Novel FGMOS Based PCS Device for Low Power Applications

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Abstract: The spice model for photo catalytic sensor (PCS) proposed by Whig and Ahmad overcomes several drawbacks like complex designing, non-linearity, and long computation time generally found in the flow injection analysis (FIA) technique by Yoon-Chang Kim et al. for the determination of chemical oxygen demand (COD). The FIA technique involves the complete analysis including sampling and washing. The flow injection analysis is an analytical method for the measurement of the chemical oxygen demand by using the photochemical column. This method uses a bulky setup and takes 10 minutes to 15 minutes to get the output result which is a tedious and time consuming job. If the conventional method is continuously used for a long time then it is stable only for 15 days. The purpose of this paper is to propose a new floating gate photo catalytic sensor (FGPCS) approach which has low power consumption and more user-friendly, and it is fast in operation by the modeling and optimization of sensor used for water quality monitoring. The proposed model operates under sub-threshold conditions which are appreciated in large integrated system design. The results of simulation are found to be fairly in agreement with the theoretical predictions. The results exhibit near linear variations of parameters of interest with appreciably reduced response time.

Keywords: FGPCS, spice modeling, simulation, photo catalytic sensor, flow injection analysis, macro model

1. Introduction

Over the past three decades, the applications of titanium dioxide (TiO2) sensors have a great demand in the field of sophisticated photovoltaic, artificial waste water analysis, and chemical oxygen demand (COD) determination [1]. This is mainly due to the reason that TiO2 has efficient photo activity, least cost, and non-poisonous nature. From the ancient times, TiO2 has been used as a white pigment and is found to be safe for human use. The conventional method used for the TiO2 photo catalytic sensor applications includes bulky and complex setups and requires sample time for computation. To overcome these limitations and make the application faster, a simulation program with an integrated circuit emphasis (SPICE) model for the photo catalytic sensor was developed by Whig and Ahmad [2]. The semiconductor technology is very popular and widely used for sensor development. Advantages like low power, high speed, small size integration, and their signal processing capability made this technology more productive. More often, computer aided design (CAD) tools are used [3] which provide simulation and synthesis of semiconductor sensors. With the
advancements in the semiconductor technology and the use of the SPICE model, one can minimize the size and power of the overall system, increase the reliability, and make it more user-friendly [4]. A good knowledge related to fundamental parameters of metal oxide semiconductor (MOS) and CAD tools are required to build the SPICE model.

The first floating gate device was reported by Sze in 1967 [5]. Early floating gates were most commonly used in digital memory applications but recently some new applications of floating gate (FG) have been developed to be used as an elementary component of the circuit. Floating gates circuits are very popular due to distinct advantages of low power consumption and controlled second-order effects compared with other technologies [6]. Although floating gates seem to be important for very large scale integration (VLSI) applications, nowadays the focus has been shifted towards solving the practical analog and digital circuits problem by utilizing FG [7, 8].

Modeling of metal oxide semiconductor field effect transistors (MOSFET) [9, 10] requires a deep knowledge of the code structure and subroutines, and it is strictly linked to a particular version of SPICE. In this paper, the SPICE macro model for floating gate photo catalytic sensor (FGPCS) is implemented. The simplest FGPCS is oxygen (O_2) sensitive where the sensitive surface is made up of insulator layer like titanium oxide (TiO_2) exposed to an electrolyte solution. A p–type semiconductor and TiO_2 insulator are placed into aqueous electrolyte solution where the response of PCS to O_2 can be explained in terms of photo catalysis.

2. Equivalent circuit of FGPCS

The structure of FGPCS is the same as that of MOSFET, the only difference in the structure is that the gate terminals are kept inside the solution and in order to include the effect of Helmontz and diffusion layer, two capacitances quantum capacitance (C_q) and oxide capacitance (C_{ox}) are included as explained by Kong et al. [11]. E_{ref} in the proposed structure is added to include the effect of reference electrode. The cross section of FGPCS is shown in Fig. 1.

![Cross section of FGPCS](image)

Equivalent circuit for the proposed structure of FGPCS is shown in Fig. 2. The FG structure of the PCS is capacitively coupled to the inputs and the voltage presented at these gates can modulate the channel current.

![Proposed structure of FGPCS](image)

One of the most common factors responsible for the inaccuracy in the macro model is the use of an inadequate nonlinear device model explained by Grattarola and Massobrio [12–15].

3. Operation of FGMOS

A floating gate MOSFET consists of a standard MOSFET without any resistive connections to its gate. Any number of electrically isolated secondary inputs can be connected above the FG.

The FG is made up of materials having very high resistivity and connected capacitively to the FG. The circuit can operate at power supply voltage levels which are well below the operational limit, thus saving a power up to 30%–40% as being compared with similar MOS devices technology in which only...
one gate input is used in comparison with the multiple inputs in the FG device. The proposed structure of FGPCS with its sensitive surface is made up of an insulation layer like TiO\textsubscript{2} shown in Fig. 3.

TiO\textsubscript{2} is used because it has very good dielectric constant which makes it suitable to be used at a deep submicron level. TiO\textsubscript{2} beads are used to vary the COD concentration in the water and its properties like non-photo-corrosive, non-toxic, and capable of the photo oxidative destruction of most organic pollutants make it a very important and inexpensive photo catalyst. A gate terminal placed directly in an aqueous solution with the help of electrodes is considered to calculate the response of FGPCS. The response of the FGPCS to COD can be explained in terms of semiconductor photo catalysis.

![Fig. 3 Sketch of PCS.](image)

Due to the photo catalysis of TiO\textsubscript{2} beads presented in the water, the current \(I_g\) through the wire varies which in turn varies the gate source voltage \((V_{gs})\) of FGPCS. As the photo catalysis occurs, the maximum current decreases. It is observed that for a given sample when a decrease in the maximum current takes place due to photo catalysis there is a corresponding decrease in the \(V_{gs}\) and drain source current \((I_{ds})\).

### 4. Mathematical modeling

On considering substrate and bulk voltage at zero potential the floating gate voltage \((V_{fg})\) is given in (1).

\[
V_{fg} = \frac{C_1 V_1}{C_{eq}} + \frac{C_2 V_2}{C_{eq}} + \frac{C_{fg} V_{ds}}{C_{eq}}.
\]  

where \(C_1, C_2\) are oxide capacitances formed between gates and substrate, \(C_{eq}\) is the equivalent capacitance of \(C_1\) and \(C_2\), \(C_{fg}\) is the oxide capacitance formed between floating gate and drain, and \(V_1, V_2\) are the voltages of respective floating gates.

The drain current of floating gate MOSFET in the linear region of operation is given in (2).

\[
I_{ds} = \beta \left\{ \left[ \frac{C_1 V_1}{C_{eq}} + \frac{C_2 V_2}{C_{eq}} - V_T \right] - \frac{V_{ds}}{2} \right\}
\]  

where \(V_T\) is the threshold voltage of floating gate metal oxide semiconductor (FGMOS), \(V_{ds}\) is the drain source voltage, and \(\beta\) is the trans conductance parameter given as

\[
\beta = \mu_n C_{ox} \frac{W}{L}
\]

where the value of \(\beta\) depends on \(\mu_n\) which is the mobility of ions, \(C_{ox}\) is the oxide capacitance, and \(\frac{W}{L}\) is the width to the length ratio of floating gate.

Since

\[
C_{eq} = C_1 + C_2.
\]  

(1) can be rewritten as

\[
I_{ds} = \beta \left[ \frac{C_1 V_1}{C_{eq}} - \frac{C_2 (V_T - V_2)}{C_1} \right] V_{ds} - \frac{C_{eq}}{2 C_1} V_{ds}^2
\]  

\[
I_{ds} = \beta \frac{C_1}{C_{eq}} \left[ (V_1 - V_{eff}) V_{ds} - \frac{C_{eq}}{2 C_1} V_{ds}^2 \right]
\]  

where

\[
V_{eff} = V_T + \frac{C_2}{C_1} (V_T - V_2)
\]

Also the drain current in the saturation region is given as

\[
I_{ds} = \frac{\beta}{2} (V_{fg} - V_T)^2
\]

Using (1), the drain current can be written as

\[
I_{ds} = \beta \left[ \left( \frac{C_1 V_1}{C_{eq}} + \frac{C_2 V_2}{C_{eq}} \right) - V_T \right]^2
\]
\[ I_{ds} = \frac{\beta}{2} K_1^2 \left[ V_G - V_{\text{eff}} \right]^2 \tag{5} \]

where \( V_{\text{eff}} \) is the effective threshold voltage which is given as

\[ V_{\text{eff}} = \frac{V_T - V_2 K_2}{K_1} \]

where \( K_1 = \frac{C_1}{C_{eq}} \) and \( K_2 = \frac{C_2}{C_{eq}} \) are the constants.

Hence, by changing the value of bias voltage, the effective threshold voltage of the device can be adjusted thereby making the device free from the second order effect like channel length modulation and body effect.

5. Results and discussion

The developed device model has been extensively tested, and the simulation results have been compared with experimental data results of the previous model. The relationship between \( I_{ds} \) with \( V_{gs} \) is shown in Fig. 4 which shows that the proposed FGPCS exhibits linear characteristic in the range of \( V_{gs} = 2.5 \text{V} \) to \( 5.0 \text{V} \).

![Fig. 4 Characteristic curve for FGPCS between \( I_{ds} \) and gate \( V_{gs} \) obtained through SPICE.](image)

The curves are drawn between \( I_{ds} \) and \( V_{gs} \) of FGPCS for \( V_{ds} = 0.5 \text{V} \). It can be seen that the proposed FGPCS is fairly linear for concentrations more than 1 mg/L extending towards 5 mg/L of O\(_2\). This is an obvious advantage of this FGPCS model.

By observation of Fig. 5 it can be seen that the graph of \( I_{ds} \) and \( V_{ds} \) by using the FGPCS model is fairly matching the plot obtained for the experimental data where \( I_{ds} \) depends on \( \Delta I \) and \( V_{ds} \) depends on O\(_2\) concentration. The comparison validates the PCS model’s working. The linear variation of \( I_{ds} \) facilitates high accuracy measurements of water quality. In addition the calibration of the instrument is also easier due to this linear behavior.

In this design, the device is free from channel length modulation and is seen consuming low power of the order of 1.46 mW as shown in Table 1. This study can be extended, more improvements in terms of power and size can be achieved at the wiring and layout characteristics level, and more effective results can be obtained.

![Fig. 5 Characteristic curves between \( I_{ds} \) and \( V_{ds} \) at O\(_2\) = 1 mg/L – 5 mg/L obtained through SPICE.](image)

**Table 1 Power analysis.**

| Parameters                  | FGMOS   |
|-----------------------------|---------|
| CMOS technology (nm)        | 70      |
| Power supply (VDD, GND)     | 0 V–1.5 V |
| Average power dissipation   | 1.465115e-003 |
| Max power                   | 2.407486e-003 |
| Min power                   | 8.981766e-010 |

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