CMOS MEMS Accelerometer for Long-Term *In Vivo* Real-Time Small Animal Biological Monitoring

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***Abstract*—A CMOS MEMS accelerometer is proposed for long term *in vivo* real time "free" small animal activity monitoring. The activity information along with other vital physiological signals such as blood pressure, temperature, EKG, etc. are critical for advanced biological and genetic research. The prototype sensor is designed and fabricated in a commercial 1.5 µm CMOS process, exhibiting a nominal sensing capacitance value of 540 fF with a designed sensitivity of 15 fF/g and self resonance of 3 kHz. The device occupies an area of approximately 800 µm × 700 µm and can be integrated with CMOS interface and signal processing electronics on a same chip, thus substantially reducing form factor, power dissipation, and packaging complexity of the final implantable microsystem.**

I. INTRODUCTION

DNA sequencing of laboratory mice together with *in vivo* real time biological information, such as blood pressure, temperature, activity, and bio-potential signals, is ultimately crucial for systems biology research, genetic function discovery, and new treatments development for diseases such as hypertension, obesity, epilepsy, and cancers [1]. A miniature, long-term, reliable bio-sensing implant network with two-way telemetry capability is highly desirable to capture a dynamic behavior of a biological system as shown in Figure 1. Existing commercial implant devices are inadequate to achieve the objectives due to large size and weight, causing severe post-implant trauma, data distortion, and limited functionalities. Figure 2 presents a general architecture of a proposed implantable bio-sensing network, which consists for an array of micro-fabricated biological sensors, low power interface and data telemetry electronics with an on-chip microprocessor control unit. The total system size and weight are expected to be less than 5 mm x 5 mm including packaging and 100 milli-gram, respectively. This paper focuses on the development of a CMOS MEMS accelerometer for *in vivo* real-time activity sensing. The CMOS MEMS approach is chosen for its integration capability with microelectronics [2], which is highly desirable for minimizing form factor, power dissipation, and packaging complexity of the overall implantable microsystem. Furthermore, due to a nearly constant operating temperature (body temperature), the proposed sensor would not suffer from thermally induced structural deformation and potential system drift.

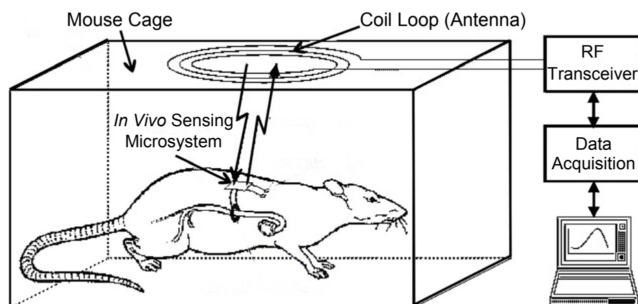

Figure 1. *In Vivo* Wireless Bio-Sensing Network System

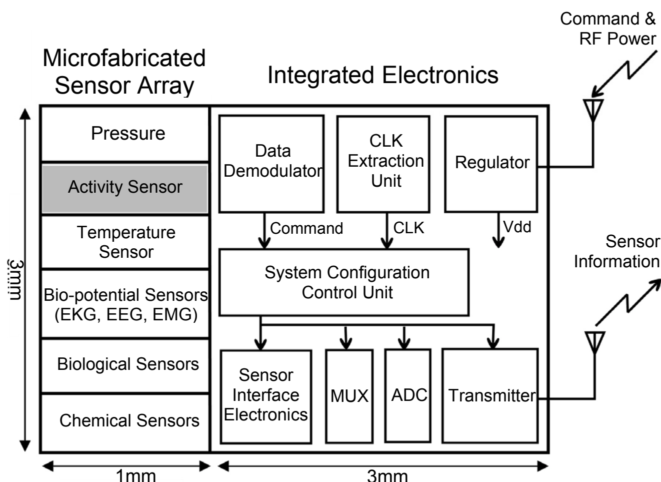

Figure 2. Implantable Microsystem Architecture

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II. *In Vitro* Activity Characterization

To obtain the CMOS MEMS accelerometer design specifications, an *in vitro* activity characterization was first performed on a laboratory mouse using a commercial accelerometer [3] to determine the acceleration signal range and bandwidth as shown in Figure 3. The accelerator chip is assembled on a testing board with discrete components to set a bandwidth of 500 Hz and is supplied by an on-board 3.6 V lithium-ion battery. The testing board occupies an area of 15 mm × 12 mm with a total weight of 2 gram and is attached on the back of a laboratory mouse for the characterization. The mouse activity is recorded by a computer interface data acquisition system. Figure 4 presents the measured acceleration ranging from 10 milli-gram to ±4g. Spectrum analysis of the signal indicates a low bandwidth of a few hertz. The large acceleration signals above 2g are likely caused by collisions between the testing board and cage housing the animal.

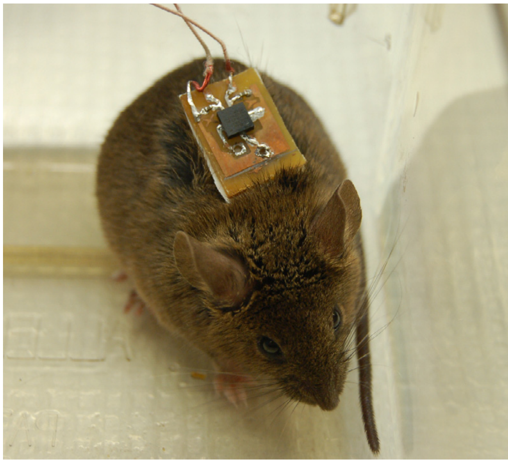

Figure 3. Laboratory Mouse Activity Measurement Setup

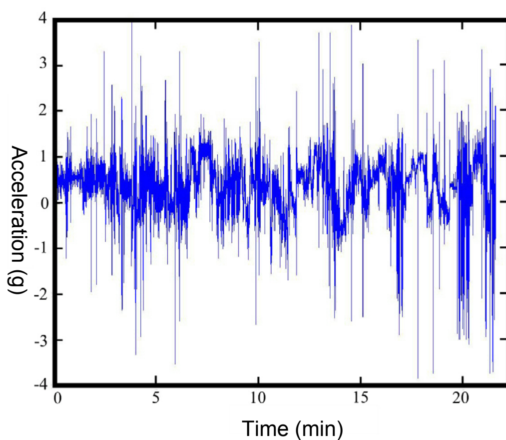

Figure 4. Measured Mouse Acceleration Waveform

III. CMOS MEMS Accelerometer

A differential capacitive sensing architecture is chosen for implementing the MEMS accelerometer as shown in Figure 5. The device consists of suspended proof mass with sensing fingers to form differential sensing capacitances with the corresponding stationary sensing structure anchored to the substrate. The sensor is designed with 168 pairs of silicon sensing fingers, each exhibiting 100 µm of length and 50 µm of thickness with 5 µm of air gap. The device occupies an area of 800 µm × 700 µm with a designed nominal capacitance value of 1.4 pF, adequate for interfacing sensing electronics with low power dissipation, which is critical for wireless implant applications. Folded beam mechanical suspensions are designed with a total compliance of 5.1 N/m, resulting in a device self resonant frequency of approximately 3 kHz, which closely matches finite element simulation results, and a differential sensitivity of 15 fF/g. The Brownian-motion-induced-acceleration noise power spectral density is estimated around 14 $\mu g/\sqrt{Hz}$ in ambient [4], which is much lower than the required sensing resolution for the proposed application, thus eliminating the need for vacuum packaging.

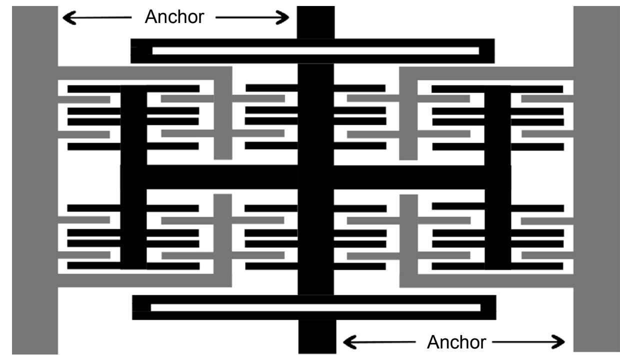

Figure 5. MEMS Accelerometer Topology

The prototype MEMS accelerometer is first fabricated in a commercial 1.5 µm CMOS process followed by using a maskless post-CMOS micromachining technique [2]. Figure 6 presents the major post-processing steps. The top metal layer, metal-2 in this particular CMOS technology, defines the MEMS device geometry as shown in Figure 6a. A back side silicon etching is used to define the sensor structural thickness to about 50 µm as depicted in Figure 6b. In the next step a front side anisotropic SiO_2 etching removes the dielectric materials uncovered by any top metal layer protection, as shown in Figure 6c, follow by a silicon deep reactive ion etch (DRIE) to release the microstructures as illustrated in Figure 6d. A final silicon isotropic etching is performed to undercut certain narrow isolation regions to achieve a proper electrical isolation shown in Figure 6e.

IV. Fabrication Result

Figure 7a shows an SEM micrograph a fabricated MEMS accelerometer on a CMOS substrate. The detailed sensing fingers with narrow isolation regions and mechanical

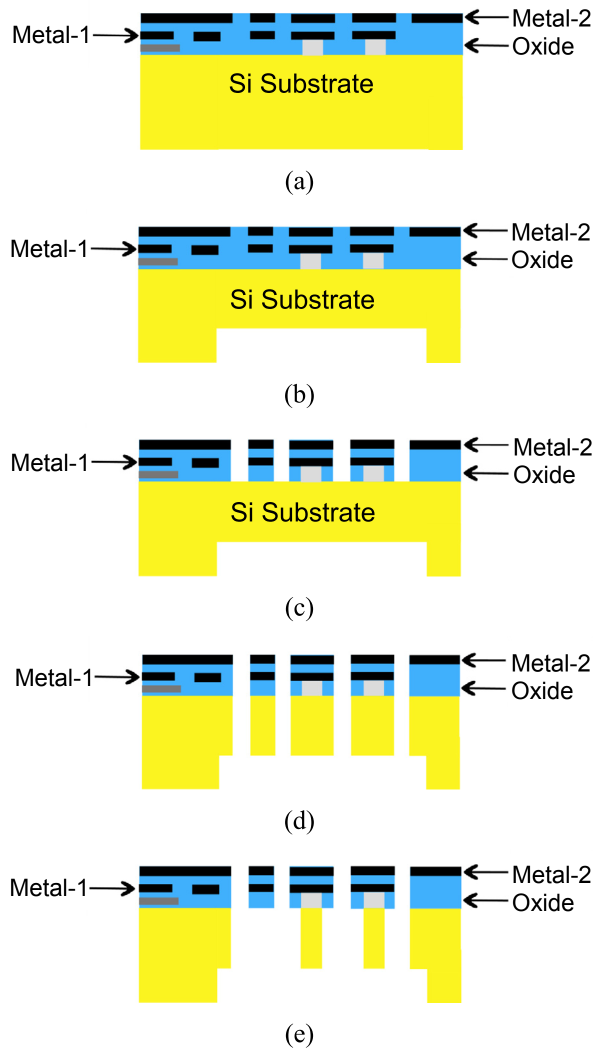

Figure 6. Post-CMOS MEMS Fabrication Process

suspension structure are shown in Figures 7b and 7c, respectively. Electrical testing indicates that the device exhibits a nominal capacitance value of 540 fF with a 1.5 kΩ of series resistance associated with the sensing structures. The measured capacitance is lower than the design value, which is likely caused by the reduced device structural thickness and extended sensing fingers gap size during the post-processing. An improved post-CMOS fabrication technology [5] can be employed in the future to improve the device capacitance accuracy. It can be shown that the series resistance associated with the sensor does not degrade the device sensitivity.

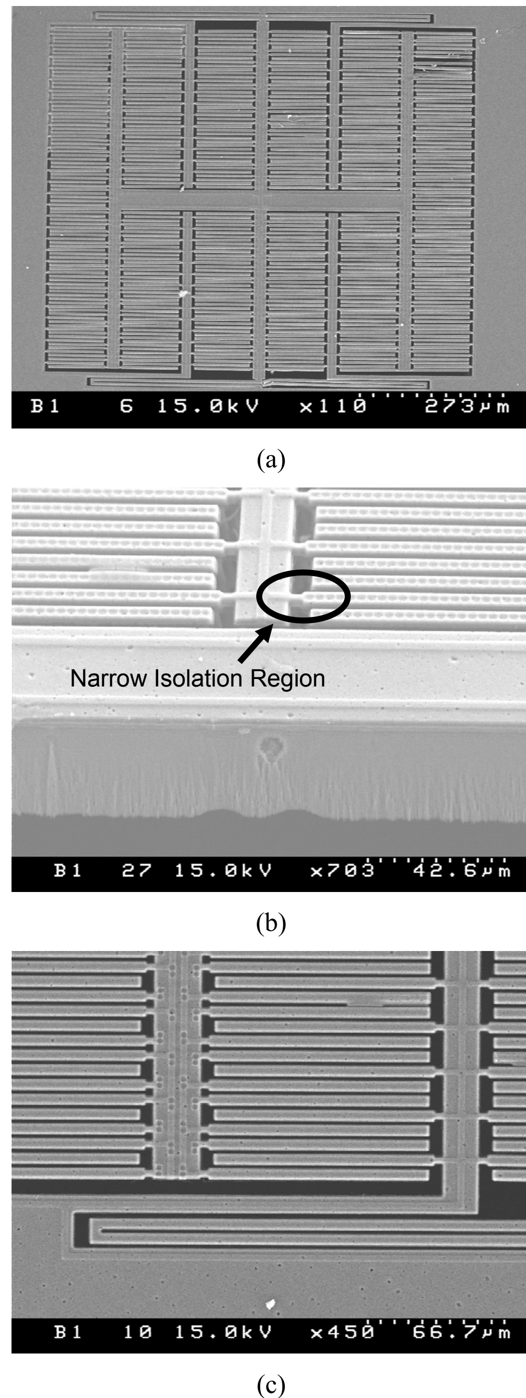

Figure 7. SEMs of Fabricated MEMS Accelerometer (a) Top View; (b) Sensing Fingers; (c) Suspension Structure

V. Integrated Activity Sensing Microsystem

An integrated activity sensing microsystem is designed with its architecture shown in Figure 8. Two MEMS accelerometers, modeled as two sets of differential capacitors, are driven by two complimentary clock signals and are interfaced by a differential charge amplifier, which converts the sensors capacitance change to an output voltage. A clock frequency of 1 MHz is chosen to modulate the sensor information away from the $1/f$ noise of the amplifier, a critical means to achieve a high sensitivity. An input common-mode feedback (ICMFB) circuit is incorporated with the charge amplifier to minimize its input common-mode shift caused by the driving clock; hence, suppressing

any offset signal due the parasitic capacitance mismatch and drift over time. The charge amplifier output is then mixed by the same clock signal and low-pass filtered to obtain the desired acceleration information [6]. Two accelerometers are employed to double the signal strength as well as to minimize any un-expected large input common-mode voltage shift due to sensors capacitance variations. The microsystem is fabricated in a commercial 1.5 μm CMOS process with the chip micrograph shown in Figure 9. The chip occupies a silicon area of 2.2 mm by 2.2 mm with a total weight of 4 milli-gram, and is currently under post-processing and performance evaluation

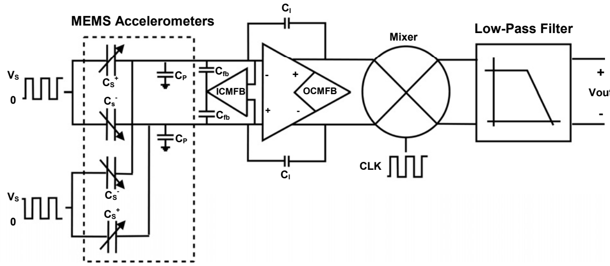

Figure 8. Integrated Acitivity Sensing Architecture

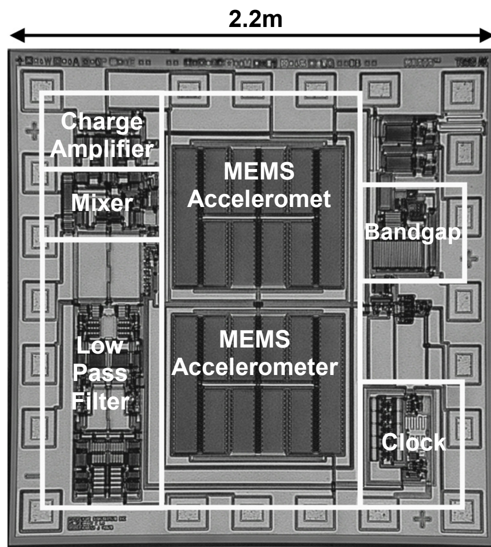

Figure 9. Microsystem Die Photo

VI. CONCLUSIONS

A CMOS MEMS accelerometer is developed for long term *in vivo* real time "free" small animal activity monitoring. The chosen approach is desirable due to its integration capability with microelectronics, thus minimizing system form factor, power dissipation, and packaging complexity. The prototype sensor is designed and fabricated in a commercial 1.5 μm CMOS process, exhibiting a nominal sensing capacitance value of 540 fF with a designed sensitivity of 15 fF/g and self resonance of 3 kHz. The device occupies an area of approximately 800 μm × 700 μm and has been integrated with CMOS interface and signal processing electronics on a same chip to realize a monolithic implantable activity sensing microsystem.

ACKNOWLEDGMENT

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