All Carbon-Based Photodetectors: An eminent integration of graphite quantum dots and two dimensional graphene

Shih-Hao Cheng, Tong-Min Weng, Meng-Lin Lu, Wei-Chun Tan, Ju-Ying Chen & Yang-Fang Chen

Department of Physics, National Taiwan University, Taipei 106, Taiwan.

Photodetectors with ultrahigh sensitivity based on the composite made with all carbon-based materials consisting of graphite quantum dots (QDs), and two dimensional graphene crystal have been demonstrated. Under light illumination, remarkably, a photocurrent responsivity up to $4 \times 10^7$ AW$^{-1}$ can be obtained. The underlying mechanism is attributed to the spatial separation of photogenerated electrons and holes due to the charge transfer caused by the appropriate band alignment across the interface between graphite QDs and graphene. Besides, the large absorptivity of graphite QDs and the excellent conductivity of the graphene sheet also play significant roles. Our result therefore demonstrates an outstanding illustration for the integration of the distinct properties of nanostructured carbon materials with different dimensionalities to achieve highly efficient devices. Together with the associated mechanism, it paves a valuable step for the further development of all carbon-based, cheap, and non-toxic optoelectronics devices with excellent performance.

In recent years, a family of carbon structures, such as fullerene1,2, carbon nanodots3, carbon nanotubes (CNTs)4–6, graphene7–10 and graphene quantum dots (QDs)11–13, have attracted tremendous research interest and trial applications due to their superior and interesting chemical, physical, mechanical and electronic properties. Taking the advantage of abundant content in the earth, chemical stability, fine biocompatibility and non-toxicity, carbon based materials have emerged as attractive candidates for the development of bioimaging, medical diagnosis, catalysis, photovoltaic and many other optoelectronic devices14–16. Especially, the unique properties of nano-carbon based materials depend notably on material dimensionality, such as graphene QDs act as zero-dimensional materials, CNTs as one-dimensional (1D) materials, and graphene sheets as ideal two-dimensional (2D) materials. Combining the unique properties arising from dimensionality and quantum confinement effects of nano-carbons, in both the pure forms of these materials and in hybrid structures, it should be able to generate unprecedented physical properties and provide a potential pathway for constructing all carbon-based devices with high performance17,18.

Among all the nano-carbon based materials, graphene QDs are emerging as one of the most attractive materials due to their size-tunable optical response, efficient multiple carrier generation, non-toxicity, superiority of a large optical absorptivity, and low cost19–21. In addition, graphene, an atomically thin film composed of a single layer of carbon, has also received intensive attention due to its outstanding electrical conductivity, high transparency and high robustness22–24. Graphene thus offers a promising conducting materials with low cost when compared with other frequently used conducting materials. Besides, it is also known that carbon-based conductive pastes are advantageous over other metal contacts for electrically contacting carbon nanostructures25–27. Therefore, stimulating by the superb optical and electrical properties of graphite QDs and 2D graphene, in this paper we provide the first attempt for the integration of zero-dimensional and 2D graphene to create novel all carbon-based photodetectors with high performance.

Figure 1 shows the structure of all carbon-based photodetector fabricated on Si/SiO$_2$ substrate studied in the present work. Quite interestingly, it is found that the photocurrent responsivity can reach up to $4 \times 10^7$ AW$^{-1}$, which is comparable with the ultrahigh gain photodetectors reported previously28–32. Except the large absorption coefficient of graphite QDs and high conduction path provided by graphene, the remarkable ultrahigh responsivity can also be well understood by the spatial separation of photogenerated electron-hole pairs due to the appropriate band alignment across the interface between graphite QDs and graphene. Our result shown here therefore illustrates an excellent example for the creation of all carbon-based optoelectronic devices with high performance. It may open up a new route for the generation of many highly efficient devices with low cost, non-toxicity, and chemical stability.
**Results**

The transmission electron microscopy (TEM) image of the synthesized graphite QDs on the surface of graphene film is shown in Fig. 2(a). It was found that graphite QDs have an average diameter of 6 nm and their distribution with a density of particle number of 2×10¹⁰/cm² on the graphene device is relatively homo-dispersed. Raman spectrum (Fig. 2(b)) provided the convincing evidence for graphene fragment structure of the graphite QDs. The peak at ~1588 cm⁻¹ named G band corresponds to the E₂g mode of graphite is related to the vibration of the sp²-bonded C atoms in a 2D hexagonal lattice, while the peak at 1348 cm⁻¹ named D band exhibits disorder due to the scattering at the edges. The relative intensity of G/D band is ~1.61, similar to the previous report. The quality and thickness of graphene sheet were also verified by Raman spectroscopy as shown in Fig. 2(c). A single symmetric 2D peak at ~2690 cm⁻¹ and a small G/2D ratio were observed, which shows the typical characteristics of single layer graphene with high quality. Figure 2(d) displays the photoluminescence spectrum of the graphite QDs at room temperature excited by a HeCd laser beam with a wavelength of 325 nm, which shows that the emission peak wavelength is located at around 470 nm. The UV–visible absorption spectrum of the graphite QDs in water measured by a PerkinElmer (Lambda 750) spectrometer shows a weak absorption band at around 360 nm arising from the band gap transition. Figure 2(e) displays the X-ray diffraction (XRD) spectrum of the graphite QDs. The calculated lattice spacing is approximately 0.4 nm, which is in good agreement with carbon based material with stratic disorder. The average particle size determined by Scherrer equation was ~8 nm, which is consistent with the observation of TEM image. It is widely known that the graphite QD is consisted by graphene like (sp² bonded) lattice from oxygen-containing functional group matrix. As shown in the previous reports, the thickness of graphene oxide is approximately 0.7 nm. To this regard, with the comparison of our TEM images, the graphite QD is composed of at least 10 to 15 layers of graphene sheets.

Figures 3(a) and (b) show the typical photocurrent and the responsivity measurements as a function of the source–drain bias under light illumination of a HeCd laser with different excitation intensities. Quite interestingly, when the graphite QDs were decorated on the graphene photodetector, the photocurrent drastically increases with increasing the illumination power. Notably, the high responsivity calculated under the optical power of 1.56 μW and the external source–drain bias of 1 V is comparable with the magnitude of ultrahigh gain photodetectors in previous reports. Here, the photoresponsivity was calculated according to the expression given by

\[ R = \frac{I_{ph}}{P_0} \]

where \( R \) is the spectral responsivity, \( I_{ph} \) is the photocurrent (A), \( P_0 \) is the incident optical power (W), and \( \lambda \) is the wavelength (nm). The small current change upon the illumination of graphene photodetector without the decoration of graphite QDs as shown in Fig. 3(a) indicates that the carrier accumulation in graphene sheet is magnified by the interaction with the charge transfer arising from the optically excited graphite QDs. Therefore, the high absorptivity of graphite QDs plays a crucial role in the behavior of the newly photosensitive detector.

To examine the underlying mechanism of the ultrahigh photosensitivity observed here, we have performed the dependence of photosensitivity on the excitation wavelength as shown in Fig. 4. The spectral responsivity of the device containing the graphite QDs basically follows the absorption spectrum of the graphite QDs as shown in Fig. 2(d). In addition, a weak photocurrent peak is also observed for the photon energy below the bandgap of graphite QDs. Markedly, the wavelength at around 470 nm of the weak photocurrent peak is consistent with the PL peak showing in Fig. 2(d), indicating that defects are responsible for both of the PL and photocurrent. A more detailed description of the photocurrent caused by defect states will be discussed below.

This result demonstrates that the spectral selectivity of the newly designed carbon-based photodetector can be manipulated well by the graphite QDs. The large photosensitivity of the graphite QDs/graphene photodetector therefore must involve the charge carrier transfer from graphite QDs to graphene and creates the spatial separation of photogenerated electrons and holes. Therefore, the excess photogenerated carriers can propagate along the excellent path provided by the graphene sheet, which leads to the giant enhancement of photocurrent.

In order to investigate the nature of the intrinsic charge transfer between graphene and graphite QDs, we have characterized the back-gated graphene field-effect transistor on Si wafer with a 300 nm thick SiO₂ layer during the graphite QDs excitation as shown in Fig. 5(a). Before the deposition of graphite QDs, the characteristics \( I_{DS} \) vs. \( V_G \) of the graphite QD, the characteristics \( I_{DS} \) vs. \( V_G \) of the graphene FET shown in Fig. 5(b) exhibits a Dirac point at \( V_G \approx 1.6 \) V, corresponding to a p type doping. The calculated field-effect mobilities are ~1200 cm²/V·s for the free carriers (electrons and holes), which are faster than those of many other bulk semiconductors.

After the decoration of graphite QDs, the I–V characteristics of the hybrid graphene transistor indicate an obvious positive shift (~48 V) of the Dirac point due to the occurrence of hole accumulation in graphene film. Namely, a higher \( V_G \) is needed to access to the Dirac point in the hybrid graphene transistor because the net negative charges in the graphite QDs can attract more photoinduced free
Figure 2 | (a) High resolution transmission electron microscope image of graphite quantum dots. (b) Raman spectra of graphite quantum dot. (c) Raman spectra of graphene sheet. (d) Photoluminescence and absorption spectra of graphite quantum dots. (e) X-ray diffraction spectrum (XRD) of graphite quantum dot.

Figure 3 | (a) Photocurrent of all carbon-based photodetector for different optical powers as a function of drain–source voltage ($V_{DS}$), showing a linear dependence on bias. The photocurrent for the pure graphene device without graphite quantum dots is also shown here, which indicates a negligible effect. (b) Responsivity of all carbon-based photodetector as functions of drain–source voltage characterized under different light irradiance.
holes in the graphene film. Furthermore, the charge transfer creates an internal field and induces asymmetric transfer curves with the reduction of the electron mobility to $682 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ and a negligible effect on the hole mobility.

The theoretical prediction of the photocurrent gain can be estimated by the expression $G = \frac{\tau_{\text{lifetime}} \times QE \times \mu \times V_{DS}}{A}$, where $\tau_{\text{lifetime}}$ is the photogenerated carrier lifetime, $QE$ is quantum efficiency, $\mu$ is the carrier mobility, $V_{DS}$ is the applied bias between source and drain electrode, and $A$ is the area of the graphene sheet under light illumination. If we insert the experimental value of $\tau_{\text{lifetime}} = 2 \text{ s}$, $\mu = 1200 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, $V_{DS} = 1 \text{ V}$, $A = 64 \mu\text{m}^2$, and $QE = 26\%$ estimated by the parallel plate capacitor model$^{28}$, the theoretical gain has a value of about $1 \times 10^9$. The experimental gain number can be calculated by $G = \frac{\tau_{\text{lifetime}}}{\tau_{\text{transit}}} \times (\tau_{\text{transit}} = \frac{d^2}{\mu V_{DS}})$. The obtained photocurrent gain is $3.75 \times 10^9$, which is in the same order of magnitude with the theoretical prediction.

**Discussion**

To understand the above behavior, let us consider the band alignment between the graphite QDs and two dimensional graphene film as shown in Fig. 6. According to the absorption spectrum shown in Fig. 2(b), the graphite QDs have a band gap of about 3.441 eV. Having symmetric linear energy dispersion relations in both valence and conduction bands near the band edges in graphite QDs make equal effective masses for both electrons and holes. According to the previous report$^{41}$, the work functions of the highest occupied states and the lowest unoccupied states of the graphite QDs are estimated to be 6.14 eV and 2.7 eV, respectively, as shown in Fig. 5. Because graphite QDs are found to be of p-type nature, the corresponding Fermi energy is close to its highest occupied states. The energy level of the Dirac point of intrinsic graphene film is at about 4.5 eV. Therefore, according the band alignment as shown in Fig. 6(a), the photogenerated holes in graphite QDs will transfer to the graphene sheet, cause the reduction of the hole carriers in graphite QDs and induce a p-type doping effect in graphene, which leads to the shift of the Dirac point from a lower voltage to a higher voltage. Such carrier transfer has been known to allow a more effective charge separation in graphite QDs and consequently inhibit the electron–hole recombination$^{32,41,42}$. 

---

**Figure 4** | Spectral responsivity of all carbon-based photodetector.

**Figure 5** | (a) Schematic of graphite quantum dots/graphene phototransistor. (b) Transfer characteristics of graphene transistors with and without the addition of graphite QDs on the graphene sheet. (c) Transfer characteristics of graphite quantum dots/graphene phototransistor characterized under UV light irradiation with different power (d) Photocurrent response switching measurements for graphite quantum dots/graphene phototransistor under UV light irradiation.
We now examine the influence of optical excitation. Under UV light illumination, the Dirac point of the transfer characteristics of the hybrid graphene phototransistor shifts toward a higher gate voltage as shown in Fig. 5(c). This behavior can be understood based on the band alignment between graphite QDs and graphene. According to the band alignment as shown in Fig. 6, the photogenerated holes in graphite QDs will transfer into graphene sheet and contribute to the photocurrent. Therefore, both of the giant photocurrent gain and the shift of the Dirac point toward a large gate voltage can be well interpreted.

Besides, it is worth noting that the turn-on transient shown in Fig. 4(d) is characterized by a relatively fast increase in the photocurrent, and followed by a relatively slow decay to a steady state value. This behavior can also be understood in terms of the charge transfer as shown in Fig. 6. The fast increase in the photocurrent under light illumination arises from the fast carrier transfer process from graphite QD to graphene and the high carrier mobility of graphene sheet. And, the slow decay after turning off the light is due to the spatial separation of electrons and holes, which defers the electron- hole recombination.

The above mechanism can also be used to interpret the photocurrent induced by the transition of defect states. We can clearly see that the photocurrent peaks at around 360 nm and 470 nm in Fig. 4 are consistent with the absorption and PL spectra as shown in Figs. 2(b) and (d). According to previous reports35–37,45,46, the graphene quantum dots consist of numerous disorder induced defect states within the π–π* gap and exhibit a broad prominent PL spectrum. Upon light illumination, the electrons in the valence band of QDs can be excited to the defect states and create holes in the valence band. The photogenerated holes due to the existence of defect absorption can transfer into graphene sheet and contribute to the detected photocurrent.

To further confirm the charge transfer of photogenerated holes from graphite QDs to graphene, we have performed PL measurement as shown in Fig. 7(a). It indicates that the PL intensity of graphene quantum dot is quenched in the presence of graphene sheet. The PL quenching in the graphite QD and graphene composite is consistent with the expectation that photogenerated holes can transfer from graphite QD to graphene, which enables to reduce the radiative recombination probability in the graphite QD. In addition, Fig. 7(b) shows the time resolved photoluminescence (TRPL) spectra measured by a near infrared ultrafast laser (Uranus 005, Polar Onyx, CA) with a wavelength 1040 nm as the source of three photon excitation. It exhibits that after the decoration of graphite QDs on graphene, the PL lifetime decreases from 0.133 ns to 0.09 ns. This implies that due to the charge transfer process, there exists an additional channel to reduce the recombination probability, and leads to the reduction of the photogenerated carrier lifetime. Therefore, both PL measurements provide an additional evidence to support our proposed mechanism for the interpretation of the ultrahigh gain photodetector made with graphite QDs and graphene.

Finally, let us compare the performance of the photodetectors consisted of graphite QDs and graphene sheet developed here with simple graphene photodetectors. It is clear that the photocurrent gain in our new device is much higher due to the large absorption coefficient of graphite QDs and the charge transfer caused by the band alignment between graphite QDs and graphene. However, the trade-off is that the response speed becomes slow because of the additional process for the spatial separation of photogenerated holes.

Figure 6 | (a) Schematic band diagram of graphite quantum dot–graphene hybrid device before light illumination. $E_g$ corresponds to the bandgap of graphite quantum dots. (b) Under light illumination, hole can transfer from graphite quantum dots to graphene sheet. The photogenerated electrons are trapped in graphite quantum dots.

Figure 7 | (a) Photoluminescence spectra of graphite quantum dots on graphene sheet and SiO$_2$ substrate. (b) Time-resolved photoluminescence decay spectra for graphite quantum dots on graphene sheet and SiO$_2$ substrate.
Electrons and holes, and the operational wavelength range for the high responsivity is restricted to the band gap absorption of quantum dots. These features arise from the inherent nature of the photodetectors with similar structure as shown in previous reports[28,42–45].

In summary, we have demonstrated that the ultrahigh sensitivity of photoreponse can be obtained based on the integration of zero dimensional graphite QDs and 2D graphene sheet. The underlying mechanisms arise from several important factors, including the large absorptivity of graphite QDs and high conductivity of graphene sheet. The charge transfer due to the appropriate band alignment between graphite QDs and graphene also plays a decisive role, which creates the spatial separation of photogenerated electrons and holes, prolongs the photoinduced electron lifetime, and improves the photocurrent responsivity. It is stressed here that the drastic improvement of photocurrent gain of the hybrid photodetectors made with of all carbon-based materials shown here can serve as an excellent illustration for the creation of the unique properties of nano – carbons with different dimensionalities. It can open up a new route for the creation of all carbon-based devices with low cost, nontoxicity, and high performance.

**Methods**

For the synthesis of QDs, 2 g 11-aminoundecanoic acid was first dissolved in 25 ml DI water then neutralized by 1 M sodium hydroxide aqueous solution. Afterward, 2 g citric acid was added to the above solution. With vigorous stirring, a thick precipitate was observed within few minutes. The precipitation was collected by filtration and allowed to dry at 85 °C for one day. The dried precipitant was then grounded into fine powder and directly oxidized in air at 300 °C for 2 hours in muffel oven under ambient atmosphere. The QD was extracted by hot water, solid impurity was removed by centrifuge. For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.

For purification, pH of extracted QD was adjusted to 2 by concentrated hydrochloric acid, which yields bulk precipitation. The soluble impurity was then removed by centrifuge. The precipitant was then treated with 50 ml 0.1 M NaOH, which causes the dissolution of precipitant. Minor insoluble impurity was then removed by centrifuge. The purification procedure was repeated for 3 times. Finally, a clear and deep-brown dense colloidal quantum dots solution with long period stability was obtained. According to previous reports[47,48], the deep brown color.
Acknowledgements

This work was supported by the National Science Council and Ministry of Education of the Republic of China.

Author contributions

Y.F.C. planned and supervised the project; M.L.L. advised on the project; S.H.C. and T.M.W. designed and performed experiments; S.H.C., W.C.T. and T.M.W. made samples and the structural measurements; S.H.C., J.Y.C. and T.M.W. performed the electrical measurements; and Y.F.C. and S.H.C. analyzed data and wrote the manuscript. All authors discussed and commented on the manuscript.

Additional information

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Cheng, S. et al. All Carbon-Based Photodetectors: An eminent integration of graphite quantum dots and two dimensional graphene. Sci. Rep. 3, 2694; DOI:10.1038/srep02694 (2013).