Compact self-powered CMOS strain-rate monitoring circuit for piezoelectric energy scavengers

C. Huang and S. Chakrabartty

Self-powered sensing refers to an energy scavenging approach where the power for sensing, computation and storage is harvested directly from the signal being sensed. Presented is a 16-transistor CMOS circuit that can be used for the self-powered sensing of strain-rates using signals produced by piezoelectric energy scavengers. By exploiting operational primitives inherent in impact-ionised hot-electron injection on a floating-gate transistor, the proposed circuit achieves computation and non-volatile storage of signal-rate statistics without the aid of batteries, intermediate energy storage, power regulation or analogue-to-digital conversion. By using a diode based analogue delay-line, the proposed circuit computes and stores the number of times the signal-rate (strain-rate) exceeds a threshold which can be programmed from 0.6 to 12 V/s. The circuit occupies 500 × 340 μm of silicon when prototyped in a 0.5 μm CMOS technology and measured results demonstrate power dissipation less than 200nW, which is ideal for self-powered sensing applications.

Introduction: Self-powered sensing refers to an energy scavenging approach where the power for signal processing and data storage is harvested directly from the signal being sensed. For example, a piezoelectric transducer could be used for sensing strain-variations, and the same sensed signal could be used for powering the computation and storage functions. This approach ensures that the signals of interest can be continuously monitored without relying on any auxiliary sources of energy (e.g. rechargeable battery or radio-frequency excitation). As a result, the self-powering approach could not only detect salient/rare events, but also keep a statistical record of vital measurements. Unfortunately, self-powered sensing imposes operational constraints that obviate the usage of conventional energy conversion/regulation and digital signal processing techniques [1].

In this Letter, we propose a 16-transistor CMOS circuit which exploits the floating-gate (FG) principle to sense, compute and store signal-rate statistics without the need for energy conversion, regulation, analogue-to-digital conversion or digital signal processing. We have tailored this circuit to a real-world application of sensing and counting the number of mechanical impacts, a statistic which has been shown to be important in prognosticating mechanical fatigue [2]. A system level architecture for the proposed circuit is shown in Fig. 1, which uses a low-frequency equivalent circuit model of a piezoelectric harvester [3]. Mechanical impacts are detected by monitoring the strain-rate (rate of voltage change) produced by the transducer. A highpass filter with a cutoff frequency ranging from 0.1 to 2 Hz is used to detect the rate-of-change of the strain-levels and a rectifier is used to extract the magnitude of the strain-rate. When the strain-rate exceeds a predefined threshold, the threshold circuit enables a data-logger which records this event and stores the cumulative statistics in a non-volatile memory [to be retrieved later].

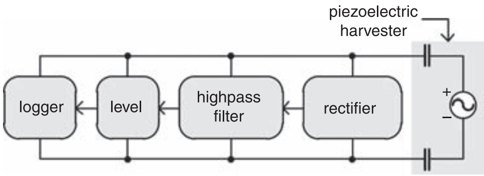

Fig. 1 *System level architecture of proposed monitoring circuit*

Operation principle: The operational principle for the proposed circuit relies on two important concepts: (a) piezoelectric transducers can generate high voltage (>10 V) but with limited current driving capability; (b) hot-electron injection in FG transistors requires high voltage (>4 V) but can operate at current levels down to a few pico-amperes. The natural match between these two principles is achieved by the basic circuit shown in Fig. 2*a*, where the supply voltage is generated by a piezoelectric transducer and the hot-electron injection on pMOS transistor M_{FG} is controlled by switch S. When the switch is ON, the high-voltage generated by the transducer triggers hot-electrons (high-energy electrons) in the channel of M_{FG} and the electrons can be injected into the FG node. The number of injected electrons is proportional to the duration when the switch S is ON, resulting in the decrease of V_S if V_{CG} is held constant. In [4], we showed that if M_{FG} is biased in weak inversion (based on the source current I_S), the source voltage V_S can be expressed as

$$V_S = \frac{1}{K}\log\left(\frac{t_0 + \int_{\tau\in\Delta t} d\tau}{t_0}\right) \tag{1}$$

where K and t_0 are process dependent constants, and Δt denotes the set of time intervals when S is ON.

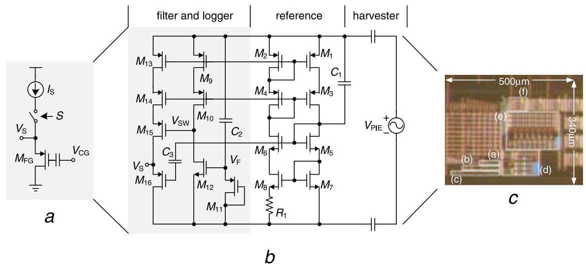

Fig. 2 *Simplified circuit model of FG injector; self-powered strain-rate monitoring circuit; micrograph of three separate monitoring channels*

a Simplified circuit model of FG injector
b Self-powered strain-rate monitoring circuit
c Micrograph of three separate monitoring channels

To apply (1) for strain-rate monitoring, the duration Δt in (1) is modulated according to the rate-of-change of the input signal. The complete strain-rate monitoring circuit is shown in Fig. 2*b* which consists of a reference circuit, a highpass filter/rectifier circuit and a FG injection circuit equivalent to Fig. 2*a*. Transistors M_1 to M_8, R_1 and C_1 form the current reference which generates the bias voltage V_{CG} and current I_S. M_{16} is the FG transistor and M_{15} acts as the switch which is controlled by V_{SW}. V_{SW} is determined by the common-source amplifier M_{12} the input of which is the output of the nonlinear highpass filter/rectifier formed by the capacitor C_2 and the pMOS diode M_{11}. When the rate-of-change of the piezoelectric signal V_{PIE} is below a threshold, the filter output transient V_F is not large enough to turn on M_{12}. In this case, V_{SW} always follows the supply voltage and the transistor M_{15} remains OFF. Otherwise, when the signal-rate is large enough, the transient V_F can increase beyond V_H (larger than V_{TH} of M_{12}). Therefore, V_{SW} is momentarily shorted to ground which triggers hot-electron injection in M_{16}. Then M_{11} behaves as a large resistor which slowly discharges V_F. Transistor M_{12} remains ON till the voltage V_F falls below the V_{TH} which stops the hot-electron injection in M_{16}. The injection duration Δt can be expressed as

$$\Delta t = \frac{[e^{-(V_H/U_T)} - e^{-(V_{TH}/U_T)}]CU_T}{SI_{D0}} \tag{2}$$

where S is the aspect ratio of M_{11}, I_{D0} is the characteristic current and U_T is the thermal voltage. Based on (2), the delay Δt can be modulated by changing the aspect ratio S of the pMOS. It is important to point out that the accuracy and regulation of the current reference is not critical for this design since the operation of the injection device [as summarised by (1)] is theoretically independent of the bias current [4]. In the implementation, we have integrated three different monitoring circuit channels where a different aspect ratio S in (2) has been chosen to generate a different time constant for the highpass filter.

Measured results: A prototype of the self-powered strain-rate monitoring circuit was fabricated in a standard 0.5 μm CMOS process the micrograph of which is shown in Fig. 2*c*. The three different delay-line circuits are labelled as: (a) channel 1; (b) channel 2; (c) channel 3; each consisting of a pMOS diode M_{11} with a different aspect ratio S. The micrograph also shows other modules for the proposed circuit: (d) reference; (e) FG transistor array; and (f) test buffers. The size ratio of M_{11} in each channel is 1:10:20. The transient response of the delay-line was first verified by applying a step input across the two input terminals and then measuring the delay in the response for V_{SW} [shown in Fig. 3*a*]. As shown in Fig. 3*a*, $\Delta t_1 - \Delta t_3$ are measured to be 140, 15 and 8 ms, respectively (offset by the start-up delay for the current reference circuit). The ratio of $\Delta t_1 - \Delta t_3$ is in close agreement with theoretical values in (2) according to the sizes of transistors.

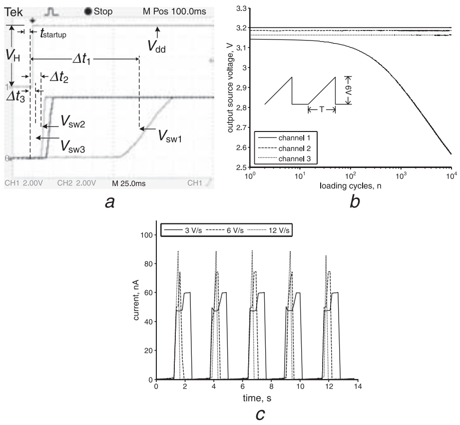

Fig. 3 *Measured results showing computation of strain-rate statistics*

a Step responses
b Injection responses
c Power consumptions

The next set of experiments verified the functionality of the fabricated prototype for self-powered computation of the strain-rate statistics. A PZT piezoelectric transducer was emulated using a low-frequency quasi-static model [3], where a 6V ramp signal with different rise-time T was applied across the input terminals of the prototype. The impact rate is calculated to be $(6/T)$ V/s and each signal was applied for 10^4 cycles the injection responses of which were recorded. For channel 1 with the largest time constant Δt_1 as shown in Fig. 3*a*, the injection was triggered for $T <$ 10s (0.6 V/s); channel 2 was triggered for $T <$ 1s (6 V/s) and channel 3 was triggered for $T <$ 0.5s (12 V/s). Fig. 3*b* shows the measured output V_S for each channel when the signal-rate is 3 V/s. Only channel 1 is triggered as shown by the change in its measured output V_{S1} which conforms to the theoretical result in (1).

Fig. 3*c* shows the current consumption for the proposed circuit (computed for all three channels and the reference circuit). When the signal-rate is 3 V/s, only one channel is activated and the total current flowing through the circuit is determined by the reference circuit and the channel 1 monitoring circuit. When the signal-rate is greater than 12 V/s, all three monitoring channels are activated and the peak current was measured to be about 90 nA. This results in an active power dissipation of each channel to be 180 nW for a 6 V input which is sufficient for self-powering using miniature piezoelectric transducers.

Conclusion: A 16-transistor CMOS circuit is presented which can be used for self-powered sensing of strain-rates using a piezoelectric transducer. The proposed circuit consumes less than 180 nW of power, when active, and can be powered directly from the signal generated from the piezoelectric transducer. This eliminates the need for other auxiliary power sources such as batteries or RF radiation, making it suitable for micro-scale, long-term, continuous monitoring applications (e.g. structural health monitoring [5]).

30 November 2010
doi: 10.1049/el.2010.3430
One or more of the Figures in this Letter are available in colour online.

C. Huang and S. Chakrabartty (*Department of Electrical and Computer Engineering, Michigan State University, East Lansing, Michigan, USA*)

E-mail: shantanu@egr.msu.edu

References

1 Yi, J., Ki, W.H., and Tsui, C.Y.: 'Analysis and design strategy of UHF micro-power CMOS rectifiers for micro-sensor and RFID applications', *IEEE Trans. Circuits Syst.*, 2007, **54**, (1), pp. 153–166
2 Suresh, S.: 'Fatigue of materials' (Cambridge University Press, 1998, 2nd edn)
3 Mateu, L., and Moll, F.: 'System-level simulation of a self-powered sensor with piezoelectric energy harvesting'. Int. Conf. Sensor Technologies and Applications, Valencia, Spain, October 2007, pp. 399–404
4 Huang, C., and Chakrabartty, S.: 'Calibration and characterization of self-powered floating-gate usage monitor with single electron per second operational limit', *IEEE Trans. Circuits Syst. I, Reg. Pprs*, 2010, **57**, (3), pp. 556–567
5 Elvin, N., Lajnef, N., and Elvin, A.: 'Feasibility of structural monitoring with vibration powered sensors', *Smart Mater. Struct.*, 2006, **15**, (4), pp. 977–986