ISSN:1226-7244 (Print)
ISSN:2288-243X (Online)
논문번호 17-04-07

j.inst.Korean.electr.electron.eng.Vol.21,No.4,375~380,December 2017
http://dx.doi.org/10.7471/ikeee.2017.21.4.375

A Differential Current-to-Time Interval Converter Using Current-Tunable Schmitt Triggers

Won-Sup Chung*★

Abstract

A differential current-to-time interval converter is presented for current mode sensors. It consists of a ramp voltage generator, a current mode sensor, a reference current source, two current-tunable Schmitt triggers, a one-shot multivibrator, and two logic gates. The design principle is to apply a ramp voltage to each input of the two current-tunable Schmitt triggers whose threshold voltages are proportional to the drain current values of the current mode sensors. A proposed circuit converts a current change in the ISFET biosensor into its equivalent pulse width change. A prototype circuit built using TSMC 0.18 nm CMOS process exhibit a conversion sensitivity amounting to 726.9 μs/pH over pH variation range of 2-12 and a linearity error less than ±0.05 %.

Key words : differential current-to-time interval converter, current mode sensor, ISFET biosensor, current-tunable Schmitt trigger, operational transconductance amplifier

* Dept. of Semiconductor Engineering, Cheongju University
★ Corresponding author
E-mail:circuit@cju.ac.kr, Tel:+82-43-229-8462
※ Acknowledgment
This work was supported by the research grant of Cheongju University (2016. 03. 01-2018. 02. 28)
Circuit simulation tools were supported in part by IDEC in Korea.
Manuscript received Nov, 30, 2017; revised, Dec, 6, 2017 ; accepted, Dec, 20, 2017.

I. INTRODUCTION

The sensor represents the first and main element in measurement and control systems. All sensors may be of two kinds as reported in Table 1: passive and active [1]. Typical passive sensors are resistive bridge sensors. One of their signal processing circuits is reported in [2]. In order to apply the active sensors which directly produce an out current in a variety of applications dealing with chemical measurements as well as biomedical diagnoses, a precision read-out circuit connected to the sensor is indispensable. These sensor measurement circuits can be voltage or current mode of operation. Current-mode circuits can obviously provide some advantages over voltage-mode implementations when the analog signal to be processed comes in form of a current (e.g. the output current from a photodetector), since they can perform a straight conversion of the signal without needing current-voltage converters [3].

Table 1. Active and passive sensors and their typical electrical outputs

Main group	Type of sensor	Type of signal	Typical range
Active sensors	Thermopiles, pyroelectric, piezoelectric	Voltage	nV − mV
	pyroelectric, magnetic	Current	nA − mA
Passive sensors	Humidity, gas, pressure	Capacitance	fF − nf
	Piezoelectric	Charge	fC − pC
	Pressure, chemical, gas	Resistance	kΩ − GΩ

The current-mode method is a promising approach because of its easy current differencing operation, wide dynamic range, and lower power consumption. An analog read-out circuit by using the operational floating current conveyor (OFCC) as a current-mode device is reported in [4]. It has good linearity, but it needs the analog-to-digital (A/D) converter to acquire a digital output.

In this paper, we present a new current-to-time interval converter with good linearity. The output time interval is proportional to the differential current of current mode sensor and reference current. The converter circuit is a modified version of the circuit in [5], but its operation principle is different. The design principle of the converter is to apply a ramp voltage to each input of the two current-tunable Schmitt triggers whose threshold voltages are proportional to current values of the current mode sensors.

II. CIRCUIT DESCRIPTION AND OPERATION

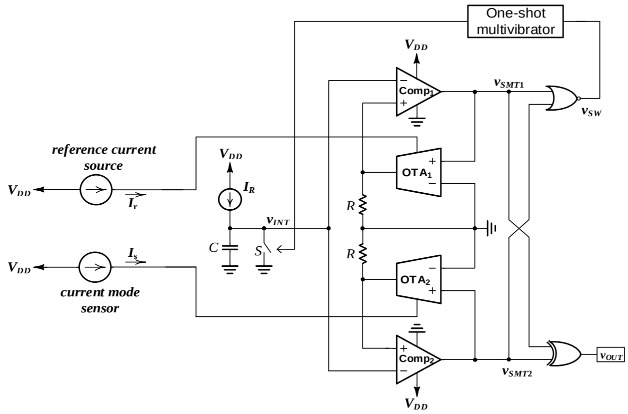

Fig. 1. Circuit diagram of the differential current-to-time interval converter for current mode sensors.

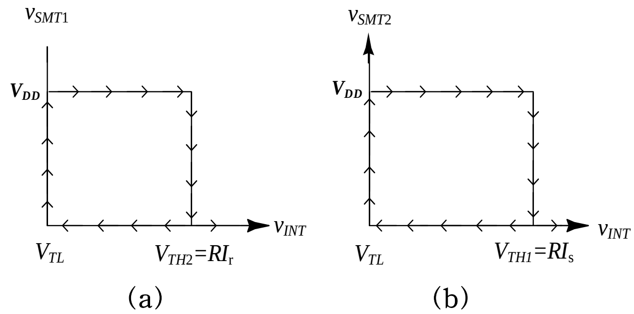

Fig. 2. Transfer characteristics of the current-tunable Schmitt triggers in the converter. (a) Upper current-tunable Schmitt trigger (b) Lower current-tunable Schmitt trigger

Fig. 1 shows the circuit diagram of the proposed differential current-to-time interval converter for current mode sensors. It consists of a current mode sensor, a reference current source, two current-tunable Schmitt triggers, a ramp voltage generator, a one-shot multivibrator, and two logic gates. The upper current-tunable Schmitt trigger is composed of a voltage comparator (Comp1), an operational transconductance amplifier (OTA1), and a resistor R. Similarly, the lower current-tunable Schmitt trigger is composed of Comp2, OTA2, and R. The transfer characteristics of the current-tunable Schmitt triggers are shown in Fig. 2. It is notable that the threshold voltages of the upper current-tunable Schmitt trigger are proportional to output current of the reference current source I_r, whereas the threshold voltages of the lower current-tunable Schmitt trigger are proportional to the output current of the current mode sensor I_s.

To see how the differential current-to-time interval converter operates, refer to Fig. 3, which shows the signal waveforms at the various nodes of the converter, and assume that both of the current-tunable Schmitt triggers are at their positive saturation levels V_{DD}. Prior to the start of the conversion cycle, the switch S connected in the ramp voltage generator is closed, thus discharging the timing capacitor C of the ramp voltage generator and setting the input voltage of the current-tunable Schmitt triggers v_{INT} to 0 V. The conversion cycle begins with opening the switch S. Since the reference current I_R flows through the capacitor, v_{INT} rises linearly with a slope of I_R/C. When v_{INT} reaches the high threshold voltage of the upper Schmitt trigger V_{TH1}, the output of the upper Schmitt trigger v_{SMT1} falls to zero and the output of the Exclusive OR gate v_{OUT} becomes high. Denoting t_1 the time duration for which v_{SMT1} keeps V_{DD}, we can write

$$t_1 = \frac{C}{I_R} V_{TH1} = \frac{C}{I_R} RI_r \tag{1}$$

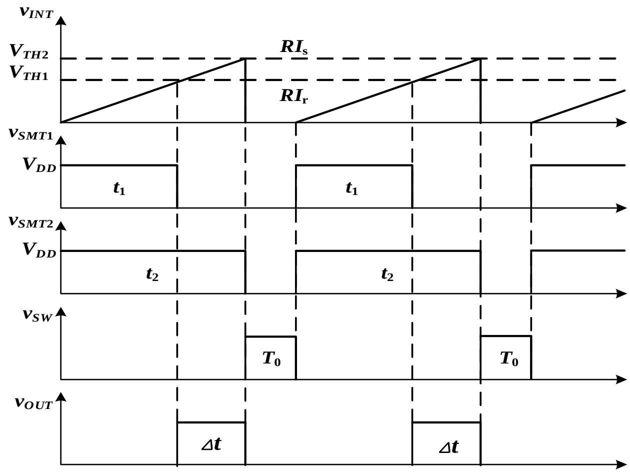

Fig. 3. Voltage waveforms at the various nodes of the converter.

The conversion process continues until v_{INT} reaches the high threshold voltage of the lower Schmitt trigger V_{TH2}. At this instant the output of the lower Schmitt trigger v_{SMT2} falls to zero, thereby v_{OUT} becomes low and the output of the NOR gate v_{SW} becomes high. The switch S in the ramp voltage generator is now closed and thus clamping the voltage v_{INT} to ground. This in turn triggers the Schmitt triggers, causing their outputs rise to V_{DD}, respectively, and v_{SW} go to low. The switch S is now opened after the fixed duration T_0 of the one-shot multivibrator and a new conversion process is started. Denoting t_2 the time duration for which v_{SMT2} keeps V_{DD}, we can write

$$t_2 = \frac{C}{I_R} V_{TH2} = \frac{C}{I_R} RI_s \tag{2}$$

The time interval of v_{OUT} pulse is given by

$$\Delta t = t_2 - t_1 \tag{3}$$

Combining (1) and (2) onto (3), one can obtain

$$\mathrm{D}t = \frac{C}{I_R}(RI_s - RI_r) = \frac{CR}{I_R}(I_s - I_r) \qquad (4)$$

Equation (4) indicates that the converter offers an equivalent output pulse whose time interval is proportional to the difference between the current mode sensors. It also indicates that the conversion sensitivity of converter can be controlled by the ratio of the dc current I_R and resistor R. The digital equivalent output can be obtained by counting the time interval with an external clock.

III. SLMULATION RESULTS

In order to test its applicability, the proposed converter is used to implement ISFET measurement circuits [6]. Fig. 4 shows the circuit diagram of the differential current-to-time interval converter for ISFET biosensor, where REFET is a passivated FET.

In order to the theoretical prediction of the proposed converter, we use Cadence for the simulation of the converter with TSMC 0.18 nm process. CMOS implementation of the OTAs is shown in Fig. 7. The aspect ratios (W/L) of the MOS transistors were taken as 20/1 for M_1 - M_6 and 40/1 for M_7 - M_{12}. CMOS implementation of the comparator is shown in Fig. 8. The aspect ratios of the MOS transistors were taken as 20/1 for M_1 - M_6 and 10/1 for M_7 - M_{10}. The supply voltages V_{DD} was 3.3 V. The resistor R was 20 kΩ. The ISFET and REFET has conversion sensitivity of 7.2 μA/pH and 1.7 μA/pH for pH, respectively [7].

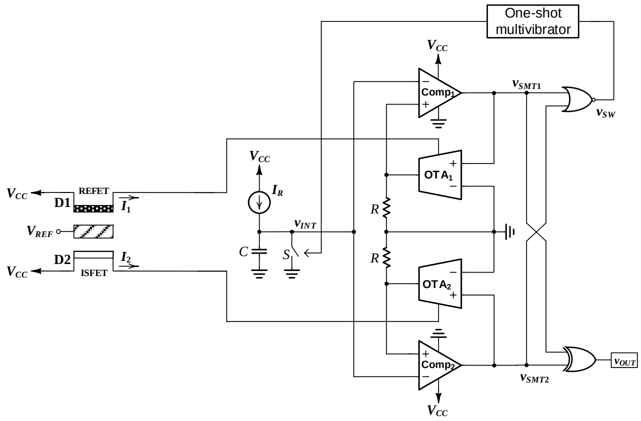

Fig. 4. Circuit diagram of the differential current-to-time converter for ISFET biosensor.

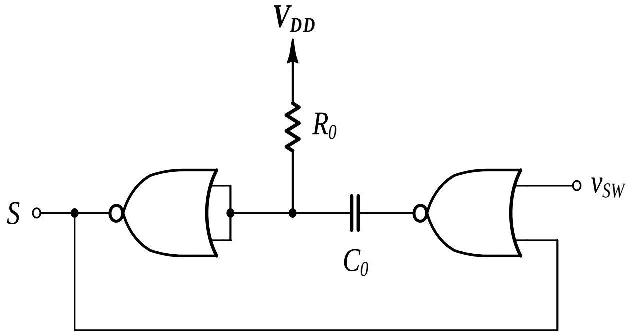

Fig. 5. Circuit diagram of the one-shot multivibrator.

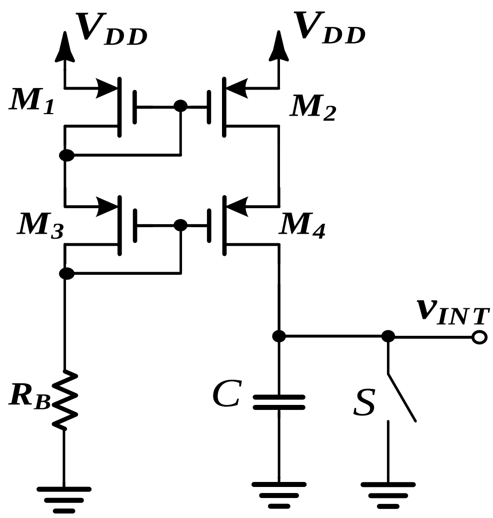

Fig. 6. Circuit diagram of the ramp voltage generator.

The one-shot multivibrator shown in Fig. 5 was constructed by using two NOR gates, a capacitor C_0 of 47 nF, and a resistor R_0 of 25 kΩ. The following component values were adopted for the ramp voltage generator shown in Fig. 6: C =100 nF and I_R = 15 μA. A Wilson current mirror and a resistor of 95.5 kΩ were used for producing the DC current source I_R.

The simulation results are shown in Fig. 9. It appears that the conversion sensitivity amounts to 726.9 μs/pH over the pH variation range of 2-12. The linearity error of the conversion characteristic is less than ±0.05 %.

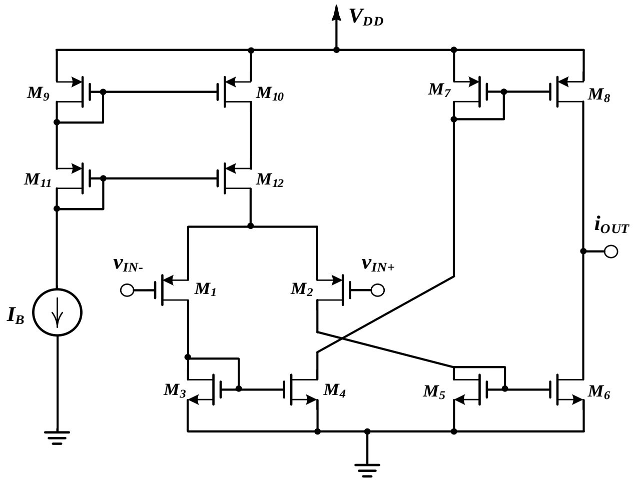

Fig. 7. CMOS implementation of the OTAs.

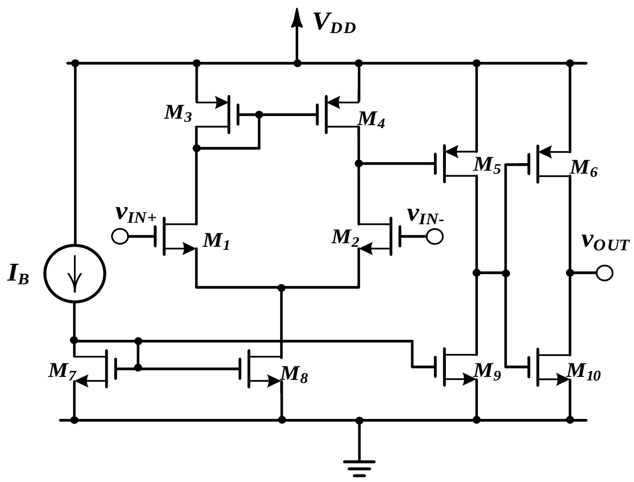

Fig. 8. CMOS implementation of the comparators.

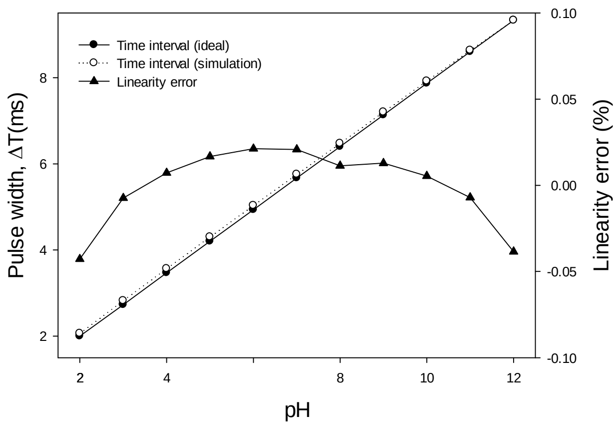

Fig. 9. Measured time interval versus pH characteristic of the differential current-to-time converter for ISFET biosensors and its linearity error.

Ⅳ. CONCLUSION

A new circuit converting a current change into its equivalent time interval change has been described. The converter features high sensitivity and good linearity. These properties together with its low power perform make the circuit suit for implementing the 'smart sensor' using the current mode sensors, which gives a digital output directly connectable to a microprocessor. The proposed converter is expected to find wide applications in signal processing of differential current sensors.

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BIOGRAPHY

Won-SupChung (Member)

1977 : BS degree in Electrical Communication Engineering, Hanyang University.
1979 : MS degree in Electrical Communication Engineering, Hanyang University
1986 : PhD degree in Electrical Science Engineering, Shizuoka University
From 1986 to Present : Professor in Department of Semiconductor Engineering, Cheongju University.