Novel FGMOS Based PCS Device for Low Power Applications

Pawan WHIG[1*] and Syed Naseem AHMAD[2]

[1]*Department of Electronics and Communication Engineering, Rajasthan Institute of Engineering and Technology, Jaipur, India*

[2]*Department of Electronics and Communication Engineering, Jamia Millia Islamia, New Delhi, India*

[*]Corresponding author: Pawan WHIG   E-mail: pawanwhig@gmail.com

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 (TiO_2) 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 TiO_2 has efficient photo activity, least cost, and non-poisonous nature. From the ancient times, TiO_2 has been used as a white pigment and is found to be safe for human use. The conventional method used for the TiO_2 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 to 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.
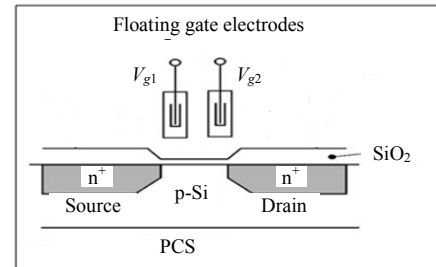

Fig. 1 Cross section of FGPCS.

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.
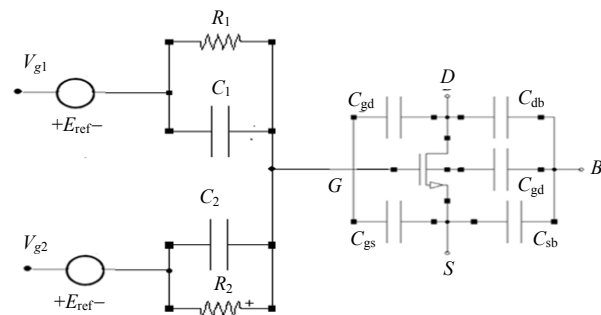

Fig. 2 Proposed structure of FGPCS.

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_2 shown in Fig. 3.

TiO$_2$ is used because it has very good dielectric constant which makes it suitable to be used at a deep submicron level. TiO$_2$ 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.
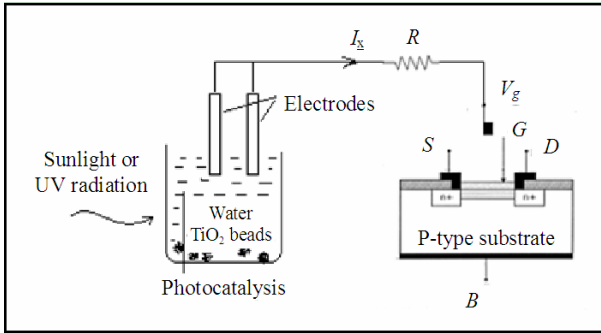

Fig. 3 Sketch of PCS.

Due to the photo catalysis of TiO_2 beads presented in the water, the current I_x 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).

$$V_{fg} = \frac{C_1 V_1}{C_{eq}} + \frac{C_2 V_2}{C_{eq}} + \frac{C_{fd} V_{ds}}{C_{eq}}. \tag{1}$$

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_{fd} 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).

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

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

$$\beta = \mu_n C_{ox} \frac{W}{L}$$

where the value of β depends on μ_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

$$C_{eq} = C_1 + C_2. \tag{3}$$

(1) can be rewritten as

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

$$I_{ds} = \beta \frac{C_1}{C_{eq}} \left[(V_1 - V_{Teff}) V_{ds} - \frac{C_{eq}}{2C_1} V_{ds}^2 \right] \tag{4}$$

where

$$V_{Teff} = V_T + \frac{C_2}{C_1}(V_T - V_2)$$

Also the drain current in the saturation region is given as

$$I_{ds} = \frac{\beta}{2} \left(V_{fg} - V_T \right)^2$$

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

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

$$I_{ds} = \frac{\beta}{2} K_1^2 \left[V_1 - V_{Teff} \right]^2 \qquad (5)$$

where V_{Teff} is the effective threshold voltage which is given as

$$V_{Teff} = \frac{V_T - V_2 K_2}{K_1}$$

where $K_1 = \dfrac{C_1}{C_{eq}}$ and $K_2 = \dfrac{C_2}{C_{eq}}$ 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} = 2.5V to 5.0 V.
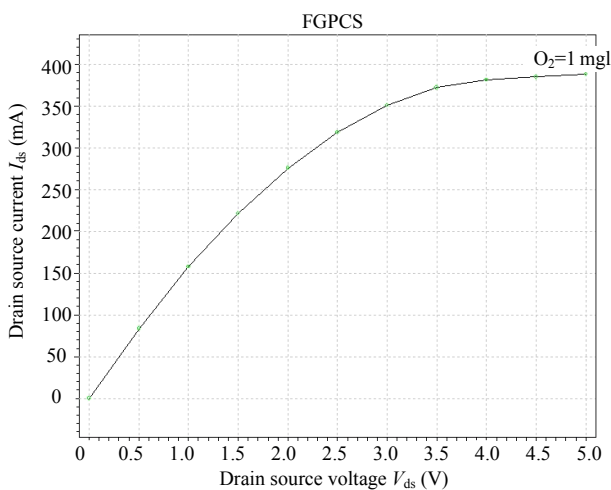

Fig. 4 Characteristic curve for FGPCS between I_{ds} and gate V_{gs} obtained through SPICE.

The curves are drawn between I_{ds} and V_{gs} of FGPCS for V_{ds}=0.5 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 ΔI 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.
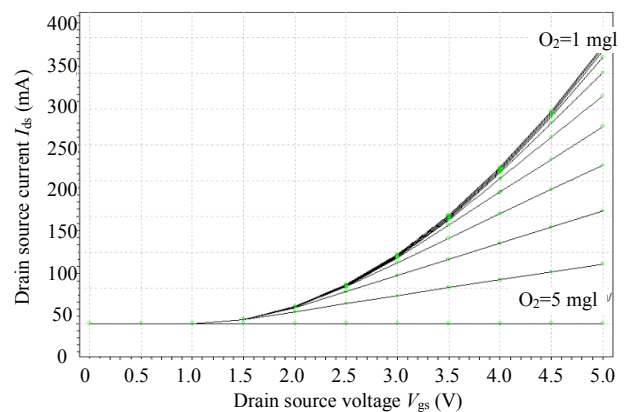

Fig. 5 Characteristic curves between I_{ds} and V_{ds} at O_2 = 1 mg/L−5 mg/L obtained through SPICE.

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

References

[1] L. L. W. Chow, M. M. F. Yuena, P. C. H. Chanb, and A. T. Cheung, "Reactive sputtered TiO_2 thin film humidity sensor with negative substrate bias," *Sensors and Actuators B: Chemical*, 2001, 76(1–3): 310–315.

[2] P. Whig and S. N. Ahmad, "Simulation of linear dynamic macro model of photo catalytic sensor in SPICE," *Compel The International Journal of Computation and Mathematics in Electrical and Electronic Engineering*, 2013, 33(1/2): 611–629.

[3] P. Whig and S. N. Ahmad, "A novel Pseudo NMOS integrated ISFET device for water quality monitoring," *Active and Passive Electronic Components*, 2013, 10(1): 1–6.

[4] P. Whig and S. N. Ahmad, "Development of economical ASIC for PCS for water quality monitoring," *Journal of Circuits, Systems and Computers*, 2014, 23(6): 1–13.

[5] D. Kahng and S. M. Sze, "A floating gate and its application to memory devices," *The Bell System Technical Journal*, 1967, 46(4): 1288–1295.

[6] Y. Berg, T. S. Lande, and S. Naess, "Low-voltage floating-gate current mirrors," in *Proceedings of the 10th Annual IEEE International ASIC Conference and Exhibit*, Portland, OR, pp. 21–24, 1997.

[7] T. S. Lande, D. T. Wisland, T. Saether, and Y. Berg, "FLOGIC-floating-gate logic for low-power operation," in *Proceedings of the 3rd IEEE International Conference on Electronics, Circuits, and Systems*, Rodos, pp. 1041–1044, 1996.

[8] E. Rodriguez-Villegas, *Low Power and Low Voltage Circuit Design with the FGMOS Transistor*, vol. 20 of IET Circuits, Devices & Systems Series, London, UK: The Institution of Engineering and Technology, 2006.

[9] G. Massobrio and P. Antognetti, *Semiconductor Device Modeling with SPICE*, New York, USA: McGraw-Hill, 1993.

[10] M. Peterson, J. Turner, and A. Nozik, "Mechanistic studies of the photocatalytical behavior of TiO_2 particles in photo electrochemical slurry and the relevance to photo detoxification reactions," *Journal of Physical Chemistry B*, 1991, 95(1): 221–225.

[11] M. M. Polycarpou, J. G. Uber, W. Zhong, S. Feng, and M. Brdys, "Feedback control of water quality," *IEEE Control Systems Magazine*, 2002, 22(3): 68–87.

[12] Y. C. Kim, S. Sasaki, K. Yano, K. Ikebukuro, K. Hashimoto, and I. Karube, "Photocatalytic sensor for the determination of chemical oxygen demand using flow injection analysis," *Analytica Chimica Acta*, 2001, 432(2): 59–66.

[13] 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*, 2012, 4(11): 91–98.

[14] P. Whig and S. N. Ahmad, "On the performance of ISFET-based device for water quality monitoring," *International Journal of Communications Network and System Sciences*, 2011, 4(11): 709–719.

[15] P. Whig and S. N. Ahmad, "DVCC based readout circuitry for water quality monitoring system," *International Journal of Computer Applications*, 2012, 49 (22): 1–7.