Impact of Parameters on Characteristic of Novel PCS

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\textbf{Abstract}

Macro model for Photo catalytic sensor (PCS) proposed by Whig et al in 2014 has great advantage as it overcomes several problems like complex designing, non-linearity and long computation time found in the FIA analysis. In this paper, effects of change in various parameters like Gain(K), threshold voltage(Vt), Source resistance (Rs) and Drain resistance (Rd) on the transfer characteristic of novel PCS is presented. The paper proposes an approach for easy and fast operation optimization of power of electronic devices using Simulation Program with Integrated Circuit Emphasis (SPICE) model. It mainly focuses on a more general user friendly quick response time approach. Some exciting results including the effect of change in strength of sensor output signal with the above parameters are helpful during the fabrication of device. The real implementation of PCS has been done in VLSI Lab experimental results are included to validate the results. The results of simulation were found to be fairly in agreement with the theoretical predictions. The results exhibited near linear variations of parameters of interest with appreciably reduced response time.

1. Introduction

The method of semiconductor photo catalysis is employed while the radiations are used to create electron pairs/holes helps in the above phenomenon as shown in the Fig.1, [1, 2]. The electron produced as a result of the above reacts with the oxygen in turn (with the sample) producing $O_2$ while the holes reacts with surface groups to form OH- radicals with the liberation of carbon di oxide and water upon further reacting with organic molecules.

The result of the photo catalysis leads to the formation of a positive hole in the valence band upon excitation of electrons from the same band, results in the reducing of the organic molecule given by [3, 4]. The hole reacts with water to form hydroxyl radicals which helps in oxidizing the organic pollutants. Most of the photo catalytic processes apply TiO$_2$ as catalyst due to its friendly properties with regards to the above. The COD of a given catalyst can be calculated by noticing the
change of the dissolved oxygen concentration under photo catalytic conditions (Sze, 1994) [5, 6].

The objective is to study, observe and examine the variations of various internal parameters based on the transfer characteristics of novel PCS which is based on measurement of changes in oxygen resulting from Photo catalytic oxidation of organic compounds.

![Diagram to show Photocatalysis](image)

**Figure 1.** Diagram to show Photocatalysis

2. **PCS Macro model**

The PCS, similar to MOFSET where the current – voltage relationship in non-saturated mode is same while the only construction difference being that the gate terminal is connected with the chip in form of reference electrode placed in the solution [7]. The current –voltage relationship is given below:

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

(1)

Where \( C_{ox} \) is the oxide capacitance per unit area, \( \mu \) is electron mobility in channel with \( W \) and \( L \) being its width and length respectively. In the above relationship \( I_d \) is a function of \( V_{gs} \) only if all other internal parameters are constant. The relationship of the threshold voltage \( V_{th} \) with other parameters is given below:

\[ V_{t} = \frac{\phi_M - \phi_{si}}{q} - \frac{Q_{ox} + Q_{ss} + Q_B}{C_{ox}} + 2 \phi_f \]  

(2)

Where
- \( \phi_M \): work function of gate metal.
- \( \phi_{si} \): work function of silicon gate.
- \( Q_{ox} \): oxide charge.
- \( Q_{ss} \): Interface charge carriers
- \( Q_B \): depletion charge carriers.

The fabrications steps being the same as that of MOFSET including the results of the above equation, yet there are two additional terms found.
The constant reference electrode potential $E_{\text{ref}}$. Interfacial potential which consists of chemical input parameter which in turn depends on concentration of $O_2$ in input parameter ($\Psi$) and surface dipole potential $\chi_{\text{sol}}$. The above mentioned parameters along with eq.2 constitute resultant threshold equation of PCS shown below in eq.3.

$$V_{\text{th (PCS)}} = E_{\text{Ref}} - \Psi_{\text{sol}} + \chi_{\text{sol}} + \frac{-\phi_s - Q_{\text{oxy}} + Q_{\text{ox}} + Q_{\text{B}}}{c_{\text{ox}}} + 2\phi_f$$  (3)

According to the characteristics of the MOFSET gate to source voltage/reference voltage, drain current is allowed to vary with drain to source voltage keeping reference voltage constant. The eq.3 has been modified such that the $\Psi_{\text{sol}}$ is taken as function of $O_2$ concentration in place of a function of $pH$ is given. Comparing PCS with MOSFET while maintaining the concentration of oxygen at $1\text{mg/L}$ it is found that the curve resembles the characteristics curve of $V_{\text{ds}}/I_{\text{ds}}$ curve of MOSFET keeping the $V_{\text{gs}}$ constant. Now keeping the reference voltage $V_{\text{ref}}=0$ it is observed that for different concentration level of $O_2$, different $V_{\text{ds}}/I_{\text{ds}}$ curves are obtained. From the above it is observed that as oxygen concentration level decreases saturation cut-off current $I_{\text{ds}}$ increases hence it is concluded that PCS can be treated as MOSFET on the basis that the chemical input parameter $\Psi_{\text{sol}}$ is a function of $O_2(\Psi_{\text{sol}}=f(\text{oxygen}))$ as given by Whig and Ahmad in SPICE Macro model of PCS in 2014.

3. Proposed Experimental Set up

The proposed structure of PCS with its sensitive and insulated surface made of materials like $\text{TiO}_2$ as shown in Fig.2. $\text{TiO}_2$ beads are used to vary the COD concentration of the water and its properties, its di-electric constant is suitable for study of parameters at sub micron level. It is also capable of photo oxidative destruction of most of organic pollutants in water ensures it as one of the indigenous, cost effective photo catalyst to date. A gate terminal is positioned along with electrodes in the solution to calculate the response of PCS. Further PCS and COD can be explained in terms of semiconductor photo catalysis.

![Figure 2. Sketch of PCS](image)
Due to the photo catalysis of TiO\textsubscript{2} beads present in the water, current I\textsubscript{x} through the wires varies which in turn varies the gate voltage $V_{gs}$ of PCS. With the continuation of process, the maximum current decreases with corresponding decrease in $V_{gs}$ and drain current $I_d$. The calibration curve obtained through FIA analysis of COD sensor for the dissolved oxygen in solution is a second order equation. Further analysis of the data indicates that the experimental points fits in curve with the range of 0.69-4.83 ppm of O\textsubscript{2} concentrations. The regression equation referred in the above paragraph is

$$\Delta C = -0.0095 \Delta O_2^2 + 0.115 \Delta O_2 + 0.0077$$  \hspace{1cm} (4)

Where $\Delta C$ is the peak decrease in current, $\Delta O_2$ is the dissolved oxygen concentration decrease in ppm, on plotting a linear trend line between $\Delta C$ and the $\Delta O_2$ the co-efficient of determination $R^2$ is found to be $91.81\%$ with standard error of 0.040. The co-efficient of determination $R^2$ is useful because it gives the proportion of the variance (fluctuations) which is predictable through the other. The measurement allows us to determine the efficiency of the design and model. The co-efficient of determination is measured to calculate how well the regression line represents the data, explanation of data would be possible if it were to pass through every point on scatter plot. For the value of $R^2=96.57\%$ with standard error 0.026 obtained through spice model can be stated that nearly $97\%$ of total variations in $\Delta C$, which can be further explained by the linear relationship between $\Delta O_2$ and $\Delta C$. The other $3\%$ of total variation in $\Delta C$ may be due to non – linearity of the device in a particular region of the characteristics curve and also due to limitation of PCS model. The percentage improvement in standard error over FIA is $35\%$ hence certainly indicates the uplifted accuracy.

4. Result Analysis

Fig. 3 shows circuit diagram of PCS to study the variations of different parameters on the characteristic of PCS. The circuit is simulated on the Simulink in Mat lab 2013. For Gain $K$, varying from 1 to 10 and constant value of threshold voltage $V_{th}=0.6V$ the curves obtained. It is observed that for small values of $V_{ds}$ the curves are nearly straight lines passing through the origin and this region simply define the behaviour of PCS resistance. Here the slope of the curve is controlled by $V_g$. For small value of $V_g$ the line is essentially Flat shows a large resistance to the input signal $V_g$. For large value of $V_g$ the resistance appear to small and more linear curve. As the value of gain increased it is observe that the overall resistance of the PCS decreases which in turn increases the linearity. Also by observing the results it is interpreted that by increasing gain, the drain current increase and pinch off voltage of PCS decreases results in the increase in sensitivity of
PCS. So, it is concluded that by increasing in gain the sensitivity of the PCS can be improved. The characteristic curve for K=1 is shown in Fig.4.

![Figure 3. Circuit Diagram of PCS to obtain characteristic](image1)

![Figure 4. Characteristic curve for gain K = 1.](image2)

For $V_{th}$ varying from 0.1 to 0.9 and at constant value of gain K=1 it is observed that for change in threshold voltage the overall resistance of PCS decreases which in turn increases the linearity of the system. The Characteristic Curve for $V_{th} = 0.1$V is shown in Fig.5.

![Figure 5. Characteristic curve for $V_{th} = 0.1$V](image3)
For Varying $R_s$ and $R_d$ and keeping all other parameters kept constant it is observed that increase in the value of source resistance will leads to increase in linearity. It is also observed that increase in source resistance beyond a certain value concentrate all curves on a single curve which means the curve are no longer depends upon input value. From the result shown it is interpreted that by increasing source resistance the drain current decreases there by decrease in the sensitivity of the PCS. This can be useful in controlling the effect of noise, non-ideal behaviour and other second order effects like Channel Length Modulation, Body Bias and Latch up. The characteristic curve when drain resistance 1 Ω and 10 Ω is shown in Fig. 6 and Fig.7.

![Figure 6. Characteristic curve when Drain resistance 1Ω](image)

Perhaps the most striking aspect of these curve is power being controlled by PCS. In upper right hand side of the curve we have a current 12mA and the voltage drop 4V which is a power dissipation of 4.8mW ways beyond the thermal limit of the package say 0.25mW as shown in Fig.8. By selecting the region of operation one can decide the value of current and voltage for a given device. The real implementation of PCS carry out at VLSI LAB at Rajasthan Institute of Technology, Jaipur India is shown in Fig. 9.

![Figure 7. Characteristic curve when Drain resistance 10Ω](image)
From the observations of the effect of change in various parameters like Gain (K), Threshold voltage (V_t), Source resistance (R_s) and Drain resistance (R_d) it is concluded that by varying gain and threshold voltage, the sensitivity of the PCS increases which in turn increases the accuracy. On the other hand by increasing the value of R_d and R_s one can improve the effect of noise, non-ideal behaviour and other second order effects like Channel Length Modulation, Body Bias and Latch up.

References


