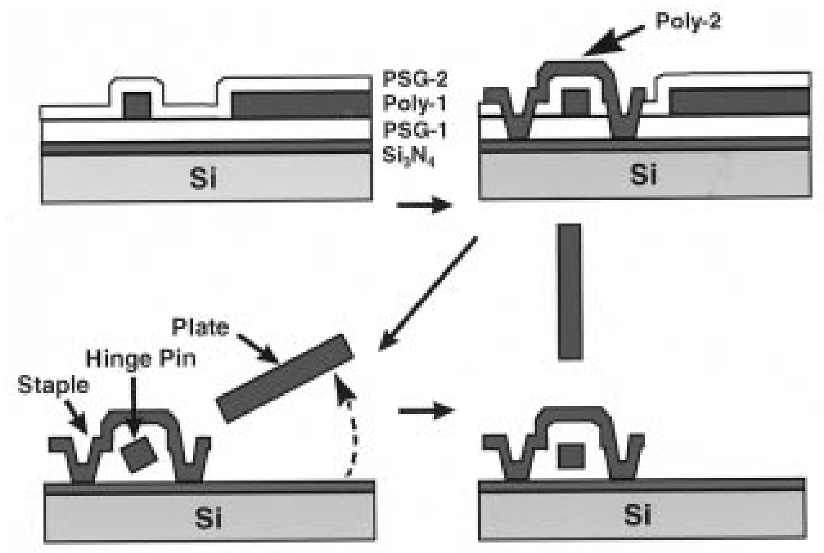

Fig. 5. Schematic of the fabrication process for surface-micromachined microhinges (after [24]).

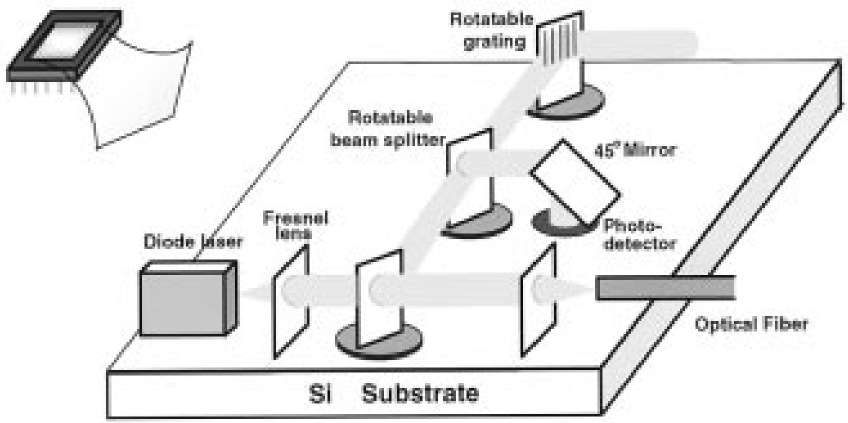

Fig. 6. Schematic illustrating the concept of FS-MOB. Microoptical elements, micropositioners, and microactuators are monolithically integrated on silicon substrate by surface micromachining.

elements and the optomechanical structures are made at the same time by the photolithographic processes, they can be aligned during layout of the photomasks. The accuracy of the alignment is limited by the misalignment error of photolithography and the mechanical clearance between the movable structures, which is on the order of a micrometer. Fine optical alignment (< 0.1 μm) can be achieved by on-chip microactuators. The integrated microactuators also allow dynamic tracking of alignment. The optical prealignment enables the "interconnections" between optical elements to be fabricated at the same time as the optical elements. This allows a functional optical system to be monolithically integrated and aligned on a single chip. This is similar to the concept of VLSI, in which the interconnections between transistors are fabricated monolithically. Combining the large number of transistors and the monolithic interconnections, highly functional electronic systems such as microprocessors have been produced.

FS-MOB represents a paradigm shift for the optical systems. The conventional optical system is assembly intensive. The optical elements are made separately and then assembled into optical systems. FS-MOB resembles more the VLSI systems: it is design intensive, and the same standard process is used to fabricate different functional circuits. It is based on batch processing techniques and is more suitable for mass production. In the following, we describe the basic building blocks of FS-MOB.

A. Diffractive Microlenses

Diffractive microlenses are very attractive for integrating with FS-MOB because:

1) their focal length can be precisely defined by photolithography;
2) microlenses with a wide range of numerical apertures (F/0.3–F/5) can be defined;
3) microlenses with diameters as small as a few tens of micrometers can be made;
4) their thickness is on the order of an optical wavelength [29]–[31].

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