SINGLE-CHIP CMOS OPTICAL MICROSPECTROMETER

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ABSTRACT

A single-chip CMOS optical microspectrometer containing an array of 16 addressable Fabry-Perot etalons (each one with different resonance cavity length), photodetectors and circuits for readout, multiplexing and driving a serial bus interface has been fabricated. The result is a chip that can operate using only five external connections (including V_{dd} and V_{ss}) covering the optical range of 380-500 nm with FWHM=18 nm. Frequency output and serial bus interface allow easy multi-sensor, multi-chip interfacing using a microcontroller or a personal computer. Power consumption is 1200 μW for a clock frequency of 1 MHz.

INTRODUCTION

Numerous applications, e.g. systems for chemical analysis by optical absorption and emission control of gas outlets, will benefit from the availability of low-cost single-chip spectrometers. Miniaturized spectrometers will offer significant advantages over existing instruments, including size reduction, low cost, fast data-acquisition and high-reliability. Previously developed microspectrometers, fabricated using bulk or surface micromachining, contain movable parts to perform wavelength tuning [1-2]. As the result, these are less reliable and suitable only for operation in a limited spectral band (mostly near-IR) [3-4]. Moreover, high-voltage electrostatic actuation is necessary for resonance cavity tuning. In this paper a fully integrated array-type single-chip microspectrometer with a light-frequency converter and a bus interface is presented.

MICROSPECTROMETER DESIGN

An array-type microspectrometer based in the Fabry-Perot etalon was developed. The principle is shown in Fig. 1. The impinging spectrum is filtered in the Fabry-Perot resonator and the intensity of the selected spectral component is measured in transmission using an underlying integrated photodiode array (4x4 matrix arrangement). On top of each photodiode an Al/SiO_2/Ag multilayer stack is deposited functioning as the Fabry-Perot optical filter. The thickness of the PECVD silicon dioxide layer, which is enclosed in between two semi-transparent metallic mirrors, determines the wavelength to be tuned [5]. An oxide layer is present between the cavity and the photodiode and introduces a wavelength-dependent transmission of the incident radiation. Its thickness was designed for anti-reflectance performance over the visible spectral range [5-6]. Evaporated metallic mirrors were used instead of high-performance dielectric mirrors, to maintain fabrication simplicity (only one layer must be deposited). Another advantage of metallic mirrors is the suitability for use over a wide spectral range [7]. Silver and aluminum have been selected for high reflectivity at visible wavelengths (see Fig. 3). Fabry-Perot filters using metallic mirrors cannot provide both high finesse (ratio between the Free Spectral range and FWHM) and high transmittance simultaneously, due to the optical absorption in the metal layers.

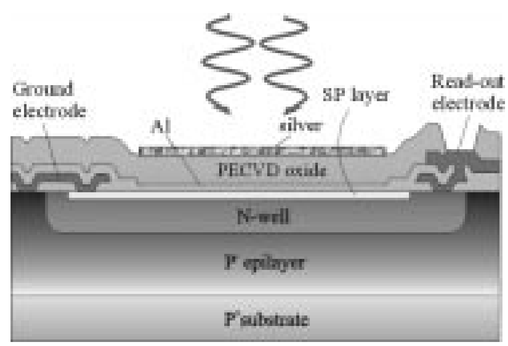


Fig. 1: Fabry-Perot etalon and photodetector structure.

The photodetector is a vertical PNP device, with the deep junction formed by the P-epilayer and the N-well, and the shallow junction formed by the N-well and a P+ implanted layer, normally used for the drain/source contacts (SP). Both junctions are used for photodetection and charge storage.

Fig. 2 shows the block diagram of the read-out circuit. Basically it can be considered as a first order (or relaxation) oscillator circuit.

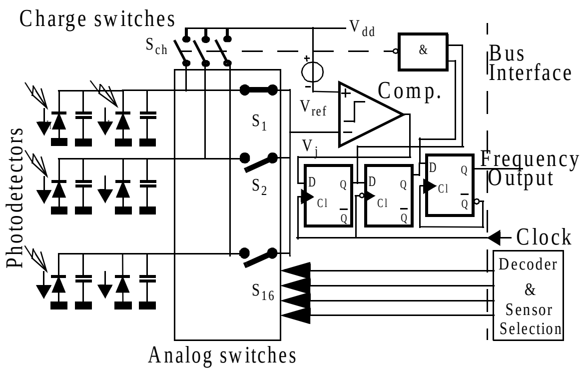


Fig. 2: Readout circuits.

These circuits can be tuned over a very wide range, since only one pole (or frequency controlling element) is present. Only one photodiode is connected to the comparator at a time using the multiplexer S_1-S_N. The voltage V_j across the junction of the photodiode varies continuously between V_{dd} and V_{ref} in a feedback loop, with the comparator, flip-flops and switch S_{ch}, forming a relaxation oscillator circuit. The charge generated by the photoelectric effect directly modulates the charge across the integrating junction capacitance, thereby modulating the output frequency [8]. The 16 channels are arranged in a 4x4 array of square photodiodes, each with an active area of 500x500 mm^2.

A block diagram of the bus interface is shown in Fig. 3. The improved Integrated Smart Sensor bus (ISS-bus) [9] was chosen, as the standard bus interface. This bus interface is simple enough to be on-chip merged with sensors or/and actuators and is able to handle both digital and semi-digital signals.

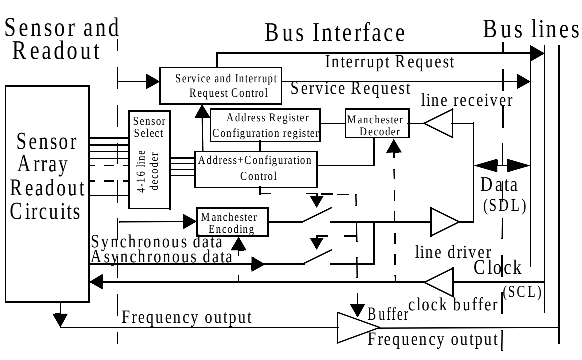
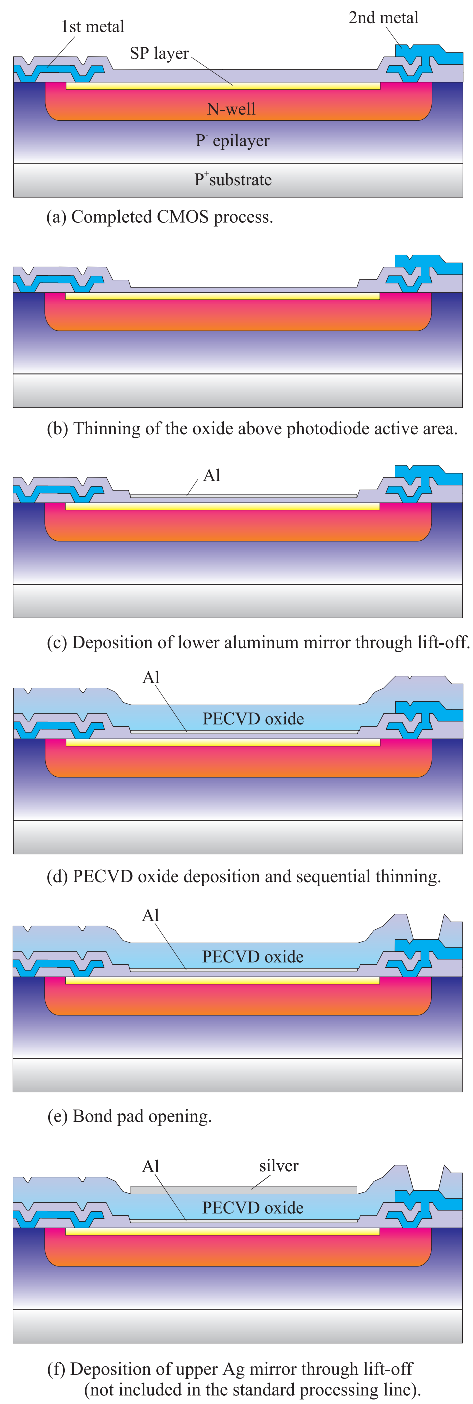


Fig. 3: Block diagram of the bus interface.

FABRICATION

After, completion of a conventional CMOS process (where the readout circuits and photodiode array were fabricated), a CMOS-compatible low-temperature postprocessing was used for Fabry-Perot etalon fabrication. This consists of an Al/SiO_2/Ag multilayer stack deposition on top of each photodiode (see Fig. 4).



(a) Completed CMOS process.

(b) Thinning of the oxide above photodiode active area.

(c) Deposition of lower aluminum mirror through lift-off.

(d) PECVD oxide deposition and sequential thinning.

(e) Bond pad opening.

(f) Deposition of upper Ag mirror through lift-off (not included in the standard processing line).

Fig. 4: CMOS postprocessing fabrication sequence.

An Al layer is used for compatibility reasons as bottom mirror and the Ag layer (upper mirror) is deposited in the very last step. This stack functions as a Fabry-Perot resonance cavity. The thickness of the PECVD silicon dioxide layer, enclosed between the two semi-transparent metallic mirrors determines the transmission peak wavelength. The initially deposited PECVD oxide layer (300 nm) is thinned using four etching steps with four different masks. This results in 16 channels, each with a different resonance cavity length (225 nm-300 nm with 5 nm steps).

A photograph of the complete chip is shown in Fig. 5. The die measures 4.2 mm by 3.9 mm.

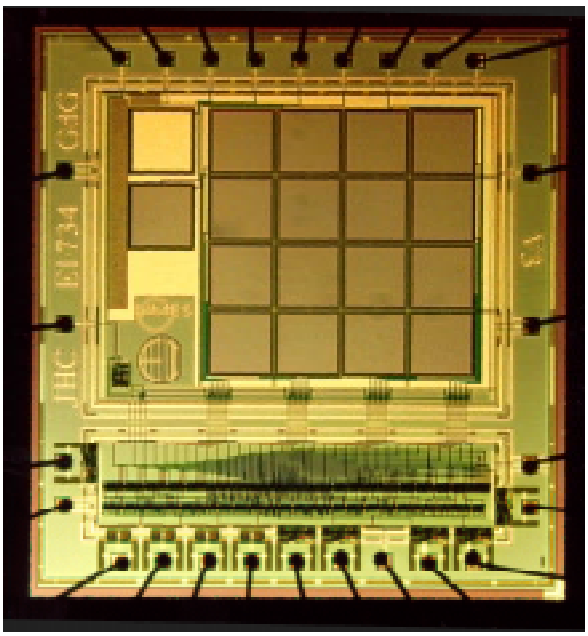


Fig. 5: Photograph of the single-chip optical micro-spectrometer.

The analog circuits, the sensor array, the analog switches, a photodiode without filter for measuring absolute intensity, a metal-covered photodiode (for dark current compensation), a reference circuit, a reference capacitor and the comparator, are in the upper part of the chip. The bus interface, the multiplexer and some other digital circuits reside in the lower part.

EXPERIMENTAL RESULTS

Fig. 6 presents the spectral responsivity (A/W) between 400 nm to 800 nm for all 16 channels. The relatively high stray light, beam divergence and the roughness surface are responsible for the background signal. The detectors are sensitive in only one narrow spectral band in the entire visible spectral range with a FWHM of 18 nm. Frames of eight bits are used to address the microspectrometer. The four most significant bits are used for addressing the chip (this allows to use more than one device in network), so up to 16 chips can be addressed. The four least significant bits are used to select one of the 16 channels.

After selection, the output frequency of the corresponding sensor is available on the bus. This timing sequence is shown on the oscilloscope plots in Fig. 7 and Fig. 8.

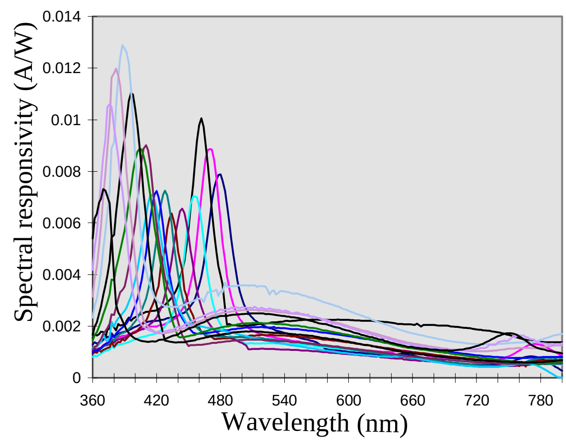


Fig. 6: Spectral responsivity of the 16 channel micro-spectrometer for a 45 nm Ag / SiO_2/ 20 nm Al layer stack. The SiO_2 layer thickness is used as a parameter and changes from 225 nm to 300 nm in 5 nm increments.

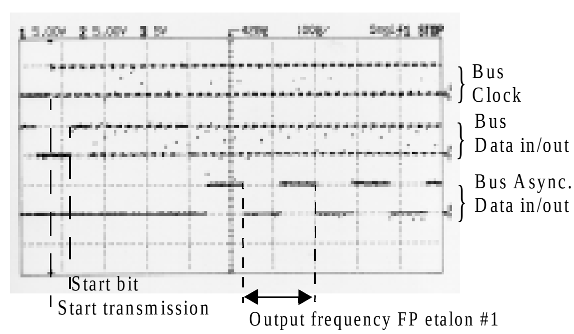


Fig. 7: Oscilloscope plot of the bus signals for a high light level.

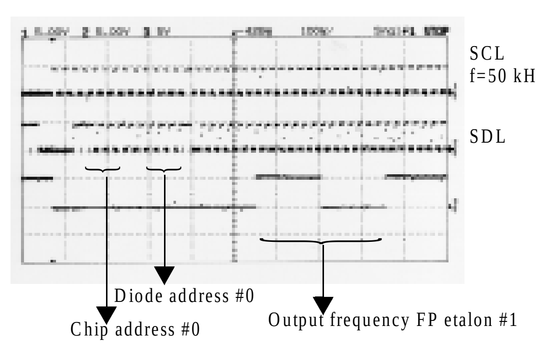


Fig. 8: Oscilloscope plot of the bus signals for a low light level.

Table 1: Electrical and optical characteristics.

Feature	Result
Technology	CMOS
Device size area	4.2 x 3.9 mm^2
Operating voltage	5 V
Power dissipation @1 MHz	1250 µW
Power dissipation @100 kHz	700 µW
Maximum clock frequency	6 MHz
Dark frequency @25°C	0.05 Hz
Free spectral range	380-500 nm
FWHM	18 nm
Responsivity (no FP etalon)@480 nm	0.18 A/W
Sensitivity@670 nm reference used [10] (no FP etalon)	1.1 kHz/Wm^{-2}

CONCLUSIONS

A single-chip CMOS optical microspectrometer containing an array of 16 addressable Fabry-Perot etalons (each one with different resonance cavity length), photodetectors and circuits for readout, multiplexing and driving a serial bus interface was fabricated. The result is a chip that can operate using only five external connections (including V_{dd} and V_{ss}) covering the optical visible range. Strictly, only four external connections to the chip are needed because the bidirectional dataline (SDL) can also be used for transmission of the frequency output. The advantage of the device presented is that it can easily be tuned during fabrication to cover a different spectral band, by adjusting the etching time only, without affecting the device layout. Therefore, also microspectrometers for different regions of the electromagnetic spectrum are feasible by means of this technique.

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