Monitoring of Repeated Head Impacts using Time-dilation based Self-powered Sensing

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***Abstract*—Measuring head impacts in helmeted sports is important for prognosticating onset of mild traumatic brain injuries (MTBIs) or concussions. In this paper we present a miniature battery-less, self-powered sensor that can be embedded inside sport helmets and can continuously monitor and log the statistics of different levels of helmet impacts. At the core of the proposed sensor is a novel time-dilation circuit which allows measurement of the high-levels of impact energy. An array of linear floating-gate injector is used for storing the location of the sensor on the helmet and for logging the statistics of helmet impacts which can be retrieved using an external plug-and-play reader. Measured results from prototypes fabricated in a 0.5 µm CMOS process validate the functionality of the sensor when subjected to controlled drop tests.**

I. Introduction

Understanding the relationship between head impacts in helmeted sports like American football and the risk of concussive and long-term brain injury is an active area of research [1]. While there are significant disagreements in literature about the relevance of different impact parameters (linear acceleration, rotational acceleration, location and time of impact, history of impacts, etc.) on prognosticating concussions, a common agreement has been the need for measuring and recording head impact data during the normal course of play [1]. The most popular approach in this regard has been to embed battery-powered accelerometers inside helmets and estimate the inertial response of the human brain during the impact [2]. While this is an attractive solution for controlled studies, the use of batteries increases the risk of leakage (due to high-acceleration impacts) and increases the overhead of routine helmet maintenance and recharging. In this paper, we explore a self-powering approach for monitoring helmet impacts by harvest operational energy from the impact itself.

The challenge for designing self-powered sensors for helmets is that the level of acceleration (and hence the energy) during impacts could easily exceed 100g [2]. This is depicted in Fig. 1, which illustrates the impulsive nature of the signal subjected on a helmet sensor. To prevent damage to the sensor, a typical architecture will dissipate most of the impulse energy through over-voltage protection circuits; sensors would be rendered unable to accurately measure the magnitude of energy, and hence the acceleration of the impact [3]. Therefore, we propose a time-dilation approach where the impulsive signal is stretched out in time (as shown in Fig. 1) while retaining its energy content (area under the curve). In this manner, the sensor can be operated within the levels of electronic compliance and safety. However, this mode of self-powering introduces additional challenges which will be discussed in section II, where we present the principle of operation and schematic of a time-dilation circuit.

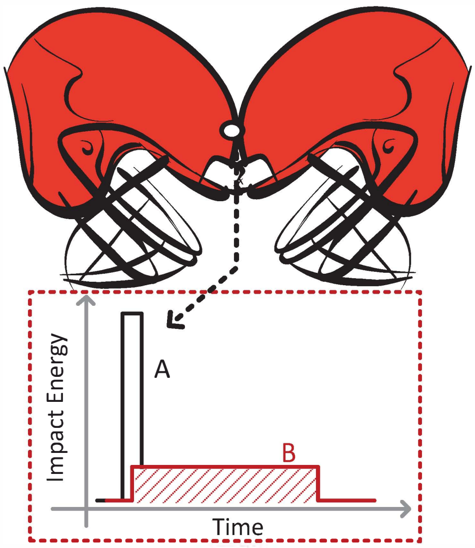

Fig. 1. Impulsive nature of the head impacts and the proposed time-dilation method to spread the energy over time while operating the sensor electronics within the compliant voltage levels.

II. Time-dilation Circuit

Fig. 2 shows the equivalent circuits of a typical piezoelectric self-powered sensor with and without the proposed time-dilation circuit. In both the circuits, the piezoelectric transducer is modeled by a simple current source I_p to model the impulse current generated due to the mechanical impact, and a capacitance C_p which models the mechanical stiffness of the transducer. I_L models the load current of the sensor, C_L the load capacitance, and D_L represent a zener diode which models the over-voltage protection circuits. In practice, the current I_L is triggered only when the voltage V_out exceeds a minimum threshold level V_min. The resistors R_1 and R_2

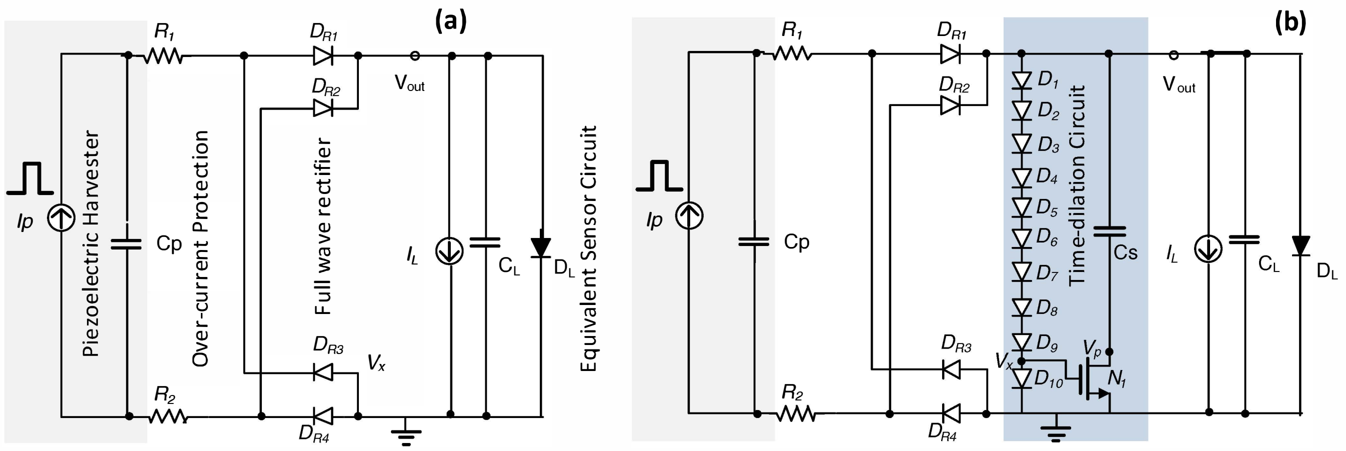

Fig. 2. Equivalent circuit of a self-powered sensor: (a) without, and (b) with the time-dilation circuit.

implement an over-current protection circuit and the full-wave rectification is achieved using the diodes $D_{R1} - D_{R4}$ formed using a bulk-driven cross-coupled pMOS circuit which was reported in [3].

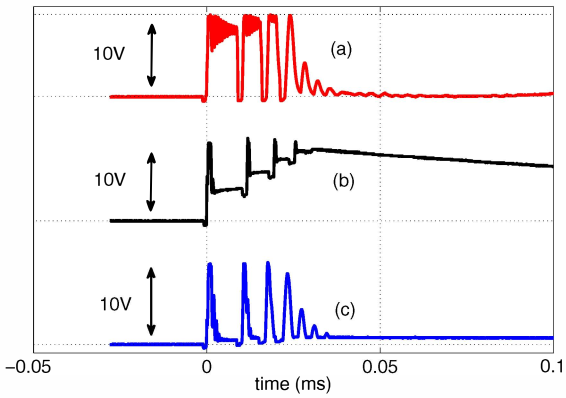

Fig. 3. Measured results showing V_{out} for the sensor with: (a) no time-dilation circuit; (b) time-dilation circuit with $C_{\mathrm{S}} = 50$ nF; and (c) time-dilation circuit with $C_{\mathrm{S}} = 1\ \mu$F.

For the circuit without the time-dilation (shown in Fig. 2(a)), the rectified current of I_p increases the voltage V_{out} past the minimum threshold V_{min} which then activates the sensor and hence the current I_L. If the current I_p exceeds the sensor current I_L, the voltage V_{out} will increase until the zener, D_{L}, starts drawing the extra current. Thus, for large impulse currents most of the impact energy is dissipated through the zener. The time-dilation circuit shown in Fig. 2(b) mitigates this problem in the following manner. Initially the sensor voltage $V_{\mathrm{out}} = 0$ implies that the nMOS transistor N_1 is OFF and hence the storage capacitor C_{S} is disconnected. Therefore, during start-up the behavior of circuit Fig. 2(b) is identical to the start-up for the circuit in Fig. 2(a). But when the voltage V_{out} exceeds KV_{th}, with K being the number of diodes in the chain D_1-D_K and V_{th} being the threshold voltage of the transistor N_1, the storage capacitor C_{S} is connected in parallel with the sensor. Thus, any extra piezoelectric current now charges up the storage capacitor without dissipating through the zener. When the impulse is over (after the impact) the charge stored on the capacitor C_{S} drives the sensor current until V_{out} falls below the activation voltage, V_{min}. Thus, using time-dilation, the sensor can more accurately measure the level of impact energy.

Fig. 3 shows measured results from a fabricated prototype (described in later sections) comparing the voltage V_{out} under three different conditions: (a) without any time-dilation, based on the schematic shown in Fig. 2(a); (b) time-dilation using $C_{\mathrm{S}} = 50$ nF; and (c) time-dilation using $C_{\mathrm{S}} = 1\ \mu$F. As shown in Fig. 3(a), the zener clips the output voltage at $V_{\mathrm{max}} = 10$ V and the sensor shuts down after the impulse decays. Where as for the time-dilation circuit in Fig. 3(b), the storage capacitor C_{S} holds the extra charge. Note that in Fig. 3(b), the start-up response remains unaffected which is important for logging different levels of impact. The result in Fig. 3(c) shows that choosing the right range of values for C_{S} is important as a large storage capacitor (even though it can store more charge) will take a longer time (hence duration of impulse event) to push the voltage V_{out} beyond V_{min} and activate the sensor.

III. Self-Powered Energy Measurement and Data-Logging

The magnitude of impact can be determined by estimating the amount of charge that is deposited on the storage capacitor. This in turn can be determined by the time it takes to discharge the storage capacitor. Also, for self-powered operation the measured data has to be stored on a non-volatile memory for subsequent retrieval. Linear time-measurement on a non-volatile memory can be readily implemented using our previously reported linear floating-gate injector topology [4]. The circuit level schematic of the linear floating-gate injector is shown in Fig. 4. The circuit consists of a floating-gate pMOS transistor M_{fg} whose source is driven by a constant current source I_{ref} which is powered by either a piezoelectric transducer (during battery-less operation) or by an energy

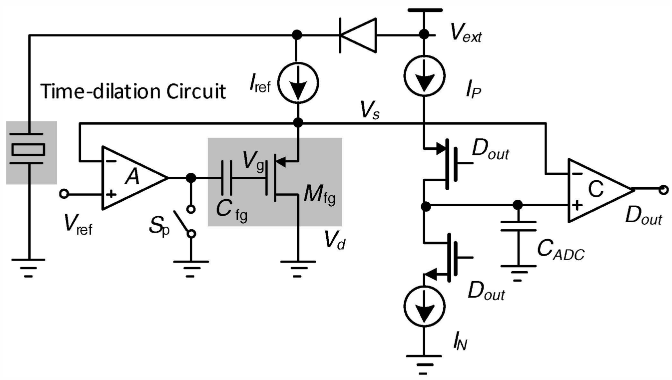

Fig. 4. Schematic of the data-logging circuit with a floating-gate based linear injector and a spiking analog-to-time converter

source V_{ext} (when the data is being retrieved by a reader). Note that the energy sources are isolated by a diode which allows V_{ext} to supersede the signal generated by the piezoelectric transducer. The opamp A (connected to V_{ref}), the constant current source I_{ref}, and the floating-gate transistor M_{fg} form a negative feedback configuration when the switch S_{P} is open, thus ensuring that the source V_{s} and gate V_{g} voltages remain constant. Since the drain voltage of M_{fg} is tied to ground, if the reference voltage V_{ref} exceeds 4.2V, the negative feedback will cause the source-to-drain voltage of M_{fg} to also exceed 4.2V. In such a case, hot-electrons are generated in the channel of M_{fg} due to impact ionization; when the electron energy exceeds the gate-oxide potential barrier ($\approx$ 3.2eV) they can get injected onto the floating-gate. Note that the polysilicon gate of the pMOS transistor is electrically insulated by silicon-dioxide (hence the name "floating-gate"), therefore, any electron injected onto the gate is retained for a long period of time. Because all terminal parameters of the floating-gate transistor are held constant during the injection process, the injection current I_{inj} remains constant. Thus, the amount of charge injected onto the floating-gate, or the decrease in floating-gate voltage V_{fg}, is proportional to the duration for which the source current I_{ref} is activated and S_{P} is open. This can be expressed as

$$\Delta V_{\text{fg}} = \frac{1}{C_T}\int_0^T I_{\text{inj}}dt = \frac{I_{\text{inj}}}{C_T}\tau(T) \tag{1}$$

where τ is the duration of injection and C_T is the total floating-gate capacitance which includes C_{fg}, tunneling capacitance, and other parasitic capacitances associated with the floating node. The change in floating-gate voltage ΔV_{fg} is measured by closing the switch S_{P} which breaks the feedback loop by shorting the other terminal of C_{fg} to ground. Because the source current I_{ref} is constant, $\Delta V_{\text{s}} = \Delta V_{\text{fg}}$ which is read-out using a spiking analog-to-time converter as shown in Fig. 4. The voltage V_{s} is used as a voltage reference to a comparator whose output D_{out} periodically toggles the pMOS and the nMOS switches, one at a time. Thus the current I_P charges the capacitor C_{ADC} to the voltage V_s after which the current I_L is turned ON which discharges C_{ADC} and generates a spike, as shown in the measured response. The time-difference between the two spikes is proportional to the voltage V_{s} and is used to determine the floating-gate voltage V_{fg}.

IV. Measurement Results

A prototype sensor IC has been fabricated in a 0.5μm CMOS process and its micrograph is shown in Fig. 5(a). It consists of 21 linear floating-gate injector channels where 14 of the channels are programmed to trigger at different levels of impacts. The 7 remaining channels are used for storing: (a) an identification code for the sensor; and (b) placement location on the helmet. The sensor IC also integrates functional modules that are required for programming the linear injectors and retrieving data using an external reader. The circuit level implementation for many of the modules has been reported [5] and is omitted here for the sake of brevity. Fig. 5(b) shows a football helmet (manufactured by Riddell Inc.) which was used for testing the fabricated sensor. A fully integrated sensor board is shown in Fig. 5(c) which hosts the sensor IC, the time-dilation capacitor, the piezoelectric interface and the programming interface. The size of the sensor is $2\,\text{cm} \times 1.5\,\text{cm}$ and easily fits in between the helmet's cushion pads.

The measurement setup emulated at a smaller scale, the drop-test procedure reported in [6]. The helmet with the integrated sensor was dropped from two height levels: Height A (1 foot) and Height B (2 feet). Fig. 6 shows the output of the piezoelectric transducer (without the sensor attached) when the helmet is dropped from heights A and B. The response clearly shows the impulsive nature of the piezoelectric signal generation and the voltage level clearly shows the need for the time-dilation approach. Fig. 7 shows the data recorded from the sensor when the helmet is dropped repeatedly from 1 feet. Note that even at this height the first three channels record the level of impact indicated by the change in their output voltage. The linearity of the response shows that the voltage measurements could be calibrated to different impact energy levels with corresponding acceleration levels. Fig. 8 shows data recorded from the sensor when multiple helmet drops from 3 different heights. The Control signifies when the helmet was just tapped while at rest. The result shows the sensor's gain changing with at various heights, validating the sensor's ability to log diverse levels of impact.

V. Conclusions

In this paper we presented a miniature sensor system that can be used to monitor the level and frequency of head impacts in helmeted sports. A time-dilation circuit enables the sensor to measure high energy impulses and a linear floating-gate injector enables the sensor to record data on non-volatile memory. The sensor is self-powered and operates by harvesting the energy from the head-impact with no need for batteries. The small form-factor and low-cost of the sensor enables it to be embedded at multiple places inside the helmet, providing MTBI researchers mapping data to effectively prognosticate concussions during the course of normal play.

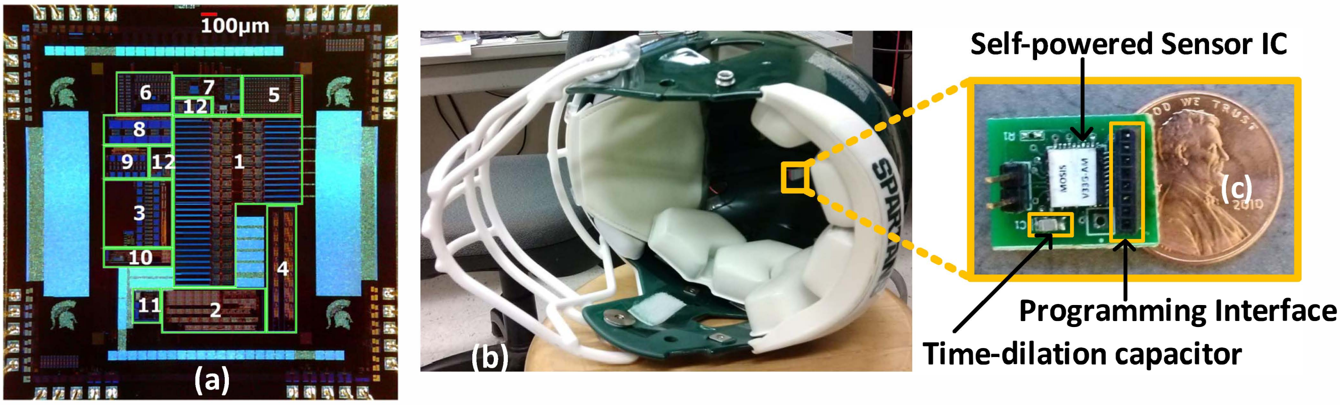

Fig. 5. (a) Micrograph of the sensor IC integrating different modules: 1. Floating Gate Array; 2. Digital Decoder; 3. Tunneling Voltage Charge-pump; 4. Level Shifter; 5. Injection Control; 6. Diode Protection & Rectifier; 7. Voltage References; 8. Tunneling Charge-pump; 9. Injection Charge-pump; 10. Ring Oscillator; 11. Analog-to-time Converter; 12. Supporting circuitry, power-on reset, buffers, etc.; (b) test helmet used for the impact measurement study; and (c) the sensor board hosting the sensor IC and the time-dilation capacitor.

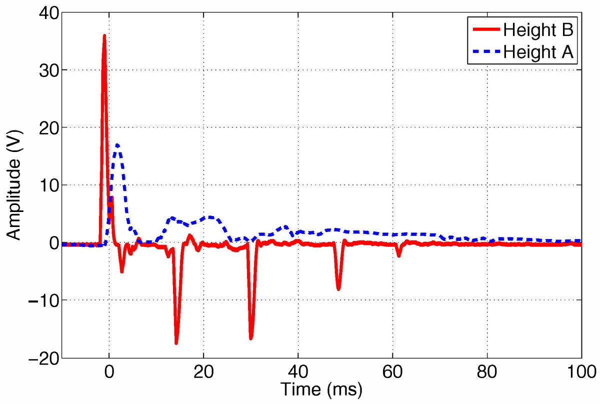

Fig. 6. Signal recorded at the output of a PZT-5H piezoelectric transducer (10MΩ load) when the helmet is dropped from 1 foot and 2 feet respectively.

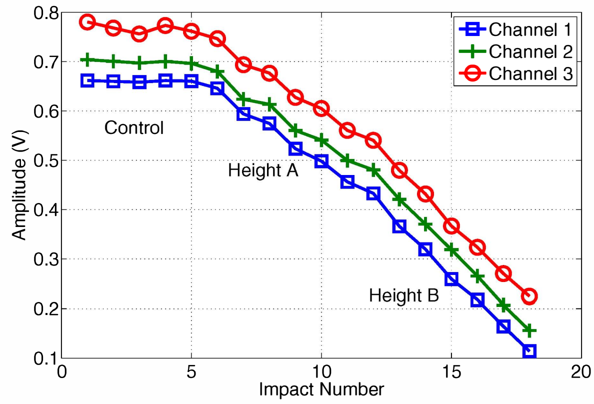

Fig. 8. Measured output from three of the sensor channels when the helmet is repeatedly dropped from different heights.

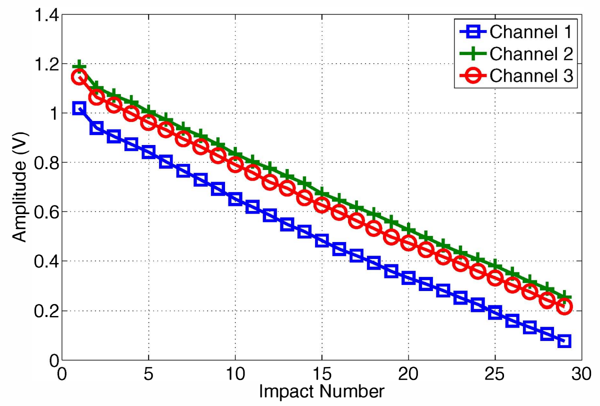

Fig. 7. Measured output from three of the sensor channels when the helmet is repeatedly dropped from 1 foot.

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