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Exfoliated-graphene/MoS_2/metal Vertical Field Effect Transistor with Large Current Modulation and On Current Density

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Abstract

Owing to the absence of a band gap, the direct applicability of graphene for transistors and logic devices is still limited. Recent studies have shown that the van der Waals heterostructure of graphene and other materials can be a great candidate to overcome these issues; such heterostructures demonstrated vertical field effect transistor (FET) operations as well as large current ON-OFF ratio. However, realization of a large ON-OFF ratio simultaneously with a large ON current density has been still challenging and not demonstrated yet. In our study, we fabricated a graphene/MoS_2/metal vertical heterostructure by using mechanical exfoliation and dry transfer of graphene and MoS_2 layers. The van der Waals interface between graphene and MoS_2 exhibits a well-defined Schottky barrier, and this barrier height is strongly modulated by an external gate electric field. We obtained a large current ON-OFF ratio exceeding 10^5 simultaneously with a large ON current density of ~10^4 A/cm^2. We believe that our fabricated devices reveal superior performance to other existing graphene-based vertical transistors and present an important advance toward electronics applications.

1. Introduction

Recently, van der Waals heterostructures of graphene (Gr) and other layered crystals such as h-BN, MoS_2, and WS_2 etc. have been received considerable attentions [1]. Owing to its weak van der Waals interlayer coupling, it is revealed that one can mechanically exfoliate these layered crystals down to one or few monolayers and also possible to fabricate heterostructure together with different layered crystal connected with van der Waals force. Among these heterostructure, devices utilizing vertical transport across the heterointerface reveal potential high performance for electronics and optoelectronics applications. Examples of these applications are vertical tunnel transistor based on Gr/h-BN/Gr and Gr/WS_2/Gr structure [2,3], vertical field effect transistor based on Gr/MoS_2/metal structure [4]. Among these devices, a large ON-OFF ratio of 10^5–10^6 has been demonstrated in Gr/WS_2/Gr vertical tunnel transistor [3]. However, in these devices, the ON current density tends to be small (around 10^1–10^2 A/cm^2). In comparison with these devices, the Gr/MoS_2/metal (GMM) vertical heterostructure provides significant advantages in terms of a large driving current [4]. In particular, the GMM device exhibits an ON current density of ~10^3 A/cm^2, which is a significant improvement over the ON current density values of other Gr-based vertical transistors. However, thus far, the experimentally observed ON-OFF ratio in such GMM structures has been limited to values below ~10^3. Extending the performance limit of GMM devices is crucial for realizing Gr-based electronics. In this study, we fabricated an exfoliated-graphene/MoS_2/metal vertical heterostructure via mechanical exfoliation and dry transfer of Gr and MoS_2 layers. The mechanical exfoliation technique affords a high-quality graphene layer and interface between Gr and MoS_2. The interface between Gr and MoS_2 exhibits near-ideal Schottky-diode behavior, thereby facilitating strong current rectification. Furthermore, we demonstrate a large current modulation exceeding 10^5 together with a large ON state current density of ~10^4 A/cm^2 [5]. These values indicate superior device performance when compared with those of all existing Gr-based vertical FET devices.

2. Experimental methods

The schematic of our Gr/MoS_2/metal device is shown in Fig. 1(a). First, a single-layer Gr bottom electrode was fabricated on a 300-nm-thick SiO_2/*n*-Si(001) substrate via mechanical exfoliation of Kish graphite. Second, multi-layer MoS_2 was exfoliated from a synthetic MoS_2 crystal and deposited on the Gr electrode through the dry transfer technique. The advantage of this transfer process is that we could prepare freshly cleaved Gr and MoS_2 surfaces, which were then brought into contact with each other, thereby ensuring minimum contamination at the Gr/MoS_2 interface. Finally, Au/Ti metal top electrodes were fabricated on MoS_2 via standard electron beam (EB) lithography and EB evaporation. We fabricated a series of GMM devices with different MoS_2 thicknesses ranging from 2.4 to 40 nm and confirmed these thickness values using AFM measurements. These thicknesses correspond to the layer number range N = 4–62, assuming the single-monolayer thickness of MoS_2

to be 0.65 nm. For characterizing vertical transport across the GMM devices, we applied a source-drain bias V_B in between the Au/Ti electrode and Gr. A back-gate bias V_G was applied between the Si substrate and the Gr layer, thereby enabling control over the carrier concentration and thus the Fermi level of Gr. The Dirac point of the Gr layer for our series of devices was located in the range of V_G = 0–15 V, and the carrier mobility for Gr was 3000–5000 cm^2/Vs, as determined from two-terminal resistance measurements. The junction area was 1–3 μm^2.

3. Results and discussion

First, we examine the transport properties of the GMM device for N = 37. The photograph of this device is shown in Fig. 1(b). The current–voltage characteristics (I–V) were measured between electrodes A and B [shown in Fig. 1(b)] over a voltage range of V_G = -50 to +50 V; the results are shown in Fig. 1(c). The current values are normalized with the junction area of 1 μm^2 for this device. Here, +V_B corresponds to electron flow from Gr to MoS_2. We observed a significant change in the I–V curve with respect to change in V_G. In particular, the modulation of current is large in the + V_B region, whereas it is relatively small in the -V_B region. A large current ON-OFF ratio $I(V_G = +50\ V)/I(V_G = -50\ V)$ exceeding 10^5 at V_B = +0.5 V was observed in our exfoliated-Gr/MoS_2/Ti vertical heterostructure. This value is significantly higher than the previously reported values observed in CVD-Gr/MoS_2/Ti devices, although the device structures of both devices are fairly similar [4]. Since the ON current density is comparable between our results and those in ref. 4, we speculate that the large ON-OFF ratio in our GMM device is due to the significant reduction in the OFF current density as a consequence of using exfoliated Gr as the electrode [5].

4. Conclusion

The achievement of both a large ON-OFF ratio (~10^5) and a large ON-current density in the range of ~10^4 A/cm^2 in an exfoliated-graphene/MoS_2/metal vertical heterostructure demonstrates superior device performance when compared with those of other graphene-based vertical transistors. We believe that the use of this type of 2D crystal heterostructure can lead to further developments in electronics applications.

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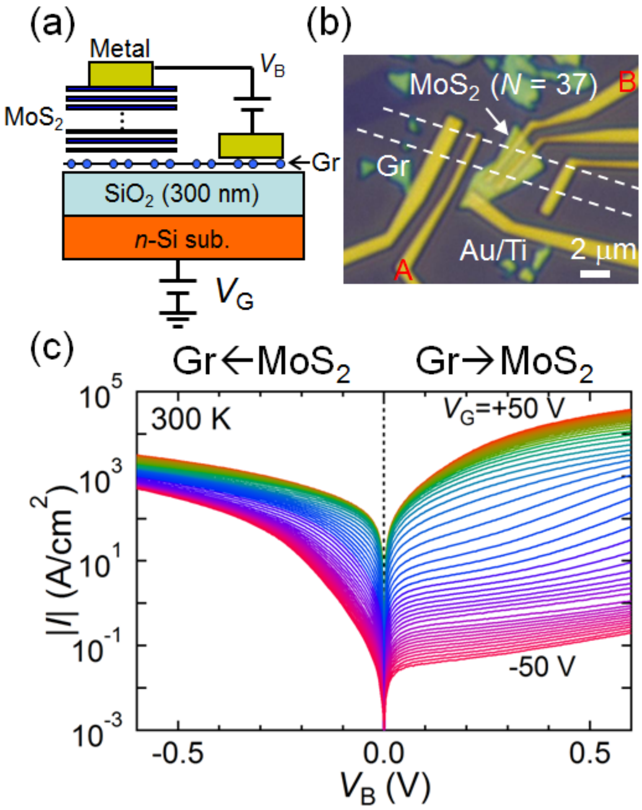

Fig. 1 (a) Schematic of Gr/MoS_2/metal (GMM) vertical heterostructure and measurement circuit. (b) Optical microscope image of the GMM device. (c) Current–voltage (I–V) characteristics of the GMM device measured at different V_G values at 300 K.