Effects of Poly(3-hexylthiophene) Concentration on Performance of Extended-Gate Field-Effect Transistor for Silver Ion Detection

E-Ling Huang¹, Wei-Fan Chen¹, Wei-Chou Hsu¹*, Jung-Chuan Chou¹, Chiu-Sheng Ho¹, En-Ping Yao¹, Hsiang-Wei Liu¹, Ying-Chun Kao¹
¹ Institute of Microelectronics, Department of Electrical Engineering, and Advanced Optoelectronic Technology Center, National Cheng Kung University, No. 1 University Road, Tainan, 70101, Taiwan, Republic of China
Phone: +886-6-2757575#62350 E-mail: wchs@eembox.ncku.edu.tw


Abstract

The characteristics of selective silver ion sensors are developed by extended-gate field-effect transistor (EGFET) are reported. In comparison with various concentrations of P3HT, the 70 mg/ml P3HT exhibits an excellent sensitivity of 68.15 mV/decade and a linearity of 0.969 in the silver ion range of 10⁻¹ M to 10⁻⁷ M. We believe that broad orientation distribution of crystalline domains, which caused more interaction between Ag⁺ and conjugated polymer backbone, and lead 70 mg/ml P3HT films in Ag⁺-EGFET have high sensitivity.

1. Introduction

In 1983, J. V. D. Spiegel et al [1] investigated extended gate field effect transistor (EGFET). The characteristic of EGFET structure is chemical sensitive area isolated from MOSFET, and this makes the device has many advantages, including simplicity of packing and passivation. In 2000, the research of J. C. Chou. et al [2] is different from Van Der Spiegel et al, which designed silicon oxide (SiO₂) sensing membrane to connect with gate of commercial MOSFET CD4007 UB, realized that great linearity and sensitivity of pH sensor. Recently, numerous researchers attempted to extend EGFET application for ion sensor and biosensor by using several sensing membrane integrated with biological and chemical modification, such as tin dioxide [3], carbon nanotube[4], ZnO nanostructure[5] and gallium nitride [6].

Conducting polymer (CP) has been widely applied for organic thin film transistor (OTFT), solar cell, chemical sensor and biological sensor because of desirable properties [7]. The chemical bond and electrical conductivity made the CP more multifunctional than traditional semiconductor, for example J. W. Jenong et al [8] developed gas sensor based on poly(3-hexylthiophene) (P3HT) transistors by P3HT acting NH₃ gas receptor and signal transformer. Recently, M. Vazquez et al [9] investigated the poly(3-octylthiophene) (POT) applied for silver ion selective electrodes (Ag⁺-ISEs) that indicated Ag⁺ interacts with sulfur atom and double bonds in POT and other poliythiophenes. According to above investigations, we integrated P3HT thin films into EGFET as silver ion sensed membrane, and had developed extended gate field effect transistor for selective silver ion sensors (Ag⁺-EGFET) successfully. Furthermore, effects of various P3HT concentrations on surface morphology and crystalline structure correlate to performance of EGFET applied for silver ion are investigated.

2. Results and Discussion

The diagram of extended-gate field-effect transistor (EGFET) is shown in Fig. 1(a). Extended-gate FET structure includes two parts: One of parts is electrochemical cell, also called sensitive part, where includes working electrode (WE) and reference electrode (RE), the other is commercial n type metal-oxide-semiconductor field-effect-transistor (n-MOSFET, CD4007). The gate of n-MOSFET connects to working electrode as extended-gate. The structure of electrochemical cell is shown in Fig. 1(b). The reference electrode was Ag/AgCl (sat. NaCl). The ITO glass substrates, purchased from Luminescence Technology Corp, Taiwan, which sheet resistance is 5 Ω/sq. Poly(3-hexylthiophene) (P3HT), obtained from Luminescence Technology Corp, blended with 1,2-dichlorobenzene (DCB) to obtain various concentrations of P3HT solutions range from 30 mg/ml to 70 mg/ml. Teflon tape was used for package and defined 3 mm diameter sensor area. X-ray determination method was recorded using Rotating Anode X-ray Generator (D/MAX 2500, Rigaku) with a low grazing angle incidence.

![Fig. 1](image-url)
The drain-source current ($I_{ds}$) versus reference electrode voltage ($V_{ref}$) curves of extended-gate field-effect transistor for selective silver ion sensors (Ag⁺-EGFET) based on 70 mg/ml P3HT thin film were measured in various AgNO₃ concentrations ranging from $10^{-1}$ M to $10^{-7}$ M, shown in Fig. 2. It can be observed that $I_{ds}$ decreased as AgNO₃ concentrations increased, and lead the threshold voltage ($V_{th}$) is changed. In Fig. 3, threshold voltage were extracted from curves of ($I_{DS}$)$^{1/2}$ versus $V_{ref}$ for each AgNO₃ concentration, and we could observe that $V_{th}$ decreased when the AgNO₃ concentrations increased. For FET devices, $V_{th}$ is an important parameter, which is defined the gate voltage at minimum to turn “on” transistor, and it could be dependent on the interface between gate and channel. Therefore, Ag⁺ concentration increased caused more Ag⁺ on the P3HT surface and gate electrode become more positive bias and lead to $V_{th}$ decreased. Furthermore, changing the concentrations of P3HT fabrication from 30 mg/ml to 70 mg/ml, the 70 mg/ml has excellent linearity and a high sensitivity of 68.15 mV/dec in silver ion range $10^{-1}$ M-$10^{-7}$ M.

Besides, X-ray diffraction (XRD) profiles of various concentrations P3HT films were measured, shown in Fig. 4. It indicated that 70 mg/ml P3HT films had broad orientation distribution of crystalline domains. Therefore, we believe that broad orientation distribution of crystalline domains, which caused more interaction between Ag⁺ and conjugated polymer backbone, and lead 70 mg/ml P3HT films in Ag⁺-EGFET have high sensitivities.

Fig. 2 $I_{ds}$-$V_{ref}$ curves for Ag⁺-EGFET sensor with 70 mg/ml P3HT thin film.

Fig. 3 Threshold voltages of Ag⁺-EGFET sensor with 30 mg/ml, 50 mg/ml and 70 mg/ml P3HT thin films in various Ag⁺ activities.

3. Conclusion

The extended-gate field-effect transistor for selective silver ion sensors (Ag⁺-EGFET) based on poly(3-hexylthiophene) (P3HT) has been developed successfully. Changing the concentrations of P3HT fabrication from 30 mg/ml to 70 mg/ml, the 70 mg/ml has excellent linearity and a high sensitivity of 68.15 mV/dec in silver ion range $10^{-1}$ M-$10^{-7}$ M. As results shown, the 70 mg/ml P3HT film has rough surface morphology and broad orientation distribution of crystalline domains, which caused more interaction between Ag⁺ and conjugated polymer backbone, and make Ag⁺-EGFET has high sensitivity.

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