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Physical Science & Biophysics Journal
ISSN: 2641-9165

Graphene-Quantum Dots Hybrid Based Dual Band Photodetector

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Research Article
Volume 7 Issue 1
Received Date: February 01, 2023
Published Date: February 27, 2023
DOI: 10.23880/psbj-16000234

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Abstract

Graphene, which can detect a broad spectrum from ultraviolet to terahertz, is a promising photodetector material because it offers a broad spectral bandwidth and fast response times. However, the nature of weak light absorption has limited the responsivity of graphene-based photodetectors. Here, we demonstrate a responsivity of up to ~6.7×10^3 A/W in a hybrid photodetector that consists of monolayer or bilayer graphene covered with a thin film of colloidal quantum dots. At the same time, benefits from gate-tunability, the device can response from the short-wavelength infrared to the visible, and compatibility with current circuit technologies.

Keywords: Graphene; Quantum dot; Photodetector; Hybrid structure

Introduction

Photodetectors (PDs) play an important role in modern society, which convert light into electrical signals [1-4]. PDs are applied to extremely wide range of applications, including imaging [5], security [6] and optical communication [7]. Although commercial photodetectors based have been widely used, traditional semiconductor materials, such as HgCdTe and InSb, they have limited absorption bands and absorption coefficients [8]. Compared to traditional semiconductor materials, 2D materials are considered to be the most promising materials for photodetectors due to their unique optical and electrical properties [9]. Graphene, one of the most popular two-dimensional materials, interacts strongly with light, with ultrahigh carrier mobility (up to 60,000 $cm^2\ V^{-1}s^{-1}$ on a substrate and at room temperature [10]) and no dangling bonds on the surface. For monolayer graphene (thickness about 0.335 nm), the optical absorption coefficient is 2.3% in a wide wavelength range that results the low photoresponsivity [11]. In order to improve the optical absorption of graphene, graphene has been integrated into microcavity [12], waveguide [13] and plasmon resonator [6,14,15] to enhance the light-graphene interaction. Graphene/quantum dots hybrid photodetectors have shown ultra-high responsivity up to 10^8 A/W, which relies on a highly absorbing layer in close proximity to graphene [16]. The absorbing layer induces a shift of the graphene chemical potential upon absorption, hence modifying its channel resistance. Here, based on graphene-quantum structure, we realized the detection of visible to the short-wavelength infrared.

Results and Discussion

The graphene/quantum dots hybrid photodetector we proposed is illustrated in Figure 1(a). By using standard mechanical exfoliation process, single layer graphene is prepared of graphite with tape, then deposited on a Si/SiO_2 (285 nm) wafer. And Ni/Au electrodes were fabricated by magnetron sputtering, which defined as the source and drain. Graphene back-gate field effect transistors (FET) have been demonstrated by using addition gate voltage. The application of a gate voltage (V_G) can create an electrostatic potential difference Φ between the graphene and the gate electrode, leading to a shift in the Fermi energy level (E_F) of graphene. The relationship between V_G and E_F is given as $V_G = E_F / e + \Phi$ [17]. For a back gate, $\Phi = ne / C_{BG}$, where n is the carrier concentration and C_{BG} is the geometric capacitance. The FET we fabricated is shown in Figure 1(b). After fabricating graphene FET, the PbS quantum dots (QDs) in toluene (25 mg/mL) were deposited through a layer by layer film deposition and ligand exchange process [18]. Ethanedithiol (EDT) in acetonitrile stock solution was first prepared for ligand exchange. The final optical microscope image of the device is shown in Figure 1(c).

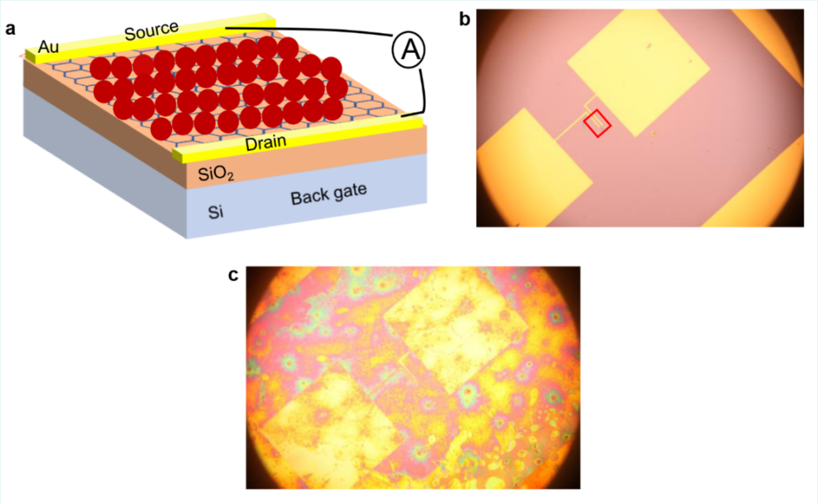

Figure 1: a) Schematic of the proposed device in which a graphene flake is deposited onto a Si/SiO_2 structure and coated with PbS quantum dots. b) Optical microscope image of the fabricated graphene FET, and the rectangle with red solid lines inside represents graphene. The effective area of the device is about 10×30 μm^2. The golden parts are the source/drain electrodes. c) The optical microscope image of graphene/PbS quantum dots hybrid photodetector.

After device fabricated, we tested its electrical properties. Figure 2(a) shows one of the dark current of devices we fabricated, from which we can conclude that there is a good ohmic contact between graphene and electrode. Figure 2(b) shows that changing the back-gate voltage, the current also changes, and the modulation of the Fermi energy level of graphene is achieved. At the same time, spin-coating the quantum dots induces the Dirac peak shift of graphene and changes the graphene mobility. The mobility change of graphene is likely due to increased disorder induced by the quantum dots and the shift of Dirac peak caused by the difference in the work function between graphene and quantum dots.

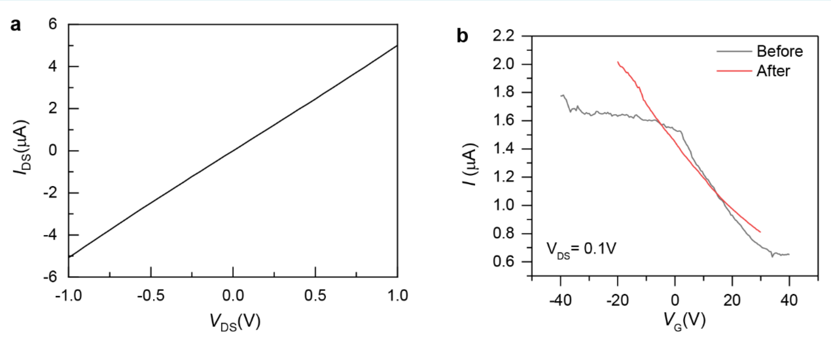

Figure 2: a) Dark current of the fabricated device without applying back gate voltage. b) Drain-source current (I_{DS}) as a function of back-gate voltage for the graphene device before and after decorating with small QDs in ambient conditions, where the V_{DS} is set to 0.1 V.

The photo-detection measurements of our device are illustrated in Figure 3. We first tested pure graphene FET optical response as shown in Figure 3(a). There is no obvious optical response under laser irradiation, because of the low absorption of monolayer graphene. Then we tested the device after PbS quantum dots deposition optical response. It demonstrates that graphene/PbS quantum dots structure is capable of detecting from visible to near-infrared wavelengths. We turn to the specifics of the device and describe the physical mechanism underlying the observed photocurrent response (Figure 3b-d). Quantum dots layer acts as an absorption layer, under the irradiation of light, when the photon energy is above the Fermi energy level energy of the quantum dot, the photon will be absorbed. Photon absorption in PbS quantum dots creates electron–hole pairs, which separate by an internal electric field which induced by the work function mismatch between graphene and the quantum dots. Due to the high charge mobility of graphene and long charge lifetime, the photogenerated electrons or holes will circulate in the graphene channel, leading to photoconductive gain. The photoconductive gain is given by $G = \tau_{\text{lifetime}} / \tau_{\text{transit}}$ [19]. From our calculations, we conclude that the responsivity of the device (R_{ph}) can reach to 6.7×10^3 A/W, which is calculated by following $R_{ph} = I_{ph}/P_{in}$ where I_{ph} and P_{in} represent the photocurrent and incident power, respectively [3].

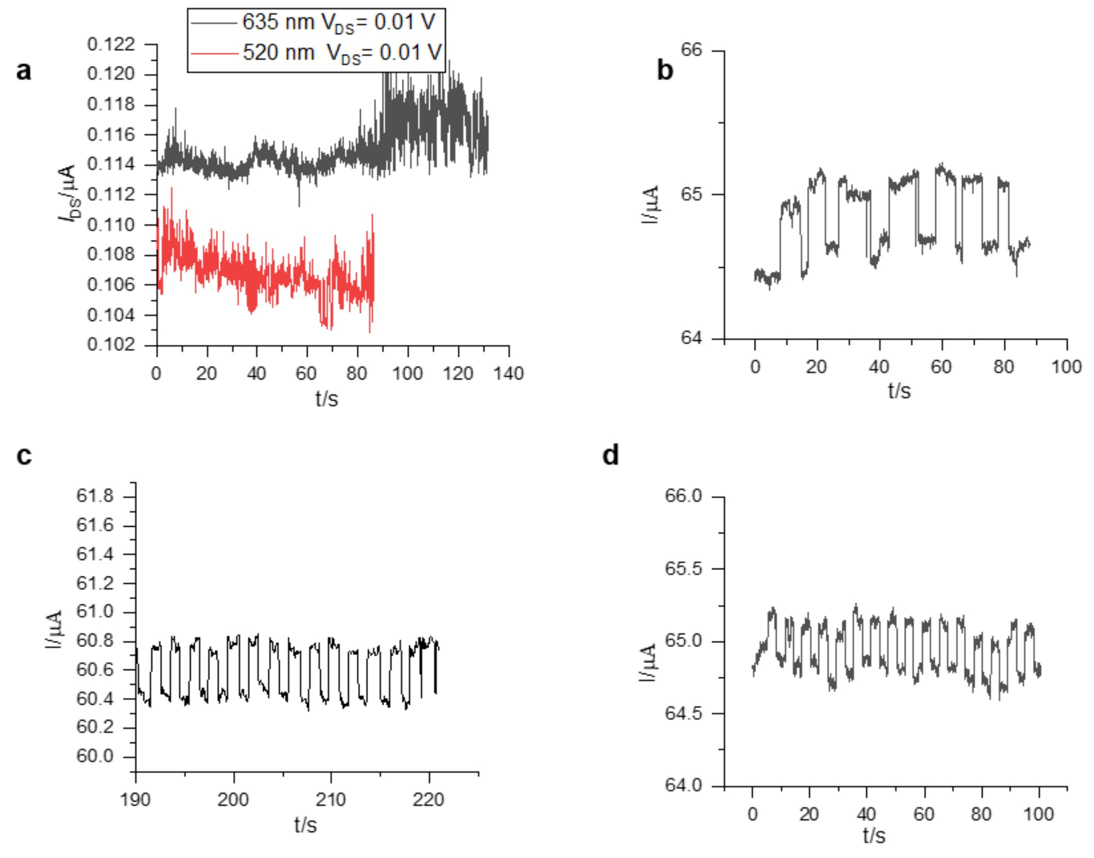

Figure 3: Photoelectric response test results. a) *I-t* curves of pure graphene device under 635 and 520 nm laser illumination. b-d) *I-t* curve of graphene/PbS quantum dot hybrid photodetector under 520, 635 and 785 nm respectively.

Conclusion

We achieved the detection of visible and near-infrared wavelengths by combining graphene with quantum dots. The process of this approach is simple and low cost. At the same time, the size of quantum dots determines their absorption band, and the modulation of the device band can be achieved by changing the size of quantum dots. Therefore, it is possible to achieve the detection of different wavelengths by this way.

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