Enhanced photoresponse of ZnO quantum dot-decorated MoS$_2$ thin films†

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Transition metal dichalcogenide (TMD) thin films have been used in the development of nano- and opto-electronic devices, such as ambipolar and high-quality field-effect transistors, digital integrated circuits, electric double-layer transistors, and highly responsive photodetectors. TMD materials have been widely investigated through theoretical or experimental studies, such as the investigation on charge transfer and photon–exciton interactions. One of the basic methods to tune the optical properties of TMDs involves controlling the charge carrier density. One of the mostly used TMD materials that has been widely investigated is molybdenum disulfide (MoS$_2$). Different methods used to inject charge carriers in TMDs were intensively studied; these methods include tuning of charge carriers by using back gate voltage, O$_2$ and H$_2$O molecule adsorption, chemical process of molecule interaction, and plasmonic hot electron doping. Thus, finding a suitable means of efficient doping to achieve superior optical properties of TMDs is necessary.

Semiconductor quantum dots (QDs) demonstrate unique behaviors, such as size-tunable atomic-like characteristics resulting from quantum confinement in the nanometer scale. A number of semiconductors consisting of QDs have been widely used in different research fields because of their anomalous behavior. Groups II–VI semiconductor QDs, such as CdSe and ZnSe, display an advantage over IV and III–V materials due to their higher exciton energies and the stronger phonon–exciton interaction among them. Unfortunately, the bandgap of CdSe in bulk form is 1.74 eV, which is very difficult to tune in the ultraviolet (UV) region. Moreover, CdSe is toxic and unsafe for medical applications. On contrary, ZnSe can be used in UV-blue range of energies. However, ZnSe-based devices demonstrate less efficient performance because of certain defects. Zinc oxide (ZnO), which displays a wide direct bandgap of 3.37 eV at room temperature, is a good candidate for short wavelength applications. ZnO has become famous as the brightest emitter among available wide-bandgap semiconductors. Zinc oxide (ZnO) QDs have been extensively used in photo-detection, bioelectronics, optoelectronics, and gas sensing.

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Introduction

Photovoltaic cells, photodetectors, sensors, light-emitting diodes (LEDs), and LED displays will eventually require opto-electronic materials that demonstrate more efficient characteristics than those currently used. Graphene is an emergent electronic material, which has been widely studied because of its high mobility, ultra-thinness, and flexibility. Graphene has been extensively used in photodetection, bioelectronics, optoelectronics, and gas sensing.

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This study comparatively explored the photoresponse of pristine MoS$_2$ and ZnO-QDs/MoS$_2$ heterostructures. We investigated a number of electrical and photoelectrical properties, such as carrier mobility, responsivity ($R_s$), detectivity ($D^*$), external quantum efficiency, and linear dynamic range with and without ZnO-QDs. All of these parameters were investigated at various back gate voltages ($V_{bg}$). High carrier mobility when ZnO-QDs is deposited over MoS$_2$ is caused by reduced carrier.

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‡Electronic supplementary information (ESI) available. See DOI: 10.1039/c7ra01222e
transit time (the time required for an electron or other charge carrier to travel between two electrodes in a transistor) within a field-effect transistor (FET). Moreover, rise and decay times of carriers in a photodetector were calculated, and the results showed that after ZnO-QDs interacted with pristine MoS$_2$, the decay time dramatically changed suggesting the efficient charge transfer that occurred between ZnO-QDs and MoS$_2$ surface. Furthermore, this work discusses the proposed mechanism of charge transfer between ZnO-QDs and pristine MoS$_2$.

**Experimental section**

**Sample preparation**

Naturally available MoS$_2$ was mechanically exfoliated using the scotch tape method over a heavily p-doped Si as substrate with 300 nm-thick SiO$_2$ as capping layer. The desired flake with a suitable thickness was chosen by using an optical microscope. A large Cr/Au pattern with a thickness of 6/30 nm was subsequently deposited around the desired flake by using photolithography. To make source and drain contacts, we performed e-beam lithography, followed by the final deposition of an 8/80 nm-thick Cr/Au in an evaporation chamber, in which a high vacuum of $2 \times 10^{-6}$ Torr was maintained. Electrical measurements using Keithley 2400 Source Meter and Keithley 6485K Picoammeter were subsequently performed by placing the sample in a vacuum at room temperature. To study photoresponse, we placed our sample in a vacuum and illuminated by deep UV light (DUV) with an intensity of 11 mW cm$^{-2}$ and a wavelength of 220 nm. Structural investigation and material identification were performed using Raman spectroscopy and atomic force microscopy (AFM). Fig. S1† shows the results of the Raman analysis of our flake, and the results confirm the multilayer nature of MoS$_2$ with peaks located in exactly the same positions as described in a number of publications. Laser wavelength was obtained at 514 nm, and a low power of less than 1 mW was chosen to avoid structural degradation caused by heating effects of laser. The size of laser spot used in Raman spectroscopy is 0.7 $\mu$m. Fig. S2† shows the AFM micrograph of MoS$_2$, and the image confirms the multilayer nature of MoS$_2$ which is 7 nm thick (~11 layers).

**Synthesis and characterization of ZnO QDs**

ZnO-QDs were synthesized in methanol via hydrolysis method. Typically, 20 mmol methanol solution of ZnAc$_2$:2H$_2$O was prepared and maintained at 60 °C followed by dropwise addition of 200 mmol methanol solution of KOH for 10 min under vigorous stirring for 2 h. Finally, the QDs were collected by centrifugation and then washed multiple times with methanol. The ZnO-QDs solution was drop casted over MoS$_2$ photodetector device and then baked gently at 70 °C for 10 min. To confirm the nature of the material, we measured the excitation and emission of matrix (EEM) of ZnO-QDs by using a spectrophotometer (Hitachi, F7000, Japan). The measured excitation/emission wavelength was adjusted to 220-500 nm/280-550 nm at a scan step of 5 and 1 nm for excitation and emission, respectively. Moreover, a polarized cut off filter of 290 nm was placed in front of a lamp to remove Rayleigh scattering, and Milli-Q water was used as blank and subtracted from the EEM of each sample.

**Results and discussion**

Fig. 1a shows the 3D schematic of a photodetector consisting of ZnO-QDs decorated MoS$_2$ as channel flake. The MoS$_2$ is supported on SiO$_2$/p-Si wafer substrate with 300 nm-thick SiO$_2$. Fig. 1b shows the optical image of the MoS$_2$ FET with a channel length of 1.52 $\mu$m and a width of 6.34 $\mu$m.

Raman spectroscopy is the most useful tool utilized in non-destructive analysis of structural properties.$^{35-42}$ We chose a desired flake by using an optical microscope and then performed Raman analysis to confirm flake thickness and to identify the material. The Raman spectra of the MoS$_2$ flake were obtained at room temperature. Fig. S1† shows the Raman spectra for our MoS$_2$ flake. The in-plane ($E_{2g}$) and out-of-plane ($A_{1g}$) vibrational modes for multilayer MoS$_2$ (ML-MoS$_2$) was found at ~384 and ~408 cm$^{-1}$, respectively. The difference between $E_{2g}$ and $A_{1g}$ of the ML-MoS$_2$ is ~24 cm$^{-1}$, consistent with previous results.$^{35-42}$ The black curve represents pristine MoS$_2$ and the red curve represents the ZnO-QDs/MoS$_2$ heterostructures. The peak positions did not change after ZnO deposition. Fig. S2† shows the AFM images used to further confirm the thickness of the layer of the ML-MoS$_2$ flake. The measured thickness of our flake is 7 nm (11-layer). We found that the average height of ZnO-QDs is 2–4 $\AA$ and the average width is 10–20 $\mu$m (Fig. S3†).

We determined the electrical characteristics under vacuum by applying $V_{bg}$. Transfer characteristics of pristine MoS$_2$ and ZnO-QDs/MoS$_2$ structures were examined and the results are shown in Fig. 1c. We maintained the drain–source voltage ($V_{ds}$) at 0.5 V throughout our measurements. The drain current ($I_{ds}$) increases after drop casting ZnO-QDs over MoS$_2$ in positive gate voltage range while decrease in negative gate voltage because of increase in leakage current in that region. The field-effect mobilities can be calculated using the fundamental formula

$$\mu = \frac{L}{W} \left( \frac{dI_{ds}}{dV_{bg}} \right) \frac{1}{V_{ds}C_{ig}},$$

where $L$ and $W$ are the channel length (1.52 $\mu$m) and width (6.34 $\mu$m) of our MoS$_2$ flake, respectively, $dI_{ds}$ is the slope of the linear region of transfer curves, and $C_{ig}$ is the gate capacitance (~115 aF $\mu$m$^{-2}$) of Si substrate with 300 nm-thick SiO$_2$ as capping layer. Therefore, the field-effect mobilities are 5.75 and 25.09 cm$^2$ V$^{-1}$ s$^{-1}$ before and after decorating ZnO-QDs on MoS$_2$ flake, respectively.

Fig. 2a and b show the output ($I$–$V$) characteristics before and after drop casting ZnO-QDs over MoS$_2$ surface. Output characteristics of pristine MoS$_2$ show a linear relationship with $I_{ds}$ and $V_{ds}$ at different $V_{bg}$ values, demonstrating that contacts (Cr/Au) on the surface of MoS$_2$ are ohmic and that no Schottky barrier exists at the metal–semiconductor junction interface. Moreover, Fig. 2b shows the output characteristics after decorating ZnO-QDs over MoS$_2$. The output characteristics again show ohmic nature of the contacts but with increased $I_{ds}$, confirming that ZnO-QDs on the surface of MoS$_2$...
does not damage the contacts or cause structural deformation, which is beneficial for the applications of FET in optoelectronics.

We further investigated MoS$_2$ photodetectors by determining the time-dependent photoresponse of pristine MoS$_2$ and ZnO-QDs/MoS$_2$ heterostructures under varying $V_{bg}$ values. To
determine the photoresponse behavior of our device, we placed our device in a vacuum and illuminated by DUV in a way that light falls vertically on its surface with an effective area of 9.64 μm². All measurements were performed at V_{ds} = 0.5 V. As DUV light falls on MoS2 surface, the photocurrent (I_{ph}) increases with increasing V_{bg}, caused by the increase in carrier drift velocity and the corresponding reduction in carrier transit time (defined as T_{c} = L^{2}/μV_{ds}, where μ is the field-effect mobility and L is the channel length). Our calculation showed that the carrier transit time for ZnO-QDs/MoS2 is lower than that for pristine MoS2. As a result, the current increases with increasing V_{bg}; thus, I_{ph} becomes dominant over thermionic and tunneling currents at all V_{bg} values.46

I_{ph} for pristine MoS2 and ZnO-QDs/MoS2 are shown in Fig. 3a and b, respectively, and I_{ph} of ZnO-QDs/MoS2 is greater than that of pristine MoS2 at all V_{bg} values (0–30 V). This phenomenon was observed because in the case of ZnO-QDs/MoS2 heterostructures, ZnO-QDs provide surplus carriers to MoS2, and these carriers equally contribute to the increase in overall photoresponse behavior under DUV light.47 Another important parameter in evaluating devices under light illumination is R_s, R_s indicates the response of a device to light (specific wavelength) and is defined as “I_{ph} produced per unit power of incident light on effective area of a photodetector”.48

\[
R_s = \frac{\Delta I_{ph}}{P \Delta \lambda}
\]

where P is the light intensity, A is the effective area of photodetector, and \(\Delta I_{ph}\) is the photocurrent generation (\(\Delta I_{ph} = I_{ph} - I_{dark}\)). R_s is highly dependent on wavelength of incident light. Responsivity (R_s) is negligible for a light of wavelengths >680 nm,14 which corresponds to an energy level of 1.8 eV, the bandgap for monolayer MoS2. Thus, to excite the electrons from the valence band to the conduction band, we must use a light of shorter wavelength. R_s of our photodetector with an effective area of 9.46 μm² was measured under DUV light with an intensity 11 mW cm⁻² and a wavelength of 220 nm. \(\Delta I_{ph}\) and the corresponding R_s of pristine MoS2 and ZnO-QDs/MoS2 are shown in Fig. 4a and b respectively. \(\Delta I_{ph}\) and R_s both increased in ZnO-QDs/MoS2 heterostructures at all V_{bg} values because of the increase in charge carriers transferred from ZnO-QDs to MoS2 surface (see Table S1 in ESI†). We measured the dark current without and with ZnO-QDs, and Fig. 4c shows that the dark current is higher after decorating ZnO-QDs over MoS2 at all V_{bg} values. We also measured detectivity (D*) as shown in Fig. 4d, which is defined as the “ability of a device to detect weak optical signal”. Given that dark current mainly contributes to noise factor of photodetector, then D* is expressed as follows:49

\[
D^* = \frac{R_s A^{1/2}}{\sqrt{2eI_{dark}}}
\]

where R_s is responsivity, e is the electronic charge, and I_{dark} is the current in the absence of light. D* is expressed in jones, where 1 jones = 1 cm Hz¹/² W⁻¹. In this study, D* is in the order of 10¹¹ jones. Low D* of heterostructures at low V_{bg} values (Fig. 4d) is due to the increase in dark current at these voltages (Fig. 4c).

We prepared a schematic of energy band (Fig. 5) to illustrate photodetector behavior of our pristine MoS2. In the absence of light illumination and any V_{ds} or V_{bg}, the device is at equilibrium state. When light with a wavelength of 220 nm falls on pristine MoS2 in its OFF state (V_{bg} = 0 V), light is absorbed by the pristine MoS2, resulting in the excitation of electrons to the conduction band even when V_{bg} was zero (Fig. 5b). A low number of charge carriers will move to the conduction band when V_{bg} < V_{th}, and the drain current is very low (Fig. 5c). In contrast, in the ON state (V_{bg} > V_{th}), photo-generated, thermionic, and tunneling currents contribute cumulatively to I_{ph} enhancement (Fig. 5d). Our devices showed good R_s at room temperature relative to that of the reported devices.49,50

Dynamic response to light irradiation was studied, and the rise and decay times were measured by fitting the curves to exponential decay function51,52.

Fig. 3 Photocurrent (I_{ph}) versus time under different V_{bg} values ranging from V_{bg} = 0 V (black curve) to V_{bg} = 30 V (blue curve). Photoreponse of (a) pristine MoS2 measured at different V_{bg} values with equal steps of 10 V and V_{ds} = 0.5 V under deep ultraviolet illumination with an intensity of 11 mW cm⁻² and a wavelength of 220 nm with alternating on and off cycles. (b) The photosresponse of the same device after ZnO-QDs drop casting shows higher I_{ph} at all V_{bg} values. The photosresponse at V_{bg} = 0 V has been omitted in order to see the clear interpretation of plot.
The photocurrent generation ($\Delta I_{ph}$) in blue circles and responsivity ($R_{ph}$) in red circles versus back gate voltage ($V_{bg}$) for (a) pristine MoS$_2$ and (b) ZnO-QDs/MoS$_2$ heterostructures; $\Delta I_{ph}$ and $R_{ph}$ both increased after decorating ZnO-QD on MoS$_2$. (c) Dark current versus $V_{bg}$ before and after ZnO-QD decoration. Dark current is higher in ZnO-QDs/MoS$_2$ heterostructure than in pristine MoS$_2$ at all $V_{bg}$ values. (d) Detectivity ($D^*$) versus $V_{bg}$ before and after ZnO-QDs at a power of $10^{11}$ jones. Low value of $D^*$ at a low $V_{bg}$ is caused by high dark current at these values.

$$I_{ph}(t) = I_{dark} + A \exp\left(\frac{-t}{\tau_{decay}}\right)$$

where $A$ is the scaling constant, $\tau_{decay}$ is the time constant for decay, and $t$ is the time after switching on or off of DUV light. We can determine the time constant ($\tau$) by fitting the experimental curves. The decay and rise times at different $V_{bg}$ values showed similar average values, indicating that $V_{bg}$ does not considerably contribute to the changes in decay and rise times. Fig. 6 shows the rise and decay times at different $V_{bg}$ values before and after decorating with ZnO-QDs. For pristine MoS$_2$, the rise time at each $V_{bg}$ is lower than the corresponding decay times (Fig. 6a and c). Our results are consistent with previous findings.\(^{14}\) In $I_{ph}$ dynamics, environmental effects are very important in a photodetector. The decay time can be varied in the range of 0.3–4000 s under various surface treatments probably because of the difference in surface hydrophobicity.\(^{53,54}\) The device response of our pristine MoS$_2$ is slow, with rise and decay times longer than $\sim 12$ and $\sim 26$ s at $V_{bg} = 0$ V, respectively. This slow response is attributed to either charge impurity states or defects in the bandgap or to the existence of trap states\(^{14,43,55}\) between the underlying SiO$_2$ layer and MoS$_2$. To further enhance the $R_{ph}$ and degrade the response time, we spread ZnO-QDs over MoS$_2$ surface to form heterostructures.

The considerable change in transfer characteristics of ZnO-QDs/MoS$_2$ heterostructures is convincing. Fig. 6b and d show the rise and decay times for ZnO-QDs/MoS$_2$ heterostructures. The rise time ($\sim 24$ s) of our heterostructures at $V_{bg} = 0$ V increases to more than $\sim 12$ s (for pristine MoS$_2$) because of the surplus charge carriers transferred from ZnO-QDs to MoS$_2$ surface. Moreover, drain current significantly increases in ZnO-QDs/MoS$_2$ heterostructures possibly caused by the increase in carrier concentration resulting from the transfer of charge carriers from ZnO-QDs to pristine MoS$_2$. Another notable phenomenon is the reduction in decay time in ZnO-QDs/MoS$_2$ heterostructures; fast decay is speculated to be related to direct recombination of light-excited carriers and to sub-bandgap emissions caused by the existence of charge impurity and trap states in the bandgap of MoS$_2$ surface.\(^{56}\) This fast decay is related to the efficient charge transfer between MoS$_2$ surface and ZnO-QDs. Oxygen molecules adsorb onto oxide surfaces and thus occupy free electrons available in n-type metal oxide semiconductors, along with the formation of less conductive depletion layer near ZnO-QD surface. In ZnO-QDs, existence of hole trap states is highly probable because of high surface-to-volume ratio,\(^{27}\) consistent with the 3D-PL spectrum shown in Fig. S4.\(^{1}\) When these heterostructures are illuminated under a light with a photon energy that is larger than the ZnO
bandgap, electron–hole pairs are produced and immediately separated from the holes trapped at the surface (caused by band bending) leaving behind unpaired electrons that quickly transfer to MoS$_2$ channel and are gathered by means of $V_{ds}$. The trapped holes recombine with negatively charged oxygen ions, producing neutral oxygen molecules, which are then desorbed from the surface of ZnO-QDs. Water and oxygen molecules present in air also physisorb at MoS$_2$/SiO$_2$ interface and create p-doping MoS$_2$ channel. However, deposition of ZnO-QDs onto MoS$_2$ surface causes Dirac point to shift from high voltage to low voltage because of electron transfer from ZnO-QDs to MoS$_2$ surface, compensating the doping of physisorbed oxygen at the ZnO-QDs/MoS$_2$ channel surface.

To understand the mechanism of $I_{ph}$ generation in our heterostructures, we prepared a schematic of energy band (Fig. 7). Fig. 7 shows the band bending and carrier transfer direction when ZnO-QDs and MoS$_2$ interact with each other. The electron affinity$^{48}$ of ML MoS$_2$ is approximately 3.9 eV, which is comparable to that of ZnO-QDs. Our ML MoS$_2$ film is 7 nm thick (~11 layers) and its indirect bandgap$^{48}$ is 1.2 eV, which is
considerably smaller than the bandgap of ZnO-QDs (3.37 eV). Considering that both ZnO-QDs and MoS2 are n-type materials, we proposed energy band diagrams showing the bandgap before and after formation of heterostructures (Fig. 7a and b). Fermi level for ZnO-QDs is closer to vacuum level as compared with that for MoS2 (Fig. 7). Fig. 7a shows basic schematic for MoS2 and ZnO-QDs contains information about electron affinity and bandgap before their heterojunction. When MoS2 and ZnO-QDs

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Fig. 6  Photocurrent ($I_{ph}$) versus time at different back gate voltages ($V_{bg}$) ranging from $V_{bg} = 0$ V (red curve) to $V_{bg} = 30$ V (blue curve). (a) $I_{ph}$ relaxation for pristine MoS2 at different $V_{bg}$ values in the absence of DUV light. (b) Dramatic increase in $I_{ph}$ relaxation for ZnO-QDs/MoS2 at all $V_{bg}$ values. (c) Rise time for pristine MoS2 under DUV light at different $V_{bg}$ values. (d) Rise time after ZnO-QDs decoration over MoS2. The data were fitted by eqn (3) and indicated by black lines in all graphs.

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Fig. 7  (a) Energy diagram for MoS2 and ZnO quantum dots (QDs) before contact. (b) Energy diagram of the interface between MoS2 and ZnO-QDs after construction of heterojunction; different Roman numerals represent different proposed mechanisms of carrier transformation across junction, as well as between valence and conduction bands. (I) Shows photon excitation of charge carriers in MoS2 and ZnO-QDs; (II) indicates that carriers de-excite the photon emitted by ZnO-QDs and that the emitted photon is re-absorbed by MoS2; (III) electrons tunnel from ZnO-QDs to MoS2; (IV) holes transfer from ZnO-QDs to MoS2; and (V) electrons from ZnO-QDs are thermally agitated toward MoS2.
QDs interact to form heterostructures caused by van der Waals forces, we proposed that there exist number of ways of carrier injection between MoS2 and ZnO-QDs. When light falls on heterostructure, there occurs injection of electrons from ZnO-QDs conduction band into MoS2 conduction band as explained by process “III”. The electrons in the valence band also move from ZnO-QDs to MoS2 due to thermal agitation shown by process “IV”. The motion of electrons causes band bending, which is manifested as a small energy barrier. When these heterostructures are illuminated under DUV light, photo-generation occurs because both ZnO-QDs and MoS2 strongly absorb light photon and electrons move from valence to conduction band explained by process “I”. Also, some of the electrons in the conduction band move back to the valence band of ZnO-QDs and emit light photon which caught by electrons in the valence band of MoS2, and get excited toward conduction band of MoS2 explained by process “II”. The enhancement is generally caused by a large number electron–hole pairs, resulted from tunneling of electrons from ZnO-QDs to MoS2 surface. Given that the decay time of the heterostructures is shorter than that of pristine MoS2, the recombination rate and consequently the photoresponse is faster in ZnO-QDs/MoS2 than in pristine MoS2.

Two more parameters, namely, external quantum efficiency (EQE) and linear dynamic response (LDR) were investigated to better assess the photodetector performance. These parameters were observed at different Vbg values without and with interaction of ZnO-QDs. EQE is given by the formula:

\[
\text{EQE} = \frac{hcR_l}{e\lambda}
\]  

(4)

EQE is defined as the “number of photo-induced carriers per incident photons” h is Planck’s constant, e is the speed of light, \(e\) is the elementary charge, \(R_l\) is the photo responsivity, and \(\lambda\) is the wavelength of illumination. Fig. 8a shows the EQE values versus \(V_{bg}\) with and without ZnO-QDs. EQE values at all \(V_{bg}\) values are higher in ZnO-QDs/MoS2 than in pristine MoS2. EQE can be improved by increasing \(R_l\) factor and by irradiating the samples with incident light with short wavelength. The high EQE values for ZnO-QDs/MoS2 heterostructures are mainly caused by the increase in photo-induced charge carriers, as well as by accumulation of carriers by ZnO-QDs. Another factor that we investigated is LDR, which is the maximum linear response of a detector relative to its noise. LDR or photosensitivity measures the image quality in biomedical image processing and sensing and is given by the following formula:

\[
\text{LDR} = 20 \log \left( \frac{I_{ph}}{I_{dark}} \right)
\]  

(5)

where \(I_{ph}\) is the value of current measured by our device under illumination with a light intensity of 11 mW cm\(^{-2}\) and \(I_{dark}\) is the dark current at different \(V_{bg}\) values in the absence of light. Fig. 8b compares LDR versus \(V_{bg}\) of the pristine MoS2 and ZnO-QDs/MoS2 heterostructures. The LDR values of the heterostructures are low because of low \(\text{LDR}_{\text{dark}}\) ratios. In other words, the increase in dark current in ZnO-QDs/MoS2 heterostructures (Fig. 4c) degrades LDR.

To confirm the size of ZnO-QDs, we obtained an AFM image (Fig. S3†), which shows that the average height of ZnO-QDs is 2-4 Å and the average width is 10-20 nm. Moreover, we obtained a 3-D fluorescence plot by choosing a range of wavelength of light to be used to irradiate our samples (Fig. S4†). By using the formula \(E_x = \frac{hc}{\lambda_x}\), we determined the height excitation peak at \(\approx 378\) nm, leading to a bandgap of 3.28 eV, which corresponds to the bandgap of our 10 nm ZnO-QDs. The EEM of ZnO-QDs was measured using a spectrofluorometer. The EEM clearly shows the maximum emission peak at approximately 440 nm at 378 nm excitation. The red thick line is caused by Raman scattering of ZnO-QDs dispersed in methanol solution.

Fig. 8 (a) External quantum efficiency (EQE) versus back gate voltage (Vbg) for pristine-MoS2 and ZnO-QDs/MoS2. EQE is high after ZnO decoration over MoS2. (b) Linear dynamic range (LDR) versus Vbg for pristine MoS2 and ZnO-QDs/MoS2. LDR decreases after ZnO-QD decoration at all Vbg values because of the increase in dark current as shown in Fig. 4c.
Conclusion

We investigated for the first time a high-response photodetector based on MoS2/ZnO-QDs heterostructures. The junction between MoS2 and ZnO-QDs forms n–n type heterostructures, resulting in enhanced carrier mobility caused by injection of electrons from ZnO-QDs into MoS2. A number of factors were investigated. R, increased after ZnO-QDs were deposited over MoS2 surface, and this phenomenon resulted from the increase in I, caused by the surplus carriers cumulatively transferred from ZnO-QDs to MoS2 surface. EQE increased after ZnO-QDs were drop casted over MoS2, whereas after decorating with ZnO-QDs, D increased caused by the massive increase in dark current. Moreover, LDR degradation corresponds to the increase in dark current in ZnO-QDs/MoS2 heterostructures. We extensively discussed the basic phenomenon of charge transfer in pristine MoS2 and ZnO-QDs/MoS2 heterostructures. In addition, this report presents a number of proposed factors that contribute to the increasing I, resulting from generation of charge carriers across the junction of the ZnO-QDs and MoS2 surfaces. We suggest that generation of charge carriers, which contribute to I, enhancement, is affected by the five parameters mentioned above (Fig. 7). This high photosresponse is largely caused by the effect of light–matter interactions based on tunneling of photo-excited carriers from ZnO-QDs to MoS2 and by re-absorption of emitted photons from ZnO-QDs by MoS2. Our work describes the basic mechanism of charge transfer between ZnO-QDs and MoS2.

Acknowledgements

This research was supported by Nano-Material Technology Development Program (2012M3A7B4049888) through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning. This research was also supported by Priority Research Center Program (2010-0020207) and the Basic Science Research Program (2016R1D1A1A09917762) through NRF funded by the Ministry of Education.

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