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Fabrication of Graphene-Based Back-Gated Field Effect Transistor for Cortisol Detection

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ABSTRACT

In this work, we fabricated graphene-based back-gated field effect transistor for biosensor applications. Back-gated field effect transistors were fabricated on p-type silicon substrate with 300nm thermally grown silicon oxide layer. The effect of different drops of graphene which were one drop, two drops and three drops were characterized using Scanning Electron Microscope (SEM) and Keithley 4200 Semiconductor Parametric Analyzer (SPA) to study the effect of different drops of graphene towards the conductivity of the BGFET. The fabricated device was then functionalized with linker molecules and immobilized with antibody for selective sensing of cortisol biomarker. The changes at each modification steps were studied through the changes in electrical conductivity of the device.

Keywords: Biosensor, Cortisol, FET, Graphene.

1. INTRODUCTION

The advancement in nanotechnology has played a great role in scientific and technological development. Nanotechnology can be defined as technology at nanoscale. Nanotechnology is the application of scientific knowledge to manipulate and control matter with the scale between 1 to 100 nanometers in at least one dimension [1]. Nanomaterials on the other hand are materials with any external dimension in the nanoscale or having internal structure or surface structure in the nanoscale [2]. The discovery of nanomaterials such as fullerenes, carbon nanotubes, quantum dots, nanopores and graphene has made revolution in the field of nanotechnology.

Graphene is one of the most studied nanomaterials due to its interesting properties. Graphene is a well-known building block of graphite for more than 60 years. Graphene was first isolated in 2004, where researcher from University of Manchester reported on the discovery of single layer graphene which was exfoliated from graphite using scotch tape method [3]. Graphene is a two-dimensional structure carbon atom arranged in a honeycomb lattice structure with 0.142 bond length between carbon to carbon atoms. Graphene, the thinnest and lightest sp2 carbon nanomaterial, has exhibited more extraordinary properties than CNT in terms of fast electron mobility, high current density, strong mechanical strength, excellent electrical conductivity and having larger surface area [3]. These emergent properties have attracted researchers' attention for utilizing graphene in various sensor application such as gas sensor [4], bacteria sensor [5], protein sensor [6] and enzyme sensor [7].

Transistor-based sensor which combines a sensor and an amplifier have the potential for the development of miniaturized and portable sensor system. Field effect transistor integrated with nanomaterials as a kind of biosensor have shown great criteria for recognition of a broad range

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of biomolecules due to the label-free, real-time monitoring, highly specific and sensitive properties that guarantees transformation of bioanalytical research.

In this work, we fabricated back-gated field effect transistor with graphene as the transducing material. The effect of different drops of graphene were studied by conducting morphological characterization using Scanning Electron Microscope (SEM) and Keithley 4200 Semiconductor Parametric Analyzer (SPA) to measure the effect on electrical conductivity. The device was later functionalized with linker molecule and immobilized with cortisol antibody for selective sensing of cortisol. Later, detection of cortisol was conducted starting from the lowest cortisol concentration to highest concentration that is starting from 1 ng mL^{-1} followed by 10 ng mL^{-1} and 100 ng mL^{-1}.

2. MATERIAL AND METHODS

2.1 Materials and Reagents

Graphene Nanoplatelets was purchased from Graphene Supermarket (Calverton, New York). 1-pyrene butanoic acid succinimidyl ester (PBASE) was purchased from Anaspec while mouse monoclonal cortisol antibody (Anti-Cab) was purchased from Abcam. All other chemicals and biomolecules used in this study were purchased from Sigma Aldrich.

2.2 Device Fabrication

Back-gated field effect transistor device was fabricated using p-type silicon wafer. A cleaned silicon wafer undergoes wet oxidation process and was thermally grown with approximately 300nm thick of oxide layer in the oxidation furnace. A part of the oxide layer was then removed using buffer oxide etch (BOE) for the formation of back-gate. Aluminum was deposited on the sample through physical vapor deposition (PVD) using Thermal Evaporator The sensing channel was later patterned using standard photolithography process. The length and width of the channel were 500 µm × 1000 µm, respectively. Graphene dispersion was dropped-coated on the sensing channel to serve as the transducing material of the fabricated BGFET. The surface morphology was characterized using Scanning Electron Microscope (SEM). The electrical conductivity of different drops of graphene was measured using Keithley 4200 Semiconductor Parametric Analyzer (SPA). A constant bias drains voltage of 0.1 V was applied across the drain and source terminals electrodes. The device was configured as graphene-based BGFET (G-BGFET). Figure 1 shows the fabrication step of BGFET using silicon wafer.

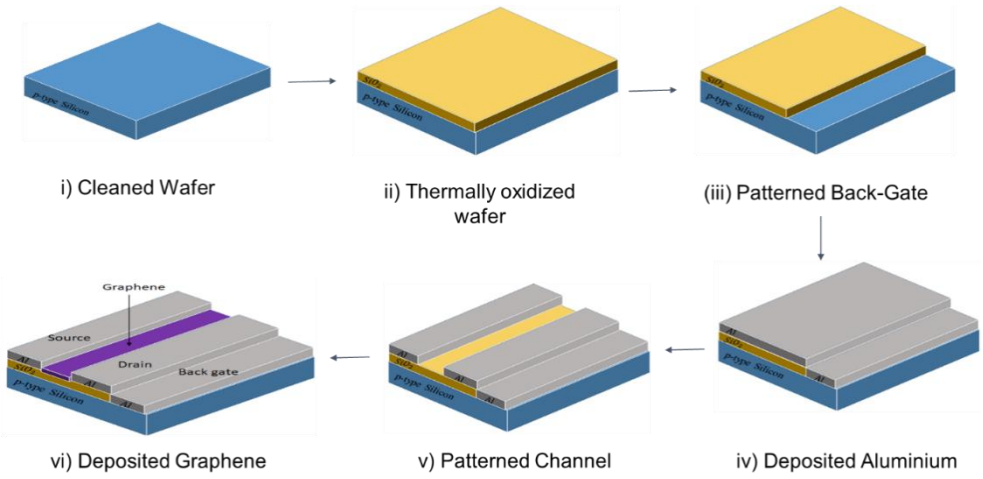

Figure 1. Fabrication step of graphene-based back-gated field effect transistor (G-BGFET) device.

2.3 Surface Functionalization

The G-BFFET was first functionalized with 6mM of 1-pyrenebutanoic acid succinimidyl ester (PBASE) diluted in dimethylformamide (DMF). 6 µl of PBASE solution was dropped on the device and incubated for 2 hours at room temperature. Then the device was extensively rinsed with 1 µM (pH 7.4) phosphate buffered saline (PBS) solution. The device was later immobilized with 10 µg mL-1 mouse monoclonal cortisol antibody diluted in 10 mM PBS solution (pH 7.4) and incubated for 3 hours at room temperature and was successively rinsed with PBS and DI water to remove the weakly bound antibody. Next, the device was treated with 100 mM ethanolamine for 30 minutes to passivate the excess and unreacted groups remaining on the graphene surface. The device was rinsed with DI water to remove excess unbound molecules. Lastly, the device was used for detection of cortisol biomarker using different concentrations which are 1 ngmL-1, 10 ngmL-1 and 100 ngmL-1. The change in electrical conductivity at each modification step was measured using Keithley 4200 Semiconductor Parametric Analyzer (SPA).

3. RESULTS AND DISCUSSION

Different drops of graphene dispersion were deposited on the sensing channel of the device and were characterized morphologically and electrically. Figure 2 shows the surface morphology of different drops of graphene deposited on the sensing channel characterized using Scanning Electron Microscope (SEM) under 1000 x magnification. It can be seen that with increasing amount of graphene dropped, more graphene flakes were deposited. Figure 3 shows the I_{DS}-V_{GS} graph in response to different amount of graphene dropped. It can be observed that the current increases with increasing amount of graphene dropped on the sensing channel. This agrees with the findings reported previously [8]. Hence, we can conclude that with increasing amount of graphene dropped, more graphene flakes have been deposited on the sensing channel, thus increasing the current response.

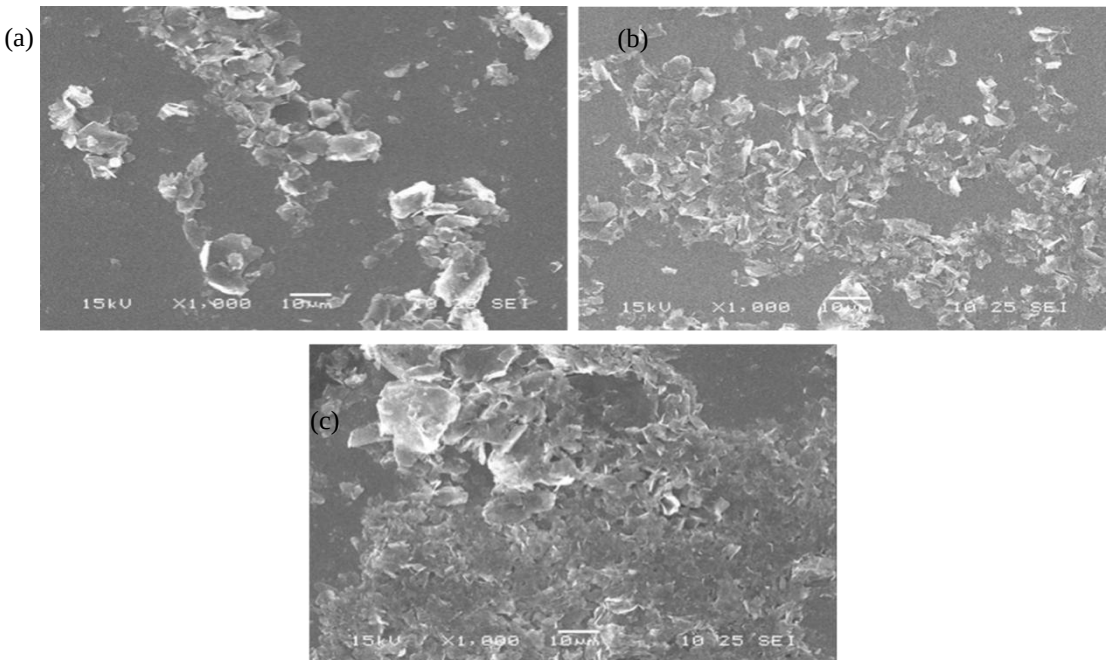

Figure 2. Surface morphology of different drops of graphene deposited on the sensing channel (a) one drop (b) two drops and (c) three drops of graphene using SEM under 1000x magnification.

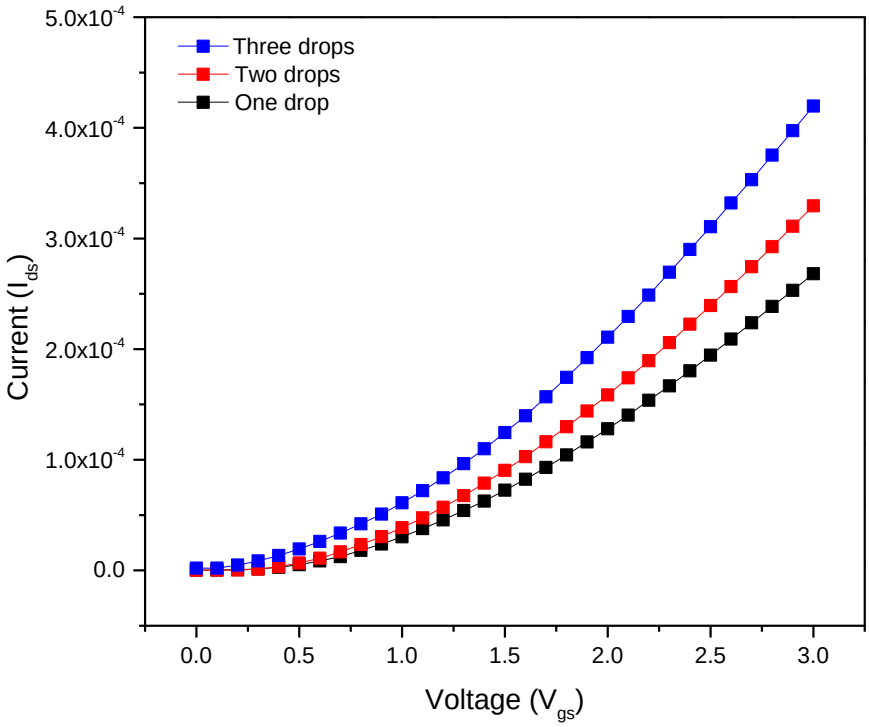

Figure 3. Electrical measurement of different drops of graphene deposited on the sensing channel.

Figure 4 shows the I_{DS}-V_{GS} graph of the fabricated BGFET at each modification step. Based on the graph, there is a shift in the transfer curve upon introduction of biomolecules. The graph shows decrease in conductivity when PBASE was introduced to the device. This might be attributed to the electron being transferred from DMF to graphene since nitrogen in DMF has non-bonding pair of electrons. This later causes the electron to be transferred to graphene. This causes n-doping effect on the graphene surface and hence decrease the conductivity [9]. Attachment of PBASE on graphene likely to have occurred because pyrene tetra-rings in PBASE which resembles a honeycomb-like structure promote π-π non-covalent stacking on outermost surface of graphene nanoplatelets [10]. While the other terminal in PBASE molecules extend free NHS-ester group, enabling covalent attachment with amino groups of antibody specific to cortisol antigen. We can observe that with introduction of cortisol antibody, the graph shows further decrease in conductivity. Cortisol antibody with isoelectronic point of 5.0 to 5.5 is negatively charged when immersed in solution with pH 7.4. Hence, the negative charge creates a depletion region on the device thus decreasing the conductivity. Incubating the device with ethanolamine further decreases the conductivity of the device which might have attributed to the blocking of non-specific binding on the device surface. The device was later incubated with cortisol target. Cortisol target might cause accumulation of charges at the surface of the device as the transfer curve shows increase in conductivity. Finally, the device was examined for the ability to enhance the current in the aspect of sensitivity upon introduction of target molecules. The detection is conducted starting from the lowest concentration which is from 1 ng mL^{-1}, followed by 10 ng mL^{-1} and then 100 ng mL^{-1}. As illustrated in Figure 5, the graph shows that the I_{DS} current increases as the cortisol concentration increases. The highest cortisol concentration generates the highest current. The changes in the graph response upon introduction of the target show that the fabricated device is sensitive to small changes in concentration of target.

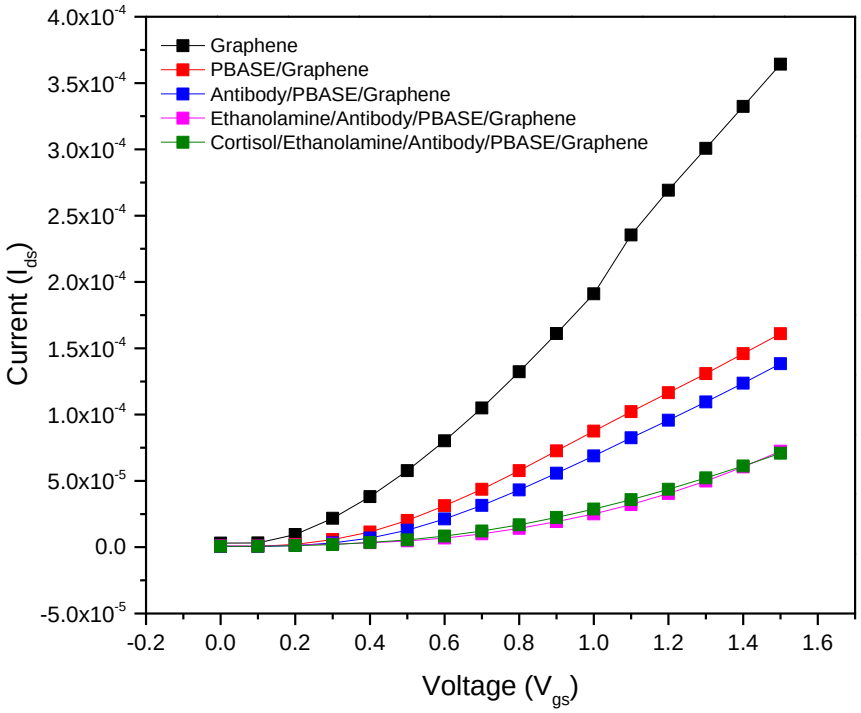

Figure 4. Graph of I_{DS}-V_{GS} at each modification steps of functionalization and immobilization of biomolecules.

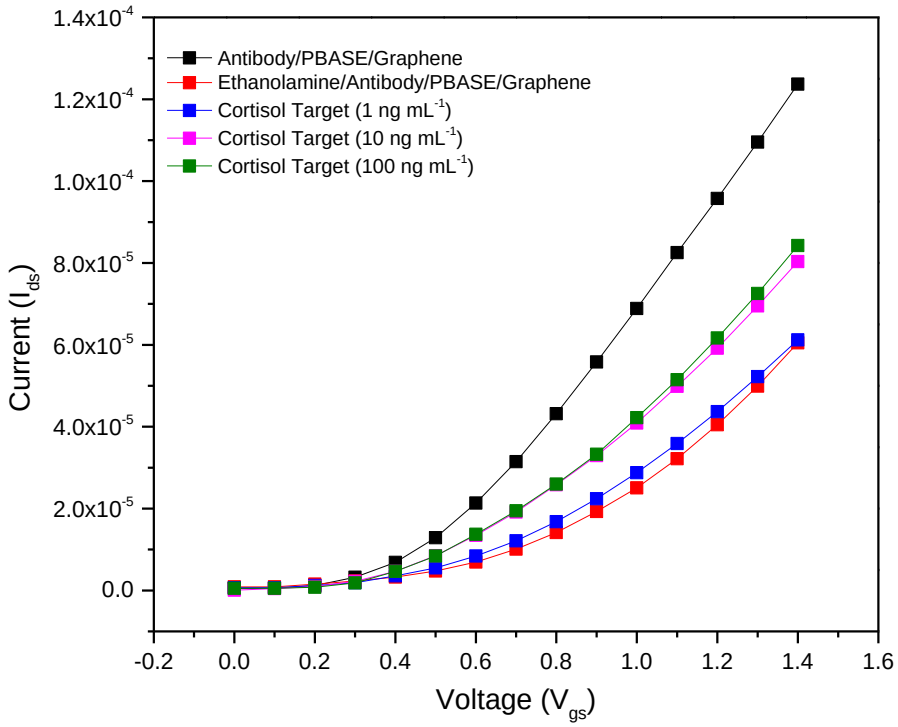

Figure 5. Graph of I_{DS}-V_{GS} when introduced with cortisol target of different concentrations.

4. CONCLUSION

In this work, we have successfully demonstrated the fabrication step of G-BGFET. The BGFET was deposited with different drops of graphene and was characterized and analyzed. Increasing

drops of graphene dispersion deposited on the sensing channel shows increasing conductivity of the fabricated BGFET. The fabricated BGFET was successfully functionalized and immobilized with linker molecules and antibodies for selective sensing of cortisol biomarker. The device response sensitively towards small changes in concentration of target molecules. Hence, graphene-based back-gated field effect transistor has the capability to be implemented for label-free sensing of cortisol and perhaps other biomarker related diseases.

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