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A Low-Cost Acoustic Microsensor based System in Package for Air Quality Monitoring

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***Abstract*—In this paper we report on the development of a novel hybrid System in Package (SiP) microsensor utilizing high frequency acoustic wave devices for the real time monitoring of airborne fine particulates. The hybrid particle sensing system consists of a zinc oxide (ZnO) based solidly mounted resonator (SMR) device interfaced to a CMOS application-specific integrated circuit (ASIC) chip. Air is drawn into a virtual impactor where $PM_{2.5}$ particles are separated and then deposited onto the SMR surface. The mass loading due to the fine particles is measured as a shift in the resonant frequency of the SMR working at 894 MHz. Experimental results performed in both laboratory conditions and real outdoor environment showed that the hybrid system is capable of detecting fine particles with a sensitivity of 7.5 kHz per μg/m^3. This system is used as a basis towards a fully integrated portable smart particle sensor based on CMOS-SMR devices for the continuous, real-time and low-cost monitoring of airborne particulate matter.**

Keywords— air quality monitoring, CMOS sensor, particle sensing, particulate matter, solidly mounted resonator.

I. Introduction

Air pollution due to particulate matter (PM) pose a significant threat not only for the environment but also to human health causing several diseases and reducing the life expectancy of the population worldwide. Airborne particles found in indoor and outdoor environments can stem from human activities such as domestic and industrial processes, road traffic and solvents use. It is their size that make these pollutants particularly hazardous as fine particles with diameters of 2.5 µm or smaller ($PM_{2.5}$) can penetrate deeply into the lungs. Trying to minimize human exposure to PM and the related adverse health effects, exposure limits of $PM_{2.5}$ have been established by organizations such as the European Commission (EC) and the World Health Organization (WHO) [1].

There is an increased need of monitoring personal exposure to particulate matter. Commercial instruments such as the tapered element oscillating microbalance (TEOM) analyser and optical based instruments have been used for a long time. However, they are complex, costly and bulky [2]. Acoustic wave based devices have been proposed as an alternative approach for particle detection.

In this work we use solidly mounted resonators as they offer significant advantages with respect to size, cost and complexity. Furthermore, their compatibility with low-cost silicon technologies and small footprint make them suitable candidates for fully CMOS integration as opposed to other acoustic wave devices such as Surface Acoustic Wave (SAW) devices and Quartz Crystal Microbalances (QCM).

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II. Description of the System in Package

A. Overall description of the microsensor system

A novel low-cost acoustic SiP microsensor for particulate matter ($PM_{2.5}$) detection has been developed as part of a study into environmental air quality monitoring. The microsensor system is based on a thin film Solidly Mounted Resonator vibrating at 894 MHz driven by a CMOS Pierce oscillator circuit, which forms part of an ASIC chip. The pictorial illustration of a SiP particle sensor for PM detection is shown in Fig. 1.

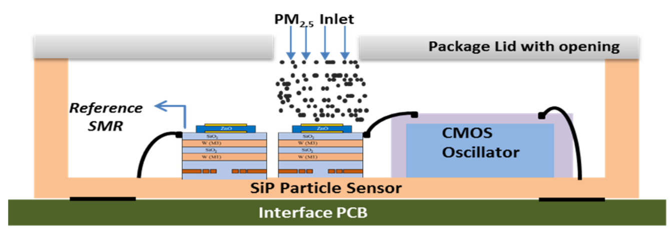

Fig. 1. Block diagram representation of a SMR microsensor system for the detection of particulate matter.

The particle sensor SiP employs a dual mode configuration in order to eliminate common mode interferences, where one SMR forms the sensing device while the other one forms the reference sensor. The ASIC oscillator chip is designed using the standard AMS (Austria Micro Systems) 0.35 um CMOS process and with the help of an on-chip RF Mixer, a differential output is obtained (0-5 MHz). Fig. 2 shows the schematic block diagram of the components inside the ASIC chip along with the off-chip dual SMR devices.

B. Solidly Mounted Resonator

The SMRs consisted of a 2.96 µm thick ZnO piezoelectric layer with top and bottom aluminium electrodes with a thickness of 200 nm. Three pairs of Molybdenum and silicon dioxide layers formed an acoustic mirror that reflects and traps the acoustic wave over the resonant frequency range. The device was fabricated on a 500 µm thick 4-inch p-type silicon substrate using standard micro fabrication technologies.

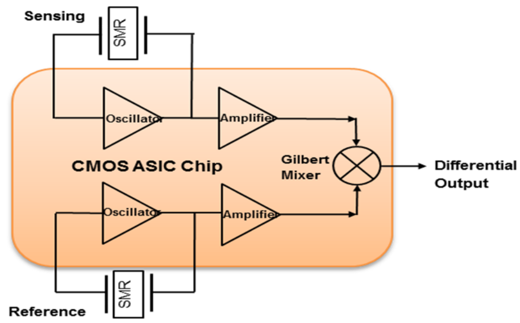

Fig. 2. Block diagram of the hybrid ASIC-SMR SiP.

The SMRs were designed in a coplanar waveguide (CPW) structure with a characteristic impedance of 50 Ω for maximum power transfer. The electrodes are linked to the coplanar transmission line, which helps in reducing the parasitic effects of the structure. A top view micrograph of the fabricated SMR is shown in Fig. 3[a].

C. CMOS Oscillator ASIC

Hybrid integration of SMR devices with CMOS oscillator circuitry minimizes the spatial and parasitic load limitations of externally coupled oscillators. The composite micrograph of the fabricated ASIC die with a size of *2.5* x *2.5 mm* is shown in Fig. 3[b]. The ASIC chip fabricated at AustiaMicroSystems (AMS) using a 0.35µm 3.3v CMOS process, has the capability of supporting two single-ended SMRs using inverter-based Pierce oscillator circuits and providing a differential signal using a gilbert mixer circuitry. The output of the Pierce oscillator is fed to a 2-stage CMOS inverter amplifier which amplifies the weak signal, before it is fed to the analogue mixer.

The ASIC chip also contains an analogue mixer based on Double Balanced Gilbert cell topology. The sensing SMR is connected to the RF input port while the reference SMR is connected to the LO (local oscillator) port of the mixer.

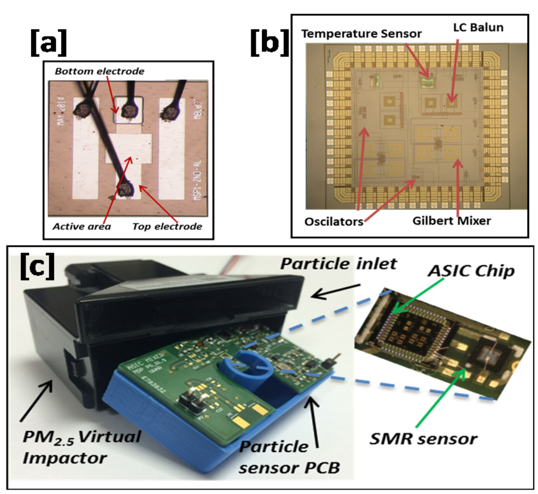

Fig. 3. [a] Top view of fabricated SMR. Device is 1 mm x 1 mm; [b] Composite micrograpgh of the ASIC die and [c] Photograph of the hybrid SMR-ASIC system placed inside the $PM_{2.5}$ virtual impactor.

A differential output frequency is obtained at the IF (intermediate frequency) port of the mixer, which is further amplified and sent to an off-chip low-pass filter and comparator to obtain a low frequency square signal that can be fed to a microcontroller.

The particle system was placed inside a commercial $PM_{2.5}$ virtual impactor (Sharp Microelectronics) and the complete system is as shown in Fig. 3[c]. The impactor separates the $PM_{2.5}$ fraction from the air flow and $PM_{2.5}$ particles are fed to the sensor surface for detection, providing an active sampling rather than a pure gravimetric deposition.

III. SPRECTRERF SIMULATION RESULTS

The simulation of CMOS ASIC oscillator chip has been performed using Cadence® Design Systems Spectre®RF circuit simulator. The schematic of the 3-inverter Pierce oscillator is shown in Fig. 4.

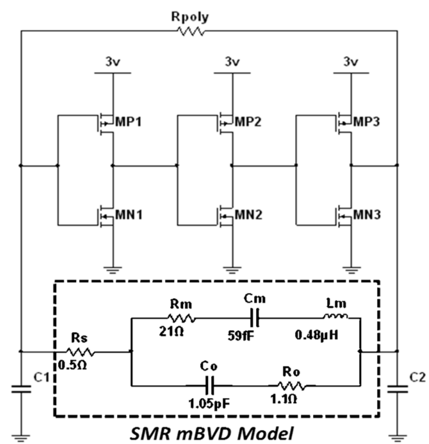

Fig. 4. Inverter based CMOS pierce oscillator schematic showing the mBVD model of the SMR device.

The SMR is connected to an inverting CMOS amplifier to form a hybrid integrated CMOS-SMR oscillator. The inverting amplifier is formed by three RF MOSFET-based CMOS inverters, which ensures sufficient gain to overcome the SMR insertion losses and to provide sustained oscillations [3]. The resistor *Rpoly* provides sufficient biasing to the MOSFETs. C1 and C2 along with the parasitic capacitances and inductances within the loop, helps in oscillator start-up. This helps to generate continuous noise energy within the SMR, resulting in increased current flow into the resonator [4]. The modified Butterworth-Van Dyke circuit model of the SMR is described in Fig. 4, which serves as a resonant tank for the oscillator.

The Spectre®RF simulations of the oscillator circuit after layout are shown in the Fig. 5. The output voltage levels during transient simulation are shown in Fig. 5[a]. The voltage gain (20dB modifier) at the fundamental resonant frequency is 0 dB, obtained from the periodic steady state analysis of the oscillator circuit, as shown in Fig. 5[b]. Fig. 5[c] and Fig. 5[d] show the loop gain magnitude and phase at the oscillator frequency, respectively. Close inspection of the magnitude and phase curves shows that the oscillator satisfies the Barkhausen criterion for sustained oscillations, because there is a gain of 0 dB (unity) and a phase of 0 degree, occurring simultaneously at the oscillator frequency.

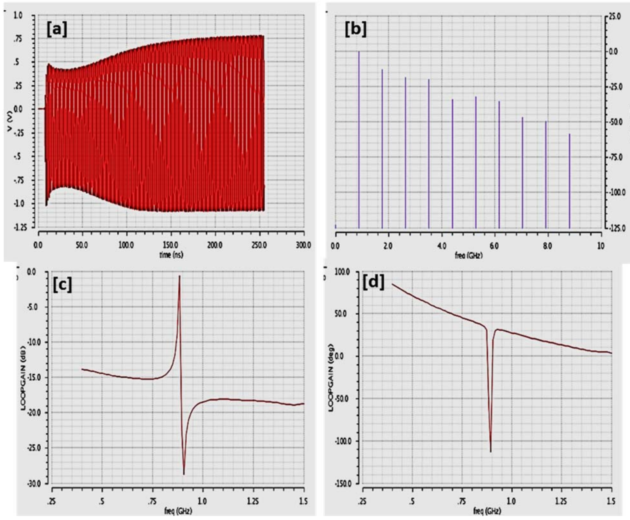

Fig. 5. Post layout SpectreRF simulation results of CMOS Oscillator detailing [a] Transient stability; [b] Periodic Steady state; [c] Loop gain magnitude and [d] Loop gain phase.

The performance of the ASIC oscillator has been verified using the Tektronix MDO3012 Mixed Domain Oscilloscope, which produced the output spectrum of the oscillator as shown in Fig. 6. This shows the oscillator frequency of 893.6 MHz, which is similar to that of SMR resonant frequency.

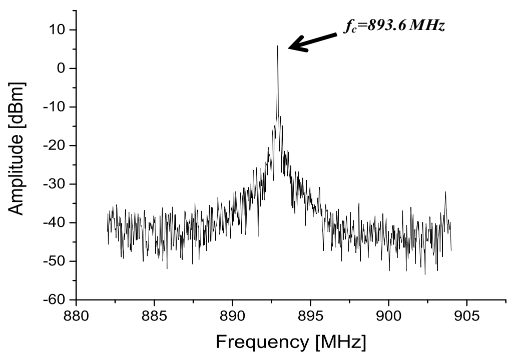

Fig. 6. Output Spectrum of the SMR-CMOS oscillator resonating at frequency (fc) of 893.6 MHz.

IV. Experimental Results

In order to demonstrate particulate matter detection, an experimental setup was constructed that comprises of a test chamber and a dust generator system. Commercial instruments such as Grimm dust monitor (model 1.108), DC1700 AQM (Dylos Corporation) and a QCM sensor (Vitrocell Systems GmbH) were also employed for benchmarking. The sensors were exposed to artificial aerosols such as Dolomite powder (0–20µm) and Ultrafine Test Dust (UFTD) (1–20µm) and $PM_{2.5}$ concentration levels were monitored inside the test chamber. The deposition of micro-particles onto the SMR surface causes a shift in the resonant frequency of the oscillator, which is measured as a differential signal.

Preliminary results were also obtained for outdoor $PM_{2.5}$ monitoring, when the SMR-based SiP was exposed to car exhaust at VITO campus.

Fig. 7 shows the response of the SMR-based SiP together with the reference instruments. Grimm and Dylos monitors showed similar response curves as they both are optical based devices. On the other hand, the QCM device and the SMR-based SiP, both acoustic resonators, presented a similar response pattern as their resonant frequencies decreased after the addition of micro particles. After a series of laboratory and outdoor experiments, the sensitivity of the SMR-based SiP was found to be 7.5 kHz per µg/m^3, considerably high compared to that of the commercial QCM device.

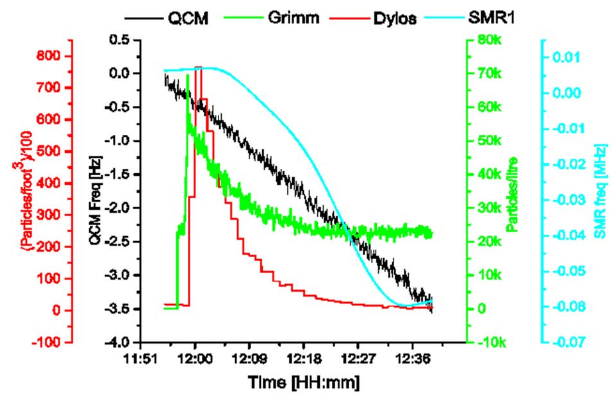

Fig. 7. Frequency response of the SMR particle sensor, due to particle deposition, shown along with data from Grimm, Dylos and QCM Devices.

V. Conclusions

We have reported the development of a low-cost hybrid SMR microsensor based SiP for particulate matter ($PM_{2.5}$) detection. A 0.35um CMOS ASIC chip containing Pierce inverter based oscillators and a gilbert mixed circuit, produces a differential low frequency output signal. The ASIC SMR shows a superior sensitivity of 7.5 kHz per µg/m^3 compared to the QCM device. In order to provide UFP, $PM_{2.5}$ and PM_{10} detection, it is possible to tailor the frequency dependent sensitivity based on the size of particles. Further work is underway towards the monolithic integration of both SMR and interface ASIC into a smart, portable, low-power and low-cost nano-particle sensor.

Acknowledgment

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References

[1] World Health Organisation, “Health effects of Particulate Matter,” 2013.

[2] A. Hajjam, J.C. Wilson and S. Pourkamali, "Individual Air-Borne Particle Mass Measurement Using High-Frequency Micromechanical Resonators". IEEE Sensors Journal, vol. 11, no. 11, pp. 2883-2890, 2011.

[3] M. L. Johnston and I. Kymissis, “An array of Monolithic FBAR-CMOS oscillators for Mass sensing Applications,” pp. 1626–1629, 2009.

[4] EPCOS, “Design-guide for the SAW oscillator,” 2008.