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Characterization of an ISFET with Built-in Calibration Registers through Segmented Eight-Bit Binary Search in Three-Point Algorithm Using FPGA †

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Abstract: Sensors play the most important role in observing changes in an environment they are a part. They detect even the smallest changes and send the information to other electronic devices. Making sure that these sensors provide an accurate output is equally crucial, as the data it measures and collects are used for analysis. Until now, calibrating sensors has been done manually by following a sequence of procedures, and is usually performed on-site or in a laboratory prior to deployment. To eliminate the manual procedure in the calibration (at the very least), an ion-sensitive field-effect transistor (ISFET) with a built-in calibration registers circuit was created through segmented eight-bit binary search in a three-point algorithm using a field-programmable gate array (FPGA). The circuit was created using a three-point calibration algorithm and three standard buffers (pH 4, pH 7, and pH 10). The block diagram, schematic diagram, and the number of logic gates were derived after synthesizing the Verilog program in Xilinx/FPGA. An average of 0.30% error was computed to prove the reliability of the created circuit using FPGA. Having an ISFET with built-in calibration registers will alleviate the work of experts in performing calibrations. This would follow the plug and play standard, hence its being a calibration-ready ISFET device. With this feature, it could be used as a pH level meter or a remote sensor node in several applications.

Keywords: ISFET; ion sensitive field-effect transistor; calibration; segmented; binary search; pH level; FPGA; three-point algorithm; Verilog

1. Introduction

An electrochemical sensor, such as an ion-sensitive field-effect transistor (henceforth ISFET), plays an important role in the industry. Its broad application in environmental, agricultural, aquaculture, biomedical, pharmaceutical, food, and other industries makes it in demand and popular [1–6]. The ISFET is normally used for data acquisition and monitoring the potential of hydrogen (pH) levels [2,3,6–8]. Characteristics of pH sensors vary in time because of the changes in its electrodes [7,8]. Changes in the performance of the electrodes might affect the accuracy of its measurements [3]. Monitoring of the pH level is necessary to avoid further chemical reactions in a substance [2,6,9]. An estimated time drift of -1 ± 0.5 mV/h and temperature drift of -0.9 ± 0.5 mV/°C are some of an ISFET's downsides [2]. Hysteresis occurs when the previous output will be reconsidered to produce the desired output, which then affects the accuracy of the ISFET's pH measurement [2]. Trapped charges are in the oxide or nitride layer of an ISFET, which affects the threshold voltage and causes change in the sensor's sensitivity. ISFET devices have different sensitivities and linearity, which can be attributed to different sensing membranes and trapped charges. Through calibration, the sensitivity of the ISFET will be maintained; hence, the measurements will be accurate and reliable [3]. One way to minimize errors due to non-linearity is by using multiple calibration points such as the three-point calibration [10,11].

The calibration of an ISFET is done manually and where it is deployed. In such cases, an expert may be needed and a sequence of procedures should be followed [1]. The procedure of calibrating an ISFET includes the measurement of a known solution and of an unknown one [3,9]. The pH's equivalent voltage of a measured known solution is saved in the memory registers inside the system for reference during calibration [1,9]. Having an ISFET with built-in calibration registers will alleviate the work of experts in performing calibrations. This would follow the plug-and-play standard, hence its being a calibration-ready ISFET device. With this feature, it could be used as a pH level meter or a remote sensor node in several applications.

It may also lessen the power consumption of the system because the registers are already included in the sensor itself. With built-in registers in a sensor, the logic gates and the design will be simplified; thus, the area occupied by the circuit may also be reduced. In a segmented three-point calibration, the three standard buffers pH 4, pH 7, and pH 10 were utilized. One-point calibration is ideal; however, three-point calibration will result in better sensor modeling, especially for those with non-linear characteristics [10,11].

2. Background, Related Literature and Studies

2.1. Ion-Sensitive Field-Effect Transistor (ISFET)

The ISFET is a modification of a metal–oxide–semiconductor field-effect transistor (MOSFET). The polysilicon in the MOSFET has been removed from the metal gate to become hydrogen ion-sensitive [9,12]. It has been put on top of the gate dielectric to extend the sensitivity to any different ions, which is directly connected to a solution or substance [9,12]. Low power consumption, low cost, robustness, rapid response time, smaller size, on-chip integration, and sensitivity are some of its features [1,8,9,13]. From then on, the ISFET became highly favored and was used as a chemical sensor in several different applications throughout the industry. It has been used in environmental, biochemical, aquaculture, biomedical, and food industries, to name a few, for data acquisition and pH level monitoring [1–3,6]. Figure 1 [12] illustrates the difference between the MOSFET and ISFET.

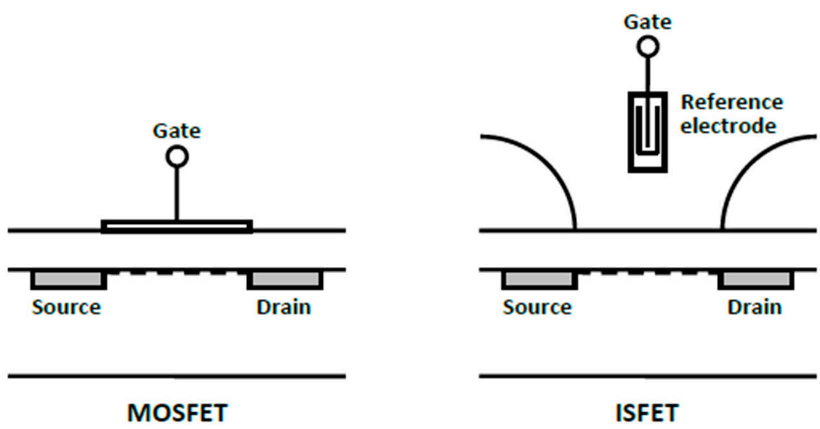

Figure 1. Difference between metal–oxide–semiconductor field-effect transistor (MOSFET) and ion-sensitive field-effect transistor (ISFET).

As expected, this sensor was not perfect, as it had several drawbacks [1,2,6,8,14]. Several studies have been conducted to improve the performance of the ISFET. These studies included time drift, temperature drift, hysteresis, and calibration of the ISFET [1,2,6,8,14]. For example, [13] designed an instrumentation system, electronic conditioning [14], and a compensation method. After all the experiments and following their created protocols, they argued that their proposed solution overcomes all the drawbacks related to long-term drift, hysteresis, and thermal drift of the ISFET. The only limitation they faced was the drain-to-source maximum voltage value of the ISFET, as this is determined by the sensor and its technological fabrication process [14].

Another study by [1] addressed the problem of temperature and thermal drifts. Temperature is one of the factors that affect the sensitivity of the sensor; thus, it gives the possibility of an inaccurate measurement. Even a slight variation in the temperature could produce a reliable output, and can make the response time quick, or the other way around. In their first research, they used a V_T (threshold voltage) extractor as temperature sensor and a discrete temperature compensation chip was successfully fabricated to improve the ISFET's thermal drift. The conclusion was that the V_T extractor and the temperature compensation chip were effective solutions, because the ISFET demonstrated a more accurate pH measurement [1].

2.2. pH Level

The hydrogen potential of a substance is crucial, as it is used to measure the acidity of a substance. If it is not maintained, the pH of a substance may lead to changes in its chemical property and unwanted chemical reactions. One of the reasons why the pH should be neutral and monitored is that it could bring either safety or danger to every human. Most things around humans are H_2O-based. If the pH of the H_2O is below normal, it means acidity and toxin content are very high, which is extremely dangerous. Likewise, if the pH is greater than normal, it becomes basic or *alkaline*, which is likewise not safe for continuous consumption [15–17].

The ISFET is normally used to measure pH or serves as a pH meter. One such study aimed at minimizing the toxicity of high-dose methotrexate (MTX) therapy. Nurses used either a dipstick or a pH meter to monitor the pH of the urine of a patient undergoing therapy. The results between the dipstick and pH meter were different, which suggests that pH meters—whatever the make is—do not produce the same results. The clinical cut-off for the urine pH should be pH 8.0, but after several experiments and sampling, the result using the dipstick was less than pH 8.0. However, when a pH meter was used, the result was greater than pH 8.0 [18].

Another study was done on the implementation of the pH meter for monitoring purposes, as part of wireless sensor networks for aquaculture [5]. Aquaculture demands effective management, because it is one of the fastest growing sources of food. There are many factors that can affect the pH of the H_2O—many of which are uncontrollable. Environmental conditions, such as changes in climate, natural phenomena, human activities, and even the produce that live in the aquaculture, can directly affect the water. A PH 400/450 series pH value sensor whose range is from pH 2 to pH 16, was chosen because of its accuracy in measuring the pH level, its advancement in the temperature compensation feature, and its minimum requirement for maintenance. Using two smart sensor nodes, gateway, and the generated software, the research successfully designed, implemented, and argued for the need for a pH meter like the ISFET [5]. It can work and can be applied in wireless sensor networks (*wsn*) for data acquisition and monitoring for several applications [4,5].

2.3. Calibration

A sequence of procedures must be followed and should always be done in any environment to come up with correct and accurate results [1,2]. Many factors affect the sensitivity of any type of sensor (e.g., an ISFET), such as the temperature, how it is manufactured and fabricated, the make, and sometimes the solution itself that needs to be measured [1,3,6,8,9,14]. Through calibration, these kinds of variations will be addressed and compensated [2,3].

There are several approaches to implementing calibration. One is the use of the two-point calibration, which utilizes the two standard buffers pH 4 and pH 7. A research application specific integrated circuit (ASIC) for ISFET by [1] compared various pH meters and determined the difference between the measured and calculated values using the two-point calibration algorithm. Table 1 shows the tabulation of the comparison and their research results. They calculated for the error ΔpH, the percent error between the standard, measured, and the calculated pH. Their research found that a lower pH value variation of −0.0023 pH/°C was produced [1].

Table 1. Comparison of pH using various pH meters.

Target Buffer Solution (25 °C)	Radiometer PHM290 (2-Point Cal)		Sentron Argus (2-Point Cal)		The Proposed ASIC (2-Point Cal)	
	Measured pH	**Error ΔpH**	**Measured pH**	**Error ΔpH**	**Measured pH**	**Error ΔpH**
pH 2.00	1.94	−0.06	1.89	−0.11	2.03	0.03
pH 4.00	3.96	−0.04	3.98	−0.02	4.04	0.04
pH 6.00	6.01	0.01	5.99	−0.01	5.99	−0.01
pH 8.00	7.91	−0.09	7.93	−0.07	7.89	−0.11
pH 10.00	9.77	−0.23	9.81	−0.19	9.76	−0.24
pH 12.00	11.73	−0.27	11.93	−0.07	11.87	−0.13

A signal processing application specific integrated circuit (ASIC) for ISFET-based chemical sensors.

Calibrating the ISFET—especially if it is applied in an array—is important according to [7]. This importance is due to some of its drawbacks. They proposed, designed, and tested an automatic calibration system for ISFET chemical sensing arrays. They found that the system has compensated the deviation in the performance of the ISFET in a large array. The system was able to tune out the entire mismatch in the ISFET's sensitivity and compensated the deviation by 24%, constraining the error to 1.5% [7]. Therefore, calibration is a norm, resulting in accuracy of the output [1–3].

2.4. Two-Point Calibration Algorithm (Bi-Section Method)

One of the techniques used in finding the root of a function or a number is a two-point calibration algorithm. Two values are used to serve as an interval. If the root is not found in the interval, a midpoint will be computed. The midpoint is computed by adding the interval and dividing it by two. Iteration will continue as needed until the root of a function or a number is found [1,2].

The research by [1] used the binary search method in their signal processing ASIC-based sensor system. Figure 2 illustrates the two-point calibration algorithm [2]. In MEASURE, if the RESET is *HI*, voltage unknown will be processed; otherwise, the calibration will end. In CALIBRATION, if the RESET is *LO*, CALIB_MODE parameters one to two will be tested and the process will end. In 2PT_ALGO, if the STATE value is *IDLE* and the START signal is set to *HI*, the voltages of the two standard buffers will be saved into the registers. If the STATE value is *CHECK*, a two-point calibration algorithm is performed. The standard buffers pH 4 and pH 7 were used as the interval. If the root is not found in the interval, a midpoint will be computed. The midpoint is computed by adding the interval and dividing it by two [19]. This procedure will be repeated as needed until the correct pH is found. Recursion will only stop if the input data is equal to the recorded standard buffers [1,2].

Another study by [2] used the binary search method to design a clock-gated and low-power standard cell library for the ISFET two-point calibration processor chip. They also used the two standard buffers (i.e., pH 4 and pH 7) [2].

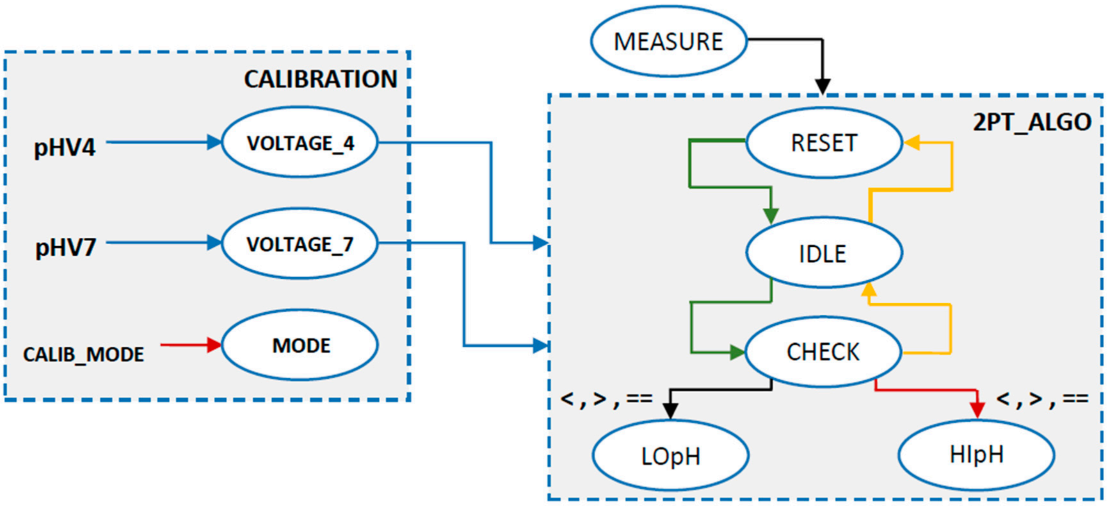

Figure 2. The finite state machine (FSM) for two-point calibration algorithm.

3. Methodology

The three standard buffers were assigned with eight-bit binary equivalents and are shown in Table 2. The voltage for every change in pH unit is 58.16 mV [20]. The Equation (1):

$$\frac{Max_{pH} - Min_{pH}}{Max_{bit} - Min_{bit}} \tag{1}$$

was used to compute for the interval, which is 0.02362 pH/bit. This is how the look-up table library was derived, which has the binary, decimal and voltage equivalents for each pH value. A Xilinx/field-programmable gate array (FPGA) test bench using Verilog programming [21] was used to simulate the behavior of the ISFET with built-in registers using a three-point calibration algorithm. The voltage equivalent of each pH value (which was derived and written in the lookup table library) was used as the voltage unknown (input) during the simulation.

Table 2. Eight-bit assignment to pH.

pH	8-bit Assignment
4	0000 0000
7	0111 1111
10	1111 1110

3.1. Measure Module Algorithm

The Measure module is used for reading the VoltageUnknown or voltage readout (normally, it is the unknown solution's pH voltage equivalent, the V_{rout}). Registers are declared and initialized. If RESET is *HI*, set VoltageUnknown to VoltageUnknown in. If not, check if the respective registers START and CALIBRATED are set (i.e., equal to 1), and set VoltageUnknown_in to VOLTAGE.

3.2. Calibration Module Algorithm

The Calibration module is used for reading the known solution and storage of the standard pH buffers pH 4, pH 7, and pH 10. Registers are declared and initialized before setting the parameters. These are Voltage4Set, Voltage7Set, and Voltage10Set. If the RESET value is *HI*, registers will be initialized to zero (0); otherwise, the MODE parameter is checked. If the MODE parameter is equal to one (SET4), Voltage4_in is set to VOLTAGE and Voltage4Set is set to 1. If registers Voltage7Set and Voltage10Set are set, the calibration is ended. The same procedure will take place if the MODE parameter is set to either 2 (SET7) or 3 (SET10), the other registers are all set, and then the calibration will end.

3.3. Three-Point Calibration Algorithm

Figure 3 describes the segmented three-point calibration algorithm in MEASURE. If the RESET is *HI*, voltage unknown will be processed; otherwise, the calibration will end. In CALIBRATION, if the RESET is *LO*, mode parameters one to three will be tested and the process will end. In SEG3PT _ALGO, if the STATE value is *IDLE* and the START signal is set to *HI*, the voltages of the three standard buffers will be saved into the registers. If the STATE value is *CHECK*, a segmented three-point calibration algorithm is performed.

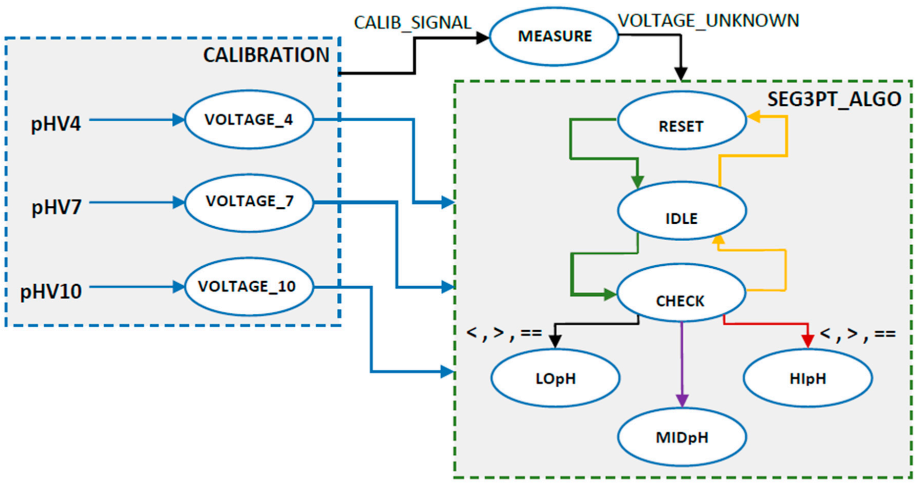

Figure 3. The finite state machine (FSM) of the three-point algorithm.

3.4. Register-Transfer Level (RTL)

Figure 4 illustrates the RTL for the ISFET with built-in registers. It shows the block diagram of each component for the whole system. The diagram simulates the advantage of having the registers built-in to the sensor. The sensor itself will read the standard buffers pH 4, pH 7, and pH 10, and will be stored in the built-in registers Voltage4, Voltage7, and Voltage10, respectively. The content of each register will serve as the reference during the calibration.

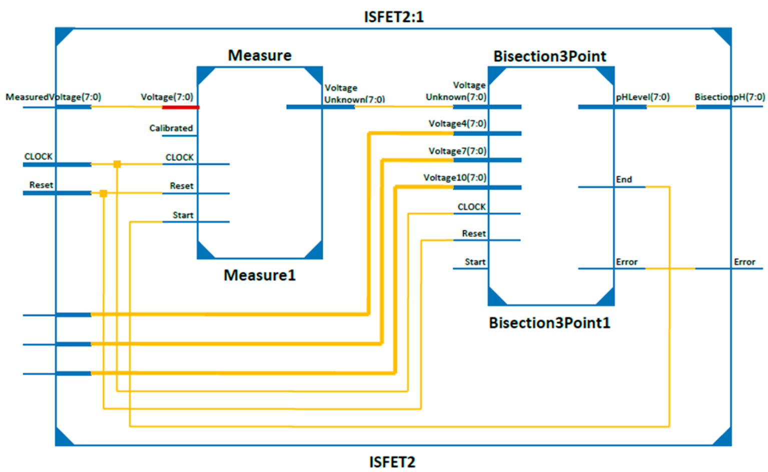

Figure 4. The register-transfer level.

3.5. Schematic Diagram

Figure 5 illustrates the schematic diagram of the ISFET with built-in registers as follows: The number of *Slices* is 142 (the area occupied by the circuit); the number of *Slice Flip-Flops* is 84; the number of *4-input lookup tables (LUTs)* is 263 (the number of 4-input Boolean functions); the number of *bonded input/output blocks (IOBs)* is 43 (the number of pins used). The clock period is 11.636 ns, while the maximum frequency is 85.937 MHz. The estimated power consumption is 37.25 mW. The power consumption includes all the circuitry, hence it is estimated that the power consumption of the ISFET with built-in registers is relatively low.

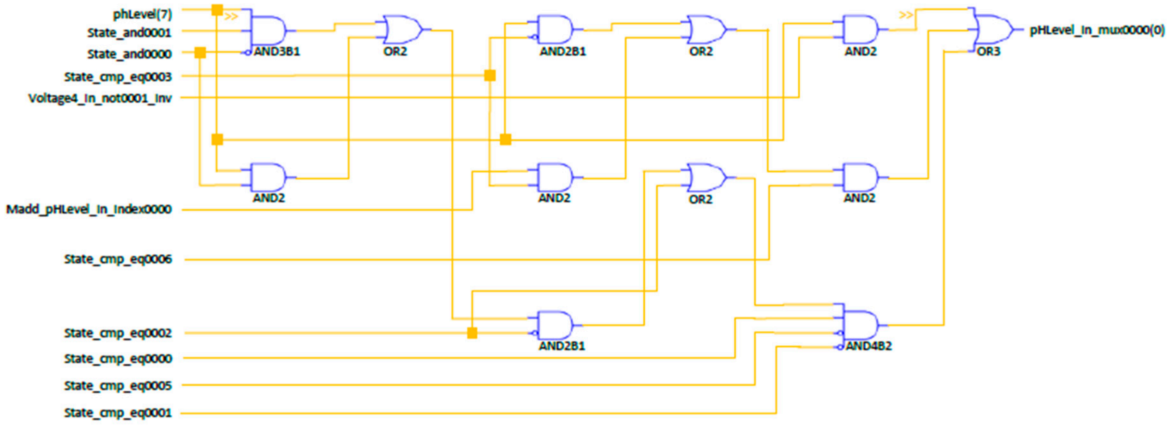

Figure 5. Schematic diagram of the ISFET with built-in registers.

4. Test and Results

This section will prove that the designed circuit is working and is producing the correct output. In Table 3, the calculated pH was derived from the simulations through test bench in Xilinx/FPGA. The voltage unknown (input) equivalent of pH 4 is −173.4302745, pH 5 is −114.5320784, pH 6 is −57.00360781, pH 7 is 0.52486277, pH 8 is 59.42305884, pH 9 is 116.9515294, and pH 10 is 174.48, respectively—all from the derived lookup table. The output in pH can be in decimal or in binary form, as these are included in the derived lookup table. The Equation (2):

$$\frac{Measured_{pH} - Expected_{pH}}{Measured_{pH}} \times 100 \tag{2}$$

was used to compute the percentage of error between the expected pH and the calculated pH. For pH 4, pH 7, and pH 10, there was a 0% error; for pH 5, there was 0.78% error; for pH 6, there was 0.52% error; for pH 8, there was 0.489% error; for pH 9, there was 0.348% error. An average of 0.30% error was calculated after the series of simulations.

Table 3. Expected pH vs. calculated pH.

Expected pH	Voltage Unknown (V_{rout}) in mV	Calculated pH			%Error
		Decimal	Binary	Output (pH)	
4	173.4302745	254	1111 1110	4	0
5	−114.5320784	210	1101 0010	5.03937	0.78124845
6	−57.00360781	168	1010 1000	6.031496	0.52219217
7	0.52486277	127	0111 1111	7	0
8	59.42305884	83	0101 0011	8.030937	0.48971499
9	116.9515294	41	0010 1001	9.031496	0.34873514
10	174.48	0	0000 0000	10	0

Table 4 shows the sample of the data simulation using two different algorithms. The measured pH 4.04, 5.99, 7.89, and 9.76 (the highlighted in column "pH in 2-point") in a research ASIC for ISFET by [1] were considered parts of the data simulation to get the coefficient of determination (R^2) between the two different algorithms [7]. The research ASIC for ISFET by [1] achieved the comparison between various pH meters using the same two-point calibration algorithm [1]. Figure 6 illustrates that the three-point algorithm produces a more linear output (R^2 = 0.9586) compared with the two-point algorithm (R^2 = 0.957).

Table 4. Data simulation using two different algorithms.

Expected pH	pH in 3-Point	pH in 2-Point
4	4.04	4.04
5	4.188976	4.11811
5	4.377953	4.30709
5	4.661417	4.59055
5	4.944882	4.89764
6	6	5.99
8	7.566929	7.566929
8	7.92	7.89
8	8.03937	8.06299
8	8.464567	8.48819
9	9.102362	9.14961
9	9.338583	9.40945
10	9.78	9.76

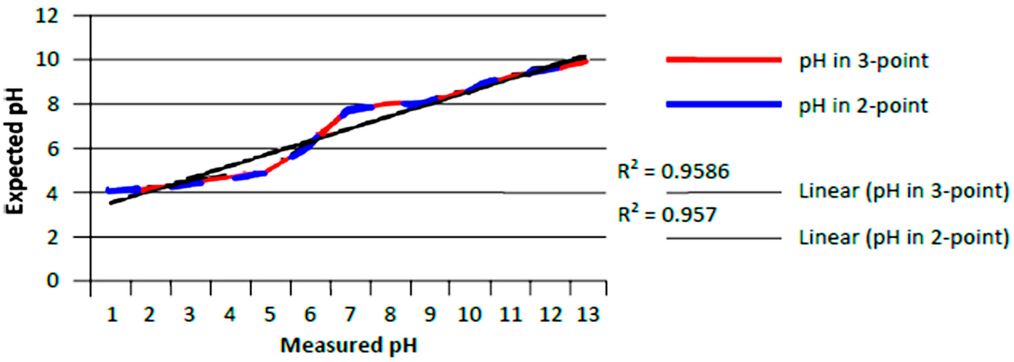

Figure 6. Linearity between the two different algorithms.

5. Conclusions

The ISFET with built-in calibration registers through segmented eight-bit binary search in three-point algorithm produced an average of 0.30% error. The calculated pH from simulations through test bench in Xilinx/FPGA proves that the created circuit is reliable. Through synthesis, the schematic diagram was derived. The number of slices is 142. The number of slice flip-flops used is 84. The number of four-input Boolean functions used is 263. The number of pins used in the circuit is 43. The clock period is 85.937 MHz. The estimated power consumption of the whole circuitry is 37.25 mW. The created circuit will alleviate the work of experts in performing calibrations and can be used as a pH level meter or a remote sensor node in several applications.

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Author Contributions: The main author, Cyrel Ontimare Manlises, carried out the programming, the synthesis and the writing of the paper. Febus Reidj Cruz guided the main author and taught her the principles of ISFETs, including programming and synthesis. Wen-Yaw Chung recommended the idea/topic and provided all the information about ISFETs. Arnold Paglinawan checked and verified the documentation and data analysis.

Conflicts of Interest: The authors declare no conflict of interest.

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