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A triboelectric charge top-gated graphene transistor

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ABSTRACT

A graphene channel with polymer polymethyl methacrylate (PMMA) or Polydimethylsiloxane (PDMS) passive layer were fabricated on a Si/SiO_2 substrate. The gate-effect of triboelectric charges on a foreign stimulator and in situ generated triboelectric charges on the passive layer are tested by controlling the foreign stimulator (PDMS or Acrylic plate) touch or not with the passive layer. When the negatively charged PDMS (positively charged Acrylic) stimulator approach and leave the device without touching the passive layer, the channel resistance shows a pulsed decrease (increase) with amplitude less than 1%. When the stimulator has a temporary touch with the passive layer, the in situ generated triboelectric charges on the PMMA (PDMS) passive layer cause stepwise increase (decrease) of the channel resistance. The amplitude of the resistance change steps of the device with PMMA passive layer (2 μm in thickness) is about one order larger for than that of the device with PDMS passive layer (about 60 μm in thickness). The significant different response of the device depending on whether the stimulator touches or not with the passive layer suggests two possible operation models for the tribo-charge top-gated graphene channel. It may enable diverse design of tactile sensors and pressure sensors based on the tribotronic effect.

1. Introduction

Triboelectrification is normally looked at as negative effect in electronics. Recently, triboelectrification process is widely explored as a promising way of mechanical energy harvesting from the environment, which is pioneered by Professor Zhong Lin Wang [1,2,3]. As intensive efforts have been put into this area, the triboelectric properties of some widely used polymer materials such as polytetrafluoroethylene (PTFE) and polytetrafluoroethylene (PTFE) are intensively utilized and studied in developing energy harvesting devices [4,5,6]. With accumulation knowledge in this area, tribotronics is proposed as a new field of electronic devices tuned/controlled by electrostatic potential created by triboelectrification [2,3]. The fundamental physical processes in a tribotronic device are the triboelectric charge generation and electrostatic effect introduced charge flow. By coupling triboelectricity with conventional semiconductor devices, it enables diverse device designs towards applications such as self-powered systems, distributed sensor networks and flexible electronics [7–10]. In 2014, a tribo-charge-tuned Si-based field-effect transistor (FET) was reported [11]. Recently, a tactile switch and a tribotronic phototransistor based on the MoS_2 channel have also been demonstrated [12,13]. The essential device design of those tribotronic transistors is the integration of a triboelectric nanogenerator (TENG) with a MoS_2 transistor. In those devices, a PTFE frictional layer is attached to the highly doped Si back gate of the MoS_2 transistor and a foreign Aluminum layer has been used as another frictional layer. Once the negative charges on the PTFE and positive charges on the Aluminum layer have been induced by triboelectrification, the movement of the Aluminum layer will change the channel conductance. However, besides the movement of Aluminum layer, the change of the triboelectric charges on the fixed frictional layer is of equally importance in determine the device performance. In this work, we tried to distinguish the response of the device to the movement of a charged foreign stimulator and the in situ generated triboelectric charges on a fixed frictional layer.

A typical application of tribotronic device could be tactile sensors [14,15]. When a transistor is used in a tactile sensing element as signal amplifier, the sensitivity could be highly enhanced [16,17]. For example, Yaping Zang et al. reported an ultra-sensitive pressure-sensing device based on organic thin-film transistor with flexible suspending gate [18]. However, in this kind of device design, a top-gate structure is normally adopted for the sake of fabrication convenience towards fully flexible device. For a tribotronic transistor, a top-gate structure is also highly appreciated.

In this work, spin coated polymer passive film on the top of the channel is served as a fixed frictional layer. The triboelectric charges generated on the surface of the polymer passive layer should be reflected by the change of the channel resistance. Graphene is chosen as channel material due to its nearly linear transfer curve at either n branch or p branch. In such case, the resistance change is proximately proportional to the amount of triboelectric charges on the passive layer. Polymethyl methacrylate (PMMA) and PDMS are used as passive layer partially because

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their good film forming ability. These two materials could be easily cured without damaging the graphene. According to the triboelectric series [19], PDMS and Acrylic stimulator are intentionally chosen as their counter frictional layer, respectively. They induce opposite charges onto the PMMA and PDMS passive layer. The results of this work provide valuable messages for developing flexible tactile sensors or pressure sensors.

2. Experiment

Fig. 1(a) shows the schematic of the graphene transistor with polymer passive layer, which is PMMA or PDMS here. The device is fabricated on a silicon substrate with 300 nm thermally grown SiO_2. The graphene used in our device is prepared by typical chemical vapor deposition (CVD) method on copper substrate [20,21]. Then the graphene is transferred to the substrate by wet transfer method with PMMA vehicle. Ti/Au (15 nm/100 nm) electrodes are deposited by electron beam evaporation method. The PMMA and PDMS passive layer are prepared by spin coating method. The PMMA spin coating speed is 3000 r/min and the obtained film thickness is about 2 μm. The PDMS spin coating speed is 1500 r/min and the obtained film thickness is about 60 μm.

Fig. 1(b) shows the optical microscopy of the device with and without PMMA passive layer. The dimension of the graphene channel is 2 mm (width) × 20 μm (length). The quality of the graphene is confirmed by Raman spectrum as shown in Fig. 1(c). The high ratio of sharp 2D band (2670 cm^{-1}) and G band (1580 cm^{-1}) I_{2D}/I_G is ~2 and the D (1350 cm^{-1}) band is barely visible. Fig. 1(d) is the transfer characteristic curve of the graphene field-effect transistor (G-FET) with back-gate at $V_{ds} = 0.1$ V. The Dirac point of the device locates at $V_{gs} = 28.5$ V. It indicates that the graphene channel is heavily p type doped at atmosphere. The mobility of graphene channel is in the range from 700 $cm^2/s \cdot v$ to 1200 $cm^2/s \cdot v$.

There are two test strategies, approach-and-leave and attach-and-detach, which is shown in Fig. 2(a) and (b), respectively. In an approach-and-leave test, the PDMS stimulator is moved approaching to the channel until it is stopped by a polyester (PET) spacer, which defines a 2 mm space between the stimulator and the passive layer. In this way, the stimulator will not touch the passive layer and so it avoids an in situ generation of triboelectric charge on the surface of the passive layer. In an attach-and-detach test, there is no PET spacer and the stimulator will come into a contact with the passive layer. The triboelectric charges will be induced onto the surface of the passive layer.

For the device with PMMA passive layer, a PDMS plate is used as stimulator, while for the device with PDMS passive layer, an Acrylic plate is used as stimulator. According to the well established triboelectric series, triboelectrification between PDMS and PMMA induces positive charges to the PMMA side and the triboelectrification between Acrylic and PDMS induces negative charges to the PDMS side [19]. To distinguish the effect of the in situ generated triboelectric charges and the triboelectric charges on the stimulator, the stimulator is intentionally charged up for the approach-and-leave test. The PDMS stimulator is negatively charged through inductive coupled plasma treatment. The obtained surface potential of the PDMS stimulator is about −1500 V. The Acrylic stimulator is positively charged by friction with a PTFE plate and the obtained surface potential is about 1500 V. The resistance of the graphene channel is monitored by Keithley 2000 digital multimeter. The surface potential is measured by an electrostatic voltmeter (ME297) with resolution of 1 V.

3. Results and discussion

The test results of the device with PMMA passive layer and a control device without passive layer are shown in Fig. 3. In the approach-and-leave test, a temporary pulsed reduction of the channel resistance is observed, as shown in Fig. 3(a). The temporary reduction of the channel resistance should be attributed to the effect of negative charges on the surface of the foreign PDMS stimulator. As the PDMS stimulator approaching to the channel, the negative charges on its surface attract

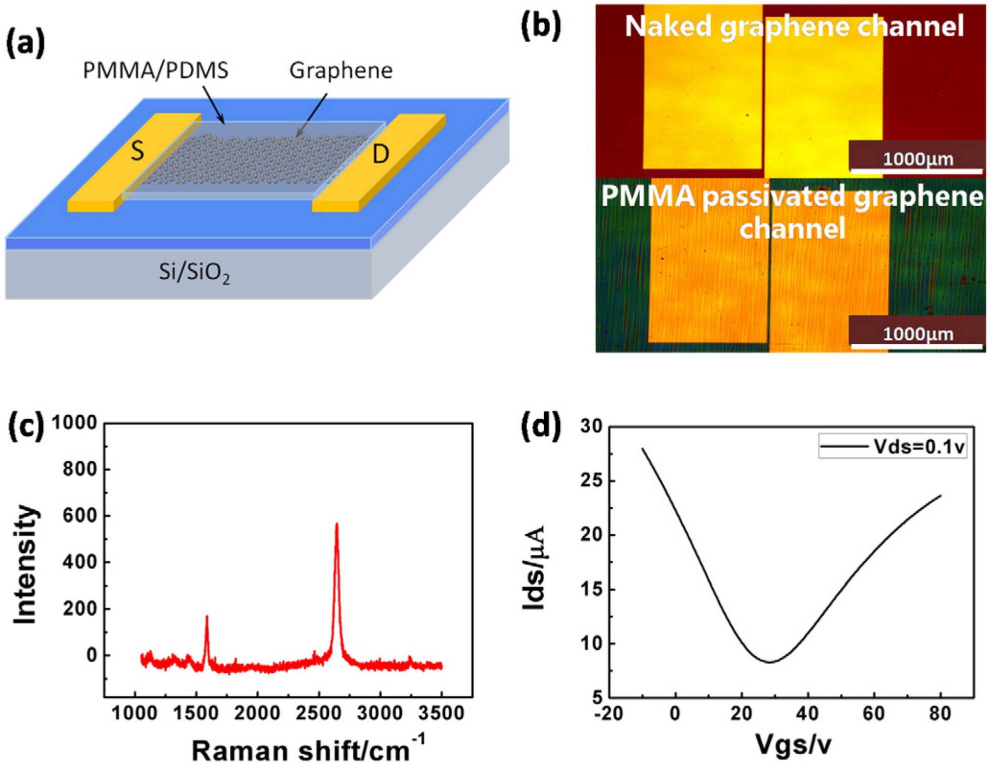

Fig. 1. Device design and graphene channel characterization. (a) Schematic of a graphene channel with polymer passive layer fabricated on a Si/SiO_2 substrate. (b) Optical microscopy images of the naked graphene channel and PMMA passivated graphene channel. (c) Raman spectrum of the graphene channel. (d) Transfer characteristic curve of the graphene field-effect transistor with silicon back-gate at $V_{ds} = 0.1$ V.