# Modeling and discussion of threshold voltage for a multi-floating gate FET pH sensor*

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**Abstract:** Research into new pH sensors fabricated by the standard CMOS process is currently a hot topic. The new pH sensing multi-floating gate field effect transistor is found to have a very large threshold voltage, which is different from the normal ion-sensitive field effect transistor. After analyzing all the interface layers of the structure, a new sensitive model based on the Gauss theorem and the charge neutrality principle is created in this paper. According to the model, the charge trapped on the multi-floating gate during the process and the thickness of the sensitive layer are the main causes of the large threshold voltage. From this model, it is also found that removing the charge on the multi-floating gate is an effective way to decrease the threshold voltage. The test results for three different standard pH buffer solutions show the correctness of the model and point the way to solve the large threshold problem.

**Key words:** pH sensor; MFGFET; threshold voltage

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## 1. Introduction

The ion-sensitive field effect transistor (ISFET) first used as a pH sensor was proposed and demonstrated by Bergveld in 1970[1]. An ISFET can be considered as a special type of MOSFET without a gate, and the gate oxide is coated with a sensitive layer. When the ISFET is placed in solution, surface chemistry generates a potential drop $\phi_{e0}$ at the electrolyte–insulator (EI) interface. The Nernst equation relates $\phi_{e0}$ to the activity in a solution of $H^+$ based on the site-binding model, and this equation predicts a change in $\phi_{e0}$ of 58 mV per pH unit[2]. The variation of $\phi_{e0}$ induces alteration of the electric field in the insulator semiconductor interface and modulation of the channel conductance and current. This change also reflects the variations of the threshold voltage.

pH sensors compatible with the CMOS process can be directly applied to the design of systems which include pH sensors, signal-processing circuits and other CMOS compatible sensors. A multi-floating gate field effect transistor used as a pH sensor was reported by Bausells in 1999[3]. The device is fabricated by an unmodified CMOS technology, with an electrically floating gate consisting of a polysilicon layer and multi-layer metals. The passivation silicon nitride layer acts as the pH-sensitive material. It is found to have a very large threshold voltage and cannot be explained by the usual sensitive ISFET model[4]. Compatible with the CMOS process is a way to realize the trend of lab-on-a-chip, and a new model of this new structure is necessary to deepen the research.

Based on the 0.6 $\mu$m 2 poly, 2 metal CMOS process supported by the MPW project, this paper presents a totally unmodified CMOS integrated pH sensor. Different interfaces in the MFGFET pH sensing unit are abstracted and analyzed. The threshold voltage sensitive model of MFGFET is built according to electric neutrality. From the model, the large threshold voltage is caused by the trapped charge on the multi-floating gate. The voltage drop on the multi-floating gate is perceived as an equal shift in the ISFET threshold voltage. The test results verify the correctness of this model. Also, according to the model, an effective way to expose the device to UV radiation is to remove the charge on the multi-floating gate and decrease the threshold voltage.

## 2. Modeling and testing

### 2.1. ISFET threshold model

The threshold model describing the behavior of the ISFET can be derived from the analogous MOSFET model, by taking into account the potential differences among the new EI interface of the system[5]:

$$V_{th} = E_{ref} + \phi_{lj} + \chi^{sol} - \phi_{e0} + 2\phi_f + \phi_{MS} - \frac{Q_i}{C_{ox}}, \qquad (1)$$

where $V_{th}$ is the threshold voltage of ISFET, $E_{ref}$ is the potential of the reference electrode; $\phi_{lj}$ is the liquid-junction potential difference between the reference solution and the electrolyte; $\chi^{sol}$ is the electrolyte-insulator surface dipole potential; $\phi_{e0}$ is the potential of the EI interface, which is modeled as a linear voltage source based on site-binding theory and the Gouy–Chapman–Stern model[6]; $\phi_f$ is the Fermi potential of the semiconductor, and $\phi_{MS}$ is the difference in work functions

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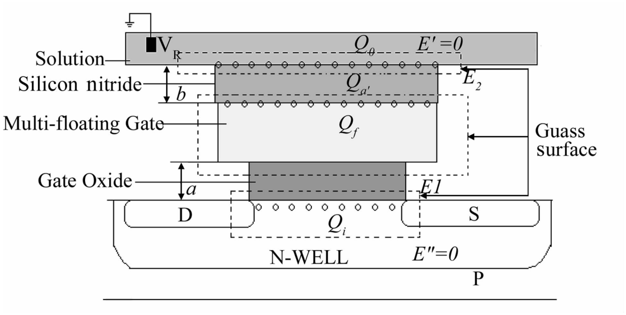


Fig. 1. Effective model of the CMOS MFGFET.

between the gate and the semiconductor. $Q_i$ includes the silicon surface states charge and the depletion charge in the silicon, and $C_{ox}$ is the capacitance of the gate oxide.

It is clear that $E_{ref}$, $\phi_{lj}$, $\chi^{sol}$ are constants dependent on the solutions, sensitive layer materials and deposition process. Together with $\phi_{e0}$, they give an additional value to the normal MOSFET threshold voltage. So, the pH change can be obtained from monitoring the threshold voltage of the ISFET.

### 2.2. MFGFET threshold model

The structure of the MFGFET pH sensing unit is different from that of the ISFET. The polysilicon gate is retained, which is necessary in the standard CMOS process. We can analyze and research the CMOS pH sensor in depth by modeling it. ISFET noise has been shown to be dominated by the noise in the FET which at low frequencies is predominantly $1/f$ noise. The $1/f$ noise in a pMOSFET is nearly 100 times lower than in an nMOSFET, so an MFGFET based on a pMOSFET was designed[7]. Figure 1 shows the layers in the CMOS MFGFET model. The model mainly considers the two insulators and the conducting multi-floating gate. The first insulator is the thin gate oxide, and the second insulator is the silicon nitride, which is the sensitive layer. There are three Gauss surfaces as indicated in Fig. 1. According to the Gauss theorem, we get the following equations:

$$Q_0 + Q_d = \varepsilon_0\varepsilon_2 E_2, \tag{1}$$

$$Q_f = \varepsilon_1\varepsilon_0 E_1 - \varepsilon_2\varepsilon_0 E_2, \tag{2}$$

$$Q_i = -\varepsilon_1\varepsilon_0 E_1, \tag{3}$$

where $Q_0$ is the solution charge, $Q_d$ is the charge adsorbed in the sensing layer, $Q_f$ is the multi-floating gate charge, and $E_1$, $E_2$, $\varepsilon_1$, $\varepsilon_2$ are the electric fields and dielectric constants.

Figure 2 shows the charges in the layer and potential profiles of a CMOS MFGFET system. A balance equation is written after applying a voltage $V_R$ to the solution.

$$V_R = E_{ref} + \phi_{lj} + \chi^{sol} - \phi_{e0} + E_1 a + E_2 b + V_S + \phi_{MS}, \tag{4}$$

where $a$ and $b$ are the thicknesses of the gate oxide and silicon nitride. From Eqs. (2)–(4), we get:

$$V_R = E_{ref} + \phi_{lj} + \chi^{sol} - \phi_{e0} + V_S + \phi_{MS} - \frac{Q_i}{C_A} - \frac{Q_f}{C_2}, \tag{5}$$

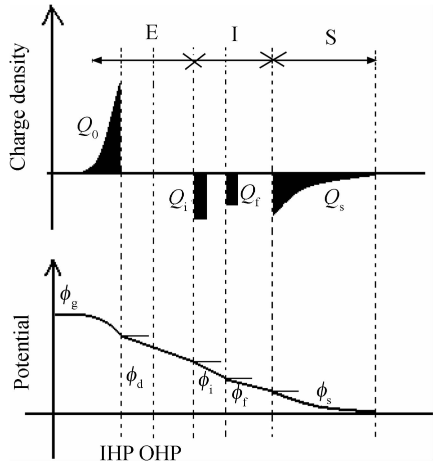


Fig. 2. Charges and potential profiles of a CMOS MFGFET system.

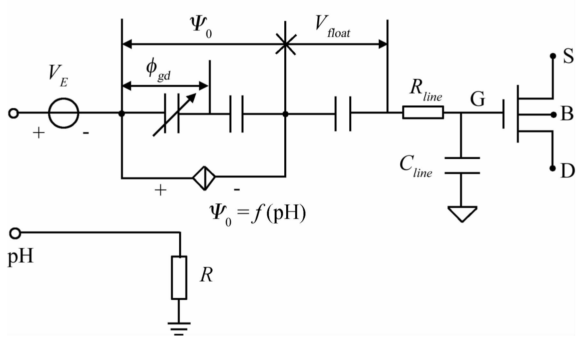


Fig. 3. Equivalent electric circuit of the MFGFET structure.

where

$$\frac{1}{C_A} = \frac{1}{C_{ox}} + \frac{1}{C_2},$$

$$C_{ox} = \varepsilon_1\varepsilon_0/a, \ C_2 = \varepsilon_2\varepsilon_0/b.$$

The threshold voltage of MFGFET $V_{th}^{*}$ can be obtained when the surface voltage in the oxide and silicon substrate reaches twice the Fermi voltage.

$$V_{th}^{*} = E_{ref} + \phi_{lj} + \chi^{sol} - \phi_{e0} + 2\phi_f + \phi_{MS} - \frac{Q_i}{C_A} - \frac{Q_f}{C_2}. \tag{6}$$

It is obvious that the new extra multi-floating gate layer causes some changes. The capacitance of the gate oxide $C_{ox}$ is substituted by the series capacitance of the gate oxide and silicon nitride. Also, a linear shift $Q_f/C_2$ is added, and the value is decided by the charge and thickness of the multi-floating gate layer. Here, we hypothesize that the charge density on the gate is not interrupted by other interface charges. The charge trapped on the multi-floating gate is decided by the CMOS process, and has no influence on the EI potential $\phi_{e0}$. So, the multi-floating gate structure will bring in an extra potential drop, and linearly change the threshold voltage.

The new equivalent circuit (macromodel) of the MFGFET is shown in Fig. 3. The electrochemical stage of the MFGFET has been translated into an equivalent circuit and results in a macromodel. $R_{line}$ is the resistance of the metal interconnect, and $C_{line}$ is the capacitor of the metal and substrate.

The equivalent circuit of the MFGFET, which models the electrochemical behavior, can be used as a new device unit for

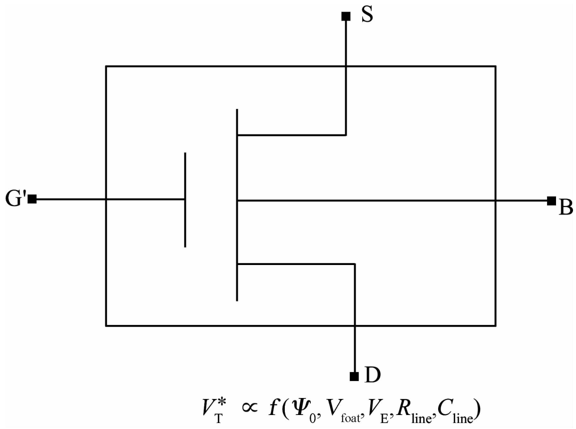


Fig. 4. SPICE subcircuit block.

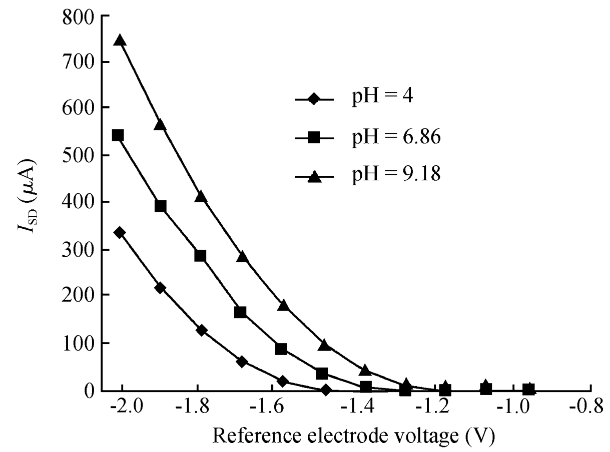


Fig. 5. Simulation results of input characteristic of the MFGFET (PMOS) when $Q_f = 0$.

designing pH sensors or MFGFET-based microsystems. We define the macromodel in SPICE as a subcircuit block. Figure 4 shows the outer connection of the block, where G' stands for the reference electrode. The threshold voltage model file can be modulated according to Eq. (6), so the input characteristic in different pH solutions can be simulated.

When simulating the input characteristic of the MFGFET, the charge on the floating gate is not clear and cannot be estimated. We hypothesize that the charge on the floating gate is zero. The simulation result is shown in Fig. 5. The threshold voltage is about $-1.47$ V when the pH of the solution is 4.

In order to verify the model, we have fabricated an MFGFET in the 2-metal, 0.6 $\mu$m process from the MPW project in Shanghua[8]. The MFGFET has a channel length of 20 $\mu$m and width of 1 mm. The source and drain regions were arranged interleaved.

A semiconductor parameter analyzer was used to measure the threshold voltage of the MFGFET pH sensor. The source drain voltage was kept at 0.2 V. A group of curves in different standard pH buffer solutions (4, 6.86, and 9.18) are shown in Fig. 6. The electrical threshold voltage is –1.0 V, and the threshold voltage in solution is about –7.1 V. It is larger than simulated.

Though the threshold voltage of the MFGFET pH sensor

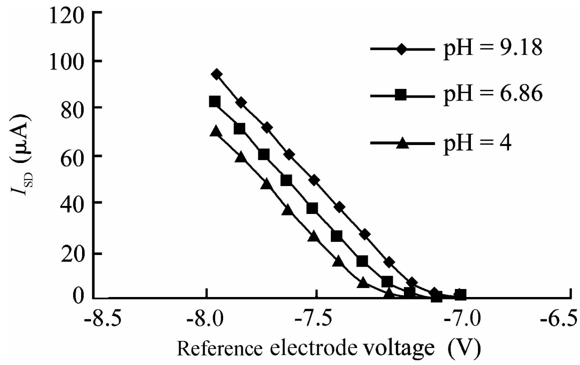


Fig. 6. Input characteristic in different pH solutions.

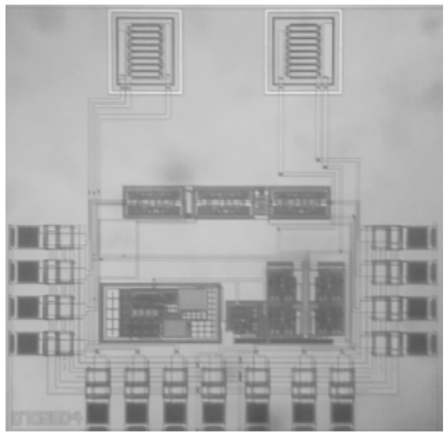

Fig. 7. Photo of the MFGFET pH sensor.

is large, the trend that voltage increases with the pH value is the same as the simulation results. Combined with the model we get, the large drift of the threshold is caused by the multi-floating gate. The existence of $Q_f$ has significantly shifted the threshold voltage. In different solutions, the charge on the multi-floating gate is considered to remain constant. It will not affect the sensitivity of the MFGFET, and the pH sensitivity of the MFGFET was investigated through a shift in the different threshold voltages. The sensitivity of the MFGFET is around 35.8 mV/pH.

The big negative threshold voltage cannot be adopted by the CMOS power voltage, and it is difficult to bias the MFGFET properly. As the model shows, an effective way is to reduce the charge on the multi-floating gate. According to the mechanism to erase the EPROM, the sensor chip was exposed to UV radiation with 398 nm wavelength. The UV radiation can reach the multi-floating gate layer, and force the trapped charge across the gate oxide and into the substrate. After exposing the MFGFET pH sensor to UV radiation for 10 h, the threshold voltage increases from –7.1 to –1.38 V when the pH of the solution is 9.18.

The test results above indicate that the MFGFET can be used as a pH sensing unit. The threshold voltage sensitive model can reflect the characteristic of the MFGFET correctly. The threshold voltage is large because of the multi-floating gate structure. After exposure to UV radiation, the threshold voltage is increased and the output linear range is not changed.

A photo of the new structure pH sensor is shown in Fig. 7.

The area of the chip is $2 \times 2$ mm$^2$. All the pads are arranged on one side of the chip for easy insulating.

## 3. Conclusion

The new MFGFET pH sensing unit is completely compatible with the standard CMOS process. The threshold voltage of the MFGFET pH sensor is large. A new sensitive model is built in this paper. The model considers two insulating layers and a multi-floating gate layer. The basic principles of the Gauss theorem and charge neutrality are adopted. From the model, the charge on the multi-floating gate and the thickness of the sensitive layer are the main factors of the large threshold voltage. The signal processing circuit cannot be biased properly because of the large threshold voltage. From the model, one way of reducing the threshold voltage is to remove the charge on the floating gate. The best way we can come up with is UV radiation. We can explain the large threshold voltage successfully and point the way to solve this problem based on the model. The test results verify the correctness of the new model. Thus, the pH sensor is compatible with the CMOS process, and can be integrated with other CMOS electronics and sensors. Here, a qualitative analysis based on the new model is clear; how the threshold voltage is affected by the layout structure of the drain/source and the size of the multi-floating gate layer will be the subject of our subsequent research.

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