A Watchdog Sensor for Assuring the Quality of Various Perishables with Subthreshold CMOS Circuits

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Abstract

We developed a CMOS integrated-circuit sensor that emulates the change in quality of various perishables. This sensor is attached to perishable goods such as farm and marine products and is carried from producers to consumers along with the goods. During their distribution process, the sensor experiences the surrounding temperature and emulates the deterioration of the goods caused by the surrounding temperatures. By reading the output of the sensor, consumers can determine whether the goods are fresh or not. This sensor consists of subthreshold CMOS circuits with a low-power consumption of 5 μW or less.
(Keyword: CMOS sensor, subthreshold, ultra-low-power, quality guarantee)

I. Introduction

Controlling the quality of consumer goods in a distribution process is very important but not easy for perishables such as farm, marine, and dairy products. This problem can be solved by developing a smart sensor, or a watchdog sensor, that monitors the deterioration of perishables during distribution from producers to consumers. Such monitoring can be performed by electrically emulating the thermal chemical reaction that causes the deterioration of perishables. The sensor is attached to the perishables and is carried from producers to consumers along with the goods. It experiences the surrounding temperatures and emulates the deterioration of the goods caused by the temperature. By reading the output of the sensor, consumers can determine whether the goods are fresh or not.

Previously, Hirose and others proposed a prototype chip of watchdog sensor circuits consisting of analog integrators and multipliers based on operational amplifiers [1]. However, the circuit had a difficulty to emulate a large activation energy of chemical reaction because of its limited dynamic range. In this work, we propose an improved watchdog sensor whose simple circuitry differs from the previous device; it can emulate the deterioration of perishables with a wide range of activation energy by using a combination of analog and digital circuits.

II. Model of the Deterioration Process

The deterioration process of perishables can be approximately expressed by a simple chemical reaction, A + B $\rightarrow$ C, where A and B are the constituent elements of the perishables,

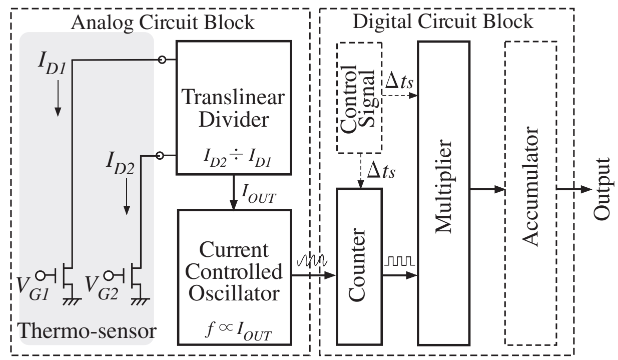

Fig. 1. Block diagram of the sensor device.

and C is an undesirable spoiling substance produced by the reaction [2]. According to this reaction, the concentration of the undesirable product $[C]$ can be given by

$$[C] = [A]_0[B]_0 k_0 \int_0^{t=t1} \exp\left(-\frac{\Delta E_a}{k_B T}\right) dt, \quad (1)$$

where $[A]_0$ and $[B]_0$ are the initial concentrations of constituents A and B. The concentration $[C]$ corresponds to the deterioration and is greatly affected by the thermal history that the perishables experience during their distribution process.

III. Circuit Implementation of a Sensor

To emulate the deterioration process of (1) with electrical circuits, we use the transfer characteristics of a MOSFET operated in the subthreshold region. The subthreshold current I_D through a MOSFET is an exponential function of the gate-source voltage and is given by

$$I_D = I_0 \exp\left(\frac{e(V_G - V_{TH})}{\eta k_B T}\right), \quad (2)$$

where I_0 is a process-dependent parameter, e is the elementary charge, η is the subthreshold slope factor, and V_G is the input gate-source voltage for the MOSFET.

Figure 1 shows a block diagram of the sensor we proposed. The thermo-sensor MOSFETs produce two subthreshold currents of I_{D1} and I_{D2}. The translinear divider, operated in the subthreshold region, accepts these currents and produces output current I_{OUT} given by

$$I_{OUT} = I_{REF}\frac{I_{D2}}{I_{D1}} = I_{REF}\exp\left(-\frac{\Delta E_0}{k_B T}\right). \quad (3)$$

Therefore, the output current emulates (1) for deterioration. Activation energy ΔE_0 of the circuit can be controlled by adjusting the difference between two bias voltages V_{G1} and V_{G2} for the thermo-sensor MOSFETs.

The current-controlled oscillator (CCO) accepts current I_{OUT} and produces oscillation pulses with a frequency f proportional to I_{OUT}. The oscillation frequency depends on applied current I_{OUT} and is given by

$$f = \frac{1}{2mt_p} = \frac{I_{OUT}}{2mC_L V_{dd}}, \quad (4)$$

where m is the number of inverters in the oscillator, t_p is the propagation delay of the inverter, and C_L is the load capacitance for each inverter.

The digital counter records the number of the pulses at a short intervals Δt_s to produce a counting output $P(\Delta E_0)$, which is proportional to frequency f. The counting output $P(\Delta E_0)$ at Δt_s is expressed by

$$P(\Delta E_0) = \int_t^{t+\Delta t_s} f dt. \quad (5)$$

From this, we can calculate the degree of deterioration.

To emulate the deterioration process for a large activation energy, the counting output is raised to a higher (n-th) power by the digital multiplier and is stored in the accumulator. On condition that the temperature is almost constant in a short time Δt_s (this is true for a few seconds or minutes), we can consider that

$$P\left(\Delta E_0\right)^n = P\left(n\Delta E_0\right). \quad (6)$$

In this way, activation energy ΔE_0 can be increased to $n\Delta E_0$. The output of the accumulator at time $t1$ is

$$output = \left(\frac{I_{REF}}{2mC_L V_{dd}}\right)^n \int_0^{t1} \exp\left(-\frac{n\Delta E_0}{k_B T}\right) dt. \quad (7)$$

The output of the accumulator is an electrical analog of (1) with activation energy $n\Delta E_0$; therefore we can emulate the process of deterioration with large values of activation energy.

IV. Measurement Results

Figure 2 shows a chip micrograph of our sensor, designed with a 0.35 μm, 2-poly, 5-metal CMOS process. Chip area is 900 μm × 830 μm. Figure 3 shows the output waveforms of the CCO for four temperatures. The oscillation frequency is increased with temperature. Figure 4 shows the output of the multiplier as a function of time, with changing temperature. The dashed line shows a results for activation energy $\Delta E_0 =$ 0.2 eV, and the solid line shows a results for $\Delta E_0 = 0.4$ eV (produced by the multiplier with raising factor $n = 2$). Each output is normalized to the value at –20 ℃. The output of the multiplier (solid line) is raised to the second power. The integral of the output curve corresponds to the amount of the deterioration; therefore, from the output of the accumulator, we can determine whether perishables are fresh or not. By adjusting bias voltage $V_{G1} - V_{G2}$ and raising factor n, a wide range of activation energy can be achieved.

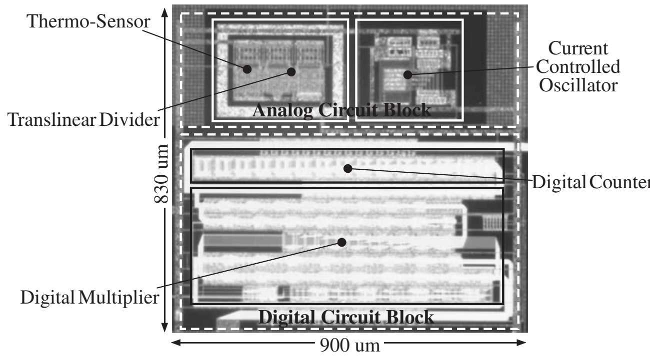

Fig. 2. Chip micrograph of a watchdog sensor.

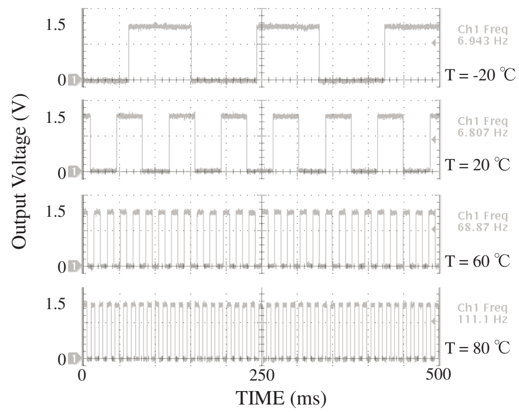

Fig. 3. Measurement result of a CCO waveforms at different temperature.

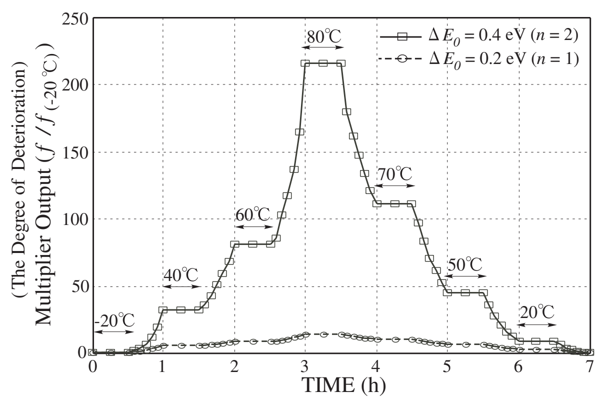

Fig. 4. Measurement result of a multiplier output.

V. Conclusion

We developed a CMOS watchdog sensor circuit for product-quality guarantees by making use of the subthreshold characteristics of MOSFETs. We fabricated a sample chip with a 0.35 μm CMOS process confirmed the device operation with measurement. By using a combination of analog and digital circuits, a wide range of activation energy can be achieved. This enables us to emulate the deterioration of most perishables such as farm, marine, and dairy products.

References

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