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CMOS Pulse-Width-Modulation Readout Circuit for ISFET-Based Sensors

Ruey-Lue Wang[1], Wei-De Wu[1], Chi Yu[1], Po-Hung Chiu[1], Jian-Liang Shi[1], Yi-Fan Hao[1], Hsin-Hao Liao[2], Hann-Huei Tsai[2] and Ying-Zong Juang[2]

[1] Department of Electronic Engineering, National Kaohsiung Normal University
No.62, Shenjhong Rd., Yanchao District, Kaohsiung City 824, Taiwan(R.O.C.)
Phone: +886-7-7172930ext7916 E-mail: rlwang@nknu.edu.tw
[2] National Chip Implementation Center, National Applied Research Laboratories
7F, Chimei Builiding, Tzu-Chiang Campus, No.1, Ta-Hsuch Rd., Tainan City 701, Taiwan(R.O.C.)

Abstract

A CMOS pulse-width-modulation readout circuit for sensors based on ion-sensitive field effect transistor (ISFET) is presented. The circuit consists of a voltage-to-current (V-I) converter, a charging and discharging module (CDM), a comparator module, a reference source module, and an output module. An input voltage, V_{sen}, is converted into a current I_{sen} by the V-I converter and then the I_{sen} is used to generate a single pulse through the CDM, the comparator module and the output module under the control of an added control signal generator. The pulse width linearly depends on the V_{sen} with a linearity of at least 99.996%. The integration of the readout circuit with an ISFET exhibits a measured transfer characteristic of pulse width versus pH value with a sensitivity of -31.6 μs/pH and a linearity of 99.35% after a charging time of 500 μs at 25 °C.

1. Introduction

For several decades, much attention has been paid to silicon-based biosensors in the biomedical applications. Ion-sensitive field effect transistors (ISFETs) are being developed for many applications in the fields of environmental and biomedical analyses [1-3]. The ISFET is a floating-gate MOSFET. Its gate oxide or an extra coated gate insulator such as Si_3N_4, Al_2O_3 is used as a sensing membrane for H^+ ions. The ISFET, traditionally referred to as a pH sensor, has been used to measure H^+-ion concentrations in a solution, causing an interface potential on the gate insulator. Under a bias voltage V_{ref} from an added reference electrode which is usually considered as the gate of the ISFET, the variation in the ion concentration is measured as a change in the threshold voltage [2] or a change in the effective floating-gate voltage [4]. To make the implementation of sensing membrane flexible, an extended metal electrode, on which a sensing film is coated, can be interconnected to the polysilicon gate of a standard MOSFET [4-5]. By using the topology, the sensing area will be not constrained by gate size and the ISFET is easily integrated with its readout circuit. In this paper, a pulse-width-modulation (PWM) readout circuit for ISFET-based biosensors has successfully been implemented by the TSMC 0.35μm process. The supply voltage is 3V. The circuit simulation was done by using a software tool called HSPICE.

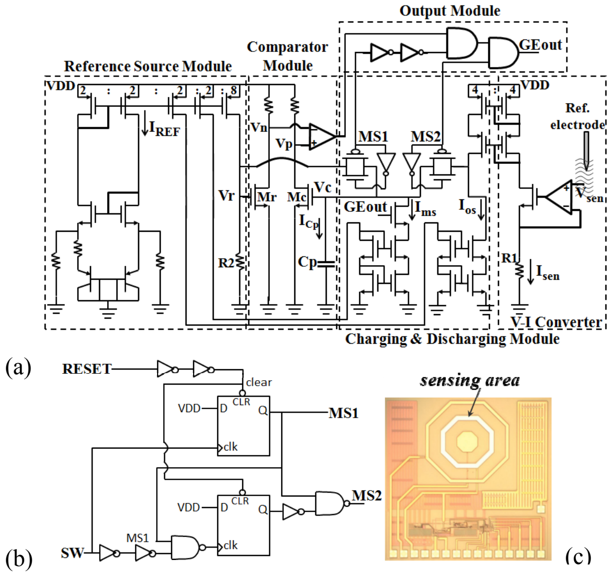

Fig. 1 (a) The circuit schematic, (b) control signal generator, and (c) chip photograph of the readout circuit

2. Circuit Design and Measurement Results

Fig.1 shows the circuit schematic, the control signal generator, and the chip photograph of the readout circuit. The circuit consists of a voltage-to-current (V-I) converter, a charging and discharging module (CDM), a comparator module, a reference source module, and an output module. An input voltage, V_{sen}, is converted into a current I_{sen} (=V_{sen} /R1) by the V-I converter and then the I_{sen} is used to generate a single pulse through the CDM, the comparator module and the output module. The reference source module is based on a bandgap reference current source and produces the reference voltage Vr of the comparator, the discharging current I_{ms}, and the offset current I_{os}. With two signals RESET and SW, the control signal generator produces two control signals MS1 and MS2 to control transmission-gate switches of charging and discharging the capacitor Cp. The two control signals also enable the output of the single pulse in the output module. In the operational amplifier of the V-I converter, the gate of the positive-input transistor is interconnected to an extended octagonal-ring top aluminum (Al) metal on which the native alumina (Al_2O_3) is used as a sensing membrane, as shown in Fig. 2. The inner and outer diameters of the sensing area are 400 and 454 μm, respectively. Post-processing deposited gold on the outer octagonal-ring and inner octagonal metal of the sensing area can be used as on-chip reference electrodes in the future. In this work, an external Ag/AgCl reference electrode is used to bias the ISFET. The effective floating-gate voltage decreases with the increase of pH value of the solution [4].

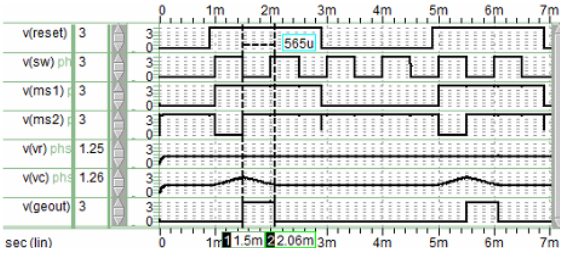

Fig. 2 Simulated voltage waveforms of the readout circuit under the V_{sen}=1.05V.

Fig. 2 shows the simulated signal waveforms under the V_{sen}=1.05 V with an SW of 1 kHz and an RESET of 250 Hz. The circuit operates under a fixed charging time and a fixed discharging current. The signal Vr is designed to be 1.25 V and is compared with the voltage drop Vc across the capacitor Cp in order to generate a single pulse. When the RESET is at the "0" level, the signal MS1 is cleared and the signal MS2 is preset. At the same time, the output signal V_{GEout} at the GEout is also cleared. When the RESET is at the "1" level, the waveform patterns of the signals MS1 and MS2 are produced with the SW waveform, as shown in Fig. 2. When the signals MS1 and MS2 are at the "1" and "0" levels, respectively, the Cp is charged by the current I_{Cp}=I_{sen}−I_{os}. The I_{os} is used to reduce the offset of the pulse width within the detected V_{sen} voltage range. When the signal MS2 goes from low level to high level, the V_{GEout} also goes form low level to high level and hence the Cp is discharged by the current I_{ms}. When the voltage Vc goes below the referred Vr, the discharging of the Cp stops and the V_{GEout} goes from high level to low level immediately. By this procedure, a single pulse, which pulse width is linearly proportional to the V_{sen}, is generated at the GEout. If the RESET is a continuous pulse, as shown in Fig. 2, a continuous pulse which high-level width is modulated by the V_{sen} is generated at the GEout.

Fig. 3 shows the simulated and measured transfer characteristics of pulse width versus input voltage V_{sen} under the control of the SW signals of 1 and 2 kHz, respectively, at 25 °C. The linear operation ranges of input voltage V_{sen} are about from 0.5 to 1.1 V and from 0.35 to 0.95 V respectively for the simulation and measurement data. The linearity is at least 99.996%. The upper limit of the V_{sen} originates from the limit of the input common-mode voltage or the device-size induced current limit of transistors in the V-I convertor. The simulated and measured sensitivities are very approximate. The sensitivities are about 1 and 0.5 μs/mV under the SW signals of 1 and 2 kHz, respectively. The measured pulse widths are slightly larger than the simulated ones probably owing to process-variation induced biasing-current drift, resistance drift, or variations of other device parameters. Fig. 4 shows the measured transfer characteristic of pulse width versus pH value in a phosphate buffered saline (PBS) solution under the V_{ref} of 0.8 V from an external Ag/AgCl reference electrode. The sensitivity and linearity are -31 μs/pH and 99.35%, respectively, under the SW signal of 1 kHz. The larger sensing area will enhance the sensitivity.

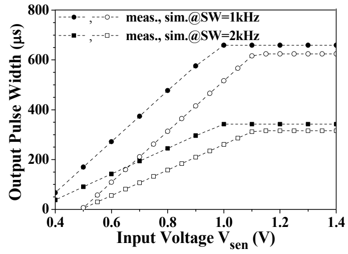

Fig. 3 Simulated and measured transfer characteristics of pulse width versus input voltage under the control of the SW signals of 1 and 2 kHz, respectively, at 25 °C.

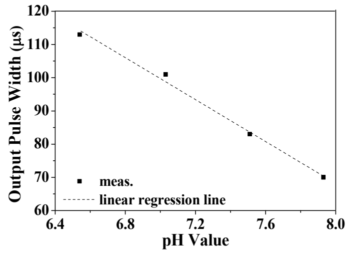

Fig. 4 Measured transfer characteristic of pulse width versus pH value under the V_{ref} of 0.8 V.

3. Conclusions

A CMOS PWM readout circuit for ISFET-based biosensors has successfully been designed and fabricated. The readout circuit itself occupies a chip area of about 2×0.55 mm^2 and the current consumption is about 1 mA. The output pulse width linearly depends on the V_{sen}. If the discharging current comes from a multi-channel scaled current mirror, the resolution and sensitivity of the readout circuit will be more flexible. The thinner native Al_2O_3 can be applied to test the solution with pH value ranging from 6 to 8 at least, but the pH-ISFET is still suitable for humans because the normal pH values are about 7.34~7.45 and 6.35~6.85 for human blood and saliva, respectively.

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