J-2-1(Invited)

Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp1117-1119

Modeling and simulation of CMOS integrated MEMS: application to low-cost sensors

Frederick Mailly, Laurent Latorre and Pascal Nouet

Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier
LIRMM, University Montpellier 2 / CNRS
161 rue Ada, 34095 Montpellier Cedex 5, France
Phone: +33-467 418 527 E-mail: nouet@lirmm.fr

1. Introduction

Interest for cheap integrated sensors is constantly growing with the development of mobile consumer products or disposable medical appliances. In this context, low-cost integration of multi-sensor systems making use of standard CMOS technology together with cheap post-process enables the batch fabrication of monolithic multi-sensor circuits that include accelerometers, magnetometers, microphones, temperature, pressure sensors and many other physical sensors [1].

Fabrication of different sensors in the same technology is extremely favorable to decrease time-to-market similarly as for standard microelectronics. However, realizable sensors are always sub performing compared to their competitors fabricated with dedicated and optimized process. This is the reason why a system approach of CMOS-MEMS design is required to balance various constraints on the different elements of the system (sensor, front-end electronics, data converters and digital electronics). Optimization is driven by market constraints and mainly concerns power consumption, package size and cost.

In this presentation, it is first recalled how to fabricate MEMS sensors from a CMOS die. Our preferred system modeling approaches are then presented with two main simulation directions: high-level simulation using Matlab-Simulink or low-level electrical simulation using Cadence-Virtuoso. Finally, several realization examples are given to illustrate both simulation flows.

2. CMOS-MEMS Fabrication technology

Various CMOS compatible post-processes for MEMS fabrication have been proposed over the last twenty years and most of them are today compatible with mature CMOS processes such as analog 0.35µm processes (see figure 1 or [2] for more information). More recently, additional post-processes have been proposed to extend the possibility of CMOS-MEMS. A good example is the fabrication of MEMS resonators using the top metal layer of a commercial 0.35µm CMOS technology as a structural layer and post-CMOS processed using a simple mask-less wet-etching that allows an easy monolithic integration with CMOS circuitry [3]. Presented examples are based on FSBM (Fig. 1-c) mainly due to its availability in multi-project wafers in France. This process leads to large horizontal and vertical gaps and consequently, resistive transduction is preferable.

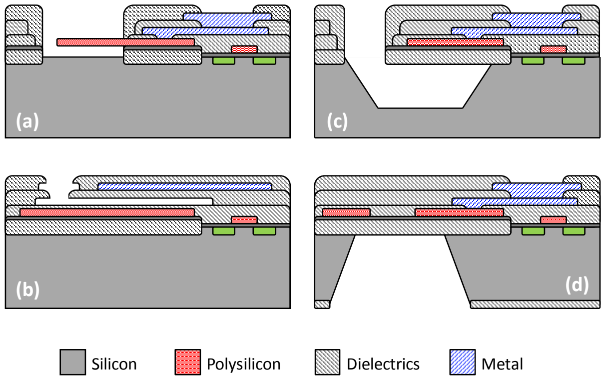

Fig. 1: main post-processes for MEMS fabrication from a CMOS die: (a) surface micromachining with SiO_2 as a sacrificial layer and polysilicon as a structural layer; (b) surface micromachining with metal as a sacrificial layer and Metal/SiO_2 structural stack; (c) front-side bulk micromachining (FSBM); (d) back-side bulk micromachining for membrane realization.

3. System-level modeling approaches

System-level modeling and simulation for MEMS is illustrated in two design flows. The first one uses Matlab-Simulink and is particularly adapted for long transient simulations such as in a ΣΔ modulator. The second is based on the Cadence EDA flow within Virtuoso and makes use of verilog-A or VHDL-AMS to describe heterogeneous devices.

Modeling and simulation with Matlab-Simulink

Figure 2 illustrates a convective accelerometer and its electrical model. This sensor was fabricated in a standard CMOS technology after FSBM. Each suspended bridge is 5 µm thick and embeds a polysilicon resistor, for heating (R_H) and temperature sensing (R_{d1} and R_{d2}) purposes. The value of these resistances as a function of temperature T (in K) expresses:

$$R = R_0 \cdot (1+TCR \cdot (T-T_0)) \quad (\Omega) \qquad (1)$$

The central bridge locally heats air by Joule's dissipation and heating expands the air thus creating a gradient of air density. Acceleration along the sensing axis *x* thus induces buoyancy force in the hot air bubble which creates free convection. This produces a heat transfer that heats one detector and cools the other one. Differential Wheatstone bridge output V_{out} is thus proportional to acceleration along the *x*-axis. More details about sensor operating principles and dimensions can be found in [4].

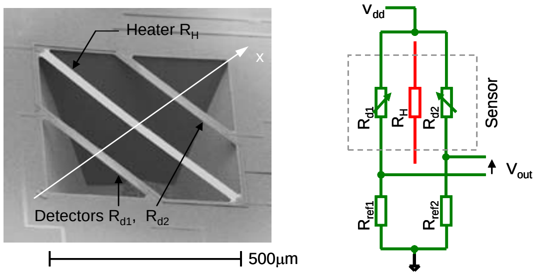

Fig. 2: thermal convective accelerometer and associated electrical model.

Figure 3 shows the small-signal, differential model of the sensor. Convection produces a differential heat transfer ΔP_D between detectors (S_p in μW/g). This phenomenon is low-pass (time constant, τ). Detector bridges thermal parameters are R_{th} (in K/W) and a time constant (τ_D). Wheatstone bridge sensitivity is S_{wheat} (in mV/K) and each resistor generates a noise ($4 \cdot k_b \cdot T \cdot R$).

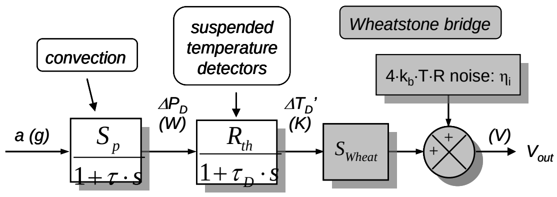

Fig. 3: Thermal convective accelerometer model with differential electrical output.

Main limitation of this accelerometer is the small bandwidth due to the thermal convection phenomenon and to the thermal inertia of the detectors. For the thermal convection, local optimization can be performed by acting on package size, gas nature or pressure within the cavity [5]. This optimization is part of the packaging design. Concerning the thermal inertia of the detectors, local optimization consists in reducing the size of the detectors and the time constant accordingly. Global optimization leads to a closed-loop system architecture that maintains the temperature of the detectors whatever the acceleration and the convection are. Obtained architecture (Figure 4) can be studied efficiently in Matlab-Simulink as each simulation requires very long transient time to analyze the bit stream output.

Modeling and simulation with Cadence Virtuoso

As an example of realization, a one-chip Inertial Measurement Unit is presented. This multi-sensor platform has been developed to demonstrate our expertise in sensor integration. Most of the know-how of the research team is illustrated in this project: sensor behavioral modeling, system-level simulation, front-end electronics, power management, wireless communication, embedded software, machine human interface...

The choice of a mature technology for the sensor makes the system possibly suitable for low-end applications for consumer electronics where the main performance trade-off concerns the power consumption, the cost and the volume. Our objective is thus to develop a low-cost, low-power, medium performance, highly integrated system.

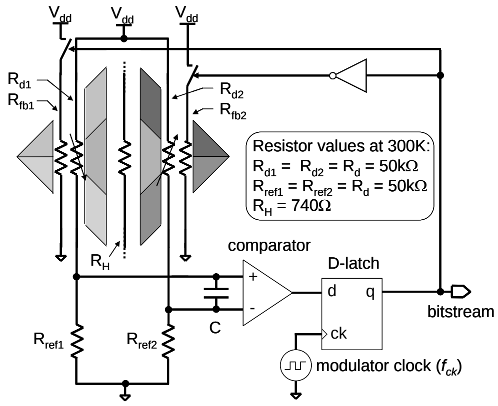

Fig. 4: Thermal ΣΔ modulator for convective accelerometer.

The complete system is composed with three different sensors (a 2D in-plane accelerometer, a 1D out-of-plane accelerometer, a 2D in-plane magnetometer). All are issued from our previous research and have been extensively studied. Each sensor is connected to a specific front-end electronics that allow efficient offset compensation and cancellation schemes that are mandatory due to the low intrinsic performance of bare sensors. This architecture is completed with an external controller and a wireless communication module. The whole is powered by a battery.

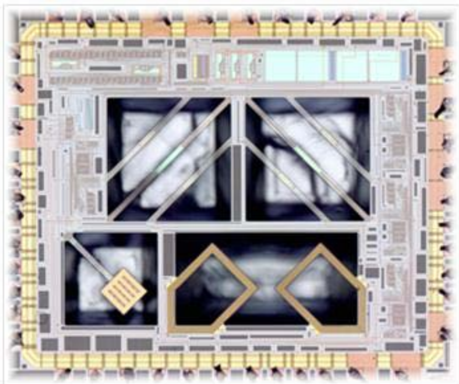

Fig. 5: One-Chip IMU includes three different sensors representing five degrees of freedom and the front-end electronics on a single CMOS die.

References

[1] B. Alandry et al., *A Fully Integrated Inertial Measurement Unit: Application to Attitude and Heading Determination*, IEEE Sensors Journal, vol.11, no.11, pp.2852-2860, Nov. 2011.

[2] H. Baltes et al., *IC MEMS Microtransducers*, IEDM Technical Digest, 1996, pp. 521-524.

[3] J. Verd et al., *Integrated CMOS-MEMS with on-chip readout electronics for high-frequency applications*, IEEE El. Device Letters, vol. 27 (6), pp. 495-497, 2006.

[4] O. Leman et al., *HDL modeling of convective accelerometers for system design and optimization*, Sensors and Actuators A: Physical, Vol. 142, pp. 178-184, March 2008.

[5] S. Billat et al., *Micromachined inclinometer with high sensi-*

tivity and very good stability, Sensors and Actuators A, Vol. 97–98, pp. 125-130, April 2002.