CMOS compatible optical sensors with thin film interference filters: fabrication and characterization

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Abstract—**Optical microsystems with high spectral selectivity and fabrication compatible with a standard CMOS process have been realized. PN junction photodiodes are used for photodetection. A multi-layer optical filter fabricated on top of the active photodiode forms a Fabry-Perot optical resonance cavity. The resonance wavelength can be designed within the entire visible spectrum. The filters are fabricated by depositing thin layers (SiO_2, Al, Ag) with thickness and composition optimized for the required spectral response. Operation is demonstrated on a device with a 20nm Al/250nm SiO_2/45nm Ag filter resulting in a narrow transmission peak (FWHM=18nm) with maximum responsivity of 14.8 mA/W at 420nm. IC-fabrication compatibility of this device allows the on-chip integration of A-to-D conversion based on a frequency or bitstream signal.**

Keywords—**CMOS optical sensors, thin film filters, fabrication compatibility**

I. INTRODUCTION

Methods for fabrication of miniaturized total (bio-) chemical analysis receive an increasing interest [1-4]. Optical techniques based on spectral analysis have a huge potential in this application, because of the relative ease of operation and reliability. An optical detection method could be used to detect the wavelength shift according to optical transmission change in a flowing sample between a light source and an optical detector. Photodetectors with a high spectral selectivity over a relatively wide wavelength range are required in such an application. Most macroscopic analyzing systems are based on a grating as dispersive element. However, on-chip integration of such a system is difficult, due to the limited optical path length available [5]. A Fabry-Perot interferometer can be used in an optical sensing system to pass a specific part of the spectrum [6- 8]. This device is an optical element consisting of two parallel mirrors separated by a cavity. Figure 1 shows the principle of operation. When the cavity width is equal to an odd multiple of a half wavelength of the incident light, the optical transmission is maximum. This effect is due to multiple reflection and interference of the light in the cavity. Flatness and reflectivity of the two mirrors are therefore very important for achieving high performance. The reflectivity is a parameter determined by material used for the mirrors. However, the flatness and parallelism of the mirrors are typical microfabrication issues.

Research is presently aiming on a multi-spot electrostatically deflectable mirror pair. Electrostatic actuation and simultaneous capacitive displacement sensing is used to tune the filter, This approach has three disadvantages: fabrication requires complex micro-machining, which is difficult to be merged with a standard process, (b) operation is difficult and (c) large voltages are required for actuation. An alternative is an array of differently sized fixed cavity width devices with solid material between two reflective mirrors. Such a device is relatively simple to operate, however, also imposes potential fabrication compatibility infringements. This study is about the comparison of the conventional bulk micromachined device and the fixed-width Fabry-Perot filters from the fabrication compatibility perspective. In the first post-micromachining is required and in the latter several layers have to be deposited on top of the CMOS metallization.

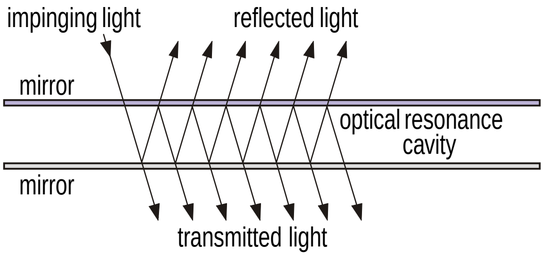

Fig. 1. The principle of Fabry-Perot optical filter.

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For the first concept a compatible bulk-micromachining process has been used to realize a microsystem with on-chip photodiodes, readout circuits and analog-to-digital conversion using voltage switching and capacitor switching have been developed [9]. In the second approach a sensor with a set of Fabry-Perot etalon filters and fully integrated read-out circuitry has been fabricated by adding several low-temperature post-processing steps after completion of the standard CMOS process. General problems in the fabrication of Fabry-Perot elements after completion of a CMOS process are: Fabrication compatibility with already integrated circuitry in terms of limited deposition temperature range, lithographic problems due to variations in surface topology, attack of passivation layers and clean room re-entrance.

These restrictions apply in a much lesser extend to the fixed width array device. The solid cavity length can be tuned by the thickness of cavity material (PECVD oxide) during fabrication. In this paper, optical sensor with multi-layer thin film filter with solid cavity on top of sensing area and integrated read-out and A-to-D conversion circuit is presented.

II. Sensor Structure

Figure 2 show the schematic structure of the realized optical sensor with thin film filter. The PN junction photodiode is located underneath the multi-layer thin film filter, which consists of 20nm aluminum, PECVD oxide (variable thickness) and a 45nm silver on top. The photodetector is basically a vertical PNP device, that is two stacked PN junctions: the deep junction is formed between the N-well and P^- epilayer and the shallow junction is formed by N-well and P^+ implanted shallow layer. Aluminum and PECVD oxide are fully compatible with standard CMOS process. Only the non-fabrication compatible silver layer (which was used because of its superior reflection properties at visible wavelengths compared to aluminum) was deposited at the end of the fabrication. The thickness of cavity sandwiched between two semi-transparent metallic mirrors determines the wavelength tuned. This is set during the fabrication process to transmit only in a relatively narrow spectral band in the visible spectral range. The oxide passivation layer on top of the photodetector (between Fabry-Perot filter and Si substrate surface) is thinned before making the multi-layer thin film filter to reduce its influence on the spectral response.

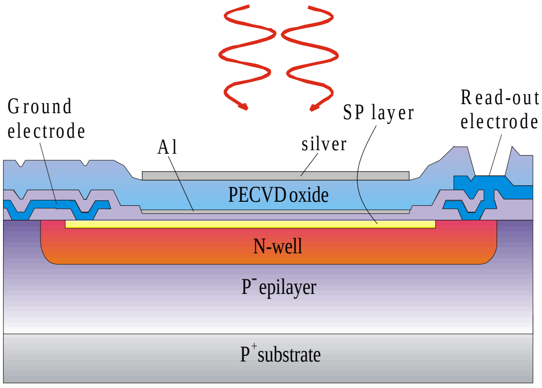


Fig. 2. Cross sectional view of sensor structure.

III. Readout

The block diagram of the read-out circuit is shown in figure 3. Operation is based on integration of the photocurrent (I_{ph}) by the junction capacitance of the sensor (C_j). The junction is charged periodically and the charge variations are converted in the charge-to-frequency converter into a semi-digital output, as described in [10].

The charge across an identical junction, but completely covered with a shielding metal, is used as a reference for the read-out circuit, compensating for the dark current of the sensor. The output frequency is used to drive a bus interface.

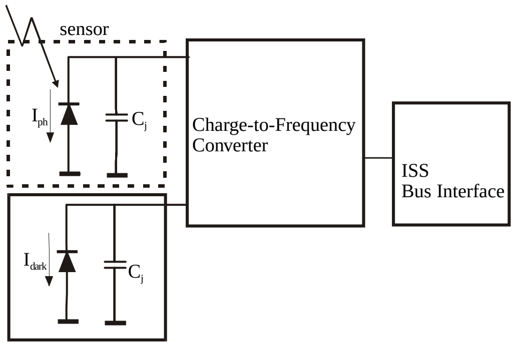
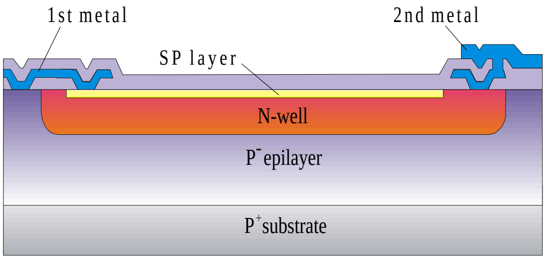


Fig. 3. Block diagram of the read-out circuit.

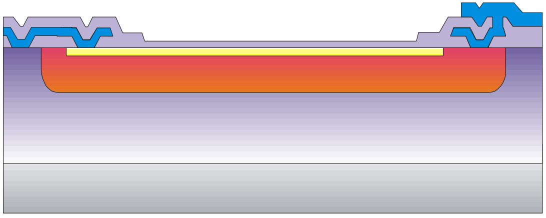
IV. Fabrication

The circuitry and the photodetector have been realized in a standard double-metal, single polysilicon 1.6 μm CMOS process. After completion of the standard CMOS process, except for the last silicon nitride deposition step for scratch protection, post-processing was used to fabricate the Fabry-Perot filter. This consists of a thin film stack (silver/PECVD oxide/aluminum) on top of photodetector. Figure 4 schematically shows the fabrication sequence. The photodetector was formed in the N-well in the P-epilayer using shallow boron implantation.

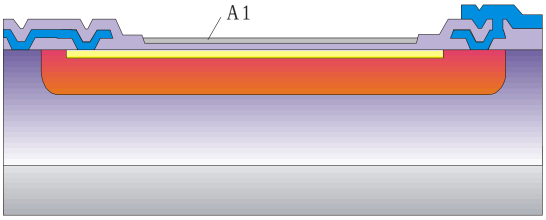
Since the oxide layer on top of the photodiode is rather thick just after the CMOS process and before the process for multi-layer filter, this oxide layer has been thinned to 300nm to minimize the effect of the thick oxide layer for



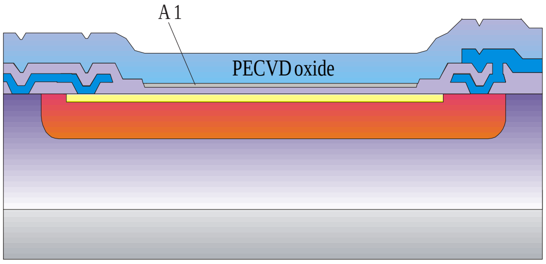
(a) completed CMOS process



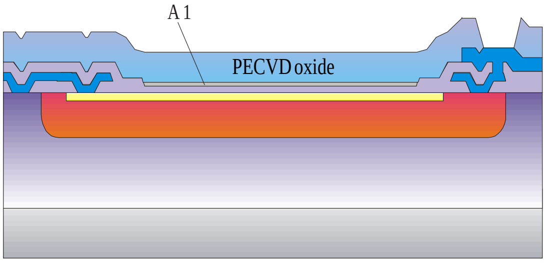
(b) Thinning of the oxide above photodiode active area



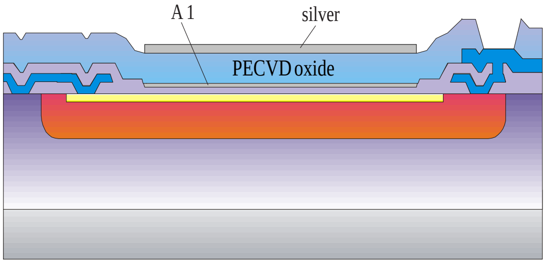
(c) Lower aluminum mirror deposition using lift-off



(d) PECVD oxide deposition



(e) Bond pad opening



(f) Upper Ag mirror depositioning using lift-off (outside the standard processing line)

Fig. 4. Schematic of the fabrication sequence

transmittance. The 20nm thick aluminum, 250nm thick PECVD oxide and 45nm thick silver layers have been stacked on it, subsequently.

The fabricated chip with sensor and on-chip integrated read-out circuit is shown in figure 5. The metal covered diode was added for dark current compensation. The read-out circuit was placed in the area between the two photodiodes.

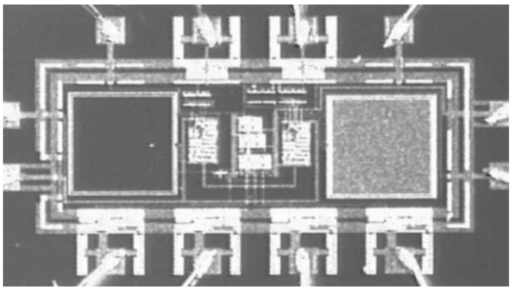


Fig. 5. Fabricated optical system with multi-layer thin film filter and read-out circuit.

V. RESULTS

A. Simulation Results

Simulation results on the transmittance of the thin film interference filter as a function of wavelength for different mirror materials are shown in figure 6. The optical effect of the thinned 300nm thick oxide layer between the interference multi-layer filter and the photodiode was also included in the simulation. The photodiode spectral response was considered ideal (wavelength independent unity quantum efficiency). The red line in the graph expresses the simulation result with the multi-layer filter consisting of 45nm silver/250nm PECVD oxide/45mn silver layers (both of the upper and lower mirror are formed by deposition of 45nm silver). The blue line shows the result with 20nm thick aluminum layer for the lower mirror. As mentioned, the reflectivity of the silver mirror is higher

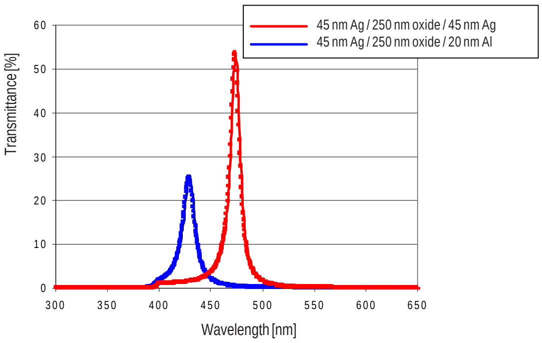


Fig. 6. Simulated transmittance of the 250nm PECVD oxide cavity with different mirror materials.

than that of aluminum. Therefore, a better transmittance was observed when using silver for both upper and lower mirror. However, aluminum was used for the lower mirror of the presented device, to fully comply with CMOS process compatibility.

B. Measurement Result

Measurement of the spectral responsivity have been performed on the fabricated micro optical detector with multilayer optical filter consisting of 45nm Ag/250nm PECVD oxide/20nm Al. As can be seen in figure 7, a sharp peak of spectral responsivity with FWHM=18nm was achieved at about 430nm, compared to FWHM=13nm at 420nm in the simulation shown in figure 6. This peak value can be tuned by the thickness of the oxide cavity as mentioned before. And when this detector is used for biochemical analysis in a μTAS, the shift of the peak value might be detected. By using silver layer for the lower mirror of the filter instead of the aluminum the performance can be further improved.

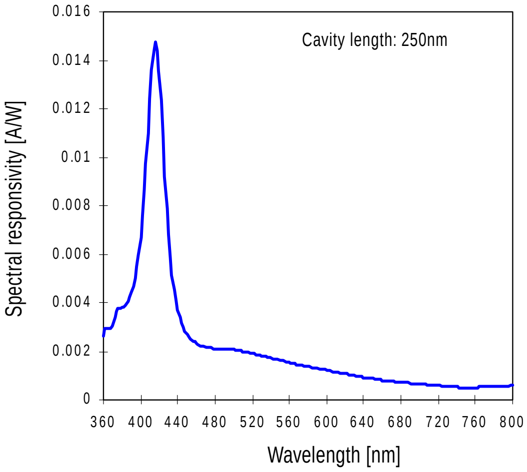


Fig. 7. Measurement result of spectral on a 20nm Al/250nm SiO_2/45nm Ag filter as a function of wavelength.

VI. CONCLUSIONS

Optical microsystems compatible with a standard CMOS process have been realized. After completion of the CMOS process used for fabrication of the photodiode and circuit, Fabry-Perot filters for use in the visible spectrum were fabricated on top of the photodiode area. The filter was fabricated by deposition of thin layers (PECVD-SiO_2, evaporated Al, Ag), with thickness and composition optimized for the required spectral response. Full fabrication compatibility of the multi-layer filter allowed integration of on-chip readout and Analog-to-Digital conversion, based on a frequency or bitstream output. The experiments described are based on one single fixed-width solid cavity. This technique can be extended to a multi-channel array microspectrometer with differently sized solid cavities using a series of masked oxide etches. Compared to the micromechanical device, the fixed-width resonator features: improved CMOS process compatibility, a higher reliability and stability and the necessity of electrostatic actuation for tuning is avoided. The device was composed of a 270nm thick cavity between a 45nm thick upper silver mirror and a 20nm thick lower aluminum mirror. A FWHM=18nm was measured at 430nm, thus yielding a high selectivity in visible range This single chip integrated device might be applicable to systems for biomedical or chemical analysis based on optical absorption.

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