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Lipid bilayer on wrinkled-interfaced graphene field effect transistor

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ABSTRACT

This study describes lipid bilayer-based sensor interface on SiO_2 encapsulated graphene field effect transistors (GFET). The SiO_2 layer was utilized as a lipid compatible surface that drives bilayer formation. The two types of surface morphologies i) wrinkled morphology by thermal evaporation (TE) and ii) flat morphology by pulsed electron deposition (PED) were obtained. The sensing performance of wrinkled and flat interfaced-GFETs were investigated, pH sensitivity of wrinkled interfaced-GFETs were found to be ten fold larger than the flat ones. The enhanced sensitivity is attributed to thinning of the oxide layer by formation of wrinkles thereby facilitating electrostatic gating on graphene. We foresee that described wrinkled SiO_2 interfaced-GFET holds promise as a cell membrane mimicking sensing platform for novel bioelectronic applications.

1. Introduction

The biosensing capability of graphene have been well reviewed in detail by exemplifying the utilization of graphene based sensing platforms to detect of glucose, cytochrome-C (Cyt-c), hemoglobin (Hb), cholesterol, gas, and DNA [1]. The analytical performance of graphene-based sensor platforms fulfills the unmet needs of not only clinical but also environmental, and food sciences [2]. Therefore, graphene and other two-dimensional (2D) materials have emerged as key components of bioelectronics devices by their enhanced performance for sensing of small biomolecules to large proteins [3,4]. However, due to its 2D nature of graphene, the electronic band structure is extremely sensitive to external perturbations, such as molecular interactions which introduce perturbations in the band structure of graphene, and a variation of the change of its conductivity [5]. To avoid instability, the encapsulation of graphene with thin oxide layer is suggested, and previous studies revealed that the oxide layer deposition on graphene provides sufficient protection against air, humidity and other perturbations and therefore completely suppresses the conductivity instability of graphene [6,7]. SiO_2 surfaces were used to be employed for lipid bilayer formation. Electrical characteristics of GFETs with wrinkled and flat surface morphologies have been investigated upon lipid vesicle adsorption and lipid bilayer formation. Adsorption, fusion and lipid bilayer formation characteristics of lipid vesicles wrinkled SiO_2 surface was demonstrated to be reproducible and sensing performance of GFET with wrinkled SiO_2 surface was found to be one order of larger than GFET with flat SiO_2 surface. We anticipated that the wrinkled interfaced-GFET sensing platform would be a good candidate for bioelectronic devices.

2. Material and methods

Epitaxial graphene layer was grown on 6H-SiC substrates by in-vacuum Joule heating method. For monolayer graphene, SiC was annealed at 1350 °C for 5 min. in an ultra-high vacuum chamber Cr/Au (3 nm/80 nm) source/drain electrodes were thermally deposited for two terminal I-V measurements of GFET. Then, SiO_2 film was deposited onto GFET with two different evaporation methods. For thermally evaporation (TE), 15 nm thick SiO_2 deposited on GFET samples whereas 100 nm thick SiO_2 thin film by using pulsed electron deposition (PED) technique. The surface morphology of the samples was characterized by Atomic Force Microscopy (AFM) and all the electrical characterizations were performed with HP4145B parameter analyzer.

For pH measurements, various buffers with different pH value were prepared with a 1 L stock of 1X PBS. pH can be adjusted from 5 to 9 using hydrochloric acid (HCl) or sodium hydroxide (NaOH). Furthermore, lipid vesicles are prepared by French Pressure Cell

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(extrusion) method, for this purpose a stock solution of phosphatidylcholine (PC) is prepared. A membrane filter with pore size of 200 nm was utilized for the process.

3. Results and discussion

The Fig. 1a and b briefly illustrate the different surface morphologies of the SiO_2 thin film deposited on the epitaxially grown graphene on SiC substrate by TE and PED techniques. The TE technique yielded a wrinkle pattern reflecting the hexagonal symmetry of the underlying epitaxial graphene template whereas PED produced a flat SiO_2 layer. Here wrinkles form upon cooling from the deposition temperature down to room temperature. This surface dynamics indicates that the wrinkling can be associated with the sudden relaxation of the TE grown SiO_2 thin film on the epitaxial graphene layer due to the compressive strain. Fig. 1c and d suggest probable lipid bilayer formation both on wrinkled and flat surfaces. It is expected to have significant electrical response provided by wrinkled oxide layer GFET as compared to flat oxide layer devices (see the device geometry in Fig. 1e). This oxide layer thickness profile may potentially exhibit substantial differences in electrical response of GFET devices upon lipid adsorption and bilayer formation (Fig. 1f).

The topography measurements of the SiO_2 wrinkle structures on epitaxial graphene was characterized by AFM operated in the tapping mode. The wrinkle size of the wrinkle network was found to range between 35 and 40 μm and the average wrinkle to wrinkle distance measured along different surface orientations was determined as ~13 μm (Fig. 2).

The change in conductivity of flat and wrinkled interfaced-GFET due to different pH values is shown in Fig. 3. It is obviously seen in pH measurements, when H^+ ions density decreases from 10^{-5} to 10^{-6}, for the wrinkled surface, the maximum current changes 199.5 μA (Fig. 3b) while on the flat surface is 2.59 μA (Fig. 3a) at 3 V bias. The sensing mechanism for H^+ ions on SiO_2 surface relies on the electrostatic gating effects based on the Gouy-Chapman-Stern- Graham model [8]. H^+ ions in the solution interact with hydroxyl species (–OH) on SiO_2 dielectric surface and therefore different H^+ concentrations can induce changes of the surface charge density on the dielectric. The conductivity of wrinkle surface is approximately 100 times higher (1027 μA at pH 9) than flat surface at 5 V bias. The inset graphs show current versus pH at −3V and 3 V for flat and wrinkled surface GFETs indicating that wrinkled surface GFETs are 80 times responsive to pH change as compared to flat one. Fig. 3c-d shows the time dependent conductivity change after exposure to the lipid solution (black line) and blank buffer (red line) and their I-V measurements between −3V and 3 V bias. The four-stepped characteristic responses have been recorded upon lipid vesicle addition to bilayer formation. These four steps are considered as vesicles adsorption (1), surface satura-

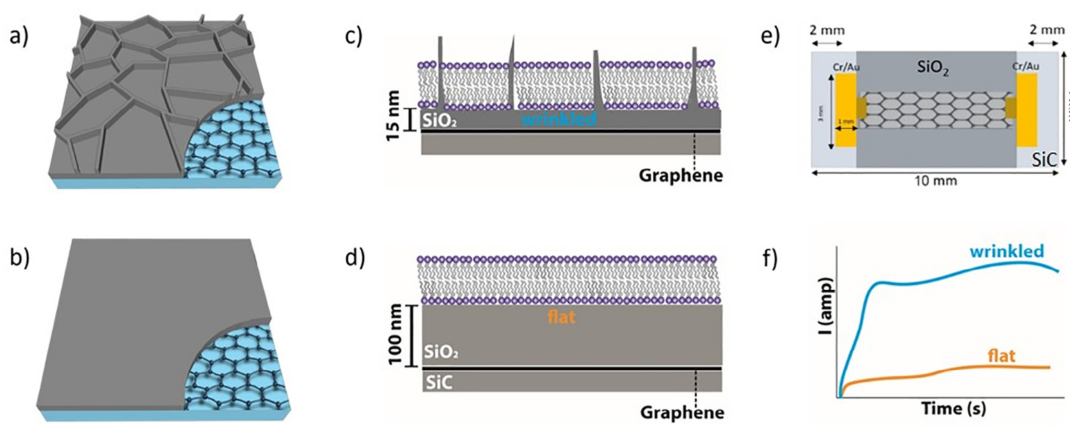

Fig. 1. Schematic representation of wrinkle a) and flat b) surface after SiO_2 thin film deposition on epitaxial graphene grown SiC substrate with TE and PED, respectively. Schematic figure of lipid bilayer formation on wrinkled c) and flat d) SiO_2 surface. e) Schematic representation of GFET device and f) time dependent current difference of wrinkled and flat SiO_2 surface after lipid adsorption.

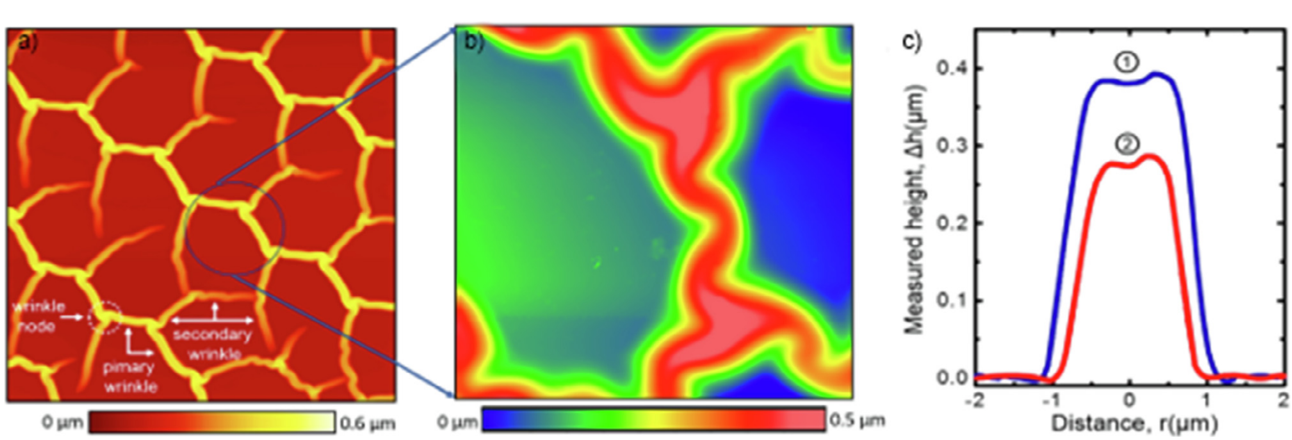

Fig. 2. a) 50 × 50 μm^2 AFM topography image of TE deposited SiO_2 wrinkle network on epitaxial graphene b) 10 × 10 μm^2 AFM topography image of localized height protrusions c) Cross-sectional line profiles of primary and secondary wrinkles (1 and 2 indicates the primary and secondary wrinkles, respectively).

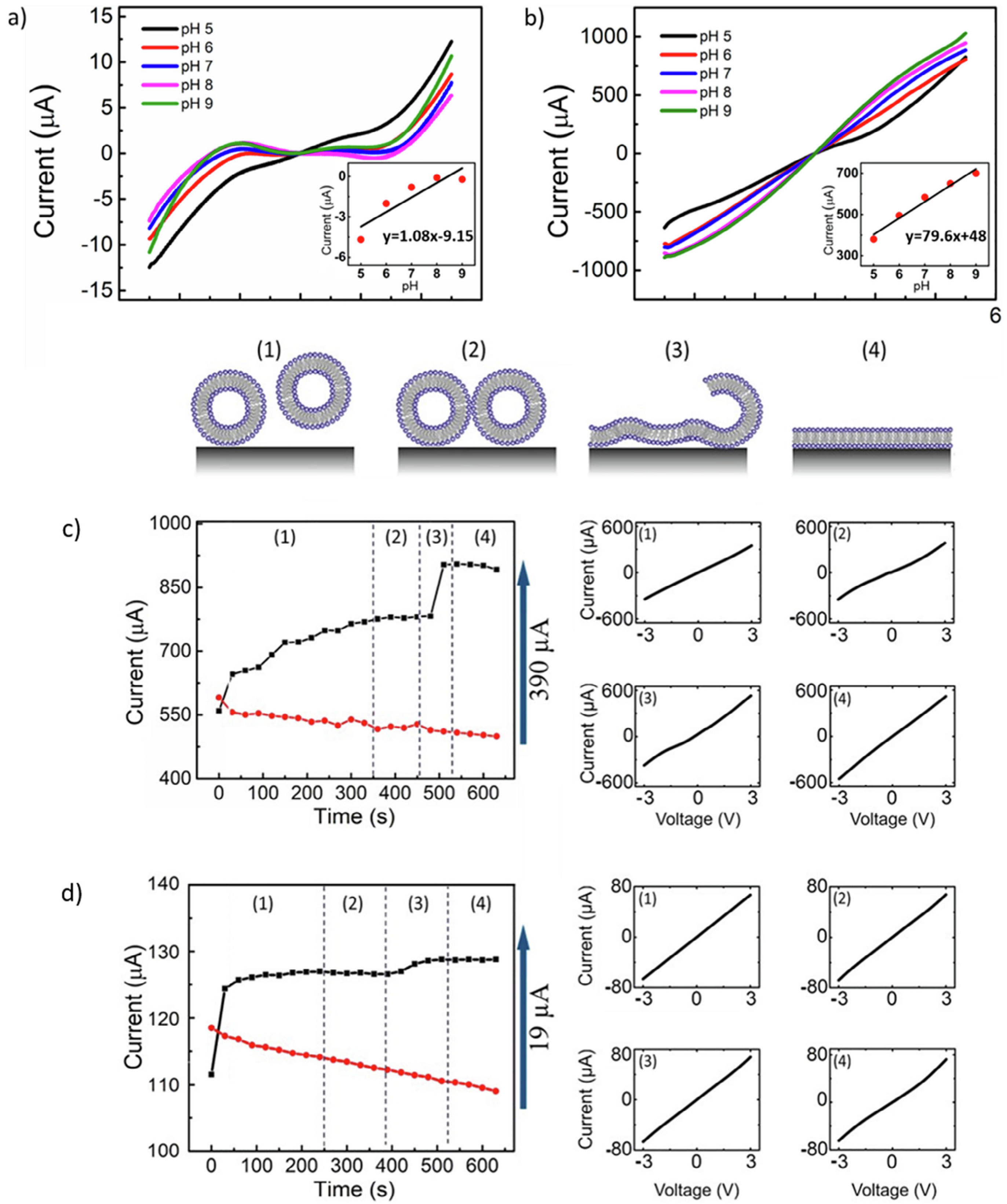

Fig. 3. I-V characteristics of pH dependence of a) flat interfaced-GFET b) wrinkle interfaced-GFET. Insets show linear fitting of current versus pH values of flat interfaced-GFET and wrinkle interfaced-GFET, respectively. Time dependent current measurements of lipid vesicle adsorption characteristics of c) wrinkle and d) flat interfaced-GFET surface and their I-V measurements of corresponding parts between −3V and 3 V bias.

tion by vesicles (2), vesicle rupture (3) and bilayer formation (4). In step 1, a sudden increase in current observed within 350 s for both wrinkled and flat surfaces. Upon vesicle injection, the current has ramped from 550 μA to 750 μA (Δi = 250 μA) for wrinkled interfaced-GFET (Fig. 3c) whereas the current has changed from 110 μA to 127.5 μA in 250 s for flat interfaced-GFET (Fig. 3d). As it was discussed earlier the current changes vary between 10 and 100 μA upon vesicle exposure to graphene surface that refers to our results were in similar range [9]. More explicitly, by the lipid vesicle adsorption changes of the Fermi energy level of graphene causing a decrease in the resistance. In the second step "saturation of surface by vesicles" current change has stopped and reached to intermediate baseline both for wrinkled and flat interfaced-GFETs. At this step the SiO_2 surfaces of wrinkled and flat interfaced-GFETs are considered to be saturated by vesicles [10]. At the third step, the current has increased sharply from 750 μA to 875 μA (Δi = 1 25 μA) for wrinkled interfaced-GFET while it exhibited just ~4 μA for flat interfaced-GFET. The reason for the current increase may be considered to be vesicle rupture causing reorganization of surface charge and eventually electrostatic gating. The response to vesicle rupture was found to be substantially different for wrinkled and flat interfaced-GFET. The performance difference of both GFETs is attributed to the thickness of the oxide layer of the GFET devices that is directly affecting electrostatic gating. The fourth step, the current response was stabilized for both type GFETs that refers to stable lipid bilayer on the surface. In overall the bilayer formation, there is a 19 μA current change is observed on the flat surface while this value is 390 μA on the wrinkled surface. This dramatic difference reveals that the lipid binding of the wrinkle surface is 19 fold more sensitive than the flat surface. Additionally, devices were repetitively tested for and the loss of response were found to be less than 5%. This result assures that devices exhibit enough durability provided by its oxide layer (See Fig. S1 in Supplementary Information).

4. Conclusion

In this report we aimed to communicate a facile fabrication methodology of graphene field effect transistors having lipid bilayer interface. The described methodology promises expedite fabrication of GFETs having lipid bilayer biointerface that facilitate the utilization of bioelectronic devices mimicking cell membrane.

CRediT authorship contribution statement

Dilce Ozkendir Inanc: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Cem Celebi:** Investigation, Resources, Writing - original draft, Writing - review & editing. **Umit Hakan Yildiz:** Conceptualization, Methodology, Resources, Writing - original draft, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.matlet.2020.128998.

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