A low-cost acoustic microsensor based system-in-package for air quality monitoring

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***Abstract*— In this paper[1], 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 environmental 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. An air sample 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 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, safe exposure limits of PM2.5 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. 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 a suitable candidate for fully CMOS integration.

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II. Description of the System in Package

A. Overall description of the micro sensor 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 figure 1.

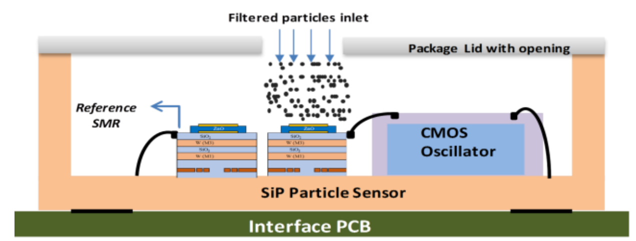

Figure 1: The block diagram representation of an SMR microsensor system for the detection of particulate matter.

The particle sensor SiP employs a dual mode configuration, where one SMR forms the sensing device while the other one forms the reference sensor; in order to eliminate common mode interferences. 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). The figure 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. 3 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. The SMR micrograph is shown in figure 3[a].

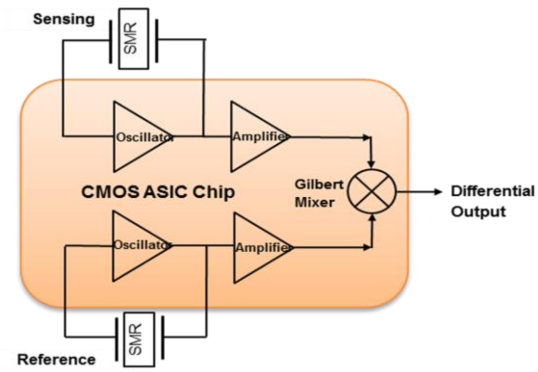

Figure 2: Block diagram of the hybrid ASIC-SMR SiP .

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.

C. *CMOS Oscillator ASIC*

Hybrid integration 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 figure 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

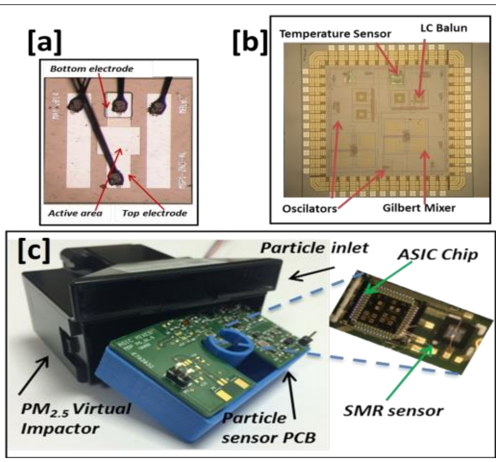

Figure 3: [a]: Top view of fabricated SMR. Device is 1mm X 1mm [b]: Composite micrograph of the ASIC die, [c]: Photograph of the hybrid SMR-ASIC system, placed inside the $PM_{2.5}$ virtual impactor.

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. 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 figure 3[c]. The air sucked into the impactor is filtered and fed to the sensor surface for detection, providing an active sampling rather than a pure gravimetric deposition.

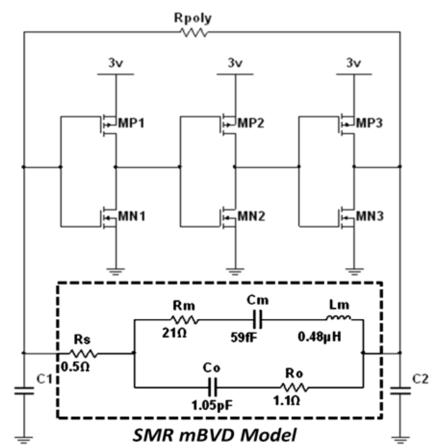

Figure 4: Inverter based CMOS pierce oscillator schematic showing the mBVD model of the SMR device.

III. SPECTRERF SIMULATION RESULTS

The simulation of CMOS ASIC oscillator chip has been

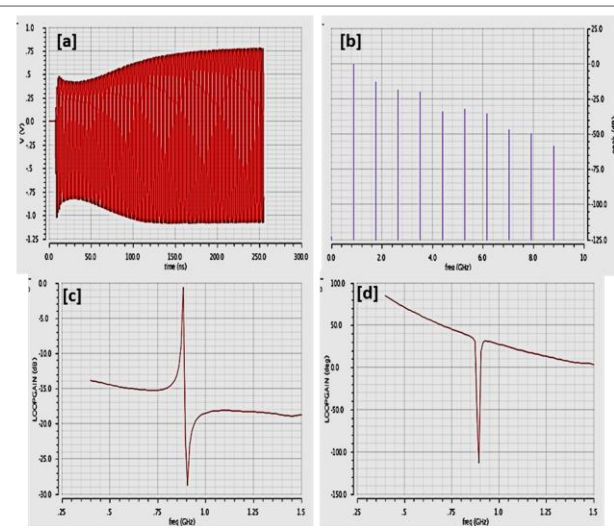

Figure 5: Post layout SpectreRF simulation results of CMOS Oscillator detailing [a]: Transient stability [b]: Periodic Steady state [c]: Loop gain magnitude and [d]: Loop gain phase.

performed using cadence spectreRF circuit simulator. The schematic of the 3-inverter pierce oscillator is shown in figure 4. The SMR is connected to an inverting CMOS amplifier to form a hybrid integrated CMOS-SMR oscillator. Three CMOS inverter amplifiers formed by RF mosfets ensure sufficient gain to overcome the SMR insertion losses and to provide sustained oscillations [2]. 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 [3]. The modified Butterworth-Van Dyke circuit model of the SMR is described in the figure 4, which serves as a resonant tank for the oscillator.

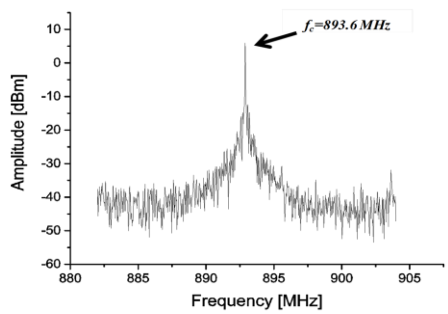

Figure 6: Output Spectrum of the SMR-CMOS oscillator resonating at frequency (fc) of 893.6 MHz.

The spectreRF simulations of the oscillator circuit after layout are shown in the figure 5. The output voltage levels during transient simulation are shown in the figure 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 5[b]. Figure 5[c] and 5[d] shows the loop gain magnitude and phase at the oscillator frequency, respectively. Close inspection of the magnitude and phase curves show 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.

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 figure 6. This shows the oscillator frequency of 893.6 MHz, which is similar to that of SMR resonant frequency.

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 aerosol monitor, DC1700 AQM (Dylos Corporation) and a QCM sensor (Vitrocell Systems GmbH) were also employed for benchmarking and calibration. The sensors were exposed to artificial aerosols such as Dolomite powder (0–20µm) and Ultrafine Test Dust (UFTD)(1–20µm) and $PM_{2.5}$ levels were monitored. The addition of micro-particles onto the SMR surface causes a shift in the resonant frequency of the oscillator, and is measured as a differential signal.

Preliminary results were also obtained for outdoor $PM_{2.5}$ monitoring, when exposed to car exhaust at VITO campus.

The responses of all the sensors are plotted in figure 7. It could be noted that as Grimm and Dylos are both optical devices, both of the show similarity in their response curves. Also SMRs and QCMs are both acoustic devices, and hence their resonant frequency decreases on the addition of microparticles. On analysing a series of laboratory and outdoor experiments, it was confirmed that the sensitivity of SMR device was quite high (7.5 kHz per ug/m^3), when compared to the commercial QCM device. Also, the particle sensor exhibited a minimum level of detection of 8 ug/m^3, which satisfies the Air Quality Standards of $PM_{2.5}$ exposure limit of 25 ug/m^3.

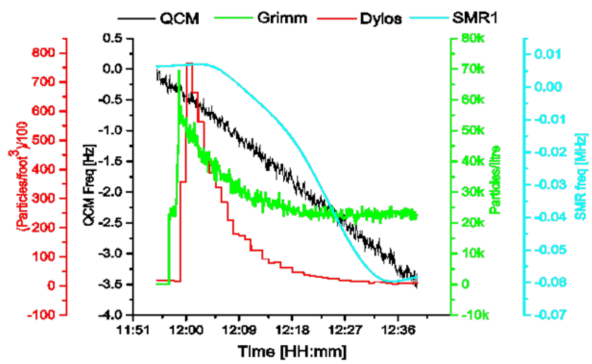

Figure 7: Frequency response of the SMR particle sensor, due to particle deposition, shown along with data from Grimm, Dylos and QCM Devices

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 ug/m^3 compared to the QCM devices. 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] M. L. Johnston and I. Kymissis, "An array of Monolithic FBAR-CMOS oscillators for Mass sensing Applications," pp. 1626–1629, 2009.

[3] EPCOS, "Design-guide for the SAW oscillator," 2008.