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Low Pull-in Voltage Graphene Contact Switch Fabricated without Acid-Etching

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Abstract

A simple bottom-up procedure using polymer sacrificial spacer is presented to fabricate graphene electromechanical switch without using acid-etching. Low pull-in voltage of below 2 V is realized with good consistency on a run-to-run basis. In addition, the formation of carbon-gold bonds at contact position is proposed as an important failure mechanism for the irreversible switch besides the irreversible static friction.

1. Introduction

Graphene has an ultra-high Young's modulus of 1 TPa, making it a promising candidate for future nanoelectromechanical (NEM) applications. The graphene NEM contact switches showed minimized electrical leakage, sharp switching response, low actuation voltage and high on/off ratio [1–4]. Despite these advantages, graphene has yet to outperformed conventional materials because of its low reliability [1, 4]. So far, only few reports show multiple cycles of switching operation [2]. The common failure is that graphene is stuck on electrode, which is simply attributed to irreversible static friction. But the details are still unclear. In addition, the switch with suspended graphene achieved using conventional buffered hydrofluoric (BHF) etching suffers from some drawbacks [5]. BHF attacks titanium, the frequently used adhesive material for Ohmic contact. Moreover, as an isotropic process, SiO_2 below metal contacts is also removed rapidly. Both lead to the mechanically unstable structure. Therefore, it is crucial to find a method to produce suspended graphene device that excludes this aggressive BHF etching step.

Here, we report a simple bottom-up fabrication for graphene switch without using acid-etching. Low pull-in voltage is achieved in the two-terminal graphene switch with good consistency in different switching cycles. Furthermore, the failure of irreversibility is studied to have a better understanding of the mechanism behind it.

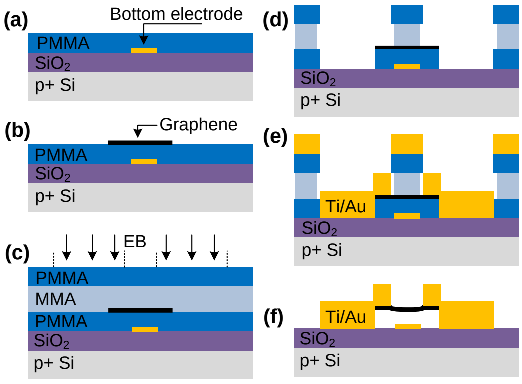

Fig. 1 Schematics of fabrication procedure of graphene switch.

2. Fabrication Procedure

The bottom-up process is illustrated in Fig. 1. (a) The 35 nm thick bottom electrode is defined with Ti/Au on the p-doped silicon substrate covered with 300 nm SiO_2 via conventional fabrication processes. Afterwards, a thin polymethyl methacrylate (PMMA) polymer (495K A4) spacer of 170 nm is spun onto the substrate. (b) Graphene is mechanically exfoliated from highly oriented pyrolytic graphite onto the PMMA spacer. Possible bilayer graphene locating on top of bottom electrode are identified using optical microscopy. The number of layers is verified using Raman spectroscopy [6]. (c) Methylmethacrylate 8.5 methacrylic-acid (MAA) EL9 copolymer and PMMA are coated. Top contacts to graphene are defined via electron beam lithography. A large electron-beam dose is chose to expose through all polymer layers. (d) After exposure, a well-controlled development process opens exposed areas, but leaves the part of PMMA spacer underneath graphene undeveloped. (e) Top contacts are deposited with 10 nm Ti and 190 nm Au in an electron-beam evaporator. The thick metal stack assures the continuity of the electrical contacts and a good mechanical stability of the structure. (d) Hot N-methyl-2-pyrrolidone solvent is used to dissolve all polymers and lift off metal. Finally, sample is dried using a critical point drier to prevent surface-tension induced collapse of suspended graphene.

Figure 2(a) shows a fabricated bilayer graphene switch. The atomic force microscopic image shows that the graphene locates at 170 nm above the SiO_2 substrate, verifying the suspension of graphene (Fig. 2(b)).

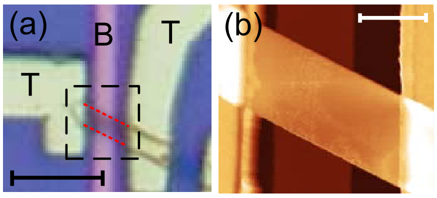

Fig. 2 (a) Microscopic photo of a graphene switch. Red dot-lines indicate the edges of graphene. T and B denote the top and bottom electrode, respectively. Scale bars: 5 μm. (b) AFM image of the dash-box in (a). Scale bar is 1μm.

3. Results and Discussions

The characterizations of graphene switches are performed at a low pressure of 0.1 Pa to reduce the impacts from ambient. Firstly, the electrical contact at two top electrodes and leakage current between top and bottom electrodes are examined (graphene: 2.5 μm × 1 μm) (Fig. 3(a)). The linear $I-V$ response between two top electrodes indicates the Ohmic contact. Low leakage current of 3 pA is measured between top and bottom electrodes, which also reveals the suspension of graphene.

The $I-V$ characterization of the above switch with two-terminal configuration is exhibited in Fig. 3(b). A voltage V_{tb} increased from 0 V is applied between top and bottom electrodes, which electrostatically deflects the graphene downwards. At low V_{tb}, small leakage current is measured as "switch-off" status. At 3.5 V, the current abruptly increases, indicating the physical pull-in of graphene onto the bottom electrode, which is known as "switch-on". Comparing to these using back gates as actuation electrodes [7], the stronger electrostatic force generated by the local bottom electrode brings about the low pull-in voltage. Interestingly, as voltage continuously increases, we note an unique transition in current response. Current firstly increases following a slow slope after pull-in; at 4.2 V, a transition to a sharper slope suddenly occurs and current dramatically reaches the high compliance current of 0.9 mA. The slow increase of current at the beginning of "switch-on" is probably attributed to the poor electrical contact between graphene and bottom electrode. A large contact resistance may exist at the interface, as a result of the barrier of adsorbates at contact interface. The Joule heating generated by the current could gradually improve the contact condition. At ~ 4.2 V, the high current density of 10^{10} A/m^2 generates high temperature, which could create carbon-gold (C-Au) bonds by removal absorbates at contact interface [8]. Hence, the sudden transition arises. The switch is not reversible after this operation. The linear

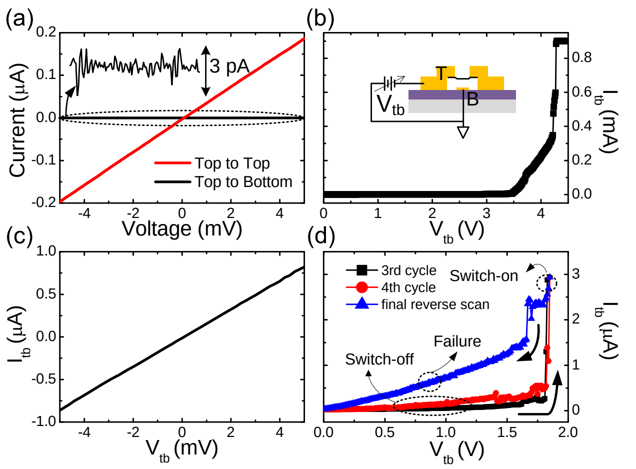

Fig. 3 (a) $I-V$ responses at top-top and top-bottom electrodes before operation. Inset: zoom-in of leakage current. $I_{tb}-V_{tb}$ measurements of same switch (b) during operation and (c) after failure; Inset of (b): two-terminal configuration. (d) $I_{tb}-V_{tb}$ curves of a different switch under multiple switching cycles. Thick arrows show the scan direction.

behavior in the failed switch shows the well-established Ohmic contact at graphene/bottom electrode interface, implying the presence of C-Au bonds (Fig. 3(c)).

A different switch device is also characterized. Here, the applied voltage V_{tb} is immediately retracted once physical pull-in is observed. Thus Joule heating is limited to prevent the formation of C-Au bonds. Several cycles of reversible switching are achieved (Fig. 3(d)). Due to a narrower width of graphene (2.5 μm × 0.5 μm), a much lower pull-in voltage of ~ 1.85 V is measured compared with the previous one. The consistency of pull-in voltages observed in different cycles highlights a good mechanical stability of the structure. A reverse scan of V_{tb} is conducted after failure. An abrupt drop of current at 1.65 V, known as pull-out, is pronounced. However, current does not reduce to the leakage level, but gradually decreases to zero following a quasi-linear curve, which reveals that partial contact still remains. The large contact resistance read from the small slope echoes the little contact area. Despite the limited Joule heating, the large potential difference between graphene and bottom electrode at the moment of pull-in causes a voltage pulse which is also sufficient to remove absorbates at the contact position and creates C-Au bonds locally [8]. It interprets the failure of the partially reversible graphene contact.

4. Conclusions

We demonstrate mechanically stable graphene switch fabricated using simple etching-free method with polymer sacrificial spacer. Low pull-in voltages of below 2 V are measured with good consistency in multiple cycles. The formation of C-Au bonds is suggested as a possible factor of failure besides the irreversible static frictions. By limiting them, multiple switching cycles are realized.

Acknowledgements

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