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A high precision SOI MEMS–CMOS ±4g piezoresistive accelerometer

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ABSTRACT

System development and characterization of a low noise low offset SOI MEMS–CMOS PCB-integrated multi-chip ±4*g* piezoresistive accelerometer sensor comprising a coupled multi-bandwidth variable-gain amplifier block and a thermal sensitivity and offset compensation block is presented in this work. Custom design and fabrication has been carried out for both the SOI MEMS sensor and the analog front-end for high precision and operational reliability. The system is shown to have a scale factor of ∼4 mV/*g* and an output nonlinearity <1% of full-scale output with a cross-axis sensitivity <1%. Cyclic loading experiments exhibit distortionless operation over ∼1000,000 cycles without failure indicative of an extremely robust system.

1. Introduction

Low frequency inertial measurements form the basis of an exhaustive range of applications such as motion guidance and navigation [1,2], flow and orientation sensing [3,4], geophysical and industrial structural health monitoring [5], biomedical vibration sensing and nanoscale detection systems [6,7]. Rapidly evolving microelectronic fabrication techniques and micromachining processes have led to the development of microelectromechanical systems (MEMS) sensors principled upon inertial measurements carried out through electromechanical signal transduction of various kinds and conditioning the raw sensor output using front-end CMOS interfacing technology. Among the plethora of such combined implementations, the MEMS accelerometer has been one of the most extensively researched sensors apart from devices such as pressure sensors [8] and gyroscopes [9] and has been commercialized in recent years, finding usage in a range of applications from smart phones to automobiles. Current state-of-the-art in MEMS accelerometer technology employed commercially exploits compliant mechanisms of surface and bulk micromachined MEMS microstructures for capacitive [10], piezoelectric [11], piezoresistive [12,13], optical [14], quantum tunneling [15] and other transduction mechanisms [16] in response to externally applied inertial forces. Exhaustive research has been conducted on the analysis [17–19] and process development of piezoresistive accelerometer devices [20–22], architecture and implementation of their respective front-end circuits [23,24] and testing methodologies [25]. However, to the best of our knowledge, not a lot of complete literature is available on the development and interfacing issues in piezoresistive MEMS–CMOS accelerometer applications and its impact on the system under test. Interfacing low frequency piezoresistive MEMS accelerometers involves the design of a readout circuit which drives the sensor electronics as per the operating condition requirements. In this work, we concurrently develop our sensor and circuit blocks, adding the flexibility of multi-bandwidth variable-gain operation to a novel temperature compensation scheme which eliminates the need for on-board temperature sensing elements while being compatible with progressively shrinking CMOS processes in terms of sensitivity. We investigate the functioning of the integrated system shown in Fig. 1 (green sensor block and red circuit block) on a printed circuit board (PCB) which is subjected to extensive system-level dynamic excitation tests after the individual chips are thoroughly characterized for interfacing.

Detailed development of the MEMS–CMOS accelerometer system is elaborated on in the subsequent sections which are organized as follows: Section 2 develops the background of the MEMS–CMOS system presented here. Section 3 covers the implementation of the SOI MEMS accelerometer sensor and the CMOS front-end as well as their interfacing while the test results of the

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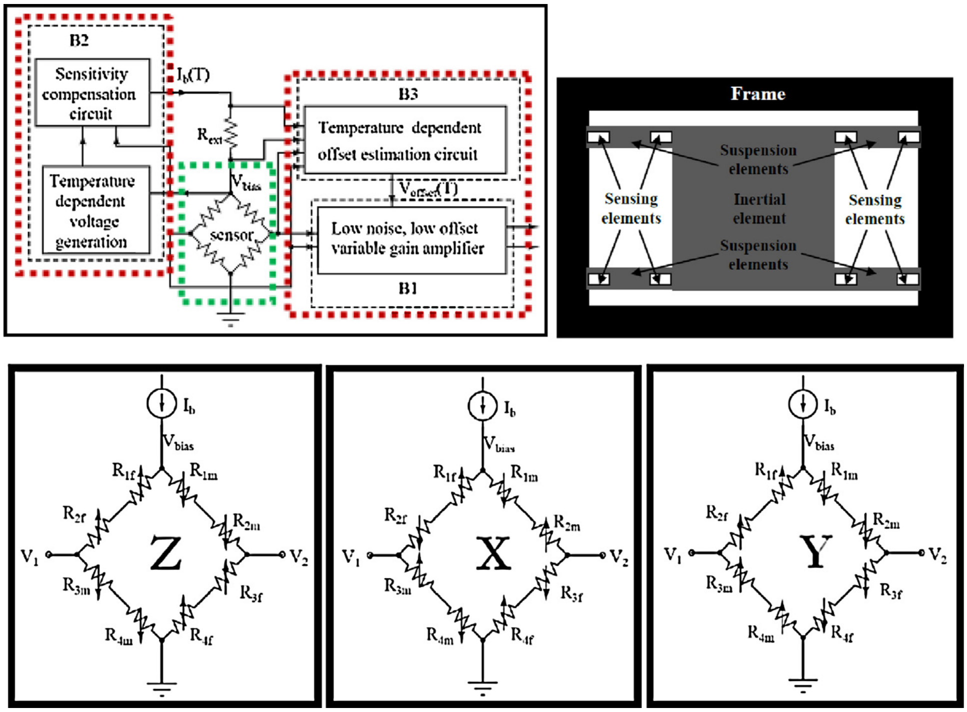

Fig. 1. (top left) Complete SOI MEMS–CMOS accelerometer system schematic (green section: MEMS piezoresistive accelerometer; red sections: ASIC blocks) (top right) MEMS out-of-plane accelerometer schematic illustrating system suspension elements (beams), inertial element (seismic mass) and sensing elements (resistors) where the sensing direction is normal to the plane of the diagram (bottom) Current biased Wheatstone bridge schematic showing resistance response during sensor operation due to applied stresses along the relevant axes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

individual blocks and PCB-interfaced system are elaborated upon in Section 4. Concluding observations regarding performance and reliability issues are summarized in Section 5 along with suggestions for future design and fabrication improvements.

2. MEMS–CMOS piezoresistive accelerometer: System development

2.1. MEMS piezoresistive acceleration sensor

An inverse nonlinear dependence of output sensitivity on temperature affects the deployment of piezoresistive sensors despite appreciable sensitivity and efficient noise performance (conductance fluctuation induced $1/f$ noise is the primary source of low frequency distortion [26]) with electrostatic and piezoelectric mechanisms being preferred and alternative variants (optical, thermal, SAW) being researched intensively. Besides temperature sensitivity, uniaxial bulk micromachined sensors are highly susceptible to temperature offsets as well as electromechanical crosstalk between the primary out-of-plane sensing axis and the in-plane perturbations due to foundry mismatch and schematic layout issues resulting in loss of precision.

To nullify the device and system-scale disadvantages of piezoresistive accelerometers, the authors propose a current-biased accelerometer system implemented by the schematic illustrated in Fig. 1 which employs a Wheatstone-bridge type piezoresistive out-of-plane acceleration sensor interfaced with a low-noise variable gain amplifier block and a thermal sensitivity and offset estimation and compensation block for MEMS output conditioning and bridge bias generation over user-defined bandwidths. A quad-beam mechanical structure (Fig. 2) was implemented for our MEMS sensor with an adaptively-biased piezoresistive Wheatstone-bridge for signal transduction. Current bias (I_{bias}) is preferred due to reliability in varied ambient conditions and its insensitivity to the downscaling of CMOS technology which results in sensitivity retention. The Wheatstone bridge is configured such that perturbations along the out-of-plane axis are registered as bridge terminal voltages while those along the in-plane lateral axes are nullified as depicted in Fig. 1.The MEMS accelerometer sensor can be modeled as a distributed mass-spring-damper (MSD) system [27]. Dynamics of driven quad-beam single degree-of-freedom (SDOF) MSD systems realized using bulk micromachining fabrication techniques can be expressed as

$$M_{MSD}\ddot{u} + \Psi(u, \dot{u}) = F_M(t) : \forall t \in R\oplus \tag{1-a}$$

$$\Psi(u, \dot{u}) = \sum_{i \in Z\oplus} K_i u^i + \sum_{i \in Z\oplus} C_i \dot{u}^i \approx K_{MSD}u + C_{MSD}\dot{u} \tag{1-b}$$

where M_{MSD} (=$LBH\rho$) is the equivalent distributed mass of the MSD system, Ψ is a function denoting the inertial forces acting on the system and is a function of transducer displacement (u) and velocity ($\dot{u}$) while F_M is the applied mechanical excitation expressed as a function of time t. Ψ can be decomposed into a sum of polynomials whose coefficients represent the respective stiffness and damping constants. Ignoring the nonlinear terms, the system reduces to a linear MSD model with a distributed spring constant K_{MSD} (=$4Ebh^3/l^3$) and damping constant C_{MSD} (=$\mu\beta B^3 L/d^3$) where l, b, h are the length, breath and thickness of the flexures; L, B, H are the length, breadth and thickness of the seismic mass, ρ is the density of the device material, d is the gap between sensor and wafer-scale glass cap for damping and over-range protection, assuming symmetry in mass displacement during device operation, μ is the viscosity of the air ambient within the glass encapsulation while E is the Young's modulus of the compliant sensor material and β is a damping factor dependent on the ratio B/L of the damped mechanical structure. Sensor design is primarily guided by the attempt to maximize out-of-plane sensitivity while completely rejecting lateral signals with the Wheatstone bridge configuration explained earlier. The seismic mass and the beams are of dimensions 2200 μm × 2200 μm × 675 μm and