Synthetic Metals 205 (2015) 6–10

Contents lists available at ScienceDirect

Synthetic Metals

journal homepage: www.elsevier.com/locate/synmet

Size-controlled ambipolar graphene nanoribbon transistors by an all-dry mask method

Guiru Xue, Qingxin Tang *, Yanhong Tong, Yichun Liu

Key Laboratory of UV Light Emitting Materials and Technology under Ministry of Education, Northeast Normal University, Changchun 130024, PR China

ARTICLE INFO

Article history:
Received 31 October 2014
Received in revised form 19 March 2015
Accepted 23 March 2015
Available online 31 March 2015

Keywords:
Graphene nanoribbon
Size-controlled
All-dry mask method
Ambipolar

ABSTRACT

Conventional graphene nanoribbon (GNR) field-effect transistor (FET) fabrication involved the wet process with the separated nanoribbon formation and device fabrication. Here, we demonstrate one simple and novel non-solution method to integrate the GNR formation and the FET fabrication, where a gold film is used as mask for electrode deposition, following by using a SnO_2 nanoribbon as mask for the formation of GNR. The channel length and width can be controlled by the widths of the gold film and the SnO_2 nanoribbon, respectively. It is found that the GNR with the width up to 330 nm presents the promising ambipolar field-effect properties in air ambient, the hole and electron mobilities are respectively as high as 904 and 703 $cm^2 V^{-1} s^{-1}$, which benefits from the all dry process for both GNR fabrication and device fabrication.

1. Introduction

Recently, graphene nanoribbons (GNRs), have received worldwide attention because of their promising potential to replace silicon in future electronics [1–3]. It has been reported that the GNR with the width less than 10 nm demonstrated the semiconductor properties due to the quantum confinement effect, and their field-effect transistors (FETs) presented the excellent switching speed and extremely high mobility [3,4]. Conventional GNR FET fabrication was always separated into two steps: first the nanoribbon formation and then the device fabrication. For example, Li et al. got the GNRs by sonicating the graphite in the 1,2-dichloroethane (DCE) solution [5]. In order to fabricate devices based on these GNRs, they soaked a Si/SiO_2 wafer with pre-prepared metal markers into the GNR solution, recorded the location of GNR with AFM, and deposited the electrodes by electron beam lithography [6]. The previously reported GNR fabrication method includes the chemical and physical processes. In the chemical method, the GNRs were obtained by chemical synthesis [7,8], chemical vapor depositon [9–12], or by unzipping the carbon nanotubes [13,14] with a solution-based oxidative process. In the physical method, the GNRs were obtained by cutting the sheet-like graphene/graphite into the narrow nanoribbon with sonication [5,6,15] or etching process [16–18], or by unzipping the carbon nanotubes [19] with plasma treatment. Almost all the GNR fabrication methods introduced the wet process. At the same time, the previously reported GNR device fabrication processes employed e-beam lithography or optical lithography (see Supplementary material of Table S1), which inevitably involved a wet etching technology. A few research groups have addressed that such a wet process possibly made O_2 or other species physisorbed onto the GNR [6,8,19,20]. As a result, all the reported as-prepared GNR FETs measured in air presented *p*-type characteristics (Table S1). These GNR FETs also required the small width of the GNR in order to show the gate-dependence field-effect characteristic. For example, Dai et al. fabricated the GNR by plasma etching the carbon nanotubes [19]. Their devices showed the obvious gate-modulated effect only when the width of GNR was lower than 10 nm. Further, by sonicating the graphite in a 1,2-dichloroethane (DCE) solution of poly (m-phenylenevinylene-co-2, 5-dioctoxy-p-phenylenevinylene), they broadened the critical width of GNR up to 60 nm [6].

Here, we develop a simple masking method to integrate the GNR fabrication and device fabrication. This novel method minimizes the fabrication steps of GNR FETs. The electrodes were first deposited by using a gold film as mask, and then the GNR was formed and at the same time the device was successfully fabricated by oxygen plasma treatment with a SnO_2 nanoribbon as mask. The channel width, i.e., the width of the GNRs, can be adjusted by the SnO_2 nanoribbon mask. The channel length can be tuned by the width of the gold film mask. No wet processes were employed at any stages of the GNR and device fabrication, which avoids the surface contamination of the semiconductor and device. Our GNR with the width up to 330 nm not only shows the obvious gate-

* Corresponding author. Tel.: +86 431 85099873; fax: +86 431 85099873.
E-mail address: tangqx@nenu.edu.cn (Q. Tang).

http://dx.doi.org/10.1016/j.synthmet.2015.03.024
0379-6779/

modulated electrical properties, but also presents the unique ambipolar field-effect properties in air ambient with high hole and electron mobilities.

2. Fabrication process

Fig. 1(a–f) and Fig. 2(a–f) are the schematic and optical images of the GNR-FET fabrication process, respectively. The detailed procedure can be divided into four stages as follows: (i) The graphene sheet on Si/SiO_2 (300 nm) substrate was first obtained by mechanical exfoliation from graphite crystals (see Fig. S1 and movie for details in supplementary material). Then a SnO_2 nanoribbon was mechanically transferred onto the graphene with a probe under observation of an optical microscope [21] (Fig. 1(a) and Fig. 2(a)). (ii) A gold film was placed across the SnO_2 nanoribbon as the mask (Fig. 1(b) and Fig. 2(b)), and the 25-nm-thick semitransparent Au layer was deposited to form the source/drain electrodes (Fig. 1(c) and Fig. 2(c)). (iii) Duo to the week van der Waals force between gold film and other layers, the adhered gold film can be moved away from their original position by the mechanical probe [22,23] (see Supplementary material of Fig. S2 for details) (Fig. 1(d) and Fig. 2(d)), and oxygen plasma was carried out by using SnO_2 nanoribbon as mask for 50 s)Fig. 1(e) and Fig. 2(e)). (iv) By using a mechanical probe to cross the Au electrodes, the SnO_2 nanoribbon was taken away, and the GNR-FET device was formed (Fig. 1(f) and Fig. 2(f)).

In our experiments, we used oxygen plasma to selectively etch away the unprotected graphene, leaving the GNR underneath the SnO_2 nanoribbon mask. In this way, the width of the resulted GNR scales well with the width of SnO_2 nanoribbon, and the width can be adjusted by the width of the SnO_2 nanoribbon. The length is also controlled by the gold film mask. As shown in Fig. 2, when a gold film with the width of ~26 μm was used, the Au electrodes with a 26 μm gap could be obtained. The semitransparent Au layer and the weak contact interaction between layers are key to GNR device fabrication. Due to the deposited Au layer is thin (~25 nm), the stamped SnO_2 nanoribbon and gold film under the Au layer are visible, as shown in Fig. 2(c), which enables to pinpoint the locations of the gold film and the SnO_2 nanoribbon. The weak contact interaction (van der Waals force) between gold film, SnO_2 nanoribbon and graphene, also helps to successfully peel the gold film and SnO_2 nanoribbon from their original adhered locations by a mechanical probe.

3. Experiments and discussion

In order to confirm the good protective effect of SnO_2 nanoribbon on graphene under plasma treatment, the electrical properties of the sheet graphene devices before and after O_2 plasma treatment, and the device fabricated according to Fig. 1, were measured. For all of devices, the graphene was obtained on Si/SiO_2 substrate by mechanical exfoliation, and Au was deposited as electrodes. All devices present the linear behaviour in the *I–V* measurements (see Supplementary material of Fig. S3 for details), indicating the good Ohmic contact between Au electrodes and graphene. The transfer curve of Fig. 3(a_1) reveals that the wide

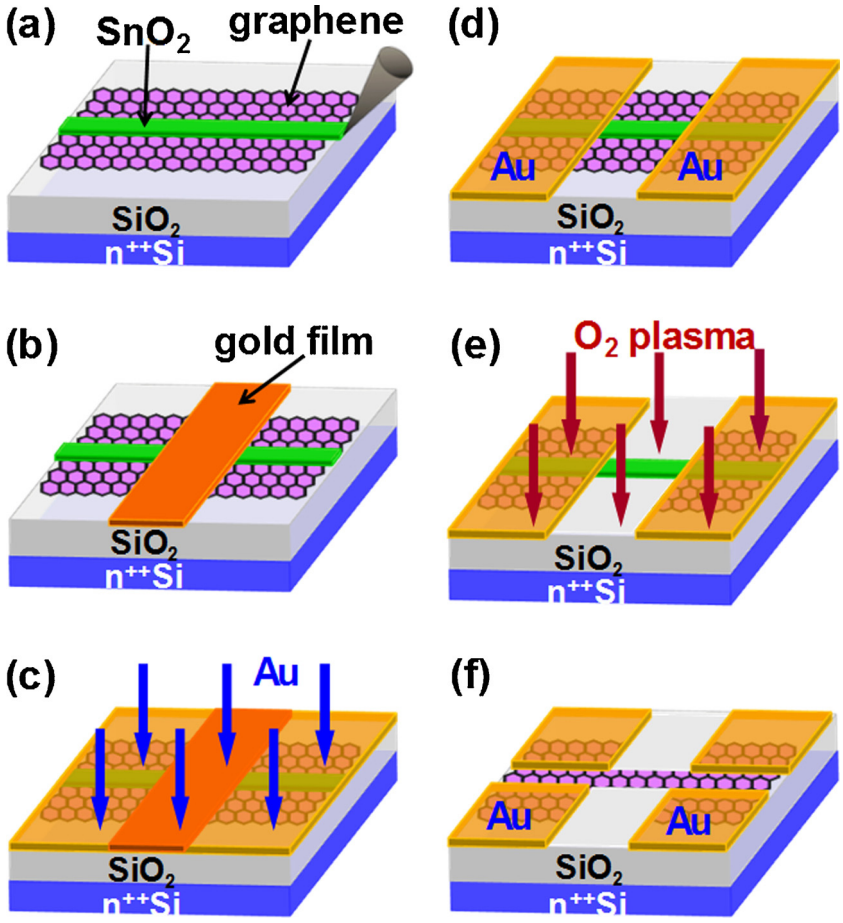

Fig. 1. Schematic illustration of the GNR-FET fabrication process: (a) transfer a SnO_2 nanoribbon on the graphene surface, (b) place a gold film across the SnO_2 nanoribbon, (c) deposit Au layer with the gold film as mask, (d) move away the gold film with the mechanical probe, (e) treat the sample with the oxygen plasma, (f) move away the SnO_2 nanoribbon.