Graphene-based FET Structure: Modeling FET Characteristics for an Aptamer-based Analyte Sensor

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INTRODUCTION

Graphene is a very promising electronic material that has attracted vast research interests due to its unique electronic properties [1]. In this paper, a graphene-based FET-like aptamer sensor is modeled for the case of an aptamer that binds to a cocaine surrogate. Methylene-blue (MB) is a nanoscale molecule that functions as an electron donor. The graphene in these structures exhibits p-type semiconductor behavior with holes as carriers. 1-pyrenebutanoic acid, succinimidyl ester (P130) is used as linker molecule to noncovalently bind the aptamer to the graphene surface by the pyrene group. In this work, the graphene-based FET characteristics are modeled to understand the use of this device as a sensor of molecular analytes.

THEORY

It is known that electrical contacts to a graphene surface typically exhibit high resistance. This is possibly due to the forbidden or weak electron conduction between the graphene surface and the metal caused by Bloch symmetry [2]. In the graphene-based FET structure of Fig. 1, if charges from the electron donor (MB) had been trapped at the interface, the inversion layer charge in the semiconductor will compensate the change and the threshold voltage will be shifted [3]. Herein, the net charge density is shown to be:

$$Q_P(Net) = -C_o(V_G - V_T - \phi) - Q_{ext} \quad (1)$$

where Q_{ext} is the trapped external charges from MB. It is further shown that the current relation is:

$$I_D = \frac{Z\overline{\mu}_P C_o}{L}\left[(V_G - V_T)V_D - \frac{V_D^2}{2}\right] - \frac{Z\overline{\mu}_P V_D}{L} Q_{ext} \quad (2)$$

Taking the derivative of Eq. 2, it follows that,

$$\frac{dI_D}{dV_G} = \frac{Z\overline{\mu}_P C_o}{L} \quad (3)$$

This shows the relationship between slope of I_{SD}-V_{BG} curve to the dimensions of FET device (Z/L) in triode regime.

COMPARISON OF MODEL WITH EXPERIMENT

After device fabrication, cocaine in water is sensed. The original I_{SD} curve shows typical p-type graphene behavior and agrees well with Yang et al. [4], where the current decreases with increasing V_{BG} from -60 V to 60 V. After the cocaine aptamer is immobilized on the graphene surface, the I_{SD} current experiences a current decrease from 20.5 μA to 15.8 μA at -60 V and from 19.7 μA to 15 μA at 60 V. Further, when cocaine is present, the I_{SD} continues reduce with increasing concentration of cocaine. This can be explained by the device scheme in Fig. 1. When the graphene surface is exposed to cocaine and causes the conformation change of the aptamers, MB will approach the graphene surface and contribute electrons. Increasing the cocaine concentration will cause more aptamers to make configurational changes, and lead to more electrons being trapped on the surface. The current decrease or conductance reduction is quite stable in the variable V_{BG}. This is because the change in threshold voltage depends on the amount of electron charges trapped at the interface. The relationship between trapped electron charges and shift of voltage may be written as: $\Delta V_{TH} C_o = Q_{ext}$ [5]. Thus, more electrons contributed by MB will directly lead to shift of voltage.

CONCLUSION

The characteristics of a graphene-based FET aptamer sensor have been modeled and compared with experiment. The device performs as a signal-off sensor and detects cocaine in micromole scale. The electronic properties of graphene FET are studied. Electron trapping is observed and modeled using modified FET characteristic equations.

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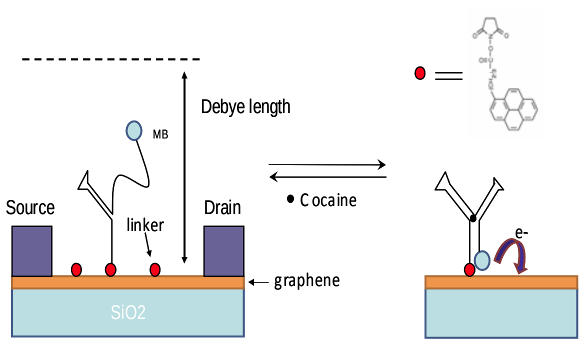

Fig. 1. Scheme of graphene-based FET structure for detecting charges from MB close to the graphene surface.

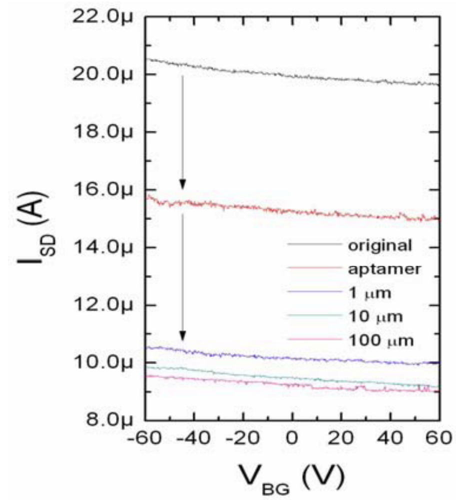

Fig. 2. I_{SD} versus V_{BG} curves of different conditions: original device, aptamer-immobilized, 1 μM, 10 μM, and 100 μM cocaine-in-water-tested with the arrow indication.