A LOW-COST SINGLE-CHIP READOUT CIRCUIT FOR PH SENSING

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Key words: ROIC, ISFET sensor, sensor interfacing circuit, single-chip sensor solution

Abstract: A readout interface circuit for ISFET-based pH sensor with temperature compensation is described. The ROIC, together with our in-house developed enhancement-type ISFET could lead to single-chip pH sensor solution, leading to low cost sensor for precision agri- and aqua-culture. Temperature coefficient (TCF) cancellation technique has resulted in ISFET temperature dependency of being a negligible 0.2mV/^{O}C over a temperature range of 0^{O}C to 65^{O}C - close to ideal case of 0 mV/^{O}C. Preliminary results of sub-blocks that were fabricated in earlier runs indicate close resemblance of test results to the simulated results hence the conclusion that the silicon is functioning properly.

Nizkocenovno vezje na čipu za odčitavanje pH vrednosti

Kjučne besede: ROIC, ISFET senzor, senzorsko vmesno vezje, senzor na enem čipu

Izvleček: V prispevku opišemo vmesno čitalno vezje (ROIC) za pH senzor na osnovi tranzistorja ISFET. Vezje ROIC skupaj z ISFET tranzistorjem lahko pripelje do cenene izvedbe pH senzorja na enem čipu, primernega za široko uporabo. Temperaturna odvisnost tranzistorja je zanemarljivih 0,2 mV/°C v temperaturnem območju 0°C do 65°C, zahvaljujoč tehniki ničenja temperaturnega koeficienta, TCF. Preliminarne meritve na izdelanih blokih kažejo na dobro ujemanje s simuliranimi rezultati.

1. Introduction

Advancement in the microelectronics and semiconductor technology has led to various research and development activities in the field of sensor and electronics interfacing. One such area is FET-based pH sensor development, or also known as Ion-Sensitive Field Effect Transistor (ISFET) development. Slight modification of a field effect transistor by replacing certain layers with pH sensitive materials such as silicon nitride, aluminum and tantalum has resulted in a miniaturized FET-based pH sensors (ion-sensitive field-effect transistor, ISFET)/1/. This also promises the possibility of lab-on-a-chip solution, i.e. integration of sensor and the electronics on the same silicon. The end product is targeted to be low cost and suitable for field deployment.

An ISFET sensor is cheap and has good sensitivity characteristics. These features, coupled with the fact that it is silicon-based, have made these sensors as one of the main candidate for single-chip implementation. On top of the positive sides of ISFET pH sensor, among the problems faced in ISFET pH sensor development is reproducibility, stability, drift and temperature dependency /2/. Improvements made in each of the problems will, thus, make the use of ISFET sensor more appealing.

Analog readout interface circuit (ROIC) plays an important role in acquiring and processing the signal produced by ISFET sensor and passing it to a data converter for further signal processing. Many research works in the area of ISFET ROIC design have been reported in open literature /3/-/5/. Some of the approaches used as part of the sensing mechanisms are bridge type technique /3/, complementary ISFET-MOSFET pair technique /4/ and Constant-Voltage-Constant-Current (CVCC) technique /5/. CVCC technique has the advantage in terms of robustness and suitability for precision agriculture application.

In view of precision agriculture application where the sensors are placed in a field for a long period, with periodic data collection time at a center, temperature effects and drifting are some of the issues that need to be handled by the ROIC circuit properly. This means, a need for temperature sensing and cancelling the effects either at the ROIC stage or at the DSP stage for a true pH reading. The latter could be expensive in terms of processing power, leading to the solution not being suitable for field deployment where power is a concern. To do correction due to temperature effects at the ROIC stage, work in /5/, although using CVCC technique but it uses resistor temperature sensor. Resistor temperature sensor is resistive-based, hence producing thermal noise. Due to very low signal being read from the sensor, the thermal noise generated might hinder a single-chip solution hence could potentially increase the cost of the sensor solution. Our work solves this problem through the use of parasitics bipolar transistor to sense

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the temperature. /4/ cancels out the temperature effect by using complementary ISFET-MOSFET pair technique.

In this work, CVCC technique is implemented for sensing a signal from sensor due to its robustness. Parasitic bipolar is used as a temperature sensing element to correct the actual pH reading (a temperature-independent pH measurement). This also solves the problem faced by /5/, hence making it suitable for single-chip implementation.

This paper is divided into four sections. Section 2 briefly describes the ISFET pH sensor. The proposed readout interface circuit with temperature coefficient cancellation method is presented in section 3. The SPICE simulation results of readout interface circuit with and without temperature compensation are presented in section 4. Finally, the conclusions are summarized in section 5.

2. Isfet Device

A basic cross-section of an ISFET structure is shown in Fig. 1. It is similar to the conventional MOSFET device, except for the standard metal gate which is replaced by a reference electrode and an electrolyte /1/. In base or acidity (pH) sensor, a sensing membrane sensitive to hydrogen ion concentration such as Si_3Ni_4, Al_2O_3 and Ta_2O_5 is used as gate insulator /3,4,5/. A change of pH or hydrogen ion concentration in an electrolyte induces a change in the electric field in the insulator-semiconductor interface and hence changing ISFET threshold voltage (V_T). Thus, different levels of pH can be represented by the drain currents (I_{DS}) of an ISFET device.

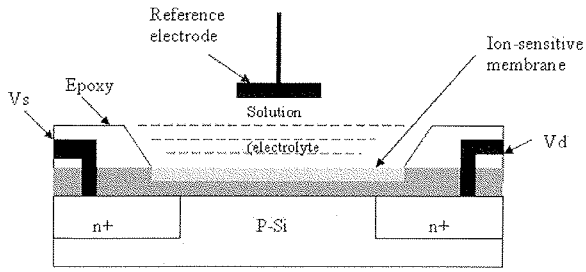

Fig. 1. Basic cross-section of Ion Sensitive Field Effect Transistor (ISFET)

To investigate the characteristic of ISFET, an established behavioral macro-model from previous publication is used in the design simulation. The model was firstly introduced by Sergio Martinoia and Guiseppe Massobrio in 1999 /6/ . It is based on a modified SPICE MOS transistor model in which the threshold voltage is influenced by the gate surface potential induced by hydrogen ions present in electrolyte flowing over the gate structure. It is suitable for the simulations of the device operating in a relatively wide range of temperature and hydrogen ion concentration.

3. pH Sensor interfacing circuit

The proposed ROIC for ISFET pH sensor with temperature compensation consists of three componets: a parasitic bipolar vertical pnp temperature sensor, constant-voltage-constant-current (CVCC) circuit and a summing circuit (Fig. 2). The principle of this readout circuit is to cancel the positive temperature coefficient (+ve TCF) of ISFET with the negative temperature coefficient (-veTCF) of parasitic bipolar vertical pnp device. Temperature coefficient of both devices can be combined through a summation circuit. As a result, a temperature-dependent characteristic of an ISFET is improved compared to the solution proposed by /5/. A non-temperature independent solution such as the one by /5/ is not suitable for deployment in an uncontrolled environment such as agriculture.

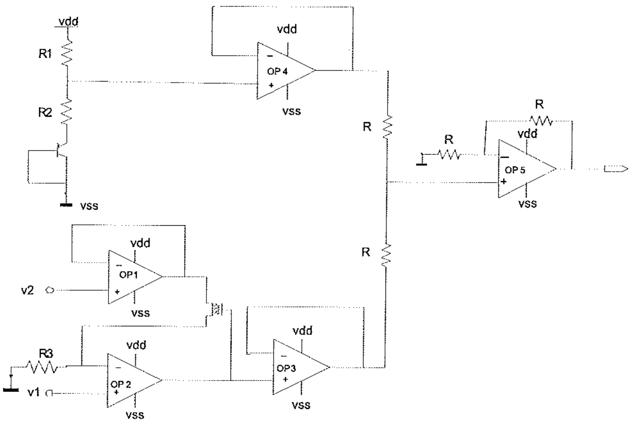

Fig. 2. Readout circuitry with temperature compensation

3.1 Constant Voltage Constant Current (CVCC) Circuit

In order to ensure the ISFET device operates in linear region at fixed VDS, a CVCC circuit is implemented. The schematic of this circuit is shown in Fig. 3.

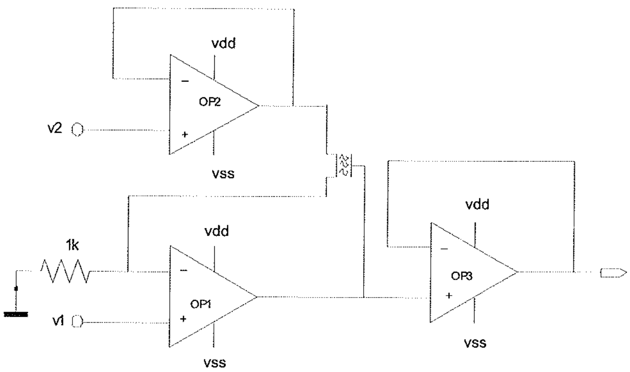

Fig. 3. Constant voltage constant current (CVCC) circuit

It consists of three operational amplifiers OP1, OP2 and OP3. OP1 is connected to the source of ISFET while OP2 is connected to the drain and provides a feedback to the ISFET gate. The gate voltage serves as an output signal in response to electrolyte solutions. In addition the feedback gate voltage, which is connected to a reference electrode will establish a stable electrolyte potential with respect to the surface potential of ISFET sensing gate. The varying of the gate voltage will restore the drain current as electrolyte parameters are changed. Another amplifier, OP3, serves as an output buffer.

3.2 Vertical PNP Temperature Sensor

In order to develop temperature sensor using CMOS compatible process with no required additional mask, a parasitic bipolar pnp device is employed. The circuit configuration of a bipolar pnp temperature sensor is shown in Fig. 4(a). Fig 4(b) shows the layout structure of bipolar vertical pnp. Area used for the emitter is 100µm2. Generally, the base-emitter voltage of parasitic bipolar pnp provides a negative temperature coefficient. By adding and controlling the value of the two resistors (R1 and R2) that are connected to the parasitic bipolar pnp, the temperature coefficient of the temperature sensor can be tuned closely to the negative of the ISFET temperature coefficient.

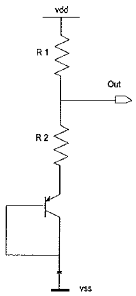

Fig. 4(a) Schematic of bipolar temperature sensor.

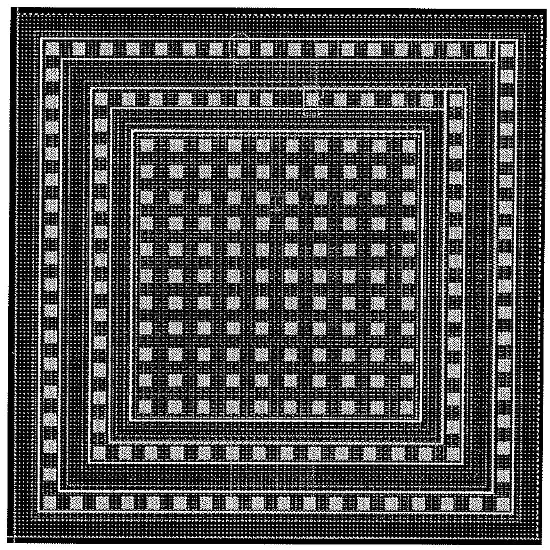

Fig. 4(b) Layout of bipolar vertical pnp device. © 2008 MIMOS Berhad

3.3 Summation Circuit

A summation circuit consists of a simple amplifier with several resistors. Fig. 5 illustrates the circuit configuration of the summation circuit employed in this work. This summation circuit is used to combine the output of ISFET and bipolar pnp temperature sensor. The positive temperature coefficient (+TCF) of ISFET is cancelled by adding to negative temperature coefficient (-TCF) of pnp temperature sensor.

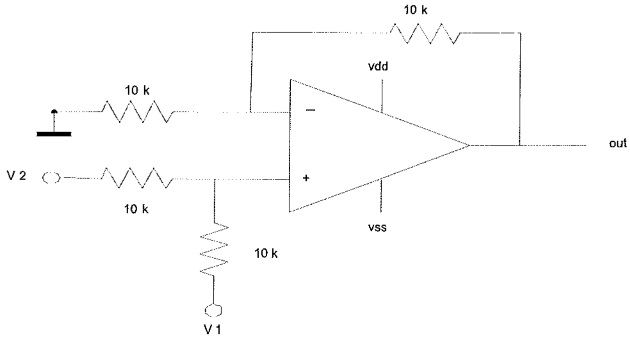

Fig. 5. Circuit schematic of summation circuit.

4. Results

In this work, the ROIC is simulated and fabricated using MIMOS 0.35µm process technology. Fig. 6 shows measured data for the ROIC. The average sensitivity is 50.16 mV/pH, showing adherence to the specification which is from 50 to 55 mV/pH. Fig. 7 shows measured output voltage for 3 different pH values, confirming the functionality of the ROICs. Fig. 8 shows test setup for the ROIC. Values for R1 and R2 are set to bias the ISFET's Vds to 0.5V. Fig. 9 and Fig. 10 show the simulation result of the output voltage signal from the ISFET and temperature sensor, respectively. This result is obtained for the temperature range of 0^{O}C to 65^{O}C. The simulated temperature coefficient (TCF) for ISFET is +1.420mV/^{O}C. Meanwhile the designed temperature sensor gives temperature coefficient (TCF) of -1.418mV/^{O}C.

The readout circuitry is completed by feeding both the temperature sensor and ISFET output voltages with different gains into a summing circuit that mutually offset their temperature coefficient and produce a temperature independent output signal. To validate the improvements of the proposed compensation method, the output voltage signal with and without compensation is shown in Fig. 11 and Fig. 12 respectively. For pH 4, 7 and 10, the corresponding temperature coefficient (TCF) before compensation in 0^{O}C to 65^{O}C ranges is 1.42mV/^{O}C. On the contrary, temperature coefficient (TCF) with compensation has a near zero slope (temperature independent) curves. Thus, the temperature sensitivity compensation method presents a more accurate pH measurement.

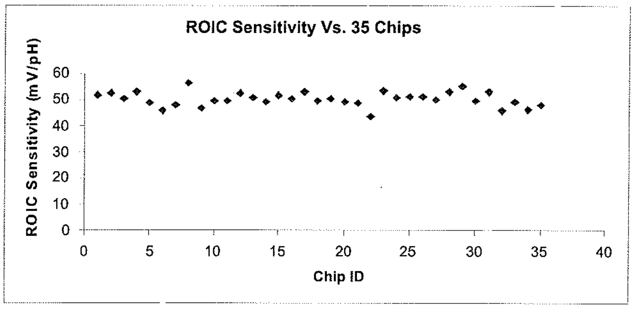

Fig. 6. Measured ROIC's sensitivity. © 2008 MIMOS Berhad

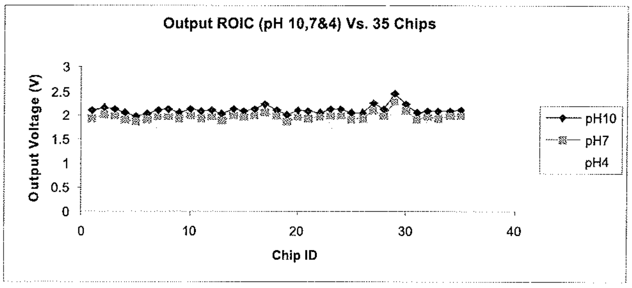

Fig. 7. Measured of ROIC's output voltage for three pH values. © 2008 MIMOS Berhad

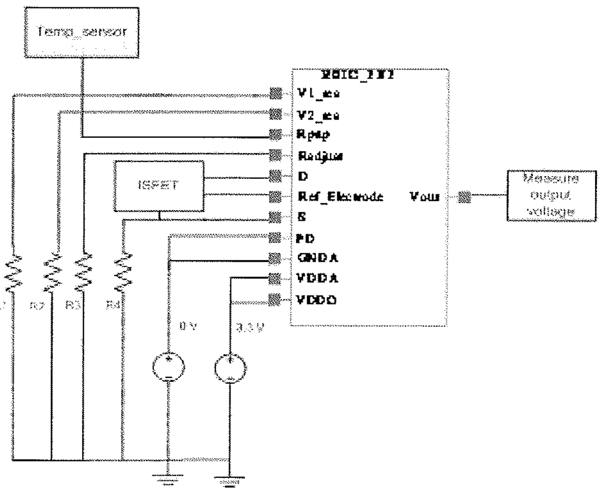

Fig. 8. Test setup for the ROIC. © 2008 MIMOS Berhad

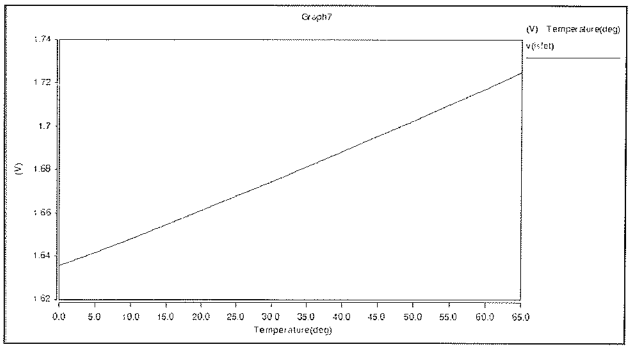

Fig. 9. Simulated temperature coefficient (TCF) for ISFET using CVCC configuration. © 2008 MIMOS Berhad

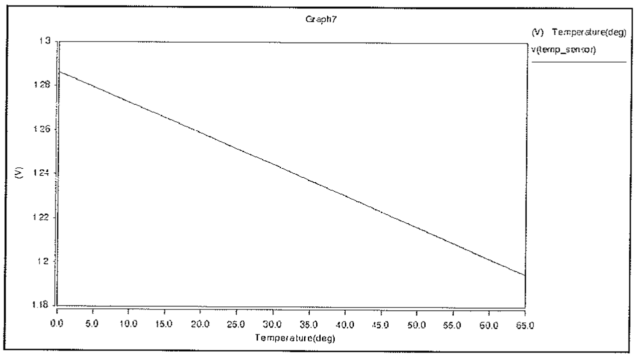

Fig. 10. Simulated temperature coefficient (TCF) for temperature sensor. © 2008 MIMOS Berhad

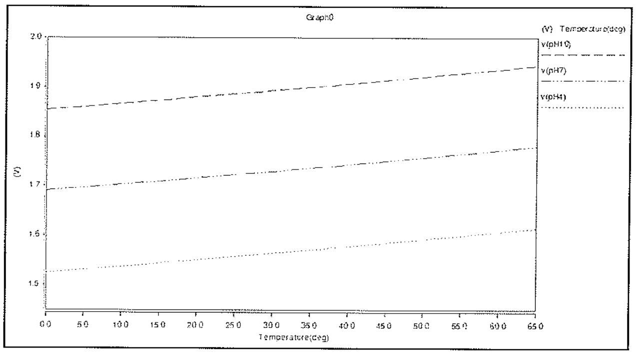

Fig. 11. Output signal voltage of readout circuit without temperature compensation. © 2008 MIMOS Berhad

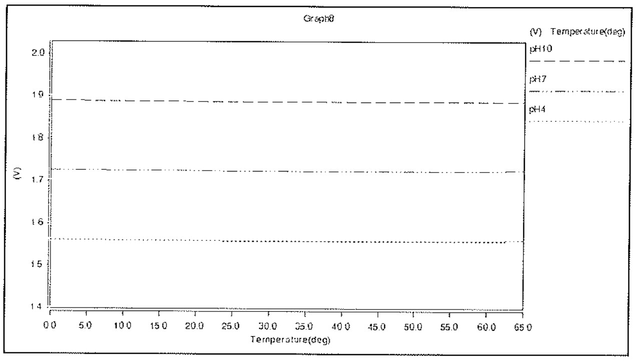

Fig. 12. Output signal voltage of ROIC with temperature compensation. © 2008 MIMOS Berhad

5. Conclusion

A readout circuitry for ISFET based sensor with temperature compensation has been developed and presented. Using temperature coefficient (TCF) cancellation technique, the ISFET temperature dependence is improved from 1.42mV/^{O}C to less than 0.2mV/^{O}C over a temperature range of 0^{O}C to 65^{O}C. The design has been targeted to MIMOS 0.35μm CMOS technology and has been fabricated as shown in Fig 13. Preliminary results of indicated close resemblance of test results to the simulated results hence we can safely conclude that the silicon is functioning properly and meeting all the specifications. The circuit, single-chip sensor solutions and the precision agriculture sensor solutions have been filed for patent under patent file: PI 20072136.

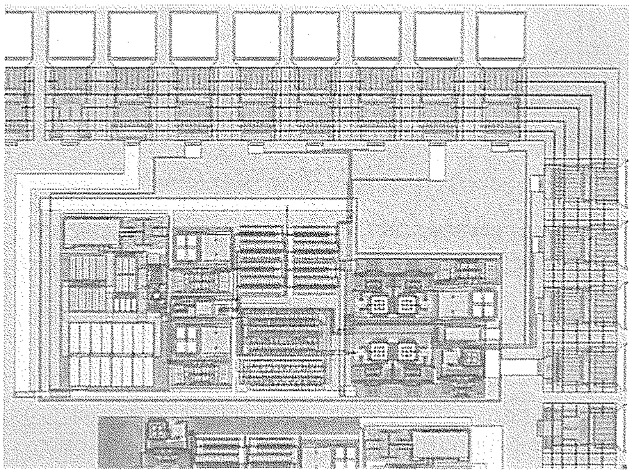

Fig. 13. ROIC on wafer. © 2008 MIMOS Berhad

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