Micromachining technology in optoelectronic sensing technologies

Christophe Gorecki (Fellows SPIE)
Institut des Microtechniques de Franche-Comté
32 avenue de l'Observatoire
25044 Besançon Cedex, France
Tel: +33-3-81666607, fax: 33-3-81666423
E-mail: christophe.gorecki@univ-fcomte.fr

Abstract:

This paper examines the contribution of MEMS/MOEMS technology in the specific context of optical fiber sensing technology. A number of demonstrator sensors will be discussed, with special emphasis to sensors with micromachined integrated optic structures, nano-scale SNOM sensors, and fiber-to-waveguide coupling systems.

Keywords: Optical MEMS, Integrated Optics, Silicon Micromachining

1. Introduction

Micromachining technology potential is suitable to fabricate precision-defined Integrated Optic (IO) circuits and offers a relative easy alignment procedures of optical fibers, reducing the packaging cost. Main difficulties in fiber sensing technologies are cost alignment requirements for optical fibers, and high sensitivity to temperature and vibration effects, and phase noise. The alternative, which offers MEMS/MOEMS in approaching these problems, is the combining fiber-optic technology and silicon micromachining. Integrated sensors, when linked by optical fibers, can provide immunity to electromagnetic interferences and isolation from high voltage circuits as well. Detecting displacements of cantilever beams, microbridges, or membranes sense the physical parameter. Such microstructures convert a mechanical displacement to a change in optical intensity and serve as the basis for sensors, since many physical parameters (temperature, pressure, force, acceleration) can be converted to a displacement or strain.[1] The interest of silicon micromachining is also well demonstrated in coupling of optical fibers to optoelectronic devices by passive alignment of fiber on the V-groove shaped silicon microbench. Finally, highly reproducible processes such as Focused Ion Beam (FIB) may fabricate the near-field optical sensors with nanometer apertures at the apex of tapered fibers. In the following sections, a number of demonstrator sensors will be discussed, analyzing how silicon micromachining contributes to fiber optic sensor technology.[2]

2. Fiber optic sensors with micromachined IO structures

IO circuits require optical waveguides that connect various passive or active optical components. The use of V or U grooves enables insertion of fiber optics into IO circuits. Incorporation of diaphragm or cantilever beams in the path of a waveguide permits to measure the physical effects that changes the effective refractive index of guided waves induced by motion or deformation of MEMS structure.

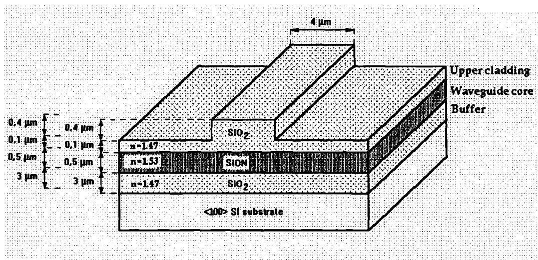

Fig. 1. Single-mode SiO_xN_y strip-loaded waveguide.

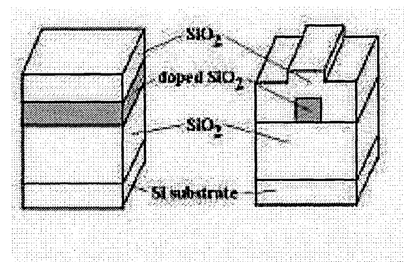

Fig. 2. P-doped SiO_2/SiO_2 channel waveguide.

Channel waveguides are the most common IO components, using mainly silicon substrate/SiO2/SiOxNy/SiO2 or silicon substrate/SiO2/doped SiO2/SiO2 . The waveguides with SiOxNy as core layer have the refractive index contrast in the range from 0.05 to 0.55, so these waveguides are suitable to match to optical fibers. An example of single-mode strip-loaded waveguide, operating at 0.633-µm wavelength, is shown in Fig. 1.3 The core of this waveguide is a SiOxNy layer fabricated by PECVD, sandwiched between two PECVD SiO2 cladding layers. In the upper SiO2 cladding a 4-µm wide rib is structured by RIE. The optical losses are less than 0.5 dB/cm.

Silica-doped waveguides have the index contrast in the range from 5x10-3 to 0.05. LETI developed an approach of phosphine-doped channel waveguides on silicon4 (Fig. 2) where silica layers are deposited by PECVD. The optical loss of such waveguides is 0.2-0.3 dB/cm at 0.633-µm wavelength. RIE etching of the core layer in doped silica followed by the deposition of silica overlayer and a second dry etching are performed to fabricate the channel structure. The coupling efficiency to single-mode fibers of these waveguides is greater than 90%.

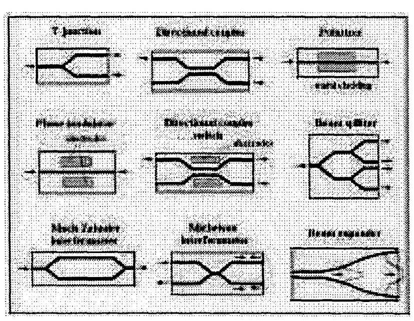

Fig. 3. Schematic of some IO components.

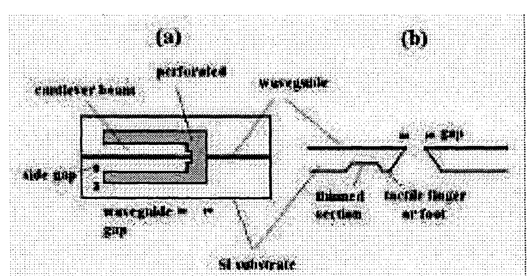

Fig. 4. Amplitude-modulated accelerometer: (a) top view; (b) edge view.

Figure 3 shows schematically other waveguide-related IO components including Y-junctions, X-crosses, couplers, polarizers, beam splitters, polarization converters and splitters, modulators, and interferometers.[2] All the components may be fabricated by standard IC fabrication methods. Two more important elements are the Y-junction and directional coupler because the most of other components consists of combination of both these elements.

2.1 Modulated optical sensors

Fiber optic sensors can be based on amplitude-modulated or phase-modulated detection. The interaction microstructure-waveguide induces a phase or intensity modulation and thus sensing function may be performed. The first category can use movable microstructures that interact with a guided wave through evanescent coupling or by affecting the waveguide transmission characteristics. The principle of intensity modulated micromachined cantilever beam accelerometer is illustrated in Fig. 4.[5] The read-out based on integrated optical waveguide is located in the path of the cantilever beam, coupling the light across the air gap and providing the relationship with the amount of deflection of the beam tip. Displacements of few hundreds angstroms could be measured by a seismic mass incorporated onto the end of the beam via the measurements of accelerations. Standard photolithography and anisotropic etching of silicon substrate fabricate the cantilever. A planar waveguide is deposited on the top of the wafer with a buffer layer of thermal SiO_2 and a core layer of LPCVD silicon nitride film.

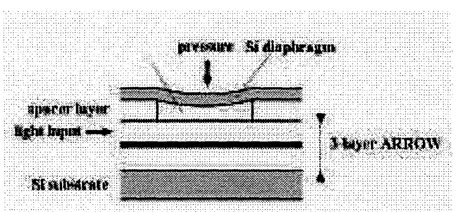

Fig. 5. ARROW pressure transducer.

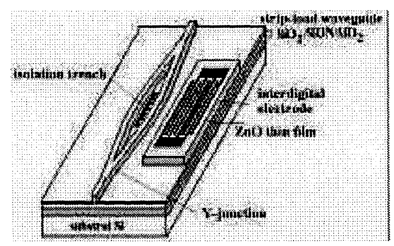

Fig. 6. Phase-modulated MZI by elastooptic effect.

The use of evanescent-field interaction in amplitude-modulated pressure sensor is shown in Fig. 5.[6] This is based on the modulation of the output power via ARRO waveguide. The sensor is based on a deformable silicon diaphragm clamped at a fixed distance away from the waveguide surface. When external pressure is applied to the diaphragm, it deflects and goes into closer proximity with the waveguide, producing the light coupling from the waveguide into the diaphragm. Pressure can be measured by monitoring the light intensity modulation due to the deflection of the diaphragm. The upper half part of the device including the diaphragm and spacer layer is formed by deposition of thermal oxide followed by plasma etching of the silicon to form the diaphragm. Waveguide and diaphragm wafers are anodically bonded together.

Phase-modulated sensors are often based on Mach-Zehnder interferometer configuration. In the reference arm of MZI some means are provided for shifting the optical frequency or phase modulating. This often results in high accuracy and a large dynamic range at the expense of a higher cost because complex electronics are required. To obtain a MZI under phase modulation, Bonnotte[3] proposed to generate surface acoustic waves by means of a thin-film piezoelectric ZnO transducer deposited near the optical channel waveguide, as shown in Fig. 6. Acoustooptic interaction mechanism is then based on the change in the index of refraction caused by mechanical strain which is introduced by the passage of SAWs. The strip-load waveguide of Fig. 1 have been deposited by PECVD and ZnO film is sputtered on the top of the SiO_2 upper cladding near the reference arm of the interferometer. A phase shift of 1.3 rad was demonstrated.

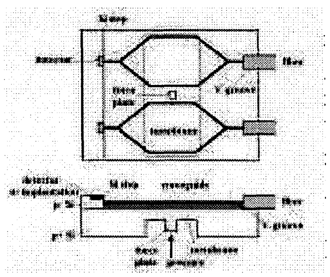

Fig. 7. MZI pressure sensor using elastooptic effect.

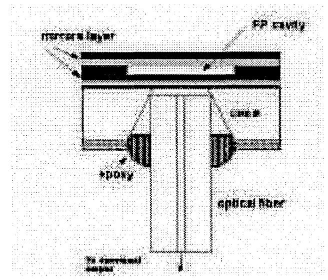

Fig. 8. FP pressure sensor.

An example of micromachined optical pressure sensor is shown in Fig. 7.[7] This uses two MZIs crossing a silicon membrane with a force plate located at the center. Both arms of each interferometer are situated inside the square membrane, one at its center, and other at its outer edge. When a pressure is applied on the force plate, the deflection causes strains in the membrane thereby modifying the optical path length of the interferometer. He-Ne source laser is coupled via a fiber to the input Y-junction of the interferometer and pressure induced phase shift is detected at the output Y-junction via an integrated detector. The waveguide technology is based on the waveguide, similar to that described in Fig. 1. A p-i-n detector is integrated in the epilayer on the silicon substrate.

Another approach to measure, for example pressures and temperatures, is based on the use of Fabry-Pérot interferometer, as shown in Fig. 8.[8] An air-gap cavity is formed by etching a sacrificial layer. LPCVD polysilicon is used as a sacrificial layer and KOH as the etching solution. FP principle can also be used to measure the displacement of the seismic mass in accelerometers. In this case, FP cavity can been formed between the exit facet of the optical fiber and the moving mass, as shown in Fig. 9. When illuminated by a broad spectrum, the FP spectrum reflected by the cavity shifts when the mass is moving. By measuring the shift, a practical resolution of 500 μg has been demonstrated[9] for a dynamic range of ±10 g. Thanks to the fiber optics detection, a distant measurement can be performed, which allows to use the sensor in a harsh environment.

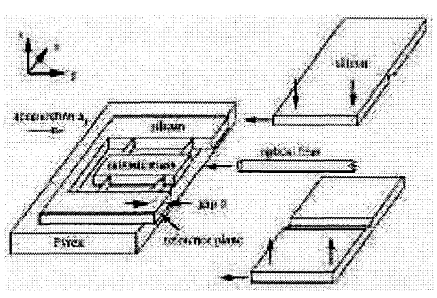

Fig. 9. Micro-accelerometer with FP detection

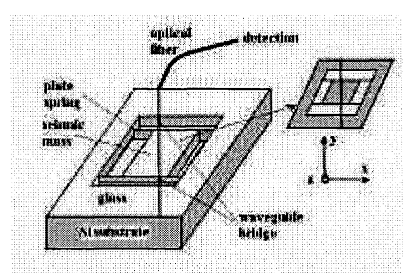

Fig. 10. Optical accelerometer with waveguide Bragg gratings.

2.2 Micromachined Bragg grating sensors

The combination of micromachined Bragg gratings with an optical waveguide can be used as strain-sensing elements. An accelerometer based on the strain using Bragg grating in optical waveguide is illustrated in Fig. 10.[10] Four parallel springs and two waveguide bridges suspend a seismic mass. The sensitive y-axis is perpendicular to the spring plates that ensure the movement of the seismic mass only along the x-axis. The symmetry axis of waveguide bridges is parallel to the y-axis. Waveguides act as dominating springs in this direction, operating at the same time as strain gauges. When the structure is subjected to accelerations along the y-axis, the waveguide bridges come under compression. The Bragg gratings are written in the surface of the planar waveguide using UV two-beam interferometry. Wet etching in KOH solution is used for releasing of the bridge structures. An accelerometer structure with the waveguide propagation loss less than 1 dB/cm and Bragg grating reflectance of 80% have been obtained. The mechanical sensitivity of the accelerometer is 1.4 nm/g.

3. Micromachined nano-scale SNOM sensors

One of the promising tools in 3D nano-fabrication is the FIB etching, where gas molecules above a specimen may be dissociated resulting in a local etching or deposition of the specimen. FIB system may be utilized in 3D micromachining and SNOM/AFM/STM tip manufacturing. Figure 10 shows examples of realization.[11] Figure 10a illustrates a SNOM fiber-optic tip firstly metal coated, cutted, and metallized, before that a circular aperture of 300 nm diameter was made by FIB milling. Figure 10b shows a polyhedral optical fiber tip obtained by milling after the fiber diameter reduction to 10 μm by chemical etching. Finally, Fig. 10c shows a view and a schematic diagram of an integrated thermocouple sensor using the previous techniques.

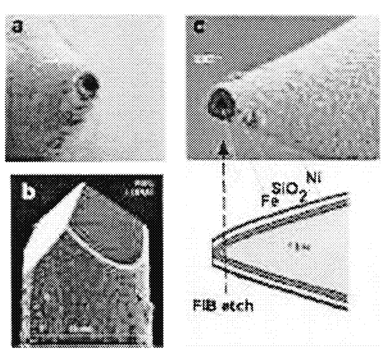

Fig. 10. SNOM tips (a-b), and thermocouple sensor (c)

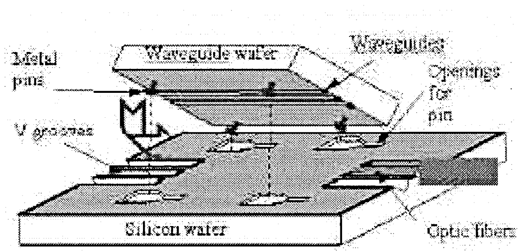

Fig. 11. Principle of a silicon alignment platform.

4. Micromachining technologies for optical packaging

Micromachining offers specific advantages for the packaging of fiber optic sensors, especially for the connection from the fiber to micromachined optical sensors. Manufacturing ultra precise silicon V-grooves is a key point to align optical fibers to integrated optics or MOEMS devices. Such V-grooves can easily be manufactured with a sub-micron precision by a batch fabrication process, involving wet etching of silicon by a KOH solution. It is possible to manufacture the V-groove, which supports the fiber in the same substrate as the sensor[12]. If the sensor is not based on a silicon substrate, it is still possible to manufacture a silicon platform, which can support the fiber and the integrated optics device.[13] Figure 11 shows a configuration where the alignment of the IO device relies on metal microstructures, which can be precisely positioned by photolithography, and electrodeposited. The base of the metal pins has a diameter of 200 μm and a height of 25 μm. Pins are fabricated by UV-LIGA and the openings in the Si platform are made by RIE of a 25-μm thick membrane.

5. Conclusions

Silicon micromachining realize mass production and high precision micromechanical structures, offering an evident potential and good matching with fiber sensor technologies. The practical penetration of these technologies has, to date, been relatively modest because only some interferometric sensors are commercially available. Further developments in the field of IO circuit integration and optical packaging are necessary to improve the interpenetrating efforts of all the concerned scientific communities, and to adjust the contribution of MEMS/MOEMS in fiber sensing with the benefit of proposed potentialities.

6. References

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