Simulation and performance analysis of Multiple PCS sensors system

Pawan Whig, Syed Naseem Ahmad and Surinder Kumar

Abstract—**In this paper, a novel circuit is presented which overcome a serious limitation found in case of multiple sensors system. In this novel system design only one reference electrode and few active components used that makes the implementation of a low-cost system for the supervision of water quality. Photo Catalytic Sensor (PCS) estimates the parameter BOD (Biological Oxygen Demand) which is generally used to estimate quality of water. The system proposed in this paper involves a balanced bridge approach using few electronic components that provides a correlation in the input - output signals of low-cost sensors. 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 transconductance 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.**

Index Terms— **Biological Oxygen Demand, Multiple Sensor System, Photo Catalytic Sensor, Environment.**

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I. Introduction

WATER is an elixir for life and with the development of industries and tanneries, water bodies are getting polluted. The wastes from these industries are discharged into water resulting in degradation of water. Health issues are a major concern due to increased quantities of the pollutants in water systems. The pollution in the water reduces the oxygen content which disturbs the balance in the aquatic life. So there is a strict need to monitor the quality of water and prevent further pollution being done. Chemical Oxygen Demand (COD) is used to determine the amount of organic pollutants in water [1]. The flow injection analysis (FIA) method proposed by Kim is used to determine the COD by using photochemical column. However, this approach is very time consuming and requires a complex setup [2]. Ample amount of computation time is required to get the results. To address this problem, a SPICE model for PCS is introduced by Whig and Ahmad, which is more user friendly and has less response time [3]. The circuit previously designed is not suitable for the multiple input PCS one of the major reason is that there are as many input reference electrodes are needed as the number of input sensors are increased, in other words the circuit is not suitable for the multiple input sensors network [4]. To deal with such a problem a new circuit is implemented with the facility of multiple inputs using only the single reference electrode and few active components. The major advantage of this circuit is that with the use of few active components and grounded reference electrode can make the circuit to overcome the problem of using multiple reference electrodes as inputs in an array of sensors.

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II. Photo Catalysis Process

The process of photo catalysis is a proficient method for degrading organic compounds. Various literatures are available on the different mechanisms and equations involved in the process for gaining a better knowledge [5-7]. The semiconductor material consists of two bands which are valence band and conduction band. The energy gap between these two bands is known as band gap given by E_g. The electrons from the valence band jump to conduction band which may be empty when a light of energy higher than band gap energy falls on the semiconductor material. Holes are left behind in the valence band due to excitation of electrons to higher energy band. These holes on reaching the surface of the organic molecule reacts with water to give OH^- radicals for oxidizing the organic pollutants. The dissolved oxygen in the molecular form acts as a scavenger of the photo generated electrons and forms a superoxide radical ion. Titanium oxide has the ability to cause photo-oxidative destruction of the organic pollutants and is non- corrosive in nature due to which it is used as a catalyst in the process [8-10]. The oxygen content in any given sample can be determined by observing the change in dissolved oxygen concentration during the process of photo catalysis.

In Photo catalysis process a floating gate electrode is used. The sunlight or UV radiations fall on TiO_2 which further act as a catalyst to speed up the photo catalysis process. PCS senses the changes in the oxygen concentration and its voltage levels change as an indication. The complete Photo catalysis process is shown in Figure 1.

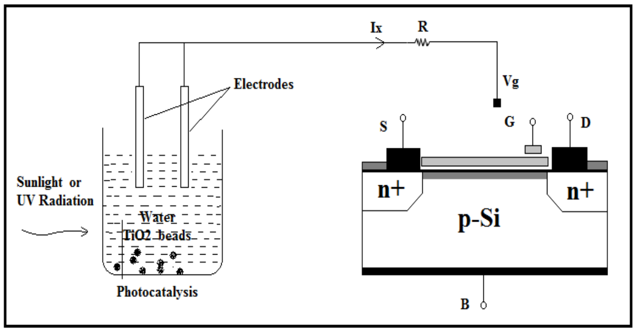

Figure 1 Photo catalysis process

III. Photo Catalysis Sensor

The SPICE model for PCS is given in [3]. It is basically a MOSFET having structural difference in which the gate terminal is kept inside the solution and diffusion and quantum capacitances are added to overcome the effect of Helmholtz and diffusion layer [11-13]. The cross section of PCS is shown in Figure 2.

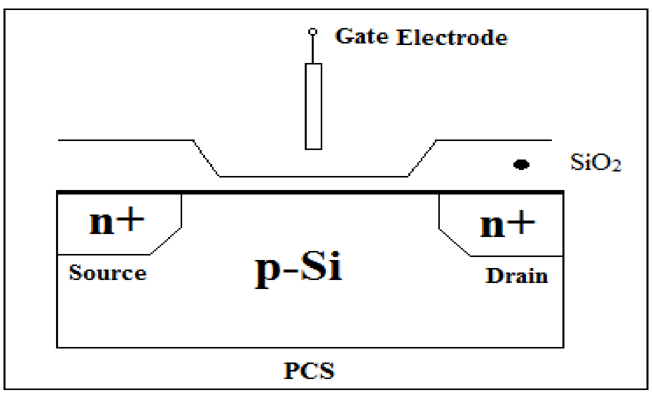

Figure 2 Cross-section of PCS

The threshold voltage equation for the PCS model is given as:

$$V_{th(PCS)} = E_{Ref} - \Psi_{sol} - \chi^{sol} + \frac{-\Phi_s}{q} - \frac{Q_{ox} + Q_{ss} + Q_B}{C_{ox}} + 2\Phi_f \quad (1)$$

Ψ_{Sol} is an input parameter of the equation which is dependent on the concentration of O_2 in the solution and surface dipole potential χ^{sol}. Here E_{Ref} is the constant reference electrode potential. For different concentrations of O_2, different V-I curves for PCS can be plotted .Ψ_{sol} is a function of O_2 and as the saturation cut-off current I_{ds} increases the value of the oxygen concentration level decreases. The circuit for PCS as given in [14] is shown in Figure 3.

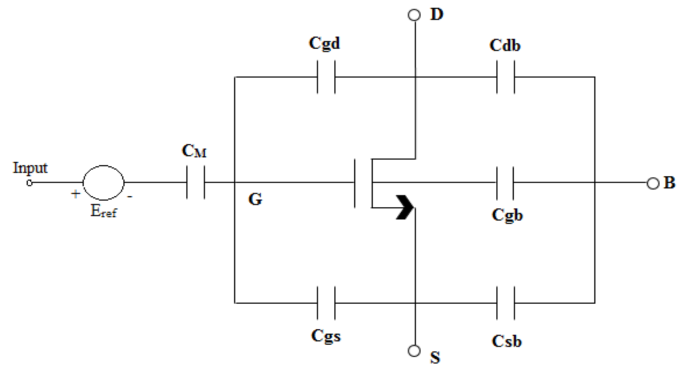

Figure 2 Circuit for PCS

Here C_M is the resultant of C_{ox} and C_q which are oxide and quantum capacitances respectively. The equivalent capacitance C_M is given as:

$$\frac{1}{C_M} = \frac{1}{C_q} + \frac{1}{C_{ox}} \quad (2)$$

The drain current equation in non-saturation mode for PCS is given as:

$$I_{ds} = C_{ox}\mu \frac{W}{L}\left[\left(V_{gs} - V_t\right)V_{ds} - \frac{1}{2}V_{ds}^2\right] \quad (3)$$

Where

C_{ox} = Oxide capacitance per unit area,
μ = Mobility of electrons in the channel,
W = Channel width
L = Length of the Channel

Various Process Parameters including length of channel and channel width are chosen according to the 120 nm CMOS process model.

According to the characteristics of the MOSFET gate to source voltage, Vgs known as reference voltage drain current is allowed to vary with drain to source voltage keeping reference voltage constant. Comparing PCS with MOSFET keeping the concentration of O_2 = $1_{mg/l}$ it is found that the curve resembles with the characteristic Vds /Ids curve of MOSFET keeping Vgs constant. Now keeping the reference voltage Vgs=0 it is observed that for different concentration levels of O_2 , different Vds/Ids curves are obtained as shown in Figure 4. From the above it is observed that as the oxygen concentration level decreases saturation cut off current I_{ds} increases hence it is concluded that PCS can be treated as MOSFET on the basis that the chemical input parameter Ψ_{sol} is a function of O_2 (Ψ_{sol} = f (Oxygen)). For the different values of oxygen content the curves between I_{ds} and V_{ds} is shown in Figure 4.

IV. Device Description and Analysis

The PCS generates potential proportional to activity of detected oxygen ion. Potential in PCS is measured against the reference electrode. The Potentiometric method previously used had a serious limitation that for multiple sensors network multiple reference electrodes are needed [4].

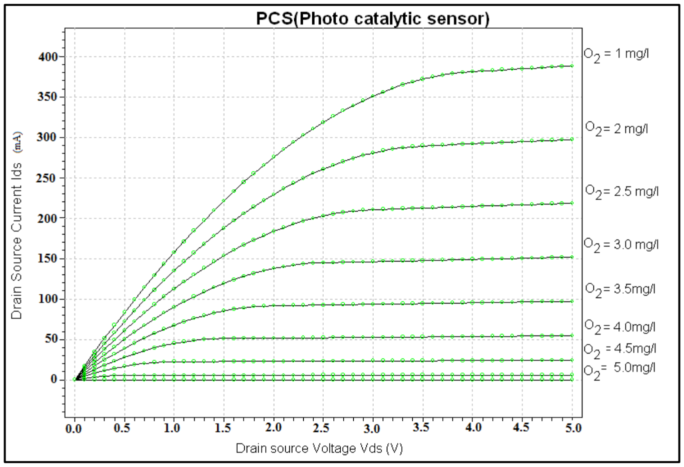

Figure 4: I_{ds} Vs V_{ds} curve for different value of oxygen content

To measure the change in the concentration of dissolved oxygen through a corresponding shift in the device threshold voltage in case of multiple sensor network using single electrode and few passive components is shown in Figure 5.

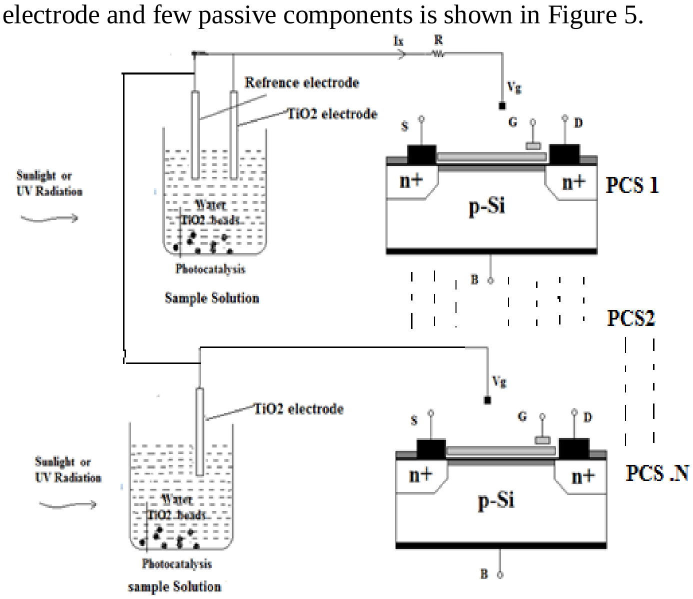

Figure 5: Multiple sensor network using single reference electrode

The sensing readout circuit detect the ion concentration of the solution with the feature of Constant Voltage Constant Current (CVCC) operation mode and floating reference electrode which made the design simple and robust. In this configuration, a Zener diode is used to stabilize the bridge network from any variations occur due to source. The bridge network is further use to maintain a constant potential difference across the inverting and non-inverting terminals of Op- Amp. PCS is connected at one of the arm of Balance Bridge as shown in the Figure 6. Any change occur at gate terminal of the PCS will be detected at the output of Op -Amp. 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 determine 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.

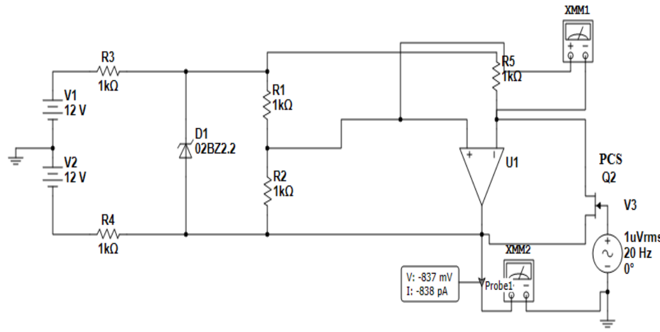

Figure 6: Circuit diagram of a device

V. Simulation

Various simulation analysis carried on the multiple sensor network using single reference electrode device are included as follow

A. Transient analysis

The transient analysis of the multiple sensor network using single reference electrode device is done on Multisim Version 11 of National Instruments and shown in Figure7 and it is observed that the response is highly linear indicating that the device is stable. 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 0.02. 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 point on the scatter plot, it would be easy to explain all the variations.

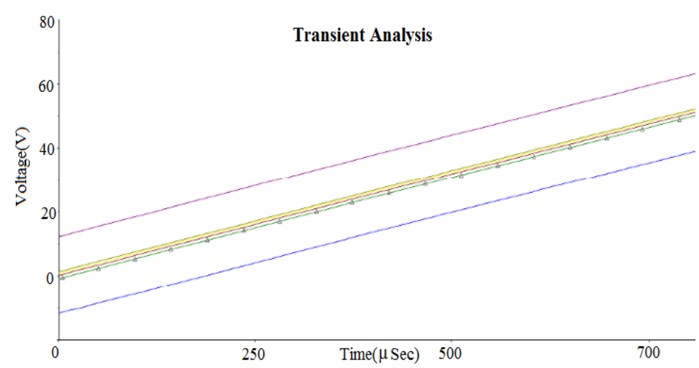

Figure 7. Transient analysis of the simulated device

B. 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 multiple sensor network using single reference electrode 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 (onoise) 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 (inoise). 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.

TABLE 1
INTEGRATED NOISE ANALYSIS

Potentiometric Circuit	Integrated Noise Analysis
Onoise_total	0.00876p
Inoise_total	0.00880p

The noise figure is used to specify the extent of noise in a device. 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 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,

Noise Figure = 10log10F

$$F = \frac{\text{Input}SNR}{\text{Output}SNR} \qquad (4)$$

The noise figure analysis of the device is observed to be 0.0399db.

C. Fourier analysis

Fourier analysis is a method of analysing 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 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 spectrum of the device is shown in Figure 8.

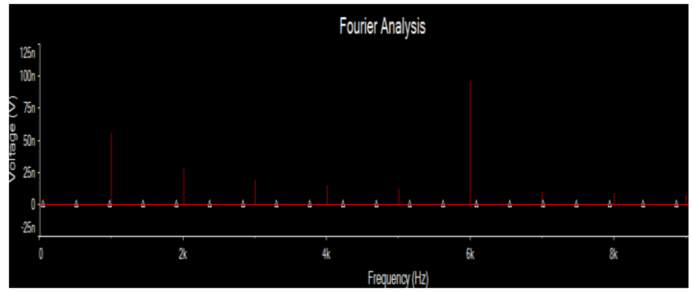

Figure 8. Fourier spectrum of the device

TABLE 2
FOURIER ANALYSIS OF THE DEVICE

Fourier Analysis for V(Out)			
DC component		4.5	
No. Harmonics		9	
THD		290%	
Harmonics	Frequency(Hz)	Magnitude	Phase
1	1000	0.0855	-92.54
2	2000	0.0876	-94.58
3	3000	0.0851	-95.94
4	4000	0.0847	-97.88
5	5000	0.0842	-99.87
6	6000	0.11	-102.89
7	7000	0.0831	-103.86
8	8000	0.0825	-105.93
9	9000	0.081	-108.03

The comparison between Spice Model and the FIA analysis readings has been shown in Table.3.

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	Non linear

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 (ΔO2) 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.

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

VI. Result

Various analyses on the multiple sensor network using single reference electrode device reveal that the device has fairly good performance. Power analysis on Tanner Tool shows that the device consumes very low power in order of 10 µW. The slew rate of the device is good. The output observed in Figure 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 0.02. A significant advantage of the proposed design is that with the use of only few active components and using grounded reference electrode one can overcome the problem of using multiple reference electrodes as inputs in an array of sensors.

VII. Conclusion

In this paper a simple and powerful approach to develop simulated computer models of multiple bioelectronics sensor network using single reference electrode is presented. The device has 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. This technique can be the area of interest for the new researcher working in the same field.

References

[1] P. Whig and S. N. Ahmad, Development of Economical ASIC For PCS For Water Quality Monitoring , JCSC Vol. 23, No. 6, 2014. W.-K. Chen, *Linear Networks and Systems* (Book style). Belmont, CA: Wadsworth, 1993, pp. 123–135.

[2] Kim, Y.-C., Sasaki, S., Yano, K., Ikebukuro, K., Hashimoto, K. and Karube, I.,"Photocatalytic sensor for the determination of chemical oxygen demand using flow injection analysis", Analytica Chimica Acta, Vol. 432 No. 2, pp. 59-66, 2001.

[3] P. Whig and S. N. Ahmad, "Performance analysis of various readout circuits for monitoring quality of water using analog integrated circuits," *International Journal of Intelligent Systems and Applications*, Vol. 11, pp. 91–98, 2012.

[4] P. Whig and S. N. Ahmad, Simulation of linear dynamic macro model of photo catalytic sensor in SPICE, Compel the Int. J. Comput. Math. Electric. Electron. Eng. Vol. 33, pp. 611–629, 2014.

[5] Brown, W.D. and Grannemann, W.W. , "C-V characteristics of metal titanium dioxide-silicon capacitors", Solid-State Electron, Vol. 21, pp. 837-846, 1978.

[6] P. Whig, S. N Ahmad and Suriender Kumar, "Simulation and Performance Analysis of Low Power Quasi Floating Gate PCS Model", The International Journal of Intelligent Engineering and Systems",Vol. 9, pp. 8-13, 2016.

[7] Campbell, S.A., Gilmer, D.C., Wang, X.-C., Hsieh, M.-T., Kim, H.-S., Gladfelter, W.L. and Yan, J. , "MOSFET transistors fabricated with high permitivity TiO2 dielectrics",IEEE Transactions on Electron Devices, Vol. 44 No. 1, pp. 104-109, 1997.

[8] Duffy, J.A. (1990), Bonding Energy Levels and Bands in Inorganic Solids, Wiley, New York, NY.

[9] Massobrio, G. and Antognetti, P. (1993), Semiconductor Device Modeling with SPICE, McGraw-Hill, New York, NY.

[10] Peterson, M., Turner, J. and Nozik, A. , "Mechanistic studies of the photocatalytical behavior of TiO2 particles in photo electrochemical slurry and the relevance to photo detoxification reactions", Journal of Physical Chemistry B, Vol. 95, pp. 221-225,1991.

[11] P. Whig and S. N. Ahmad, Novel FGMOS based PCS device for low power applications, Photonic Sensors, Vol. 5, pp. 123–127, 2015.

[12] Rausch, N. and Burte, E.P. , "Thin high-dielectric TiO2 films prepared by low pressure MOCVD", Microelectronic Engineering, Vol. 19, pp. 725-729 1992.

[13] Sobczynska, A. and Sobczynski, A. , "The application of photocatalysis on semiconductorsin environmental protection", Polish Journal of Applied Chemistry, Vol. 38, pp. 25-33,1994.

Sobczynski, A., Duczmal, Ł. and Zmudzin´ ski, W. , "Phenol destruction by photocatalysison TiO2: an attempt to solve the reaction mechanism", Journal of Molecular CatalysisA: Chemical, Vol. 213, pp. 225-230, 2004.