Silver-based reflective coatings for micromachined optical filters

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SUMMARY

Silver films of 40 nm thickness, evaporated on a 300 nm thick low-stress silicon nitride layer, are used as high-quality mirrors operating in the visible and near IR spectral range. Using a silicon nitride membrane under tension, within a square Si frame after bulk micromachining, improves the initial mirror flatness. Two parallel mirrors, with square aperture of up to 2x2 mm^2 and an electrostatically controlled spacing, form a tunable Fabry-Perot optical filter. Investigation of the silver-based reflective coatings, and mirror characterisation, including influence of bulk micromachining, are presented.

Keywords: Silver mirror, nitride membrane, micromachining, Fabry-Perot interferometer.

INTRODUCTION

In recent years much attention has been paid to the development of tunable micromachined optical filters based on a Fabry-Perot (F-P) resonator [1, 2, 3]. Research has been primarily focused on the near-infrared region (wavelength of 1.3 and 1.55 µm) because of interest in the multi-mode optical fibre communication. In this application operation in a narrow optical band and the transparency of Si substrate in the spectral region of interest facilitate the system design.

Attempts to fabricate a device in the visible spectral range have also been reported [4], but were less successful. The goal is to develop an integrated spectrometer. In such an application, the requirements are much more demanding. Wide optical band operation is required (preferably over the entire visible spectral range 400 - 800 nm). Furthermore, the mirror flatness becomes more critical due to the decreased wavelength.

The most important part of the F-P device are the mirrors. Two types of reflective coatings are used: dielectric and metallic. The dielectric mirrors, if properly designed and fabricated, feature high performance (high reflectivity, low absorption losses), but their nature (distributed character) requires the deposition of a sequence of two (or more) different dielectric materials with well-controlled thickness, forming a stack of many layers. To be effective in a wide optical band, usually more than 15 layers for one mirror are required [5]. This complicates fabrication.

Although, the metallic-based coatings have much higher losses, these can be attractive in certain application due to simplicity of fabrication (only one layer must be deposited). Another advantage is that metallic mirrors generally perform well over a wide spectral range. Aluminum, gold and silver are the mostly used metals for reflective coatings. Fig. 1 shows their reflectance in the near-UV, visible, and near-IR spectral region [5].

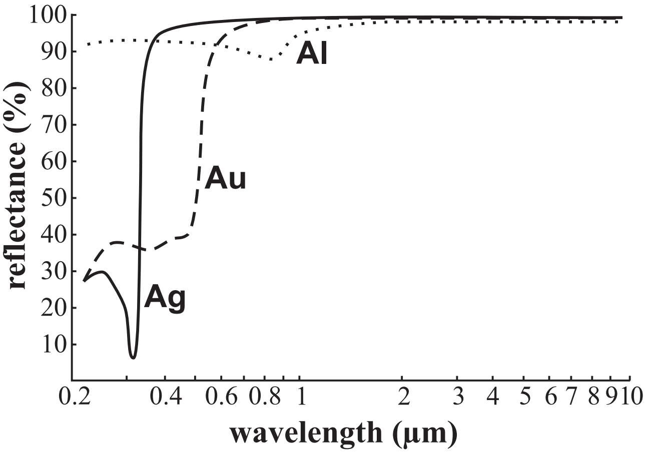


Fig.1: Reflectance of silver, gold, and aluminum as a function of the radiation wavelength, after [5].

Al would be the most suitable material in terms of fabrication compatibility, but unfortunately Al has higher absorption losses than Ag or Au in the visible and near-IR. For the visible and near-IR spectral regions, silver is the best choice, but exhibits poor long-term stability (tendency to tarnishing). Gold is more corrosion resistant than silver and would be the best choice if it were not for its poor visible and ultraviolet performance. Unlike macroscopic applications of silver-based reflective coatings [6], the poor environmental resistance of silver is not critical in a microsystem application. Sealing of a complete system would avoid any environmentally caused mirror degradation. Advantage is also, that Ag is a natural low-pass filter, cutting off the UV range (see Fig. 1). Silver-based mirrors have been previously reported for use in non-tunable distributed filters composed of a wedge shaped dielectric film sandwiched between two reflective (Ag) thin films [7].

This paper presents results on the investigation of the feasibility of silver-based reflective coatings, with a goal to develop a miniature F-P based spectrometer for the visible spectral range.

MICROMACHINED FABRY-PEROT OPTICAL FILTER

For initial tests a device similar to that of Raley at al. [4] was chosen. Fabrication is based on bulk micromachining as shown schematically in cross-section in Fig. 2. The tunable Fabry-Perot optical filter is formed by two parallel 40 nm thick silver mirrors supported by a 300 nm low-stress silicon nitride membrane with a square aperture of 2x2 mm^2 and an initial cavity gap of 1.2 µm. One of the mirror is fixed, the other is under tension on a movable Si frame, which is electrostatically deflected using several distributed electrodes to control the mirror spacing and parallelism.

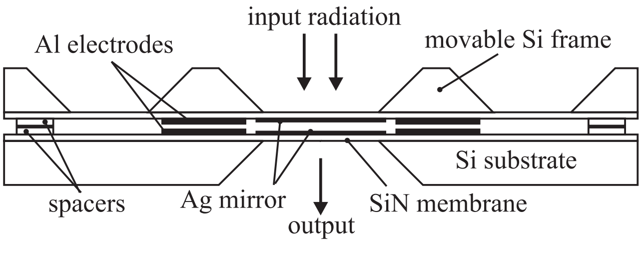


Fig. 2: Cross-section of the proposed micro-machined Fabry-Perot optical filter.

A thin film optics software package (TFCalc 3.2.5) was used to perform optimisation of the mirror layer thickness, composition and order (optical data in [8]). The silver layers must be inside the resonance cavity to avoid excessive absorption losses in the silicon nitride layer during multiple reflections. The simulated transmittance for the optimised 40nm-Ag/300nm-SiN mirrors with a 500 nm spacing (air gap cavity) is shown in Fig. 3. The Ag layer thickness is a trade off between achievable FWHM and absorption loss.

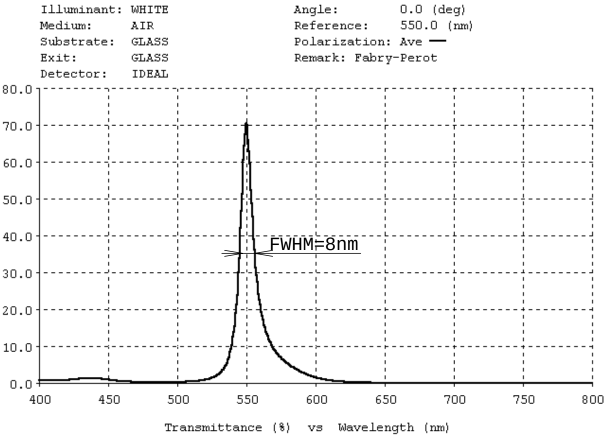


Fig. 3: Calculated transmittance for 300 nm SiN - 40 nm Ag - 500 nm air - 40 nm Ag - 300 nm SiN layer stack .

FABRICATION

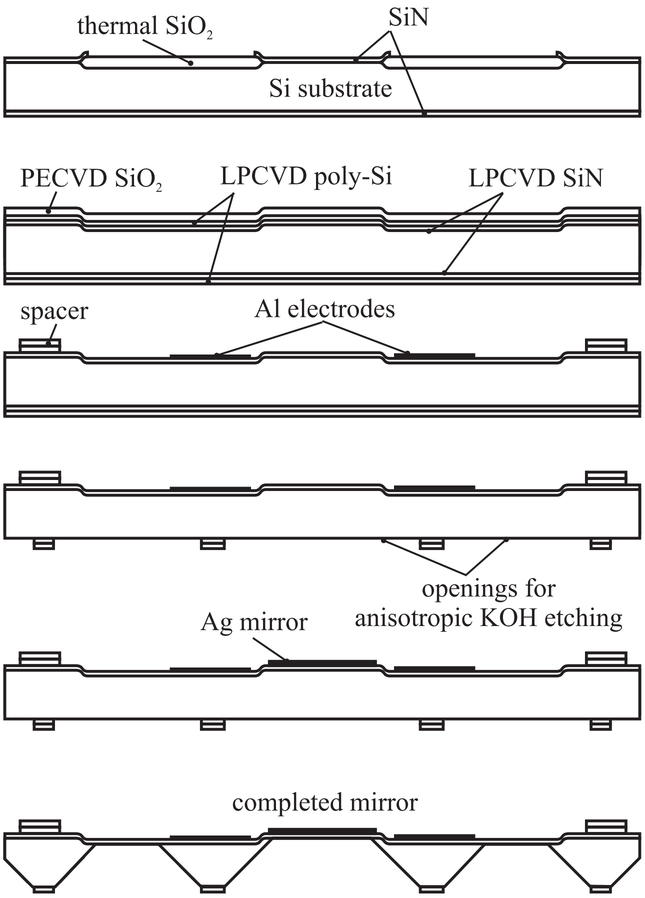


Fig. 4: Schematic fabrication sequence (see text for details).

On the same wafer (100 mm, double-side polished), upper and bottom dies have been fabricated using a 5-mask process (see Fig. 4). Firstly, 400 nm recesses are formed using LOCOS. Subsequently, a 300 nm low-stress (<0.15 GPa) LPCVD silicon nitride layer is deposited and protected by a 300 nm LPCVD poly-Si layer. Then, PECVD oxide (0.3-1 µm) is deposited on a wafer front-side with thickness 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 mirror layers 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 holder to protect the Ag mirrors. To facilitate the wafer dicing into the individual dies, deep V-shaped trenches are formed during KOH etching. After the bottom die is mounted on a PCB, the upper die is attached and fixed using glue.

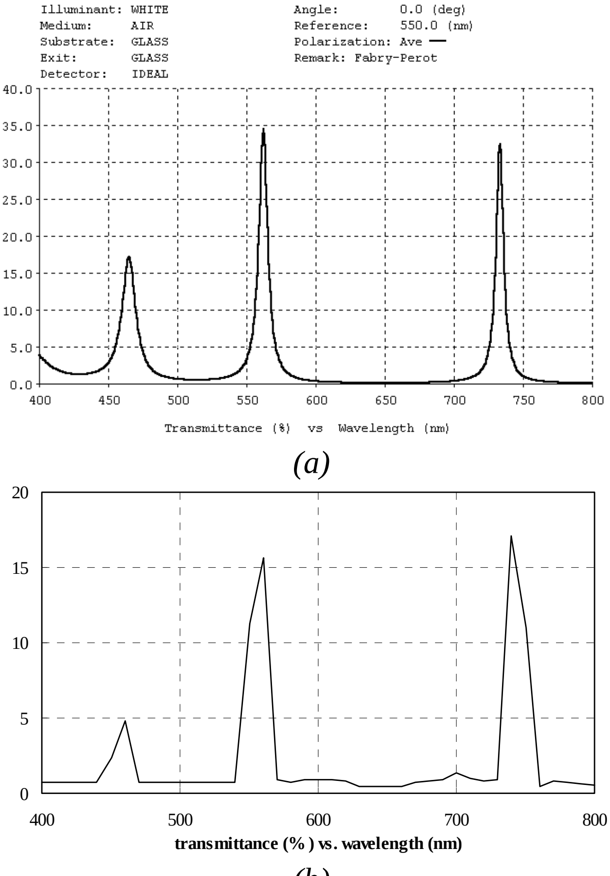
RESULTS

To test the concept of silver-based mirrors, a 40 nm Ag layer was deposited on a SiN membranes from one or both sides after bulk micromachining. The interference measurements (projected interference fringes) have shown an excellent initial mirror flatness. The LPCVD silicon nitride membrane which is under tension after the release using anisotropic KOH etching improves the initial flatness of the silver mirror.

The optical response has been measured using a large area photodiode (5.1 mm^2) and HP4142B DC source/monitor controlled by a HP 9000/700 computer. A 100 W tugsten lamp and Oriel 77250 monochromator with a ruled grating were used as a light source.

Fig. 5 shows the simulated and measured transmission for 40nm-Ag/450nm-SiN/40nm-Ag layer stack. A SEM photograph of the surface morphology of an on-SiN evaporated silver layer is shown in Fig. 6.

The initial complete fabrication tests resulted in a stained mirrors. This was found to be due to problems with cleaning after anisotropic KOH etching. In the fabrication sequence the Ag mirrors were patterned using lift-off in an ultrasonic bath using acetone. Three cascaded baths with fresh clean acetone yields clean Ag mirrors. For protection purposes the wafer was then covered by a photoresist layer to avoid any mechanical damage to the wafer surface during further processing.



(b)

Fig. 5: Calculated (a) and measured (b) transmittance for 40 nm Ag - 450 nm SiN - 40 nm Ag layer stack.

The anisotropic KOH etching was performed using a sealed stainless steel holder. After the SiN membranes were completely cleared from Si on entire area, the wafer in holder was carefully taken out from the KOH solution an rinsed for 30 min in de-ionised water. The sealed holder was then opened and wafer was separately rinsed again for 30 min. The protection photoresist layer on the wafer front side was subsequently removed in acetone. The resulting structures (Si frame hanging on a SiN membrane) are very fragile and extreme care must be taken during further handling. Therefore, any 'aggressive' drying method is not allowed. Slow drying in a nitrogen flow resulted in a stains on most of the membranes. These were found to be probably organic residue from the protective photoresist layer. Improvement was achieved using isopropyl alcohol after acetone cleaning, or by completely avoiding protective photoresist layer. However, the best solution will be deposition of the Ag layer at the very end of the fabrication sequence. This improvement is incorporated into the fabrication sequence for our next generation of the F-P devices. Fig. 7 shows a photograph of the fabricated miniature F-P device. The square-shaped pyramidal openings at the periphery of the device are used during the assembly of the bottom and upper die to perform the manual alignment.

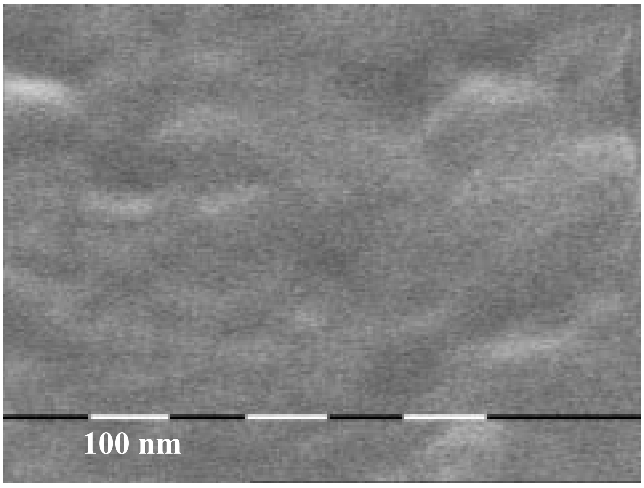


Fig.6: SEM photograph of the evaporated silver layer surface.

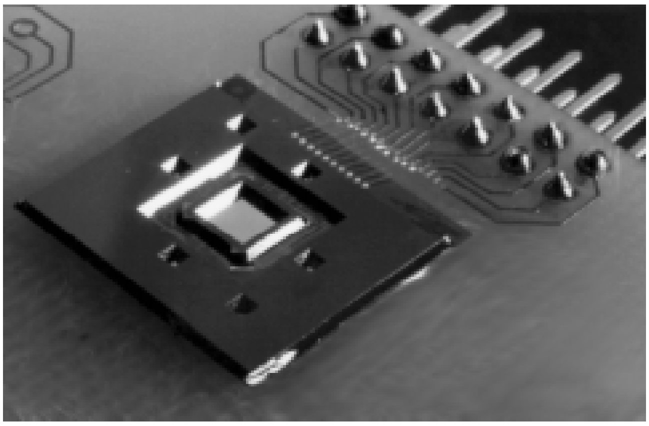


Fig. 7: A photograph of the fabricated miniature Fabry-Perot tunable intererometer device.

CONCLUSIONS

Silver films of 40 nm thickness, evaporated on a 300 nm thick low-stress silicon nitride layer (which is, after anisotropic etching in KOH, under tension on a square silicon frame), have been investigated for use as a high-quality mirrors operating in the visible and near IR spectral range. Two parallel mirrors, with square aperture of up to 2x2 mm^2 and an electrostatically controlled spacing, forms a tunable Fabry-Perot optical filter. Special care is required to maintain high mirror quality, if a silver layer is to be deposited before anisotropic KOH etching. The best choice is to deposit silver at the very end of the fabrication sequence. For our present device that is not possible, and care must be taken to protect the silver layer from degradation during the anisotropic KOH etching and subsequent cleaning.

ACKNOWLEDGMENTS

The authors wish to thank the staff of Delft Institute of Microelectronics and Submicron Technology (DIMES), especially J. Groeneweg, for technical assistance in fabrication of the devices. The work presented here has been supported in part by STW, project DEL 55.3733, and JNICT - Portugal, PRAXIS XXI-BD/5181/95.

REFERENCES

[1] A.T.T.D. Tran, Y.H. Lo, Z.H. Zhu, D. Haronian, E. Mozdy, Surface Micromachined Fabry-Perot Tunable Filter, IEEE Photonics Technology Letters, Vol. 8, No. 3, 1996, pp. 393-395.

[2] G.L. Chhristenson, A.T.T. Tran, Z.H. Zhu, Y.H. Lo, Surface micromachined long wavelength LED/Photodetector with a continuous tuning range of 75 nm, Proc. MEMS'97, Nagoya, Japan, 1997, pp. 61-65.

[3] J. Patterson, B. van Zeghbroeck, Fabrication and analysis of Si/SiO$_2$ Micro-mechanical Modulators, Digest IEEE/LEOS 1996 Summer topical meeting on optical MEMS and their appl., 1996, pp. 25-26.

[4] N.F. Raley, D.R. Ciarlo, J.C. Koo, B. Beiriger, J. Trujillo, C. Yu, G. Lomis, R. Chow, A Fabry-Perot Microinterferometer for Visible Wavelength, Proc. 5th IEEE Solid State Sensor and Actuator Worksh., Hilton Head Island, SC, USA, 1992, pp. 170-173.

[5] H.A. Macleod, Thin-film optical filters, Adam Hilger Ltd, 2nd edition, 1986.

[6] D.-Y. Song, R. W. Sprague, H. A. Macleod, M. Jacobson, Progress in the development of a durable silver-based high-reflectance coating for astronomical telescopes, Appl. Optics, Vol. 24, No. 8, 1985, pp. 1164-1170.

[7] J.W. Holm-Kennedy, K.W. Tsang, W.W. Sze, F. Jiang, D. Yang, A Novel Monolithic, Chip-Integrated, Color Spectrometer: The Distributed wavelength Filter Component, SPIE Vol. 1527, 1991, pp. 322-331.

[8] D.P. Poenar, R.F. Wolffenbuttel, Optical properties of thin-film silicon-compatible materials, Applied Optics, Vol. 36, No. 21, July 1997, pp. 5122-5128.