OPTICAL MICROSPECTROMETER USING A MICRO-INSTRUMENTATION PLATFORM

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Abstract

MEMS are usually designed for measuring one parameter and on-chip co-integration of sensor (microstructure) and readout circuits is often pursued. In a multi-parameter measurement system, yield considerations and fabrication compatibility problems favor micro-instruments based on active Si-MCM techniques. The generic device is based on a stacked structure with a universally applicable active silicon MCM platform that contains all the infrastructural functions of a measurement system. Customizing the microsystem requires flip-chip attach of sensor dies and a commercially available microcontroller die, which is subsequently programmed for the intended application. The micro-instrument features a data pre-processing capability to provide high-level data (e.g. spectral information rather than raw sensor data) and to communicate with a host processor intelligently.

The micro-instrument has been used to enhance the resolution of a single-chip 16-channel CMOS microspectrometer. This chip contains an array of 16 addressable fixed-cavity Fabry-Perot etalons, photodetectors and circuits for read-out, multiplexing and driving the ISS sensor bus has been fabricated. This resulted in a chip that can operate using only five external connections (including V_{dd} and V_{ss}) covering the optical range of 400-500 nm with FWHM=18nm. Bonding several of these chips, each with a different set of 16 channels, onto the micro-instrumentation platform enables the fabrication of a high-resolution spectral analyser.

Introduction

The integrated silicon smart sensor with sensor and readout circuits merged on one single chip has found widespread application in e.g. airbag deployment systems and domestic appliances etc. [1]. However, this concept is less suitable for solving complex measurement problems, because of the massive data processing often required. On-chip integration of data-processor with sensor and readout circuits would result in a huge die area and a complex mixed analog/sensor/digital process. The resulting low yield and fabrication compatibility constraints limit economic feasibility of the fabricated devices. For this reason hybrid techniques are still in use for the fabrication of complex measurement systems.

The micro-instrumentation system is intended to enable a further system integration without violation of yield or compatibility constraints. The concept is basically micro-assembly on the chip level. A chip will be designed that serves as an 'active platform' containing all universal functions such as power/thermal management and local sensor bus. Part of the die area is intentionally left open to allow a microcontroller chip and sensor chips to be bonded. The resulting stacked structure can be referred to as an active-MCM (Multi-Chip Module). Almost any application can be realized by microcontroller software and populating the platform with the appropriate sensors. The smart sensor concept will be pushed to sensible limits by on-chip integration of the sensor bus interface

A silicon micro-instrument aims on bridging the gap between the capabilities of integrated silicon smart sensors and the demands of complex measurement systems. It, therefore, serves as a kind of 'active PC-board' supporting all the functions required in any state-of-the-art measurement system. The micro-instrumentation system is used in measurement problems where the information is contained in a spectrum. Firstly, combining the information of several micromachined Fabry-Perot etalons results in an optical spectral analyser, which features a wide and unambiguous operating spectral range with high selectivity. Secondly, a system for condition monitoring of mechanical machines based on the analysis of the vibration spectrum is under investigation. This can be used to generate an early alarm in case of upcoming malfunction. Such systems are commonplace in power generators. The micro-instrumentation system would facilitate the penetration of such systems in consumer products, such as automotive. This paper presents the microspectrometer and the use of the micro-instrument to enhance the resolution.

Microspectrometer design

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 [2], [3]. As a result, these are less reliable and suitable only for operation in a limited spectral band (mostly near-IR) [4], [5]. Moreover, high-voltage electrostatic actuation is necessary for resonance cavity tuning. Also, the readout electronics and interface facilities for these microspectrometers are not an integral part of the design.

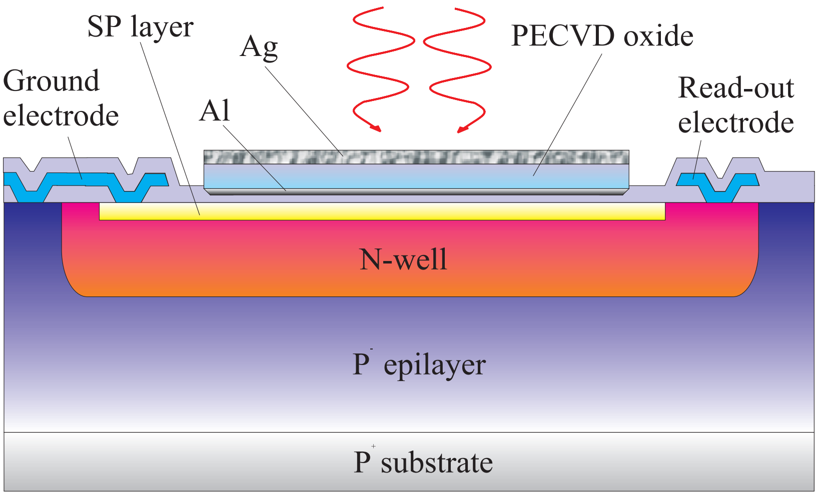

Fig. 1: Fabry-Perot etalon and photodetector structure.

To overcome these limitations a fully integrated on-chip spectrometer with a light-frequency converter and a bus interface was developed. 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. On top of each photodiode an $Al/SiO_2/Ag$ layer 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 tune [6]. In N subsequent-masked plasma etching steps, the initially deposited PECVD oxide layer is thinned forming 2^N channels, each with different resonance cavity length. 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 [7]. 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 [8]. 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. The circuit and photodetectors have been integrated in a conventional 1.6 µm CMOS n-well process. The basic sensor structure is shown in cross-section in Fig. 1.

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.

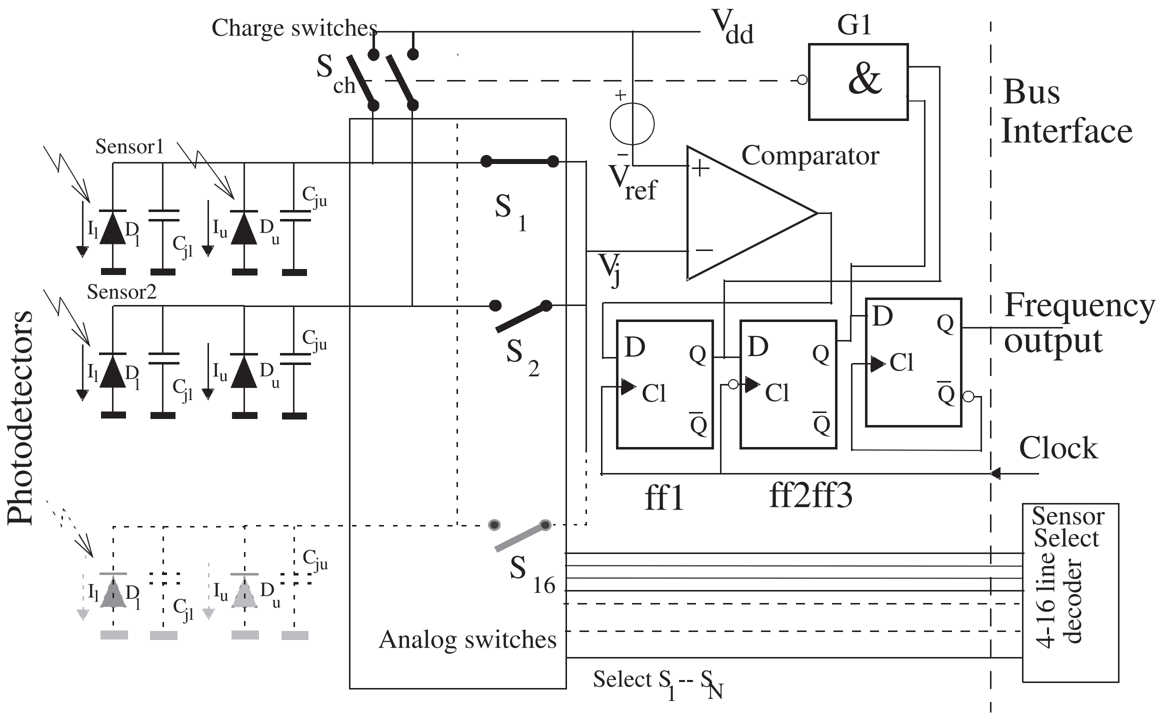

Fig. 2: Readout circuits.

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 S1-SN. 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. The sensors 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.

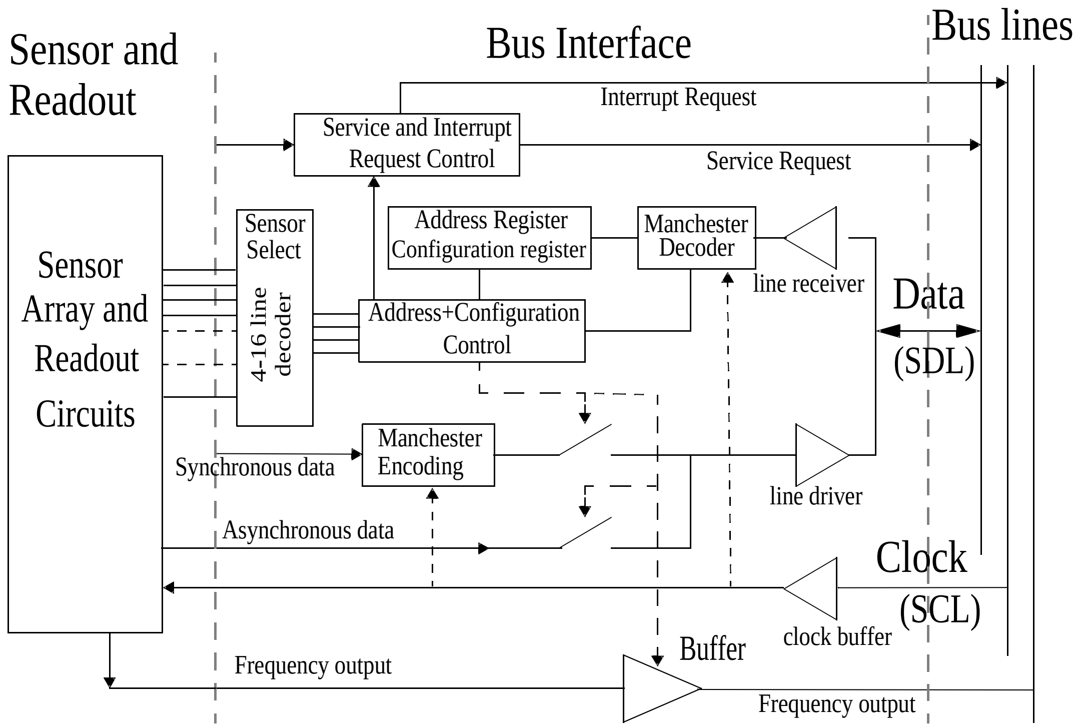

Fig. 3: Block diagram of the bus interface.

Fabrication

A CMOS-compatible low-temperature post-processing was used for Fabry-Perot etalon fabrication. This consists of an $Al/SiO_2/Ag$ layer stack deposition on top of each photodiode after completion of the CMOS process (see Fig. 4).

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 4.2x3.9 mm^2. The analog circuits, the sensor array, the analog switches, a normal photodiode (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 [10].

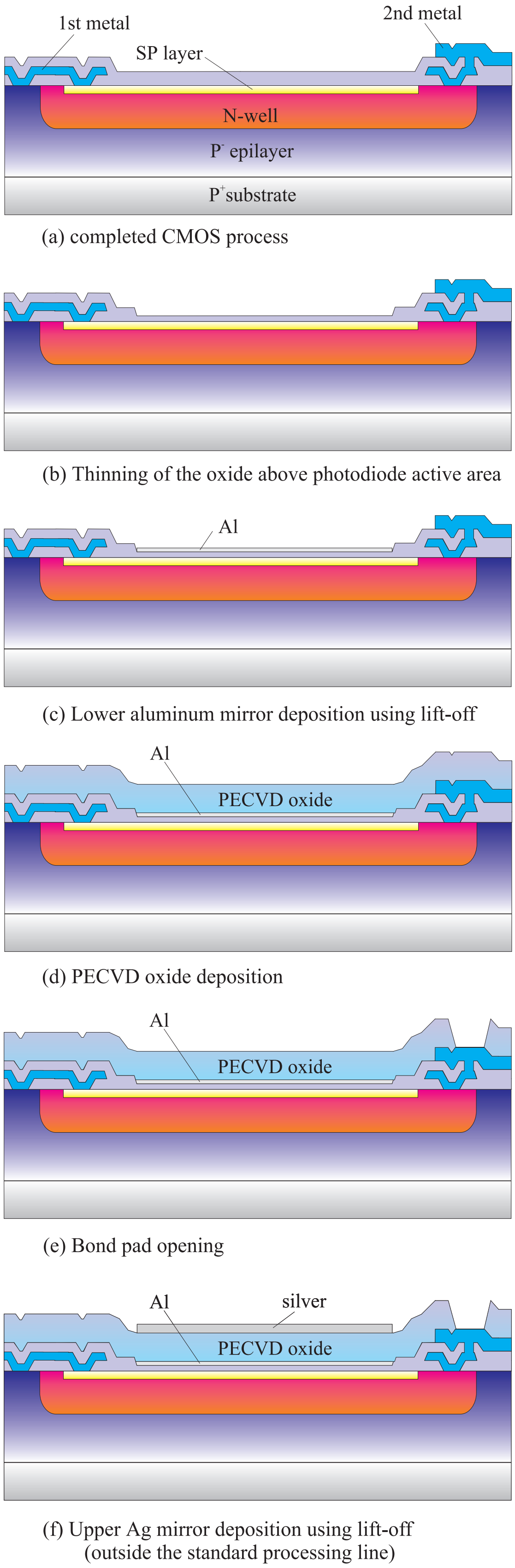

Fig. 4: CMOS post-process fabrication sequence.

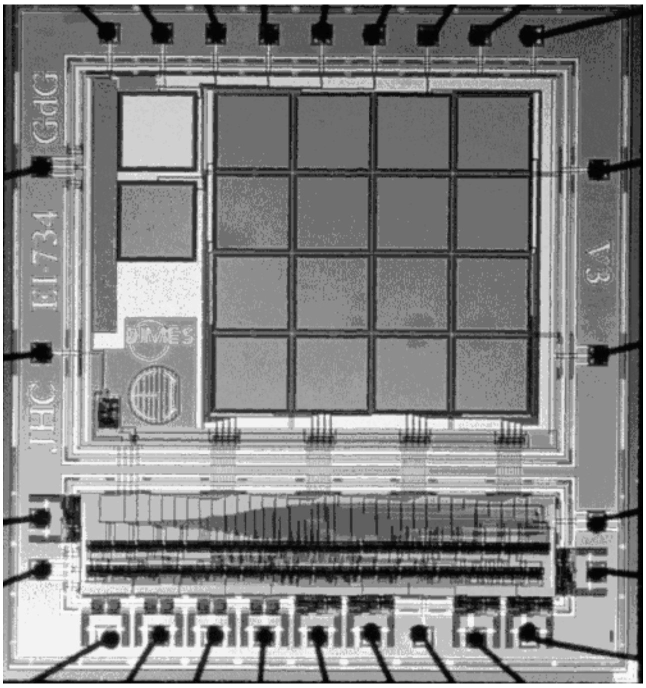

Fig. 5: Photograph of the single-chip optical microspectrometer.

Experimental results

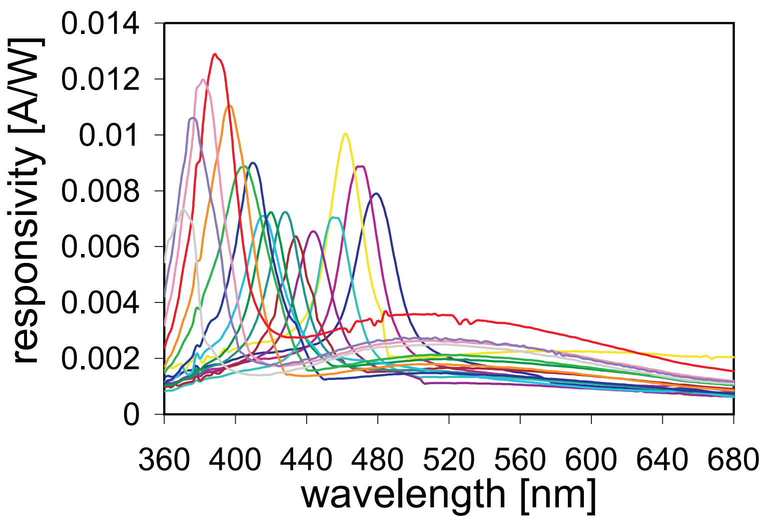

Fig. 6: Spectral responsivity of the 16 channel microspectrometer for a 45 nm Ag / SiO_2/ 20 nm Al layer stack. The SiO_2 layer thickness is used as a parameter and changes from 225 nm to 300 nm in 5 nm increments.

Fig. 6 presents the spectral responsivity (A/W) between 400 nm to 800 nm for all 16 channels using on-chip photodiodes. The ratio between the base line and the peak maximum ranges from 4 to 7. Large variations in the height of the peaks is due to: the spectral sensitivity of the integrated photodiodes and the relatively high stray light sensitivity (no shielding between the individual Fabry-Perot channels was used). The detectors are sensitive in only one narrow spectral band in the entire visible spectral range with a FWHM of 18 nm. To address the microspectrometer frames of eight bits are used. 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.

Enhancing the spectral resolution

The same mask set can be used to fabricate on-chip microspectrometers operating with high-resolution in adjacent narrow spectral bands by varying the oxide-thinning step. The resulting chips are placed on a micro-instrumentation platform to form a high-resolution spectral analyser operating over a relative wide spectral band. The bus driving capability highly simplifies in-system data transfer and microsystem control using the on-platform microcontroller. The major requirement is that the incident beam should irradiate the different chip in the same way. This optical signal conditioning can be simplified using the on-chip photodiode to compensate for intensity variations.

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 were 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 bi-directional 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, microspectrometers for the UV and IR are feasible by means of this technique. Bonding several of these chips, each with a different set of 16 channels, onto the micro-instrumentation platform enables the fabrication of a high-resolution spectral analyser.

Acknowledgements

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