Monolithic CMOS-MEMS integration for high-g accelerometers

Narasimhan, Vinayak; Li, Holden; Tan, Chuan Seng

2014

Narasimhan, V., Li, H., & Tan, C. S. (2014). Monolithic CMOS-MEMS integration for high-g accelerometers. Proceedings of SPIE 9254, Emerging Technologies in Security and Defence II; and Quantum-Physics-based Information Security III, 9254.

<https://hdl.handle.net/10356/106720>

<https://doi.org/10.1117/12.2070667>

© 2014 Society of Photo-optical Instrumentation Engineers. This paper was published in Proceedings of SPIE 9254, Emerging Technologies in Security and Defence II; and Quantum-Physics-based Information Security III and is made available as an electronic reprint (preprint) with permission of Society of Photo-optical Instrumentation Engineers. The paper can be found at the following official DOI: [<http://dx.doi.org/10.1117/12.2070667>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Monolithic CMOS-MEMS integration for high-g accelerometers

Vinayak N.^a, Holden L.^b and Chuan Seng T.^c

^aTemasek Laboratories @ Nanyang Technological University, 8th Storey, BorderX Block,
Research Techno Plaza, 50 Nanyang Drive, Singapore 637553

^bSchool of Mechanical and Aerospace Engineering, Nanyang Technological University, 50
Nanyang Drive, Singapore 639798

^cSchool of Electrical and Electronic Engineering, Nanyang Technological University, 50
Nanyang Drive, Singapore 639798

ABSTRACT

This paper highlights work-in-progress towards the conceptualization, simulation, fabrication and initial testing of a silicon-germanium (SiGe) integrated CMOS-MEMS high-g accelerometer for military, munition, fuze and shock measurement applications. Developed on IMEC's SiGe MEMS platform, the MEMS offers a dynamic range of 5,000 g and a bandwidth of 12 kHz. The low noise readout circuit adopts a chopper-stabilization technique implementing the CMOS through the TSMC 0.18 μm process. The device structure employs a fully differential split comb-drive set up with two sets of stators and a rotor all driven separately. Dummy structures acting as protective over-range stops were designed to protect the active components when under impacts well above the designed dynamic range.

Keywords: CMOS-MEMS integration, high-g, accelerometer, shock sensing

1. INTRODUCTION

Monolithic CMOS-MEMS integration in microsystems is much sought after today as it enables the design and manufacturing of smaller packages at lower overall instrumentation costs.^{1,2} In contrast, the conventional modular hybrid approach is still adopted by majority of current MEMS devices through chip-to-chip bonding, wafer-to-wafer bonding, etc. as being modular, it reduces the lead and development time when compared to a monolithic approach. But owing to higher packaging costs, large volume manufacturing of modular systems prove to be far more time consuming and expensive as opposed to monolithically integrated systems.^{1,3,4} In the case of high-g accelerometers, robustness of the sensor is pivotal to its reliability. Case studies of popular high-g inertial MEMS accelerometers point to interconnect failure as the key source for package level failure when under impact conditions.⁵ A monolithic integration scheme greatly increases accelerometer reliability and response characteristics at high-g ranges as it obviates the need for delicate interconnects. This is simply because instead of fragile and rather long wirebonds, a monolithic system would use short vias between the MEMS and the CMOS leading to faster response as well. Furthermore, such an integration leads to better signal-to-noise ratio (SNR) through a reduced interconnect parasitics, lower power consumption and increased sensitivity.¹⁻³

IMEC's SiGeMEMS technology is based on a MEMS-last approach. The MEMS is processed on top of the CMOS readout circuits. The standard modules provide a CMOS protection layer, MEMS via and poly-SiGe electrode, an anchor and poly-SiGe structural layer, and thin-film poly-SiGe packaging.

This modern approach has proved to be the most promising means of integration as it enables independent optimization of the MEMS and CMOS to an extent. Also, new generations of CMOS can be appended to the structure without impacting the MEMS. However, this multilayer monolithic approach limits the thermal budget

Further author information: (Send correspondence to Holden L.)

Holden L.: E-mail: HoldenLi@ntu.edu.sg,

Chuan Seng T.: E-mail: TanCS@ntu.edu.sg

Figure 1. Schematic of cross-section of SiGe MEMS process (Adapted from IMEC resources^{2,8}).

for processing the MEMS. Poly-SiGe meets material and reliability requirements for MEMS applications at significantly lower process temperatures than poly-Si which makes it best suited for MEMS-last integration.^{1,6,7}

The MEMS was designed and electromechanically simulated using the IMEC design PDK on *Coventor* clearing all design rules. Tests were conducted to mathematically model the capacitance response using *Simulink* by inputting several high-g linear dynamic loads while driving each comb set uniquely.

Through differential sensing, excellent linearity was achieved through the split comb-drive. Also, response characteristics such as response and settling time as well as damping conditions were adequately simulated. Finite element analysis was conducted iteratively to observe the structural integrity of the system under harsh out-of-plane dynamic loads. Finally, Input noise characteristics of the ASIC were simulated for good SNR within the operational bandwidth.

Die-level characterization in the form of C-V testing was done to observe the functioning of several device samples under a high voltage sweep simulating to a certain degree the MEMS performance under high-g military grade conditions.

2. SENSOR DESIGN

Fig. 1 shows a schematic of the cross-section of IMEC's SiGe MEMS process indicating materials, functional parts and main dimensional features.^{2,8}

Figs. 2 and 3 present an isometric and top view of the MEMS active area as designed on *Coventor* using the SiGe MEMS PDK. The SiGe mechanical and anchor layer are shown in magenta while the SiGe electrode and Al bondpad layers are shown in green and blue respectively.

2.1 Simulations

A series of electromechanical simulations were conducted to evaluate the structural robustness, optimize the comb-drive structure and map the electrical response of the sensor to impact loads.

Figure 2. Isometric view of the MEMS designed using the *Coventor* SiGe MEMS PDK with layers coloured as per Fig. 1.

Figure 3. Top view of the MEMS with overall dimensions.

Figure 4. A linear high-g dynamic electromechanical analysis of capacitance variation around the 5,000 g dynamic range. Reduced non-linearity obtained upon using differential sensing.

2.1.1 Differential sensing

A split comb-stator assembly was used to achieve full differential sensing capability. Capacitance $C1$ exists between the red stator and white rotor while capacitance $C2$ exists between the blue stator and white rotor as seen in Fig. 4. This figure presents an electromechanical linear dynamic loading simulation upto 5,000 g over 300 μ s conducted using *Coventor* to highlight the reduced non-linearity through the use of a differential capacitance. This relationship can be mathematically modelled as follows:

$$\Delta C = C1 - C2 \approx \frac{\epsilon_r A}{d - \Delta} - \frac{\epsilon_r A}{d + \Delta}$$

$$\Delta C \approx \frac{\epsilon_r A}{d} \left[\left(1 + \frac{\Delta}{d} + \frac{\Delta^2}{d^2} \right) - \left(1 - \frac{\Delta}{d} + \frac{\Delta^2}{d^2} \right) \right] \quad (1)$$

here, $C1$ and $C2$ are as described earlier while ϵ_r , A , d and Δ are the permittivity of the medium, area of the capacitor, sense gap of the capacitor and physical separation upon loading respectively. As per 1, the non-linearity arising from the higher order terms such as Δ^2/d^2 are subtracted away while those from cubic terms such as Δ^3/d^3 can be neglected since $\Delta^3 \ll d^3$. Therefore, the capacitance output will be:

$$\Delta C \approx \frac{\epsilon A}{d} \left(\frac{2\Delta}{d} \right) \quad (2)$$

2.1.2 Mechanical simulations

Mechanical simulations were conducted to observe the structural behaviour when under high-g linear dynamic impact loads. When under an in-axis high-g load of 5,000 g, the sensor proofmass displacement is around 0.82 μ m which is well below the minimum allowable comb separation of 2 μ m. This allows for a safety-factor of over 2 thus preventing an undesired pull-in effect. This simulation is shown in Fig. 5.

Figure 5. Proofmass displacement upon high-g linear dynamic loading. Displacement is seen to be well within acceptable bounds.

Generally, all micromachined accelerometer structures are modelled after the conventional spring-mass-damper system. They consist of a proofmass m that is suspended by complaint beams or flexures of spring constant k anchored to a fixed frame. Additionally, there is a viscous damping factor b impacting the movement of the mass. External acceleration displaces the proofmass relative to the fixed frame, which in turn stresses the flexures. By employing this physical phenomenon, several sensing schemes can be used to determine the external acceleration. The transfer function in 3 below can be used to mathematically map the aforementioned relationship,⁹

$$H(s) = \frac{x(s)}{a(s)} = \left(s^2 + \frac{bs}{m} + \frac{k}{m}\right)^{-1} = \left(s^2 + \frac{\omega_r}{Q} + \omega_r^2\right)^{-1} \quad (3)$$

Here, x is the displacement of the proofmass and a is the external acceleration. The resonance frequency of the structure is given by $\omega_r = \sqrt{k/m}$ and the quality factor of the system is $Q = m\omega_r/b$.

The sensitivity of the accelerometer can be mathematically described as in 4,

$$\frac{x}{a} = \frac{m}{k} = \frac{1}{\omega_r^2} \quad (4)$$

It is evident that in order to measure large shock accelerations, a wide frequency bandwidth is required to protect the sensor from resonance.^{10,11} As per simulations, the bandwidth of this structure was close to 12 kHz which is sufficiently high to meet the 5,000 g dynamic range.

2.1.3 Electrical response

A simulation was conducted to observe the response characteristics of the MEMS. The comb driving voltage was a 2 V DC overlaid by a 0.5 V AC signal. Step inputs from 0 to 2,000 g up to 0 to 7,000 g were employed to simulate the MEMS capacitance output. The response time in the two cases were at 200 μ s and 300 μ s respectively which implies fast and effective tracking of an impulse load. Furthermore, there is good control of overshoot through damping.

Fig. 7 presents a block diagram generated on *Simulink* to electromechanically simulate the capacitance response to the aforementioned step inputs.

Fig. 8 presents the electrical response for the 0 to 2,000 g and 0 to 7,000 g step inputs. The response time in both cases is clearly indicated.

Figure 7. *Simulink* block diagram for electrical response analysis.

Figure 8. a) Step response for input ranging from 0 to 2,000 g and b) Step response for input ranging from 0 to 7,000 g.

3. SENSOR CHARACTERISTICS

Fig. 9 presents a similar image of the cross-section of the accelerometer after ion-milling. The labelled layers are as per the schematic shown earlier in Fig. 1. Further, optical images of the die layout are presented in Fig. 10. The overall device dimensions along with salient features such as the comb-drive assembly as well as the support flexures are clearly indicated.

The overall dimensions of the MEMS was measured to be 1.6 x 1.1 mm. The simulated resonant frequency was around 12 kHz.

The ASIC supply voltage is 3.3 V with a power consumption of 3.368 mW. The input referred noise of the ASIC was computed to be around 41.51 nV/ $\sqrt{\text{Hz}}$. Fig. 11 presents an input noise plot as well as an inset of the block diagram of the ASIC used. The readout comprises of three essential building blocks – Band-Pass Gain Stage, Synchronous Demodulator and Low-Pass Filter. The Gain Stage consists of a single ended amplifier, based on folded-cascode architecture, and helps to boost the SNR. It works within the frequency range 100 kHz–18 MHz, where the low corner frequency is determined by $1/2R_fC_f$ while the upper corner by the unity-gain bandwidth of the amplifier. The MEMS accelerometer is excited by fully differential sinusoidal carriers and the output in response to the acceleration experienced is fed to the readout. The frequency of carriers is typically kept within 150 kHz–1 MHz to ensure that the results are obtained in the flat-band region. The amplified signal is then synchronously demodulated by envelope detection. This is followed by an on-chip 2nd order Sallen-Key low-pass filter that helps to remove the high frequency noise components. The cut-off frequency of low-pass filter is close to 200 Hz.

Figure 9. SEM image of the CMOS-MEMS accelerometer cross-section upon ion-milling.

Figure 10. a) Optical images of MEMS, b) Split comb-drive (highlighted in the black box), c) Support flexures (highlighted in the black box) and d) MEMS sensor die placed with a Singapore five cent coin.

Figure 11. ASIC input noise plot with an inset of ASIC block diagram.

Figure 12. C-V characterization of the MEMS.

Finally, initial characterization in the form of C-V testing was done to observe the functioning of eight different working MEMS samples under a voltage sweep. The high voltage would simulate to a certain degree the MEMS performance under high-g conditions.

As seen from figure 12, all working devices perform similarly indicating good design and process control as well as repeatability.

4. CONCLUSION

This paper has outlined work done towards the conceptualization, simulation, fabrication and initial testing of a silicon-germanium integrated CMOS-MEMS high-g accelerometer for shock and impact sensing. Based on IMECs SiGe MEMS platform, this sensor was developed to be more robust under high-g conditions while providing far better SNR, lower power consumption and increased sensitivity. The MEMS offers a measuring range of 5,000 g with a bandwidth of 12 kHz. Chopper-stabilization technique was adopted for the low noise readout circuit with the CMOS implemented through the TSMC 0.18 μm process. Being on of its kind, the integrated SiGe CMOS-MEMS high-g accelerometer was realised overcoming several design and process related constraints and is now in further testing phase. Currently, a hermetically sealed surface mounted packaging of the device is in progress following which further characterization is to be carried out.

REFERENCES

- [1] Witvrouw, A., "CMOS-MEMS Integration: Why, How and What?," ICCAD '06. IEEE/ACM Int. Conf., 826-827 (2006).
- [2] ElectronicsWeekly, "IMEC Offers SiGe-MEMS Foundry Service [Web Page]," Available: <http://www.electronicsworld.com/news/manufacturing/imec-offers-sige-mems-foundry-service-2010-06/>, (2010).
- [3] Mansour, R. R., "RF MEMS-CMOS Device Integration: An Overview of the Potential for RF Researchers," IEEE Microw. Mag., 14(1), 39-56 (2013).
- [4] Pieters, P., "Versatile MEMS and MEMS integration technology platforms for cost effective MEMS development," Proc. Microelectronics Packaging Conf., 1-5 (2009).
- [5] Davies, B. R., Montague, S., Bateman, V. I., Brown, F. A., Chanchani, R., Christenson, T., Murray, J. R., Rey, D. and Ryerson, D., "High-g accelerometer for earth-penetrator weapons applications," Sandia Report, 21-40 (1998).
- [6] Sedky, S., Howe, R. T. and King, T-J., "Pulsed-laser annealing, a low-thermal-budget technique for eliminating stress gradient in poly-SiGe MEMS structures," J. Microelectromech. Syst., 13(4), 669-675 (2004).
- [7] Lin, B. C-Y., King, T-J. and Howe, R. T., "Optimization of Poly-SiGe Deposition Processes for Modular MEMS Integration," Proc. MRS, 782, A2.4 (2003).
- [8] IMEC - Europractice, "SiGeMEMS Process Handbook v3.0," (2010).
- [9] Yazdi, N., Ayazi, F., and Najafi, K., "Micromachined inertial sensors," Proc. IEEE, 86(8), 1640-1659 (1998).
- [10] Wang, J. and Li, X., "A high-performance dual-cantilever high-shock accelerometer single-sided micromachined in (111) silicon wafers," J. Microelectromech. Syst., 19(6), 1515-1520 (2010).
- [11] Fan, K., Che, L., Xiong, B. and Wang, Y., "A silicon micromachined high-shock accelerometer with a bonded hinge structure," J. Micromech. Microeng., 17(6), 1206-1210 (2007).