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Optimization of silicon solar cell performance through RF magnetron-sputtered WS_2 thin films: Effect of coating thickness on photovoltaic characteristics

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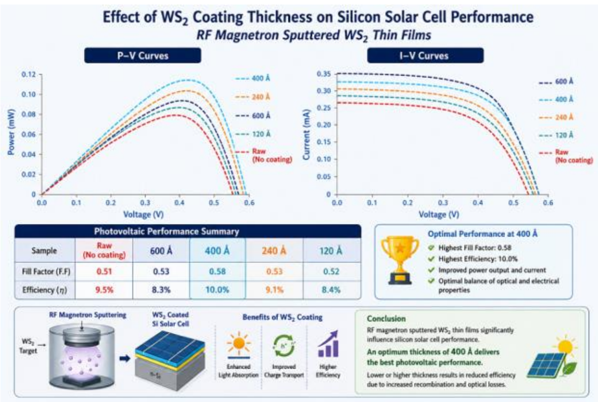
Abstract

This study investigates the effect of tungsten disulfide (WS_2) thin-film coatings deposited by Radio-frequency (RF) magnetron sputtering on the performance of silicon solar cells. WS_2 layers with thicknesses of 120, 240, 400, and 600 Å were applied, and the photovoltaic characteristics were evaluated through I–V and P–V measurements. The results showed that coating thickness significantly influences cell performance. Efficiency improved for thicknesses between 120 and 400 Å, with the best performance obtained at 400 Å, where the fill factor increased from 0.5 to 0.6 and the conversion efficiency increased from 9.5% to 10.0%. However, a thickness of 600 Å reduced efficiency due to increased optical and electrical losses. The findings indicate that an optimum WS_2 thickness exists and that RF magnetron sputtering is an effective method for enhancing silicon solar cell performance.

Graphical Abstract



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1. Introduction

The growing global demand for sustainable and clean energy has intensified research efforts toward improving the efficiency of photovoltaic technologies[1,2]. The increasing global demand for clean and sustainable energy has intensified research efforts aimed at improving the efficiency and reducing the cost of photovoltaic technologies. Among various photovoltaic devices, crystalline silicon solar cells remain the dominant technology due to their abundance, long-term stability, and well-established manufacturing processes [3, 4]. Nevertheless, optical losses, surface recombination, and inefficient charge-carrier transport continue to limit their maximum achievable efficiency, motivating the development of advanced surface engineering techniques and functional coating materials [2,3,5].

Recent investigations have reported that improving the structural design of silicon solar cells can significantly enhance their energy conversion efficiency. In particular, proper engineering of device architecture and interfaces leads to improved charge collection and overall device performance. In a broader context, nanostructured architectures have been shown to further enhance light absorption and charge transport in solar energy systems, and are therefore considered effective strategies for improving photovoltaic performance and addressing the growing global energy demand [6,7].

Transition metal dichalcogenides (TMDCs), including WS_2, WSe_2, and WTe_2, have attracted significant attention due to their unique layered structures and tunable electronic properties. These materials exhibit strong light–matter interaction and are considered promising candidates for next-generation electronic and optoelectronic applications[8].In addition, two-dimensional TMDC-based devices have demonstrated excellent electronic behavior and environmental stability, making them suitable for advanced semiconductor and sensing applications. Their properties further highlight their potential for integration into energy conversion systems[9].

In recent years, transition metal dichalcogenides (TMDCs) have emerged as promising materials for optoelectronic and energy-related applications because of their unique electrical, optical, and structural properties [10-12]. Tungsten disulfide (WS_2), a member of the TMDC family, exhibits excellent light absorption, suitable band-gap characteristics, high chemical stability, and favorable charge transport properties, making it an attractive candidate for photovoltaic applications [11, 13]. Previous studies have demonstrated the potential of TMDC materials in enhancing carrier separation, reducing recombination losses, and improving the performance of semiconductor-based devices [10, 12].

Among the various thin-film deposition techniques, Radio-frequency (RF) magnetron sputtering offers precise control over film thickness, good uniformity, and high reproducibility, enabling the fabrication of high-quality thin films for photovoltaic applications [14]. The performance of solar cells coated with WS_2 is strongly dependent on the thickness of the deposited layer, as both optical absorption and electrical transport characteristics are influenced by film morphology and thickness [11,15].

Therefore, the present study aims to investigate the effect of WS_2 thin-film thickness deposited by RF magnetron sputtering on the performance of silicon solar cells. WS_2 coatings with thicknesses of 120, 240, 400, and 600 Å were deposited, and their influence on the current–voltage (I–V) and power–voltage (P–V) characteristics was systematically evaluated. The results provide insight into the optimal thickness range required to enhance photovoltaic performance and contribute to the development of efficient silicon-based solar cells incorporating TMDC functional layers.

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2. Materials and Methods

2.1. Solar Cell Preparation

A commercial crystalline silicon solar cell was used as the substrate in this study. To establish reliable electrical connections for photovoltaic characterization, two silver ribbons were soldered onto the front and rear contacts of the solar cell. Prior to thin-film deposition, the electrical performance of the cell was evaluated under controlled illumination conditions, and the initial current–voltage (I–V) and power–voltage (P–V) characteristics were recorded.

2.2. WS_2 Thin-Film Deposition

Tungsten disulfide (WS_2) thin films were deposited onto the silicon solar cell surface using the (RF) magnetron sputtering technique. To investigate the influence of film thickness on photovoltaic performance, coatings with nominal thicknesses of 120, 240, 400, and 600 Å were prepared. The deposition process was carried out under identical operating conditions, while the deposition time was adjusted to obtain the desired film thicknesses.

2.3. Electrical Characterization

The photovoltaic performance of the solar cells was evaluated before and after WS_2 deposition using an I–V tracer system under the same illumination conditions. Current–voltage (I–V) curves were measured to determine the principal electrical parameters, including short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and maximum output power (P_{max}).
The fill factor (FF) was calculated using:

$$FF = P_{max} / I_{sc} \times V_{oc} \quad (1)$$

and the power conversion efficiency (η) was determined from:

$$\eta = (P_{max} / P_{in}) \times 100 \quad (2)$$

where P_{max} is the maximum output power and P_{in} is the incident optical power.
In addition, power–voltage (P–V) characteristics were obtained from the measured I–V data to evaluate changes in the maximum power point following thin-film deposition.

2.4. Performance Evaluation

The effect of WS_2 coating thickness on solar cell performance was assessed by comparing the electrical parameters of the uncoated cell with those of the coated samples. Particular attention was given to variations in I_{sc}, V_{oc}, Pmax, fill factor, and conversion efficiency. The optimal thickness was identified based on the maximum improvement in photovoltaic performance.

3. Results and Discussion

The effect of WS_2 thin-film deposition on the photovoltaic performance of silicon solar cells was investigated by comparing the electrical characteristics of the uncoated cell with those obtained after deposition of WS_2 layers with thicknesses of 120, 240, 400, and 600 Å. The performance evaluation was based on the current–voltage (I–V) and power–voltage (P–V) characteristics, as well as the extracted photovoltaic parameters including short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), maximum output power (P_{max}), fill factor (FF), and conversion efficiency (η).

3.1. Electrical Performance of the 400 Å WS_2-Coated Solar Cell

Among all investigated samples, the solar cell coated with a 400 Å WS_2 layer exhibited the best photovoltaic performance. **Table 1** summarizes the principal electrical parameters before and after deposition.

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Table 1. The characteristics of the raw and 400 Å deposited layer.

Parameters	Raw	After 400 Å Deposited Layer
I_{sc}	336.81 mA	305.71 mA
V_{oc}	0.55V	0.56 V
P_{max}	0.0952W	0.0998 W
$F \cdot F$	$F \cdot F = \frac{P^{o}{}_{max}}{I_{sc} \times V_{oc}} = 0.51$	$F \cdot F = \frac{P^{s}{}_{max}}{I_{sc} \times V_{oc}} = 0.58$
η(%)	$\eta = \frac{P^{s}{}_{max}}{P_{in}} \times 100 = 9.52 \approx 9.5\%$	$\eta = \frac{P^{s}{}_{max}}{P_{in}} \times 100 = 9.98 \approx 10\%$

The results indicate that the short-circuit current slightly decreased from 336.81 mA to 305.71 mA after deposition. However, the open-circuit voltage increased from 0.55 V to 0.56 V, while the maximum output power increased from 0.0952 W to 0.0998 W. Consequently, the fill factor improved from 0.51to 0.58, corresponding to an increase of approximately 13.01%. Similarly, the conversion efficiency increased from 9.52% to 9.98%, representing an improvement of about 4.76% relative to the uncoated device.

The observed enhancement suggests that the WS_2 layer improves the optoelectronic properties of the silicon solar cell. The increase in V_{oc} and FF indicates a reduction in recombination losses and improved charge-carrier collection efficiency. Although the reduction in I_{sc} may be attributed to partial absorption of incident light by the coating layer, the overall gain in voltage and fill factor compensates for this decrease, resulting in a higher output power and efficiency.

3.2. Analysis of the P–V Characteristics

Fig. 1 presents the power–voltage (P–V) curves of the solar cell before and after deposition of the 400 Å WS_2 layer. A noticeable increase in the maximum power point can be observed after coating. Furthermore, the peak of the P–V curve shifts toward a higher operating voltage, indicating improved electrical performance of the device.

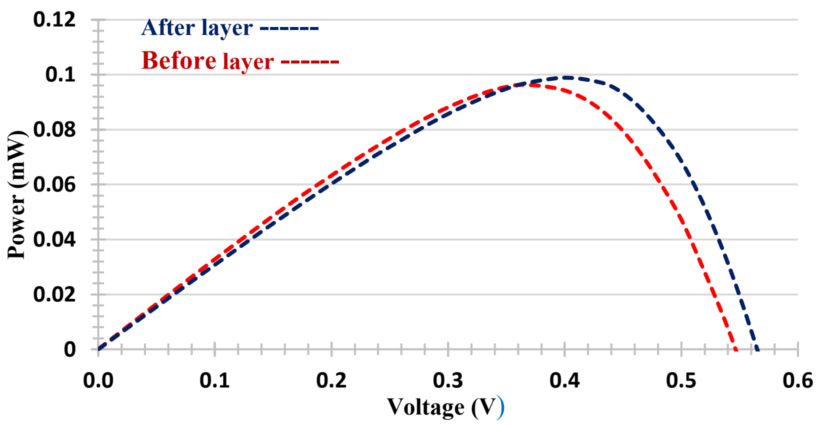

Fig. 1. Comparison of the (P-V) raw and the 400 Å coated sample.

The enhancement of the maximum power point demonstrates that the deposited WS_2 layer contributes positively to the energy conversion process. This behavior can be attributed to improved carrier transport at the interface between the coating and the silicon substrate, resulting in more efficient extraction of photogenerated charge carriers.

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3.3. Analysis of the I–V Characteristics

The current–voltage characteristics shown in **Fig. 2** further confirm the beneficial effect of the WS_2 coating. Comparison of the I–V curves before and after deposition reveals an improvement in the operating region of the solar cell and an increase in the attainable output power.

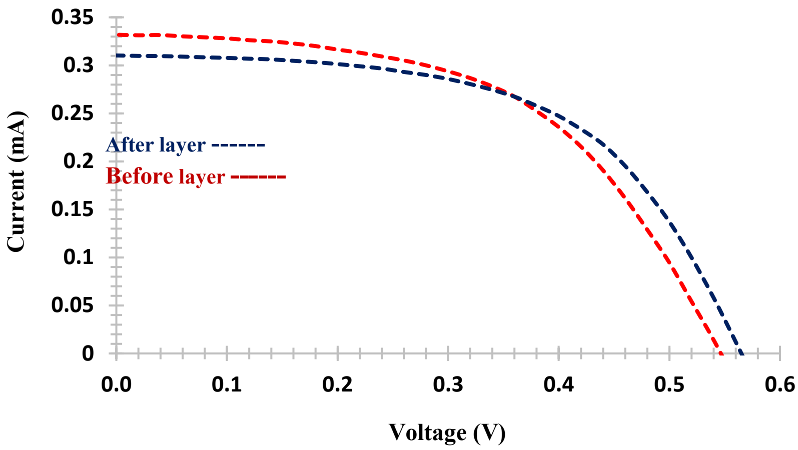

Fig. 2. Comparison of the (I-V) raw and the 400 Å coated sample.

The enhanced shape of the I–V curve is reflected by the higher fill factor obtained after deposition. Since the fill factor is strongly influenced by internal resistive losses and carrier recombination processes, the increase in FF suggests that the WS_2 layer contributes to improving the electrical quality of the device and reducing performance-limiting losses.

3.4. Effect of WS_2 Thickness on Solar Cell Performance

To determine the optimum coating thickness, the photovoltaic performance of all coated samples was compared with that of the uncoated solar cell. The results are summarized in **Table 2**.

Table 2. Fill factor and efficiency of the coated solar cells with various thicknesses.

	120Å	**240 Å**	**400Å**	**600 Å**	**Raw sample**
F.F	0.52	0.53	0.58	0.51	0.53
η(%)	8.4	9.1	10.0	8.3	9.5

Fig. 3 compares the current–voltage (I–V) characteristics of the uncoated silicon solar cell and the cells coated with WS_2 layers of different thicknesses. The figure clearly demonstrates that the electrical behavior of the solar cell is strongly influenced by the thickness of the deposited film. As the coating thickness increased from 120 Å to 400 Å, an improvement in the shape of the I–V curve and the operating region of the device was observed. The 400 Å-coated sample exhibited the most favorable characteristics, corresponding to the highest fill factor and maximum output power. In contrast, the 600 Å-coated sample showed a deterioration in performance, indicating that excessive film thickness adversely affects carrier transport and increases internal electrical losses. The results confirm that moderate WS_2 thicknesses provide more efficient charge collection and improved photovoltaic operation.

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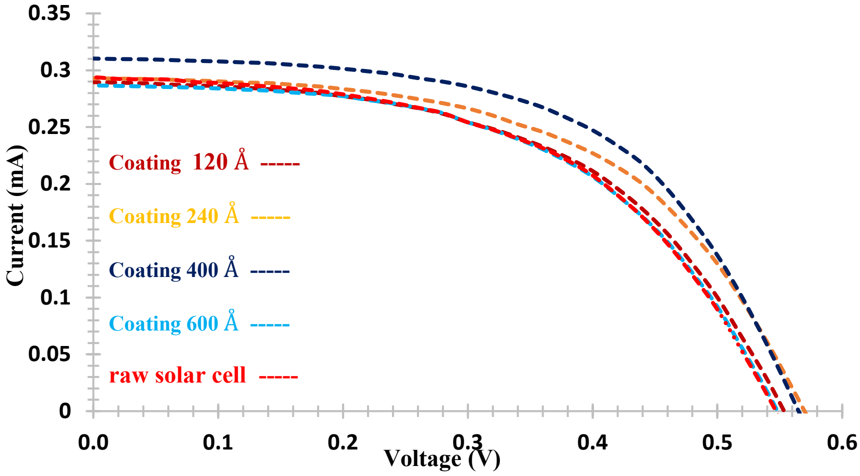

Fig. 3. Comparison of all coating states for (I-V).

Fig. 4 presents the power–voltage (P–V) curves of the silicon solar cell before and after deposition of WS_2 layers with different thicknesses. The maximum power point gradually increased as the coating thickness increased from 120 Å to 400 Å, demonstrating the positive influence of the WS_2 layer on energy conversion efficiency. The highest power output was obtained for the 400 Å sample, which is consistent with the efficiency and fill-factor results presented in Table 2. However, a further increase in thickness to 600 Å resulted in a reduction in the maximum power output. This behavior suggests that although the WS_2 coating improves the optoelectronic properties of the solar cell within an optimal thickness range, excessively thick films introduce additional optical absorption and electrical resistance that limit device performance.

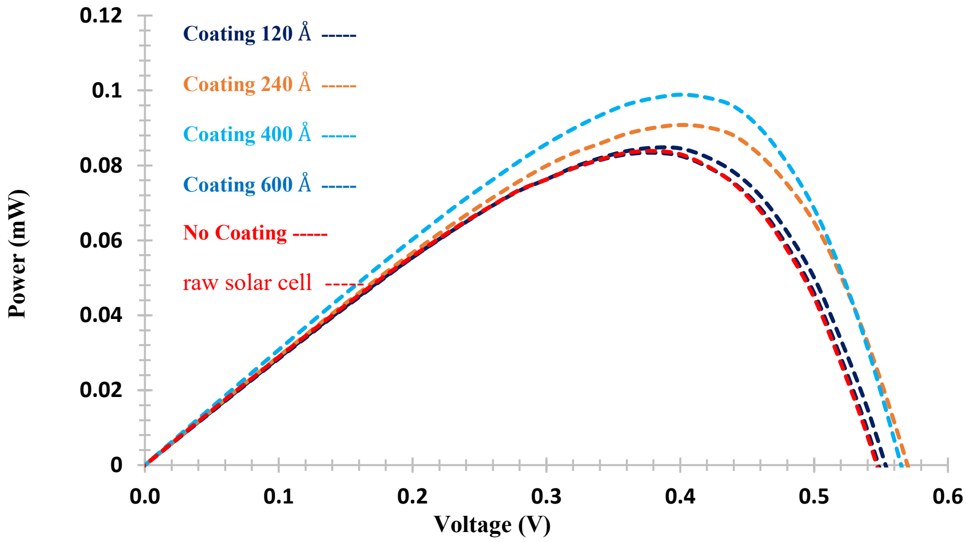

Fig. 4. Comparison of all deposition conditions (P–V).

A gradual improvement in efficiency was observed as the WS_2 thickness increased from 120 to 400 Å. The conversion efficiency increased from 8.4% at 120 Å to 9.1% at 240 Å and reached a maximum value of 10.0 % at 400 Å. A similar trend was observed for the fill factor, which increased from 0.52 at 120 Å to 0.58 at 400 Å.

The improvement in performance at moderate thicknesses can be attributed to enhanced light utilization, reduced surface recombination, and improved charge transport properties provided by the WS_2 coating. The deposited layer likely acts as a favorable interfacial medium, facilitating carrier extraction while minimizing electrical losses.

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However, when the thickness was increased to 600 Å, the efficiency decreased to 8.3%, and the fill factor dropped to 0.53. This behavior indicates that excessive film thickness adversely affects device performance. Thicker films may introduce additional series resistance, increase optical losses due to absorption and scattering, and hinder efficient carrier transport across the interface. As a result, the beneficial effects observed at lower thicknesses are partially offset, leading to reduced photovoltaic performance.

3.5. Optimum Thickness Determination

The experimental findings clearly demonstrate the existence of an optimum WS_2 thickness range for silicon solar cells. While thin and moderately thick coatings enhance device performance, excessively thick films introduce additional losses that outweigh their benefits. Among the investigated samples, the 400 Å WS_2 layer provided the most favorable balance between optical and electrical properties, resulting in the highest fill factor, maximum output power, and conversion efficiency. Therefore, the results suggest that WS_2 coatings with thicknesses between 240 and 400 Å are the most suitable for improving the performance of silicon solar cells fabricated using RF magnetron sputtering. These findings highlight the importance of thickness optimization when integrating transition metal dichalcogenide thin films into photovoltaic devices.
The optical absorption spectrum of the WS_2 film deposited on a SiO_2 substrate exhibits a distinct absorption feature at approximately 635 nm, which can be attributed to an excitonic transition in WS_2. This feature confirms the interaction of WS_2 with visible light and indicates that the WS_2 layer can modify the optical environment at the surface of the silicon solar cell. Although thickness-dependent absorption spectra were not measured for the individual WS_2-coated solar cells in this study, the observed optical response provides qualitative evidence for the potential optical contribution of the WS_2 layer to the photovoltaic performance.
The dependence of solar-cell performance on WS_2 thickness can be interpreted as a balance between optical and electrical/interfacial effects. At relatively low to intermediate thicknesses, increasing the WS_2 thickness can enhance light–matter interaction at the WS_2/Si interface and modify the local optical field. In addition, the WS_2 layer may influence interfacial recombination and charge-carrier extraction, thereby contributing to improvements in the fill factor and overall device performance. These effects are most favorable at a thickness of 400 Å, where the conversion efficiency increased from 9.5% for the uncoated cell to 10.0%, while the fill factor increased from 0.51 to 0.58.
However, increasing the WS_2 thickness beyond the optimum value can introduce additional optical and electrical losses. The decrease in efficiency to 8.3% at 600 Å, together with the reduction in the fill factor to 0.53, suggests that excessive film thickness may increase parasitic optical losses and electrical resistance, thereby limiting charge-carrier transport and collection. The efficiency at 120 and 240 Å was 8.4% and 9.1%, respectively, indicating that the photovoltaic performance initially improves with increasing WS_2 thickness and reaches its maximum at 400 Å. Therefore, the thickness-dependent photovoltaic response can be considered the result of a competition between the beneficial optical and interfacial effects of the WS_2 layer and the losses associated with excessive film thickness. Under the experimental conditions of this study, the 400 Å WS_2 coating provides the most favorable balance between these effects and results in the highest photovoltaic performance.

4. Conclusion

In this study, tungsten disulfide (WS_2) thin films were successfully deposited onto silicon solar cells using the RF magnetron sputtering technique, and the influence of coating thickness on photovoltaic performance was systematically investigated. The experimental results demonstrated that the electrical characteristics of the solar cells strongly depend on the thickness of the deposited WS_2 layer.

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The deposition of WS_2 films with thicknesses of 120, 240, and 400 Å led to improvements in the photovoltaic performance compared with the uncoated solar cell. The best performance was achieved at a thickness of 400 Å, where the fill factor increased from 0.51to 0.58, and the power conversion efficiency improved from 9.5 % to 10.0 %, corresponding to an efficiency enhancement of approximately 4.76%. In addition, the maximum output power increased from 0.0952 W to 0.0998 W, indicating improved charge-carrier collection and reduced performance losses.

In contrast, increasing the film thickness to 600 Å resulted in a decrease in efficiency and fill factor, suggesting that excessive coating thickness introduces additional optical and electrical losses that negatively affect device performance. These findings confirm the existence of an optimum WS_2 thickness range and demonstrate that thickness optimization is a critical factor in achieving enhanced photovoltaic performance.

Overall, the results indicate that WS_2 thin films deposited by RF magnetron sputtering can effectively improve the performance of silicon solar cells when an appropriate coating thickness is employed. The optimum thickness range identified in this work (240–400 Å) provides useful guidance for the integration of transition metal dichalcogenide (TMDC) materials into next-generation silicon-based photovoltaic devices.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data is used in this article

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