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DEVELOPMENT OF ECONOMICAL ASIC FOR PCS FOR WATER QUALITY MONITORING*

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In this paper, the design of an ASIC is presented that implement a low-cost system for the supervision of water quality in urban areas or rivers. Photo catalytic sensor (PCS) estimates the parameter biological oxygen demand (BOD) which is generally used to estimate quality of water. The system proposed in this paper involves a simple potentiometric approach that provides a correlation in the input–output signals of low-cost sensors. This approach which is more users friendly and fast in operation is obtained by modeling and optimization of sensor for water quality monitoring. This is to overcome several drawbacks generally found in the previous flow injection analysis method of determining chemical oxygen demand (COD)-like complex designing, nonlinearity and long computation time. The system constitutes a significant cost reduction in the supervision of water quality monitoring. The main reason of employing a readout circuit to PCS circuitry, is the fact that the fluctuation of O_2 influences the threshold voltage, which is internal parameter of the FET and can manifest itself as a voltage signal at output but as a function of the trans-conductance gain. The trans-conductance is a passive parameter and in order to derive voltage or current signal from its fluctuations the sensor has to be attached to readout circuit. This circuit provides high sensitivity to the changes in percentage of O_2 in the solution. In this design simple potentiometric approach with few passive components are used to build a readout circuit. The paper focuses on the electronic implementation of the readout system for the PCS which optimize the circuit performance and increases reliability.

Keywords: Biological oxygen demand; potentiometric; photo catalytic sensor; environment.

1. Introduction

Water is vital for all known forms of life. With the expansion of industrial production and increase in the population every year, wastewater produced by industry is discharged into rivers and lakes due to which the quality of water is degraded. Hence, it

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is most urgent to take effective measure to monitor and protect the water resources. The supervision of water quality is generally done by taking and analysing some sample liquid in the laboratory. The chemical oxygen demand (COD) and biological oxygen demand (BOD) are the two main indices which are used globally to determine the overall quality of the water.[1] The method is very expensive, tedious and it can take several weeks to get results of the tests. One approach to solve this problem is to use several low cost sensors and try to detect correlations with the COD and BOD. Many research works have contributed to design quality measuring devices.[2] But it is always a challenge to select a more precise and accurate device for monitoring the quality. Analog integrated circuits play an important role in most modern communication systems as well as in application where miniaturization, low cost and low power is needed. In modern hybrid integrated systems of analog and digital, i.e., mixed mode signal processing on a chip, IC designer must familiar with characteristics and limitations of analog signal processing and its on-chip components such as transistors, amplifiers and filters.[3] Analog VLSI can address almost all real world problems. In today's overdeveloped scenario and for the sake of future, monitoring the quality of the water is very necessary. For this purpose it is various micro sensors are used like photo catalytic sensor (PCS) and ion sensitive field effect transistor (ISFET).[4–6] Although these micro sensors are developed but the fact that the fluctuation of measuring indices (pH, oxygen) influences the threshold voltage, which is internal parameter of the FET and can manifest itself as a voltage signal at output but as a function of the trans-conductance. Also these micro sensors are suffering from several drawbacks related to thermal dependency, long-term drift, linearity, dynamic range. The trans-conductance is a passive parameter and in order to derive voltage or current signal from its fluctuations the sensors has to be attached to conditioning and transmitting circuit.[7] Also, to improve the accuracy in the biomedical applications, it is necessary to find the compensation method to make the applications free from these effects. In order to capture the output response of these sensors, a readout interface is necessary.

2. PCS Macro Model

Over the past 25 years the potential applications of TiO_2 sensors are in the field of sophisticated photovoltaic, antifogging, biomedical, artificial waste water analysis and COD determination. This is for the reason that TiO_2 has efficient photo activity, the highest steadiness and the least cost. From the ancient times, TiO_2 has been used as a white pigment and is found to be safe for human use. The use of TiO_2 PCS achieved results in good agreement with those from the conventional dichromate method. The conventional method used for TiO_2 PCS applications includes bulky and complex setups and require ample time for computation. To overcome these limitations and make the application faster a Simulation Program with Integrated Circuit Emphasis (SPICE) model for PCS was developed.[8] With the advancements

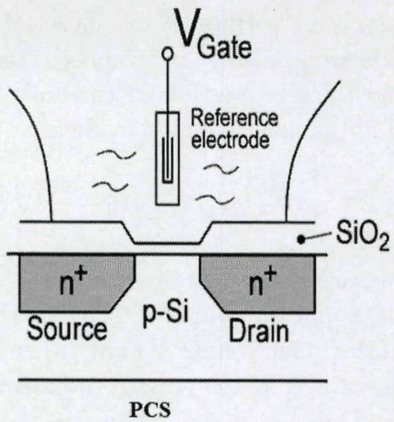

Fig. 1. Cross-section of PCS.

in semiconductor technology and the use of SPICE model one can minimize the size of the overall system, increase the reliability and make it more user friendly.

The structure of PCS is same as that of MOSFET, only difference in the structure is that the gate terminal is kept inside the solution and in order to include the effect of Helmontz and diffusion layer two capacitances C_q and C_{ox} are included. E_{ref} in the proposed structure is added to include the effect of reference electrode. The cross section of PCS is shown in Fig. 1.

Equivalent circuit for proposed structure of PCS is shown in Fig. 2. In the proposed structure of PCS quantum and oxide capacitances are connected in series and the equivalent capacitance of the model is denoted by C_M is given by

$$\frac{1}{C_M} = \frac{1}{C_q} + \frac{1}{C_{\text{ox}}} = \frac{t_{\text{Tio}_2}}{A\epsilon_{\text{Tio}_2\,\epsilon_0}} + \frac{\langle x \rangle}{A\epsilon_{\text{Si}}\,\epsilon_0}\,. \tag{1}$$

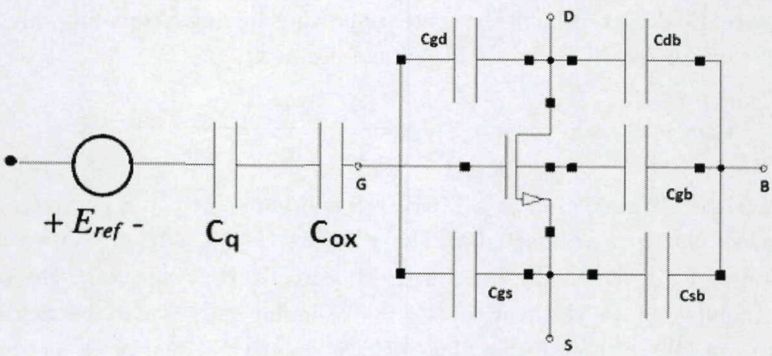

Fig. 2. Structure of PCS.

The PCS is in fact a MOSFET with the gate connection separated from the chip in the form of a reference electrode inserted in an aqueous solution which is in contact with the gate oxide.[9] The general expression for the drain current of the MOSFET and thus also of the PCS in the non-saturated mode is

$$I_{\mathrm{d}} = C_{\mathrm{ox}}\mu \frac{W}{L}\left[(V_{\mathrm{gs}} - V_{\mathrm{t}})V_{\mathrm{ds}} - \frac{1}{2}V_{\mathrm{ds}}^2\right], \tag{2}$$

where C_{ox} is the oxide capacity per unit area, μ is the electron mobility in the channel, W and L the width and the length of the channel, respectively. The drain current I_d is a function of the input voltage V_{gs} only when the geometric sensitivity parameter $\beta = \mu C_{\mathrm{ox}} W/L$, as well as the applied drain source voltage V_{ds} and the threshold V_{t} are constant. Thus, V_{gs} is the only input variable. Defining the metal connection of the reference electrode as a remote gate inserted in an aqueous solution, suggests that any interfacial potential in the input circuit should be described in terms of V_{t}. Therefore, the second important MOSFET equation is that of the threshold voltage:

$$V_{\mathrm{t}} = \frac{\phi_M - \phi_{\mathrm{si}}}{q} - \frac{Q_{\mathrm{ox}} + Q_{\mathrm{ss}} + Q_B}{C_{\mathrm{ox}}} + 2\phi_f\,, \tag{3}$$

where the first term reflects the difference in work function between the gate metal (ϕ_M) and the silicon (ϕ_{si}), the second term is due to accumulated charge in the oxide (Q_{ox}), at the oxide–silicon interface (Q_{ss}) and the depletion charge in the silicon (Q_{B}), whereas the last term determines the onset of inversion depending on the doping level of the silicon. All terms are purely physical in nature.

In case of the PCS, the same fabrication process can be used, resulting in the same constant physical part of the threshold voltage. However, in addition to this, there are two or more contributors first the constant potential of the reference electrode E_{ref}, second the interfacial potential $\Psi + \chi^{\mathrm{sol}}$ at the solution/oxide interface of which Ψ is the chemical input parameter, shown to be a function of the solution O_2 and χ^{sol} is the surface dipole potential of the solvent and thus having a constant value. Hence the expression for the PCS threshold voltage becomes

$$V_{\mathrm{th(PCS)}} = E_{\mathrm{Ref}} - \psi_{\mathrm{eol}} + \chi^{\mathrm{sol}} + \frac{-\phi_s}{q} - \frac{Q_{\mathrm{ox}} + Q_{\mathrm{ss}} + Q_{\mathrm{B}}}{C_{\mathrm{ox}}} + 2\phi_f\,. \tag{4}$$

In case the PCS is treated as a MOSFET and connected to a curve tracer with the reference electrode connected to the V_{gs} port, $I_{\mathrm{d}}/V_{\mathrm{ds}}$ curves can be recorded as function of V_{gs} as is usually done with MOSFETs. However, with the reference electrode connected to the source ($V_{\mathrm{gs}} = 0$) similar curves can be achieved by changing the COD of the solution. The effect is due to the relation $\Psi = f$ (oxygen).

3. Semiconductor Photo Catalysis

Major semiconductor photo catalysis is a process of detoxifying toxic organic pollutants by the use of ultraviolet or visible radiation. These radiations are used to create electron/hole pairs in semiconductor which further helps in photo catalysis phenomenon as shown in Fig. 3. The electron produced as a result of phenomena then reacts with oxygen in the sample to form O_2^- and hole reacts with surface hydroxyl groups to form OH radicals.[10] The radical species then attack the organic molecule and oxidized the organic molecules into carbon dioxide and water. Also, it will produce HCl if the organic molecule contains chlorine.

The photocatalysis is an efficient method for the degradation of organic compounds. A semiconductor material has a filled valence band separated from a vacant conduction band by a gap called band gap E_g. When light having energy more than band gap falls on the semiconductor material, an electron is excited from the valence band to the conduction band, leaving behind a positive hole. On the way to the surface, the electron would reduce any available organic molecule. In contrast, when the hole reaches the surface, it would react with water to produce hydroxyl radicals, which helps in oxidizing organic pollutants.[11] Many of photo catalytic processes apply the TiO_2 as a photo catalyst because it is non-photo corrosive, non-toxic and capable of the photo oxidative destruction of most organic pollutants. The COD of a given sample can be calculated by noticing the change of the dissolved oxygen concentration under photo catalytic conditions.[12–14] The objective of this study was to develop a simple, fast, inexpensive, and safe ASIC for determination of COD.

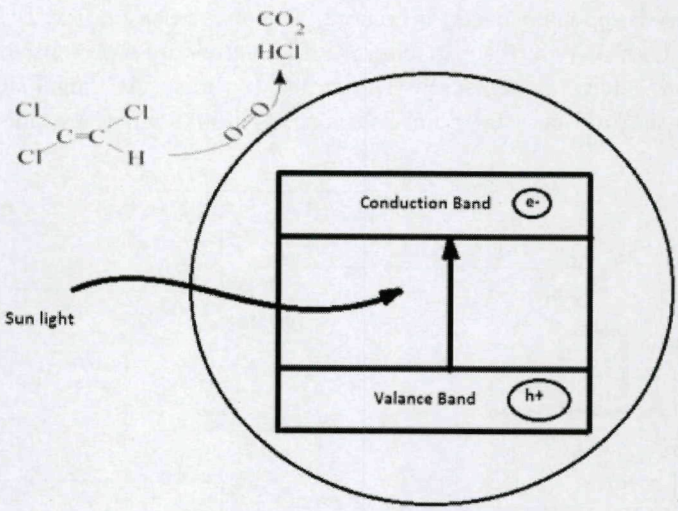

Fig. 3. Diagram to show photocatalysis.

4. Device Description and Analysis

The PCS generates the potential proportional to the activity the detected oxygen ion.[15–17] Potential in PCS is measured against the reference electrode. The potentiometric method has been used to measure the change in the concentration of dissolved oxygen through a corresponding shift in the device threshold voltage. The sensing readout circuit detect the ion concentration of the solution with the feature of CVCC operation mode and floating reference electrode which made the design simple and robust.[18] In this configuration, two constant voltage sources 0.7 V and 0.2 V are fed to the two positive terminals of the amplifiers which causes the drain terminal and the source terminal of the PCS to keep a constant drain source voltage difference of 0.5 V. Also there is one off chip resistor that can be used for setting of a biasing point of the PCS for a constant drain current of 50 μA. To maintain and operate the PCS in the linear region, the gate to source voltage variation of PCS threshold voltage should be directly proportional to the variations of the dissolved oxygen values. Potential difference between the gate sensing membrane and the reference electrode is determined by the ion concentration of the solution. The readout circuit is to be implemented by integrated circuit. The measured signal is the output from amplifier output 2 connected with reference electrode as shown in the Fig. 4.

4.1. *AC analysis*

AC analysis is used to calculate the frequency response of linear circuits. In AC analysis, the DC operating point is first calculated to obtain linear, small-signal models for all nonlinear components. Then a complex matrix (containing both real and imaginary component parts) is created. To construct a matrix, DC sources are given zero values. AC sources, capacitors and inductors are represented by their AC models. Nonlinear components are represented by linear AC small-signal models, derived from the DC operating point solution. All input sources are considered to be

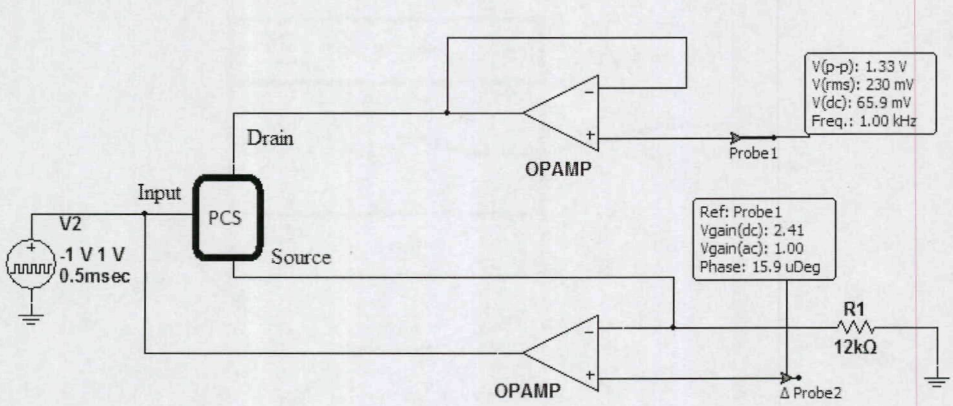

Fig. 4. Circuit diagram of device.

sinusoidal. The frequency of the sources is ignored. If the function generator is set to a square or triangular waveform, it will automatically switch internally to a sinusoidal waveform for analysis. AC analysis then calculates the AC circuit response as a function of frequency. AC analysis of the given device is shown in Fig. 5.

4.2. *Fourier analysis*

Fourier analysis is a method of analyzing complex periodic waveforms. It permits any non-sinusoidal period function to be resolved into sine or cosine waves and a DC component. This permits further analysis and allows you to determine the effect of combining the waveform with other signals. Each frequency component of the response is produced by the corresponding harmonic of the periodic waveform. Each term is considered as a separate source. According to the principle of superposition, the total response is the sum of the responses produced by each term. It is observed that, amplitude of the harmonics decreases progressively as the order of the harmonics increases. This indicates that comparatively few terms yield a good approximation. Fourier analysis of the device is shown in Fig. 6.

4.3. *Noise analysis*

Noise is electrical or electromagnetic energy that reduces the quality of a signal. Noise affects digital, analog and all communications systems. For noise analysis a noise model of the circuit, using noise models of each resistor and semiconductor device is obtained. It calculates the noise contribution of each component and propagates it to the output of the circuit sweeping through the frequency range specified in the analysis dialog box. Noise analysis calculates the noise contribution from each resistor and semiconductor device at the specified output node. Each resistor and semiconductor device is considered a noise generator. Each noise generator's contribution is calculated and propagated by the appropriate transfer function to the output of the circuit. The "total output noise" at the output node is the root mean square (RMS) sum of the individual noise contribution. The result is then divided by the gain from input source to the output source to get the "equivalent input noise". This is the amount of noise which, if injected at the input source into a noiseless circuit, would cause the previously calculated amount of noise at the output. The "total output noise" voltage can be referenced to ground or it may be referenced to another node in the circuit. In this case, the total output noise is taken across these two nodes. The onoise and inoise for the given device is shown in Table 1.

The noise figure is used to specify exactly how noisy a device is. For a transistor, noise figure is simply a measure of how much noise the transistor adds to the signal during the amplification process. In a circuit network, the noise figure is used as a "figure-of-merit" to compare the noise in a network with the noise in an ideal or noiseless network. It is a measure of the degradation in signal-to-noise ratio (SNR) between the input and output ports of a network. When calculating the noise figure

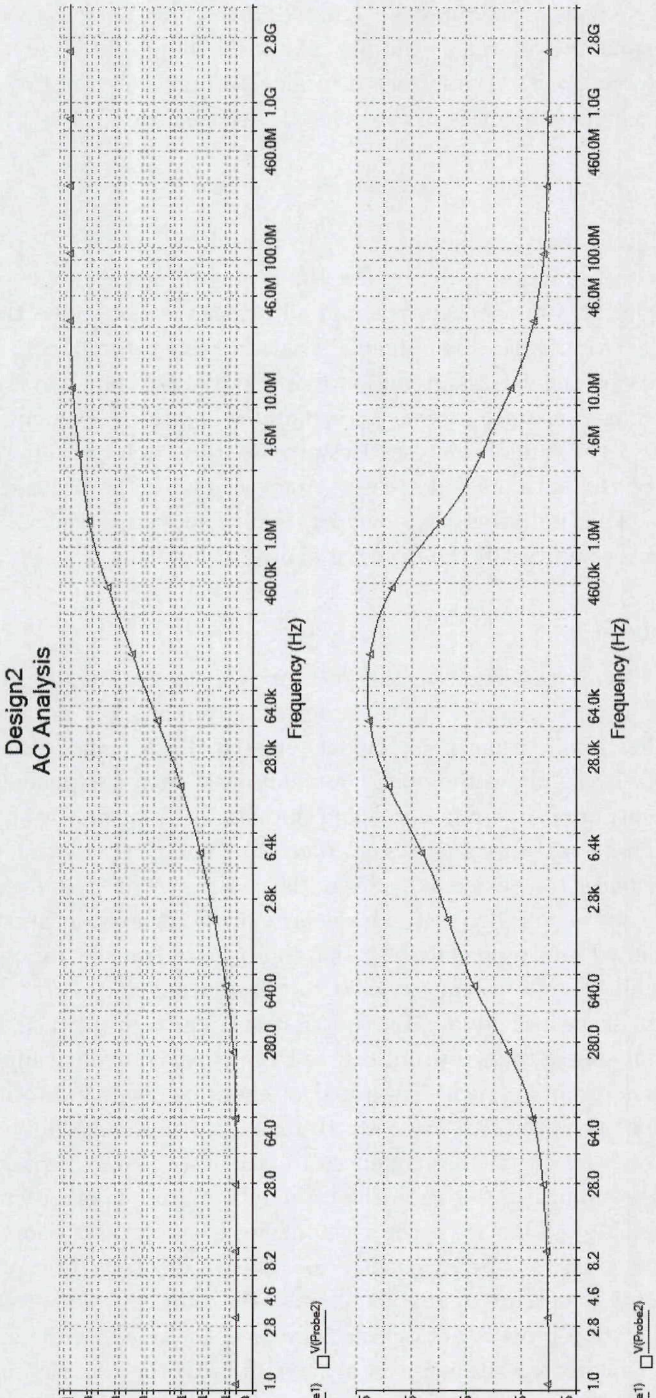

Fig. 5. Output waveform obtained by AC analysis.

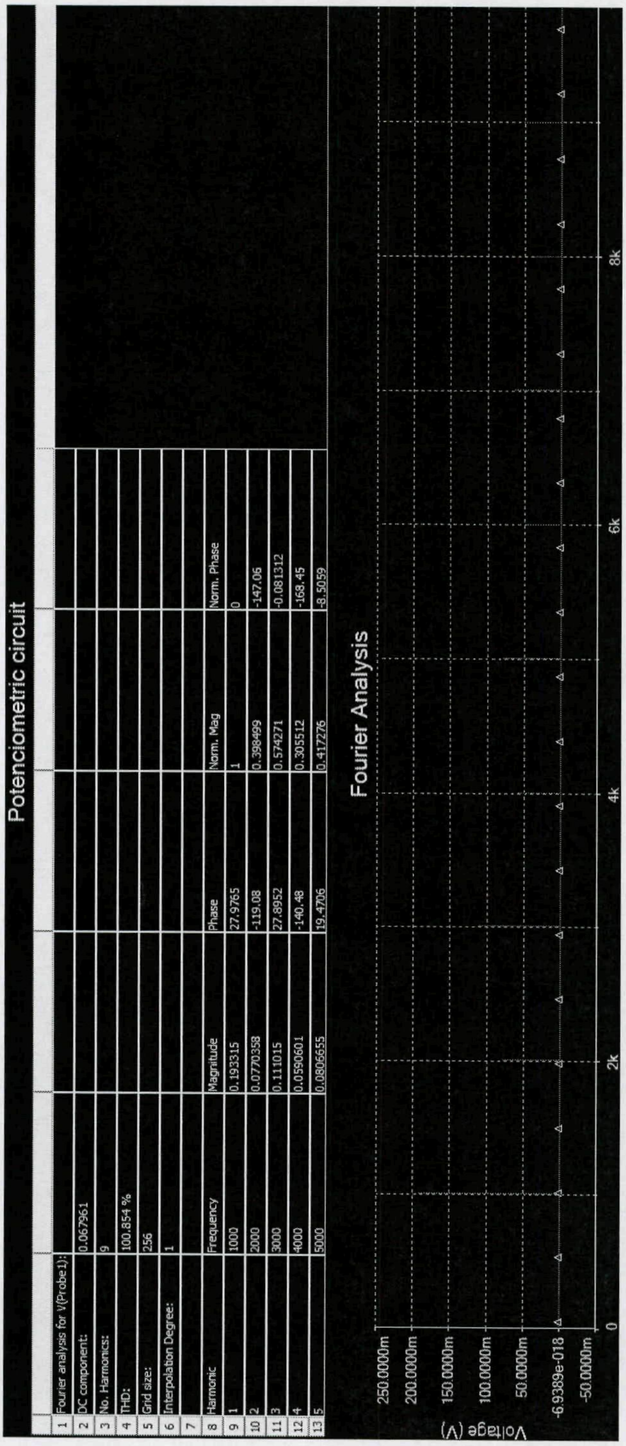

Fig. 6. Fourier harmonic analysis of the device.

Table 1. Integrated noise analysis.

Potentiometric circuit	Integrated noise analysis
Onoise_total	743 m
Inoise_total	74332528T

of a circuit design, noise factor (F) must also be determined. This is the numerical ratio of noise figure, where noise figure is expressed in dB. Thus,

$$\text{Noise figure} = 10\log_{10}F\,,$$

$$F = \frac{\text{Input SNR}}{\text{Output SNR}}\,.$$

The noise figure analysis of the device is observed to be 400 db.

4.4. *Transient analysis*

The transient analysis of the potentiometric device is done on the tanner tool version 15 and it is observed that the response is highly linear indicating that the device is stable as shown in Fig. 7.

On plotting a linear trend line between V_{out} and V_{in} the coefficient of determination R^2 is found to be 99.7% with standard error of 0.026 shown in Fig. 8. The coefficient of determination R^2 is useful because it gives the proportion of the variance (fluctuation) of one variable that is predictable from the other variable. It is a measure that allows us to determine how, certain one, can be in making predictions from a certain model. The coefficient of determination is a measure of how well the regression line represents the data. If the regression line passes exactly through every

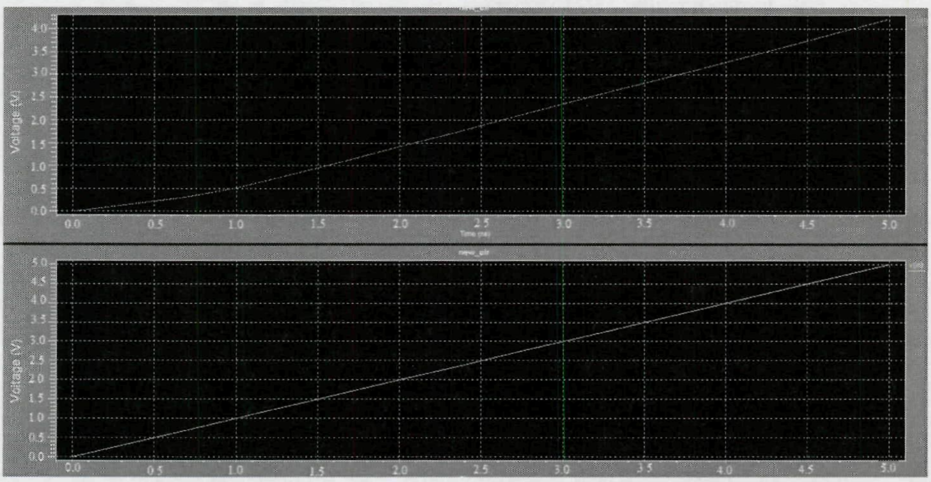

Fig. 7. Transient analysis of the device.

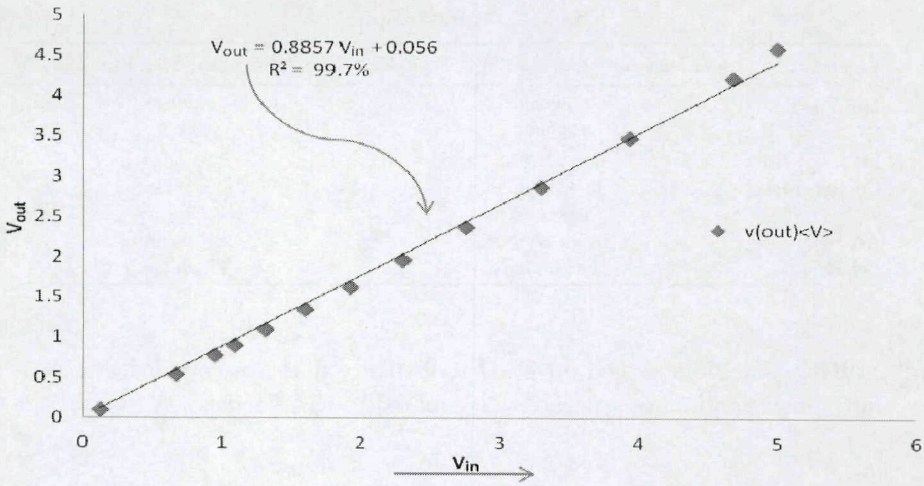

Fig. 8. Plot between V_{out} and V_{in}.

Table 2. Various parameters of the device.

Parameters	Device
Technology	CMOS
Power supply (VDD, GND)	5–0 V
No. of MOSFETs	23
Capacitor	2
Current source	0
NMOS	17
PMOS	10
Resistor	1
Voltage source	3
Average power dissipation (W)	1.251657e-005
Max power (W)	1.435946e-005
Min power (W)	0000000e-000
Stability analysis	Closed loop stable

point on the scatter plot, it would be easy to explain all the variations. The various design parameters are shown in Table 2.

The comparison between SPICE model readings and the FIA analysis readings has been shown in Table 3.

4.5. *Inference from table*

(a) The value of R^2 in case of SPICE model which shows the direction of a linear relationship between peak height decrease in current (ΔI) and dissolved oxygen concentration decrease (ΔO_2) is greater compared to FIA model.
(b) The value of standard error in SPICE model is found to be smaller which shows better accuracy of the SPICE model.

Table 3. Result comparison.

Parameters	Results obtained from SPICE model	Results obtained from FIA analysis
Multiple R	0.983	0.958
R^2	0.966	0.918
Standard Error	0.026	0.040
Complexities	Less complex	More complex
Cost	Inexpensive	Expensive
Accuracy	More accurate	Less accurate
Behavior	Fairly linear	Nonlinear

(c) SPICE model is designed on CAD tools hence it is less complex, inexpensive, fairly linear and more accurate as compared to FIA Model.

5. Result and Conclusion

Various analyses on the given device reveal that the device has fairly good performance. Power analysis on tanner tool version 15 shows that the device consumes very low power in order of $12\,\mu$W. The slew rate of the device is good. The output observed in Fig. 7 is highly linear, indicating that the device is stable. Coefficient of determination R^2 is found to be 99.7% with standard error of 0.026. A significant advantage of the proposed design is a simple architecture, and hence it is very suitable for water quality monitoring applications. This study may be extended for further improvements in terms of power and size, besides the wiring and layout characteristics level.

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