Simulation and Performance Analysis of Low Power Quasi Floating Gate PCS Model

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Abstract: The Spice Model for photo catalytic sensor (PCS) proposed by Whig and Ahmad overcome several drawbacks like complex designing, non-linearity and long computation time generally found in Flow Injection Analysis (FIA) technique by Yoon-Chang Kim et al for the determination of Chemical Oxygen Demand (COD). FIA technique involves the complete analysis including sampling and washing. Flow Injection Analysis is analytical method for the measurement of chemical oxygen demand using photochemical column. This method uses a bulky setup and takes 10-15 minutes to get the output result which is a tedious and time consuming job. If conventional method is continuously used for a long time than it is stable only for 15 days. The purpose of this paper is to propose a new Quasi Floating Gate Photo Catalytic Sensor (QFGPCS) approach which has low power consumption and compared the results with the conventional models. The proposed model operates under sub threshold conditions which are appreciated in large integrated system design. The results of simulation were found to be fairly in agreement with the theoretical predictions. The results are exhibited near linear variations of parameters of interest with appreciably reduced response time.

Keywords: QFGPCS, SPICE modeling, Simulation, Photo catalytic sensor, Flow injection analysis, Macro model.

1. Introduction

In the field of artificial waste water analysis and COD determination, TiO_2 sensors have large number of potential applications due to their highly efficient photo activity, steadiness and least cost. From the earlier times TiO_2 is used as white pigment which is safe for human use. The results achieved by the use of TiO_2 Photo Catalytic Sensor are in good agreement with those from the conventional Dichromate method. Very complex and bulky set up is needed for the conventional method used for Photo Catalytic Sensor applications and consumes a plenty of time for computation. To provide a solution to these problems and make the application faster, Whig and Ahmad (2013) developed a Simulation Program with Integrated Circuit Emphasis (SPICE) model for Photo Catalytic Sensor. With the advancement in semiconductor technology development of sensors has become easy due to advantages of low power, high speed signal processing capabilities. CAD tools are an added advantage as they provide a method for simulation and synthesis of semiconductor sensors. By using the SPICE model, the size and power of the overall system can be minimized thus increasing the reliability of the system.

The first floating gate (FG) device was reported by Sze in 1967 [1]. FG's are generally used in digital memory applications but recently some new applications of FG have been developed in which they are used as circuit elements. FG circuits are generally considered for systems requiring low power consumption and controlled second order effects as compared to other technologies. There is a

recent trend towards utilizing FG to solve the practical problems associated with analog and digital circuits.

An FG is made up of a poly silicon gate which is covered by silicon dioxide. FG technology is used by Harrison and colleagues to remove the on chip biasing voltages. This is done by providing these voltages on-chip with arrays of programmable FG voltages [2]. FG technology is also used in advanced analog or mixed mode VLSI chips having large numbers of inputs and analog parameters. On chip technology reduces the complexity of the system due to negligible interconnection length. A new name called neuron MOS transistors had been given to FG devices by Shibata and Ohmi [3], due to analogy between the function performed by these devices and cells in the nervous system. These devices are referred as multiple input FGMOS by Yang and Andreou [4]. The concept of FGMOS transistors introduced by Shibata and Ohmi has resulted in a number of interesting analog and digital signal processing circuits, which also includes a multiple input FG, differential amplifier [5] and D/A converters.

There is a strict requirement of knowledge of code structure and sub routines for modeling the MOSFETs [6] and it is based on an appropriate SPICE version. This paper presents a SPICE macro model for FGPCS which has been implemented in Tanner tool. A large number of MOSFET models operating in sub threshold region are present in this tool. The basic model of FGPCS consists of an oxygen sensitive surface which has an insulator layer of Titanium Oxide (TiO_2) exposed to an electrolyte solution. When a p–type semiconductor and TiO_2 insulator are placed in an aqueous electrolyte solution the reaction (response) of FGPCS to O_2 can be elucidated in terms of photo catalysis. At submicron level, gate oxide has very small thickness. As the dimension of gate oxide decreases the leakage currents of MOSFETS are increased due to tunnelling of the charge carriers which results in diminution of reliability of the device. For continuous reduction of the dimensions materials having much higher permittivity than silicon dioxide are used. The combination of Cassius–Mosetti equation with permittivity is given by Stephen *et al.* (1997). According to them, when permittivity of the dielectric increases, the band gap of dielectric material decreases resulting in tunnelling phenomenon [7]. Brown and Grannemann in 1978 studied that capacitance in accumulation is generally found to depend on gate bias. But as compared to Capacitance Voltage (CV) curve of SiO_2 capacitor this effect is less pronounced

in TiO_2 capacitor sensor. From the CV measurements of TiO_2 capacitor it was found that mid-gap interface state density was typically found to be between 3×10^{10} and 10^{11} $V^{-1}cm^{-2}$. It is described by Fuyuki and Matsunami (1986) that the magnitude of the interface state density for TiO_2 capacitor is given by the product of conductance of TiO_2 at fixed dc bias and peak conductance frequency. The width of accumulation layer is determined by the wave function of the Eigen states explained by (Duffy, 1990; Rausch and Burte, 1992). The solution of the Schrodinger equation at the interface leads to Airy function which produces an average position for accumulation of carriers in the ith energy state.

$$ Ei \approx \left[\frac{h^2}{8\pi^2 m^*}\right]^{\frac{1}{3}} \left[\frac{3\pi}{2} qF_s \left(i + \frac{3}{4}\right)\right]^{\frac{2}{3}} \qquad (1) $$

Where q is the electron charge, F_s is the electric field at the surface, E_i is the ith energy level, m^* is the effective mass and h is Plank's constant. For reasonable assumptions the accumulation layer thickness (x) should be of the order of 40 Å. Thus the tunnelling effect is small for TiO_2 layers with thickness much greater than 15 Å. To consider this effect a series capacitance is added to C_{ox} which is called quantum capacitance C_q and therefore equivalent capacitance C_M is given by

$$ \frac{1}{C_M} = \frac{1}{C_q} + \frac{1}{C_{ox}} = \frac{t_{Tio_2}}{A\varepsilon_{Tio_2}\varepsilon_o} + \frac{\langle x \rangle}{A\varepsilon_{Si}\varepsilon_o} \qquad (2) $$

In this research study the simulation of Low Power Quasi Floating Gate PCS is presented further the result obtained is compared with previous PCS designs.

2. Floating Gate PCS (FGPCS) Model

The structure of FGPCS is similar to that of PCS model having gate terminal placed in the solution proposed by [8] Whig and Ahmad. The gate of the FGPCS is electrically isolated which creates a floating node in the DC, and a number of secondary gates called control gates are deposited above the floating gate which are electrically isolated. The voltage on the floating gate can be determined by the amount of charge deposited on it and the voltage on the multiple gates, source, drain and substrate which in turn modulates the channel conductivity [9].The structure of FGPCS is shown in Fig. 1.
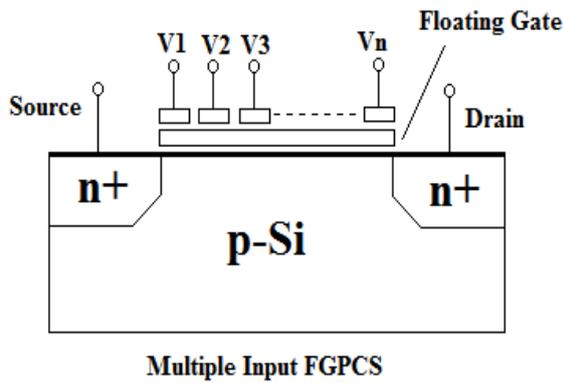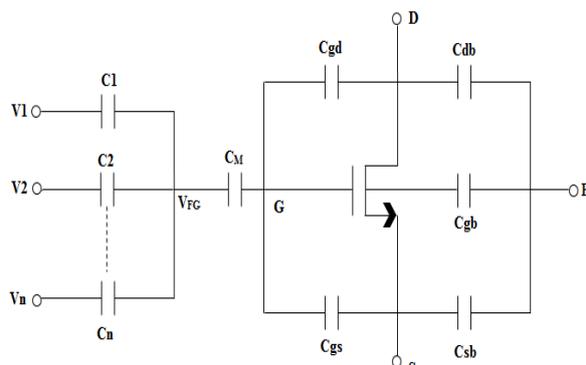
Figure.1 Cross section of FGPCS.

Figure.2 Circuit for FGPCS

The equivalent circuit for structure of FGPCS is shown in Fig.2. The FG of the structure is capacitive coupled to the inputs and the voltage present at these gates can modulate the channel current. The expression for the floating gate voltage V_{FG} for FGPCS is given as:

$$VFG = \frac{C_{gd}V_D + C_{gs}V_S + (C_{gb} + C_{db} + C_{sb})V_B + q_{FG} + \sum_{i=1}^{N} C_i V_i}{C_{Total}}$$

(3)

Where
C_{Total} = Total parasitic capacitance
V_{FG} = Floating gate voltage
V_i = Voltage of ith control gate
q_{FG} = Total charge on floating gate
C_{fgs} = Capacitance between gate and source.
C_{fds} = Capacitance between drain and source.
C_{fgd} = Capacitance between gate and drain.
C_{fgb} = Capacitance between gate and bulk.
C_{fdb} = Capacitance between drain and bulk.
V_S= Source Voltage
V_D= Drain Voltage
V_B= Bulk Voltage

Large number of striking features consisting of low-voltage and low-power are provided by FGPCS device. Both linear and non-linear functions can be implemented easily with it. Moreover, designers can add extra inputs to provide tunability to the circuit.

The FGPCS has a sensitive surface which 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 deep submicron level. TiO_2 beads are used to vary the COD concentration in the water and its properties like non photo-corrosive, nontoxic and capable of the photo oxidative destruction of most organic pollutants makes its 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.
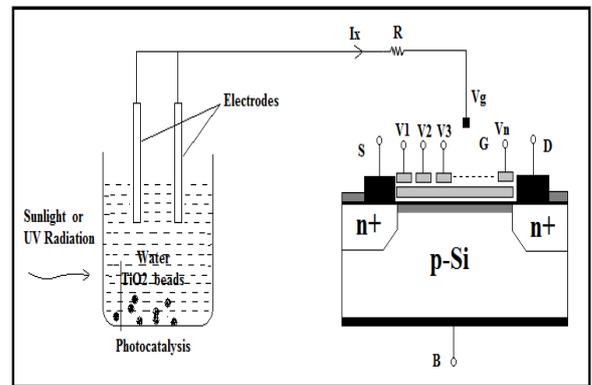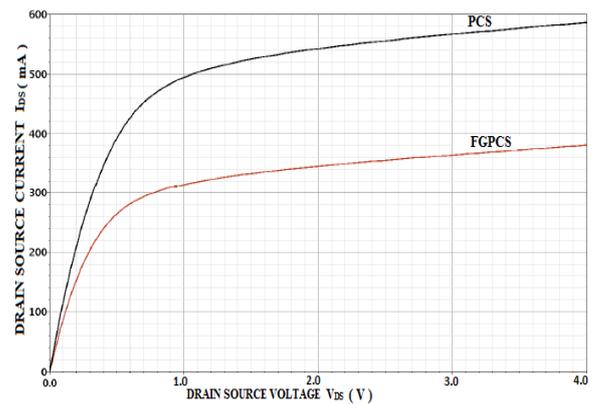

Figure.3 Sketch of PCS.

Figure.4 Characteristics curves for FGPCS and PCS

Due to the Photo Catalysis of TiO_2 beads present in the water the current I_x through the wire varies which in turn varies the gate voltage V_g of FGPCS. As the photo catalysis occur, the maximum current decreases. It is observed that for a given sample

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when decrease in maximum current takes place due to photo catalysis there is corresponding decrease in the V_{gs} and drain current I_{ds}.

The output characteristics for the conventional PCS and FGPCS are shown in Fig 4. The curves are drawn between I_{ds} and V_{ds} for PCS and FGPCS for O_2=1mg/L with E_{ref}=0. It can be seen from the figure that current for FGPCS is lower than PCS at same voltage thus saving a power of about 30-40 % and the threshold voltage for FGPCS is less than conventional PCS model.

However, the FGPCS model is not suitable because it gives low frequency response and requires large chip area. Moreover, due to isolated floating gate in FGPCS, static charge gets accumulated on it.

3. Quasi Floating Gate PCS (QFGPCS) Model

The structure of the QFGPCS is same as FGPCS model but the floating gate in QFGPCS is weakly connected to one of the supply rails through a high value of the resistor. The quasi floating gate of the PCS model is connected to the V_{DD} through a reverse bias diode connected P type MOS which acts as a large value resistor. This pull up resistor sets the dc voltage at Q_{FG} to either power rails and eliminates the power due to accumulated charge on the floating gate during fabrication process and also reduces the supply voltage requirements. The proposed structure of the QFGPCS is shown in Fig 5.
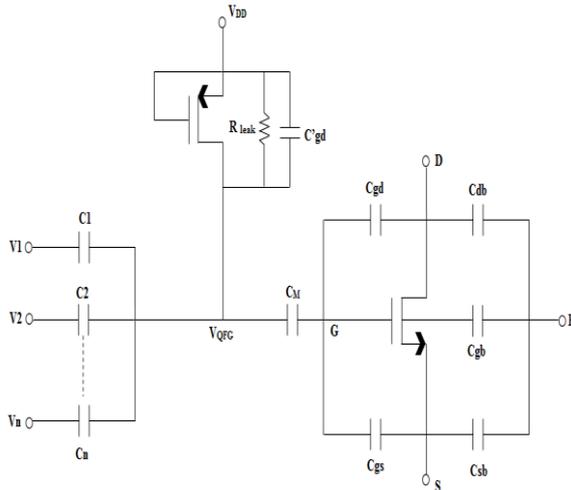

Figure.5 Proposed QFGPCS

The use of large resistance makes the quasi floating gate effectively floating for low frequency signals and ac operation of the signals of these frequency range remains unaffected.

4. Mathematical Modeling

A mathematical model is a description of a system using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modeling. The parameters like quasi floating gate voltage, parasitic capacitances, leakage resistance, drain bulk and source voltage of the given system are used to describe mathematical model.

Various parasitic capacitance of device are considered to calculate total capacitance of the device. By considering total capacitance and leakage resistance the quasi floating gate voltage V_{QFG} is given in eq. 4:

$$V_{QFG} = \left[C_{fgd}V_D + C_{fgs}V_S + \left(C_{fgb} + C_{fdb} + C_{fsb}\right)V_B + \sum_{i=1}^{N} C_i V_i\right] * \frac{sR_{leak}}{1 + sR_{leak}*C_{total}} \quad (4)$$

Where,
V_{QFG} = quasi floating gate voltage
C_{total} = Total capacitance
R_{leak} = Leakage Resistance
V_D = Drain Voltage
V_S = Source Voltage
V_B = Bulk Voltage

The drain current for QFGPCS operating in linear region is given in Equation (5):

$$I_D = \beta \left[\left(V_{QFG} - V_T\right) - \frac{V_{DS}}{2}\right] V_{DS} \quad (5)$$

Where ,
$\beta = \mu_n C_{ox} \frac{W}{L}$
μ_n = Mobility of charges
C_{ox} = Oxide Capacitance
V_{QFG} = Quasi Floating Gate Voltage
V_T = Threshold Voltage
$\frac{W}{L}$ = Width to length ratio

From Equation (4) it is observed that input signals encounter a high-pass filter with a cut-off frequency of $\frac{1}{2\Pi R_{leak}C_{total}}$ which is very low due to large value of R_{leak}. Therefore, even for very low frequencies, Equation (4) becomes a weighted average of the AC input voltages determined by capacitance ratios plus some parasitic terms.

5. Results & Discussion

The simulation of the device has been done on Tanner tool Version 15 for 90nm technology. The

developed device Model has been extensively tested and the simulation results have been compared with experimental data results of previous model. The relationship of I_{ds} with V_{gs} is shown in the Fig.6 which shows that proposed QFGPCS exhibits linear characteristic in the range of $V_{gs} = 2.5V$ to $5.0V$.
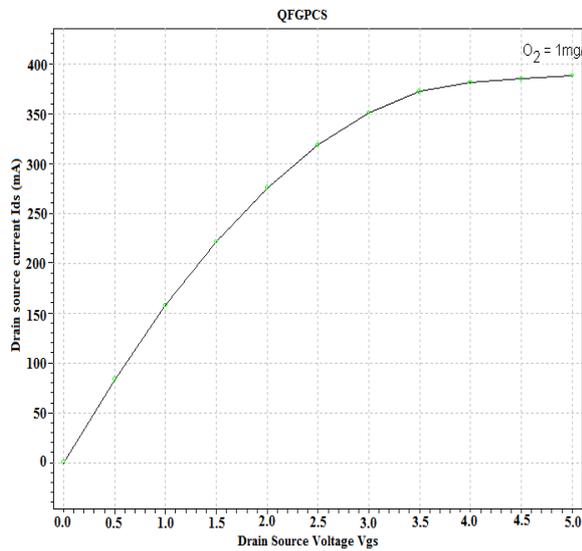

Figure.6 Characteristic curves between I_{ds} and V_{gs} at $O_2 =$1-5 mg/L obtained through SPICE.
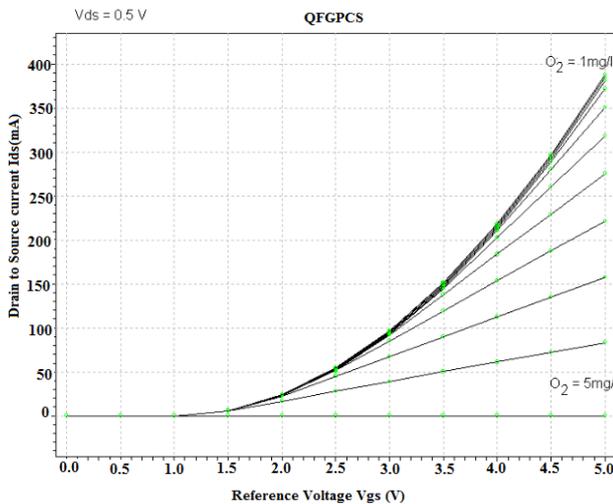

Figure. 7 Characteristic curve for QFGPCS between I_{ds} and V_{ds} obtained through SPICE.

The curves are drawn between I_{ds} and V_{gs} of QFGPCS for $V_{ds} = 0.5V$ it can be seen that the proposed QFGPCS is fairly linear for concentrations more than 1mg/L extending towards 5mg/L of O_2. This is an obvious advantage of this QFGPCS model.

By observation of Fig.7 it can be seen that the graph of I_{ds} Vs V_{gs} using QFGPCS 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 QFGPCS 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.

Table 1: Power and statistical Analysis

Parameters	PCS	FGMOS	QFGMOS
CMOS technology(nm)	70	70	70
Power supply	0 -1.5V	0 -1.5V	0 -1.5V
Average power dissipation	1.43×10^{-3}	1.44×10^{-3}	1.46×10^{-3}
Max power	2.40×10^{-3}	2.41×10^{-3}	2.42×10^{-3}
Min power	8.987×10^{-10}	8.989×10^{-10}	8.99×10^{-10}
Multiple R	0.983	0.987	0.990
R Square	0.966	0.971	0.981
Standard Error	0.026	0.023	0.020

In this design, the device is free from channel length modulation 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 2.4 mW as shown in Table 1. The slew rate of the device is good. The output observed in Fig. 4 is highly linear, indicating that the device is stable. The output of the device is obtained and statistical analysis has been done. The various parameters are tabulated in the Table 1. Coefficient of Determination R^2 is found to be 98.1% with standard error of 0.020.

6. Conclusion

A significant advantage of the proposed design is a simple architecture, and hence it is very suitable for water quality monitoring applications. This study can be extended and more improvement in terms of power and size can be achieved at wiring and layout characteristics level and more effective results can be obtained.

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