Graphene/CuS/PbS nanocomposite as an effective counter electrode for quantum dot sensitized solar cells

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Abstract:

In this paper, we introduce graphene/CuS/PbS nanocomposite as an effective counter electrode (CE) for quantum dot sensitized solar cells (QDSCs). The result indicated that the catalytic performance of CuS/PbS CEs was enhanced by pre deposition of graphene (G) sheets on the fluorine doped tin oxide (FTO) coated glass substrates. Here, various CEs are made by the simple successive ionic layer adsorption and reaction (SILAR) method. The result indicates that the fill factor of the cells with FTO/G/CuS/PbS CEs enhances in compare with the FTO/CuS/PbS CEs. Here, for the CdS/CdSe QD sensitized cells and G/CuS/PbS CEs, the cells' efficiency and fill factor is obtained 3.21 % and 0.51 respectively which is enhanced compared to the CuS/PbS CEs with 2.54 % efficiency and 0.36 fill factor. The present results indicate that the compact structure of the CuS/PbS CEs, replaces with a porous structure after graphene pre deposition which is expected to enhance the electrolyte/CE interface and consequently the fill factor. According to the obtained results, in spite of the poor catalytic activity of the graphene in the polysulfide electrolyte, it simply modifies the morphology of the CuS/PbS CEs for enhancing their performance. The results also demonstrated that G pre deposition can be systematically applied to enhance the performance of CEs in QDSCs.

Key words: quantum dot, solar cell, counter electrode, graphene, SILAR, fill factor

1. Introduction

Currently solution processed semiconductor nanocrystals are promising for making low cost, large scale and efficient quantum dot solar cells [1-10]. Optoelectrical properties of semiconductor quantum dots could simply tailored by controlling their size, shape and other synthesizing parameters. QDs show high extinction coefficients, large dipole moments and also multiple exciton generation under specified conditions [11, 13]. Recently, considerable research is conducted on all components of QDSCs containing photoanode, electrolyte and counter electrode in order to enhancing the QDSCs photovoltaic properties. For example one dimensional photoanode structures such as nanorods, wire and tubes are sensitized with QDs in order to improve the charge transport in the photoanode structure [14-17]. Chemical composition of the redox electrolytes is optimized and tens of different cathode electrodes are applied in QDSCs [18-20]. Regarding the mentioned optimizations currently the efficiency of QDSCs is boosted more than 8 % which is interesting [21, 22]. Literature review indicates that the open circuit voltages [23] and current densities [24] of QDSCs have improved noticeably in the last few years. However, the typical energy conversion efficiencies of QDSCs are still lower than dye sensitized solar cells (DSCs) which are mainly originated by the low fill factors in QDSCs. The fill factor in QDSCs is generally less than 0.6 (fill factors of 0.75 - 0.8 is simply obtained in DSCs) which restricts the further efficiency enhancements [25, 28]. According to the previous researches, reducing the series resistance of the CE and improving the charge transfer kinetics at the CE/electrolyte interface clearly improves the fill factor [29- 31]. Until

now, various CEs like Pt, Au, PbS, CuS, CoS, CuS/PbS, graphite, carbon black, carbon nanotubes, and graphene are utilized in QDSCs [32-38]. Among the mentioned CEs, metal sulfides such as CuS, CoS, PbS and their composition like CuS/PbS have generally a better catalytic performance and stability in the polysulfide redox electrolyte which is generally used in QDSCs [39-41]. Currently the chemical treatment of the metallic brass and Pb substrates is generally utilized in order to make CuS and PbS CEs respectively [39-41]. Metallic based CEs have a suitable porous structure with moderate catalytic properties [40-43]. However sealing these metallic CEs with the photoanode which is prepared on the FTO coated glass substrate is a challenge. Regarding the challenges of metallic based CEs, recently various CEs like CuS, PbS and CoS are prepared on the FTO coated glass substrates by SILAR method [1, 31, 43-45]. SILAR method is simple, cost effective, and suitable for large scale production. Also most importantly is easy for sealing the cells without electrolyte leakage. Regarding the simple procedure of SILAR method, recently various nanocomposite cathode electrodes like CoS/CuS, CuS/PbS are developed and enhanced the catalytic performance of the bare CuS, PbS and CoS CEs [10, 31, 45]. In spite of the interesting properties of SILAR deposited CEs on FTO coated glass substrates, these cathode electrodes have a compact structure in comparison to the CEs which are made on metallic substrates. The compact structure of the CE limits the CE/electrolyte interface which consequently restricts the charge transfer at CE/electrolyte interface [10]. Restricted charge transfer at the CE/Electrolyte interface, accumulates space charges and therefore diminish the fill factor considerably [41, 46-47].

Here we show that graphene pre deposition on the FTO coated glass substrate could simply modify the compact structure of the SILAR deposited CuS/PbS CEs to a more

porous structure. For the CdS/CdSe QD sensitized cells and FTO/G/CuS/PbS CEs, the cell performance with 3.21% (V_{oc} =550 mV, J_{sc} =11.43 mA/cm², FF=0.51) efficiency was obtained which was enhanced in comparison with the photovoltaic properties of the cells with normal FTO/CuS/PbS CEs with 2.54 % efficiency (V_{oc} =526 mV, J_{sc} =13.4 mA/cm², FF=0.36). Especially the fill factor of the cells is improved by graphene pre deposition on the FTO substrates. The present general study indicated that the G pre deposition could offer a simple systematic method for improving the performance of the solution-processed CEs with noticeable catalytic activity in polysulfide redox electrolytes.

2. Experimental methods

2.1 Photoanode preparation. Photoanodes are made of a transparent and also an opaque TiO₂ layer. Transparent layer was deposited from a paste with 20-30 nm nanoparticle sizes [48]. Opaque layers are made from a paste with 20-400 nm core-shell of TiO₂-SiO₂ nanoparticles and were deposited on the transparent layer as the light scattering layer [49]. All the Photoanodes were annealed at 450°C for 45 min in order to enhancing their electrical properties. TiO₂ photoanodes were sensitized by CdS/CdSe/ZnS QDs using SILAR and chemical bath deposition (CBD) methods. CdS QDs were deposited by the SILAR method [50]. Here, Cd²⁺ precursor were prepared from a 0.05 M ethanolic solution of Cd(NO₃)₂·4H₂O and sulfide source was a 0.05 M solution of Na₂S·9 H₂O in methanol/water (50/50 V/V). TiO₂ electrodes were put into the Cd²⁺ precursor, and subsequently, into the S²⁻ solution for both 1 min (this is termed a single SILAR cycle). After each precursor bath, the photoanode was dipped into the corresponding solvent to remove the chemical residuals and then dried by an air gun. CdSe QDs were deposited by the CBD method [50]. A chemical bath was made by mixing 80 mM of Na₂SeSO₃

and CdSO_4 with 120 mM of nitrilotriacetic acid sodium salt. Na_2SeSO_3 solution was made by refluxing Se and Na_2SO_3 powders in Milli-Q water at 80 °C. CdS sensitized TiO_2 working electrodes were put in the bath solution at 10 °C for 12 h. Finally, ZnS was coated on CdS/CdSe TiO_2 sensitized electrodes by two SILAR cycles according to the previously described method [51]. It is generally known that ZnS improves the performance of QDSCs by reducing the recombination and enhancing the stability of the cells [51].

2.2 CEs preparation. CEs were made by SILAR method. CuS layers were made from $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ and $\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$ precursors. Cu^{2+} ions were deposited from a 0.5 M aqueous solution of $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ and S^{2-} sources were the 0.5 M solution of $\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$ in methanol/water (50/50 V/V). CuS deposition consisted of 1 min dip-coating of the FTO substrate into the metal precursor and subsequently into the sulfide solution for 1 min (termed as a single SILAR cycle). After each Cu^{2+} and S^{2-} precursor bath, the photoanode was rinsed by the corresponding solvent and then dried by an air gun. For the PbS deposition, a 0.02 M methanolic solution of $\text{Pb}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ and a 0.02 M solution of $\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$ in methanol/water (50/50 V/V) were used as Pb^{2+} and S^{2-} ions respectively. FTO coated glass substrates subsequently dip coated into the Pb^{2+} and S^{2-} precursors for 1 min (a single SILAR cycle). After each bath, photoanodes were rinsed by the corresponding solvent and then dried.

In order to make G/CuS/PbS CEs, graphene sheets were prepared from natural graphite powder by a modified Hummers' method as we described before [25]. Graphene suspension (0.5 mg/ml) spin coated with 2000 rpm on FTO substrates. After each spin coating, samples were put in an oven at 100 °C for 5 minutes in order to dry

the deposited layers. Spin coating process was repeated for 1-12 times in order to make various structures of CEs. G/CuS/PbS CEs were prepared by deposition of CuS and PbS layers on the graphene pre coated FTO substrates by SILAR method as described above. CuS CEs were also prepared on the metallic substrates for comparison their structure with SILAR deposited CEs. The CuS counter electrodes were prepared by immersing brass substrates in HCl solution at 70°C for 10 min and subsequently dipping it into the polysulfide solution for 3 min.

2.3 QDSC preparation. The sensitized photoelectrodes and CEs were sealed by means of a Surlyn spacer (thickness 30 microns). Polysulfide electrolyte was contained 1 M Na₂S, 1 M S, and 0.1 M NaOH solution in Milli-Q ultrapure water. Area of the cells was 0.25 cm².

2.4 Photoanode and solar cell characterization. J-V measurements were carried out by PGSTAT-30 from Autolab Company. Cells were illuminated using a solar simulator at AM1.5 G, and the light power was adjusted to 100 mW/cm².

3. Results and discussion

SEM micrograph from the transparent TiO₂ layer which is deposited on the FTO substrates is indicated in Figure 1a. According to this figure, TiO₂ layer contains 20-40 nm particle sizes which prepare enough surface area for the QDs sensitizer deposition. Figure 1b shows the SEM micrograph from the scattering layer with 20-400 nm particle sizes that is deposited on the first transparent layer.

Figure 1.

Before making G/CuS/PbS CEs structures, we first optimized the number of graphene spin coating by making simple G/PbS CEs structures. First category of the cells was made by pre deposition of graphene on the FTO substrates with various numbers of spin coating (from 1 to 12 times) and then depositing the PbS on the graphene coated FTO substrates by 6 SILAR cycles. Figure 2 indicates the SEM micrograph of graphene sheets on the FTO coated glass substrate. From this figure it could be seen that graphene sheets distorts the uniform topology of the FTO substrates as indicated by arrows inset the figure. This non uniformity could potentially change the kinetic of the PbS deposition on the FTO/G substrate relative to its deposition on the bare FTO substrates.

Figure 2.

Figure 3 indicates the current-voltage properties of CdS/CdSe sensitized cells which are made by G/PbS CEs under light illumination (figure 3a) and dark conditions (figure 3b). In this Figure the number of spin coating of graphene layer and number of SILAR cycles for PbS deposition are indicated in parentheses against the G and PbS. For example G(2)/PbS(6S) means that graphene has been deposited by two times spin coating and then PbS is deposited on graphene by 6 SILAR cycles. According to this figure, noticeable difference is not observed in the current voltage properties of the cells with various number of G deposited layers. In order to have more accurate comparison of photovoltaic parameters, open circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF), and conversion efficiency (E) of QDSCs, are shown in Table 1.

Figure 3.

Table 1: Photovoltaic parameters of the QDSCs: photocurrent j_{sc} , open circuit voltage V_{oc} , fill factor FF , and efficiency E , as a function of the CEs structure tested under standard conditions (100 mW/cm² AM 1.5G).

Cathode Type	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF	E (%)
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G(1)/PbS(6S)	532	9.41	0.41	2.05
G(2)/PbS(6S)	529	8.62	0.47	2.14
G(4)/PbS(6S)	510	7.30	0.41	1.52
G(6)/PbS(6S)	539	8.55	0.44	2.03
G(8)/PbS(6S)	524	7.97	0.51	2.13
G(10)/PbS(6S)	532	8.91	0.45	2.13
G(12)/PbS(6S)	529	8.74	0.45	2.08

As can be seen in this table, the efficiency of the cells with G(1)/PbS(6S) CEs (2.05 %) is improved to 2.14 % in G(2)/PbS(6S) CEs. Regarding this little efficiency improvement by increasing the number of G layers, graphene spin coating process was repeated for 12 times. According to Table 1, efficiency is not improved any more by increasing the number of graphene deposited layers from 4 to 12 and the best efficiency was obtained 2.13 % for G(8)/PbS (6S) and G(10)/PbS (6S) CEs which is almost same by G(2)/PbS(6S) CEs (2.14 %). Also the efficiency of the cells with 6, 8, 10 and 12 layers of graphene and the same number of SILAR deposited PbS layer is very similar (from 2.03 to 2.13 %). This result indicates that PbS is mainly responsible for the catalytic properties of the G/PbS nanocomposite CEs and increasing the number of G spin coatings more than 2 times, has no beneficial effect (Table 1). Regarding the unique properties of the graphene structures, stability of the electrodes was investigated under aging in room temperature from 0 to 72 hours. Here we applied Graphene/PbS as counter electrodes and TiO₂ was sensitized by CdS/CdSe QDs. Photovoltaic parameters of QDSCs, containing: open circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF), and conversion efficiency (E) are shown in Table 2.

Table 2: Photovoltaic parameters of the QDSCs prepared and analyzed: photocurrent j_{sc} , open circuit

voltage V_{oc} , fill factor FF , and efficiency E , as a function of aging time.

Aging time(h)	V_{oc} (mv)	J_{sc} (mA/cm ²)	FF	E
0	503	8.95	0.47	2.11
24	524	9.39	0.47	2.31
48	525	8.61	0.45	2.03
72	511	8.51	0.44	1.91

According to this table, the as prepared cells showed an energy conversion efficiency of 2.11% and V_{oc} , J_{sc} and efficiency was found to have enhanced after 24 hours aging ($E=2.31$ %, $V_{oc}=524$ mV, $J_{sc}=9.39$ mA/cm², $FF=0.47$). This improvement could be related to the enhanced electrolyte diffusion into the porous structure of the CEs by aging. Also the efficiency of the cells is reached to 90% (1.91 %) of their initial value (2.11 %) which is considerable. The present results, indicates that graphene structures have considerable stability in the polysulfide electrolyte and even more stable cells could be prepared by improving the sealing quality.

Current-voltage properties of CdS/CdSe sensitized cells which are made by G, PbS and G/PbS CEs is presented in figure 4 and table 3 for comparison.

Figure 4.

Table 3: Photovoltaic parameters of the QDSCs prepared and analyzed: photocurrent j_{sc} , open circuit voltage V_{oc} , fill factor FF , and efficiency E , as a function of the CEs structure

Cathode Type	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF	E (%)
G(2)	464	2.38	0.23	0.25
PbS(6S)	515	12.99	0.20	1.34
G(2)/PbS(6S)	529	8.62	0.47	2.14

From the results in the Table 3, the beneficial effect of G pre deposition on the FTO substrate is clearly observed specially on the fill factor, resulting in more efficiency to

be obtained.

The second category of the cells was made by deposition of CuS/PbS/.../CuS/PbS CEs [10]. Here CuS/PbS/.../CuS/PbS CEs were made by 6 to 12 cycles of SILAR deposition in order to optimize the CE structure.

Figure 5 indicates the current-voltage properties of the cells which are made by deposition of CuS/PbS/.../CuS/PbS CEs under light illumination (figure 5a) and dark conditions (figure 5b). Here the numbers of the SILAR cycles are indicated in parentheses against. For example: CuS/PbS/.../CuS/PbS (6S) means that CuS and PbS layers are deposited one by one and totally for 6 cycles.

Figure 5.

In order to have more accurate comparison of the results, open circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF), and conversion efficiency (E) are shown in Table 4.

Table 4: Photovoltaic parameters of the QDSCs prepared and analyzed: photocurrent j_{sc} , open circuit voltage V_{oc} , fill factor FF , and efficiency E , as a function of the CEs structure.

Cathode Type	$V_{oc}(mV)$	$J_{sc}(mA/cm^2)$	FF	E (%)
CuS/PbS/.../CuS/PbS(6S)	520	10.82	0.34	1.91
CuS/PbS/.../CuS/PbS(8S)	526	13.4	0.36	2.54
CuS/PbS/.../CuS/PbS(10S)	510	9.73	0.42	2.08
CuS/PbS/.../CuS/PbS(12S)	420	7.55	0.36	1.14

Here the best performance of the cells is obtained for CuS/PbS/.../CuS/PbS structures with 8 SILAR cycles (2.54 % efficiency) but the fill factor is 0.36 which is low in comparison to the fill factors values which are normally observed in QDSCs. According

to Figure 5b, the dark current is enhanced for the samples with 10 or 12 SILAR cycles which leads to lower efficiencies according to Table 4. Figure 6a indicates the SEM micrograph from the CuS/PbS/.../CuS/PbS (8S) CE which are prepared on the FTO substrates by SILAR method. The structure of the CuS CE which are made on the metallic brass substrates is indicated in Figure 6b for comparison.

Figure 6.

According to this figure; CuS/PbS/.../CuS/PbS CE has a compact structure in comparison to the CE which are made on metallic substrates (figure 6b) which could decrease the interface area between the CE and electrolyte which consequently restricts the charge transfer at CE/electrolyte interface. Restricted charge transfer at the CE/Electrolyte interface, accumulates space charges and therefore creates s-shaped deformations in the current voltage characteristics (as it is seen for CuS/.../PbS (6) and CuS/.../PbS (8S) CE in the figure 5a) of the cells [46, 47]. As a result, performance of the cells decreases by diminishing fill factor (Figure 5 and Table 4) considerably. Regarding the low fill factors for CuS/.../PbS CE (table 3) and their compact structure (Figure 6a), graphene was pre deposited on the FTO substrates before CuS and PbS deposition, in order to enhance the performance of CE. Graphene was spin coated on the FTO substrates and then CuS and PbS layers were deposited on the FTO/G substrates as explained in the experimental section.

Figure 7 indicates the current-voltage properties of the cells which are made by deposition of CuS/PbS/.../CuS/PbS CE on the FTO/graphene substrates, under light (Figure 7a) and dark conditions (Figure 7b). Here graphene was spin coated 2 times in all samples and the number of CuS/.../PbS deposited layers was varied from 6 to 12 cycles.

Figure 7.

For a more clear investigation, open circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF), and conversion efficiency (E) are shown in Table 5.

Table 5: Photovoltaic parameters of the QDSCs prepared and analyzed: photocurrent j_{sc} , open circuit voltage V_{oc} , fill factor FF , and efficiency E , as a function of the CE's structure tested under standard conditions (100 mW/cm² AM 1.5G).

Cathode Type	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF	E (%)
G(2)/CuS/PbS/.../CuS/PbS(6S)	520	11.11	0.43	2.48
G(2)/CuS/PbS/.../CuS/PbS(8S)	550	11.43	0.51	3.21
G(2)/CuS/PbS/.../CuS/PbS(10S)	495	9.40	0.45	2.09
G(2)/CuS/PbS/.../CuS/PbS(12S)	429	8.11	0.40	1.39

Here the best performance of the cells is obtained for G(2)/CuS/PbS/.../CuS/PbS (8S) structures (3.21 %) which is more than the cells without pre deposition of graphene and the same cycles of CuS/PbS/.../CuS/PbS structure (2.54 % efficiency) according to Tables 4 and 5. According to Figure 7b, the cells with G(2)/CuS/PbS/.../CuS/PbS (8S) CE's have the lowest dark current which is in agreement with their best performance under light condition. Also the fill factor is 0.51 in the case of G(2)/CuS/PbS/.../CuS/PbS (8S) CE's (Table 5) which has improved in comparison to the CuS/PbS/.../CuS/PbS (8S) CE's with the fill factor of 0.36 (table 4). If we compare the fill factors of the each CuS/.../PbS CE structures in the table 4 with the fill factors of the CE's that have a same number of deposited CuS/.../PbS layers but have a pre deposited graphene layer (Table 5), a systematic enhancement in the fill factors could be observed in case of graphene pre deposited layers. These results indicates that the

performance of SILAR deposited CEs could systematically enhanced by graphene pre deposition on the FTO substrate. Figure 8 indicates the SEM micrograph of G(2)/CuS/.../PbS (8 S) CEs. From this figure it can be seen that the morphology of the layer is completely different in comparison to the CuS/.../PbS (8S) CEs (figure 6a).

Figure 8.

Comparison between figure 6a and 8 indicates that the compact structure of the CuS/.../PbS structure (figure 6) converts to a more porous structure after graphene pre deposition on the FTO substrate (figure 8). The schematic structure of the various CEs without and with graphene pre deposition is presented in figure 9a and 9b respectively.

Figure 9.

According to this scheme more porous structures are obtained by graphene pre deposition in comparison to conventional FTO coated CuS/.../PbS CEs. The more porosity could increase the CEs surface area which consequently, improves the charge transfer at the CE/electrolyte interface noticeably. The improvement in the charge transfer at the CE/electrolyte interface decreases the internal resistance and concentration gradients of the redox species in the electrolyte, parameters that could strongly affect the fill factor. This is confirmed by the improved fill factors that are obtained in G/CuS/.../PbS structures (table 5) compared to the CuS/.../PbS structures (table 4) as it was explained before. According to the present results, an improvement in the efficiency of QDSCs, especially fill factors, is obtained by applying the pre deposited graphene on the FTO substrate and improving the porosity of the CE. From the present study, it can be concluded that the performance of the conventional SILAR deposited CEs could be simply enhanced by graphene pre deposition on the FTO substrates.

4. Conclusions

Here, the graphene pre deposition method was introduced for modifying the current CEs which are generally used in QDSCs. For the CdS/CdSe QD sensitized cells and G/CuS/.../PbS CEs, the cell performance with 3.21% ($V_{oc}=550$ mV, $J_{sc}=11.43$ mA/cm², FF=0.51) efficiency was obtained which was enhanced compared with the photovoltaic properties of the cells with CuS/.../PbS CEs with 2.54 % efficiency ($V_{oc}=526$ mV, $J_{sc}=13.4$ mA/cm², FF=0.36). SEM results indicated that the compact structure of the conventional CuS/.../PbS CEs converts to a more porous structure by a simple graphene pre deposition on the FTO substrates. We showed that the G pre deposition method could offer new opportunities for the simple improving the performance of the solution-processed CEs with considerable performance in polysulfide redox electrolytes.

Figure and Table Captions:

Figure 1. SEM micrograph from transparent (a) and scattering layer (b), scale bars are 500 nm and 1 micron for figure 1a and 1b respectively.

Figure 2. SEM micrograph from graphene sheets on the FTO substrates, scale bars is 500 nm and arrows indicate the non uniformities on the surface

Figure 3: Current-voltage characteristic of cells with G(1)/PbS(6), G(2)/PbS(6),..., G(12)/PbS(6S) counter electrodes at AM 1.5 high illumination (a) and dark condition (b).

Figure 4: Current-voltage characteristic of the cells with G(2), PbS(6S) and G(2)/PbS(6S) counter electrodes at AM 1.5 high illumination

Figure 5: Current-voltage characteristic of the cells with CuS/PbS/...CuS/PbS CEs structures at AM 1.5 high illumination (a) and dark condition (b).

Figure 6. SEM micrograph from CuS/PbS/.../CuS/PbS (8 S) CEs which are deposited on the FTO substrates (a), SEM micrograph from CuS CEs which are made on the metallic brass substrates, scale bars is 500 nm in figure a and 2 microns in figure b.

Figure 7: Current-voltage characteristic of the cells with G(2)/CuS/.../PbS(6S), G(2)/CuS/.../PbS(8S),..., G(2)/CuS/.../PbS(12S) counter electrodes at AM 1.5 light illumination (a) and dark condition (b).

Figure 8. SEM micrograph from G(2)/CuS/PbS/...CuS/PbS (8 S) CEs, scale bars is 500 nm

Figure 9: Schematic structure of the CuS/.../PbS CEs without (a) and with graphene pre deposition on the FTO substrate (b).

Table 1: Photovoltaic parameters of the QDSCs prepared and analyzed: photocurrent j_{sc} , open circuit voltage V_{oc} , fill factor FF , and efficiency E , as a function of the CEs structure tested under standard conditions (100 mW/cm² AM 1.5G).

Table 2: Photovoltaic parameters of the QDSCs prepared and analyzed: photocurrent j_{sc} , open circuit voltage V_{oc} , fill factor FF , and efficiency E , as a function of aging time.

Table 3: Photovoltaic parameters of the QDSCs prepared and analyzed: photocurrent j_{sc} , open circuit voltage V_{oc} , fill factor FF , and efficiency E , as a function of the CEs structure

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Figure 1.

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Figure 2.

Figure 3.

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Figure 7.

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