Optical and impedance characteristics of EGFET based on SnO_2/ITO sensing gate

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Abstract: In this research, the optical effect and contact area characteristics of extended gate field effect transistor (EGFET) based on tin oxide/indium tin oxide (SnO_2/ITO) sensing gate were investigated. This separate structure EGFET is formed by dividing an ion sensitive membrane from the field effect transistor. Accordingly, the field effect transistor does not need to put into solution, so we can realize the pure characteristics of optical of SnO_2/ITO sensing film. The instantaneous variation of output voltages are linear increase as the light intensity with a slope of 0.033mV/kLux. We realize that a traditional pH-ISFET sensitive film such as Si_2N_3, SiO_2, Al_2O_3 and Ta_2O_5 could not be an available sensitive film in EGFET. To interpret this phenomenon, a simplified equivalent circuit was used to understand the impedance effect of an EGFET.

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1. Introduction:

Forty years have passed since ion-selective effect transistor was proposed by P. Bergveld in 1970 [1]. The first pH-sensitive membrane is silicon dioxide (SiO_2), followed by Al_2O_3, Si_3N_4, Ta_2O_5, and SnO_2 successively put forward by researchers [2-7]. Open gate structure of ISFET makes its elements easily affected by optical effect [8]. Due to separate structure EGFET framework, the light cannot directly irritate the channel, so only surface potential of sensitive membrane will be influenced by light. This study will investigate optical effect under framework of separate structure EGFET. Furthermore, we also find traditional high resistance sensitive membrane materials such as SiO_2, Al_2O_3, Si_3N_4 and Ta_2O_5 are not applicable to separate structure EGFET. The present paper will use equivalent circuit simulation to explain influences of impedance on element signal.

2. Experimental:

Making and reading circuit and material of SnO_2/ITO EGFET are the same with references [9]. Tin oxide thin films utilize R.F. sputtering system to conduct deposition. Output signal Vo uses HP3478 to read out. Optical effect experiment uses halogen lamp, which is 30 cm away from the element.

3. Results and discussions:

3.1. Optical effect of SnO_2/ITO glass

Fig.1 shows the spectrum of the halogen lamp light source. The influence of light exposure is an inherent problem in conventional open gate ISFET. The optical radiation can result in a considerable threshold voltage shift which is caused by a perturbation of the carrier concentrations throughout the semiconductor [10]. Fig.2 shows the optical effect of the commercial ISFET (Beckman Φ™, standard probe P/N 140609).

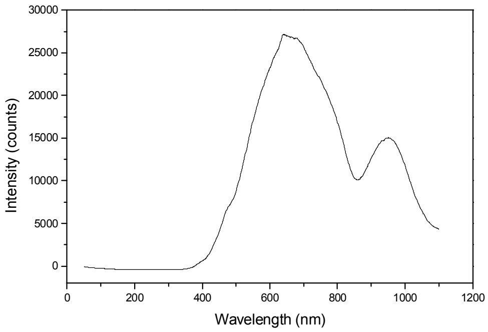


Fig. 1 Optical spectrum of the halogen lamp light source

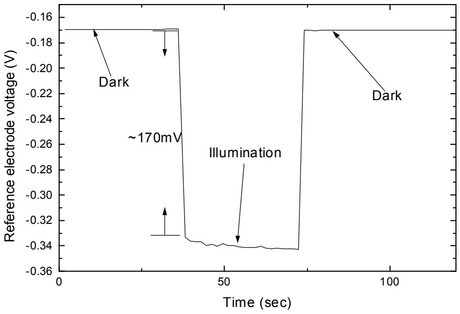


Fig. 2 Optical effect (10000Lux, pH7) of the commercial open gate ISFET (Beckman Φ™, standard probe P/N 140609)

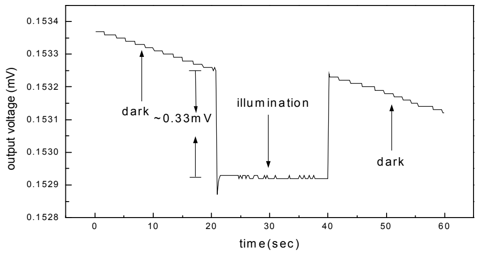


Fig. 3 Optical effect (5000Lux, pH7) of SnO_2/ITO glass EGFET

For a separate EGFET structure, that proposed in this thesis, the MOSFET part was encapsulated completely, so optical will not cause any disturbance in MOSFET part. In this situation, the optical effect will be much smaller than traditional ISFET device, and the optical effect that take place in the interface between solution and sensing film can be observed clearly. Fig.3 shows the optical effect of SnO_2/ITO glass structure EGFET. The result shows an instantaneous variation of output voltage about 0.33mV which is much smaller than the optical effect of open gate ISFET. Fig.4 shows the optical effect of SnO_2/ITO glass EGFET in different light intensity. The instantaneous variation of output voltages are linear increase as the light intensity with a slope of 0.033mV/kLux.

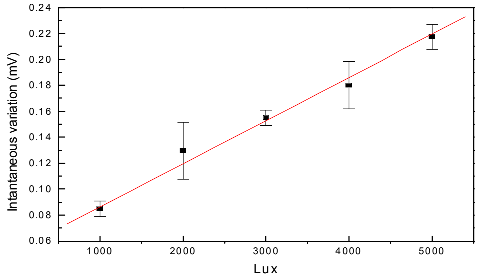


Fig. 4 Instantaneous variation of output voltages of SnO_2 /glass EGFET in different light intensity, pH7 standard buffer solution

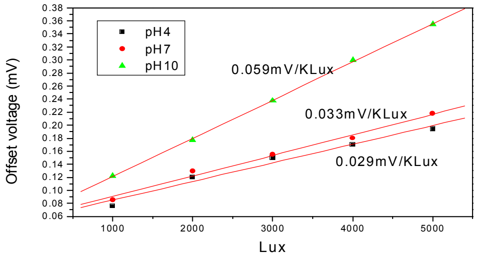


Fig.5 Optical effect of SnO_2/ITO glass in ▲pH10, ● pH7 and ■pH4 buffer solutions

According to the Boltzmann equation which can be expressed as below:

$$[H^+]_s = [H^+]_b \exp(-\frac{q\psi_0}{kT}) \quad (1)$$

where the $[H^+]_b$ and $[H^+]_s$ are the bulk and surface activity of H^+ ion, others notations are defined in ref.[8]. The pairs of electron and hole composite effect will occur in the surface of sensing film when the EGFET was illuminated. This effect will cause a decrease of the concentration of surface hydrogen ion, $[H^+]_s$. By the Eq.(1), the decrease of ψ_0, which meaning the decrease of output voltage. In additional, in a fixed light intensity, the quantity of $[H^+]_s$ reduced is fixed, too. But the total $[H^+]_s$ is decrease as pH value increase. Therefore, higher pH value will show serious optical effect.

3.2 Contact area effect of SnO_2/glass and SnO_2/ITO glass

In 1983, J. Van Der Spiegel et al. introduce the extended gate chemically sensitive field effect transistor [11]. This structure consists of an integrated coaxial cable whose signal line is connected to a high input impedance electrometer with the shield bootstrapped in order to reduce capacitive charging effects. The extended coaxial line is fabricated with a triple poly-silicon NMOS process. The chemically sensitive thin films of IrO_x, LaF_3, AgCl and Ag_2S were deposited and patterned on the four EGFETs which were used as H^+, F^-, Cl^- and Ag^+ sensors, respectively. In 1986, T. Katsube et al. used the reactively sputtered iridum oxide film (SIROF) based pH-EGFET pH-EGFET to develop the urea and glucose sensitive FETs [12]. Before our lab.'s presentation of SnO_2 film EGFET, all of the literatures that relative to pH-sensitive EGFET were used the iridium oxide film which shows very low resistance (4e-3Ω-cm)[11-13]. Moreover, there is no other literature about any development or application of EGFET. The reason is that high impedance materials, such as SiO_2, Si_3N_4, Al_2O_3, Ta_2O_5, etc., which usually used as a traditional pH-ISFET sensitive film, could not be an available sensitive film in EGFET. The equivalent circuit of non-symmetrical ion-selective device, which suggested by Janata (1983), can interpret this phenomenon (shown in Fig.6) [14]. In opinion of Janata, there are two groups of potentiometric chemical sensors: one in which the ion-sensitive membrane is part of a symmetrical arrangement (i.e., solution/membrane/solution) and devices with the arrangement, solution/membrane/solid contact. Conventional ISEs with internal filling solution/reference electrode fall into the first category, while coated wire electrode and ISFETs fall into the second. The equivalent circuit in Fig.6 describes the asymmetrical device. The reference electrode, liquid junction and the sample solution are lumped together as E_{REF}. The section SOLID can be a conductor, such as in coated wire electrode or ISFETs with a thin metallic coating. The VOLTMETER can be the solid state portion of ISFET. Consider the case when the charge-transfer resistance R_2 is very high, so much so that this interface becomes capacitive. In that case the parasitic capacitance must be small and invariable the parasitic resistance must be infinitely high in order to obtain a stable output from the voltmeter.

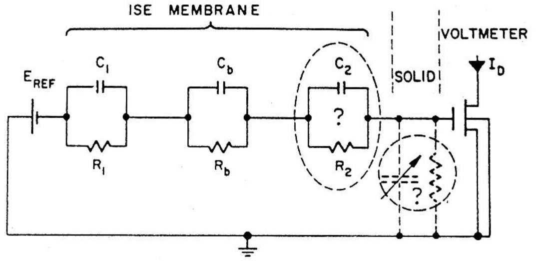


Fig.6 Equivalent circuit model for an ion sensor with solid-state internal contact[14]

In Fig.6, the parallel combinations of resistance and capacitance, R_1C_1 and R_2C_2, represent the membrane/solution and membrane/solid interface, respectively. R_bC_b represents the bulk region of the membrane. The parasitic capacitance and leakage associated with the voltmeter input are presented in the circle.

An ISFET, however, in which the membrane is placed directly at the input insulator of the voltmeter, is an extreme case in which the length of the conductor is zero [14]. Let's now consider the time response of EGFETs, which the simplified equivalent circuit was show in Fig.7, where V_o is the applied voltage step, C_{gs} and R_{gs} are the input capacitance and resistance, respectively, R_B and C_B are the lumped parallel resistance and capacitance of the membrane, respectively.

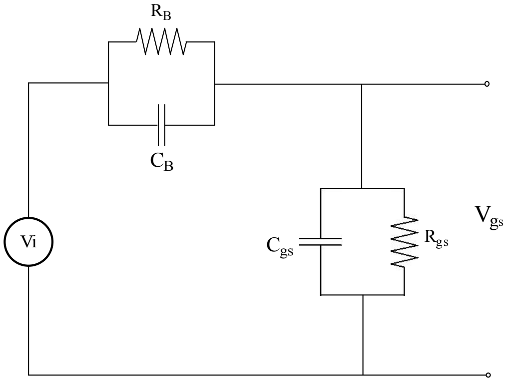


Fig. 7 The simplified equivalent circuit of EGFET

In the case that the sensitive film is low impedance material, such as I_rO_x, SnO_2 films, the input resistance R_{gs} can be seen infinite. The formula for the time response of the gate-to-source voltage, V_{gs}, is:

$$V_{gs} = V_o \frac{C_B}{C_B + C_{gs}} \exp(-\frac{t}{R_B(C_B + C_{gs})}) + V_o(1 - \exp(-\frac{t}{R_B(C_B + C_{gs})})) \quad (2)$$

and

$$V_{gs}(t = 0) = V_i \frac{C_B}{C_B + C_{gs}} \quad V_{gs}(t = \infty) = V_i \quad (3)$$

But in the case of very high impedance materials, such as Ta_2O_5, Si_3N_4, etc., the response time will be longer and the output voltage will be shared by the R_B and R_{gs}. The time response of V_{gs} is:

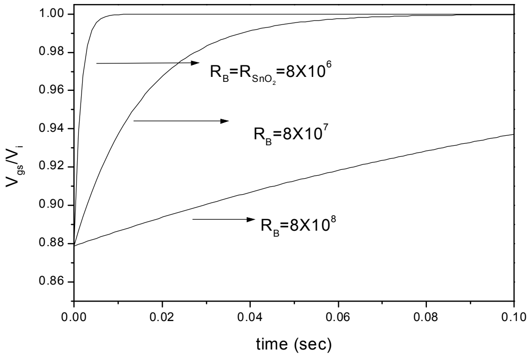
$$V_{gs} = V_o \frac{C_B}{C_B + C_{gs}} \exp(-\frac{t}{(R_B // R_{gs})(C_B + C_{gs})})$$

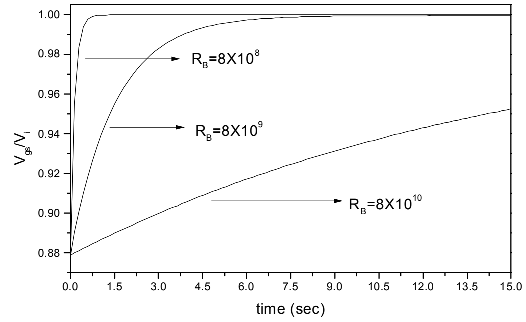
$$+ V_o \frac{R_{gs}}{R_{gs} + R_B} (1 - \exp(-\frac{t}{(R_B // R_{gs})(C_B + C_{gs})})) \quad (11)$$

and

$$V_{gs}(t = 0) = V_i \frac{C_B}{C_B + C_{gs}} \quad (4)$$

$$V_{gs}(t = \infty) = \frac{R_{gs}}{R_{gs} + R_B} V_i \quad (5)$$





The simulation of V_{gs}/V_o time response with different sensitive film resistance (R_B) is shown in Fig.8. The simulations are based on a MOSFET with a C_{gs}=23pF and R_{gs}=0.1935X10^{14}Ω, and a SnO_2 sensing film with $R_B=R_{SnO_2}$=8X10^6Ω and $C_B=C_{SnO_2}$=166.7pF. The results of Fig 18(a),(b),(c) show that the response time will be increase as the resistance of R_B. In other word, the initial voltage effect, $V_{gs}(t=0) = V_i \frac{C_B}{C_B + C_{gs}}$, will be more serious in the situation of higher resistance R_B, and the variation of parasitic capacitance in conduction line will make more noise. In additional, if the resistance of R_B more close R_{gs} or higher than R_{gs}, the voltage sharing effect of R_B in steady state will be more serious. In a conclusion of the simulation of EGFET circuit model, for a sensitive film of EGFET, high capacitance and low resistance material properties are necessary. SnO_2/ITO glass EGFETs show a normal pH-sensitivity as the contact window beyond 0.8 mm^2, which the result shows in Fig. 9.

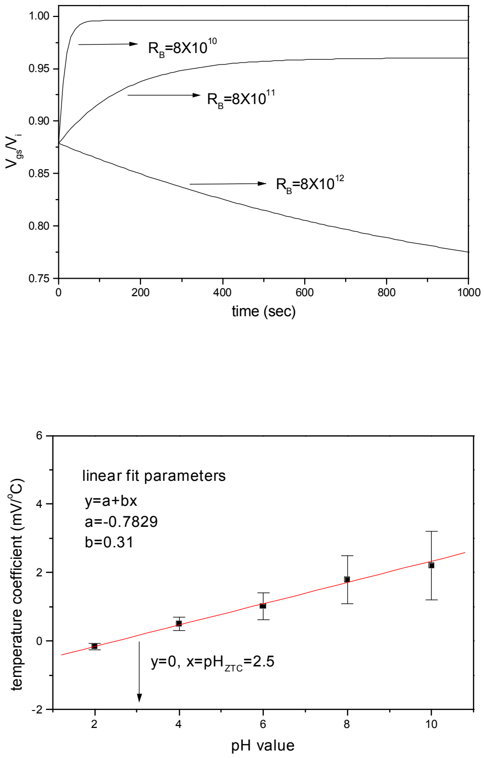


Fig. 8 The simulation of equivalent circuit of EGFET, C_B=166.7pF, C_{gs}=23pF, R_{gs}=0.1935X10^{14} Ω, (a)R_B=8X10^6Ω, 8X10^7Ω and 8X10^8Ω,(b) R_B=8X10^8Ω,8X10^9Ω and 8X10^{10}Ω, (c)R_B=8X10^{10}Ω,8X10^{11}Ω and 8X10^{12}Ω.

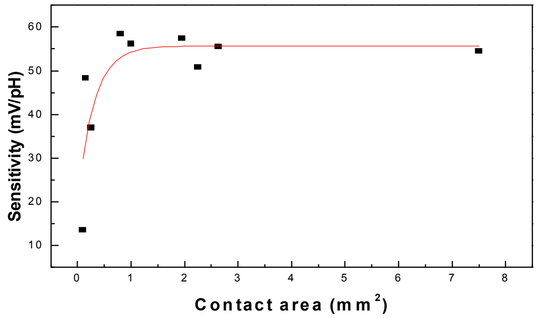


Fig. 9 The relation between contact area and pH-sensitivity SnO_2 / ITO glass structure EGFET

4. Conclusions:

The experimental data show that the separate EGFETs based on SnO_2/ITO glass have a minor optical effect. The instantaneous variation of output voltages are linear increase as the light intensity with a slope of 0.033mV/kLux. The result shows that the optical effects are not only dependent on the sensing material and light intensity but also the pH value, which means higher pH value causes more serious optical effect.

A simplified equivalent circuit was used to interpret the contact window effect of an EGFET. Basically, a smaller contact window shows lower resistance and capacitance of the sensing film, serious voltage sharing effect and temporal response effect. It also gives a reason that highly insulated materials, such as Al_2O_3, Si_3N_4, Ta_2O_5, Al_2O_3, cannot be used as a sensing film for EGFET. Separate EGFET based on SnO_2/ITO glass shows a contact window effect below a contact area of 0.8mm^2.

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