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A Subnanowatt Vibration-sensing Circuit for Dust-size Battery-less Sensor Nodes

T. Shimamura, H. Morimura, M. Ugajin, and Shin'ichiro Mutoh

NTT Microsystem Integration Laboratories
3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan
Phone: +81-46-240-2415 E-mail: tshima@aecl.ntt.co.jp

1. Introduction

"Ambient intelligence", which is based on sensor networks with large numbers of nodes, is expected to provide new services for context awareness [1]. Node miniaturization is important since distributed match-box-sized nodes in large numbers would be noticeable in rooms. When the power source is miniaturized to a few millimeters cubed, generated power is reduced to the nanowatt-level according to estimation based on energy density [2]. When the generated power is smaller than that needed for radio, the sensor nodes have to accumulate energy for radio [1]. The architecture of a sensor node with functions for energy accumulation is shown in Fig. 1. The power management circuit accumulates energy from nano-ampere power generator in the accumulation capacitor, and supplies power to the vibration-sensing circuit. When an event occurs at the node, the radio sends data about the strength of vibration. The power of the sensing circuit needs to be reduced to the subnanowatt level since the sensing function needs to be active with nanowatt power generation. To meet this requirement, we proposed a subnanowatt vibration-sensing circuit [3]. This paper describes the principle and the sensing characteristics.

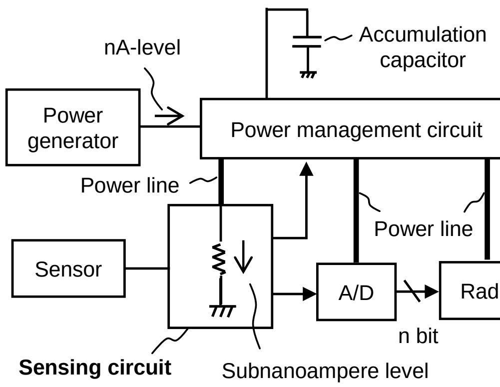

Fig. 1. Sensor node architecture with energy accumulation using nanoampere-level power.

2. Subnanowatt Vibration-sensing Circuit

We explain the principle of proposed circuit using the circuit models shown in Fig. 2. In the conventional circuit, the signal generated by the sensor is amplified using a source-grounded MOSFET and a load resistor [Fig. 2(a)]. In this case, DC bias current that flows from the power supply to the ground becomes submicroamperes because it is difficult to fabricate a resistor of more than gigaohms in millimeter square size. Even when the state-of-the-art fine process is used, the circuit suffers from offset voltage variation and flicker noise in output signal due to the load resistance. The proposed circuit is based on mechanical charge transfer [Fig. 2(b)]. When the variable capacitance C_s in the sensor is large, the voltage of C_s decreases and C_s is charged through diode D1 from the power supply. Next, when C_s becomes small, the voltage of C_s increases and the charge is transferred through D2 to capacitor C_i. These operations iterate alternately, which increases the voltage of C_i. Thus, the capacitance change in C_s is detected without signal amplification by using DC bias current. The circuit configuration is shown in Fig. 3. A capacitance-change-integrating (CCI) circuit detects capacitance change in the differential variable capacitor formed in the movable structure of the vibration sensor using three diode-connected MOSFETs. A ramp detection circuit converts the ramp signal to PWM pulses using two threshold circuits with different logic thresholds and an exclusive-OR gate. When a Schmitt trigger circuit is used for threshold circuit, short-circuit current with a microampere level flows since its input voltage is intermediate. The proposed circuit includes switches (Q_{P1}, Q_{P2}) and current sources (Q_{N1}, Q_{N2}). The gate voltage of Q_{N1} and Q_{N2}, V_{ref}, is biased under the threshold voltage, which limits the short-circuit current to the subnanoampere level. At first, Q_{P1} and Q_{p2} are "on" state. Increasing V_{cci} makes them close to "off" state. The threshold operation is executed when the current of the switch equals to that of the current source. The difference in logic thresholds is determined by channel length and width on Q_{N1} and Q_{N2}, which makes it easy to adjust the deep subthreshold current. In the above manner, the vibration is sensed with sub-nanowatt-level power using mechanical charge transfer.

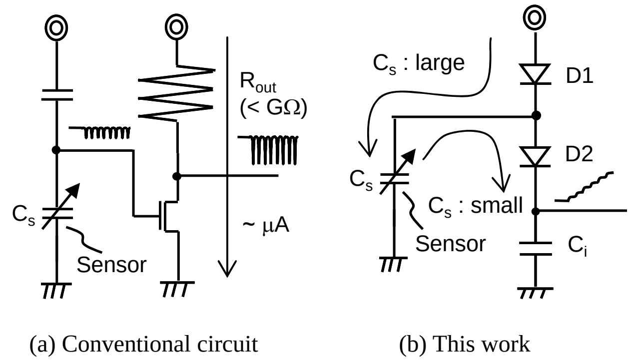

Fig. 2. Principle of subnanowatt vibration-sensing circuit.

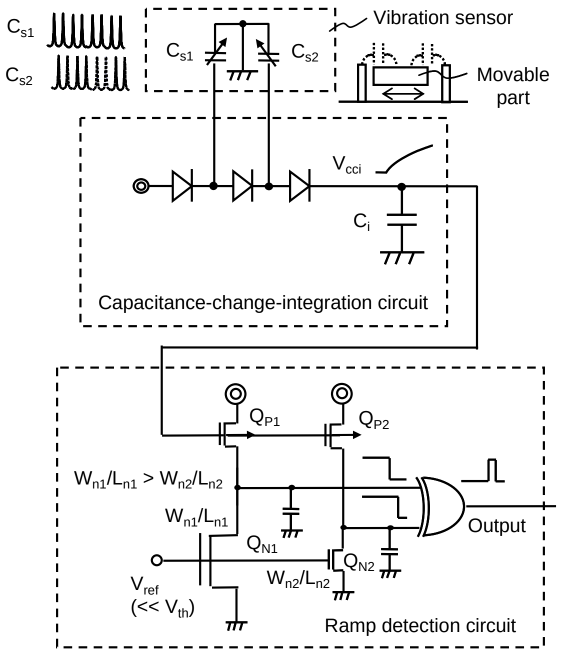

Fig. 3. Vibration-sensing circuit configuration.

3. Experimental Results

To evaluate the effectiveness of the proposed circuit, we fabricated a test chip using the 0.35-μm CMOS process. Figure 4 shows the evaluation board and a chip microphotograph. The chip size is 2 x 2 mm^2. A vibration sensor was mounted on the board to evaluate the vibration-sensing capabilities. The sensing characteristics were evaluated for two vibration sensors with different resonance frequency f_{res}. The output pulse width changed by the acceleration of applied vibration, which confirms the vibration of sub-hectohertz is detectable. The power dissipation of the proposed circuit is shown in Fig. 6. The power dissipation, calculated by using the measured power for the converting and waiting mode (solid line), is 0.7nW in the range of less than 1000 events per hour. A reported circuit with a low-power sensor interface [4] (dashed line) consumes 450 nW independently of the vibration-occurrence frequency. The power of the proposed circuit is 1/600 that of the reported one.

4. Summary

We proposed a vibration-sensing circuit based on mechanical charge transfer. The evaluation of test chip confirms that the vibration of sub-hectohertz is sensed with subnanowatt power.

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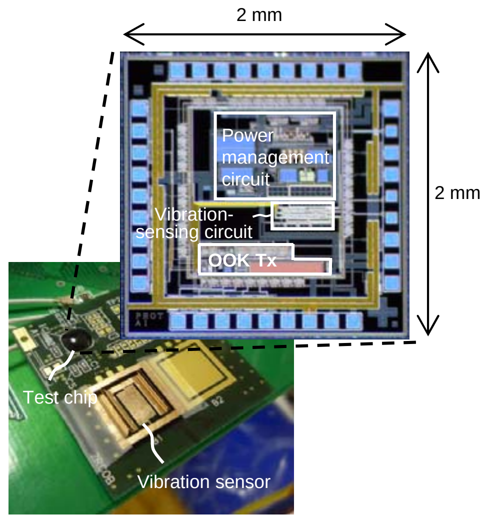

Fig. 4. Evaluation board and chip microphotograph.

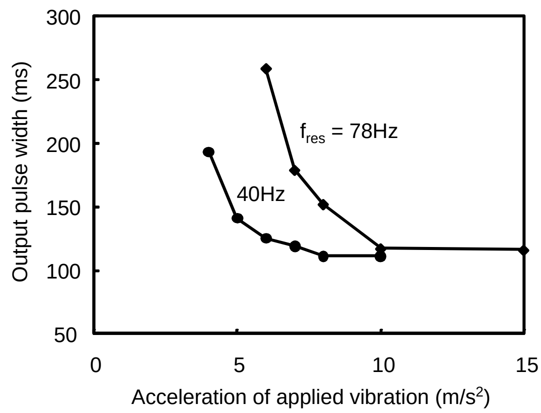

Fig. 5. Sensing characteristics depending on resonant frequency of vibration sensor.

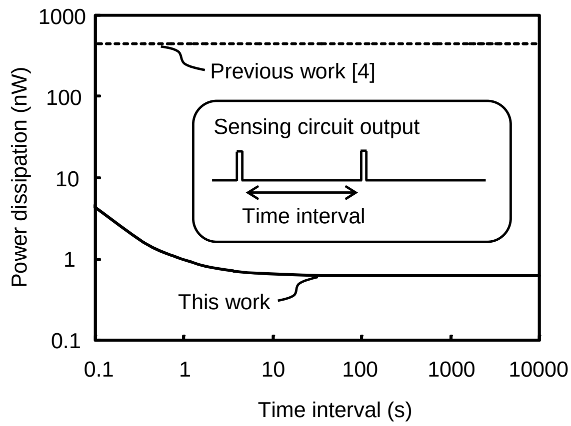

Fig. 6. Power dissipation of vibration-sensing.

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