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Room-temperature Mid-infrared Photodetector via Hybrid Graphene Nanoribbon-C₆₀ Phototransistor

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Abstract: We demonstrated that depositing C₆₀ film on graphene nanoribbons greatly enhance the electron trapping efficiency. As a result, the graphene nanoribbon photodetectors with C₆₀ layer exhibits high responsivity of ~0.4 A/W under infrared laser (10 μ m) illumination at room temperature.

OCIS codes: (040.5160) Photodetectors; (040.6070) Solid state detector; (040.3060) Infrared

1. Introduction

Graphene has drawn tremendous attention as a candidate for electronic and optoelectronic applications owing to its extraordinary properties, such as broadband absorption and ultrahigh mobility [1]. The absence of a band gap in pristine graphene makes it unfavorable as a transistor for digital electronic or photodetection applications due to its low on/off ratio. Patterning graphene into nanoribbons with sub-10-nm dimension is an effective strategy to open the band gap using the quantum confinement effect [2]. However, patterned graphene nanoribbons suffer from the high carrier scattering loss and recombination rate. In this work, Graphene nanoribbon-C₆₀ based mid-infrared photodetector with high responsivity and photoconductive gain is demonstrated. The outstanding performances achieved in our devices are contributed to the bandgap opening of sub-10 nm graphene nanoribbon and effect electron trapping efficiency of C₆₀. The outstanding performances achieved in our devices are contributed to the bandgap opening of sub-10 nm graphene nanoribbon and effect electron trapping efficiency of C₆₀.

2. Results and discussion

Figure 1 (a) Scanning electron micrograph (SEM) image of the hydrogen silsesquioxane (HSQ) resist mask prior to the oxygen plasma reactive ion etching (RIE) process. The scale bar is 100 nm. The inset presents a close-up SEM image of the 10-nm-wide HSQ resist mask. (b) Schematic design of the hybrid GNR-C₆₀ structure. (c) Electronic states in GNR/C₆₀ and photoexcited charge transfer processes.

Through the EBL process, the width of the GNR is controlled to ~10 nm as shown in Fig. 1(a-b). C₆₀ thin film is deposited via thermal evaporation strategy in a quartz tube as illustrated in Fig. 1(b). The thickness of the C₆₀ thin film can be controlled by the deposition time and determined by AFM height profiles. C₆₀ is known to be a remarkable electron acceptor and introduce p-type doping in the beneath materials, as shown in Fig. 1(c) that charge transfer doping occurs in the hybrid system. The mechanism can be easily understood by the semiconducting behavior of GNR-C₆₀ hybrid phototransistor that the device is turned off with higher positive gate voltages, since the photocurrent generation is dominant by the absorption of GNR rather than C₆₀ film in the mid-infrared regime. The charge transfer between GNR and C₆₀ film may be attributed to the role of defect states in the C₆₀ film between the HOMO and LUMO levels, or the defect states in the GNR on the edge or surface introduced in the nano-fabrication processes [3].

Figure 2 Optoelectronic properties of GNR-C₆₀ hybrid phototransistor measured with laser wavelength of 10 μm . (a) Time resolved photocurrent of GNR-C₆₀ hybrid phototransistor with 6 nm C₆₀ film. (b) Gate voltage dependence of photocurrent generation of GNR-C₆₀ hybrid phototransistor with 6 nm C₆₀ film. (c) Photocurrent generation of GNR-C₆₀ hybrid phototransistor with different thickness of C₆₀. The power intensity of the measurements in (a,b,c) is constantly $\sim 2.5 \text{ Wcm}^{-2}$.

We measured the optoelectronic properties of bare and HfO₂ capped GNR-based FET devices and their time-dependent photoresponse under laser excitation with wavelength of 10 μm by a tunable quantum cascade laser (QCL). The photoresponse of the GNR-C₆₀ hybrid phototransistor under global irradiation is $\sim 0.4 \text{ A/W}$ as shown in Fig. 2(a), which is ~ 8 times higher than pure GNR phototransistor. From Fig. 2(a), the rising time and falling time are ~ 4 seconds. No obvious changes in the rise and fall times are observed, even though the overall photocurrent of the hybrid phototransistor increases ~ 8 times compared with that of pure GNR phototransistor. In the hybrid structure, the functionality of C₆₀ is an effective electron trapping center as shown in Fig. 1(c). Furthermore, we measure the gate voltage dependence of the GNR-C₆₀ hybrid phototransistor. It is clearly demonstrated in Fig. 2(b) that the photocurrent drops dynamically with the increase of gate voltage. The trend can be easily understood by the semiconducting behavior of GNR-C₆₀ hybrid phototransistor as shown in Fig. 2(b) that the device is turned off with higher positive gate voltages, as the photocurrent generation is dominant by the absorption of GNR rather than C₆₀ in the middle infrared range. The charge transfer between GNR and C₆₀ may be attributed to the role of defect states in the C₆₀ film between the HOMO and LUMO levels, or the defect states in the GNR on the edge or surface introduced in the nano-fabrication processes. The response of the phototransistor is found to be influenced by the amount of C₆₀. The effects of C₆₀ thicknesses on the performance of the GNR-C₆₀ hybrid phototransistor is shown in Fig. 2(c). The photocurrent increases with the increase of the thickness of the C₆₀ film under the same laser irradiation and tends to saturate when the thickness exceeds 8 nm.

3. Conclusion

In conclusion, we have fabricated a GNR-C₆₀ hybrid structure and demonstrated that it shows a dramatic improvement of photoresponsivity, where the photoconductive gain in the mid-infrared regime has been improved by about one order as compared to the bare GNR photodetector. The principle is that the incident light is absorbed by the 10-nm-wide GNR due to its bandgap of $\sim 100 \text{ meV}$, where the C₆₀ film is functioning as an effective electron trapping center so as to separate the photogenerated electron/hole pairs in the GNR-C₆₀ interface. Our results demonstrate the importance of electron trapping in the graphene interfaces and can be also extended to hybrid other two-dimensional materials with electron or hole trapping layers.

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