Enhanced Photo Response in p-Si/MoS₂ Heterojunction- based Solar Cells

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Abstract

High quality ultrathin transition-metal dichalcogenide films and their Vander Waals heterostructures are very promising for fabrication of optoelectronic devices for their superior photovoltaic performance, extreme flexibility and long lifetime due to suitable band gap and excellent light absorption capability. Designing the appropriate and suitable band structures of these materials is crucial for its promising applications. Especially, thin molybdenum disulfide (MoS₂) film is further attractive as compare to its monolayer counterpart for broad-spectral photo-detectors and photovoltaic application. However, very little understanding regarding the underlying physics behind the photo-response behavior of thin MoS₂ films is known. Here, we demonstrate a large photovoltaic response in thin MoS₂ films which produces an enormous photo-generated carrier and enhance the photocurrent by forming a heterojunction with p-type Si substrate. MoS₂ based photovoltaic devices efficiently produce high short-circuit photocurrent values of 18 mA/cm² and reasonably high power-conversion efficiency up to 4.5%. The present work will provide valuable scientific input of layered MoS₂ films for other emerging optoelectronic applications.

Keywords: MoS₂; Thin Film; Optimization; Photovoltaic; Heterostructure

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1. Introduction

The significance of two-dimensional (2D) layer materials has been revealed by a abundance of interesting functionalities demonstrated in graphene, a monolayer material of carbon atoms with no band gap by nature [1,2]. In contrast to graphene, transition metal dichalcogenides (e.g., MoS₂, WSe₂, and WS₂) exhibit very attractive optoelectronic properties, such as observation of unique valley-polarized optical response, very good light absorption over a broad wavelengths range as well as a fast photo response [3,4]. Interestingly, a single layer of semiconducting transition metal dichalcogenide, having thickness less than a nanometer, can absorb significant amount of sunlight and generate more photocurrents as compared to thicker GaAs semiconductor [5]. Therefore, semiconducting transition metal dichalcogenides are extremely good to offer further advantages for utilizing as active photovoltaic (PV) materials, due to their outstanding chemical stability, good mechanical flexibility, low production cost and durability comparable to graphene. Dichalcogenides provide suitable electronic and optical properties for engineering well-designed interfaces with other 2D materials, so that it can make a fine quality heterojunction and interfaces with an enormously low areal density of dangling bonds and charge traps [6].

Although very high light absorption coefficients as well as strong light-matter interactions are observed in semiconducting transition metal dichalcogenides [5,7] their photovoltaic devices with superior PV behavior is not demonstrated. To obtain an improved photocurrent output for its practical applications, fabrication of multilayer PV devices based on suitable transition metal dichalcogenides are needed. However, the current multilayer transition metal dichalcogenides-based PV device demonstrate reasonably weak values of critical figure of merit, such as low short-circuit photocurrent density, open circuit voltage, as well as photo conversion efficiency, which is less than 2% [5,8,9]. Hence, in order to improve the

performance of these materials, suitable engineering of the band structures is necessary. Particularly, advanced approaches are needed for creating transition metal dichalcogenide-based photoactive layer devices, which favor for the collection of photo-generated carriers to efficiently suppress the reverse dark saturation currents, and to enhance the output photo-voltages. As the electronic properties are strongly dependent on the thicknesses of the 2D layered materials [10,11], ultrathin layer of MoS₂ shows an interesting direct band gap semiconducting behavior with band gap of 1.9eV. Therefore, MoS₂ ultrathin layer emerges as a promising candidate for many novel advanced nanoscale photonic and optoelectronic devices, such as photodetectors [12,13], photovoltaic [14], and light emitters [15]. Here, we report the photovoltaic properties of MoS₂ films grown on p-type Si substrates by the pulsed laser deposition technique. The p-n junction photovoltaic devices demonstrate remarkable PV performance, claiming as an important alternate PV material.

2. Experimental section

MoS₂ target with purity (99.99%) was used to make the MoS₂ films using pulsed laser deposition technique. An excimer laser of KrF with 148 nm wavelength was employed to ablate MoS₂. During deposition, we fixed the angle between the incident laser beams to the laser beam normal to the target surface to be 45°. The laser pulse energy was set to be 220 mJ with repetition pulse rate of 4 Hz. During the deposition of the MoS₂, the rotation of the target was at raster velocity of 10°/sec and angle of 4 degree. Boron doped p-type Si (100) substrates were used to grow the MoS₂ film. The substrates were washed using Radio Corporation of America (RCA) cleaning method to eliminate the native oxide and other organic and ionic impurities before being loaded into the PLD deposition chamber. Prior to the deposition, the substrate was heated and upheld at a desired substrate temperature (T_s). The deposition chamber was evacuated to a base pressure of 3×10^{-8} Torr prior to film deposition. The thickness of the films

was varied from 3.8, to 41.7 nm, respectively by varying the number of pulses. Circular shape 25 nm thick chromium was deposited as top and back contact with diameter of 180 μ in an ultra-high vacuum using electron-beam evaporation. Before making the back contact the samples are etched in 10% hydrogen fluoride solution in deionized water to remove the native SiO₂ on the back side of the Si substrates.

Characterizations: Thickness of the samples was examined with a profilometer (Make-Bruker, DektakXT). Photoluminescence spectra were collected using Hitachi F-7000 spectrophotometer. Raman spectrum was collected in a Raman spectrophotometer system (Make-Horiba Scientific, Labram HR evolution) with an exciting laser of wavelength 785 nm having very small diameter of laser beam, approximately of 0.5 mm. The photocurrent (J-V) measurement is done using a Keithley 4200-SCS semiconductor characterization system. The power density of white light source used for illumination and was calibrated using power meter. X-ray photoelectron spectroscopy (XPS, Phi V5000) was used to determine the chemical composition of the sample. Here we do not report the results of the device grown at 300°C and 500°C substrate temperature, because they are showing systematic increment value with respect to the other samples.

3. Results and discussion

Fig. 1(a) shows the schematic illustration of detail experimental fabrication procedures of the PV device for the measurement of the photocurrent under illumination of light source. In order to study the growth rate per pulse of the MoS₂ thin films, the thickness of films deposited at the substrate temperature of 200°C for different number of laser pulses are measured and shown in Fig. 1b. It is observed that the thickness of the films increases with increase in number of laser pulses as expected and the film grown at 300, 1000, 2000, and 4000 laser pulses are approximately 3.8, 12.1, 21.6, and 41.7nm, respectively. However, from the photovoltaic

performance point of view, the 12.1 nm thick sample exhibits relatively satisfactory values of critical figures of merit, including good short circuit photocurrent density, open circuit voltage, fill factor (FF) and photo conversion efficiency (PCE). To further improve these performance parameters, we grew a few samples of 1000 laser pulses with repetition pulse rate of 4 Hz at different substrate temperatures. The substrate temperature (100, 200, 400, and 600°C) dependent thicknesses of the samples are shown in Fig. 1c. It is observed that the thickness of the film slightly decreases with increase in growth temperature from 100 to 600°C.

Fig. 2a shows the room temperature photoluminescence (PL) spectra for 3.8, 12.1, 21.6, and 41.7nm thick MoS₂ thin films grown at 200°C. The PL intensity was measured at room temperature under identical excitation wavelength 450nm for all thinner and thicker samples grown at 200°C. The observed optical spectra in thin MoS₂ film have several interesting characteristics. The direct transition exhibited by the excitation creates two prominent PL peaks, around ~631 and ~668 nm, in thin sample by the energy transition between the bottom of the conduction band edge and the top of the valence band. Therefore, appreciable PL intensity is observed in our thinner MoS₂ sample due to direct band gap nature which favors a direct electronic transition as compared to thicker films. However, the PL intensity decreases and shifts towards higher wavelength with increase in layer thickness [10]. The PL peak around ~630 nm shifts slowly to higher wavelength side with the increase in number of layers, hence exhibits a indirect-gap PL with weak rate of radiative recombination. Similarly, PL behavior for films grown at different substrate temperatures (100, 200, 400, and 600°C) is shown in Fig. 2b. As the temperature increase from 100° to 400°C, the PL intensity of the samples increases. However, further increase in substrate temperature decreases in PL intensity due to increase in surface roughness at higher temperature. The PL spectra indicate that the luminescence quantum efficiency strongly depends on MoS₂ thin layer than in thick as well as bulk sample.

To study the layers as well as the quality of the crystal accurately, we used Raman spectroscopy to identify the layer number of 2D materials [16, 18]. The Raman spectra are shown in Fig. 3 for 3.8, 12.1, 21.6, and 41.7nm thick MoS₂ films. Two main Raman peaks are observed in the samples and corresponding to E_{2g}¹ (~386 cm⁻¹, in-plane mode resulting from the opposite movement of two S atoms respect to the central Mo atom) as well as A_{1g} (~404 cm⁻¹, is attributed to out-of-plane vibration of S atoms in opposite directions) modes [24]. It is believed that the E_{2g}¹ mode is strongly affected with increase in film thickness by the dielectric tensor and is originated due to columbic interaction of long-range orders between molybdenum interlayer atoms [19]. However, the A_{1g} mode is not significantly affected [19]. Similarly, the film thickness also affects the characteristic of the Raman peaks and the intensity of the two peaks prominently increases in thicker film with respect to the thinner one. Moreover, the frequency of E_{2g}¹ peak reduces to that of A_{1g} peak by increasing film thickness and this behavior of the films is due to the change of force constant as observed by other researchers [17,19]. It is also seen that, A_{1g} mode of the Raman spectra undergoes a blue shift from thinner to thicker sample, whereas the E_{2g}¹ mode experiences a red shift. The frequency differences between E_{2g}¹ and A_{1g} peaks is more useful to detect the thickness of the film. Hence, the observed value of frequency difference of 17, 18, 19, and 21 cm⁻¹ between E_{2g}¹ and A_{1g} peaks are seen in 3.8, 12.1, 21.6, and 41.7nm samples respectively.

In order to study the quality of the MoS₂ film grown using PLD, the high-resolution XPS spectra for molybdenum, and sulfur MoS₂ thin film grown at 400°C is shown in Fig. 4. The two peaks attributed to Mo doublet states, Mo 3d_{5/2} and Mo 3d_{3/2} corresponding in binding energy around 229.3 eV and 232.4 eV, respectively. Similarly, 162.1 eV and 163.2 eV, represents the binding energy for S 2p_{3/2} and S 2p_{1/2}. These experimental results well agree with the hexagonal

symmetry nature of MoS₂ [24]. From XPS analysis, the estimated atomic ratio of molybdenum to sulfur is ~1:2, confirming the growth of high quality MoS₂ layer on to the Si substrate.

After fabrication of several PV device on p-Si with different MoS₂ layer thickness (3.8, 12.1, 21.6, and 41.7 nm) grown at 200°C, we characterized the solar cell performance in dark and under illumination of white light source with different power density from 25, 50, 75, and 100 mW/cm² as shown in Fig. 5. Before light illumination, the p-n junction device presented a perfect rectification characteristic, by keeping the reverse bias in 200 μ A/cm² range, whereas the forward current increased quickly. After illumination under white light the reverse photocurrent rapidly improved, and come up to a value of 10 mA/cm² at 100 mW/cm² power density. The 3.8 nm thick film device exhibits a low J_{sc} value as well as relatively poor values of power conversion efficiency as a reduced light is absorbed by the thin MoS₂ layer. The efficiency sometimes known as the power conversion efficiency or PCE of a solar cell (abbreviated η) represents the ratio where the output electrical power at the maximum power point on the IV curve is divided by the incident light power.

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{inc}}$$

where V_{oc} is the open-circuit voltage; where I_{sc} is the short-circuit current; FF is the fill factor and P_{inc} is the incident power. Similarly fill factor can be calculated as

$$FF = I_{max} V_{max} / I_{sc} V_{oc}$$

where I_{max} is the maximum current and V_{max} maximum voltage of solar cell.

However, increase in thickness from 3.8 to 12.6 nm MoS₂ layer, the PV device shows reasonably better performance with relatively high values of J_{sc} (14.5), V_{oc} (0.34 V), FF (0.39), and PCE (1.87%). On further increase in film thickness, ≥ 21.6 nm the performance of the device is not significantly improved. The current-voltage characteristics of the p-Si/MoS₂

heterojunction solar cell in dark and under illumination of light source with power density of 100 mW/cm^2 are shown in Fig. 6a - d. This systematic study revealed that 12.6 nm thick MoS_2 photoactive layer of PV device exhibits better PV performance among all devices having maximum J_{sc} , V_{oc} , FF, and PCE parameters. Hence, this study more concentrated on fabrication of 12.6 nm thick MoS_2 layer PV device with different substrate temperature. The J_{sc} , V_{oc} , FF, and PCE parameters of 3.8 to 41.7 nm MoS_2 film PV devices grown at 200°C are shown in Fig. 7.

Fig. 8 shows the J-V characteristics of MoS_2 sample deposited at different temperature of the substrate such as 100, 200, 400, and 600°C under illumination of white light source with different power density ranging from 25, 50, 75, and 100 mW/cm^2 . The inset of a, b, c, and d represents the trend of photocurrents with increasing of power density. At low temperature deposition of MoS_2 on Si substrate, the device shows higher J_{sc} , but open circuit voltage is lower than the device grown at 200°C . However, increase in substrate temperature from 200°C to 400°C , the device shows very ideal J-V characteristic with highest value of figure of merit such as the observed J_{sc} (18 mA/cm^2), V_{oc} (0.39V), FF (0.63), and PCE (4.46%) as compared to other PV devices. On further increase in substrate temperature to 600°C does not improve any enhancement in photo-response value as compared to films grown at 400°C . We noticed that, the growth temperature has great impact on the performance of the devices, especially for the substrate temperature between 100 to 400°C , and the p-Si/ MoS_2 solar cell shows improved V_{oc} from 0.18 to 0.39 V, J_{sc} from 12 to 18 mA/cm^2 , and FF from 0.37 to 0.63 giving rise to an efficiency of 4.5%. Fig. 9a - d shows the J-V characteristics of the p-Si/ MoS_2 heterojunction solar cell grown at different substrate temperature under illumination of white light source with power density of 100 mW/cm^2 . Since, the work function of MoS_2 is close to that of Cr, the carrier recombination between Cr and MoS_2 can be minimized to enhance charge carrier

collection efficiency. Therefore, J_{sc} and FF can be further improved. Accordingly, the MoS₂/p-Si device exhibits an efficiency of 4.5%, which is the highest among all transition-metal dichalcogenides monolayer-based solar cell devices. The J_{sc} , V_{oc} , FF, and PCE parameters for MoS₂ PV devices grown at different substrate temperatures are shown in Fig. 10.

To further understand the interactions between MoS₂ films and the p-Si substrate materials, we carried out the Atomic Force Microscopy (AFM) studies on our samples. Surface morphology study of the MoS₂ film grown at different substrates temperature is shown in Fig. 11 which reflects that the films are atomically smooth, uniform and densely packed as well as free from voids and cracks. At low deposition temperature (100°C), the film surface exhibits relatively low root mean square roughness (rms) value of 0.08 nm and favors the formation of films that is relatively smooth. However, the texture of the film changes with increase in substrate temperatures. The topography of the film revealed that the rms increases with increase in substrate temperature and become 0.10 nm, 0.17 nm, and 0.29 nm at 200°C, 400°C, and 600°C respectively.

As per the interface study of MoS₂/ p-Si based on the alignment of band in the heterostructure devices (Fig. 12), the photodiode characteristic of the vertical heterojunction device can be understood as following. From theoretical calculation, the inherent property of the MoS₂ monolayer electronic states exhibits very interesting behavior and exhibits a prominent peak in the visible wavelength region through *ab initio* calculations of the density of states, resulting in improved light absorption, as reported by Britnell et al.[5] By exposing white light source on MoS₂ monolayer (having more band-gap energy ~1.9 eV), the formation of excitons from MoS₂ layer and p-Si takes place [5]. During forward bias condition, the photo-excited holes of MoS₂ in valance band have not enough driving force to surpass and unable reach to p-Si because of enough barrier height and small values of band offset [20,21]. However, photo-

excited electrons at conduction band can move to the boundary, establishing an accumulated layer, then become combined with holes of valance band, resulting insufficient excitons separation [22,24]. Hence, there is no net increase in forward photocurrent upon light illumination. In case of reverse biased condition the minority carriers (MoS₂-hole, and Si-electron) exhibit a large potential to move under lower barriers due to the increases in the band offset between conduction and valence band, which favors the transfer of photo-excited holes in boundary region. This leads to ample separation of excitons, hence the observation of higher photo-current takes place.

To fully understand the effect of thickness as well as growth temperatures on the photo response behaviors of the MoS₂/p-Si heterojunction PV devices, the following discussion is presented. From AFM topography, some pin holes are found on the surface of the ultrathin MoS₂ layer (3.8nm) during the deposition which hinders the performance of the device. Therefore, the increase of MoS₂ film thickness from 3.8 to 12.6 produces films with reasonably free from pinholes or similar types of physical imperfections and reduce the leakage current in MoS₂ film. This could increase FF values. It is speculated that with increasing the MoS₂ thickness from 3.8, to 12.1nm, most of photo-generated excitons are able to diffuse into the interface, where they can efficiently be dissociated into free charges. Therefore, J_{SC} is seen to increase along with the thickness about 12.1 nm. In contrast, at higher thicknesses (21.6 nm) that exceed the exciton diffusion length (L_D), the amount of dissociable excitons no longer increases; instead, the bulk resistance would become larger, resulting in decreased J_{SC} and FF. On the other hand, the effect of substrate temperature has also greatly impact on the enhancement of the photocurrent. From J-V behavior, perfect device with highest efficiency performance are achieved for films grown at 400 °C. Further increases in substrate temperature make the surface of the film rougher as shown in Fig. 11. Hence, from the surface morphology

study, we concluded that slower increase in the surface roughness of the films give better efficiency of the device. The probable cause might be the large contact area among the metal electrode and MoS₂ surface, which may support more efficiently for the collection of charge in boundary region. Further, increased in roughness of the film surface might lower overall reflection losses from incident source and improve the light collection through internal reflection. It is concluded that mild rougher film surface offers a better characteristics to solar cell by improving efficiency. Furthermore, the increase in substrate temperature to 600°C, shows higher surface roughness of the films and are prone to introduce shunting and lower the cell performance.

4. Conclusion

In summary, our results have offered direct evidence that the PLD grown sample can be used as a suitable method for fabrication of good p-n junctions in between p-Si and MoS₂ layer to obtain a substantial improvement of photovoltaic characteristic in MoS₂ photovoltaic devices. Finally, to the best of our knowledge, the PV devices grown at 400°C with 11.6 nm thick MoS₂ photoactive layers exhibit the superior J_{sc} values up to 18 mA/cm², and PCE values of 4.5% among existing PV- devices based on layered transition metal dichalcogenite. The results also suggest that the photovoltaic activity of p-Si/MoS₂ device depends on the quality of the photoactive layer of MoS₂ film, and suitable value of MoS₂ thickness for attaining better activity. AFM image shows that rise in substrate temperature affect the surface roughness of the film which might favor to lower the overall reflection losses from incident source and give rise to solar cells with improved efficiency. XPS study revealed that S to Mo atomic ratio is considered to be ~2:1, strongly provide evidence for the deposition of high quality MoS₂ layer by the PLD. This result opens new direction and advanced technical approach to design the suitable band structures in developing monolayer thin 2D materials, and offer an advantage and

vital scientific visions for leveraging the exclusive optoelectronic behavior of this device for photovoltaic as well as various optoelectronic uses.

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Figures captions

Fig. 1. (a) The schematic diagram of experimental setup of MoS₂/p-Si p-n junction heterostructure. (b) Variation of thickness with number of pulses of MoS₂ thin films grown at 200°C (c) Substrate temperature as a function of thickness for 1000 pulses films.

Fig. 2. (a) Photoluminescence spectra of MoS₂ thin films grown at 200°C with average thicknesses ranging from 3.7 to 41.7 nm. Inset of (a) shows energy of the exciton peak as a function of average film thickness. (b). Photoluminescence spectra of MoS₂ thin films grown at different substrate temperature.

Fig. 3. Raman spectrum of MoS₂ thin films deposited at 200°C.

Fig. 4. Surface analysis XPS spectra of MoS₂ Film grown at 400°C (a) Mo 3d_{5/2} and Mo 3d_{3/2} (b) S 2p_{3/2} and S 2p_{1/2}.

Fig. 5. (a), (b), (c) and (d) show the J–V curves of dark and illuminated p-Si/MoS₂ heterostructure with MoS₂ films thickness 3.8, 12.1 21.6 and 41.7 nm respectively. All devices are illuminated under white light source with different power densities in a range of 25 to 100 mW/cm². The inset of (a), (b), (c) and (d) represents the reverse photocurrents increased linearly with increasing of power density.

Fig. 6. Current density-Voltage characteristics of 3.8, 12.1 21.6 and 41.7 nm thick MoS₂ thin films PV device respectively, which were measured without and under illumination of white light source (power density, 100 mW/cm²). The comparison PV performance parameters i.e., V_{oc}, J_{sc}, FF, and PCE for all above samples are reflected with each graph.

Fig. 7. Additional data systematically showing the comparison between different film thickness MoS₂ PV devices with photovoltaic response performance: (a) J_{sc}, (b) V_{oc}, (c) FF, and (d) PCE.

Fig. 8. Current density-Voltage curves of dark and illuminated p-Si/MoS₂ heterostructure grown at 100, 200, 400 and 600°C respectively. All devices are illuminated under white light source with different power densities in a range of 25 to 100 mW/cm². The inset of (a), (b), (c) and (d) represents the trend of photocurrents with increasing of power density.

Fig. 9. (a), (b), (c), and (d) Current density-voltage (J~V) characteristics of MoS₂ thin films grown at 100, 200, 400 and 600°C respectively, measured without and under illumination of white light source (power density, 100 mW/cm²). The comparison PV performance parameters i.e., V_{oc}, J_{sc}, FF, and PCE for all above samples are reflected with each graph.

Fig. 10. Additional data systematically showing the comparison between different film thickness MoS₂ PV devices with photovoltaic response performance: (a) J_{sc}, (b) V_{oc}, (c) FF, and (d) PCE.

Fig. 11. Surface morphology of MoS₂ films at different substrate temperature (a) 100 °C (b) 200 °C (c) 400 °C and, (d) 600 °C.

Fig. 12. The band alignment at the interface between p-Si and few layer of MoS₂ at equilibrium, forward bias and reverse bias under illumination. Electrons injected from the n-MoS₂ and holes from p-Si can radiatively recombine in the junction.

Fig. 1. (a) The schematic diagram of experimental setup of MoS₂/p-Si p-n junction heterostructures. (b) Variation of thickness with number of pulses of MoS₂ thin films grown at 200 °C (c) Substrate temperature as a function of thickness for 1000 pulses films.

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Fig. 3. Raman spectrum of MoS₂ thin films deposited at 200°C

Fig. 4. Surface analysis XPS spectra of MoS₂ Film grown at 400°C (a) Mo 3d_{5/2} and Mo 3d_{3/2} (b) S 2p_{3/2} and S 2p_{1/2}.

Fig. 5. (a), (b), (c) and (d) show the J-V curves of dark and illuminated p-Si/MoS₂ heterostructures with MoS₂ films thickness 3.8, 12.1, 21.6 and 41.7 nm respectively. All devices are illuminated under white light source with different power densities in a range of 25 to 100 mW/cm². The inset of (a), (b), (c) and (d) represents the reverse photocurrents increased linearly with increasing of power density.

Fig. 6. Current density-Voltage characteristics of 3.8, 12.1 21.6 and 41.7 nm thick MoS₂ thin films PV device respectively, which were measured without and under illumination of white light source (power density, 100 mW/cm²). The comparison PV performance parameters i.e., V_{oc} , J_{sc} , FF, and PCE for all above samples are reflected with each graph.

Fig. 7. Additional data systematically showing the comparison between different film thickness MoS₂ PV devices with photovoltaic response performance: (a) J_{sc} , (b) V_{oc} , (c) FF, and (d) PCE.

Fig. 8. Current density-Voltage curves of dark and illuminated p-Si/MoS₂ heterostructures grown at 100, 200, 400 and 600°C respectively. All devices are illuminated under white light source with different power densities in a range of 25 to 100 mW/cm². The inset of (a), (b), (c) and (d) represents the trend of photocurrents with increasing of power density.

Fig. 9 (a), (b), (c), and (d) Current density-voltage (J - V) characteristics of MoS_2 thin films grown at 100, 200, 400 and 600°C respectively, which were measured without and under illumination of white light source (power density, $100 \text{ mW}/\text{cm}^2$). The comparison PV performance parameters i.e., V_{oc} , J_{sc} , FF, and PCE for all above samples are reflected with each graph.

Fig. 10. Additional data systematically showing the comparison between different film thickness MoS₂ PV devices with photovoltaic response performance: (a) J_{sc} , (b) V_{oc} , (c) FF, and (d) PCE.

Fig. 11. Surface morphology of MoS₂ film grown at different substrate temperature (a) 100 °C (b) 200 °C (c) 400 °C and, (d) 600 °C.

Fig. 12. The band alignment at the interface between p-Si and few layer of MoS₂ at equilibrium, forward bias and reverse bias under illumination. Electrons injected from the n-MoS₂ and holes from p-Si can radiatively recombine in the junction.