Bulk-micromachined tunable Fabry-Perot microinterferometer for the visible spectral range

J. H. Correia, M. Bartek and R.F. Wolffenbuttel

Delft University of Technology, Lab. for Electronic Instrumentation, DIMES, Mekelweg 4, 2628 CD Delft, The Netherlands

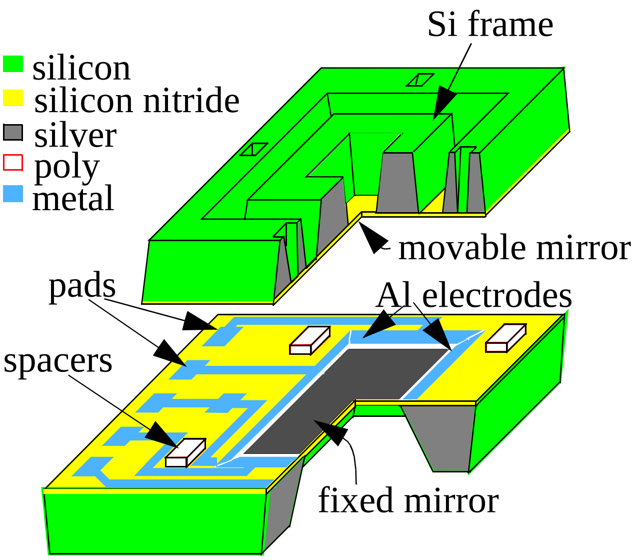
Abstract. The design, fabrication and measured characteristics of a bulk-micromachined tunable Fabry-Perot MicroInterferometer (FPMI) for the visible spectral range are presented. The FPMI is formed by two parallel 40 nm thick silver mirrors supported by a 300 nm low-tensile stress silicon nitride membrane with a square aperture (side length of 2 mm) and initial cavity gap of 1.2 μm. One of the mirrors is fixed, the other is under tension on a movable Si frame, which is electrostatically deflected, using several distributed electrodes, to control cavity spacing and mirror parallelism. Performance achieved is: high flatness of the mirrors, low control voltages (<21 V for 450 nm deflection) and simple fabrication.

1. Introduction

Micro-Electro-Mechanical-Systems (MEMS) have been, amongst many other applications, used to combine micro-mechanical and micro-optical elements on the same device. Significant improvements of the performance, functionality, reducing size and cost of optical systems are achieved merging micro-optics, microelectronics and micromechanics (micro-opto-electro-mechanical devices).

MEMS-based Fabry-Perot optical filters consist of a vertically integrated structure composed of two mirrors separated by an air gap. Wavelength tuning is achieved by applying a voltage between the two mirrors resulting in an attractive electrostatic force which pulls the mirrors closer [1].

The Fabry-Perot filters reported in the literature are usually designed for use in the near-infrared region (wavelengths 1.3 and 1.5 μm), because of interest in multi-mode optical fibre communication [2] [3] [4]. The fabrication of the mirrors is generally based on the deposition or growth of many layers (10 to 27) to form the DBR (Distributed Bragg Reflector) mirrors. Therefore, the fabrication of these Fabry-Perots is complex and costly. In this work, we present a new micro-mechanical device, which features simple fabrication, allows operation in the visible spectral range [5] and is integrable with photodetectors and electronics in silicon. The main goal of this Fabry-Perot structure (Fig. 1) is to achieve an integrated spectrometer with a wide spectral range of operation.



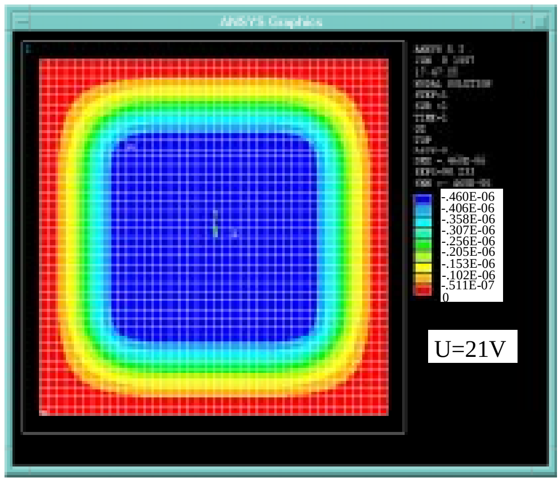


Fig. 1: Fabry-Perot MicroInterferometer (FPMI)

Fig. 2: FEM simulation of the silicon nitride membrane deflection

2. Design of the Fabry-Perot microinterferometer

Geometrical form, bending distances, deflection, stress, fatigue and flatness of a diaphragm based on a low stress silicon nitride membrane/Si frame were simulated in order to study the mechanical behaviour of a movable mirror, which is part of the FPMI.

The dimensions and materials used are set by optical constraints. Moreover, the effects of silicon nitride internal stress, stress concentration in the frame corners, zero-pressure offset and compressive stresses complicate the prediction of the load-deflection relationship before fabrication compared to a planar diaphragm.

The Finite-Element-Methods (FEM) simulations in ANSYS 5.3 (Fig. 2) predict excellent flatness [6] of the movable mirror in the whole range of required deflections (0-460 nm for the control voltages of 0-21 V).

The membrane was modeled by a three-dimensional shell element (very small thickness) and the silicon frame by a three-dimensional solid. Adaptive meshing was used only for the first approach, after it was necessary to improve by trial and error. The membrane residual tensile stress was simulated by defining a thermal-expansion coefficient and applying a temperature load.

A thin-film optics software package (TFCalc 3.2.5) was used to perform optimization of mirror layer thickness and composition [7]. Fig. 3 shows simulated transmittance for 40nm-Ag/ 300nm-SiN mirrors with mirror spacing as a parameter.

3. Fabrication process of the Fabry-Perot microinterferometer

Silver was selected as the mirror material, because of its high reflectivity (>90%) over the entire visible spectral range (Fig. 4). The main disadvantage of silver - poor long term stability (tendency to tarnishing) - is expected not to be critical in microsystems, as the dimensions allow protection by sealing.

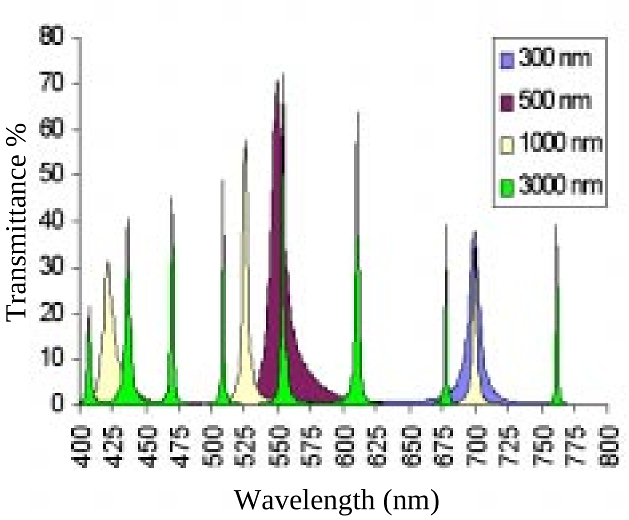


Fig. 3: Simulated transmittance for different cavity gaps

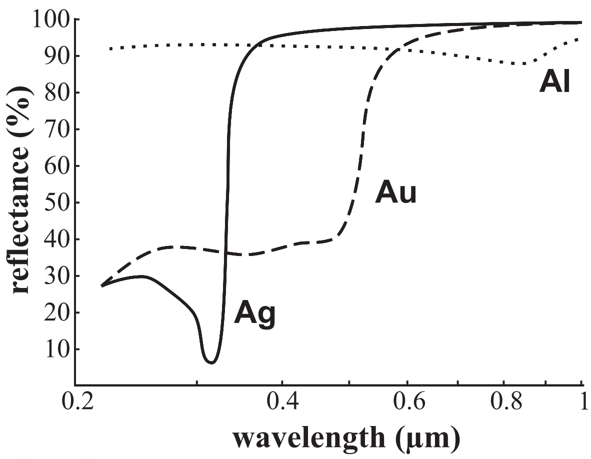


Fig. 4: Optical reflectance of Ag, Al and Au

The mechanical and optical properties of low-stress silicon nitride enable fabrication of large-area membranes (>10 mm) with excellent flatness, the refractive index non-uniformity less than 10^{-4} and optical absorption losses below 0.5%.

On the same wafer (100 mm double-side polished), upper and bottom dies are fabricated (5-mask process). Firstly, 400 nm recesses are formed using LOCOS. Subsequently, a 300 nm low-stress (<0.25 GPa) LPCVD silicon nitride layer is deposited and protected by a 300 nm LPCVD poly-Si layer. Then, PECVD oxide is deposited on a wafer front-side with thickness (0.3 - 1 µm) corresponding to the required initial resonance cavity gap.

The PECVD-oxide/poly-Si stack is patterned to form spacers between upper and bottom dies for later die attachment. The 300 nm Al interconnect and control/sensing electrodes (deposited by sputtering) are buried in 400 nm recesses to increase the initial spacing of the electrodes and avoid sticking during operation.

The wafer back-side is patterned to prepare windows for anisotropic KOH etching. Silver mirrors are e-beam evaporated and patterned using lift-off on the wafer front-side. The anisotropic KOH etching (33 wt% KOH solution at 85°C) is performed in a sealed holder to protect the Ag mirrors. To facilitate dicing of the finished wafer into the individual dies, deep V-shaped trenches are formed during anisotropic KOH etching. After the bottom die is mounted on a printed-circuit-board (PCB), the upper die is attached and fixed using glue.

3. Experimental results

The optical response was measured using a 5.1 mm^2 photodiode (Oriel 7180) and HP 4142B DC source/monitor controlled by an HP 9000/700 computer. A 100 W tungsten lamp and Oriel 77250 monochromator with a ruled grating were used as light source.

The control voltages to tune the FPMI resonance cavity width were set manually to adjust the mirror parallelism. Fig. 5 shows an example of the measured spectral response in transmittance (cavity gap ~500 nm) with the Full-Width-Half-Maximum (FWHM) of <12 nm, which is in reasonable agreement with simulation. A photograph of a fabricated FPMI is shown in Fig. 6.

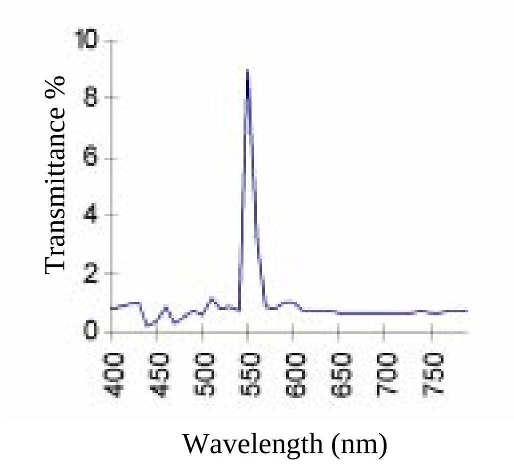


Fig. 5: Optical transmittance measured for an air cavity gap of about 500 nm

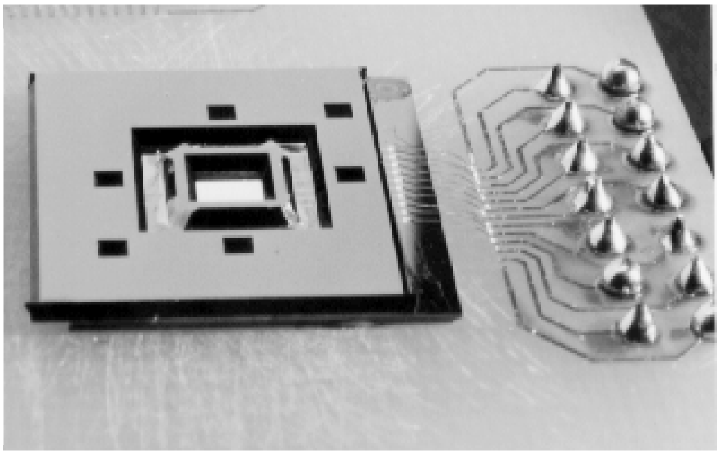


Fig. 6: Photograph of the fabricated FPMI

4. Conclusions

The microinterferometer presented is intended for use in an on-chip integrated microspectrometer (which would include FPMI, integrated photodiode and read-out electronics), with tuning over the entire visible spectral range and high spectral resolution. The materials and device properties enable a FPMI with a finesse exceeding 30 and FWHM smaller than 3 nm.

Acknowledgements

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References

[1] Patterson J D 1997 Micro-mechanical voltage-tunable Fabry-Perot filters formed in (111) silicon *Ph. D. thesis-University of Colorado*

[2] Aratani K, French P J, Sarro P M, Poenar D, Wolffenbuttel R F and Middelhoek S 1994 Surface micromachined tuneable interferometer array *Sensors and Actuators A* **43** 17-23

[3] Peerlings J, Dehe A, Vogt A, Tilsch M, Hebeler C, Langenham F, Meissner P and Hartnagel H L 1997 Long resonator micromachined tunable GaAs-AlAs Fabry-Perot filter *IEEE Photonics Technology Letters* **9** (9) September 1235-1237

[4] Jerman J H, Clift D J and Mallinson S R 1991 A miniature Fabry-Perot interferometer with a corrugated silicon diaphragm support *Sensors and Actuators A* **29** 151-158

[5] Raley N F, Ciarlo D R, Koo J C, Beiriger B, Trujilo J, Yu C, Lomis G and Chow R 1992 A Fabry-Perot microinterferometer for visible wavelengths *Proc. 5th IEEE Solid-State Sensor and Actuator Workshop, Hilton Head Island SC USA* 170-173

[6] Correia J H, Bartek M and Wolffenbuttel R F 1998 Load-deflection of a low-stress SiN-membrane/Si-frame composite diaphragm *Proc. of Modeling and Simulation of Microsystems (MSM'98) 6-8 April Santa Clara USA*

[7] Poenar D P and Wolffenbuttel R F 1997 Optical properties of thin-film silicon-compatible materials *Applied Optics* **36** July 5122-5128