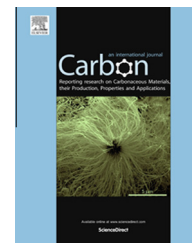


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Temperature and gate voltage dependent electrical properties of graphene field-effect transistors



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ABSTRACT

Temperature (T) and gate voltage sweep range (V_{Gmax}) dependent electrical properties of graphene field-effect transistors were investigated in the ambient atmosphere. With the increase of T from 300 to 380 K, the charge neutrality point (CNP) in the transfer characteristic curve (I_D – V_G) was shifted negatively from the positive voltage to near zero, which might be mainly due to the desorption of water adsorbates from the graphene surface and other thermally activated processes at the graphene/ SiO_2 interface at high T . Accompanying the CNP shift is the semiconducting behavior of the temperature-dependent conductivity, observed not only in the low carrier density region near the CNP, but also in the high carrier density region. The variations in the position and magnitude of the CNP in the I_D – V_G hysteresis loops were linearly enhanced by increasing either T or V_{Gmax} , which are explained in terms of the trapping/detrapping process and the chemical redox reaction at the graphene–oxide interface, as well as the thermally activated mobile ions movement in the dielectric layer.

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1. Introduction

Hysteresis behavior is usually observed in graphene devices with SiO_2 dielectric layer in the ambient atmosphere [1–4]. Several research groups have discussed and experimented on the origins of the hysteresis, which are mainly ascribed to the charge trapping and the chemical redox reaction at the graphene/ SiO_2 interface [5–10]. Considering that some special dielectrics (e.g., ferroelectrics) could also induce significant hysteresis [11,12], a simpler and more comprehensive classification is summarized by Wang et al. for the origins of hysteresis: charge transfer and capacitive gating [13], which

cause a positive and negative shift of the charge neutrality point (CNP), respectively. To detailedly investigate the hysteretic behavior of graphene, controllable factors such as variations in gate voltage sweep rate and range, temperature, air or moisture exposure, are selectively introduced in the measurements [2,13,14]. However, no investigation has been reported about the influences of temperature (T) on the graphene hysteresis with the variation in gate sweep range (V_{Gmax}).

In this study, the revolution of the electrical properties of graphene grown by chemical vapor deposition (CVD) is studied under ambient conditions with increasing T and V_{Gmax} .

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The evolutions of the CNP in the position (V_{CNP}) and magnitude (σ_{min} or ρ_{max}) are observed, and the mechanisms are discussed. Moreover, T and V_{Gmax} dependent hysteretic behavior of graphene under forward and backward sweep is investigated for the first time. The hysteresis in V_{CNP} (defined as ΔV_{CNP}) and σ_{min} (defined as $\Delta\sigma_{\text{min}}$) are enhanced with increasing T and V_{Gmax} . The relationship between the increased ΔV_{CNP} with the change of T and V_{Gmax} are quantitatively analyzed. The results reveal that ΔV_{CNP} is linearly dependent on T and V_{Gmax} , and the effects of T and V_{Gmax} are not mutually independent but co-responsible for the hysteresis in graphene with a coupling coefficient, which probably results from the thermally and electrical-field activated mechanisms.

2. Experimental

Graphene field-effect transistors (GFETs) in two-probe configuration were fabricated for the study. Briefly, the graphene film synthesized by atmospheric pressure chemical vapor deposition on the copper foil, was first transferred to the highly degenerate silicon substrate with 90 nm-thick thermally grown SiO_2 layer. Standard photolithography and the following O_2 plasma etching were then used to pattern the graphene channel. Finally, $\text{Ti}(5\text{ nm})/\text{Au}(50\text{ nm})$ film was deposited as the source/drain electrodes. Fig. 1(a) and (b) show the schematic structure and the optical micrograph of the GFET devices, respectively.

The electrical measurements were conducted by an Agilent B1500 semiconductor parameter analyzer with a variable temperature probe station in the ambient atmosphere. The test temperature was regulated from 300 to 380 K, with a step of 20 K. The transfer characteristics of the GFETs at each temperature were measured while varying the DC sweep range V_{Gmax} from 20 to 40 V, with an increase step of 10 V. The reproducibility of the results was confirmed by repeating the measurements. The drain/source voltage V_{D} was fixed at 500 mV.

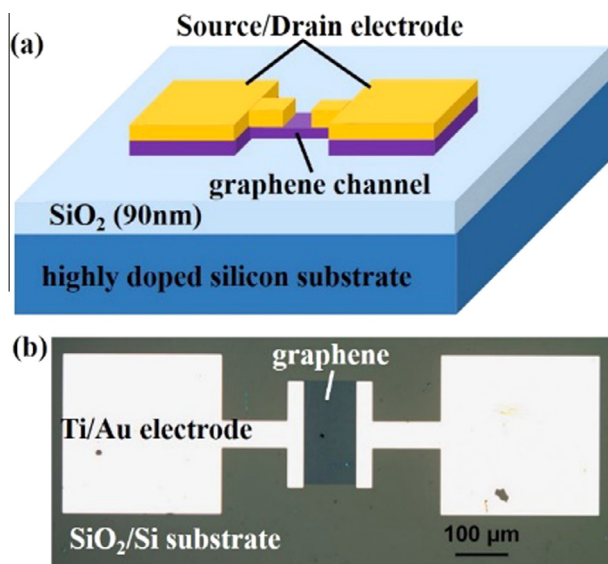


Fig. 1 – The schematic and the optical micrograph of one prepared GFET device. (A color version of this figure can be viewed online.)

3. Results and discussion

3.1. T and V_{Gmax} dependence of electrical properties in GFETs

Eight GFET samples were systematically investigated. Fig. 2 shows the $I_{\text{D}}-V_{\text{G}}$ curves of one typical GFET device with T varying from 300 to 380 K. V_{G} is swept from the negative to the positive direction, with V_{Gmax} increasing from 20 to 30, and then to 40 V, as shown in Fig. 2. The corresponding $R-V_{\text{G}}$ curves are plotted in the Supplementary information in Fig. 1S. Two remarkable changes in the electrical properties of the GFET samples are observed with the elevation in T : (i) the voltage of charge neutrality point V_{CNP} in the $I_{\text{D}}-V_{\text{G}}$ curve successively shifts towards the negative direction and (ii) the corresponding minimum current I_{min} is gradually increased under the same V_{Gmax} , as indicated by the dashed arrows. Besides, the changes of V_{CNP} and I_{min} are enlarged with the increase of V_{Gmax} . Similar changes are observed in all the investigated samples. Fig. 2S shows the $I_{\text{D}}-V_{\text{G}}$ curves of another GFET sample.

The more detailed changes of V_{CNP} and the corresponding I_{min} with temperature elevation are shown in Fig. 3. It is seen that for different V_{Gmax} , V_{CNP} and I_{min} present a consistent change with T . V_{CNP} is shifted from $\sim 18\text{ V}$ to near 0 V when T is increased from 300 to 380 K. The offset of V_{CNP} away from

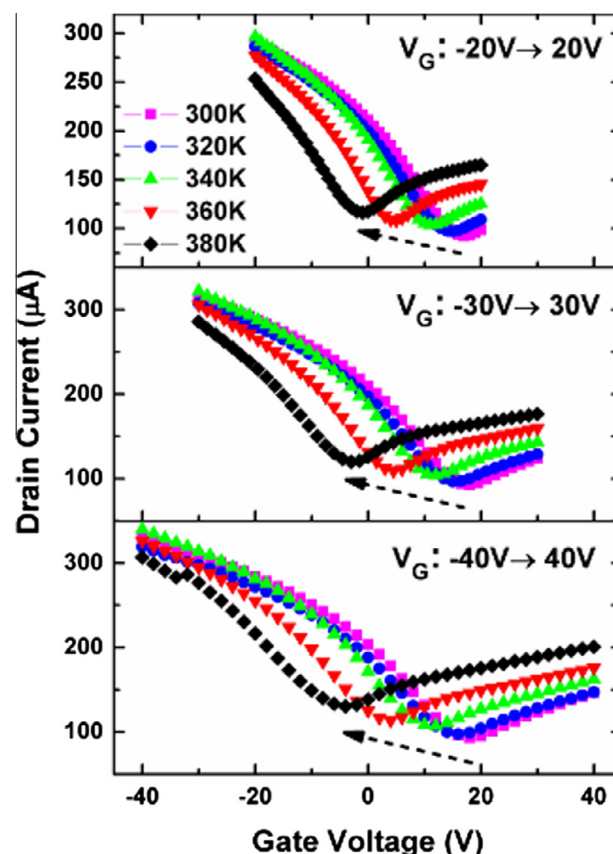


Fig. 2 – The $I_{\text{D}}-V_{\text{G}}$ curves of a typical GFET with T rising from 300 to 380 K. V_{Gmax} ranges from 20 to 40 V. (A color version of this figure can be viewed online.)

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