

Self-powered CMOS Impact-rate Monitors for Biomechanical Implants

Chenling Huang

Department of Electrical and Computer Engineering
Michigan State University
East Lansing, U.S.A.
huangc33@egr.msu.edu

Shantanu Chakrabartty

Department of Electrical and Computer Engineering
Michigan State University
East Lansing, U.S.A.
shantanu@egr.msu.edu

Abstract—We have previously reported a novel self-powered piezo-floating-gate sensor that can be used for long-term monitoring of strain levels in biomechanical implants. In this paper, we extend this work to monitor impact-rates (rate of change of strain levels) which is important for predicting mechanical fatigue. We augment the piezo-floating-gate sensor with a filtering and triggering circuit that activates the ionized-hot-electron-injection (IHEI) only when the impact-rates exceed predetermined threshold levels. Using multiple prototypes fabricated in a 0.5- μm standard CMOS process we characterize the performance of the sensor for mismatch and for its variability under different biasing conditions. Experimental results obtained using the prototypes demonstrate that the sensor can record different impact-rate levels over a duration of 10^5 cycles.

I. INTRODUCTION

In 2003, approximately 600,000 hip and knee replacement surgeries were performed in the United States, and it is expected that the demand will grow by 174% for hip replacements and by 673% for knee replacements between 2005 and 2030 [1]. Typically, most of these prosthetic implants are expected to last for at least 20 years after which patients require a revision and replacement surgery. However, a study by McGee [2] reported that wear and loosening of artificial joints leads to replacement of 10-20% of implants within 15-20 years. It has also been reported that excessive wear of artificial knee lead to joint swelling (synovitis), bone loss (osteolysis) and ultimately to fatigue due to misalignment or instability of the joint [2]. In many of these cases revision surgery has proven to be more traumatic and less successful than the initial surgery. Therefore, long-term monitoring of biomechanical implants for excessive wear and fatigue is essential for preventing premature failures and for significantly reducing patient discomfort and risk.

In [3], we reported design of a novel piezo-floating-gate sensor that can be embedded on the implant for long-term usage monitoring. The sensor used a poly-vinylidene

fluoride (PVDF) film that interfaced with an array of floating-gate transistors. The PVDF transducer harvested electrical energy proportional to the mechanical strain levels and was used to inject hot-electrons into a floating-gate array (each programmed to trigger at different strain levels). The cumulative voltage produced by the sensor would be proportional to the total number of strain cycles experienced by the implant. Even though many fatigue prediction algorithms [3] mainly rely of the statistics of the strain level crossings, it is well known that strain-rates experienced by a mechanical structure also play an important role in predicting fatigue. This is particularly important under high impact conditions (accidental loading conditions) during the usage of the biomechanical implant.

In this paper, we extend the work in [3] for designing long-term impact-rate monitors that can record statistics of strain-rate level crossings. We first describe in section II, the principle of operation of the impact-rate monitoring sensor and present its analytical model. The section also describes results from several fabricated prototypes showing that the some of the parameters of the sensor are robust to mismatch and variations in biasing conditions. Section III presents the complete schematic of an impact-rate monitoring circuit and shows some of the results obtained using simulation. Section IV describes a calibration algorithm for the sensor and present measured results from a fabricated prototype. Section V concludes the paper with some final remarks.

II. SELF-POWERED IMPACT MONITORING

A. Principle of operation

The operation of the proposed impact rate monitor is illustrated using the schematic shown in Fig. 1. It consists of the current starved floating-gate injection circuit which was reported in [3]. The circuit consists of a pMOS floating-gate transistor, M_p , whose source is connected to a constant current source I_s . The gate of the transistor V_{FG} is completely insulated (by silicon-dioxide) and as a result

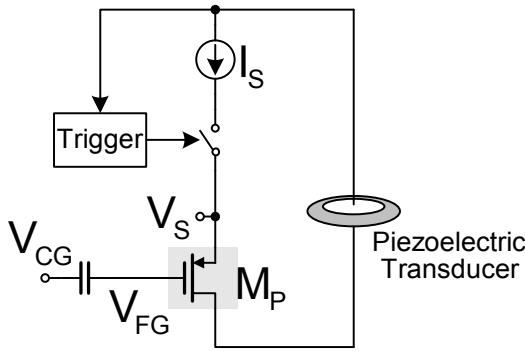


Figure 1. Schematic of a floating-gate injector.

electrons injected onto the node is retained for a long period of time. For impact-rate monitoring, a triggering circuit controls a switch which allows the reference current I_s to flow through the injector. When the voltage generated by the piezoelectric transducer is sufficiently high (typically $> 4.2\text{V}$ in a $0.5\text{-}\mu\text{m}$ CMOS process), and the switch is ON, IHEI starts and electrons are injected onto the floating-gate [4].

In [3], we presented an analytical model of the floating-gate injector which is applicable to the circuit in Fig. 1 when the triggering circuit is enabled (switch is ON). If T denotes the set of time intervals during which the triggering is enabled, then the source voltage V_s can then be expressed as

$$V_s = -\frac{1}{K_2} \log \left(K_1 K_2 \int_{\tau \in T} \partial \tau + e^{-K_2 V_{s0}} \right) \quad (1)$$

with

$$K_1 = \frac{\kappa \beta I_s}{C_t}, K_2 = \frac{1}{V_{inj}}$$

where κ is the floating-gate efficiency [6], C_t is the total capacitance of node V_{FG} , β and V_{inj} are injection parameters which only depends on the aspect ratio of the transistor and the CMOS process. Figure 2 plots the voltage V_s according to equation (1) with respect to the total triggering duration and compares it with measured result obtained from a fabricated prototype in a $0.5\text{-}\mu\text{m}$ CMOS process. The measured response is shown to be in close agreement with the mathematical model in equation (1). Under the condition when the total triggering duration satisfies $\int_{\tau \in T} d\tau \ll e^{K_2 V_{s0}} / K_1 K_2$ a linear response of V_s with respect to t is obtained. This region is highlighted in the Fig. 2 inset and is useful for short-term monitoring. For the condition $\int_{\tau \in T} d\tau \gg e^{K_2 V_{s0}} / K_1 K_2$, equation (1) can be approximated by a log-linear response as

$$V_s = -\frac{1}{K_2} \log(K_1 K_2) - \frac{1}{K_2} \log \left(\int_{\tau \in T} \partial \tau \right). \quad (2)$$

The log-linear response shown in Fig. 2 is important for long-term impact monitoring applications and will be the

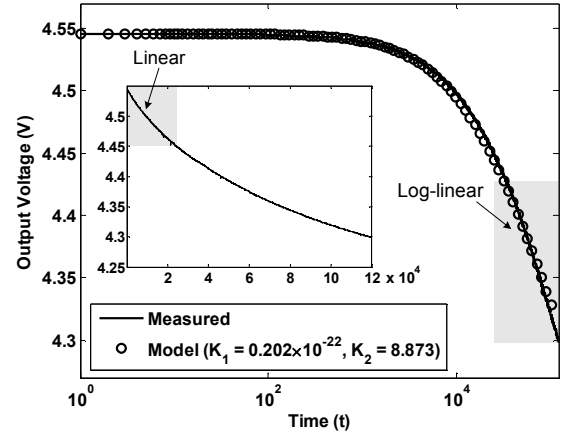


Figure 2. Mathematical and measured responses of the IHEI plotted on a logarithmic scale and on a linear scale (inset)

focus for the rest of the paper. The first part of equation (2) denotes an offset which is dependent on biasing and initialization conditions, where as the second part in equation (2) is a log-linear function of the total triggering duration and is scaled by the parameter K_2 .

B. Effect of mismatch and biasing conditions

We have verified that the response of floating-gate injectors to be robust to mismatch and variations in biasing conditions. For instance, the variation in the parameter K_2 was measured to be less than 10% when the bias current was varied by more than 100%. This result was encouraging since it implies that the precision of the source current (see Fig. 1) is not critical for the operation of the injector. The variation in the parameter K_2 for different injectors (located on different silicon dies but from the same fabrication run) was found to be less than 15%. Thus by operating the injector in a differential manner, the offset in equation (2) can be eliminated where the response can be expressed only as a function of K_2 and the total triggering duration as:

$$V_s = \frac{1}{K_2} \log \left(\frac{t_0 + \int_{\tau \in T} \partial \tau}{t_0} \right) \quad (3)$$

Here t_0 denotes a reference time with respect to which the triggering duration are measured.

III. IMPACT-RATE MONITORING CIRCUIT

A complete schematic of an impact-rate monitoring circuit is shown in Fig. 3. It consists of a cascoded current reference circuit, a start up circuit and an array of impact-rate monitoring channels. The design has been implemented in a $0.5\text{-}\mu\text{m}$ standard CMOS process and the respective circuit parameters are summarized in Table I. The impact monitoring channels consists of floating-gate injectors F1-F3 and triggering circuits comprising of a high-pass filter (formed by the R-C bridge) which is connected to common source amplifier (formed by N1-N3).

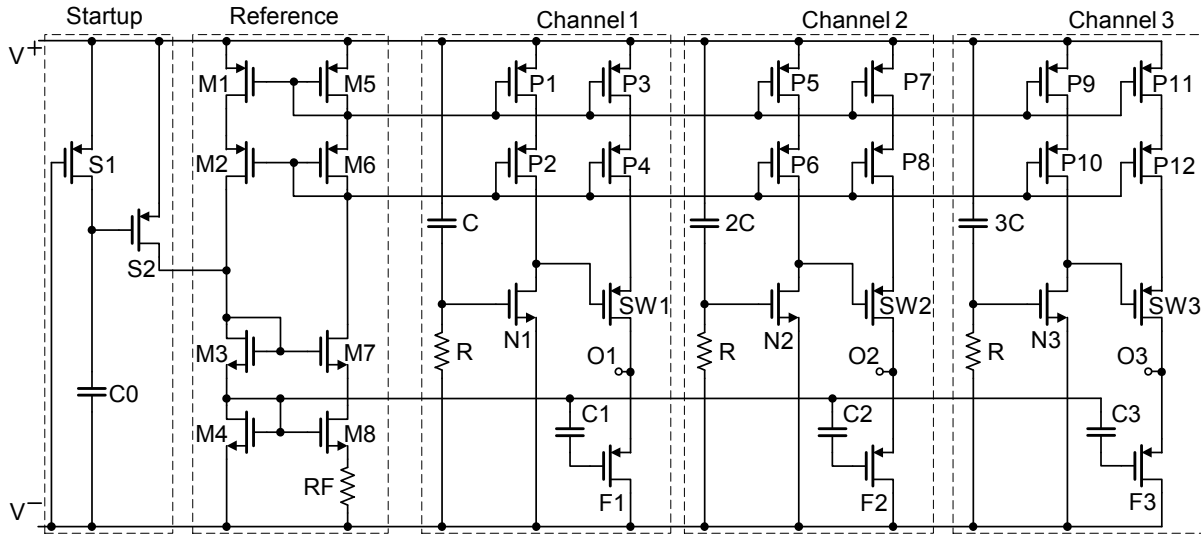


Figure 3. Complete circuit implementation of the self-powered impact-rate monitor.

TABLE I : Component sizes used in Fig. 3.

Component	Value
M1	60 μ m/10 μ m
M2, M5-M6, P1-P12	30 μ m/10 μ m
M3-M4, M7-M8	60 μ m/10 μ m
F1-F3	6 μ m/6 μ m
C1-C3	100fF
N1-N3	1.5 μ m/1.5 μ m
SW1-SW3	4.95 μ m/4.95 μ m
RF	1.5M Ω
R	2M Ω
C	5nF

The amplifier serves as a comparator and drives the switches SW1-SW3. The un-regulated supply signals V^+ and V^- are generated by the PVDF transducer and serve both as an energy source and also for impact monitoring. The capacitors for the triggering circuits (C, 2C and 3C) are all located off-chip due to their relatively large form factor.

A. Impact-rate monitoring

Before the sensor can be used for monitoring, all the outputs of the floating-gate injectors (O1-O3) are first equalized to the same potential. The equalization procedure is similar to our previous sensor [3], where injector to be initialized is first selected. The input terminals V^+ and V^- are then connected to 5.5V and the floating-gate transistor is injected till the output voltage O1-O3 reaches 4.8V. This potential is sufficient to initiate an IHEI process when the channel is triggered (by enabling the switches SW1-SW3). When the voltage level produced by the PVDF transducer exceeds a threshold voltage (3.3V), the reference current

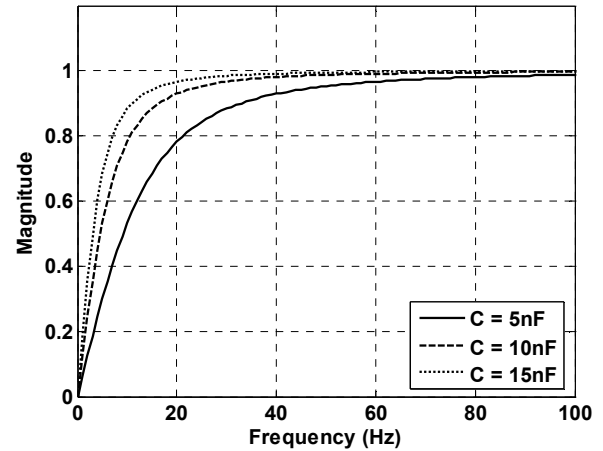


Figure 4. Injection responses for the impact with different rising speed.

circuit initializes all the current biases. For the circuit in Fig. 3 and parameters given in Table I, the startup time for the current reference was measured to be 30ms. The start-up time determines the upper bound of the impact rates that can be measured using the sensor. This was found to be <35Hz which is within the range of most biomechanical impact rates (1Hz-50Hz). Based on the rate of change of the supply voltages V^+ and V^- , the bandwidth of the high-pass filter determines the amplitude of the signal presented at the input of the comparator N1. When the signal amplitude exceeds the threshold of the comparator (determined by the bias current), the switches SW1-SW2 are triggered (active "low") and as a consequence the injectors record the occurrence of the impact. Figure 4, shows the AC response of the filters whose low-frequency cut-offs have been set to 10Hz, 5Hz and 2.5Hz. This ensures that channel 1 trigger only for a slow varying input signal (slowly changing impact). However, all the channels trigger for a fast varying input signal (high impact rates).

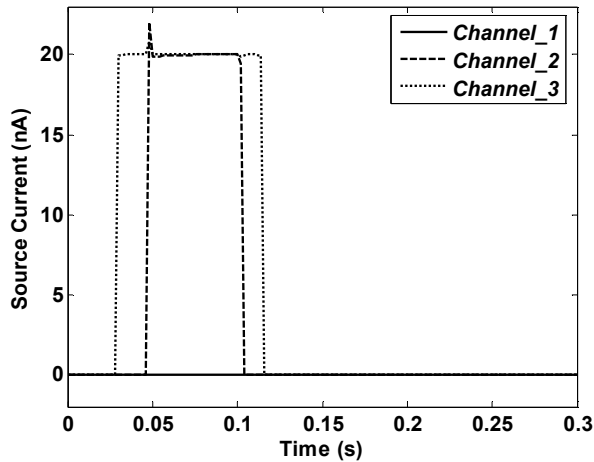


Figure 5. Injection responses for the impact with different rising speed.

Fig. 5 shows the triggering event for the three channels, when channel 1 is not triggered where as channel 2 and 3 are triggered. Note that the duration of the triggering is different for channel 2 and 3 implying that channel 3 will inject for a longer duration compared to channel 2.

IV. RESULTS

Even though the floating-gate injectors are equalized by programming the output voltage O1-O3 to 4.8V, the procedure is still prone to initialization errors. We compensate for these errors by using a calibration procedure based on the differential response of the injector as given by equation (3). All the channels are first allowed to inject for a reference duration t_0 such that $t_0 \gg e^{K_2 V_{s0}} / K_1 K_2$. This ensures that the initialization errors and biasing errors are fully calibrated before the sensor is used for monitoring. Fig. 6 shows the calibration procedure where all the three channels are injected for a duration of $t_0=3000s$. It can be seen that at the end of 3,000 cycles, the initialization errors for all the three channels have been calibrated.

After the calibration procedure, the fabricated prototype was subjected to different impact rates which were synthetically generated using a programmable signal generator. An equivalent input voltage (emulating the transducer output) to the prototype was 6.1V. The impact rates (based on the RC time-constant) were chosen such that channel 1 did not inject, where as channel 2 injected for only 85% of the duration and channel 3 injected for 100% of the duration. Fig. 6 shows that the sensor is able to distinguish different impact-rate levels, where the offset in the log-linear response is directly proportional to the relative triggering duration (calculated with respect to the total observation period). Even though Fig. 6 shows the operation of the sensor up to 40,000 cycles (seconds), we have verified its functionality beyond 10^5 cycles.

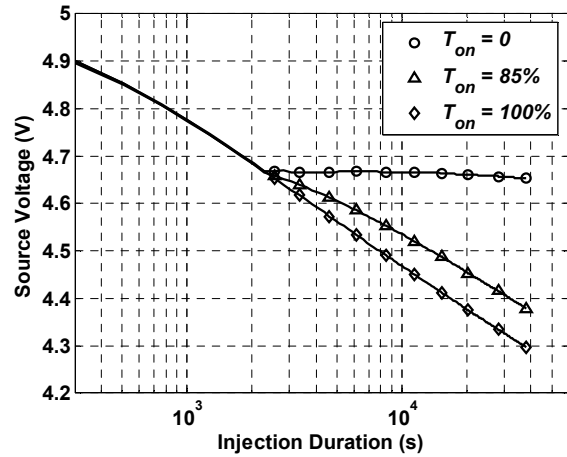


Figure 6. Measured response when the prototype is subjected to different durations (in %) proportional to impact-rate.

V. CONCLUSIONS

In this paper, we presented a battery-less self-powered sensor for monitoring impact-rates in biomechanical implants. The sensor is based on our previously reported piezo-floating-gate injector circuits that rely on computational primitives inherent in IHEI on a current starved floating-gate transistor. We augmented the functionality of the injector by interfacing a triggering circuit that controls the duration of the IHEI. The triggering circuit is programmed to respond to different impact rate threshold by choosing the bandwidth of a passive high-pass filter that drives a comparator circuit. We have demonstrated the functionality of the impact monitoring sensor for synthetically generated piezoelectric signal and we have also presented a calibration algorithm that can be used for compensating any initialization errors or mismatch in biasing conditions

REFERENCES

- [1] S. Kurtz, K. Ong, E. Lau, F. Mowat, M. Halpern, "Projections of Primary and Revision Hip and Knee Arthroplasty in the United States from 2005 to 2030" *J. of Bone and Joint Surgery*, 2007; 89(4):780-785.
- [2] M.A. McGee, et. al., "Implant retrieval studies of the wear and loosening of prosthetic joints: a review," *Wear*, vol. 241, No. 2, 2000, pp. 158-165.
- [3] N. Lajnef, et. al, "Piezo-powered floating gate injector for self-powered fatigue monitoring in biomechanical implants," *Transactions of Biomedical Circuits and Systems* (to appear).
- [4] P. Hasler, "Foundations of Learning in Analog VLSI," Ph.D. Thesis, California Institute of Technology, Pasadena, California, 1997.
- [5] C. Diorio, et. al. , "A Single-Transistor Silicon Synapse," *IEEE Trans. Electron Devices*, vol. 43, no. 11, 1996, pp. 1972 – 1980.
- [6] E. Vittoz and J. Fellrath, "CMOS analog integrated circuits based on weak inversion operation," *IEEE Journal of Solid State Circuits*, vol. 12, no. 3, 1977, pp. 224 – 231.